PROCEEDINGS
OF THE
KAON PDS MAGNET DESIGN WORKSHOP

VANCOUVER
OCTOBER 3–5, 1988

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March 1989
These proceedings bring together the papers given at the Magnet Design Workshop (October 3-5) which was held to kick off the KAON Factory PDS which was officially started on October 1, 1988.

The workshop included sessions on power supplies and measurements as well as synchrotron and kicker magnet design. The aim of the meetings was to bring together experts who could advise us on magnet and power supply techniques which, prior to the KAON era, have not been required at TRIUMF. These include fast-cycling cyclotron magnets and their power supplies, and the kickers needed to switch the beam from one ring to another or to the experimental areas. We also invited participation from industrial companies who will be potential magnet suppliers when the KAON Factory is funded. It was a pleasure to have representatives from six industrial companies amongst the participants.

A total of 51 people attended the meetings. They came from a variety of places, as listed below:

- Scientists and engineers from other laboratories: 23
- Scientists and engineers from TRIUMF: 18
- Scientists and engineers from industry: 9
- Government representatives: 1

The workshop was arranged in a little over seven weeks so the good attendance was encouraging and indicative of the world-wide enthusiasm for our project.

Several things were accomplished in the three days of presentations and discussions. We received lots of advice on how to build ac magnets and how not to build kickers. As a result of discussions and offers of help from other laboratories, our proposed kicker program has been completely revised. We also met and forged links with “the experts” from around the world, many of whom will visit us again as consultants during the PDS year.

These proceedings include a majority of the presentations given at the technical sessions plus a summary of the discussions which followed. We have also included as an appendix several written contributions sent to us as a result of ideas generated at the workshop and which are very pertinent to our KAON study.

The workshop was arranged by a committee of Ewart Blackmore, Mike Craddock, Al Otter and Lorraine King. Thanks are expressed to all the participants and particularly to our invited speakers, who came at short notice and assisted us by chairing the discussion sessions:

- B. Berkes
- D. Fiander
- N. Marks
- M. Harold
- J. Rümmler
- V. Rödel
- H. Sasaki
- W. Praeg

We would also like acknowledge the able secretarial assistance of Krish Thiruchittampalam, Margaret Lear and Maureen White during the workshop and of Jana Thomson in the preparation of these proceedings.
## CONTENTS

Preface .................................................................................. iii
Opening remarks, A. Astbury .................................................... 1
TRIUMF’s KAON Factory accelerators, M. Craddock .......................... 2

### Fast-Cycling Magnets

- Ac magnets for the KAON Factory accelerators, U. Wienands and R.V. Servranckx .......................................................... 11
- The design, manufacture and testing of the ISIS fast-cycling magnets, M.R. Harold ................................................................. 15
- Design and measurement of ac magnets at DESY II, G. Hemmje .......................................................... 27
- A dc biased rapid-cycling magnet system operating in a dual frequency mode, H. Sasaki, T. Adachi, H. Someya and I. Sakai ........................................... 33
- ESRF booster synchrotron magnet and power supply design, N. Marks ...................................................... 41
- Power supply considerations for magnet design, K. Reiniger .............................................................................. 50
- Fermilab magnet construction, J.C. Humbert ...................................................................................... 51
- The status of the booster dipole design and plans for the Project Definition Study year, A. Otter .......... 56
- KAON Factory magnets, V. Verma ........................................................................................................... 62

### Kickers

- Kicker requirements for the KAON Factory, U. Wienands ........................................ 68
- Kickers and septa at the PS complex, CERN, D. Fiander, K-D. Metzmacher and P. Pearce ...................................................................... 71
- New stripekicker in the injection chain of HERA, J. Rümmel ............................................................................. 80
- Overview of kicker magnet systems at the SPS and LEP, V. Rödel and G.H. Schröder ...................................................................................... 87
- A kicker upgrade for Los Alamos proton storage ring, H.A. Thiessen .......................................................... 96
- A preliminary design of the Los Alamos fast kicker magnet pulser and power supply, R.A. Winje .......................................................... 101

### Measurements and Radiation-Hard Magnets

- Magnet requirements for experimental areas, E.W. Blackmore and A.J. Otter .......................................................... 106
- Radiation-hardening of magnet coils, A. Harvey ...................................................................................... 112
- Search coil measurements of particle accelerator magnets, K.N. Henrichsen .......................................................... 119
- Ac magnetic measurements of the ALS booster synchrotron dipole magnet engineering model, M.I. Green, E. Hoyer, R. Keller and D.H. Nelson .............................................................................. 124
- Loss measurement programs at TRIUMF, A. Otter and W. Neves .......................................................... 132
- Methods of estimating iron losses and field errors in ac magnets, P.A. Reeve ...................................................................................... 136

### Reports on Working Discussions

- Kickers, D. Fiander ........................................................................ 139
- Fast-cycling magnets, M.R. Harold .......................................................... 142
- Magnet power supply system, N. Marks ...................................................................................... 144
- Industrial participation, A. Otter ...................................................................................... 148
Appendix

A shielded energy-storage choke for rapid-cycling synchrotrons, W.F. Praeg .......... 150
Dual versus single frequency ring magnet power supplies for rapid-cycling
synchrotrons, W.F. Praeg ................................................................................................. 157
Calculating the frequency response of magnets with laminated cores,
W.F. Praeg ......................................................................................................................... 164
A prototype kicker magnet for the kaon factory, V. Rödel ........................................ 172

List of participants ............................................................................................................. 177
Let me begin by welcoming you to this Magnet Workshop which is a part of what is known as the KAON Factory Project Definition Study. In particular I would like to thank our experts, many of whom have crossed several time zones in coming to Vancouver to help us. We believe we have some challenging problems, we know you have the expertise to solve them. It is perhaps interesting to outline the steps – but not all of them! – which have led to the present stage of the TRIUMF KAON Factory Project.

Our proposal for a 30 GeV 100 μA facility was worked on during 1984 and 1985, and finally tabled in September 1985. The two Canadian Research Councils (NRC and NSERC) struck two committees. The first of these – a Joint International Technical Review Committee – met in February 1986 and gave the proposal an extremely high rating for science and potential realisation within the proposed budget and timescales. The second committee – a Joint “Canadian” Review Committee – was charged with examining the proposal in the very broad context of Canadian Science. They endorsed the excellence of the science, but could not agree that the funding of such a major initiative in Canada would not grossly distort the support to basic science in the country. The councils of NRC and NSERC accepted this view, but of course the management of TRIUMF could not. In February of 1987 the KAON Factory Proposal was presented to the Economic Development Committee of the Cabinet of the British Columbia Provincial Government where it found immediate support to the extent of a full commitment of B.C. to provide $98M of civil engineering.

During 1987 the idea emerged of a jointly funded project which would define better the design and costs of the KAON Factory, explore fully the possibility of international contributions in a HERA style model, and study the Canadian industrial capabilities for building, and potential future enhancements which might be gained from the experience of building. This is now our Project Definition Study, and the joint Federal and Provincial agreement was signed by the Ministers Mr. Frank Oberle and Mr. Stan Hagen in Vancouver on July 21, 1988, making available $11M for the study.

We have subsequently presented our budgets to the Steering Committee and in fact these were put in place – effective October 1. Here we are now on October 3, the first official working day of the project, kicking off with our Magnet Workshop. We believe we are on the way towards building our KAON Factory, we know we have many problems to solve, we can’t think of a more pleasant beginning then sharing some of these problems with you.
THE TRIUMF KAON FACTORY ACCELERATORS

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ABSTRACT

The TRIUMF KAON Factory proposal has made considerable progress on both technical and political fronts over the last year. For the main rings a racetrack-shaped lattice has now been adopted in conjunction with a three-element slow extraction system in an effort to reduce losses to the 0.1% level. Hardware studies have continued on both magnet power supplies and on rf cavities – the latter work gaining an extra dimension from a recently instituted formal collaboration with LAMPF. The H⁻ extraction system for the cyclotron has been tested successfully with 66 μA pulsed and 10 μA average beams. On the political side, British Columbia has agreed to fund the buildings and tunnels (Cdn $87M) and is contributing jointly with the Canadian federal government to an $11 million pre-construction R & D study over the next 15 months. This will allow construction of prototypes of magnets, power supplies, kickers, rf cavities, ceramic beam pipes, targets and controls. It will also permit economic and environmental impact studies and formal consultations abroad. These will follow up on the exploratory talks last year, when it was found that a number of countries would consider making significant contributions to the cost. These steps would pave the way for project approval in mid-1990.

INTRODUCTION

This talk will outline the design of the KAON Factory accelerators and review the technical studies now under way. The TRIUMF Kaon-Antiproton-Otherhadron-Neutrino Factory is fully described in the original proposal¹ and outlined in various papers.²,³ The primary aim is to provide a 100 μA beam of protons at 30 GeV – about a hundred times more than available at present. The TRIUMF H⁻ cyclotron, which routinely delivers 150 μA beams at 500 MeV, would provide a ready-made and reliable injector. It would be followed by two fast-cycling synchrotrons, interleaved with 3 storage rings, as follows:

A Accumulator: accumulates cw 450 MeV beam from the cyclotron over 20 ms periods
B Booster: 50 Hz synchrotron; accelerates beam to 3 GeV; circumference 214 m
C Collector: collects 5 Booster pulses and manipulates longitudinal emittance
D Driver: main 10 Hz synchrotron; accelerates beam to 30 GeV; circumference 1072 m
E Extender: 30 GeV stretcher ring for slow extraction for coincidence experiments

It can be seen from the energy-time plot (Fig. 1) that this arrangement allows the cyclotron output to be accepted without a break, and the B and D rings to run continuous acceleration cycles without wasting time on flat bottoms or flat tops; as a result the full 100 μA from the cyclotron can be accelerated to 30 GeV for either fast or slow extraction.

The use of fast-cycling synchrotrons lowers the proton charge per pulse Ne to 2 μC (Booster) and 10 μC (Driver), levels at which the space-charge tune shift at injection is tolerable (∆Q≤0.2). Since ∆Q ∝ Ne*(βγ²) inj the use of a Booster permits a smaller normalized

¹On leave from Physics Dept., University of British Columbia, Vancouver, B.C., V6T 2A6.
emittance $e^*$ and hence reduces the aperture and cost of the Driver magnets. The Booster energy is chosen to minimize the total cost of the project. Since this depends mainly on magnet costs, the minimum is found to occur when the emittances set by the space charge tune shift formula are the same for both machines.$^{3,4}$

The use of a Booster also simplifies the rf design by separating the requirements for large frequency swing and high voltage (33% and 600 kV respectively for the Booster, and 3% and 2400 kV for the Driver). These high rf voltages are associated with the high cycling rates; the use of an asymmetric magnet cycle with a rise time 3 times greater than the fall (Fig. 1) reduces the voltage required by one-third, and the number of cavities in proportion.

Figure 2 shows a proposed site layout together with cross-sections through the tunnels, with the Accumulator above the Booster in the small tunnel, and the Collector and Extender rings above and below the Driver in the main tunnel. Identical lattices and tunes are used for the rings in each tunnel. This is a natural choice providing structural simplicity, similar magnet apertures and straightforward matching for beam transfer.
Separated-function magnet lattices are used with a FODO quadrupole arrangement. In the A and B rings missing dipoles are arranged to give superperiodicity $S=6$. This automatically provides space for rf and beam transfer equipment. It also modulates the dispersion function $\eta_z$ and drives its mean value $<\eta_z>$ towards zero, enabling transition to be driven above top energy. In the absence of zero-dispersion straights, nearby synchrotron resonances are suppressed by placing the rf cavities symmetrically with the magnet superperiodicity.

For the C,D and E rings a racetrack lattice has now been adopted in place of the originally-proposed $S=12$ lattice. As explained below, this provides the long straights required for a super-efficient slow extraction and collimation system in the E ring, while keeping $\gamma_t$ above top energy.

Injection into the Accumulator is achieved by stripping the H$^-$ beam from the cyclotron (see below) enabling many turns to be injected into the same area of phase space. The small emittance beam from the injector is in fact painted over the much larger three-dimensional acceptance of the Accumulator to limit the space charge tune shift. Painting also enables the optimum density profile to be obtained and the number of passages through the stripping foil to be limited.

Work on the design has continued since the proposal was issued in 1985. Up to now limited funds have restricted hardware development to rf cavities, magnet power supplies, targets and H$^-$ extraction from the cyclotron. But with the onset of the $11M Project Definition (pre-construction) Study this month prototype construction will be extended to magnets, kickers, ceramic beam pipes and controls. The following section describes individual developments. Another major development was the institution in August 1987 of a formal collaboration with LAMPF on accelerator studies. The first areas for collaboration have been rf studies and beam commissioning work on the Los Alamos Proton Storage Ring. The mutual benefits of this arrangement are already apparent.

TECHNICAL STUDIES

Magnet Lattices and Slow Extraction

Considerable thought has been given to the possibility of reducing the losses at slow extraction to 0.1% rather than the 1% typically obtainable with existing systems. U. Wienands has suggested the use of a short additional pre-septum to dilute the beam density at the main septum, demonstrating, in a simulation, a loss of only 0.2%. A third septum could not easily be accommodated in the superperiodicity-12 lattice of our main ring reference design. Instead, R.V. Servranckx has proposed a racetrack lattice (Fig. 2) with two dispersionless 167 m long straight sections. Horizontal $\beta$ values of about 100 m are obtained near the focusing quadrupoles, providing low density locations for the septa. The achromatic $180^\circ$ arcs contain 24 cells, and are tuned to $5 \times 2\pi$ ($\sim 75^\circ$) per cell. The tune of the straight sections may be adjusted to give a total tune variation for the ring of $\pm 1$ in each plane independently. A half-integer resonance may be used for extraction, to simplify the collimation process. Such a racetrack lattice is convenient for the Driver synchrotron as well as for the Extender, providing more flexibility either for the insertion of Siberian snakes, or for tuning for low depolarization without snakes, using high-periodicity arcs and spin-transparent straight sections. Investigation of the properties of the lattice in detail show that it is no more sensitive to betatron resonances than the old circular design, and hence it has been adopted as the new reference design.
Racetrack lattices are also being investigated for the Booster and Accumulator rings, where they would provide dispersion-free regions for rf cavities and beam transfer. A FODO lattice, similar to that proposed for the main rings, but with 4 superperiods and a tune of 3 per arc, has been considered, but requires rather short dipoles and too many ceramic-steel vacuum joints. Alternatives under investigation are doublet and triplet lattices, and a hybrid using combined-function dipole magnets. U. Wienands\textsuperscript{8} gives more details of the lattices and magnet specifications.

Magnet Development

Design studies are underway on both separated and combined function dipole magnets for the Booster ring and are fully described by A.J. Otter.\textsuperscript{9} One of these designs will be selected for prototyping, while design studies continue on the various other magnets needed in both accelerators and beam lines.

Magnet Power Supplies

As explained above, dual-frequency magnet excitation is planned for the synchrotrons, with a rise time three times longer than the fall. To test the performance of such a system a high-power test stand has been set up (Fig. 3). Four magnets from the decommissioned NINA synchrotron are used, one as the load and three in series as the resonant 81 mH choke. A 1000 \( \mu \)F capacitor bank may be switched in parallel with a 125 \( \mu \)F bank to change the resonant frequency from 100 Hz to 33 Hz. This stand has been operating for a short while now and successful tests have been carried out at fixed frequencies (Reiniger\textsuperscript{10}).

Fig. 3. High-power test stand for dual-frequency magnet excitation studies.
Kickers

With the increased funding available from the Project Definition Study work has recently begun on the design of the extraction kicker for the Booster ring – probably the kicker with the most challenging specifications – about 60 kV across an 8 cm gap over a length of 2 m and with a rise time ≤ 80 ns. Our aim is to have a prototype kicker operating by the end of 1989.

Radio Frequency Systems

The reference design for the Booster cavities is based on those used in the Fermilab booster. A full scale prototype cavity is almost complete and should be ready for tests with an air tuner soon (Poirier et al.11). The collaboration with LAMPF has also enabled us to study the possibility of using a version of the Los Alamos cavity which employs perpendicularly-biased microwave ferrite. Under dc bias conditions this has produced relatively high voltages (140 kV), potentially reducing the number of cavities required and, more importantly, the impedance presented to the beam and the likelihood of inducing coupled-bunch instabilities. In September 1987 the TRIUMF group was able to make measurements on the Los Alamos cavity and demonstrate its operation with good Q-values down to and below the lowest frequencies (46 MHz) required at TRIUMF (Fig. 4).

![Fig. 4. Permeability measurements on the Los Alamos booster cavity showing good behaviour over the entire frequency range required at TRIUMF.](image)

Enegren and Poirier12 have calculated the transmission-line cavity modes for the Los Alamos and Fermilab-style cavities. The effect of damping was also investigated. These studies indicate a further advantage of the Los Alamos cavity, whose shortness reduces the number of modes in a given frequency interval.

With the Los Alamos group transferring their activities to the development of a main ring cavity, they have generously made their booster cavity available on loan to TRIUMF, where it will be tested under ac bias conditions – the crucial remaining test of its viability.
R. Burge\textsuperscript{13} and W. Roberts\textsuperscript{14} have studied control of the rf systems under high beam loading. Burge presents designs of feedback circuits for phase and amplitude control. S. Koscielniak\textsuperscript{15} has made an analytical study of radial and phase control of the rf taking explicit account of time delays. Local pickups appear to be preferable to shared ones and the radial loop control signal should drive the master oscillator rather than a phase adjuster upstream. As part of its collaboration with LAMPF TRIUMF will build the low-level control system and also a solid state driver for the main ring cavity. Kwiatkowski \textit{et al.}\textsuperscript{16} have described the design of the power amplifier for the Booster cavities.

**Beam Pipe & Vacuum**

The vacuum requirements for all five rings are being carefully reviewed (Oram \& Baartman\textsuperscript{17}). The high circulating beam current makes ion desorption from the walls the most critical process. This requires a hydrocarbon-free system with all metal elements pre-baked to 300°C, and pumps spaced no more than 5 m apart. This will automatically result in vacua better than $10^{-8}$ Torr. An additional concern in the Extender ring, where the beam may be debunched, is the possibility of electron-proton oscillations; electrostatic collector plates will be needed to suppress these.

**Computer Control System**

A six-month study of the KAON Factory control system has been completed with the help of two visitors from CERN. A comprehensive review was carried out of both hardware and software options and a full report is now available (Dawson \textit{et al.})\textsuperscript{18}. A test platform is being assembled based on a VAX3200 workstation with a bridged Ethernet connexion to 2 VME crates.

**H$^-$ Extraction from the cyclotron**

To extract H$^-$ ions (instead of stripping them to protons as in normal operation) a conventional extraction system is being developed. Laxdal \textit{et al.}\textsuperscript{19} report that with 18 kV on
the rf deflector and 50 kV on the electrostatic deflector 90% of the beam (66 μA macropulses at 1% duty factory) is transmitted through the latter (Fig. 5). The 10% not transmitted is stripped by a narrow foil shadowing the septum and protecting it from irradiation; the resulting protons may be dumped or steered into an experimental beam line. The differential scan in Fig. 3 illustrates the intensity modulation and improved turn separation produced by the rf deflector in conjunction with the \( Q_r=3/2 \) resonance. In recent tests the average beam current was successfully raised to 10 μA. Design of the 4-segment magnetic channel which will steer the \( \text{H}^- \) beam out of the cyclotron is now almost complete. Detailed design of the front end of the external beam line is under way.

PROGRESS TOWARDS FUNDING

Good progress has been made over the last year, a crucial factor being the British Columbia provincial governments's strong support for the project as its top priority among federal projects and the centrepiece of its high-tech development strategy. In February 1987 the B.C. cabinet gave the project formal approval in principle; i.e. agreement to fund the civil works (\$87M Canadian) provided the federal government funds the technical equipment. A tangible symbol of the B.C. government's commitment has been its commissioning of specially-labelled "KAON Project" wine, which has already emerged the winner of an international tasting contest and which you will have the opportunity of sampling during this workshop!

On the federal side the Minister of State for Science and Technology, Mr. Frank Oberle, last year agreed to institute joint federal-provincial studies of additional university involvement and international contributions to the funding. On the first issue the four founding universities of TRIUMF have already been joined by the University of Manitoba and L'Université de Montréal as associate members, while the University of Toronto is to join shortly.

On the second item, Mr. Oberle himself, in a speech to the OECD nations in Paris, stated "we are anxious to seek and develop other joint ventures", giving us an example "...international partnership in the construction of the Kaon Factory". A Canadian delegation was appointed to explore the potential for such partnership and in November and December 1987 visited West Germany, Italy, Japan and the U.S.A. Each country agreed to consider financial involvement in construction, and indeed the possibility of support is being explicitly allowed for in the planning scenarios of both Germany and Italy. If negotiations are successful the external contributions will amount to considerably more than the \$75M recommended by the Kaon Factory Review Committee. Besides the countries mentioned above, Belgium, Britain, Israel and the People's Republic of China have all expressed interest in participating in experiments and in some cases in accelerator design and construction.

These discussions will now continue more formally under the aegis of the \$11-million Project Definition Study which began officially on 1 October, funded jointly by the governments of Canada and British Columbia. The projects being funded are as follows:

<table>
<thead>
<tr>
<th>Accelerator Design</th>
<th>Project Management</th>
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<td>RF Prototypes</td>
<td>Building Design</td>
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<tr>
<td>Magnet Prototypes</td>
<td>Tunnel Design</td>
</tr>
<tr>
<td>Magnet Power Supplies</td>
<td>Service and Power Distribution</td>
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<tr>
<td>Beam Pipe</td>
<td></td>
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<tr>
<td>Kickers</td>
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<tr>
<td>Cyclotron Beam Extraction</td>
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</table>
Shielding and Safety  Industry Development  
Targets  International Consultations  
Controls  Economic Assessment  
Systems Integration  Legal & Environmental Studies  
Experimental Areas  
Science Workshops  

This pre-construction study is expected to be complete by the end of 1989, leaving the way clear for final approval of the project in early 1990.

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the efforts of all those who have worked to improve the KAON Factory design over the past year. The author is particularly grateful to Jana Thomson for the accuracy of the typing.

REFERENCES

10. K. Reiniger, “Power Supply Considerations for Magnet Design”, these proceedings.
15. S. Koscielniak, ibid., p 262.

AC MAGNETS FOR THE KAON FACTORY ACCELERATORS

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R.V. Servranckx
Saskatchewan Accelerator Laboratory, Saskatoon, Sask., Canada S7N 0W0
and TRIUMF

ABSTRACT

The requirements for the magnets for the KAON Factory accelerators are given. Besides a tabulation of the magnet data, field uniformity is discussed and limits are derived from tracking studies. Dynamic tolerances are discussed.

INTRODUCTION

Altogether, about 800 magnets will be needed for the 5 rings of the KAON Factory accelerator complex. Of these magnets 500 will be dc magnets, 200 ac magnets cycling at 10 Hz, and 100 ac magnets cycling at 50 Hz. In this paper the requirements for the ac dipole and quadrupole magnets for the KAON Factory accelerators are discussed. The magnets will be looked at from the point of view of the beam physicist, i.e., with regard to field quality, aperture, and effective lengths, rather than from the magnet builder’s point of view, who may be concerned with other problems such as lamination thickness, pole profiles, etc. For specifying the magnets of the Driver ring we will take the newly developed racetrack lattice as the reference design, while Booster magnet data for two lattices are given, for the circular lattice as given in the KAON Factory proposal and for an alternative racetrack lattice currently under investigation. The latter uses defocusing combined-function dipole magnets and separate focusing quadrupoles, hence its being referred to as hybrid lattice. In Figs. 1 and 2 beam envelopes for the racetrack lattices are given for the nominal emittance of the beam at injection, \( \epsilon_{x} = 140 \pi \text{ mm-mrad} \), \( \epsilon_{y} = 62 \pi \text{ mm-mrad} \) for the Booster, and \( \epsilon_{x} = 36.1 \pi \text{ mm-mrad} \), \( \epsilon_{y} = 16.8 \pi \text{ mm-mrad} \) for the Driver.

MAGNET DATA

Basic data for the dipoles are given in Table I and for quadrupoles in Table II. The beam sizes contain a safety factor of two in the emittance and allowance for closed-orbit distortions and for dispersion. The beam emittances are determined by space-charge tune shift that is to be less than 0.15 at injection and contain some allowance for emittance blowup in the ring and during transfer from ring to ring. The gap height contains 1 cm allowance on each side for vacuum chamber thickness and clearance to the pole faces. The maximum fields drop with repetition rate, hence the lower peak field of 1.05 T for the Booster, while the Driver bending magnets peak at 1.35 T. The different rise and fall times of the (sinusoidal) magnet cycle reflect the proposed use of a dual frequency magnet excitation in order to reduce the maximum rf accelerating voltage needed. Of the two Booster scenarios, the hybrid racetrack Booster needs much less aperture than the circular lattice; however, the dipoles have a field index of about 50 and will be more difficult to design and build and also may have higher stored energy.
# Table I. Dipole magnets.

<table>
<thead>
<tr>
<th>Ring</th>
<th>Driver</th>
<th>Booster circ.</th>
<th>Booster (n=50)</th>
<th>Units</th>
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<td></td>
<td>hor.</td>
<td>hor.</td>
<td>hor.</td>
<td>vert.</td>
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<tr>
<td>(\sqrt{2}\beta e)</td>
<td>4.85</td>
<td>5.74</td>
<td>3.10</td>
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<tr>
<td>(d\eta)</td>
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<td>0.78</td>
<td>0.23</td>
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<tr>
<td>2 c.o.d.</td>
<td>0.32</td>
<td>0.7</td>
<td>0.7</td>
<td>0.5</td>
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<tr>
<td><strong>Total</strong></td>
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<td>7.3</td>
<td>4.1</td>
<td>3.4</td>
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All values are 1/2 values: total rounded up to next mm.

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<td>96</td>
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# Table II. Quadrupole magnets.

<table>
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<th>Booster circ.</th>
<th>Booster (n=50)</th>
<th>Units</th>
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<tr>
<td>(d\eta)</td>
<td>1.81</td>
<td>2.14</td>
<td>0.34</td>
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<tr>
<td>2 c.o.d.</td>
<td>0.32</td>
<td>0.7</td>
<td>0.7</td>
<td>cm</td>
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<tr>
<td><strong>Total</strong></td>
<td>7.3</td>
<td>9.4</td>
<td>5.5</td>
<td>cm</td>
</tr>
</tbody>
</table>

All values are 1/2 values: total rounded up to next mm.

<table>
<thead>
<tr>
<th>radius</th>
<th>8.3</th>
<th>10.4</th>
<th>6.5</th>
<th>cm</th>
</tr>
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<tbody>
<tr>
<td>length</td>
<td>1.4</td>
<td>0.65</td>
<td>1.1</td>
<td>T</td>
</tr>
<tr>
<td>(B_{\text{tip, min}})</td>
<td>0.12</td>
<td>0.17</td>
<td>0.17</td>
<td>T</td>
</tr>
<tr>
<td>(B_{\text{tip, max}})</td>
<td>1.01</td>
<td>0.63</td>
<td>0.63</td>
<td>T</td>
</tr>
<tr>
<td>(f_{\text{rep}})</td>
<td>10</td>
<td>50</td>
<td>50</td>
<td>Hz</td>
</tr>
<tr>
<td>(t_{\text{rise}})</td>
<td>75</td>
<td>15</td>
<td>15</td>
<td>ms</td>
</tr>
<tr>
<td>(t_{\text{fall}})</td>
<td>25</td>
<td>5</td>
<td>5</td>
<td>ms</td>
</tr>
<tr>
<td>number</td>
<td>48</td>
<td>24</td>
<td>32</td>
<td></td>
</tr>
</tbody>
</table>
FIELD QUALITY

In order to examine the effects of nonuniformity of the field, the horizontal field profile of a preliminary design for a Driver dipole was parametrized in the form of field harmonics. These field harmonics were simulated by multipole elements in a computer model of the Driver ring using the code DIMAD. Figure 3 shows the field shape used for the Driver dipole magnet. The field uniformity is about $\pm 4 \times 10^{-4}$ over the aperture of 7.3 cm. For the quadrupoles measured field harmonics of a standard TRIUMF 20 cm quadrupole were used, having typical field harmonics of a few $10^{-3}$ of the pole-tip field at 8 cm radius. Tracking runs showed the acceptance of the machine with these magnets to be about 1.3 times the design emittance of the beam. This is acceptable although in view of finite alignment tolerances.
of the machine and resulting orbit excursions, the requirements may eventually turn out to be somewhat more stringent. A similar study done for the circular Booster indicates an acceptance of 1.5 times the beam emittance for ±7.5 cm good-field region. Acceptance was limited by the field uniformity of the dipoles rather than of the quadrupoles.

Another issue with ac magnets is the dynamic behaviour, i.e., errors in magnet field setting, especially at injection/extraction, tracking errors, etc. In general we found variations on the order of $10^{-4}$ to be tolerable without special corrections, while errors on the order of $10^{-3}$ need corrective action by trim elements; this is true for field setting and field tracking errors. Reproducibility from cycle to cycle is almost impossible to correct; therefore, a variation of less than $10^{-4}$ from cycle to cycle is needed. For the field index of the combined function magnets of the hybrid Booster a tolerance of $10^{-3}$ appears to be tolerable.

REFERENCES

3. C. Manz, TRIUMF design note TRI-DN-87-31 (1987);
   G. Wellman, Horizontal Studies for the KAON Factory Driver Ring” (U. Wienands, private communication).
Introduction

Preliminary design work on a spallation neutron source [1] was begun in 1975. The SNS (the name was later changed to ISIS) was approved in 1977, and beam was first accelerated and extracted in 1984.

ISIS uses a synchrotron designed to provide 180 μA (2.5 E13 protons per pulse) at 800 MeV with a pulse repetition frequency of 50 Hz. Injection at 70 MeV is achieved by the stripping of H\(^+\) ions, and acceleration in two bunches is provided by six RF stations. The beam is extracted in the vertical plane and taken to the U 238 target by means of a beamline 150 m long (fig 1). ISIS presently operates at a current of about 100 μA at 750 MeV.

The synchrotron has a mean radius of 26 m and superperiodicity of 10. Much of the circumference consists of straight-section space, due to the requirements of injection, extraction, diagnostics and the RF. The design emittances are 540 and 430 mm·mrad in the horizontal and vertical planes respectively, figures which lead to large aperture magnets.

Each superperiod (fig. 2) consists of a 36 deg dipole, a quadrupole doublet and a singlet defocusing quadrupole, all of which are electrically in series. The dipole has a weak transverse gradient to provide horizontal focusing. Associated with each of the doublet quads is an independently-powered trim quadrupole, and there are eleven orbit-correcting dipoles [2]. Spaces have been reserved for sextupoles and octupoles; these have been designed but not yet manufactured. The magnet parameters are given below.

<table>
<thead>
<tr>
<th>Magnet</th>
<th>Dipole</th>
<th>Doublet P(D)</th>
<th>Singlet D</th>
<th>Trim</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of magnets</td>
<td>10</td>
<td>10(10)</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Field at injection (T)</td>
<td>0.176</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field at 800 Mev (T)</td>
<td>0.697</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normalized gradient</td>
<td>-0.06785</td>
<td>0.6377</td>
<td>-0.7262</td>
<td>0.103</td>
</tr>
<tr>
<td>Aperture, inscribed dia. (mm)</td>
<td>160</td>
<td>274</td>
<td>212</td>
<td>274</td>
</tr>
<tr>
<td>Good field region H (mm)</td>
<td>190</td>
<td>252</td>
<td>104</td>
<td>220</td>
</tr>
<tr>
<td>Good field region V (mm)</td>
<td>140</td>
<td>186</td>
<td>148</td>
<td>176</td>
</tr>
<tr>
<td>Core length (mm)</td>
<td>4400</td>
<td>609(592)</td>
<td>303</td>
<td>203</td>
</tr>
<tr>
<td>Magnetic length (mm)</td>
<td>4400</td>
<td>730(715)</td>
<td>402</td>
<td>314</td>
</tr>
<tr>
<td>Turns/pole</td>
<td>42</td>
<td>22</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Inductance/magnet (mH)</td>
<td>143</td>
<td>10</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Peak current (A)</td>
<td>1062</td>
<td>1062</td>
<td>1062</td>
<td>250</td>
</tr>
<tr>
<td>RMS current (A)</td>
<td>720</td>
<td>720</td>
<td>720</td>
<td>150</td>
</tr>
</tbody>
</table>
Pre-approval design work.

The design of the magnets was dominated by the already existing power supply. This consists (fig. 3) of a resonant choke having 10 secondaries, with the make-up power being provided by an impulse circuit (this was replaced by a rotary machine giving continuous make-up). The power supply and capacitors were donated by Daresbury Laboratory, who were replacing NINA with a synchrotron light source. The choke was rated at 14.32 kV, 722 A rms, but had never been run to its full capacity. Calculations showed that the stored energy of the ISIS magnets at 800 MeV would be very close to the power supply limit, and in order to both gain experience and test the calculations two dipoles were constructed in the laboratory.

The dipoles were roughly 1/3 rd in cross-sectional scale, 0.46 m in length and made from 0.5 mm silicon steel laminations glued together. They were placed in a White circuit (fig. 4), so that DC could be injected to produce a biased field. Instrumentation was modest, but despite this a measureable increase in make-up power was registered when the bias current was applied. This increase amounted to an additional hysteresis loss of about 75% compared with the theoretical loss with no bias.

Looking for eddy-current effects (sextupole) in the guide field, no out-of-phase field component could be detected with search coils at the edge of the good field region. We saw the expected temperature rise at the pole ends; these had a Rowgowsky rolloff which was approximated in steps rather than continuously. A neat method of measuring change in effective length against radius, at any field level but at 50 Hz, was successfully tried [3]. The DC field quality was in reasonable agreement with the GFUN [4] predictions.

For a variety of reasons it was decided at this time that all magnetic measurements would be done under DC or quasi-DC conditions. Much of the period was spent in planning the quadrupole measurement system, which was to use a rotating harmonic coil, and in determining the basic parameters of all the magnets, such as conductor composition, number of turns, yoke sizes, etc.

The choice of conductor lay between the indirectly cooled type, as used at CEA, DESY and Daresbury, or one which was directly cooled. The former is very economical in power consumption and requires only simple manifold, but is difficult to make, has a very low average current density and the coil overhangs use up valuable straight-section space. With the latter, a higher current density is possible at the expense of power consumption and more extensive manifolding. Greater reliability in service was also expected from this type of coil.

The fields in the coil slots were determined using BIM2D [5], and the eddy-losses calculated by hand (the results were confirmed some years later using PE2D [6], which was not available at the time). For all the series-connected magnets it was found that a cable consisting of four water-cooled conductors, insulated from one another but wound in
parallel, would result in acceptable losses and average temperature rises of about 20 deg C. Because of the harsh environment in which the coils were operating (high radiation, high voltage, possible vibration) the temperature rise was to be kept as low as possible to reduce mechanical stresses.

The dipole coil, because of its 4.4 m length, required manifolding (and transposition of the conductors) for each of its six layers, one layer consisting of seven turns. For the doublet quadrupoles, transposition and manifolding occurred at each pole, but for the singlets the water path could extend over two poles and this led to a much simpler and neater design.

The steel to be used for all the series-connected magnets was selected; this was British Steel Corporation's TRANSIL 315-35, a silicon transformer steel, 0.35 mm thick, with good permeability and an inorganic insulation coating.

Doublet quadrupoles

The F and D quadrupoles were so similar in strengths that they were made identical (fig. 5) apart from a difference of 17 mm in core length. Made in four quadrants, the laminations were glued together and straps welded down the outside. The 10 mm-thick endplates did not extend over the poles, and through-bolts were used to guard against de-lamination. The peak field at the pole-tips being only 0.43 T, there was no roll-off at the pole-ends: any saturation effects would be corrected with the trim quadrupoles. To reduce eddy-heating at the ends, slits were cut into the poles of the end laminations.

The pole profile consisted of a hyperbola with tangent shims, and was calculated using BIM2D and GFUN. The tolerances on gradient uniformity were not very severe because of the short (10 msec) acceleration time, and since the measurements (fig. 6) agreed with GFUN to better than 0.5% in integrated gradient, no changes were necessary to the profile. Because of our inexperience, however, after the prototype had been tested many changes were necessary to the manifolding and the supports.

In order to reduce future radiation exposure to personnel, magnet replacement was to require the minimum of alignment; a master base and alignment fixture were built and all the quadrupoles adjusted on their supports so as to be interchangeable. These supports therefore had to be particularly robust and free from 'stiction'. The doublet and trim quadrupoles were mounted on a single concrete base and then moved as a whole into the synchrotron hall. In the event of a major fault occurring, the set of four would be removed and replaced with a spare set.

The manufacturer (no longer trading) initially had difficulty in producing coils which were properly impregnated, the first coil being completely dry inside. This was traced to the fact that the resin in the mould was not adequately covering the coil tails; when air was admitted to the vacuum chamber it, rather than the resin, entered between the
insulation and the copper at the tails. Because of the 5 mm of insulation ground wrap, the resin was very slow to penetrate during the soaking period.

The quadrupoles were all measured with the harmonic coil system, and showed very good uniformity in field quality and magnetic length (\(\text{del L/L = 7 E-4}\)). They were then tested for a few hours under power at 50 Hz but without the DC component of current. Initially the manifolding vibrated with very large amplitudes, but improved coil clamps were installed and the vibration reduced to such an extent that it was just detectable, by hand, with an insulating rod. Some tests were done with an accelerometer, but these were difficult to interpret and in the end it came down to personal judgement as to what was an acceptable level of vibration.

The hysteresis loss in the cores was calculated to be about 1 kW, and at each pole end there would be an extra loss due to eddy currents. Core cooling had not been thought necessary, and this was borne out by the tests.

In the four years of operation so far, no major problems have arisen. Maintenance consists of an occasional tightening of coil clamps and visual inspection. On a few of the quadrupoles a black substance has oozed out to form pools under the quads. This has been analysed and found to be ethylene propylene, which is a high-hysteresis rubber with a melting point which decreases with oxidation. It is assumed that the manufacturer used this material for coil packing instead of the specified polyurethane. No corrective action has been taken, since the coils still appear to be well clamped.

**Dipoles**

The dipoles (fig. 7) were by far the most difficult magnets to construct and to measure. Being 36 deg magnets, curving them was essential, and since at the design stage it was thought that they would have to be split in order to introduce the ceramic vacuum chamber, they had to be made in two halves. Fanning of the laminations was also necessary, since the beam was to enter normal to the magnetic field. Finally the pole ends required a roll-off which kept both the field and gradient integrals correct across the aperture.

The method adopted was to build each half-yoke out of six modules, which in turn were constructed from eight mini-modules. Tolerances had to be specified and held at each stage. The manufacturer tried to achieve the fanning by applying a tapered coating of epoxy glue to the laminations, but this was not a success. The method finally adopted was to punch dimples of graded depth across every sixth or seventh lamination, and to vacuum impregnate the minimodule with epoxy. The composition of the epoxy was not disclosed, but it was tested for radiation hardness. It must have been very fluid, however, since the magnet reference faces did not require cleaning-off afterwards. Penetration and adhesion were satisfactory.
The mini-modules were built into modules about 0.7 m long, using cold-curing resin. 'Dog-bones' were inserted into dovetails which had been punched into the laminations, and the modules attached to one another by means of these and more resin. Bolts from upper to lower dog-bones were used to clamp the two halves of the magnet together. Again the end-plates did not extend over the poles: delamination of the pole-ends is prevented only by the adhesive.

The estimated core losses were 10 kW, and therefore surface cooling pipes were let into pre-punched slots in the laminations. The dipole was mounted on a fabricated steel frame, and again the principle of replaceability was kept, although with such a weight (about 34 tonnes) the design of the supports had to be modified slightly to overcome stiction.

The coils presented no particular manufacturing difficulties, despite their bulk and the thick ground wrap. They are held in the coil slot by clamps as shown in figure 8. Pieces of epoxy-glass laminate span the coil slot and grub screws bear down on the coil. Radiation tests showed that throughout the magnets' lifetime creep or permanent set in the laminates should not be a problem, but this solution to an awkward problem is not felt to be completely satisfactory. In fact, additional clamping of the coil overhangs was found necessary after power tests.

The prototype was measured completely using short search coils, and the field quality in the body of the magnet found to be very good. The end fields were not quite right and modification of the roll-off profiles was necessary. Because the contract was running late, the ten production dipoles were only checked dimensionally and compared with the prototype for the field integral along $R = 0$ by means of a long, curved search coil. The rms variation in this integral was about $3 \times 10^{-4}$, which was considered to be very satisfactory.

Power tests again consisted of some hours soaking at 50 Hz with no DC current. Because all the coil tails were accessible, it was possible to vary the way in which the transpositions were made from layer to layer, and in fact a small improvement in the losses was made by making alterations to those deepest in the coil slot. The inductance was measured to be about 14% greater than expected, which is a large and so far unexplained discrepancy. Unfortunately it swallows up all the voltage safety margin for the choke.

The extra clamping of the coils has already been mentioned. With this in place the vibration levels are very low, with virtually nothing detectable by hand on the yoke itself (but see below). If one had the chance of designing these dipoles again, three changes would probably be made:

a) because the vacuum section were able to produce a ceramic chamber which could be inserted without splitting the magnet, every effort would be made to have a one-piece lamination;

b) the coil clamps would be made more robust;

c) conductors would be removed from the region of highest fringe field near the pole edges. Although the average temperature rise in the coil
is modest, the inside turns get very much hotter than the rest.

Singlet quadrupole

The singlet quadrupole has an asymmetric yoke because the one in superperiod 1 lies directly under the extraction septum magnet, and so was reduced in height to provide clearance. The design was such that the magnet was made in two halves, with a coil just able to slip onto a pole without fouling its neighbour. The manifolding was much simpler here since only two water circuits were required.

Because the aperture was 212 mm and the core length only 303 mm, end effects were very significant. The dimensions of one of the ISR Terwilliger quadrupoles [7] were scaled to our aperture, and a small octupole component (to provide some Landau damping to the circulating beam) included in the profile. This all worked very well, with the length variation being measured as 9 E-4, and the octupole value being as predicted (fig 9). The coil clamps consist of epoxy-glass laminate shaped so as to slip between the coil-end and the yoke. They are pulled up by means of bolts. Although neat and simple, these clamps always need some tightening and may possibly need replacing in the future.

Trim quadrupoles

These quadrupoles have three purposes: to vary the tunes during the injection period of 450 μsec so that while the field is falling the constant-energy incoming beam has the same Q-values; to compensate for any magnetic saturation effects; and to fine-tune the machine so that maximum intensity might be accelerated. Each has its own bipolar programmable power supply, but to date all the F-quads and all the D-quads have been fed with identical functions.

The quadrupole diameters (274 mm) are greater than the yoke lengths (203 mm) and again the profile has been adapted from one of the ISR correction quads. Although the magnetic pass-band required is considerably greater than 50 Hz, the standard 0.35 mm-thick laminations were certainly good enough. With a peak current of only 250 A, a single conductor with just one water circuit was sufficient. Ceramic insulators have been used here, and the magnets have been trouble-free in operation.

The custom-built power supplies have been very reliable, though subject to occasional water leaks. ISIS can operate at 100 μA with an F- or a D-quad off; if one set goes off, its partner in the superperiod is usually switched off also.

Correction dipoles

Although spaces exist in the synchrotron for complete sets of horizontal and vertical correction magnets, lack of funds has meant that only 7 H and 4 V dipoles have been installed. They are powered by the same type of supply that feeds the trim quads. The vertical dipoles are positioned so as to create an orbit bump in the region of the extraction septum magnet, in order to reduce the demands on the fast kicker magnets.
The horizontal dipoles are used primarily to correct the closed orbit in the region of the injection straight.

The dipoles (100 mm long) consist of dry-stacked laminations clamped with stainless steel end-plates and throughbolts. The air-cooled coils surround the return legs, which leads to large fringe fields. As a result, the mild steel supports became unexpectedly hot when the magnets were tested at full power, and were replaced by stainless steel.

**Skew quadrupoles**

Superperiod 5 contains two skew quads to remove any excessive coupling in the betatron motion between the two planes. They are just two trim quads rotated through 45 deg.; their power requirements are so modest that two hi-fi amplifiers provide the drive current, governed by the standard function generators. They are not used in normal operation, but may be required at higher beam intensities.

**Operating experience**

The first turn round the machine was easily achieved, and subsequent measurements showed that without correction, the H and V closed orbit errors were a few millimeters rms and the tunes within 0.05 - 0.10 of the design values (4.31 and 3.83 in H and V). It must be pointed out that the surveying of the whole complex was excellently done, since the beam in the complicated injection and extraction lines can be aligned for the most part to 1% of the quadrupole diameters.

Problems with the ring magnets have been confined to coil clamps and packing (already mentioned) and the occasional water trip, caused by unreliable water-flow monitors. The rotary make-up power supply for some time suffered from a fault which was eventually traced to the shaft encoder coupling, and recently the sliprings were damaged as a result of an incorrect set of brushes having been fitted.

A 10 MHz crystal oscillator controls the frequency of both the AC power supply and the neutron choppers. In normal operation beating with the 50 Hz mains does not cause problems, although it is suspected that occasional timing jitter of the fast extraction kickers could be due to the fact that the thyatron heaters are fed from the mains.

The ceramic vacuum chambers are supposedly clear of all contact with magnet poles; this clearance is routinely tested, and the chambers examined for excessive vibration. Increased vibration of one of the dipoles and its vessel is currently being investigated: this may be associated with a large amplitude of vibration discovered on a neighbouring pillar which supports correction magnets.

**Acknowledgements**

Thanks are due to the following, all of whom made major contributions to this work: A Armstrong, R Bennett, R T Elliott, W R Evans, H J Jones, J Lidbury, A Slater, A Wardle.
References

Figure 2 An ISIS superperiod

Figure 3 Schematic layout of main power supply
Figure 6 The doublet quadrupole measured gradient integral

Figure 7 The dipole
Figure 8 The dipole coil clamp

Figure 9 The singlet quadrupole measured gradient integral
Figure 4 The White circuit

Figure 5 The doublet quadrupole
DESIGN AND MEASUREMENTS OF A.C.- MAGNETS AT DESY II

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ABSTRACT

This paper summarizes the content of a talk given at the MAGNET DESIGN WORKSHOP at TRIUMPF on October 3-5, 1988. After a short introduction to the DESY 2 Synchrotron lattice and magnet parameters the choice of steel will be discussed. The influence of eddy current effects in the core and endfield design will be described. Some fabrication and assembly details are given. Finally the technique of the AC- measurements will be explained and a few results will be given.

INTRODUCTION

The DESY I Synchrotron which was built in 1957-1962 was designed to accelerate electrons from 40 MeV/c to 7.5 GeV/c at 50 Hz repetition rate. Owing to high intensity operation the coils were damaged by radiation. Furthermore the 50 Hz operation caused strong vibration of the ceramic chamber and this often lead to vacuum breakdown. In order to reduce down-time and to save costs for repairs the new DESY II synchrotron was constructed [11,12]. Whereas the old DESY I machine was directly serving high energy physics experiments at 50 Hz repetition frequency the main task for the DESY II synchrotron was changed to act as an injector synchrotron for the storage rings PETRA and DORIS. Therefore the repetition rate could be reduced to 12.5 Hz and the usage of all metal vacuum chambers became possible [3].

The main characteristics of the magnets are that they run at 12.5 Hz cycling frequency with a momentum swing from 55 MeV/c to 10 GeV/c. But since the existing beamlines to PETRA can currently only handle 7 GeV/c particles the installed rf-power is only sufficient to accelerate to about 8 GeV/c. In the meantime the electron energy of LINAC I has been pushed up to 200 MeV to get to better injection efficiency.

LATTICE AND MAGNET PARAMETERS

In order that the transverse and longitudinal particle motion be damped a combined function lattice was chosen [4]. Extra sextupoles are included in the lattice to compensate the chromaticity. This is partly caused by eddy currents in the metal vacuum chamber [5]. The aperture requirements are determined by the beam emittance at injection (10 mm*mm, dp/p = 1 % at 55 MeV/c). This leads to a good field region requirement of b * H = 80 mm * 40 mm, where dB/B does not exceed ± 5*10^-4. The final design of the DESY II magnets is a result of many special constraints as for example:

1. The prior existence of stamping tools (for quadrupoles and sextupoles) and the existence of the White circuit for the dipole powersupply which could easily be changed from 50 Hz resonant frequency to 12.5 Hz.
2. The availability of steel and
3. the annual operation time of the synchrotron which affects the ratio of investment costs to the power consumption costs.
LIST OF PARAMETERS FOR MAGNET DESIGN

Repetition frequency 12.5 Hz
Max. energy (for magnet design) 10 GeV
1st completion stage 8 GeV
Lattice: sep. function 8 superperiods
6 BM + 3 QF + 3 QQ + 2 SD + 1 SF
focussing strength: KF = .365 m⁻²; KD = -.328 m⁻²
Acceptance (dp/p = ± 1%) 10 mrad*mm

Magnets (ratings refer to 10 GeV/c excitation)

| 48 dipoles | length | 3.55 m |
| gap | 160 * 45 mm² |
| bending radius | 27.12 m |
| max. field in gap | 1.23 T |
| peak current | 1147 A |
| inductance | 33.2 mH |
| power losses | 30 KW |
| good field region (dB/B <=5*10⁻⁴) | ±40 mm |

| 48 quadrupoles | core length | 0.58 m |
| gap radius | 50 mm |
| max field | 14.7 T/m |
| power losses | 6 KW |

| 24 sextupoles | core length | 0.18 m |
| max. field | 77.8 T/m² |
| power losses | 1.1 KW |

Momentum vs. time waveform

P [MeV/c] = 3587.5 - 3412.5 * cos(25° t)

Pmin=175 MeV/c; Pmax=7000 MeV/c; dE=30 KeV/turn (200 MeV/c Inject.)

THE CHOICE OF STEEL

In order to avoid severe eddy current effects in the magnet core it is clear that laminated iron had to be used. But what about the thickness of laminations? Various factors determine the choice:

1. Eddy current losses in the core that causes heating.
2. Magnetic field distortions that might cause acceptance reduction and/or tracking problems between dipole and quadrupole field excitation.
3. Saturation effects.
4. The availability of steel on the commercial market and the costs for stamping and machining.

It is well known that the magnetic flux within the individual lamination is pushed out to the surface and thus that the flux density on the surface is increased above the average flux level [6]. Consequently a part of the high magnetic field inside the laminations runs into saturation if the thickness of the lamination is not properly chosen.
The ratio of the AC-component of the peak flux density $B_s$ on the surface of the lamination to the average flux density $Bav$ is given by:

$$\frac{B_s}{Bav} = \frac{x}{12} \sqrt{\frac{\cos x + \cos \beta}{\cos x - \cos \beta}}$$

with $\beta = \pi/4 - \arctg \left( \frac{\sin x}{\sin y} \right)$, $x = d/D$ and $D = \text{skin depth} = 1/\sqrt{\mu \tau f}$

For the characteristics of the DESY II iron

- conductivity $\sigma = 3 \times 10^6 \text{ m}^2 \text{ m}^{-3}$
- repetition frequency $f = 12.5 \text{ Hz}$
- rel. permeability $\mu_r = 3000$

we calculate the following numbers:

<table>
<thead>
<tr>
<th>$d$ [mm]</th>
<th>.5</th>
<th>1.0</th>
<th>1.5</th>
<th>2.0</th>
<th>2.5</th>
<th>3.0</th>
<th>3.5</th>
<th>4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s/Bav$</td>
<td>1.0002</td>
<td>1.004</td>
<td>1.019</td>
<td>1.059</td>
<td>1.137</td>
<td>1.285</td>
<td>1.443</td>
<td>1.666</td>
</tr>
<tr>
<td>$\beta$ [°]</td>
<td>1.06</td>
<td>4.23</td>
<td>9.39</td>
<td>16.1</td>
<td>23.7</td>
<td>30.9</td>
<td>36.9</td>
<td>41.3</td>
</tr>
</tbody>
</table>

From this we estimated the thickness of lamination $d = 1\text{ mm}$ and the maximal flux density in the dipole gap to be about $B_0 = 1.23 \text{ T}$.

The cutoff frequency $f_g$ given by $x = 1$ (skin depth $D = \text{thickness} \ d$ of lamination) characterizes the uniformity of the magnetic flux and should be chosen to be well above the operation frequency.

For DESY II iron we find $f_g = 28 \text{ Hz}$.

The specific eddy current losses are given by [6],[7]:

$$N' = \frac{1}{24} \sigma \omega^2 dm^2 \frac{B_m^2}{F(x)}$$

with $F(x) = \frac{3}{4} \frac{\sin x - \sin y}{\cos x - \cos y}$ and $B_m = .42 \text{ T (effekt. AC magnetization)}$

we find $N' = 140 \text{ W/m}^3$

This number is rather small and it is obvious that no water cooling is needed for the core. Since in rapid cycling machines the ratio of eddy current power loss to eddy current field scales proportionally to the derivative of the magnetic field $dB/dt$ the heating may dominate over the effect of field distortion.

Since we wanted to operate the magnets over the full excitation range between 62 Gauss and 1.23 Tesla corresponding to a 55 Mev/c to 10 GeV/c momentum range the following specification on flux density $B$ vs. magnetization force $H$ was required:

<table>
<thead>
<tr>
<th>$H$ (A/m)</th>
<th>.20</th>
<th>.30</th>
<th>.50</th>
<th>.100</th>
<th>500</th>
<th>1000</th>
<th>5000</th>
<th>30000</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$ (T)</td>
<td>.06</td>
<td>.13</td>
<td>.34</td>
<td>.62</td>
<td>1.36</td>
<td>1.34</td>
<td>1.63</td>
<td>1.995</td>
</tr>
</tbody>
</table>

(Calculation performed with magnetostatic computer code MAGNET 80 [8])
It is obvious that in order to achieve good field quality at low excitation level the remanent field \( B_r \) caused by the coercive force \( H_c \) should be as small as possible. At \( H_c = 40 \, \text{A/m} \) we expected about 5 to 7 Gauss remanent field within the dipole gap. We had measured \( B_r = 5.5 \) to \( 6.5 \) Gauss after full DC excitation (1300 A \( \rightarrow \) 1.4 T). There is a slight transverse gradient in the remanent field caused by the various length of the fluxlines in the C-type dipole. Low coercive force implies that the iron should be carbon-free (<100ppm). Pure iron heated in a hydrogen atmosphere has \( H_c = 4 \, \text{A/m} \) and the relative permeability is quite large over the full range of magnetization. However the electrical conductivity is comparatively large (\( \sigma = 10^7 \, \text{m/} \Omega \text{m}^2 \)) so that the thickness of the lamination has to be small in order to keep the eddy current effects low enough. Since this material is rather expensive and is difficult to obtain the more economic way is to use iron containing a few percent of silicon (1...4%). The silicon content helps precipitation of carbon into graphite and thus the aging process, increases the electrical resistance and the permeability at low flux densities but reduces the saturation level of induction by about 500 Gauss per percent of silicon. The steel was prepared under careful supervision.

Only a few firms were able to offer steel according to our specification. The steel that was finally delivered had the following guaranteed properties:

<table>
<thead>
<tr>
<th>Type of material</th>
<th>300-100 a (EBG Bochum)</th>
<th>Chemical analysis [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>coercive force</td>
<td>( H_c = 40 \pm 8 , \text{A/m} )</td>
<td>C ( .003 )</td>
</tr>
<tr>
<td>conductivity</td>
<td>( \sigma = 2.3 \times 10^6 , \text{m/} \Omega \text{m}^2 )</td>
<td>Si ( 2.4 )</td>
</tr>
<tr>
<td>rel. permeability (max)</td>
<td>( \mu_r = 6550 )</td>
<td>Mn ( .25 )</td>
</tr>
<tr>
<td>saturation induction</td>
<td>( B_s = 1.995 , \text{T} )</td>
<td>P ( .04 )</td>
</tr>
<tr>
<td>lamination thickness</td>
<td>( d = 1 , \text{mm} )</td>
<td>Al ( .35 )</td>
</tr>
<tr>
<td>insulating phosphate</td>
<td></td>
<td>N ( .004 )</td>
</tr>
</tbody>
</table>

Fig. 1 Magnetization curve (measured)

**Magnet Core and End Field Design**

For ease of access to the vacuum chamber, a C-type cross section for the dipole was chosen. The metallic vacuum chamber allows the vertical beam profile to use nearly the complete gap height. Consequently the pole width could be made small and therefore the stored energy in the gap is minimal. The installation costs as well as the costs for powering the magnets became small too. The dipoles were of completely new in-house design. Fabrication and assembly were made in close cooperation between various firms and the DESY workshop.
The laminations were shuffled in order to equalize the remanent effects. They were stacked on a segment of circle in order to avoid the sagitta. The 90 mm end field blocks were glued together and the complete stacks were surrounded by strengthening plates and welded together. The end fields of the dipoles and quadrupoles were carefully shaped in order to avoid eddy current in these core regions.

Because DESY II is mainly an injector synchrotron the total operation time is only about 25% of that of the storage rings which are to be filled with particles. Therefore the current density of the excitation coils could be made comparatively high (5.5 A/mm²). This allowed us to use flat pancake coils for the dipoles with 20 turns of copper 16.5 x 9 mm² each with 5.1 mm cooling hole. The eddy current loss contribution has been estimated to be less than 15% of the RMS power losses. Some dipoles are equipped with backleg windings for high energy orbit bumping and horizontal orbit correction at injection.

The design and construction of the DESY II quadrupoles and sextupoles are similar to those of the PETRA storage ring. In order to save on tools and construction the cross sections are identical. But some modifications have been made in order to get a better fit to the DESY II parameters. In particular copper coils instead of aluminum and a shorter core length have been chosen. The core length of the quadrupoles is determined by the aim to match the saturation characteristics of dipoles and quadrupoles. This allows us to keep the tune of the machine within the given limits during acceleration without having additional control on the excitation current.

MECHANICAL AND MAGNETIC MEASUREMENTS

The permissible tolerances on the magnets have been discussed in [4]. During steel fabrication tests on chemical composition, electrical resistance, solidity, flatness, inner tension, filling factor and insulation were performed. The geometric dimensions were checked after stamping and stacking. Magnetic measurements with various probes on coercive force and remanent induction were made. For fabrication tests two dipoles were stacked using spare PETRA iron which was in stock. A prototype dipole with new steel and equipped with removable end field pieces then followed in order to check various end field shapes. The inner field was measured with a Hall probe under DC excitation.

AC MEASUREMENT METHOD

In order to measure the magnetic properties of the DESY II dipoles and quadrupoles under realistic AC excitation a new method of field measurement had been developed [9]. Movable coils of various length were used and the AC induced voltage was compensated by a reference coil positioned in the same magnet or in an extra magnet powered in series:

1. A short coil (100 x 10 mm², driven by a crank shaft) for end field measurements on dipoles with a reference coil positioned at the center of the same magnet and
2. A long coil (3600 x 10 mm², also driven by a crank shaft) for integral measurements on dipoles with a reference coil in an extra dipole powered in series (determination of relative magnetic length of dipoles).
3. Two simultaneously rotating coils for the quadrupoles mounted in the same plane at different radius with different numbers of turns for proper compensation.
The output of the coils were preamplified with high common mode rejection, then integrated using chopper stabilized amplifiers (ICL 7650, Intersil) and digitized via high resolution sample & hold with analog-digital conversion (MP260 and MP8016, Analogic).

During the ramp, up to 11 triggers in sequence were derived from backleg coils on the reference magnet. These triggers start data processing at 11 different excitation levels. Thus within one turn (about 2 sec.) of the crank shaft (dipoles) or rotation (quadrupoles) one gets a complete field mapping of the whole range of magnetization. The small integrator drift which was assumed to be constant during measurement was compensated numerically. Polynomial fits (dipoles) or Fourier analysis (quadrupoles) finally gave the coefficients of the harmonics of field errors.

MEASUREMENT RESULTS

It is obvious that AC measurements are much more difficult to perform and the results normally are not as precise as those obtained with DC. But our measurements show that the DESY II magnets satisfy the field quality requirements over the whole energy range. We did find no indications for dangerous eddy current effects. Figs. 2,3 show typical computer results from dipole- and quadrupole measurements.

Fig.2 Integral dipole field at 4 different excitations

Fig.3 Typical normalized quadrupole data

REFERENCES

A DC BIASED RAPID-CYCLING MAGNET SYSTEM
OPERATING IN A DUAL FREQUENCY MODE

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Oho 1-1, Tsukuba-shi, Ibaraki-ken, Japan, 305

ABSTRACT

A prototype rapid-cycling magnet and power supply of a high intensity proton synchrotron for condensed matter research have been constructed and tested in DC biased and dual-frequency mode at practical operation level. This report describes the design and features of the DC biasing device and the performance of the system.

1. INTRODUCTION

A rapid-cycling magnet and its exciting system are under development for a synchrotron as an intense pulsed spallation-neutron and muon source for condensed matter research at KEK.\(^1\) The development of a rapid-cycling magnet system operating in a dual frequency mode is very important and indispensable to the realization of an intense rapid-cycling proton synchrotron for the reduction of load of the RF accelerating system. A prototype rapid-cycling magnet system was constructed and successfully operated at a practical level in a dual frequency mode without any DC biasing field. The performance of this system was reported in detail in the international workshop on Hadron Facility Technology held at Santa Fe, February last year.\(^2\) After that, further development is still in progress. Namely, in order to bring the prototype magnet system into more realistic operational condition, a choke transformer, which provides the pass of a DC current biasing the magnet, has been fabricated and introduced into the resonant network. This report will describe the design and performance of the choke transformer and the operation of the prototype magnet system with a DC biasing field in a dual frequency mode.

2. MAGNET, PULSE POWER SUPPLY AND RESONANT NETWORK

Details of the prototype magnet system which includes the resonant network, GTO thyristor switching system for dual-frequency-mode operation and pulse power supply, were already reported in the reference of 2). For the sake of convenience, however, the main features of those devices are summarized here. Parameters of the system are listed in Table I.

Magnet
Configuration of the magnet is shown in Fig. 1. In order to reduce the eddy currents circulating within laminations of core around magnet end, 30mm-spacing slits are introduced at the magnet end over the pole width parallel to beam orbit. Those slits are extremely effective to suppress the eddy current heating of the magnet end without reducing the effective magnet length. A special stranded cable was developed as a new conductor material of rapid-cycling magnet coil, whose cross section is 30mm x 30mm including a 14mm outer diameter and 1.5mm thick copper pipe. The cable consists of 84 aluminum wires of 3mm in diameter, carrying 1.65 kA DC and 0.88 kA peak AC current. Any special process was not applied on the surface of the aluminum wires to insulate each other. Such a stranded cable is considerably effective to the reduction of eddy-current loss. However, there exists still plenty room for improvement.

Resonant network and pulse power supply
Table I. Parameters of prototype magnet and its AC excitation system

<table>
<thead>
<tr>
<th>Magnet</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>maximum field</td>
<td>0.697 T</td>
</tr>
<tr>
<td>DC bias field</td>
<td>0.455 T</td>
</tr>
<tr>
<td>amplitude of AC field</td>
<td>0.243 T</td>
</tr>
<tr>
<td>gap height</td>
<td>164 mm</td>
</tr>
<tr>
<td>pole width</td>
<td>540 mm</td>
</tr>
<tr>
<td>magnet length</td>
<td>1,800 mm</td>
</tr>
<tr>
<td>core material</td>
<td>0.5 mm thick silicon steel (non-oriented)</td>
</tr>
<tr>
<td>number of turns per pole</td>
<td>18</td>
</tr>
<tr>
<td>exciting current</td>
<td>1.65 kA DC and 0.88 kA peak AC</td>
</tr>
<tr>
<td>conductor of coil</td>
<td>30 x 30mm Al stranded cable with 14 mm dia. cooling copper pipe</td>
</tr>
<tr>
<td>weight of iron core</td>
<td>12 tons</td>
</tr>
<tr>
<td>weight of coil conductor</td>
<td>0.3 tons</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pulse power supply</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC power supply for pulse excitation</td>
<td>1.1 kV/25A</td>
</tr>
<tr>
<td>charging reactor</td>
<td>1.73 H</td>
</tr>
<tr>
<td>discharging reactor</td>
<td>12.0 mH</td>
</tr>
<tr>
<td>energy storage capacitor</td>
<td>93.4 μF</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resonant network</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>inductance of magnet</td>
<td>2.95 mH (top and bottom coil connected in parallel)</td>
</tr>
<tr>
<td>max. AC current</td>
<td>1.76 kA peak</td>
</tr>
<tr>
<td>max. applied voltage</td>
<td>3.3 kV peak</td>
</tr>
<tr>
<td>resonant capacitor C₁ and C₂</td>
<td>0.859 mF and 6.87 mF</td>
</tr>
<tr>
<td>switching element</td>
<td>diode, GTO thyristor and SCR thyristor</td>
</tr>
<tr>
<td>max. switching current</td>
<td>1.56 kA peak</td>
</tr>
<tr>
<td>resonant frequency</td>
<td>100/3 Hz and 100Hz</td>
</tr>
</tbody>
</table>

A system of pulse power supply and resonant network was constructed for exciting the prototype magnet in AC mode. The special interest was in the operation of this system in a dual frequency mode of 100/3 Hz in acceleration period and 100Hz in reset period by using GTO thyristor switch on a practical operation level. In the early development stage lacking in choke transformer as shown in Fig. 2a, the top and bottom coil of the magnet were connected in parallel, and the timing of the energy transfer from the energy-storage capacitor C_f to the resonant network was shifted from the instant of the magnet AC current zero in the reset period of 100Hz to that in the acceleration period of 100/3 Hz. By this procedure, the output voltage of the rectifier of the pulse power supply was set at the economical voltage level of about 1kV. The resonant network system was successfully excited in a dual frequency mode. The GTO thyristor was proven to be quite suitable for a high power switching element of resonant network operating in dual frequency mode in combination with diodes and SCR thyristors.

3. CHOKE TRANSFORMER

Design of choke transformer

Resonant network exciting ring magnets of a large-scale rapid-cycling synchrotron will consist of many identical meshes containing some of ring magnets, choke and resonant capacitors. In such a case, it is difficult in its scale and complexity to fabricate such a common large choke that the mutual coupling among chokes allocated in every mesh is expected to be as close as to unity, while it was realized in the choke in the 3-meshes resonant network of the KEK booster synchrotron magnet system. Therefore, the chokes allocated in meshes were designed so as to be completely separated in magnetic coupling from each other.
The inductance of the choke should be determined from the economical viewpoint. Assuming the cost of the choke and capacitor proportional to their stored energy, and denoting a capacitor-to-choke cost ratio per unit stored energy by \( r \), the inductance ratio \( \eta \) of the choke to the magnet inductance giving the optimum cost is determined by

\[
\eta = \frac{I_{ac}}{I_{dc}} \sqrt{1 + r}
\]

The ratio \( r \) is estimated to be 0.6 to 1. This leads to the fact that the inductance of the choke is 0.7 times as much as the inductance of the prototype bending magnet only for the purpose of the magnet test, and twice for a prototype of the choke to be set in each mesh of the resonant network of the designed synchrotron. For the sake of simplicity, finally, the inductance of the choke has been determined to be equal to that of the prototype magnet.

As for the type of choke, an iron-clad air-core choke transformer with primary and secondary windings surrounding a common magnetic air gap, was chosen in preference to alternative air-core or multi-air-gap iron-core choke.

Fig. 1 Prototype magnet

Fig. 2 Resonant network and its excitation system

DC POWER SUPPLY for PULSE EXCITATION

POWER SUPPLY for DC BIAS
The main reason for this choice is simplicity of the mechanical structure, well-known magnetic field distribution, low cost and experiences on the construction and operation. The dissipated AC power in the resonant network is supplied from a energy-storage capacitor $C_f$ through the primary winding of the choke transformer as shown in Fig. 2b. The configuration of the choke transformer is shown in Fig. 3.

As the winding of such a type of choke is exposed to an appreciable magnetic field, it should be made of stranded or transposed cable to cope with AC power dissipation due to eddy current induced in the conductor. However, application of usual stranded or transposed cable requires presumably a large oil tank housing the choke for forced cooling. This leads to a large size of the system. Fortunately, we can apply a stranded cable with water-cooling pipe to the coil of choke, which have been developed for a magnet coil material of rapid-cycling magnet, and as a result we can simplify and keep the system in a small size. Two kinds of stranded cables were prepared for the material of the secondary windings of the choke to make a comparison on their electric and mechanical properties. One of them is the same one with the cable used in the prototype magnet, which consists of aluminum wires without any insulation process on their surface as already described. Another one is a newly developed copper stranded cable with a copper cooling pipe of 15mm in diameter and 1.5mm in thickness. The latter is in the form of a 25mm x 25mm square including 58 copper wires of 2.6mm in diameter, each of which is processed on the surface by coating ester-imide film for insulation.

The secondary winding has to carry the same amount of current with that of the magnet, namely, $I_{dc} = 1.65kA$ and $I_{ac} = 0.88 \text{ kA peak}$ because of $L_{ch} = L_{m}$. On the other hand, the average current in the primary winding fed from the pulse power supply is very low compared with the secondary AC current as given by $i_{av} = n I_{ac}/Q$, where $n$ is the step-up ratio of the choke transformer and $Q$ the quality factor of resonant network. Therefore, any special device is not necessary to be prepared for cooling. In order to realize a sufficiently high coupling coefficient between the primary and secondary winding, the primary winding is in the form of strip and wound close together to the secondary winding as shown in Fig. 4. The step-up ratio is adjusted by connecting the primary windings at the output terminals of pancake in series or parallel. The total number of turns of the secondary winding is 84 turns (7 turns x 12 layers), which is divided into identical top and bottom coil by an air gap for field-monitoring space at median plane.

Grain-oriented steel is used for the core material. Application of such a material is useful to reduce the weight of the system.

Design parameters of the choke transformer and DC bias power supply are given in Table II.

Fig. 3 Choke transformer Numbers in bracket correspond to those of the aluminum cable

Fig. 4 Coil of choke transformer
Measurements of inductance, AC power dissipation and magnetic field

The measurements of the inductance and AC power dissipation of the secondary winding were carried out by applying directly a 50 Hz sinusoidal voltage to the secondary winding, which gives a nominal AC current of 0.88 kA peak. Results were as follows:

<table>
<thead>
<tr>
<th></th>
<th>aluminum stranded cable</th>
<th>copper stranded cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance</td>
<td>11.76 mH</td>
<td>12.11 mH</td>
</tr>
<tr>
<td>AC power loss</td>
<td>67.0 kW</td>
<td>27.5 kW</td>
</tr>
</tbody>
</table>

In addition to those, the coupling coefficient between the primary and secondary winding was measured, which showed a very high coupling coefficient of 99.58%. The inductance of the secondary winding of the transformer with the copper cable is somewhat higher than the design value of 11.8 mH, while the design of the choke transformer was made on a simple case such as one without air gap separating the top and bottom coil. A remarkable difference between the transformer with the secondary winding made of aluminum and copper stranded cable is in the AC power loss. The dissipated AC power in the former amounts to by 2.5 times of the dissipation in the latter. Of course, this comes of the difference in the insulation process of wires, that is, the former without any insulation process on aluminum wires and the latter processed by coating insulation film on the surface of copper wires. In order to clear the sources of the AC power dissipation, ohmic, eddy current and iron loss were estimated on the latter case, which is in a definite condition in viewpoint of insulation. Then,

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ohmic loss in conductor</td>
<td>5.00 kW</td>
<td></td>
</tr>
<tr>
<td>iron loss in yoke</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>eddy current loss in cooling pipe</td>
<td>16.12</td>
<td>8.19</td>
</tr>
<tr>
<td>sum</td>
<td></td>
<td>29.66 kW</td>
</tr>
</tbody>
</table>

Table II. Design parameters of choke transformer and DC bias power supply

| Inductance of secondary winding | 11.8 mH |
| Max. current in secondary winding | 1.65 kA DC and 0.88 kA peak AC |
| Iron core type                 | iron-clad air-core type |
| core material                  | grain-oriented silicon steel, Nippon Steel Corp. Z9H |
| thickness of lamination        | 0.3mm |
| dimensions of core             | 648 mmH x 1,460 mmW x 1,200 mmL |
| width of yoke                  | 125 mm |
| weight of iron                 | 4.35 tons |
| Coil number of turns           | 7 turns x 6 layer x 2 for both of primary and secondary winding |
| conductor material primary     | stranded aluminum wire OR IR H |
| secondary                     | stranded copper wire OR IR H |
| dimensions of coil             | 595 x 339 x 192 (mm³) OR 575 x 351 x 162 (mm³) |
| gap between top and bottom coil| 50 mm or 110 mm |
| step-up ratio                  | 1:6 or 1:3 or 1:2 |
| weight of coil                 | 0.41 tons or 1.08 tons |
| cooling of secondary winding   | 5kg/cm² or 5kg/cm² |
| number of circuit              | 21 l/min or 28 l/min |
| Magnetic field at center       | 0.401 Tesla DC and 0.214 Tesla peak AC |
| DC bias power supply           | 2kA/50V |
| bypass capacitor               | 2F/100V |
Thus, the total estimated AC loss amounts to about 30kW, which is consistent with the measured one within a error of 10%. Of those sources the eddy current loss in the copper cooling pipe is rather remarkable than that in the copper wires of stranded cable. The same calculation on the case of the transformer with aluminum stranded cable was done except for the eddy current loss in the aluminum wires, which is indefinite in the insulation condition. This gives the eddy current loss of 49kW in the aluminum wires in comparison with the measured loss. By making the insulation complete with an appropriate insulating film processed on the surface, such an amount of loss is cut down by a factor of several as seen from the case of stranded cable with insulated constituent wires. We are now in around the goal of the development of a conductor material for rapid-cycling magnet or choke. If there still exists a room for improvement, it is to replace the copper cooling pipe with a pipe made of stainless steel. By this, the eddy current loss in the pipe will be reduced by a factor of 30, i.e., the conductivity ratio of copper to stainless steel.

DC biased magnetic fields of the choke were measured by using a set of search coil and voltage-to-frequency converter. The results are shown in Fig. 5. The curve a) is the distribution of AC component of DC biased field in a dual frequency mode. For the sake of comparison, the well-known field distribution in an ideal case, which has no gap separating the top and bottom coil, is indicated by a dotted line. The curve b) shows the distribution of the field induced by eddy current circulating in the coil conductor in a DC biased single resonant frequency mode of 23.5 Hz, \( I_{dc} = 1.65 \text{ kA} \) and \( I_{ac} = 0.35 \text{ kA} \) peak. The peaking-strip method, which was used for the measurement of the field induced by eddy current in the previously reported case with no biasing field, can not be applied to the eddy-current field measurement because of saturation of the peaking strip due to a high DC biasing field. Therefore, the measurement was done by shifting the integration gate timing of the search coil signal by \( \pi/2 \) radian from that of inphase-field measurement.\(^4\)

4. OPERATION OF THE DC BIASED MAGNET SYSTEM IN DUAL FREQUENCY MODE

In order to excite the magnet system in an AC level as high as possible with a limited capacity of the pulse power supply and for saving the expense for conversion, the connection of the top and bottom magnet coil has been restored from parallel to series and the resonant capacitors have remained with no change in their capacitance. An only change of the existing equipment is the increase of capacitance of the energy storage capacitor to 176mF in consideration of a mismatch to dissipated power in the resonant network in the previous AC operation and of addition of a new source of power dissipation, i.e., the choke transformer.
Thus, the resonant frequency are lowered by a factor of $1/\sqrt{2}$ from those of the previous operation. With such a dual frequency of 23.6 and 70.7 Hz, it is possible to operate the system at around the nominal excitation level within the power limitation of the pulse power supply.

The operation of the system showed that there was essentially no change in the behavior of the system for the introduction of DC biasing current into the resonant network. Some parameters were slightly different from those of designed one, e.g., a dual frequency of 23.5 Hz and 66.7 Hz. Fig. 6 shows the voltage and current waveforms at various points of the system. A rapid oscillation of capacitor current is also observed at the instant opening the circuit for $C_2$ current through the diode as like as in the previous operation without DC biasing device. The time corresponds to the injection time in the accelerator. Such an oscillation originates from a resonance of $C_1$ and $C_2$ with a stray inductance in a loop including those

![Waveforms in the resonant network](image)

- a) magnet terminal voltage 2.5kV/div
  magnet current 500A/div

- b) total capacitor current 833A/div
  $C_1$ current 833A/div
  $C_2$ current 833A/div

- c) total capacitor current 833A/div
  diode current 833A/div
  GTO-SCRg current 833A/div

- d) $C_f$ voltage 1kV/div
  magnet terminal voltage 2.5kV/div

Fig. 6 Voltage and current waveform in the resonant network
capacitors. Even though the oscillation amplitude is high, it does not affect on the magnet current because of very high inductance of magnet. In fact, we can not find any indication of oscillation in the magnet current while a small oscillation takes place in the total capacitor current as seen from Fig. 6.

5. CONCLUSIONS

In order to operate the prototype rapid-cycling magnet system in a more realistic operational condition, a choke transformer for DC biasing was designed and constructed. An iron-clad air-core choke transformer, whose primary and secondary windings surround a common magnetic air gap, was adopted as to the type of the choke by reason of simplicity of mechanical structure, well-known magnetic field distribution, and so on. An only drawback of this type of choke, which operates in rapid cycling, is the coils exposed to higher magnetic field compared with the alternatives, e.g., multi-air-gap iron-core choke. From the viewpoint of the AC power loss due to eddy current, therefore, it should be more careful in the design of coil structure and the selection of conductor material in comparison with the coil of rapid-cycling magnet because of higher imposed field upon the coil. The choke transformer, whose exciting coil is made of copper stranded cable processed for insulation of constituent wires, showed satisfactory features, especially, in AC power loss in contrast to the one with aluminum stranded cable without any insulation process. Although such an aluminum cable is effective to reduce eddy current loss, it is considerably difficult to estimate the power loss due to eddy current induced in the cable in an indefinite insulation condition of the surface of constituent wires. Through the tests carried out so far, we have come to the conclusion that stranded cable equipped with a stainless-steel cooling pipe is an indispensable material for the coil of rapid-cycling magnet or choke, whose constituent wires is processed by insulation film on the surface.

The system with the DC biasing device has successfully demonstrated that the operation of the system in dual frequency mode is very stable and reliable by making use of GTO thyristor as a switching element operating at a practical current level in accelerator magnet in dual frequency mode. The magnet biased by a DC field seems to behave like an ideal accelerator magnet. As pointed out in the previous paper, further investigations should be made on a stable operation of GOT thyristor in higher voltage in off-state and also it is desirable to study the collective operation of many GTO thyristor switches distributing among the meshes of an actual ring resonant network of synchrotron.

At present, further development is in progress for the introduction of a flat top field into the magnet field in dual frequency mode by using GTO thyristor.

REFERENCES

3. H. Sasaki, K. Takikawa and M. Kumada; The resonant network for the KEK booster synchrotron magnet, KEK-73-2, 1973
ESRF BOOSTER SYNCHROTRON MAGNET & POWER SUPPLY DESIGN

N. Marks
ESRF, BP220, 38043 Grenoble Cedex, France.
&
Daresbury Lab., Daresbury, Warrington WA4 4AD, U.K.

ABSTRACT

The parameters of the dipole, quadrupole and sextupole magnets in the 10Hz Booster Synchrotron of the ESRF are detailed. A number of possible power supply systems are considered, and the advantages of the classical 'White Circuit' over other variants are presented. The paper then concentrates on the dipoles and quadrupoles, considering the interaction between the power supply and magnet design. The interaction of coil eddy current loss and magnet voltage is examined, and end 'roll off' geometries for both sets of magnets are presented.

THE ESRF BOOSTER SYNCHROTRON

The European Synchrotron Radiation Facility (ESRF) will have a 6 GeV electron/positron Storage Ring for generating the radiation. To inject into this ring, a 6 GeV, Booster Synchrotron is also necessary, and as an injection rate of 10Hz is required, the synchrotron magnets and power supplies must be designed for AC operation.

The Booster Synchrotron will have a separated function lattice, with dipole bending magnets, two separate families of quadrupoles (F and D types), and also two sets of sextupoles - a total of five systems. Each system will require independent control of the AC and DC excitations in the magnets, and also of the relative phases of the AC components. They will be locked in frequency, with the single dipole circuit as the standard, probably free-running at its natural resonant frequency.

The parameters of the Booster Synchrotron magnets are given in Table 1.

SUITABLE POWER SUPPLY CIRCUITS.

At an early stage in the project, before any major magnet design work had been carried out, the possible power supply circuits, suitable for magnet excitation, were considered. The standard approach in the past had been to use a resonant network producing a magnet current having the form of a biased sinwave with the sources
Table 1. Booster Magnet Parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
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<tr>
<td>Number of Dipoles</td>
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<tr>
<td>Maximum field T</td>
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<tr>
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<tr>
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<tr>
<td>Required vertical aperture mm</td>
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<tr>
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<tr>
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<tr>
<td>Maximum gradient T/m</td>
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<tr>
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</tr>
<tr>
<td>Magnetic length m</td>
<td>0.14</td>
</tr>
</tbody>
</table>

of AC and DC separated. This so called 'White Circuit' is shown in Fig 1.

The circuit has many favorable features and is well understood, having been used for many fast cycling synchrotrons, including DESY, CEA and NINA. It is possible to segment the magnets into separate cells, with the resonant capacitors located between each cell, so that a series connection is obtained, but the total series voltage does not accumulate. This segmentation leads to the auxiliary inductor ($L_{ch}$ in Fig 1) being split into separate windings which, in order to stabilise the circuit resonance, must be very closely coupled magnetically. In common with other circuits used for fast cycling magnets, the system also suffers from the presence of a 'delay line resonance', in which the stray capacitance to earth oscillates with the magnet series inductance, leading to dis-similar currents in the magnet chain. A further major problem encountered in the use of this circuit is the design of the invertor system required to excite the 10 Hz oscillation; in spite of the utilisation of the basic circuit in many different machines, there has been no common accord on the optimum invertor circuit, and many alternatives have been built and operated,
with varying degrees of success, in the past.

A variation of this circuit has been developed at Fermi Lab, and used at other accelerator laboratories. This is shown in Fig 2. The circuit has a number of major advantages over the standard circuit, the most important of which is the use of a conventional phase controlled rectifier as the single power source. Providing the choke has a higher inductance than the magnet string, the current in the power source does not change sign, and the required direct and alternating currents are generated by a voltage output waveform that includes both a direct and alternating component. However, if the power ratings of the respective supplies in the two circuits are examined, and the variations of power during a magnet cycle are plotted (see Fig 3), a major disadvantage is encountered. The modified circuit has a substantially higher peak power rating. Furthermore, the loading on the supply fluctuates by over 100% (ie during a small part of the cycle, power is returned to the supply), and the fluctuation is at the same frequency as the magnet alternating current. By comparison, the classical White circuit has approximately a 30% power fluctuation at a frequency that is double the magnet excitation rate. This difference is very significant at 10Hz, for the human eye has a maximum 'flicker' perception at that frequency, and hence the public supply systems place stringent tolerances on such load fluctuations. The high power drawn at 10Hz therefore makes the modified circuit an unattractive proposition.

A number of possible pulse circuits were also examined. However, during an early stage in the ESRF project, it was decided that the standard White Circuit presented the most favourable set of operating parameters, and the examination of a possible magnet
Fig 3 Variation of power drawn by the Classical and Modified White circuits from the public supply over one magnet cycle.

design, to determine more clearly the power supply requirements, was carried out.

DIPOLE MAGNET DESIGN

Coil Eddy Loss.

In the past, fast cycling magnets with repetition rates of 50Hz had utilised stranded conductor to reduce coil eddy current loss to an acceptable level. This produces technical difficulties concerning the cooling method. However, such complications are not regarded as necessary at 10Hz, providing the cross section of the individual turns of solid copper is reasonably small. This, however, will result in a large number of turns and consequential high voltage on the coil. As it was hoped to use a simple, single cell power supply circuit, this inter dependence between loss and voltage was studied.

A current density of $3.8 \text{ A/mm}^2$ was used to fix the total cross section of copper required in the coil, and this was distributed in two pancakes, above and below the gap, each pancake having two layers of conductor. The height per turn was kept fixed at 13.7 mm, and the number of turns and hence the breadth per turn used as the independent variable in the study. The field distribution in the coil region and vector potential across the complete gap was predicted using the two dimensional code POISSON. The resulting eddy loss was
calculated using a simple model in which the field was normal to the coil and the eddy currents did not modify the magnetic field. The results are shown in Fig 4, where the variation in coil eddy loss per magnet and total magnet alternating voltage is shown as a function of number of series connected turns per magnet. The eddy loss does not become negligible compared to the expected resistive loss in the coil until the number of turns is above 30, corresponding to circuit voltages in excess of 10 kV. Whilst such voltage levels are practical, it would be cheaper and result in less bulky insulation on many components if a lower voltage could be used.

It was therefore decided to use a series/parallel connection for the Booster dipoles, so that there are 32 turns in total, of 8mm wide conductor. There will be two pancakes on each magnet, but they will be connected to present 16 turns to the power supply circuit. The parallel connection will be made externally to the magnets, with two separate circuits around the ring. Such parallel connections result in equal alternating flux coupling the two circuits, and if this condition is not met by external geometric conditions, circulating currents will flow. Care will therefore be taken to balance the alternating fluxes coupling the circuits before paralleling occurs. Direct current balance is dependent on the DC resistances of the circuits, and it will also be necessary to ensure that there is a close resistance match between the two circuits. These two separate measures will minimise circulating current.
Magnet Ends.

At a later stage in the magnet design, the problem of how to terminate the end of the dipole was considered. It is necessary to increase the gap at the magnet end, in a smooth way, so as to prevent excessive eddy currents due to flux components normal to the end laminations and also to limit non linear effects produced by high flux densities at the pole corners. From experience gained during the design of the SRS Booster Synchrotron at Daresbury, the dimensions of a suitable linear end roll off, which would minimise 10 Hz eddy effects, were established. The resulting azimuthal section through the dipole end is shown in Fig 5. It was also known that this end profile would give a magnetic length close to the magnet's physical length, although this has no great design significance.

As the gap dimension increases, the resulting dipole field worsens in quality, with strong negative sextupole components developing. It is possible to correct for this by increasing the size of the shim at the pole edge of the end laminations with the larger gap. This leads to a complex three dimensional shapes in the end region, and resulting high engineering costs. It was therefore decided to specify a planar roll-off region, with no shim present in this area, to accept the resulting high negative sextupole field in the end region, and to correct the total dipole integrated field quality by means of a positive sextupole field in the central region of the magnet. The mid magnet pole shape needed to develop this correction sextupole field is shown in Fig 6. The resulting fields in the different gap regions of the dipole were computed using the two dimensional code MAGNET,
the calculation being made for a set of transverse slices at different azimuthal positions. These were normalised against the predicted two dimensional distribution of vertical field through the magnet in the azimuthal plane. The resulting three dimensional field array was integrated numerically, to give the variation of integrated vertical field with radial position shown in Fig 7. It can be seen that nearly full compensation of the end effects is predicted out to 20mm from the beam center line.

![Graph](image)

**Fig 7 Variation of integrated field through the Booster Dipole magnet as a function of horizontal position.**

**QUADRUPOLE MAGNET**

In the case of the quadrupole, the stored magnetic energy is much less than in the dipole, and hence there was no difficulty in designing a coil with small conductor dimensions (8.8 mm square) to limit eddy current loss, with less than 2 kV across the complete series connected quadrupoles.

**Quadrupole End Design.**

In spite of the quadrupoles having lower pole fields than the dipole, it was thought still to be necessary to cut back the pole ends. Magnet engineering indicated that this would be best accomplished by utilising sets of end lamination packages, each with a profile describing the arc of a circle. As gradient and field varies as the inverse square of the inscribed radius, the size of steps between the packages can vary as the square of the radius. The profiling
commenced with a step size of 1.2mm, which would give negligible 10 Hz eddy currents. Ten successive steps, each of 2mm width, were then used to increase the inscribed radius to 50mm, at which value, it was judged that the roll-off could terminate. The resulting azimuthal pole profile along a 45° plane is shown in Fig 8.

The pole curvature radius of each end packet, shown as $r$ in the

Fig 8 Azimuthal section through quadrupole end on 45° axis

Fig 9 Schematic diagram of end roll-off packets in quad:
$R =$ inscribed radius of each packet;
$r =$ pole curvature radius

Fig 10 Integrated gradient quality through the Booster quadrupole magnet, as a function of horizontal position.
schematic diagram of Fig 9, was established by two dimensional computations using MAGNET, and the resulting integrated gradient through the quadrupole, at differing radial positions, was determined numerically. The predicted integrated gradient quality is shown in Fig 10.

ACKNOWLEDGEMENTS

I would like to acknowledge and thank: Prof. G.Mulhaupt, deputy project head of the ESRF, with special responsibility for the Booster Synchrotron, M. M.Lieuvin, of the Magnet Group, ESRF, and M. J.F.Bouteille of the Power Supply Group, ESRF, for many useful discussions and help in the design work reported in this paper.
For the Booster and Driver rings of the TRIUMF KAON Factory, the resonant supply configuration dictates certain constraints on the magnet design.

As the magnets are excited in series, the uniformity of the magnets is a primary concern. The inductance of the magnets must be carefully controlled to assure that the stored energy in the inductive components are the same. As the resonant system is comprised of a number of resonant cells, it is important that these cells be matched as closely as possible to assure the magnetic field as a function of time in the various families of magnets is the same. This implies careful control of the mechanical configuration as well as the amount of steel in each magnet.

For the Booster ring which operates at a repetition rate of 50 Hz with frequency components of 33.3 and 100 Hz the laminations should be chosen to minimize the ac losses due to hysteresis and eddy currents. Probably one would want to go to silicon steel with a lamination thickness of 0.35 mm. This is of importance in terms of minimizing the amount of energy which needs to be replenished during each cycle. This has a direct effect on operating cost for the facility, as it represents a continuous dissipation. Minimizing the ac losses also results in fewer high voltage, high current supplies required for the pulse forming network.

With a view to limiting the voltage to ground of any magnet to less than 10 kV the inductance value must be optimized to a minimum value to result in $e = l \cdot \frac{di}{dt} < 10$ kV at the highest excitation frequency $f$. During the magnet reset interval. If the magnet inductance is too high to accommodate 2 magnets in one resonant cell, the number of resonant cells double. The existing Booster design has 12 cells with 2 magnets per cell while the Driver presently has 36 cells with 4 magnets per cell. If the number of cells could be reduced beyond this point, the system complexity is reduced.

Each resonant cell has the attendant dc bypass choke for the resonant capacitor banks. As this choke is effectively in parallel with the magnets in each cell and its inductance affects the resonant frequency, the design of the choke and magnets are interrelated. The chokes must be designed to close tolerances in terms of their inductance. It is important to realize that the peak voltage across the choke is about twice that of any individual magnet so that turn to turn insulation is a consideration, while peak-voltage to ground is the same as the individual magnet, assuming two magnets per cell.

The optimum choke inductance is about equal to 1.5 times the total magnet inductance in the individual cell. Based on the amount of ac power lost in the ring due to eddy current losses etc. one may consider a centrally located multiple winding choke or a distributed choke scenario. In either case there must be good coupling to the dc bypass secondaries to allow for system synchronization via the pulse forming network. The ac losses in the choke should also be kept too a minimum as they directly add to the total ring losses which need to be make up at high voltage. Provision should be made to center tap the dc bias secondary with individual access to both halves of the winding. In the event of a distributed choke scenario a back leg winding would have to be provided to tie all the chokes together. Backleg windings should also be considered for magnets.
We use three basic core stackers: hydraulic, screw machine and bolted type. All operate equally well but one may prefer one type over others. For very small jobs a bolted type stacker may be preferable and for long magnets a screw stacker is preferred. However, for large cross section magnets a hydraulic stacker would be preferred. We at Fermilab primarily use a screw stacker since most of our magnets are of the 10 ft to 25 ft lengths. We do also use some hydraulic stackers. When stacking cores we try to develop approximately 120 psi for proper stacking pressure. Stacking rails are used to keep the laminations in line and to keep the magnet straight.

We notch the lamination on an outside edge. The notch is usually a small "v" shaped notch and is used to keep track of the taper in the material due to rolling of the steel. When building long magnets, the variation in material thickness starts to enter into the overall length of the core. While stacking cores we flip laminations about every 3 to 4 inches. This compensates for the variation in material thickness.

While stacking laminations for ac or pulsing operating, make certain the laminations are phosphate coated or have other similar insulating material to reduce eddy currents.

There are two types of layups of cores, wet layups and dry. Dry stacking simply means, stacking laminations, compressing them and welding the core together using tie bars.

Before stacking a wet layup core, wash the laminations. This will eliminate any cutting oils left on the lamination after stamping. We use a machine called a Cleanomat with solvent. While stacking wet layup cores be careful to use a mold release agent on all stacking parts. This allows easy removal of the core from the stacking fixture after curing. In addition, a bolted type stacker is usually used in combination with a hydraulic or screw stacker. It is implied that epoxy is being used to hold the core together during a wet layup. Welding may or may not be done on wet layups, but it has been our experience that you should weld on the core when the epoxy is still uncured; this will allow a much better weld. If welding is done after the coil is cured, you will get more porosity in the weld.

We use heat cure epoxy and cure for 5 hours at 300°F after the core reaches 300°F.

Shear tests should also be made on the laminations and epoxy before stacking. Wash several laminations, cut them into 1/2 inch strips and glue them together using the epoxy that is going to be used in the wet layup. This should be cured and sent to the test lab. Shear strength should range from 1000 psi to 1200 psi. If you get in this range of figures, then the cleaning was successful. A Roller Coater is used to apply epoxy on one side of the lamination. A note of caution, we have found that some phosphate

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coating does not lend itself to epoxy gluing. You can use room cure epoxy for wet layups but you must consider pot life and bonding strength. We have found that we achieve better bonding by using heat cured epoxies.

When core stacking, you will need end packs which can be laminated or solid steel. Solid steel end packs are expensive. We have been very successful using laminated end packs, that are a wet layup of heat cure epoxy. They can be machined for contouring as long as the shop is warned as to what direction the tool is turning. The tool should rotate in a direction so as not to peel off laminations. This type of end pack is very useful in prototyping. It can be made in such a manner so it can be removed, machined and installed back onto the magnet.

COIL WINDING

When winding copper conductor for magnets, the following are some guidelines and procedures that should be considered. When ordering copper, make sure copper is specified as dead soft, or Rockwell ≤40 HRF. This very soft copper will make it easier to wind coils.

Tension must be applied to the copper when winding. The tension can take two forms, friction blocks or friction on the spool of copper. Friction blocks are installed between the winding table (winding fixture) and stationary platform. The friction blocks supply the proper amount of tension on the copper to produce a good coil package. We use tension in the range of 1000 psig. Friction blocks can be made of phenolic, nylon, G-10 or other materials.

We also use an air break type tensioner, when winding coils from spools of preinsulated wire. This is usually in the form of heavy ML or ML and Daglas. A teflon guide is used to guide the wire to the winding fixture. When forming insulated wire, be very careful not to chip or gouge the wire with forming tools (hammer and block). A small block made of nylon or teflon or some medium hard wood, is commonly used.

When winding coils, a space between turns must be added during winding. This space will take the place of the insulation to be installed after winding. We usually have 28 mils between turns so a 1/32 shim works out. A shim between layer to layer is also required. It is important to note that the winding table must be able to go in reverse. After the bottom layer is wound, a joint must be made in order to wind the top layer, unless you back wind the layer to be used later. This can usually only be done using small cross section copper.

We use a sleeve joint when joining conductor. We find this superior than just using a butt joint. This, of course, is only used on water cooled conductor. On solid and small cross section copper an overlap joint is made. When making a joint in copper a brazing fixture is usually needed. This brazing fixture holds the conductors together and maintains pressure on the joint through the use of die springs. Silflos solder is used in making our copper joints. After the joints are made, the area is filed flush to the original copper dimensions.

After the coil is wound it is prepared for sandblasting ( uninsulated type of copper) on all outside surfaces. The sandblasting does two things; it gets rid of any oxides on the surface and allows our epoxies to stick better to the surfaces. After sandblasting the coil is inspected for leaks in any joints. It is then dekeystoned on all corners. If the coil is not dekeystoned, it may cause local pressure when clamped in a curing fixture and cause a turn-to-turn short. The coil may be dekeystoned before it is sandblasted; however, this is usually a decision made on a case-by-case situation.
COIL INSULATING

When insulating bare copper conductor, insulating tapes must be chosen and there are a variety of tapes available on the market. At Fermilab we use a variety of Mica, glass and glass/polyester type of B-stage tapes. We also use glass tapes in potted magnets.

B-stage tape is impregnated with epoxy and partially cured. The percentage of epoxy in the different tapes ranges from 35% to 75%. These tapes range in size, the most common being 1 inch wide and usually 36 yards on a roll. The normal conductor tapes are usually 7 mils thick. On very large conductors, we have used a Scotchply tape. This tape comes in 10, 20 and 30 mil thickness and rolls of different widths.

When insulating a coil you must spread the coil apart so one can insulate the individual conductors. We usually use one layer of half-lapped insulation. This gives us 28 mils of insulation between turns and between layers. Butt lapping is also possible; this will have to be done twice on each conductor in order to get 28 mils. The coil is nested back together after it is insulated or can be nested back together during insulating. This is dependent on the complexity of the coil being wrapped.

We use Mica-B-Stage tape along with glass tape for ground insulation. The coils/magnets are then potted with epoxy These magnets are usually used in high radiation areas. When using plain glass cloth tape make sure it has a saline or volan finish. This allows the glass cloth to more easily absorb the epoxy during potting.

Ground insulation is the additional insulation used to hold the package of conductors together and provide additional insulation between the coil and magnet core (ground). We usually put an additional 30 mils of ground wrap insulation on the coil. This ground insulation can take the form of several tapes. We have found Scotchply and Armorflex to be a very good combination. Before installing the completed coil into a curing fixture, we wrap an additional layer of Tedlar tape on the coil. This tape is called a stripping tape. This type of tape does not stick to epoxy, and acts as a mold release. After the coil is cured it is removed from the curing fixture. The Tedlar tape is removed and any epoxy flash is removed from the cured coil.

We have several methods for curing coils at Fermilab. They consist of oven curing, Dowtherm and resistive heating. Oven curing is the easiest, but sometimes the coils are larger than the oven. When coils are larger, a system of using hot liquid (Dowtherm) or resistive heating can be used. Dowtherm heating will require the coil have a water passage so the liquid can pass through the coil and be heated internally.

Resistive heating can also be used to heat the coils. A power supply can be hooked up to the coil and heated using the power supply. On very big coils the power supply may not have enough power to cure the coil.

When curing coils, the coil is cured for 3 hours at 300°F; that is, when the coil reaches 300°F the curing cycle starts.

You can also pot coils, but we have found that the various B-stage tapes we use are just as good as potted coils. However, there may be some cases that a potted coil would be preferable. Again this must be decided on the particular coil or magnet design.

We also use a heat cure epoxy that is made in such a way that it has the consistency of a soft jell. This is useful when winding solid conductor that has been pre-insulated (heavy ML, Daglas). It provides extra epoxy between conductors and other void areas. The coil is then ground wrapped and cured.
We do some potting of magnets here at Fermilab. We insulate the conductors (usually with glass tape) and ground wrap the coil with glass tape. The coils are then installed into the core and the core is sealed. The magnet is installed into our vacuum oven, heated, and out gassed. The magnet is back filled with heat cure epoxy until it comes out of a riser at the other end. After the magnet is filled with epoxy, it is pressurized to 30 psig and the vacuum oven is brought up to air. After that point the magnet is heated internally with Dowtherm for the final cure. The riser is maintained with epoxy until the epoxy is cured.

**FINAL ASSEMBLY**

For the most part we braze on our flags onto the coil conductor using Silfos silver solder. The water fittings are usually 304 stainless steel and brazed onto the copper using B-1 flux and Easy Flo silver solder. The insulators between conductor water paths are the bolted-on type and take two forms. One type is made of ceramic and has a flare type fitting pressed onto the ends. The other type is a compression type ceramic and is held in place using compressing type fittings. The fittings we have used are Swagelok.

**INSPECTION**

We do several types of inspections on our coils/magnets produced at Fermilab. As the copper arrives from a vendor, it is checked dimensionally and a ball is passed through the water hole to make sure it has no restrictions.

When winding a coil, a joint may have to be made in the coil. After the coil is wound and sandblasted the joint is pressurized with He to 200 psig and sniffed with a He leak detector having a sensitivity of $2 \times 10^{-10}$ atm cm$^3$/sec He. No detectable leaks are allowed. A water flow test of the coils is made to check the gallons per minute flow rate of the coils. After the coil passes these tests, it is pressurized to 1000 psig hydrostatically and held there for 1/2 hour. Again, no detectable leaks are allowed. When the coil is ready for wrapping it is checked for nicks, burrs and proper dekeystoning. If it passes all these checks it is ready to be wrapped. After the coil is wrapped it is tested for resistance value ($R$), inductance ($L$), $Q$ and Ring. All through the assembly process, the coils are continually tested for $R$, $L$, $Q$ and Ring. After the coils are installed in the core one additional test is also performed, this is a dc hipot to ground. Our standard hipot is usually 3kV and ≤ 5 µa leakage to ground. However, this hipot may not work before the magnet/coils are cured/potted. Our hipot is reduced to 1 kV, and ≤ 5 µa leakage. If the area is not air conditioned you may not be able to obtain ≤ 5 µa leakage.

After the magnet is completed, bussed and electrically hooked up, we do our final checks. We flow check the entire assembly and then pressurize to 600 psig. The magnet is also surveyed for straightness and flatness and then we do additional $R$, $L$, $Q$ and Ring.

These procedures will help to insure that a quality magnet is produced.
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10. Glass Tape: B-Stage type tape. FNAL Drawing Number 2856-MA-116567.
11. Glass/Polyester: B-Stage type tape. FNAL Drawing Number 2856-MA-116568.
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17. Heat Cure Epoxy Paste: 50g 826, 16.7g 732, 60g NMA, .7g DMP30, 2g Glycerin, 8g Cab-O-Sil.
20. Ceramic Fitting: FNAL Drawing Number MC-22304.
22. Compression Fitting: Swagelok Tube Fittings, Crawford Fitting Co., 29500 Solon Road, Solon, Ohio 44139.
THE STATUS OF THE BOOSTER DIPOLE DESIGN AND PLANS FOR THE PROJECT DEFINITION STUDY YEAR

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ABSTRACT

The present status of the booster dipole design is presented together with a list of the magnet development tasks during the project definition study.

INTRODUCTION

The KAON Factory will require different types of magnets, some estimates show that as many as sixty different designs will be needed. These will be both dc and ac magnets and ac magnets are a new technology for TRIUMF. During the P.D.S. we have to concentrate on a few designs in detail. We have chosen to complete the design and build a prototype of the booster dipole because it presents the most challenge. This will give us experience in designing an ac magnet and measurements on the prototype will give us a calibration of our design methods.

BOOSTER DIPOLE STATUS

The Booster Dipole parameters listed in the KAON Factory proposal\(^1\) are as follows:

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<th>Parameter</th>
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<td>Effective Length</td>
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<tr>
<td>Vertical aperture</td>
<td>10.68 cm</td>
</tr>
<tr>
<td>Good field width</td>
<td>11.76 cm</td>
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<tr>
<td>Maximum field</td>
<td>1.05 T</td>
</tr>
<tr>
<td>Minimum field</td>
<td>0.277 T</td>
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<tr>
<td>Excitation rise time</td>
<td>33.33 Hz</td>
</tr>
<tr>
<td>Excitation fall time</td>
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</table>

These values are all subject to revision and Uli Wienands\(^2\) is actively considering a combined function dipole with gradient of 3.9 T/m, using the same central field, but a reduced vertical aperture. Most of our work has been concerned with the uniform field dipole. During the preparation of the proposal Keith Lacey of DSMA-Acton prepared basic designs for all the ring magnets using a preliminary costing program. This was similar to but not as extensive as the programme used at Argonne by Ken Thomson.\(^3\) It allowed us to prepare cost estimates and material quantities for both quadrupoles and dipoles. The dipole estimated by Lacey is shown as Fig. 1, it was not intended to be the final design.

A further study was undertaken by E.M. Gibson a summer student. The aims of this study were two fold:

- To modify the pole shape to achieve good field uniformity over the required aperture and;
- to investigate eddy current losses in the coil.
POLE GAP 10.68 cm
POLE WIDTH 27.8 cm (2.6 x GAP)
YOKE FLUX DENSITY 1.4 T
YOKE THICKNESS 13.9 cm
CONDUCTOR OUTER DIMENSION 6 mm SQUARE
CONDUCTOR COOLING HOLE ARRAY 3.4 mm ID
ARRAY 4 WIDE x 3 HIGH / TURN
TURN ARRAY 4 x 4
COIL WIDTH 11.5 cm
COIL HEIGHT 8.8 cm
$I_{dc}$ 1,973 A
$I_{rms}$ 2,135 A
MAXIMUM VOLTAGE 9.2 kV
INDUCTANCE 3.17 mH
$I^2R$ LOSS (COIL) 52.5 kW
EDDY CURRENT LOSS (COIL) 52.7 kW
IRON LOSSES 11.5 kW
MAGNET WEIGHT 8000 kg

Fig. 1. Booster dipole initial design concept.

Figure 2 shows the magnet profile which resulted from this study. The magnet width and height were increased and the pole is now tapered. Flux densities in the yoke vary from 1.24 to 1.39 T at maximum excitation. The field profile is shown in Fig. 3 and it is not quite good enough at a central field of 1.05 T. We need to make the pole wider and change

Fig. 2. Magnet profile with initial pole shim.
the shape of the shim. The field uniformity at low excitation (injection) was not considered by Gibson and Fig. 4 shows that it is far from satisfactory. The effect of increasing the magnet size to reduce the average yoke flux density to below 1 T to reduce the iron ampere turns does not solve this problem as is also shown in Fig. 4. We need to change the shim to establish a satisfactory pole profile which will give adequate field uniformity at both injection and extraction energies.

Fig. 3. Field profile at extraction energy.

Fig. 4. Field uniformity about centreline at injection and extraction energies for various yoke flux densities.
Eddy current losses in the coil were studied by estimating the loss due to transverse magnetic field over the coil region for various conductor sizes. The program Poisson was used to obtain the field and parameters were adjusted for each conductor size to get the field at the centre of each conductor. The individual losses were then summed over the coil. Figure 5 shows the losses per metre as a function of conductor size.

![Eddy current loss/metre over coil for various conductor size. Square hollow conductors.](image)

The shape of the coil was varied and it appeared that the losses were minimized for a rectangular coil section as shown below.

<table>
<thead>
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<th>Width (cm)</th>
<th>Height (cm)</th>
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</tr>
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<td>18</td>
<td>4490</td>
</tr>
<tr>
<td>11</td>
<td>13</td>
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</tr>
<tr>
<td>18</td>
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</table>

Finally losses calculated from the harmonic analysis of the dual frequency waveform were compared with those of the average frequency of 50 Hz and found to be 29% higher. It is not accurate enough to use the average frequency to design these magnets.

We needed a quicker way to estimate eddy current losses for initial design reviews and optimization studies. Ed De Vita looked into this and pointed out that if the coil is inserted into the slot as shown in Fig. 6 the field in the coil region is horizontal and increases uniformly from zero at the top of the coil to \( \frac{B_g g}{2w} \) and it is easy to show that the average value of \( B^2 \) over the coil region is \( \frac{B_g^2 g^2}{12w^2} \) where \( B_g \) is the field at the gap centre. The expression allows a very quick initial estimate of coil losses. A rectangular conductor with a rectangular hole was considered to be better than the more normal square hollow conductors. With this arrangement the losses are reduced as the coil slot width is increased. It was shown that...
with a standard rectangular conductor from Hitachi that the cooling considerations could be resolved and the coil losses reduced to 10.8 kW/magnet.

![Diagram of gradient magnet design](image)

**Fig. 6. Profile in which field in coil region is horizontal.**

**COMBINED FUNCTION DIPOLE DESIGN**

We are just starting to look at the gradient magnet design requested by Uli Wienands. The magnet increases the peak fields in the gap and in the steel but to first order the stored energy in the gap is the same for both types of dipoles, if they have the same aperture. We will make a comparison of the two designs within the next two months and then decide upon which to build as a prototype. Our schedule shows that we expect to call for tenders on this magnet early in 1989.

**PROJECT DEFINITION YEAR PLANS**

Building a prototype Booster dipole will be one of our major projects, it is not our only one, we also expect to design and build a prototype quadrupole. Our other major aims are to do optimization studies to determine the best flux density to use in the return yokes and to determine its effect on:

- Power supply cool, magnet cost and size, tunnel environment considerations such as cooling and handling.
- Review the costing and basic designs, and set up a data base with CAD sketches and preliminary designs for all the KAON Factory magnets.
- Measure core losses in electrical steels and eddy current losses in conductors at both sinusoidal and dual frequency waveform excitation.
- Make Canadian industry fully aware of our plans and involve them in our studies wherever possible.

In order to complete this work we are looking for visitors from other laboratories with magnet experience to come and work at TRIUMF with us. We also will try to set up an industrial programme in which engineers from Canadian industry will come and help us. We feel that we can learn a lot about calculating ac losses from engineers in the electrical manufacturing industry.
REFERENCES

2. U. Wienands, KAON Factory Magnet Requirements, this workshop.
KAON FACTORY MAGNETS

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TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C., Canada V6T 2A6

ABSTRACT

The KAON Factory at TRIUMF will require over 1,200 magnets of up to 60 different designs. The total cost of the KAON Factory is estimated to be $571 million (in 1986 dollars) and out of this approximately $75 million is for these magnets. This paper will describe the plans for design, procurement and installation (excluding kickers, septa and bump magnets) under a very tight scheduling constraint. Some logistics problems for testing and installing all the magnets will be outlined. We expect that discussions at this workshop will help us find solutions to some of these problems.

INTRODUCTION

Basic parameters for the accelerating and storage ring magnets are almost defined and the conceptual designs for estimating the costs were completed while writing the KAON Factory Proposal in 1985. Some conceptual designs for the magnets in the experimental halls and beam switchyards are available. TRIUMF has considerable experience in the design, manufacturing and installation of dc beam transport magnets but has no experience in the design of ac accelerator magnets. In order to produce the large quantity of magnets required for the KAON Factory under a tight schedule, TRIUMF will have to acquire a good level of competence in the design of ring magnets. The design and calculation of losses in the ac magnets will have to be better understood in order to effectively optimize the magnet designs. Moreover the services, alignment and installation techniques must be designed and implemented to achieve a very reliable operation. At target locations extremely high radiation fields of up to $10^8$ Rem/hour will be experienced. The design must consider the repairs and maintenance costs in terms of downtime, man-dose and plain dollars.

OBJECTIVES DURING PROJECT DEFINITION STUDY PHASE

TRIUMF has received a funding of 11 million dollars for Project Definition Studies (PDS) of the KAON Factory. Out of this approximately 1.2 million has been allocated for design and prototyping of ring magnets and kicker magnets. The project definition study (PDS) phase is planned to last from 12-15 months as shown on a schedule (Fig. 1). The primary objectives during this period are as follows:

1. Develop the design procedures and cost estimates.
2. Design and build prototype ac magnets for the dual frequency excitation booster rings.
3. Design and build prototype kicker magnet.
4. Start an industrial involvement program for the fabrication of magnets.
5. Continue programs to advise industrial companies in Canada for the production of the large quantities of materials (steel and copper conductor) required for all magnets.
6. Determine the measurement techniques and systems that will be required.
7. Finalize design parameters and layouts of the experimental halls, target areas and switchyards.
8. Start to look at the magnet requirements in experimental halls and in the target areas.

PRESENT PLANS AND INDUSTRIAL DEVELOPMENTS

We are not aware of many Canadian companies or consulting engineering companies that specialize in the design and fabrication of accelerator magnets from a list of parameters or specifications developed from theoretical optics design. One of the important aims to be met in the PDS phase is to start to transfer this technology and expertise to industry. At TRIUMF we have generally done the engineering design and invited other companies to fabricate the magnets for us. Fifteen years ago, all of our magnets were made outside Canada and today more than 90% of our magnet requirements are met in Canada. At the present time we deal with about four coil manufacturers and about eight companies who make steel assemblies for us.

In order to develop and enhance industrial capabilities in Canada, we would design the magnets and prepare engineering drawings and specifications. During the PDS we plan to invite visitors from other laboratories and engineers from industry, wherever possible, to assist us and work with physicists and engineers at TRIUMF on a sabbatical basis. This would apply to synchrotron magnet design and the fast kicker magnets. Two to three people may be brought in on such a basis. Canadian manufacturers will bid on the fabrication and supply of materials and other components. If Canadian industry does not respond to the challenge we will have to look to offshore suppliers and manufacturers.

SCHEDULE

Assuming a five year construction period for the KAON Factory prior to the first 30 GeV beam out, it is anticipated that major contracts for fabrication can be awarded only after 1 1/2 years of design work and qualifying the suppliers and contractors. Table I shows the estimated magnet quantities for the KAON Factory. The first block of orders will consist of magnets for the 450 MeV transfer line and rings ‘A’ and ‘B’ which will be fabricated installed first, followed by the magnets for rings ‘C’, ‘D’, and ‘E’. The magnets required for the beam switch yard and experimental halls will be a continuing requirement, and will be installed in the 5th and 6th years respectively after installing the magnets in all five rings.

According to the overall schedule in Fig. 2, the time allowed for fabrication of the first block of orders for the 450 MeV transfer line and rings ‘A’ and ‘B’ (235 magnets) is only 15-18 months which is so tight that it will be necessary to spread this contract among five or more contractors hopefully including the companies which have worked with TRIUMF staff during the design phase. It should be noted that the size of the subsequent order for ‘C’, ‘D’ and ‘E’ rings is significantly larger (792 magnets) but the time allowed is still 18-24 months. It can be met only by increasing the number of contractors, perhaps up to ten or more, and enhancing the manufacturing techniques based on the experiences of those involved earlier.

The testing and installation schedule is also very challenging. The magnets for the 450 MeV transfer line and rings ‘A’ and ‘B’ are to be tested in 12 months and then installed in another 12 months. Similarly the magnets for rings ‘C’, ‘D’ and ‘E’ are planned to be tested in 15 months and then installed in another 12 months only. This would complete the installation of magnets in rings ‘A’ and ‘B’ after 3 and 3 1/2 years respectively and in rings ‘C’, ‘D’ and ‘E’, after 4 1/2 years thereby allowing a period of six months for overall commissioning to get 30 GeV beam out.
# KAON FACTORY MAGNET SUMMARY

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<th>AREA</th>
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Fig. 2
Table I. Estimated magnet quantities for KAON Factory

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The highlights of design, measurement, testing and installation phase are outlined as follows:

Design Phase

After finishing the design and fabrication of prototype ac magnets for the booster ring in the PDS phase, the detail design for approximately 1,200 magnets will have to be done after full funding is received. It may require up to 60 different designs and will take 1 1/2 to 2 years with a proper mix of manpower :(physicists, engineers and designers) before the major contracts for materials and fabrication can be awarded. Assuming an average of three man months for a typical magnet design, we would require a team of 8-10 designers working over a period of two years for these magnets.

To meet the schedule, TRIUMF plans to invite companies who design and build ac electrical machinery and components to contract out to us engineers who can assist in the design and calculations of the magnets. These engineers would work at TRIUMF so that we can teach them about accelerator magnets and we can learn the manufacturing techniques, problems and ac design approaches from them. This would be especially useful because we would be expecting them to assist us in building the magnets at their home factories. This approach would help in meeting the engineering specifications and requirements very effectively along the transferring the technology to the Canadian industries.

Procurement Phase

There are good opportunities for material suppliers also. for KAON Factory magnets we will require up to 320 tons of conductors and up to 4250 tons of magnet steel. At the present time, there is no Canadian company that has the equipment to produce hollow copper conductors required for our magnet excitation coils. However, due to the large quantities involved it is important to explore the possibilities of helping industries in acquiring such
equipment so that the Canadian companies can supply the conductor. Pyrotenax has shown a very keen interest in expanding their capabilities to manufacture copper conductors. Initial discussions with Dofasco indicate no production problems in acquiring steel for all the magnets.

To expedite the schedule for fabrication of all magnets, the potential suppliers of magnet steel and copper conductor should be kept in touch while design is in progress. They will be informed as soon as possible regarding the quantities and specifications of materials and other major design features to allow sufficient time for developing tools, jigs, etc.

Realistic quality control specifications should be prepared and distributed before or along with the Request for Quotes. TRIUMF engineers and physicists will have to work hand-in-hand with the suppliers and contractors to provide any technical expertise and resolve technical problems as necessary. Automated magnet measuring systems will have to be designed and built to expedite the acceptance tests and wherever necessary consultants will be engaged to carry out these tests to avoid bottle-necks at the factories and to expedite the overall schedule.

**Logistics in Testing the Installation Phase**

Due to manpower, logistics and space constraints, testing and installation will have to be staggered for different rings. First of all, the magnets for the 450 MeV transfer line will be installed, followed by the magnets in ‘A’ and ‘B’ rings. Most of the services (water, electrical and interlocks) for magnets should be installed up to closest proximity and checked out before magnets are received at TRIUMF. All the alignment services and equipment should also be installed and tested before hand. It may be necessary to carry out some quick preinstallation tests which may require up to 8-10 test setups to prepare magnets for installation. Manpower for testing the installation will have to be very carefully planned and scheduled. For example, to test the magnets for the 450 MeV transfer line and for rings ‘A’ and ‘B’ in one year and install in the following year, we will have to test one magnet per day and during the installation one magnet per day should be installed, connected and tested. Similarly, for ‘C’, ‘D’, and ‘E’ rings, more than three magnets will have to be tested per day and more than three magnets per day will have to be installed, connected and checked out.

**SUMMARY**

There is a lack of experience at TRIUMF in the design of ac accelerator magnets. To meet an extremely tight schedule to procure and install over 1,200 magnets for the KAON Factory, it will be essential to achieve the active participation of Canadian industries. We would like engineers from industry to work with TRIUMF staff from the design through the installation phase. The tight delivery schedule for fabrication and assembly of magnets emphasizes the need to spread the orders among ten or more contractors and complete the acceptance tests before magnets are shipped to TRIUMF. At times, we have to test up to three magnets per day and also install and connect up to three to four magnets per day. It will necessitate a combination of careful and detailed planning, shift work, automated testing and efficient installation procedures.

**ACKNOWLEDGEMENTS**

The author wishes to acknowledge the helpful comments from Mr. A.J. Otter and the help received from Mr. Mark Keyzer for preparing time schedules.
KICKER REQUIREMENTS FOR THE KAON FACTORY

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ABSTRACT

An overview of the kickers needed for the fast injection and extraction systems for the KAON Factory rings is given. The specifications are based on the newly developed racetrack lattices. Rise time of the field and limits on field variations (ringing) are given.

INTRODUCTION

Given the number of 5 rings in the KAON Factory, there will be 8 fast injection/extraction systems. A typical transfer from one ring to the next will include an extraction kicker and septum, the transfer line, and an injection septum and kicker. Given the flexibility of the racetrack design, we can choose a somewhat higher value of the beta function in the extraction section, allowing to trade aperture of the kicker for a reduction in kick angle. For the small rings, a maximum of about 37 m has been chosen for the horizontal beta function, while for the large rings, the beta function rises up to 100 m.

Table I gives the requirements for the kickers. All angles are based on a horizontal extraction scheme and at least 1 cm clearance between kicked and circulating beam. The emittances used are as given in the proposal, 140 \( \pi \) mm-mrad horizontal and 62 \( \pi \) mm-mrad vertical at injection into the Booster. The length available for the kickers is 3 m in the small rings (A,B) and 9 m in the large rings (C,D,E). In addition there will be orbit bumps needed to steer the adiabatically shrunk beam in the accelerator rings towards the septum. Figures 1 and 2 show the lattice functions of the small rings (Booster) and the large rings (Driver). Positions of kickers and septa are indicated.

Table I. Kicker parameters for the five KAON Factory rings

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<th>mode</th>
<th>Angle (mrad)</th>
<th>Momentum (GeV/c)</th>
<th>( t_{\text{rise}} ) (ns)</th>
<th>( t_{\text{flat}} ) (us)</th>
<th>( t_{\text{fall}} ) (ns)</th>
<th>Aperture(_x) (cm)</th>
<th>Aperture(_y) (cm)</th>
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<td>1.01</td>
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<td>0.87</td>
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<td>15</td>
<td>8</td>
</tr>
<tr>
<td>A(_{alt})</td>
<td>50</td>
<td>extr.</td>
<td>4.0</td>
<td>1.01</td>
<td>10</td>
<td>0.87</td>
<td>25</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>B</td>
<td>50</td>
<td>inj.</td>
<td>4.0</td>
<td>1.01</td>
<td>5 ms</td>
<td>0.87</td>
<td>108</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>B</td>
<td>50</td>
<td>extr.</td>
<td>2.5</td>
<td>3.82</td>
<td>82</td>
<td>0.66</td>
<td>5 ms</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>C</td>
<td>50</td>
<td>inj.</td>
<td>1.5</td>
<td>3.82</td>
<td>22 ( \mu )s</td>
<td>0.66</td>
<td>82</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>C</td>
<td>10</td>
<td>extr.</td>
<td>1.5</td>
<td>3.82</td>
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<td>3.60</td>
<td>1 ms</td>
<td>15</td>
<td>6</td>
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<tr>
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<td>10</td>
<td>inj.</td>
<td>1.5</td>
<td>3.82</td>
<td>25 ms</td>
<td>3.60</td>
<td>82</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
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<td>10</td>
<td>extr.</td>
<td>1.0</td>
<td>30.90</td>
<td>80</td>
<td>3.50</td>
<td>25 ms</td>
<td>15</td>
<td>6</td>
</tr>
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<td>inj.</td>
<td>1.0</td>
<td>30.90</td>
<td>80</td>
<td>3.50</td>
<td>80</td>
<td>6</td>
<td>4</td>
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</table>
Fig. 1. Lattice functions of the Booster ring. The dipoles are vertically focusing.

Fig. 2. Lattice functions of the Driver ring.
The rise time requirements are based on the presence of a kicker gap of 5 buckets length in the beam. Extraction kickers need to rise to full field strength within passing of the gap, while for injection kickers the fall time is defined this way. The other edges of the pulse can be longer, on the order of milliseconds. At present, one of the possibilities to create this gap relies on an ultra-fast kicker for extraction from the A-ring, which would have no kicker gap in the beam, and an increase in length of the B-ring by about 11% to a harmonic number of 50, which leaves 5 buckets empty on the transfer from A to B. For extraction from the A-ring to be lossless, the kicker has to have a rise time of about 10 ns; alternatively the cyclotron can be operated in a 4 out of 5 mode leaving one bucket in the cyclotron empty and allowing for a rise time of 25 ns for the A-ring extraction. Even this is quite a challenging requirement that can almost certainly be met only by either electro-static kickers or by kickers working in transmission line mode (stripline kickers), whose parameters are given in row 2 of Table I. However, in this way, any need for a beam chopper in the A-ring injection line is obviated, which would otherwise be needed since the kicker gap cannot be created in the cyclotron due to the multi-turn extraction of H⁻ ions.

FIELD QUALITY

The field quality includes uniformity of the field as well as stability during flattop (ringing). Given that the kick to the beam has to be at least $\sqrt{2}\beta\epsilon$, an error in the kick angle of 1% leads to an emittance increase of 2% per transfer. For 8 transfers, a worst case scenario would therefore give a factor of $1.02^8 = 1.17$ or 17% in emittance blowup, which is not negligible but tolerable. More optimistically one would assume the angle error to be gaussian distributed and therefore get quadratic addition of the errors and a value of only 4% emittance blowup. This is certainly optimistic. We therefore set a limit of 1% for ringing and field uniformity.
KICKERS AND SEPTA AT THE PS COMPLEX, CERN

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ABSTRACT

The story of kickers and septa of the PS complex started in May 1963 when the first fast extracted beam was obtained from the 28 GeV synchrotron. Since those early days of the plunging small aperture kicker and its associated bending magnet there has been a constant evolution and increase in complexity as ring after ring has been added and the particle species widened. Today the complex has 20 kicker systems containing nearly 100 magnet modules and requiring no fewer than 200 thyratrons for PFN switching. The septum magnet population, whether d.c. or pulsed, approaches 40.

The design of the kicker systems has been influenced by the shortage of straight section length and the relatively short inter-bunch interval of all the PS machines. Typically needed field rise and fall times are 30 - 100 ns and the impedance levels are 8 - 30 ohms.

The paper reviews the current family of kickers, including their pulse generators, tries to justify the design options which were taken and relates the positive and negative aspects of operational experience extending over 15 years in certain cases. A similar but brief account of the septa is also given, but limited to magnet considerations.

INTRODUCTION

Kicker and septum magnet systems have become a way of life in the PS complex, accepted as mundane pieces of electrotechnical equipment and expected to have the same reliability as any other accelerator component. To a large extent this latter wish has been met, which is not to say that kickers and septa do not fail but rather that they do not fail too often. When misfortune strikes the damage can often be spectacular, which serves to remind that much of the design is often at the limits of the technically possible.

Over the past 25 years lessons have been learnt from the prolonged and arduous operation to which some of the systems have been subjected. These, together with the now available powerful and user friendly calculation programs, have allowed a continuous evolution in design such that it has become much easier today to build reliable systems of predictable performance. This is not to say that at the outset the designer is still often faced with a range of daunting questions typical of which are what voltage/impedance level to choose, what magnetic circuit (if any) to use, whether to place the kicker in machine vacuum or not and in the case of septa, whether to use d.c. or pulsed. To all these questions there is no simple or single answer because they take on a significance which depends very much on the machine environment. Suffice to say that at the PS we have striven to keep the $Z_0$ of our fastest kickers as high as possible (typically 25 - 30 Q) and never constructed a travelling wave kicker below 12.5 Q. We have also consistently opted for placing our kickers in machine vacuum, even when this has meant putting hundreds of kilograms of
ferrite in the ultra high vacuum systems of the AA and LEAR. We have tended to choose two operating voltage levels, 80 kV and 40 kV, for charging our pulse generators, the higher voltage being reserved for situations where we are desperately short of straight section length and where kick is more important than cost. All our generators have used pulsed resonant charging because we quickly discovered the enormous benefit that this type of rapid PFN charging had on the rise time of our thyratron switches. The magnetic circuits of our kickers have always been built with nickel zinc ferrites but we have used both C-core and window frame construction, the former for travelling wave magnets and the latter for lumped inductance magnets. On the septum front the uniformity of approach is even less obvious, the only two rules being that septa should not be placed in the UHV machines (where external to vacuum multturn d.c. septa are employed) and that the high repetition rate septa for the lepton programme should be d.c.. Otherwise we have a mixture of pulsed and d.c. septa installed in machine vacuum.

Hindsight always permits the redesign and improvement of everything that has ever been made and the kicker and septum systems of the PS are no exception. However, it is a fact that only one of the modern (post 1970) systems has had to be replaced because of performance weakness; all others are substantially still in the form in which they were created. The fault statistics for 1987, the last available, show that injection and ejection systems, principally but not exclusively kickers and septa, were responsible for only 6% of the total fault time (itself only 6% of the scheduled running time). This is not a bad record when considering how close to the limit some of the equipment is operated.

KICKER SYSTEM DESIGN CONSIDERATIONS

Magnets

Kicker magnets, by the very nature of their task, are fast magnets having only single turn excitation. Multi-turn magnets are not a design option where rise-times below a few hundreds of nanoseconds are concerned.

Design options do present themselves when it comes to choosing

a) environment - installed in machine vacuum
   - external to machine vacuum
b) type - transmission line of specific $Z_0$
   - lumped inductance
c) aperture - window frame
   - closed C-core
   - open C-core
d) termination - matched
   - short-circuited.

The advantage of installing kickers in machine vacuum is that aperture dimensions are minimised, reducing both voltage and current for a given kick and rise time. Metallised ceramic vacuum chambers for containment of machine vacuum and provision of image current path are
avoided. However the in vacuum magnet is costly, both in terms of its construction and its vacuum tank and pumping. More worrying, particularly in machines having short high density bunches, is the coupling impedance which the kicker presents to the beam. Machine vacuum is a reliable dielectric and PS experience has shown that even with the very large capacitor plate surfaces involved (several tens of m²) stresses of 70 kV/cm can be safely adopted without running into voltage conditioning problems. Externally mounted magnets leave open the choice of dielectric; compact dimensions can be obtained for transmission line magnets built with high e solid or liquid dielectric. Breakdown of these dielectrics, if it occurs, presents greater risk than a vacuum flashover - the solid dielectric is likely to suffer fatal failure on the first breakdown and the liquid dielectric, even if self healing, can propagate shock waves which can shatter the ceramic vacuum chamber. Perhaps through lack of courage the PS has opted for the "in vacuum" solution.

The decision between a transmission line magnet of specific $Z_0$ and a lumped inductance magnet is mainly a question of rise time. The latter has reached only 87% of its kick strength when the former is fully excited; this disadvantage can be partially overcome by adding a shunt capacitor to the lumped magnet which steepens the final stage of the rise, provoking some overshoot if the capacitor is above the critical value. How valid is this approach depends on the degree of overshoot which is acceptable and on the kick limits defining the rise time. Lumped inductance magnets, unlike transmission line ones, are traditionally installed after their terminator, in which position they are only subject to voltage during the rise and fall of the current pulse. This helps their voltage hold-off, particularly for long pulses but exposes them to bi-polar voltage. Another consequence of lumped inductance magnets is that they present a transient mismatch to the pulse generator, which results in post-pulse reflections at the magnet if specific measures are not taken to absorb them at the remote end of the PFN. The PS policy has been to use lumped inductance magnets only where the permissible rise time has exceeded 150 ns.

The choice of $Z_0$ for a transmission line magnet is a question of the available straight section length. In general the highest impedance (say up to 50 $\Omega$) should be used consistent with the length available and the chosen level of PFN charging voltage, which in turn determines the number of parallel modules needed. The higher the $Z_0$, the lower the switched current and the higher the magnet cut-off frequency. Both are particularly important elements in obtaining clean, fast, low flat-top and post-pulse ripple kick pulses. The cut off frequency $f_0$ (Fig. 1) depends on the cell inductance $L$ and capacitance $C$ and also on the equivalent series inductance $L_s$ of the capacitor, due in part to the physical inductance in the capacitor branch and in part representing the mutual coupling between cells. Whilst in theory the fall of $f_0$ with reducing $Z_0$ can be arrested by reducing the cell dimensions, in practice this leads to wafer thin capacitor plates and an impossible mechanical construction as two vacuum gaps must still be maintained per cell. Typical $f_0$ values as a function of $Z_0$ for the type of construction used in the PS are listed in Fig. 1. Aperture considerations are very much influenced by whether or not a high $\mu$ magnetic circuit is used. PS practice is always to use a
magnetic circuit because failure to do so considerably increases the effective vertical aperture, lowering in consequence the \( Z_0 \) and making control of the field quality in the useful aperture more difficult. Having decided on a magnetic circuit it remains to choose its form and the specific material. Both window frame and C-core sections are used in the PS, the former restricted to lumped inductance magnets and the latter always adopted for travelling wave designs and occasionally for the others. C-core configurations usually have the aperture closed by the return conductor but this is not possible where the beam has to be swept into or out of the aperture by RF gymnastics. In this case the return conductor is located above and below the aperture or even placed around the backleg but with a 10% or so penalty in inductance. The magnetic material is invariably nickel zinc ferrite, but this comes in a very wide variety of grades with different magnetic and outgassing properties. Slowly acquired experience in the PS has shown that for the current pulse rise times which we employ (in turn limited by what we can get out of the thyatron switches) and typically no faster than 17 ns (10-90%), ferrite with a \( \mu \) of around 1000 can track the excitation pulse with a negligible delay of a nanosecond or so. Grades which have found favour are Indiana H2, Philips 8C11 and Ceramic Magnetics CMD 5005. The one most extensively used is that of Philips, and exclusively so for the UHV machines. As a matter of routine all ferrite (fully machined) is now vacuum fired at 1000°C prior to assembly into magnets. The as installed outgassing rate is 10 Torr litre/sec/cm². Low \( H \) is required to minimize the remanent field, typically 0,2 Oersteds for \( B \) of 3000 Gauss. This holds the \( \int B_{\text{rem}} \text{dl} \) of most of our kicker systems below 0,5 Gauss-meter.

The final option, not so much of magnet design but rather of system configuration, is whether or not the magnet should be terminated or short circuited. Short-circuiting is the ultimate measure for dealing with a space shortage. It allows the same kick with the same rise time to be obtained from half the space or alternatively the \( Z_0 \) to be doubled in the same space. The price to pay is in pulse generator complexity because double endedPFN switching is required, one switch having to be bi-directional. The inability of the switches to rapidly transmit the magnet generated current wave usually results in some small post-pulse reflections, rendering this approach more, attractive for ejection than injection schemes. Nevertheless it has been successfully applied to both in the antiproton collector of the PS, space shortage obliging.
Pulse Generators

Design considerations for pulse generators fall broadly into two classes: configuration and components. The configuration possibilities often depend on the magnet options and the kick gymnastics required.

The simplest configuration is that of a cable PFN, charged to double the needed pulse voltage, switched into a terminated transmission line magnet. The switch is fully floating; if an ordinary thyatron it can be damaged by inverse current from a load short. A variant, frequently used at the PS, is to add a remote end terminator and switch which has the advantages of permitting pulse length control (partial extraction), improving the fall-time (by pre-distortion if necessary) and limiting switch damage from a load short. A lesser alternative is to double the PFN length and connect a magnet load to each end. Cable PFN's furnish ripple free pulses but low attenuation is essential if droop and "cable tail" are to be within acceptable limits for long pulses. Attenuation is adversely affected if semiconductors are added at the dielectric boundaries to improve voltage withstand. The PS solution has been to use SF pressurised PE tape cables without semi-conductors for the 80 kV systems. Typically droop is limited to 1% on a 2.7 µs 26 Ω pulse, with no HV failure in 10 years service.

The cable PFN ceases to be attractive for pulses exceeding about 3 µs on account of cost, bulk and the droop/tail problems. The alternative is the lumped element PFN with R-L-C head cell to improve the initial rise. So equipped the lumped element line can equal the cable for rise but the fall can never be made fast enough for injection applications without recourse to a shorting clipper switch on the kicker transmission. Such a clipper creates multiple reflections within the lumped element line which in turn may require a third switch and terminator at the remote end for their absorption. Thus whilst for ejection applications a lumped element line with single switch is perfectly satisfactory, at least two if not three switches are needed when the task is injection. Clipper switch rise time needs special care because it has to handle twice the magnet current. A few examples of both one and three switch lumped element PFN's exist in the PS, reserved for low Z₀ (down to 8 Ω) and long pulse (up to 24 µs) applications.

An alternative form of energy store is the Blümlein arrangement which has the virtue of generating pulses of voltage equal to the PFN charge voltage. However it requires cables of half the Z₀ of the load and the closing switch has to handle twice the magnet current. It is a current against voltage trade-off with respect to the simple cable PFN. It is not used at the PS because of the increased thyratron switching time which would result.

Some of the advantages of the Blümlein system but without its disadvantages can be obtained by incorporating the transmission line magnet as part of a cable PFN with a shorting switch at one end and a terminator and second switch at the other. The rise time is that due to a single magnet propagation and the pulse voltage is the PFN charge voltage. The fall time cannot be shorter than two magnet propagations. An additional penalty is that the magnet must withstand the PFN charge
voltage prior to the pulse and suffer partial voltage inversion during it. This arrangement is particularly attractive where space is limited and where only rise time is important. It is used in the PS for the Booster extraction and recombination kickers.

Certain ejection schemes at the PS have required the generation of staircase waveforms and short interval pulse trains. These are not of interest for the KAON factory and will not be further discussed except to say that entirely satisfactory results in both cases can be obtained by the discharge of serially combined PFN's and thyatron switches.

On the component side, principal attention has to be paid to the choice of high voltage switches, recharging power supplies and terminating resistors. Present-day practice, fully justified by results, is to use thyatron switching throughout. Care must be taken in tube selection, particularly in circuits prone to inverse current in oft repeated fault conditions. Today there exists an extensive range of bi-directional thyatrons, either of the double cathode or hollow anode type, capable of safely handling inverse current. The small cost increase which they represent is often an excellent investment. Tube ratings need to be regarded with a certain conservatism, particularly the voltage rating of multistage tubes which have to be pushed to maximum dI/dt. PS experience is that in good housings with correctly designed circuitry and triggering an average dI/dt of 100 A/ns can be readily obtained and held between the 10 and 90% points, even for the 80 kV applications. As much as 150 A/ns is possible in 6.25 Ω circuits operating at 40 kV. Repetition rates of 100 Hz have shown no additional problems. Tube lifetime in our modestly (low Hz) rep. rated systems averages more than 20000 filament hours. Jitter is greatest on multi-stage tubes but still under 5 ns, including the triggering system. Slow drift is easily stabilised by suitable electronics. The most used tubes in the PS systems are the CX 1171 and its variants for the 80 kV systems and the CX 1154 and its variants for the 40 kV systems. Glass CX 1159 tubes are used up to 30 kV. Almost without exception the tubes are oil immersed, often forced cooled.

Power supplies are, without exception, of the pulsed resonant type permitting PFN recharge in a few ms. Fast recharging has a very favourable influence on the self firing frequency of thyatrons at any given reservoir setting and is a necessity if the previously quoted dI/dt values are to be obtained. The PS supplies use a step up transformer as the resonating inductor. Core bias, which influences recovery, is applied through a tertiary winding. HV diodes when fitted between transformer output and PFN, improve operational flexibility in decoupling the power supply and thyatron trigger timing. This is always done at the PS. The primary energy store is often a large electrolytic capacitor running at about 200 V.

Terminating resistors can be of the electrolytic or carbon mass type, the latter of disc or tubular form. At the PS we have standardised on the disc carbon mass type, oil immersed with forced oil cooling. Stability, particularly in a radiation environment, is not excellent and rebuilding of resistor stacks represents a major proportion of our maintenance effort. Probably the tubular type is more stable but contact problems are more severe. The ideal terminator is yet to be found.
PS KICKERS

Historical background

The first small aperture, hydraulically actuated kicker became operational in the PS ring in May 1963. It had an aperture of 5 x 3 cms and rise time fast enough to eject cleanly one bunch. Excitation was from either short or long spark gap switched lumped element lines, located inside the machine tunnel. It remained operational until 1968 when it was replaced by another plunging magnet of useful aperture 2.0 x 2.2 cms excited from remotely positioned lumped element lines with main, dump and clipper spark gaps for full control of pulse length. In 1974 this equipment was replaced by the present full aperture kicker system. During 1964-9 a single module push-pull excited (+ 120 kV) full aperture device was developed. Its ferrite circuit, suitably impregnated with epoxy resin, formed part of the containment for machine vacuum and also furnished capacitance for the delay line magnet. Whilst it was successfully tested with beam it was abandoned in 1969 because it could not satisfy the tightening PS vacuum specification and was considered an oil hazard in the event of high voltage breakdown. At this point development started on the present PS full aperture kicker, from which most of the other kickers have since evolved.

Present situation

Table 1 lists the ratings of the present kicker population of the PS complex. Comment will be restricted to the oldest high voltage system which is the 12 module full aperture kicker of the PS ring. Commissioned in 1973, this kicker was used initially for multiple partial extractions for bubble chamber physics; in later times it has served as the ejection kicker for protons for \( p \) production and SPS fixed target physics, and most recently for leptons. It also reinjects \( p \) into the PS ring from the Accumulator. The kicker has a six shot per cycle capability with minimum interval of 30 ms. Both kick amplitude and duration can be freely varied from shot to shot. The pulse generator is a gas pressurised PFN cable with CX1171 switching at either end. Transmission distance between generators and magnets is 170 m, mainly in gas pressurised cable but with final connections in solid PE cable to facilitate maintenance. To date each module has pulsed well in excess of 10^6 times, the standard charge voltage being 80 kV. There have been no serious high voltage failures in the pulse generators and the magnet vacuum tanks have never been opened. Principal weaknesses have been the flexible coaxial cables for final connection of the transmission lines and terminator stability. Recharging power supplies using 315/1 step up transformers and 210 V electrolytic primary storage have been totally trouble-free.

PS SEPTA

Table 2 lists the ratings of the septa currently in use in the PS complex. The mixture is mainly of multiturn d.c. and single turn
pulsed magnets, with a predominance for "machine vacuum" installation despite the considerable gas load which results. Magnetic circuits are ferrite or laminated steel for the pulsed magnets; certain d.c.

Table 1. Ratings of present PS complex kickers.

<table>
<thead>
<tr>
<th>Machine</th>
<th>Application</th>
<th>Type and 2 (Q)</th>
<th>Aperture w x h (mm)</th>
<th>No. of Modules</th>
<th>Total L [Ko] (Gauss-m)</th>
<th>PFW Voltage (kV)</th>
<th>Kick (5-95%) Rise (ns)</th>
<th>Fall (ns)</th>
<th>JH [mJ]</th>
<th>Flat top (us)</th>
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<td>Booster</td>
<td>Ejection</td>
<td>Delay line 25 Q</td>
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<td>4</td>
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<td>40</td>
<td>53</td>
<td>55</td>
<td>30</td>
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<tr>
<td></td>
<td>Transfer</td>
<td>Delay line 12.5 Q</td>
<td>70 x 115</td>
<td>2</td>
<td>567</td>
<td>40</td>
<td>52</td>
<td>54</td>
<td>36</td>
<td>1.25</td>
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<td>Delay line 26.3 Q</td>
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<td>304</td>
<td>80</td>
<td>-</td>
<td>39</td>
<td>30</td>
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<tr>
<td></td>
<td>Injection (e-e)</td>
<td>Delay line 15.7 Q</td>
<td>112 x 74</td>
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<td>80</td>
<td>87</td>
<td>10</td>
<td>70</td>
<td>1.80</td>
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<td></td>
<td>Fast ejection</td>
<td>Delay line 15 Q</td>
<td>147 x 53</td>
<td>12</td>
<td>1680</td>
<td>80</td>
<td>68</td>
<td>70</td>
<td>55</td>
<td>0.10-2.10</td>
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<td></td>
<td>Fast ejection P LEAR only</td>
<td>Lumped L 25 Q</td>
<td>158 x 73</td>
<td>1</td>
<td>210</td>
<td>80</td>
<td>249</td>
<td>-</td>
<td>-</td>
<td>0.10-0.10</td>
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<td>Continuous Transfer</td>
<td>Lumped L 25 Q and 8.3 Q</td>
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<td>1 + 1</td>
<td>543</td>
<td>Up to 40</td>
<td>400</td>
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<td>Ditto</td>
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<td>-</td>
<td>165</td>
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<td>Injection Bumper (H)</td>
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<td>80</td>
<td>860</td>
<td>2800</td>
<td>-</td>
<td>0.20-28.0</td>
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<td>Antiproton Rings</td>
<td>Collector Injection</td>
<td>Delay line 15 Q</td>
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<td>140 x 72</td>
<td>2</td>
<td>2642</td>
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<td>105</td>
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<td>140 x 68</td>
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<td>105</td>
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<td>Collector Ejection</td>
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<td>250 x 100</td>
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<td>292 x 90</td>
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<td>Collector Ejection</td>
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<td>132 x 45</td>
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<td>60 x 23</td>
<td>1</td>
<td>780</td>
<td>80</td>
<td>165</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Electron Positron Accumulator</td>
<td>Injection</td>
<td>Delay line 35 Q</td>
<td>110 x 35</td>
<td>2</td>
<td>90</td>
<td>40</td>
<td>36</td>
<td>30</td>
<td>24</td>
<td>0.05 (100 Hz)</td>
</tr>
<tr>
<td></td>
<td>Ejection</td>
<td>Delay line 30 Q</td>
<td>100 x 35</td>
<td>1</td>
<td>45</td>
<td>40</td>
<td>36</td>
<td>-</td>
<td>23</td>
<td>0.05 (kHz)</td>
</tr>
</tbody>
</table>

magnets use solid cores, others laminated, particularly for storage rings. Until about 5 years ago laminated circuits comprised epoxy glued stacks. Recent practice has been to use transil steel, an inorganic insulated material, in pressure held stacks which can be vacuum baked in situ up to 150°C. The ultimate outgassing of this newer conception is lower but bakeout is essential for reasonable pump down time.

Most PS septa have performed extremely well and the average service life of a magnet is probably around 10 years. The most significant difficulty has been blockage of d.c. septa by copper oxide deposits from the interaction of dissolved oxygen in the demineralised cooling water with their copper conductors. A solution has been found.
by cooling the most dissipative d.c. septa with low oxygen (< 100 ppb) demineralised water. Typical current density and water velocity in these magnets are 70 A/mm² and 12 m/s respectively. There is only one recorded case of coil failure from cavitation, perhaps 3 or 4 from oxide blockage although prior to the introduction of low oxygen water.

### Table 2. Ratings of present PS complex septa.

<table>
<thead>
<tr>
<th>Machine</th>
<th>Application</th>
<th>Type</th>
<th>No. in service</th>
<th>Max. I (kA)</th>
<th>No. of turns</th>
<th>Length (mm)</th>
<th>Gap w x h (mm x mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Booster</td>
<td>Distributor</td>
<td>P.V.F</td>
<td>4</td>
<td>0.004</td>
<td>1</td>
<td>354</td>
<td>90 x 50</td>
</tr>
<tr>
<td></td>
<td>Injection</td>
<td>P.V.F</td>
<td>1</td>
<td>0.172</td>
<td>1</td>
<td>860</td>
<td>30 x 12</td>
</tr>
<tr>
<td></td>
<td>Ejection</td>
<td>P.V.F</td>
<td>2</td>
<td>0.136</td>
<td>1</td>
<td>860</td>
<td>30 x 12</td>
</tr>
<tr>
<td></td>
<td>Transfer</td>
<td>P.V.F</td>
<td>2</td>
<td>0.071</td>
<td>1</td>
<td>710</td>
<td>60 x 40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DC.V.SS</td>
<td>4</td>
<td>0.220</td>
<td>1</td>
<td>1170</td>
<td>80 x 24.5</td>
</tr>
<tr>
<td>PS Ring</td>
<td>Injection e⁻</td>
<td>DC.V.SS</td>
<td>1</td>
<td>0.25</td>
<td>12</td>
<td>700</td>
<td>100 x 60</td>
</tr>
<tr>
<td></td>
<td>Injection e⁺</td>
<td>P.V.TS</td>
<td>1</td>
<td>0.380</td>
<td>12</td>
<td>400</td>
<td>70 x 18</td>
</tr>
<tr>
<td></td>
<td>Slow Extraction</td>
<td>P.V.LS</td>
<td>1</td>
<td>0.415</td>
<td>2</td>
<td>500</td>
<td>70 x 18</td>
</tr>
<tr>
<td></td>
<td>Ejection p⁺</td>
<td>P.V.LS</td>
<td>1</td>
<td>1.01</td>
<td>2</td>
<td>1010</td>
<td>50 x 25</td>
</tr>
<tr>
<td></td>
<td>for LEAR</td>
<td>P.V.F</td>
<td>1</td>
<td>0.118</td>
<td>1</td>
<td>500</td>
<td>70 x 25</td>
</tr>
<tr>
<td></td>
<td>for SPS</td>
<td>P.V.LS</td>
<td>1</td>
<td>1.403</td>
<td>1</td>
<td>400</td>
<td>62 x 25</td>
</tr>
<tr>
<td>LEAR</td>
<td>Injection/</td>
<td>DC.A.LS</td>
<td>1</td>
<td>0.369</td>
<td>10</td>
<td>900</td>
<td>155 x 50</td>
</tr>
<tr>
<td></td>
<td>Ejection</td>
<td>DC.A.LS</td>
<td>1</td>
<td>0.244</td>
<td>20</td>
<td>400</td>
<td>135 x 74</td>
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<tr>
<td>Antiproton</td>
<td>Collector Injection</td>
<td>P.A.LS</td>
<td>1</td>
<td>1.665</td>
<td>2</td>
<td>1714</td>
<td>119 x 90</td>
</tr>
<tr>
<td>Rings</td>
<td>Collector Ejection</td>
<td>P.V.TS</td>
<td>2</td>
<td>0.77</td>
<td>1</td>
<td>859</td>
<td>75 x 30</td>
</tr>
<tr>
<td></td>
<td>Accumulator Injection</td>
<td>DC.A.LS</td>
<td>2</td>
<td>0.6174</td>
<td>10</td>
<td>1001</td>
<td>296 x 76</td>
</tr>
<tr>
<td>Electron</td>
<td>Injection</td>
<td>DC.A.LS</td>
<td>2</td>
<td>0.2862</td>
<td>4</td>
<td>519</td>
<td>91 x 25</td>
</tr>
<tr>
<td>Positron</td>
<td>Accumulator Ejection</td>
<td>DC.A.LS</td>
<td>2</td>
<td>0.7842</td>
<td>12</td>
<td>519</td>
<td>91 x 25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>P.V.TS</td>
<td>1</td>
<td>0.53</td>
<td>1</td>
<td>400</td>
<td>70 x 18</td>
</tr>
</tbody>
</table>

P = Pulsed  A = Air mounted  F = Ferrite  LS = Laminated steel
DC = Continuously powered  V = In machine vacuum  SS = Solid steel  TS = Transil steel

frequent rinsing with sulfamic acid was needed. All pulsed septa are operated at low repetition rate (< 1 Hz) and present no characteristic weaknesses although those with most water circuit joints within the vacuum envelope, a principle to be avoided if possible, have been least reliable.

### CONCLUSION

The range, performance and reliability of the CERN PS septa and kickers may serve as encouragement for the kaon factory project. However the PS complex is a slow cycling facility.
New stripekicker in the injection chain of HERA

J. Rümmler DESY
The data of this paper were presented at the Magnet Design Workshop at Triumf in Vancouver.

1. Summary
2. New stripekicker at DESY
3. Cross-section of an stripekicker
4. Stripekicker for rectangular pulses and short pilot pulses for tests.
5. Stripekicker for sinewave pulses.

The injection chain into HERA
1. Summary

In the HERA injection chain for the inj- and ejections many stripekickers are used to switch the beam. The kicker in PETRA must switch in an very short time. Ferrite kickers with stripes meet all the requirements. During my talk I showed a lot of kickers and septa in detail. Many aspects of the constructions can give problems in the complete injection or ejection system. I concentrate here on good stripekicker technic.

2. New stripekicker at DESY

Stripekickers work in an wide frequence range. Thyratrons can change rectangular pulses (in PETRA) from 7.5μS, the PETRA beam, to single short pulses for the pilot bunch ejection to test the transport lines.

All the kickers in the HERA elektron injection chain have been tested and work well.

The kicker idea is to have a kicker chamber which leads the rf like a vacuum chamber.

The wall of the chambers is horizontal with the outer side closed; metal leads the rf through the kicker without reflections and can also absorb synchrotron radiation.

Longitudinal stripes on the top and bottom of the chamber lead the rf and protect the ferrites from the rf.

Stripes are connected alternately on the left and right and the parallel capacities between the stripes close the chamber for the rf. But for the quick rising kicker field the stripe capacities are in series, so that the kicker field is not shorted.

The current lead of the kicker is tapered at both ends to minimize rf reflection.

There is much more to see.
HV between the stripes.
HV between stripes and ferrite.
Capacities between the stripes.
Rf reflection measurements over a wide frequency range.
And there are stripekickers for sinewave pulses, and rectangular pulses.

After HERA is already build I give more information.
cross-section of a stripe kicker  

figure 3
Petra e⁻ Ejektion 3 Kicker mit Pulser

Kickerkasten für 3 Kicker ca 4m lang

T1 Hauptthyatron
T2 Flankenthyatron

J. Rümmel

Datum: Juni 29/87
Zeit: 15:22:17

TRI1: 5.00V :2us
TRI2: 5.00V :1us

figure 4
OVERVIEW OF KICKER MAGNET SYSTEMS AT THE SPS AND LEP

V.Rödel, G.H.Schröder
CERN, Geneva, Switzerland

ABSTRACT

The 450 GeV Super Proton Synchrotron (SPS) and the Large Electron Positron Collider (LEP) at CERN are equipped with more than 40 kicker magnet systems containing about 100 high power thyratrons for injection, ejection or dumping of the various types of accelerated particles (protons, antiprotons, heavy ions, electrons and positrons). Depending on their particular application the magnets and pulse generators are built according to different design criteria.

After a short overview of the different systems the largest device, the SPS proton and positron inflector (12 independent kicker magnets, kick strength 0.43 Tm, kick rise time 145 ns, pulse duration 1 to 12μs) is described in more detail.

INTRODUCTION

The Super Proton Synchrotron (SPS) at CERN accelerates proton beams of about $3 \times 10^{13}$ particles to 450 GeV for fixed target physics. It also operates as a proton-antiproton collider at 315 GeV with a luminosity of $>10^{30}$ cm$^{-2}$s$^{-1}$. The SPS is furthermore used as pre-accelerator of the Large Electron Positron Collider (LEP), accelerating short electron and positron bunches from 3.5 GeV to 20 GeV. LEP will start operation in July 1989 and will initially run at an energy of about 55 GeV per bunch.

The SPS with its different operation modes needs various kicker magnet systems for injection, ejection, beam dumping and tune measurements. LEP requires 2 injection systems for electrons and positrons consisting each of 3 kicker magnets and a fast septum kicker magnet. All kicker systems differ considerably in their specifications with respect to deflecting power, repetition rate, kick flat-top duration, kick rise and fall times and beam apertures resulting in systems of rather different design.

This paper gives an overview of the kicker magnet systems at the SPS and LEP. The SPS proton and positron inflector is then treated in more detail as it comes closest to the future requirements of TRIUMF. Detailed descriptions of the various systems can be found in references $^1$–$^8$.

OVERVIEW

The kicker magnet systems at the SPS and LEP can be divided into 2 groups employing rather different technologies: hadron kickers and lepton kickers.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of magnets</td>
<td>12</td>
<td>5</td>
<td>7</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Kick strength per magnet (mT.m)</td>
<td>36</td>
<td>39</td>
<td>197</td>
<td>381</td>
<td>667</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Magnet impedance (Ω)</td>
<td>12.5</td>
<td>12.5</td>
<td>10</td>
<td>2</td>
<td>(0.24)</td>
<td>6.25</td>
<td>6.25</td>
</tr>
<tr>
<td>Kick flat-top duration (μs)</td>
<td>1 to 12</td>
<td>0.2</td>
<td>1 to 23</td>
<td>23</td>
<td>(quasi-sinusoidal pulse)</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>Kick rise time (2 to 98%) (μs)</td>
<td>type S: 0.145</td>
<td>0.220</td>
<td>1.1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Kick fall time (98 to 2%) (μs)</td>
<td>0.690</td>
<td>0.220</td>
<td>1</td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>5 pulses 2.4 s</td>
<td>3 pulses 15 s</td>
<td>15 s</td>
<td>15 s</td>
<td>15 s</td>
<td>4 pulses 0.1 s apart within 4 s</td>
<td></td>
</tr>
<tr>
<td>Max. generator voltage (kV)</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>12</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Max. magnet current (kA)</td>
<td>2.4</td>
<td>2.4</td>
<td>3</td>
<td>15</td>
<td>46</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Max. stored energy per pulse (kJ)</td>
<td>1.9</td>
<td>0.03</td>
<td>2.3</td>
<td>11.3</td>
<td>3.7</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Switch type:</td>
<td>CX1171B</td>
<td>CX1171A</td>
<td>CX1171B</td>
<td>CX1171B</td>
<td>CX1154</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thytratrons</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>BK7703</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ignitrons</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>BK488</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of magnet cells</td>
<td>22</td>
<td>22</td>
<td>7</td>
<td>5</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Yoke material</td>
<td>ferrite</td>
<td>ferrite</td>
<td>ferrite</td>
<td>ferrite</td>
<td>steel</td>
<td>ferrite</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.2 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnet capacitor location</td>
<td>vacuum</td>
<td>vacuum</td>
<td>oil</td>
<td>oil</td>
<td>-</td>
<td>oil</td>
<td>oil</td>
</tr>
</tbody>
</table>
The (older) hadron kickers have large oil insulated pulse generators charged up to 60 kV producing quasi-rectangular pulses of fast rise and/or fall time and low repetition rate. The ferrite magnets are of the delay line type and housed in vacuum tanks. The stored energy per pulse is considerable, amounting to more than 11 kJ in the case of the vertical beam dumping system. The main parameters are listed in Table I.

The (newer) lepton kickers operate with bursts of half sine wave pulses of very short repetition time produced in complex air insulated generators and resonant charging systems. The magnets are unmatched inductances either housed in the accelerator vacuum (in the SPS) or in air around metallized ceramic vacuum chambers (in LEP). The main parameters are given in Table II.

Hadron Kickers

For fixed target proton operation the whole SPS machine circumference is filled with particles except for 2 short gaps required for the magnetic field rise of the kicker magnets. As the hadron kickers shall give a constant deflection during up to 1 turn of the circulating beam, they must produce quasi-rectangular pulses with short rise and fall times. As a consequence these systems are built as matched travelling wave structures including delay line type kicker magnets. Depending on the rise times, different methods for matching of magnets and generators have been used.

a) For short rise times (< 150 ns) the pulse forming networks (PFN's) and the magnets are composed of many cells. In the case of the proton inflector which produces a kick rise time of 145 ns the PFN is built of 35 cells and the magnet of 22 cells. As a short rise time requires a high characteristic impedance of the system, the matching capacitors of the magnet are sufficiently small enough to be formed by parallel plates interleaved with the ferrite blocks using the vacuum as a dielectric. The plate size is still such that the vacuum tank has an acceptable diameter. This type of construction limits stray inductances in series with the capacitors and results in a high cut-off frequency of the magnet.

b) For longer rise times (< 1.5 µs) the magnets are subdivided in only 5 to 7 cells and their characteristic impedance is chosen lower resulting in a high kick strength for a given generator voltage. Examples of this type are the vertical beam dumping and the fast ejection systems. The beam dumping system has a rise time of 1 µs and an impedance of 2 Ω with 5 cells per magnet. The matching capacitors are now rather large and therefore housed in oil-filled boxes under the vacuum tank. The unavoidable stray inductances in series with the capacitors produced by the vacuum feedthroughs determine to a large extent the frequency response of the system.

c) For rise times of about 50 µs, as in the case of the horizontal deflectors (the "sweepers") of the beam dumping system, the magnets are built of 0.2 mm thick silicon steel laminations insulated by a thin oxide
Table II. Lepton Kickers

<table>
<thead>
<tr>
<th></th>
<th>SPS Positron-</th>
<th>SPS Electron-</th>
<th>LEP Injection Kicker</th>
<th>Kicker septum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ejection,</td>
<td>ejection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of magnets</td>
<td>3</td>
<td>1</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Kick strength per magnet (mT.m)</td>
<td>56.7</td>
<td>80</td>
<td>56</td>
<td>374.5</td>
</tr>
<tr>
<td>Kick rise time (0 to 100%) (μs)</td>
<td>0.7</td>
<td>0.8</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Kick fall time (100 to 0%) (μs)</td>
<td>1.5</td>
<td>1.5</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Max. generator voltage (kV)</td>
<td>30</td>
<td>30</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Max magnet current (kA)</td>
<td>3.3</td>
<td>5.6</td>
<td>1.6</td>
<td>5.1</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>&gt;65 μs between pulses, 8 pulses per burst, burst repetition rate 1.2 s</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Thyratrons</td>
<td>CX1154, CX1159, CX1181D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construction</td>
<td>ferrite magnet in vacuum tank</td>
<td>2-turn air insulated magnet, ceramic vacuum chamber</td>
<td>ferrite magnet in vacuum tank</td>
<td></td>
</tr>
</tbody>
</table>

layer and housed under vacuum. Steel is preferred for this application because of its higher saturation induction. Despite the large number of laminations (>6000) an acceptable pressure of < 10⁻⁸ Torr is obtained. No organic insulation material is used. The magnets are unmatched inductances and excited by half sine wave pulses generated with air insulated capacitor banks⁴.

Lepton Kickers

For lepton operation the requirements on the kicker magnets are considerably different: Instead of a machine circumference homogeneously filled with particles (as in the case of proton operation on fixed targets), the leptons are grouped in a few short bunches (4 or 8 in the SPS, 2x4 in LEP) of < 1ns duration with a bunch separation in the SPS of
1.6 μs and in LEP (at the kicker magnet position) of 3.2 μs. The bunches must be injected and ejected individually. The time between bunches can be used as kick rise time and the flat-top time can be very short, now determined mainly by the jitter of the discharge switches. Because of the long rise and the short flat-top times a quasi-sinusoidal excitation is used. The magnet is then a pure inductance oscillating for half a period with a pulse capacitor.

An LC oscillation circuit has many advantages compared to a matched travelling wave system: In addition to the low cost unmatched magnet, the operation voltage is comparably low (< 35 kV). This allows air insulation and the use of low cost switches. However, the pulse generator must be located close to the magnet and is therefore not accessible for maintenance during operation. Furthermore all components must be radiation resistant.

Contrary to the low repetition rate of the hadron kickers a fast burst operation is required for the lepton kickers. Up to 8 pulses (one burst) must be produced with a repetition time < 98 μs in the SPS and < 65 μs in LEP. The repetition time of the burst itself is about 1 s. Only one-gap thyratrons with their inherently short recovery time can handle the high repetition rate. Their operation voltage is limited to about 35 kV, just sufficient for this application.

The high repetition rate generators with their fast recharging systems located at up to 1 km distance from the magnets are described in references\(^5,6\).

For the magnets two different technologies have been applied:

- Magnets which deflect only the low intensity bunches are housed in vacuum tanks. This is the case of the SPS injection and ejection kickers and the pulsed injection septum magnet of LEP\(^7\).

- The 6 LEP inflector magnets through which the short high intensity bunches of the full LEP current circulate use metallized ceramic vacuum chambers. The ferrite magnets are in air and have 2-turn mica epoxy insulated excitation coils. The ferrite is screened from the bunches by the metallized chamber. This construction is necessary to avoid heat-up of the ferrite by bunch induced gyro-magnetic resonances.

Contrary to the usual practice, the LEP injection septum magnet has the same fast pulsed excitation system as the LEP kicker magnets. A d.c. or a slowly pulsed excitation system would have been uneconomic, either because of high power losses on the 1 km long transmission line, or the necessity to provide low radiation space for a generator in the accelerator tunnel close to the magnet. The septum is designed as a simple metallic plate acting as eddy current screen and requiring neither cooling nor connection to the excitation circuit.
PROTON INFLECTOR

We give now a more detailed description of the SPS proton and positron inflector as its design comes closest to the future requirements of TRIUMF. We follow the presentation given in reference 1.

The proton inflector is used to inject into the SPS:

- protons at 14 GeV/c for fixed target operation, and
- at 26 GeV/c for proton-antiproton collider operation
- positrons at 3.5 GeV/c for LEP pre-acceleration.

General

As for all other hadron kicker magnet systems of the SPS, the maximum generator voltage is limited to 60 kV mainly for two reasons:

- It allows reliable operation of the thyratron switches at pulse durations of up to 12 μs with current levels of up to 5 kA.
- Standard low cost coaxial cables RG 220/U can be used for the 250 m long transmission lines between pulse generators and magnets. These cables are readily available from industry. Higher voltages would require costly nonstandard cables.

To achieve a kick rise time of 145 ns, the magnet module length must be limited to 0.7 m. Twelve separately powered modules are then required to provide the kick strength for collider injection at 26 GeV/c.

For beam optical reasons the first 8 modules (type S) have a smaller aperture ratio and hence a shorter kick rise time (145 ns) than the 4 remaining ones (type L, 220 ns rise time).

Only the 8 S-modules are used for fixed target operation at 14 GeV/c injection momentum where the short rise time is important.

For injection of a burst of 4 positron bunches at 3.5 GeV/c the 8 S-modules are grouped in pairs and successively powered at 98 μs intervals. The pulse generators are then resonantly recharged within 30 ms and the operation is repeated to inject a further burst of 4 bunches. These 8 bunches are then accelerated together to 20 GeV and ejected towards LEP.

The magnet modules are built as delay lines terminated by matched resistances. The characteristic impedance of the magnets is about 5% lower than that of the remaining system to compensate the attenuation of the travelling wave front in the 250 m long transmission line.

The pulse generators are lumped element pulse-forming networks, equipped with 3 thyratron switches to produce pulses of adjustable flat-top duration and short fall time. The modest contribution of the generator rise time to the total kick rise time permits connection of 2
magnets in parallel to 1 pulse generator which has therefore half the characteristic impedance of the magnets. This measure reduces considerably the total cost of the generators.

Magnet Design

A C-shape ferrite yoke has been chosen. The return conductor is located at the open C-side about 5 mm from the ferrite. It is therefore non-inductive and can be put at earth allowing the use of coaxial connections with earthed outer conductors at the input and output of the magnet. The lower field quality of a C-shape magnet as compared to a window frame magnet is improved by adding shims along the gap. A C-shape yoke eliminates furthermore the risk of flash-over along the ferrite surfaces since the ferrite is at uniform high potential.

The magnet yoke is assembled from 22 C-shape blocks of ferrite, each 26 mm thick with overall dimensions of 195 mm x 136 mm. They are interleaved with 5 mm thick Al-Mg plates of about 40 cm x 50 cm forming the high-voltage side of the capacitors. Earth plates are mounted on either side of the high-voltage plates at a distance of about 5 mm. The total vacuum capacitor plate surface of the 12 modules exposed to an electric field of up to 60 kV/cm amounts to about 180 m².

Philips Ni-Zn ferrite (type 8C11) is used as magnetic material. It is particularly well suited for kicker magnet applications because of its good vacuum properties (density \( g > 5.1 \text{ g/cm}^3 \)), its high saturation flux density (\( B > 0.3 \text{ T at } 10 \text{ Oe and } 20\degree\text{C} \)) and its low coercitive force (\( H_c < 0.25 \text{ Oe} \)). The blocks are vacuum baked at 400 °C prior to assembly.

The 1-turn excitation conductor, made of titanium, is pressed against the ferrite and screwed directly onto the high-voltage plates of the capacitors. Bad injection line steering could cause the high intensity proton beam to hit the return conductor. To avoid damage of the magnet under these circumstances, the return conductor is made of beryllium which is nearly transparent to the beam because of its low density.

Twelve magnet modules are housed in 3 vacuum tanks of stainless steel 304L, each 3.5 m long. A tank is composed of a base plate onto which the magnet modules can conveniently be mounted and aligned, and a Ω-shape cover. The latter is connected vacuum tight to the base plate by means of a diamond-shaped Al-seal of nearly 9 m circumference. A vacuum pressure of \( 2 \times 10^{-9} \text{ Torr} \) is achieved with 4 sputter ion pumps and 4 titanium sublimation pumps mounted under the base plate of each tank.

The coaxial low inductance termination resistor is mounted onto the base plate of the tank and connected via a matched coaxial feedthrough to the magnet. The active resistor stack consists of ten ceramic-bound carbon discs, each 1 inch thick with 3 inches outer diameter, mounted in series, and interleaved with flat metal spirals for forced cooling by silicone fluid.
Pulse Generator Design

The pulse generator consists of a pulse forming network and 3 high power switches, each mounted in a separate metallic enclosure on top of the PFN. The PFN has 36 cells of 30 nF capacitance and 1.17 μH inductance each. The cells are arranged in 2.5 rows separated from each other as far as possible in order to avoid electro-magnetic interferences between different rows. In a PFN of constant pulse length interferences can be compensated by cell adjustment. This is however not possible when the pulse length is variable. They must therefore be avoided either by sufficient row separation or by screening.

Previous experience with a 3-switch generator had revealed interferences between the switches. In particular the clipper switch is sensitive to erratic firing if it is connected to the cathode of the main switch. In order to avoid these interferences the three switches are housed in separate tanks and the clipper switch is connected to the anode of the main switch. The connection is done with a matched stripline located in the PFN container.

The switches are three-stage ceramic thyatrons with two cathodes assemblies (double ended), type EEV CX1171B. Double ended thyatrons are used because of current reversals and higher capabilities, compared to single-ended tubes, to conduct high-current pulses of long duration. The pulse generators are resonantly charged about 10 ms prior to the firing of the main thyatrons. This mode of operation improves the voltage holding capability of the thyatrons. It allows furthermore operating them at higher gas pressure which favours a short current rise time.

Performances

The proton inflector system has been in operation since 1981 and performs as anticipated. The reliability of the complex installation with 18 high power thyatrons, more than 200 high voltage coaxial connectors and about 180 m² of capacitor plates under high voltage stress is excellent. The thyatron lifetime is between 15000 and 20000 hours. The replacement of a faulty thyatron including the 15 minutes preheating time of the new valve takes less than 1 hour.

CONCLUSION

The kicker magnet systems of CERN SPS and LEP machines presented in this brief overview are of proven design. They have operated reliably since their installation; for some of them this is more than a decade. The parameters of the proton inflector come close to the needs of TRIUMP's kaon factory. Its technology is well understood and could readily be applied.
REFERENCES


A KICKER UPGRADE FOR LOS ALAMOS PROTON STORAGE RING
(presentation at KAON PDS Magnet Design Workshop)

H.A. Thiessen
Los Alamos National Laboratory, Los Alamos, NM 87545

Collaboration

• Los Alamos
  - Vern Sandberg
  - Gary Rodenz
  - Arch Thiessen
• SAIC
  - Russ Winje
• With Lots of Free Advice From
  - David Fiander, CERN

Outline

1. Specifications
2. Current Required
3. Inductance
4. Rise Time
5. Tricks to Divide the Inductance
6. Safety Considerations
7. Accelerated Lifetime Tests
8. Effect of Ferrite Permeability
9. SPICE Calculations
10. Summary

Specifications

• Magnet Gap 9 cm
• Magnet Width 18 cm
• Kick Angle 18 mrad
• Rise Time 70 ns
• Pulse Length 400 ns
• Repetition Rate 60 Hz
• Uniformity of Kick 5%
• Available Space 4 meters
• Coupling Impedance to Beam ? Ohms

Current Required

• Assume Packing Factor = 0.5
  - 2 meters of magnet
• Assume Magnet Efficiency = 0.85

\[
B = \frac{\mu_0 I}{g \times \text{eff}}
\]

\[
I = \frac{1}{\rho}
\]

\[
P = 0.2998 \times B_p
\]

\[
i = \frac{P_0}{377 \times 10^{-6}} \times \frac{g}{I \times \text{eff}} = \frac{1460 \times 0.018 \times 9}{377 \times 10^{-6} \times 200 \times 0.85} = 3690 \text{ Amps}
\]

Inductance

\[
L = \frac{\mu_0 I \times w}{g \times \text{eff}}
\]

\[
L = \frac{4 \times \pi \times 10^{-7} \times 2 \times 0.2}{0.09 \times 0.85} = 6.6 \mu\text{H}
\]

Rise Time

\[
Z = \frac{V}{2i} = \frac{45000}{2 \times 3690} = 6.1 \Omega
\]

\[
\tau = \frac{2L}{2Z} = \frac{6.6 \times 10^{-6}}{6.1} = 1100 \text{ ns}
\]

\[
\therefore \text{must divide into multiple units}
\]
**Tricks In Division**

1. Power Each Half of Magnet Separately
   - as at ANL rapid cycling synchrotron
2. Use Push-Pull Power Supply
   - as at Rutherford ISIS

*Our Decision*
- Use First of Above
- Try Second Later
  *when 2 pulsers available*

**Number of Units**

- Approximately 16 Units Needed
  - To get 70 nanosecond Rise Time
- Pulser Can Handle 2 or More Units
  - per Thyatron

**SPICE Calculation of Rise Time**

![Graph showing the relationship between \( \frac{L}{2Z} \) and \( t(5\%-95\%) \) with the equation \( y = 12.889 + 1.5512x \), \( R^2 = 0.999 \).]
Kicker & Power Supply Module

Charging Lines: 2x3x20 Ohms 3.33 Ohms
Thyatron: CX1725 in Oil

Transmission Lines: 2x3x20 Ohms 3.33 Ohms
Kicker: In Freon or Vacuum
Terminations: 2x3x20 Ohm Oil Filled

Kicker in Vacuum
- HV Power Supply: 60 kV 120 Hz in Oil
- Transmission Lines: 2x3x20 Ohms 3.33 Ohms
- Kicker in Freon or Vacuum
- Terminations: 2x3x20 Ohm Oil Filled

Kicker in Sulfur Hex
- Water Cooled Ground Shield
- Sulfur Hex: Ceramic Vacuum Chamber
- Ferrite
- Left Conductor
- Right Conductor
- Ground Planes
- Cooled Grounded Box

Magnetic Field Calculation

Safety Considerations
- Fire Prevention Dictates
  - Silicone Oil (if indoors)
  - EPR (Ethylene Propylene Rubber)
- EPR Cable
  - more radiation resistant than polyethylene
  - more ozone resistant than polyethylene
  - compatible only with silicone oil
  - more attenuation than polyethylene
- Test of EPR Cable Attenuation
  - to be reported by Russ Winje (SAIC)
Fig. 6. Voltage life versus field strength. © Cavities in polyethylene-0.3 mm thick. ■ Cavities in polytetrafluoroethylene-0.1 mm thick. + Cavities in polyvinyl chloride-0.1 mm thick. — Voltage life of polyethylene cable according to Oudin [4].

from REUGER: RESISTANCE OF DIELECTRIC MATERIALS

**Accelerated Lifetime Testing**

Polyethylene Lifetime $\propto V^{-8.77}$

$1.3V \approx \times 10$ Lifetime Reduction

- Test at $1.3x45kV=60$ kV for 1 year
  - to get 10 year lifetime
- LAMPF Runs 6 Months per Year
  - 3 Months at 120 Hz Test Time

**Effect of Ferrite Permeability**

- Propagation Time $\sim \sqrt{\mu \varepsilon}$
  - $\varepsilon \sim 10$
  - therefore use $\mu \sim 35$ ferrite
- Field Uniformity Unaffected
  - Conductors Help Maintain Uniformity
  - in pulsed application
- But must allow for lower efficiency of magnet
- Tested by Q. Kerns, et al, Fermilab
Ferrite Choice?

C2010, C2025, C2050, C2075, N40
High Frequency Nickel-ZInc Ferrites

This group of materials was specifically engineered to give high flexibility in accommodating requirements to 1000 MHz in applications in power supplies, linear amplifiers, UHF, and VHF. They are available in sizes up to 30°. Our Engineering Department would be pleased to assist you in determining which of these ferrites is best for your application.

Typical Magnetic and Physical Characteristics

<table>
<thead>
<tr>
<th>Material</th>
<th>C2025</th>
<th>C2050</th>
<th>C2075</th>
<th>N40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Permeability, 1 MHz</td>
<td>175</td>
<td>100</td>
<td>35</td>
<td>15</td>
</tr>
<tr>
<td>Maximum Permeability</td>
<td>1100</td>
<td>380</td>
<td>150</td>
<td>50</td>
</tr>
<tr>
<td>Maximum Flux Density, Tesla</td>
<td>6200</td>
<td>3400</td>
<td>2700</td>
<td>1800</td>
</tr>
<tr>
<td>Remanent Flux Density, Tesla</td>
<td>2800</td>
<td>2400</td>
<td>1800</td>
<td>700</td>
</tr>
<tr>
<td>Coercive Force, Oersted</td>
<td>1.6</td>
<td>3.0</td>
<td>7.0</td>
<td>7.5</td>
</tr>
<tr>
<td>Curie Temperature, °C</td>
<td>276</td>
<td>340</td>
<td>420</td>
<td>510</td>
</tr>
<tr>
<td>dc Volume Resistivity, ohm-cm</td>
<td>$10^7$</td>
<td>$10^9$</td>
<td>$10^9$</td>
<td>$10^{14}$</td>
</tr>
</tbody>
</table>

* @ 40 Gauss applied field strength

Typical Design Curves

Questions Remaining

Kicker
- Vavuum or Sulfur Hex?
- 60 kV Vacuum Feedthru
- Minimizing Inductance of Magnet Feeds
- Spacing for 60kV Holdoff in Vacuum
- Construction Details

Pulser
- Air Bubbles
- 60 kV Termination
- Spacing for 60 kV Insulation
- Life of Terminating Resistors in Oil
- Mods for Push-Pull Operation
A PRELIMINARY DESIGN OF THE LOS ALAMOS FAST KICKER MAGNET PULSER AND POWER SUPPLY*

R.A. Winje
Science Applications International Corporation
227 & 230 Wall Street, Princeton, NJ 08540

ABSTRACT

The technical design of the Kicker Magnet Pulser and Power Supply is based on the switching of a precharged pulse forming network (PFN) into a matched load. Provisions are made through the selection of the main switch tube to accommodate loads that are not matched to the PFN impedance. The paper includes a description of the major components of the power supply and a summary of the performance parameters.

SYSTEM REQUIREMENTS

The design concept for the Kicker Magnet Pulser and Power Supply is based on discharging a pulse forming network (PFN) through a high speed thyatron switch into a matched resistive load. Figure 1 shows an elementary diagram of the system and Table I gives the major performance specifications.

Table I. Performance specifications.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PFN Operating Voltage, max</td>
<td>65 kV</td>
</tr>
<tr>
<td>PFN Impedance</td>
<td>3.125 ohms</td>
</tr>
<tr>
<td>Load Impedance/each of two</td>
<td>6.25 ohms</td>
</tr>
<tr>
<td>Pulse Flat Top Length, min</td>
<td>411 nsec</td>
</tr>
<tr>
<td>Pulse Rise Time, max</td>
<td>30 nsec</td>
</tr>
<tr>
<td>Pulse Repetition Rate, max</td>
<td>120 Hz</td>
</tr>
<tr>
<td>Pulse Jitter, max</td>
<td>5 nsec</td>
</tr>
<tr>
<td>Peak Output Power</td>
<td>338 MW</td>
</tr>
</tbody>
</table>

The power supply will be controlled by a local control system which serves both to coordinate all of the control and fault protection aspects of the power supply and as the interface point for the Los Alamos remote control system.

*This work is funded by Los Alamos National Laboratory under Subcontract No. 9-XF8-6797L-1.
THYRATRON SWITCH

The criteria used for selection of the thyratron tube were the following:

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Hold Off</td>
<td>70 kV</td>
</tr>
<tr>
<td>Forward Pulse Current</td>
<td>7 kA</td>
</tr>
<tr>
<td>Reverse Voltage</td>
<td>7 kV</td>
</tr>
<tr>
<td>Reverse Current</td>
<td>7 kA</td>
</tr>
<tr>
<td>di/dt</td>
<td>350 kA/μsec</td>
</tr>
<tr>
<td>Pulse Length</td>
<td>422 nsec</td>
</tr>
<tr>
<td>Pulse Repetition Frequency</td>
<td>120 Hz</td>
</tr>
<tr>
<td>Expected Life Time</td>
<td>E+09 pulses</td>
</tr>
</tbody>
</table>

The tube selected for the application is the English Electric Valve CX 1725. The principal advantage with this tube type is its ability to conduct current in the reverse direction. This tube has a special hollow anode design enhancing the ability to carry the reverse current not as a metal arc, but through electrons which have been trapped near the anode during the forward conduction part of the cycle. The tube is otherwise similar to the CX 1525 which would be the tube of choice if the load was matched to thePFN. EEV has reported greater than 2E+09 pulses achieved from a single gap version of the CX 1525 (CX 1625) operating at higher pulse currents and repetition rates.

Thyratron Support Structure

The thyratron is positioned in a coaxial mount designed to minimize the stray inductance associated with the tube. Figure 2 shows the coaxial mount. Based on this coaxial geometry, the value of the series inductance is estimated to be 88 nH. In a system where the Z₀ of the PFN and the load cables are 3.125 ohms (each), the time constant of the circuit will be \( \tau = L_{\text{stray}}/2Z₀ = 14 \text{ nsec} \). Assuming a square wave input from the thyratron switch, the pulse rise time of 30 nsec should be achieved.

Fig. 2. Support structure for the CX 1725.
The structure has been designed for a voltage withstand capability of 80 kV. As the structure will be in insulating oil and the anode section of the tube is separated from the input section by a cylindrical epoxy-fiberglass (G-10) tube, the voltage holdoff during the charge cycle should be readily achieved. The tube and support electronics will be mounted from the cover of the enclosure to facilitate maintenance. The unit can be lifted by a crane attaching to eyebolts on the cover.

Support Electronics

The thyatron filament and reservoir heaters are driven from filtered direct current power supplies to reduce output pulse jitter due to the tube. Taps on the primary of the filament heater isolation transformer will be used to set the filament voltage at the required value (6.6±5% V). The reservoir heater power will be controlled from the ground based control circuit through a voltage variable transformer to permit adjustment of the gas pressure in the tube to obtain optimum turn-on and voltage hold-off characteristics. The heater current and voltage from both circuits will be directly monitored at the local control station utilizing voltage-to-frequency and frequency-to-voltage convertors coupled together with fiber optic links for voltage isolation.

Grids G1 and G2 will be pulsed with an unloaded voltage pulse of at least 2 kV (peak) with the leading edge dv/dt of 20 kV/μsec. Figure 3 shows the circuit used for each grid pulser. The trigger amplifiers are thyatron switches (CX 2535) discharging 1 μsec, 25 ohm pulse forming networks. The trigger pulses will be transmitted from ground potential via a fiber optic cables. A pulse current of 25 to 50 A will be delivered and maintained to G1 one-half microsecond or so prior to the start of the G2 pulse. The high G1 prepulse current provides a supply of electrons to initiate the main anode current pulse with the required di/dt of nearly 350 kA/μsec.

Fig. 3. Grid pulser schematic diagram.
Two types of coaxial cables are being investigated for use in the power supply. Both polyethylene and ethylene propylene rubber (epr) based dielectrics are being evaluated for this application. In either case, the main dielectric will be shielded at both the inner conductor and the outer conductor surfaces with a high dielectric constant material ($k>10$) to reduce the electric field stress on the main dielectric. For a cable having a design lifetime of $40 \times 10^9$ pulses at 65 kV, the following construction is being considered.

<table>
<thead>
<tr>
<th>Component</th>
<th>OD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central core (rubber)</td>
<td>0.8 in.</td>
</tr>
<tr>
<td>Center Conductor</td>
<td>1.0 in.</td>
</tr>
<tr>
<td>High dielectric constant stress relief</td>
<td>1.07 in.</td>
</tr>
<tr>
<td>Dielectric (epr)</td>
<td>1.78 in.</td>
</tr>
<tr>
<td>High dielectric constant stress relief</td>
<td>1.85 in.</td>
</tr>
<tr>
<td>Outer Conductor</td>
<td>1.9 in.</td>
</tr>
</tbody>
</table>

The attenuation of this cable is 4.2 dB/100 ft measured at 50 MHz. The surge impedance of this cable is 20 ohms and with six cables in the pfn, the impedance would be 3.33 ohms. The length of the pfn cables is 33.3 m.

A special connector is being designed for the cable. Figure 4 shows a cross section of the connector. Electric field stress control is obtain by the shaping the outer shield terminal and the center conductor terminal. The connector is sealed by a wedge shaped rubber gasket.

Fig. 4. Coaxial cable high voltage, oil insulated connector.
CHARGING POWER SUPPLY

The resonant charger is shown in Figure 1 and consists of the charging dc power supply (600 V, 30 kW), thyristor, HV step-up transformer, isolating HV diode and the other associated circuitry. The output voltage from the charging power supply is 601 V which is required to produce a peak voltage of 80 kV on the pfn. To operate at 65 kV, the power supply voltage is reduced to 488 Vdc. The output capacitor was chosen to be 6200 ufd which is about 10 times the primary referred value of the pfn capacitance. It will be made up of a series-parallel array of 3100 ufd, 450 Vdc electrolytic capacitors. The capacitor is recharged during the interpulse period by the charging power supply. At a repetition frequency of 120 Hz, the average charge current is 63.6 A. However, at the prospective operating voltage of 65 kV, the average current reduces to 51 A and the required power from the charging power supply is 25 kw. Likewise, the primary rms current for \( V_{pfn} = 80 \text{ kV} \) has been calculated to be 204 A and for \( V_{pfn} = 65 \text{ kV} \), the rms current is 164 A. The transformer current ratings will be sized to the 65 kV case.

The thyristor in the charging circuit is triggered from the control system about 2 msec prior to triggering the thyratron. The thyristor will conduct the half-sine wave of primary current and will naturally commutate on the first current zero. The average current for the thyristor is 64 A which is easily in the range of a wide selection of devices. The pfn voltage will be regulated from changes in line and load conditions through a voltage feedback loop.

TERMINATION RESISTORS

Two terminating load resistor banks are required for the power supply. Each resistor bank will contain terminating resistors for each coaxial cable.

Table III. Parameters for the termination resistor assembly for 65 kV.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assy Impedance, ohms</td>
<td>6.25</td>
</tr>
<tr>
<td>Peak Current/Assy, A</td>
<td>5200</td>
</tr>
<tr>
<td>Load Impedance, ohms</td>
<td>20</td>
</tr>
<tr>
<td>Number/Assy</td>
<td>15</td>
</tr>
<tr>
<td>Peak Power, MW</td>
<td>169</td>
</tr>
<tr>
<td>Average Power, W</td>
<td>8552</td>
</tr>
</tbody>
</table>

The basic resistor used in the assembly is the Carborundum type 1038AS which has a power capability of 225 W (in air) and can withstand 65 kV. This resistor is 18 in. long and 1-1/2 in. diameter. These resistors will be mounted in a coaxial cylinder so that each individual coaxial cable is properly terminated. The termination resistor assembly will be an oil enclosure that can accommodate up to three 20 ohm resistor assemblies. The resistors will be immersed in insulating oil and the oil pumped to remove the heat and to promote voltage withstand capabilities.

CONCLUSION

A preliminary design of a thyratron based 65 kV pulser and power supply which will be used for driving a fast kicker magnet has been presented. Fabrication work is now beginning with completion projected for March 1989.
ABSTRACT

The magnet requirements for the experimental areas of the TRIUMF KAON Factory are varied and demanding. In the target areas the magnets will be located in radiation fields up to 10E7 rad/h and will also absorb thermal loads from beam heating up to several W/cm³. In this operating environment the magnets must be reliable and capable of remote installation and servicing. Other magnet designs include Lambertson septum magnets for beam splitting in the proton switchyard and superconducting or superferric magnets in the secondary channels and detectors. This paper describes some of these magnet requirements and presents some preliminary ideas on their designs.

INTRODUCTION

Figure 1 shows one possible layout of a target area for a kaon factory. Up to 100 μA of 30 GeV protons is incident on an interaction length production target and the secondary particles such as kaons and pions are collected in two beam lines which transport these particles to the experimental areas. The protons which pass through the target without undergoing interactions or large-angle scattering are transported to a beam dump or may be refocused on a second downstream production target. The kaons are produced in a forward direction with a maximum production angle of about 10°. The first element in the secondary beam line is normally a dipole which is located as close to the production target as possible for maximum acceptance. In the arrangement shown two secondary beams, one at low momentum (<1 GeV/c) and one at high momentum (>4 GeV/c) are provided. Another possible

Fig. 1. Possible arrangement of low- and high-momentum secondary channels from the same production target.
arrangement is the MAXIM concept\textsuperscript{1} for three independent secondary channels which has been developed for the AHF and EIIF proposals. The beam components in the region within several meters of the production target must survive high radiation and thermal fields. Figure 2 shows the radiation levels around a shielded target area for 100 \( \mu \text{A} \) of 30 GeV protons incident on an interaction length platinum target and Fig. 3 shows the energy density due to beam heating around a similar production target geometry.\textsuperscript{2} For reference the energy density due to resistive losses in a typical magnet coil is about 0.5 W/cm\(^3\).

For radiation doses above 1 \( \times 10^9 \) rad conventional magnet design using fibre-glass epoxy insulation and rubber hoses on water-cooling manifolds is not acceptable and techniques for producing more radiation-resistant magnets must be found. Considerable experience in the design of radiation-hard magnets exists at the meson factories\textsuperscript{3} and this same technology has to be used to produce the magnets for a kaon factory. The major difference for the latter requirement is that the magnets tend to be larger both in aperture and length as the momentum of the particles being bent is much higher. Details of the design of rad-hard magnets is given elsewhere in this workshop proceedings. Some of the considerations in transforming a large dipole to a radiation resistant design is presented in the next section.

### RADIATION RESISTANT MAGNETS

At TRIUMF most of the rad-hard magnets are fabricated using directly cooled mineral-insulated Pyrotenax conductor.\textsuperscript{4} All quadrupoles directly downstream of the production targets either in the primary beam line or on the secondary channels are made using this technique. Pyrotenax coils have also been used on dipoles although the large combination magnets at the cyclotron extraction ports use indirectly cooled Pyrotenax coils potted in a solder matrix along with copper cooling channels. Another technique has been used at TRIUMF in the fabrication of a high current, 5000 A, septum magnet.\textsuperscript{5} The coil was formed from rectangular copper conductor with a central cooling channel which was held in place by a number of ceramic spacers furnace brazed to the conductor. PSI (formerly SIN) has considerable ex-
Table I. Comparison of current densities for different methods of fabricating radiation-resistant magnet coils. Parameters for Brookhaven 30D72 or 18D72 magnet: \( B = 1.5 \) T; \( \text{Gap} = 10 \) cm; \( N1 = 130,000 \) At; Length/turn = 20 ft; \( \Delta p = 60 \) psi; \( \Delta T = 40^\circ\text{C} \).

<table>
<thead>
<tr>
<th>Conductor type</th>
<th>Conductor dimensions (in.)</th>
<th>Maximum current (A)</th>
<th>Current density Conductor (A/in.²)</th>
<th>Current density Coil (A/in.²)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Directly cooled Pyrotenax</td>
<td>0.53 x 0.53</td>
<td>500</td>
<td>4808</td>
<td>1763</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.75 x 0.75</td>
<td>1500</td>
<td>6321</td>
<td>2453</td>
<td>Multiple cooling circuits</td>
</tr>
<tr>
<td>Indirectly cooled Pyrotenax</td>
<td>0.53 x 0.53</td>
<td>500</td>
<td>4010</td>
<td>1161</td>
<td>Most expensive</td>
</tr>
<tr>
<td>Air-cooled bare conductor</td>
<td>0.375 x 8.0</td>
<td>3000</td>
<td>1000</td>
<td>521</td>
<td></td>
</tr>
<tr>
<td>Water-cooled bare conductor</td>
<td>0.73 x 1.46</td>
<td>2500</td>
<td>3316</td>
<td>1381</td>
<td>Least expensive</td>
</tr>
<tr>
<td>Fibreglass epoxy conductor</td>
<td>0.73 x 1.46</td>
<td>2500</td>
<td>3316</td>
<td>1905</td>
<td>Reference</td>
</tr>
</tbody>
</table>

experience using indirectly cooled mineral-insulated conductor with lead or solder as the heat transfer medium.\(^6\)

A typical large dipole used at Brookhaven National Laboratory was considered as an example of the type of magnet which would have to made rad-hard at a kaon factory. Table I lists the relevant parameters for this magnet and a comparison of the various coil construction techniques in terms of current densities. The much longer lengths for a single turn puts a limit on the current-carrying capability due to the pressure drop of the cooling water in one turn. It is likely that the magnet steel will also have to be cooled. For a typical energy density level of 1 W/cm\(^3\) cooling would have to be placed at 10-15 cm intervals in the magnet yoke. Magnets made from thin laminations would be precluded due to the poorer thermal conductivity across the laminations.

**TARGET CELL MAGNET CONSIDERATIONS**

The magnets for the target cell regions must be capable of remote installation and servicing. One of the important considerations is the interaction between the vacuum enclosure around the beam and the magnet design. Figure 4 shows a vertical section through a proposed target shield for the existing 500 MeV facility to indicate some of these considerations. The target is in vacuum to eliminate air activation and the necessity of windows in the high-intensity proton beam. There are three options for the magnets with respect to the vacuum enclosure. The magnets could be immersed in vacuum, the beam pipe could be continuous through the magnet as is shown, or there could be vacuum flanges at each end of the magnet and the magnet is installed or removed along with its section of beam pipe. This latter option requires the design of a rad-hard, remotely handleable vacuum flange capable
of operating under varying thermal conditions. A preferred solution is the design of magnets which can be positioned around a continuous beam pipe such as a half-quadrupole or a split quadrupole as shown in Fig. 5. Other more exotic designs could also be considered which have the additional advantage of positioning the coil further from the target region and in a more convenient position for servicing as illustrated in Fig. 6.

**PROTON BEAM SWITCHYARD MAGNETS**

The beam line magnets for transporting the 30 GeV extracted beams to the experimental areas can be of conventional design and would most likely be similar to the design of the extender ring dipoles and quadrupoles. The present KAON proposal has the slow extracted beam split into two or more beam lines using an initial electrostatic septum followed by one or more Lambertson septum magnets as done at Fermilab and Brookhaven. At the much higher intensities of a kaon factory the design of the Lambertson septum magnet has to be made rad-hard. As the Lambertson has only magnet steel exposed to the high intensity beam the design of a rad-hard version should not be too difficult and an indirectly cooled mineral-insulated conductor could be used.

**CONCLUSION**

The design of radiation-resistant, large acceptance magnets for the experimental areas for a KAON factory will provide new challenges for the magnet engineer. Much of the experience at the meson factories will be relevant but the requirements for much larger magnets
Fig. 5. Techniques for installing a quadrupole around a fixed beam pipe.

Fig. 6. Proposed long pole magnets for operation in high radiation areas.
and the additional power dissipation problems due to beam heating will require some new ideas.

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112

RADIATION-HARDENING OF MAGNET COILS

Alex Harvey
Stanford Linear Accelerator Center, etc.

1. INTRODUCTION

The first essential before embarking on the radiation-hardening of electrical insulation – mostly magnet coils – in any beam line application is to obtain a reliable estimate of the dose to the components. There are examples (switchyards at SLAC and LAMPF) where the degree of hardness specified was much higher than was required. Although experience shows that the cost premium for substantial radiation-hardening is of the order of 10%, it has also become clear that well-designed beam lines have negligible losses: hardening is required only in the vicinity of targets, collimators or other beam-intercepting devices. Where the beam is deliberately scraped, local shielding will minimize the associated radiation in the surroundings. Electron machines have their own special problems due to synchrotron radiation, so certainly coils and other electrical equipment should be kept away from the beam bend-plane.

Because proton beams interact with thick targets in the meson factories, TRIUMF, LAMPF and PSI (formerly SIN) have examples of very hard magnet coils near their target cells. The activation that is associated with these substantial doses requires remote handling of the magnets, and poses the question of whether it is worth considering repairing a damaged magnet when it fails. As disposal of radioactive waste becomes more and more difficult, repair may become more attractive, but provision for it needs to be designed-in from the start. It is these problems of radioactive handling that add substantially to the cost of radiation-hardened magnets.

An interesting disposal idea originated at PSI in Switzerland – damaged magnets were incorporated into cast concrete shielding blocks for their target cells.

2. LEVELS OF RADIATION RESISTANCE

A. "Conventional"

A standard technique for insulating magnet coils is to use epoxy resin, reinforced with fiberglass. Standard resin systems, such as Novolac, or Bisphenyl-A, with NMA hardener, can be expected to tolerate $10^9$ rad ($10^7$ Gy). Additives to avoid are the old Carbowax flexibilizer – in large parts, flexibility can be maintained with flexible epoxies such as Dow's DER 732. One advantage of epoxy systems is the color change (darkening) that indicates exposure, and allows replacement before failure.

All these epoxies can have their radiation tolerance enhanced by adding an inorganic filler, glass or alumina. Some indication of the improvement to be expected can be found in Refs. 2 and 3. Note that Ref. 2 gives some of the few available data on electrical properties following irradiation: most radiation testing is done on the basis of mechanical properties. Table I gives the recipe currently in use at SLAC.

Other organic possibilities include polyimide (Kapton) for which DuPont makes very modest radiation-resistance claims. However, its resistance exceeds $10^{10}$ rad, and it is available as a film coating on magnet wire (H-film) as well as in tapes and sheets. As a copper-polyimide composite, it can be formed by printed-circuit techniques for pole-face winding and Lambertson magnets.
Table I. Alumina-loaded epoxy mix for coil potting, SLAC 1969
(to make approximately one U.S. gallon of mixture).

<table>
<thead>
<tr>
<th></th>
<th>Per cent RM by weight</th>
<th>English pounds</th>
<th>English ounces</th>
<th>Metric grams</th>
</tr>
</thead>
<tbody>
<tr>
<td>DER-332 Bisphenyl-A epoxy</td>
<td>45.0</td>
<td>1</td>
<td>14</td>
<td>850.5</td>
</tr>
<tr>
<td>DER-732 Flexible epoxy</td>
<td>55.0</td>
<td>2</td>
<td>5</td>
<td>1048.9</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100.0</td>
<td>4</td>
<td>3</td>
<td>1899.4</td>
</tr>
<tr>
<td>Additives:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NMA Hardener</td>
<td>96.5</td>
<td>4</td>
<td>1</td>
<td>1832.1</td>
</tr>
<tr>
<td>BDMA Catalyst</td>
<td>1.7</td>
<td>1-1/8</td>
<td></td>
<td>31.9</td>
</tr>
<tr>
<td>Z6040 Silane wetting agent</td>
<td>1.0</td>
<td>3/4</td>
<td></td>
<td>21.3</td>
</tr>
<tr>
<td>Cab-o-Sil Maintains suspension</td>
<td>3.75</td>
<td>2-1/2</td>
<td></td>
<td>72.0</td>
</tr>
<tr>
<td>Al₂O₃ Inorganic, T-61</td>
<td>224.0</td>
<td>9</td>
<td>6</td>
<td>4252.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>327.0</td>
<td>13</td>
<td>11</td>
<td>6209.7</td>
</tr>
</tbody>
</table>

**Total weight per U.S. gallon**:

|                      | 17 | 14 | 8109.2 |

**NOTES:**

DER-332 and DER-732 from Dow Chemical Corp.
NMA (nadic methyl anhydride)
BDMA (benzil di-methyl amine)
Al₂O₃ iron-free and soda-free alumina, 325 mesh, from E.V. Roberts or Schoof's, Noraga, CA

One organic to be avoided is Teflon, which although an excellent high-temperature insulation, is very poor in radiation fields. Care needs to be taken to eliminate its use in hook-up wire, and in factory-installed wiring in protective devices like flow switches.

**B. Inorganics**

For maximum radiation resistance, organics must be avoided completely. There are techniques in the electrical engineering field which are largely inorganic, and adaptations of these lead to the highest levels of resistance.

Mica is a traditional insulation that withstands high temperatures and corona very well, in addition to radiation. Unfortunately, its physical format makes its application difficult in many circumstances. It has been modified by the electrical industry – reconstituted mica – to overcome the physical limitations, but often at the expense of its radiation resistance. One of the better composites is Mycalex, incorporating mica in a glass matrix. It can be hot-pressed onto substrates such as 400 series stainless steel (to match its expansion coefficient) and is useful in some applications, feedthroughs and stand-offs, for example.

Several insulation systems have been developed for accelerator applications: a hard-anodized surface on aluminum conductors and concrete, usually in conjunction with fiberglass. However, the most widely used systems found, for example, in the target cells of all the meson factories, LAMPF, PSI (SIN) and TRIUMF, is based on the use of magnesium oxide, “mineral-insulation” in the trade. Two methods of using m.i. cables are possible in coils: direct water cooling and indirect cooling.
In direct water cooling, the conductor is fabricated with a central hole, and is cooled by direct contact of the water with the current-carrying conductor. This implies that there are insulating tubes between the conductors and the water headers, which for high-radiation service, are ceramic-to-metal parts (Ref. 7). Figure 1 is a sketch of an insulating assembly produced by industry\(^8\) that has the advantages of:

1. high aspect ratio of length to cross section of water, giving low leakage current;
2. smooth internal bore – no diameter changes or pockets to accumulate deposits;
3. substantial tube ends to act as sacrificial electrodes, if they are not adequately passivated to inhibit corrosion; and
4. tube ends arranged so that installation does not apply tension to the assembly.

These features are a result of operating experience at Los Alamos.\(^9\)

![Fig. 1. Water insulator ceramaseal.](image)

The characteristics of two commercially available sizes of hollow mineral-insulated square cables are given in Table II.

Indirectly cooled mineral-insulated coils avoid the water-insulator problem by keeping the coolant in separate tubes, and conducting the Joule heat through the magnesia and a metal matrix that includes the cable sheaths. To facilitate this heat transfer, the copper sheaths are soft-soldered together, or cast in lead. Current densities over 20 A/mm\(^2\) have been demonstrated by this technique\(^10\) though the power consumption, of course, is correspondingly high. Magnets with coils of this construction are in service at Los Alamos, TRIUMF, and PSI (SIN).\(^11\)

For all applications where the magnet is in a high-radiation environment, so becoming activated, it is vital that the interlock systems be as radiation-resistant as the coils; that be at least as reliable, and preferably incorporate redundancy and if possible an in-situ test capability.

There is considerable experience in industry, world-wide, producing coils with mineral-insulated conductors. However, there have also been some disasters, and consultation with an experienced user before committing to a contract would be prudent. Moulds to contain substantial amounts of lead-tin alloy must be of adequate strength to resist deformation, and molten lead-tin dissolves copper, so the potting time has to be minimized.

The characteristics of two commercially available cables, solid-conductor, square cross section, are given in Table III. The 0.53 in.\(^2\) cable in particular has been developed for the maximum current density per unit of overall cross-sectional area.
Table II. Mineral-insulated cable, square, hollow conductor.

<table>
<thead>
<tr>
<th>SPECIFICATIONS</th>
<th>f.p.s.</th>
<th>metric</th>
<th>f.p.s.</th>
<th>metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Size</td>
<td>0.53 + 0-0.01 in sq</td>
<td>13.46 + 0-0.25 mm sq</td>
<td>0.75 + 0-0.01 in sq</td>
<td>19.05 + 0.025 mm sq</td>
</tr>
<tr>
<td>Corner Radius</td>
<td>0.063 in</td>
<td>1.6 mm</td>
<td>0.063 in</td>
<td>1.6 mm</td>
</tr>
<tr>
<td>Conductor Size, Nominal</td>
<td>0.395 in sq</td>
<td>10.03 mm</td>
<td>0.570 in sq</td>
<td>14.48 mm sq</td>
</tr>
<tr>
<td>Conductor Resistance, Maximum</td>
<td>0.08 Ω/m ft</td>
<td>0.262 Ω/km</td>
<td>0.035 Ω/m ft</td>
<td>0.115 Ω/km</td>
</tr>
<tr>
<td>Insulation Thickness, Nominal</td>
<td>0.04 in</td>
<td>1.02 mm</td>
<td>0.05 in</td>
<td>1.27 mm</td>
</tr>
<tr>
<td>Insulation Resistance (I.R.)</td>
<td>5 GΩ/m ft</td>
<td>1.5 GΩ/km</td>
<td>5 GΩ/m ft</td>
<td>1.5 GΩ/km</td>
</tr>
<tr>
<td>Dielectric Strength</td>
<td></td>
<td>1.5 kV, ac, 1 min</td>
<td></td>
<td>1.5 kV, ac, 1 min</td>
</tr>
<tr>
<td>Hole Size, Nominal</td>
<td>0.18 in sq</td>
<td>4.57 mm sq</td>
<td>0.26 in sq</td>
<td>6.60 mm sq</td>
</tr>
<tr>
<td>Water Flow, Minimum</td>
<td>0.75 USGPM at</td>
<td>0.05 l/sec at</td>
<td>2 USGPM at</td>
<td>0.126 l/sec at</td>
</tr>
<tr>
<td></td>
<td>1 psi/ft, 270 ft</td>
<td>22.6 kPa/m, 82 m</td>
<td>1 psi/ft, 230 ft</td>
<td>22.6 kPa/m, 70 m</td>
</tr>
<tr>
<td>Sheath Thickness</td>
<td>0.03 ± 0.005 in</td>
<td>0.76 ± 0.13 mm</td>
<td>0.035 ± 0.005 in</td>
<td>0.89 ± 0.13 mm</td>
</tr>
<tr>
<td>Weight (Nominal)</td>
<td>0.7 lb/ft</td>
<td>1.04 kg/m</td>
<td>1.4 lb/ft</td>
<td>2.1 kg/m</td>
</tr>
<tr>
<td>Maximum Length</td>
<td>270 ft</td>
<td>82 m</td>
<td>230 ft</td>
<td>70 m</td>
</tr>
</tbody>
</table>

Materials: Conductor, copper, 100% IACS conductivity.
Sheath, copper, commercial anneal.
Insulation, compacted magnesium oxide.

Shipping: Coiled to minimum diameter of 4 ft (1.2 m).
Ends sealed against moisture.

Tests: 1) Immersion of cable (except ends) in water at room temperature to produce no change in I.R.
2) Internal water pressure of 450 psi (3.1 mPa) to produce no change in I.R.
Table III. Mineral-insulated cable, square, solid conductor.

<table>
<thead>
<tr>
<th>SPECIFICATIONS</th>
<th>f.p.s.</th>
<th>metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Size</td>
<td>0.25 + 0.01 in sq</td>
<td>0.35 + 0.01 mm sq</td>
</tr>
<tr>
<td>Corner Radius</td>
<td>0.032 in</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>Conductor Size, Nominal</td>
<td>0.165 in sq</td>
<td>0.41 mm</td>
</tr>
<tr>
<td>Conductor Resistance, Maximum</td>
<td>0.02 in</td>
<td>0.190 Ω/m ft</td>
</tr>
<tr>
<td>Insulation Thickness, Nominal</td>
<td>0.51 mm</td>
<td>1.30 Ω/km</td>
</tr>
<tr>
<td>Insulation Resistance (I.R.)</td>
<td>0.02 in</td>
<td>5.0 GΩ/m ft</td>
</tr>
<tr>
<td>Dielectric Strength</td>
<td>0.75 mm</td>
<td>1.5 GΩ/km</td>
</tr>
<tr>
<td>Sheath Thickness Height (Nominal)</td>
<td>0.51 ± 0.1 mm</td>
<td>1.25 kV, ac, 1 min</td>
</tr>
<tr>
<td>Maximum Length</td>
<td>1000 ft</td>
<td>305 m</td>
</tr>
</tbody>
</table>

Materials: Conductor, copper, 100% IACS conductivity. Sheath, copper, commercial anneal. Insulation, compacted magnesium oxide.

Tests: Immersion of cable (except ends) in water at room temperature to produce no change in insulation resistance. Coiled to minimum diameter of 4 ft (1.2 m). Ends sealed against moisture.
3. SPECIAL CASES

Most accelerator beam lines include a few magnets with special requirements that challenge the magnet designer. Probably the commonest “special case” is the current-sheet septum, since it is inevitable that beam spill takes place on the septum conductor. Some approaches support the conductor only at its edges, so that the insulation is removed from the beam center-line (BNL); Los Alamos has used polyimide successfully in its Proton Storage Ring. At SLAC, the Damping Ring septa have plasma-sprayed alumina on copper conductors in magnets with small vertical aperture. Factors in their success are 1) use of stainless-steel tubing for cooling water, brazed to the copper (it is not oxidized by the irradiated water), and 2) double-brazing of all the conductor parts for assurance that there is adequate filler metal. These coils, which are inside the vacuum chamber, are run at their full current rating before assembly into the iron.

ACKNOWLEDGEMENT

Any account describing the usefulness of mineral-insulated cables in magnet coils for accelerator applications has to recognize the contribution of the late Sid Walker of Pyrotenax of Canada Ltd. to its successful development. Sid undertook the challenges of new configurations for the m.i. cable that the Trenton, Ontario plant produced, and cheerfully pushed their technology to the limits that the magnet designers were after. If there were more like him, everyone’s industrialization program would be a pleasure as well as a success.

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   - CERN-ISR-MAG/67-3 Epoxy
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   - CERN-ISR-MAG/PS/6455 Textiles
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8. Ceramaseal Inc., New Lebanon, N.Y.
SEARCH COIL MEASUREMENTS OF PARTICLE ACCELERATOR MAGNETS

K. N. Henrichsen
CERN, CH-1211 Geneva 23, Switzerland

ABSTRACT

Specific problems related to search coil measurements in magnets for particle accelerators are discussed. This includes the coil manufacture and calibration as well as the measurement of the magnetic flux.

INTRODUCTION

Electromagnets used as beam guiding elements in particle accelerators and storage rings require very tight tolerances on their magnetic fields. Construction techniques and measurement equipment must therefore match these requirements. The length of the magnet is usually small compared to the wavelength of the betatron oscillations. This means that only the integrals of the magnetic field and its derivatives along the beam axis are of interest. The magnetic measurements are important at various stages of an accelerator project: design, construction and operation.

MEASUREMENT METHODS

Two factors influence the choice of the measurement method and equipment: the required quality of the measurements and the number of magnets. It is interesting to note that while the measurement methods have remained virtually unchanged for a very long period, the equipment has been subject to continued development.

Figure 1 shows the accuracy which can be obtained in an absolute measurement as a function of the measured field for a few commonly used methods.

The most commonly used method for the measurement of accelerator magnets is the fluxmeter method, which is the only one we will discuss in detail below.

Hall probes are widely used for field mapping in spectrometer magnets [1] and are also preferred for stray field measurements around accelerator magnets and in special applications where the use of a search coil mechanism should be avoided.

The nuclear magnetic resonance (NMR) measurement is mainly used for calibration purposes, but has also been used for precise measurements of field integrals in long dipoles.
Fig. 1. Magnetic measurement methods

For a more complete description of the various measuring methods, reference is made to two classical bibliographical reviews [2,3].

THE INDUCTION METHOD

Based on the induction law, this method is the oldest [4] of our currently used methods for magnetic measurements, but it can be very precise [5]. It is also the most precise method for the measurement of the direction of the magnetic flux lines which is of particular importance in accelerator magnets. Measurements are performed either using fixed coils in a dynamic magnetic field or by moving the coils in a static field.

Very high accuracy may be reached in differential fluxmeter measurements using a pair of search coils connected in opposition, with one coil moving and the other fixed. A large variety of coil configurations are used in magnetic measurements, ranging from the simple flip-coil to the complex harmonic coil systems used in fields of cylindrical symmetry [6,7]. The choice of geometry and method depends on the useful aperture of the magnet. The sensitivity of the fluxmeter method depends on the coil surface and the quality of the integrator.

The coil method is particularly suited for measurements with long coils in beam guiding magnets [8], where the precise measurement of the field integral along the particle trajectory is the main problem. In this case the geometries are chosen so as to link with selected field components [9]. The search coil is usually wound on a core made from a mechanically stable material in order to ensure a constant
coil area and the wire is carefully glued to the core. Glass with low thermal dilatation or ceramics are often used as core materials. During coil winding the wire must be stretched so that its residual elasticity can assure a well defined geometry and mechanical stability of the coil.

The coil-integrator assembly can be calibrated to an accuracy of a few tens of ppm in a homogeneous magnetic field with reference to a nuclear magnetic resonance probe. Not only the equivalent surface of the coil must be measured, but also its median plane which often differs from its geometric plane due to winding imperfections. In the case of long measurement coils, it is important to meet very tight tolerances on the width of the coil. If the field varies strongly over the length of the search coil, it may be necessary to examine the variation of the effective width of the coil. A hybrid permanent dipole has been developed for this purpose at LURE, Orsay [10]. It has a magnetic length of about 60 mm and a useful width of about 30 mm.

THE FLUX MEASUREMENT

Induction coils were originally used with ballistic galvanometers and later on with more elaborate fluxmeters. The coil method was improved considerably with the introduction of the classical electronic integrator, the Miller integrator, but it remained necessary to employ difference methods in precision measurements [11]. The advent of digital voltmeters made fast absolute measurements possible and the Miller integrator has remained the most popular fluxmeter. With the development of solid state d.c. amplifiers, this integrator has become inexpensive and is often used in multi-coil systems.

Fig. 2. Analog integrator
Figure 2 shows an example of such an integrator. It is based on a d.c. amplifier with a very low input voltage offset and a very high open loop gain. The thermal variation of the integrating capacitor is the most critical problem. The integrating components are therefore mounted in a temperature controlled oven. Another problem is the decay of the output signal through the capacitor and the resetting relay. Careful guarding of these components is therefore essential in order to reduce the voltages across the critical surface resistances.

The dielectric absorption of the integrating capacitor sets a limit to the integrator precision. The best choice is a teflon capacitor. It has a temperature coefficient of -40 ppm/degree C, a dielectric absorption of 30 ppm and a very high insulation resistance. A suitable integrating resistor is much easier to find. Most metal film resistors have stabilities and temperature characteristics matching those of the teflon capacitor. Commonly used time constants are between 10 and 200 msec. The sensitivity of the integrator is limited by the d.c. offset and low frequency input noise of the amplifier. A typical value is 0.5 μV which must be multiplied by the measurement time in order to express the sensitivity in terms of flux. The overall stability of the integrator time constant proved to be better than 50 ppm over a period of three months.

A few electronic integrators have been developed by industry and are commercially available. The choice is, however, rather limited.

In recent years, a new type of digital integrator has been developed, which is based on a high quality d.c. amplifier connected to a voltage-to-frequency converter (VFC) and a counter.

![Diagram of digital integrator](image)

Fig. 3. Digital integrator
The digital integrator shown in figure 3 was developed at CERN [12] and is now commercially available. The input of the VFC is provided with an offset of 5 V in order to provide a true bipolar measurement. This offset is balanced by a 500 kHz signal which is subtracted from the output of the VFC. Two counters are used in order to be able to measure with continuously moving coils and provide instant readings of the integrator. One of the counters can then be read and reset while the other is active. In this way no cumulative errors will build up. This integrator has a linearity of 50 ppm. Its sensitivity is limited by the input amplifier as in the case of the analog amplifier.

This system is well adapted to digital control but imposes limits on the rate of change of the flux since the input signal must never exceed the voltage level of the VFC. The integration period must be of the order of a second if one wants a reasonable resolution.

REFERENCES

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AC MAGNETIC MEASUREMENTS OF THE ALS BOOSTER SYNCHROTRON DIPOLE MAGNET ENGINEERING MODEL*

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Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720

ABSTRACT

We made a minimal set of AC magnetic measurements of the engineering model of the ALS Booster Dipole Magnet as part of the process of qualifying its design for production. Magnetic induction integrals over paths approximating electron-beam trajectories were measured with long curved coils connected to an electronic integrator. Magnetic induction was measured with point coils and an integrator and independently with a Hall-effect Gaussmeter. These quantities, and magnet current, were displayed on a commercial digital storage oscilloscope as parametric functions of time.

The displayed waveforms were stored, processed and redisplayed as representations of selected magnet parameters. A waveform representing the magnet's effective-length was created by dividing the integral waveform by the magnetic induction waveform. Waveforms of the transfer functions were produced by dividing both the integral waveform and the magnetic induction waveform by the current waveform. Pairs of matched coils, connected in series opposition, provided differential measurements of field uniformity. Quadrupole and sextupole coefficients were derived from the uniformity data.

These magnet parameters were measured at 2 and 10 Hz frequencies. Together with measurements of the magnetic field at selected DC levels, the AC measurements demonstrated that the magnet design met specifications and qualified it for production.

INTRODUCTION

The ALS is a third generation, 1-2 GeV synchrotron radiation facility specifically designed to maximize the brightness of the radiation from wigglers and undulators1. This project includes a low-emittance electron storage ring optimized at 1.5 GeV, an injection system which includes a 50 Mev linac and the 1.5 GeV booster synchrotron, and a complement of insertion devices and photon beam lines. Twenty-four dipole magnets will provide the main guide field for the booster synchrotron. The synchrotron is intended to operate at 1 Hz, but the magnets are designed for 10 Hz operation.

The booster synchrotron dipole magnet is of the split H type with flat pancake coils as shown in Figure 1. To minimize the stored energy and power requirements, the core is curved to follow the electron-beam trajectory. It is constructed from 0.025 inch, C5 coated, M36 silicon steel laminations. Table 1 gives dipole magnet design parameters2. An engineering model of this dipole magnet has been designed, fabricated, qualified through magnetic measurements, and is now in production.

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.
Fig. 1 The ALS Booster Synchrotron Dipole Engineering Model

<table>
<thead>
<tr>
<th>Table I. ALS 1.5 GeV Booster Synchrotron Dipole Magnet Design Parameters</th>
<th>Table II. Dipole Engineering Model Magnetic Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Injection Magnetic Field</strong></td>
<td>0.0416 T</td>
</tr>
<tr>
<td><strong>Design Magnetic Field</strong></td>
<td>1.248 T</td>
</tr>
<tr>
<td><strong>Bend Angle</strong></td>
<td>15 Degrees</td>
</tr>
<tr>
<td><strong>Entrance/Exit Edge Angles</strong></td>
<td>7.5 Degrees</td>
</tr>
<tr>
<td><strong>Magnet Bend Radius</strong></td>
<td>4.0107 m</td>
</tr>
<tr>
<td><strong>Magnetic Length Along Orbit</strong></td>
<td>1.050 m</td>
</tr>
<tr>
<td><strong>Magnet Vertical Aperture</strong></td>
<td>4.4 cm</td>
</tr>
<tr>
<td><strong>Good Field Aperture Width</strong></td>
<td>+/- 3.0 cm</td>
</tr>
<tr>
<td><strong>Good Field Aperture Height</strong></td>
<td>+/- 1.8 cm</td>
</tr>
<tr>
<td><strong>Field Quality</strong> (excluding fringe field)</td>
<td>+/- 1.0 x10^-3</td>
</tr>
<tr>
<td><strong>Excitation Waveform @ 1 Hz</strong></td>
<td>Modified sawtooth</td>
</tr>
<tr>
<td><strong>Excitation Waveform @ 10 Hz</strong></td>
<td>DC biased sinusoid</td>
</tr>
<tr>
<td><strong>1. DC Measurements at selected field levels</strong></td>
<td></td>
</tr>
<tr>
<td>1.1 Central Vertical-Field</td>
<td></td>
</tr>
<tr>
<td>1.2 Central Vertical-Field Integral</td>
<td></td>
</tr>
<tr>
<td>1.3 Midplane Vertical-Field Integral Uniformity</td>
<td></td>
</tr>
<tr>
<td><strong>2. AC Measurements of parametric functions of time</strong></td>
<td></td>
</tr>
<tr>
<td>2.1 Central Vertical-Field Uniformity with/without the vacuum chamber</td>
<td></td>
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<tr>
<td>2.2 Central Vertical-Field Integral</td>
<td></td>
</tr>
<tr>
<td>2.3 Midplane Vertical-Field Integral Uniformity</td>
<td></td>
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</table>
MAGNETIC FIELD PARAMETERS FOR QUALIFICATION

The objective of the magnetic measurement effort for the booster dipole engineering model was to qualify the magnet design for production. Verification of the 2-D magnetostatic design and evaluation of the higher order field terms quadrupole, sextupole, etc., largely generated at the ends were mostly done with DC measurements. AC measurements were carried out largely to investigate magnet and vacuum chamber eddy current effects. The measurements performed are tabulated in Table II on the preceding page.

AC MEASUREMENT TECHNIQUES AND INSTRUMENTATION

Figure 2 shows test equipment configurations used for most of the AC measurements. Instrumentation features are tabulated in Table III. Calibration procedures provided 0.1% absolute accuracy of both the Hall probe and the coil sensitivities and enabled us to match the sensitivity of coil pairs to better than 0.02%. In operation we minimize the differential signal when one coil is on the magnet centerline and the bucking coil is at an arbitrary, stationary reference position (x=x0). Detailed descriptions of the measurement procedures are contained in a separate report.

Fig. 2 describes the magnet coordinate system used for the AC measurements. The origin of the cartesian coordinate system is defined as the centroid of the volume between the pole tips; +x extends the radius of curvature vector from the origin; +y is the upward normal to the lower pole; s is the distance from the origin along the curve consisting of a 15° circular arc (defined by the magnet bend radius) extended at each end by straight lines.

The measurement technique employed a Hall-effect Gaussmeter and point coils connected to an electronic integrator to measure magnetic induction. Magnetic induction integrals were measured with line coils shaped to conform to the nominal beam trajectory and connected to an electronic integrator. Magnet current was measured by use of a current monitoring resistor (shunt) in series with the magnet and its power supply. Data acquisition was with a digital storage oscilloscope (DSO) where signals from the Gaussmeter, integrator, and shunt were recorded and stored as parametric functions of time (t). The DSO allowed two signals to be acquired simultaneously.

Fig. 2 AC Measurement System Block Diagram
Table III. Instrumentation Features

<table>
<thead>
<tr>
<th>Equipment/Model</th>
<th>No.</th>
<th>Features</th>
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<tbody>
<tr>
<td>Storage Oscilloscope</td>
<td>Tektronix Model No. 11401</td>
<td>500 MHz bandwidths</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10-ps horizontal resolution</td>
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<tr>
<td></td>
<td></td>
<td>Simplified acquisition &amp; processing features available by &quot;touch-screen&quot; control</td>
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<tr>
<td>Electronic Integrator</td>
<td>LBL Model No. 71</td>
<td>1-MicroVolt Second resolution (over several minute periods)</td>
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<tr>
<td>Point Coils &amp; Line Coils</td>
<td>LBL Designs</td>
<td>Absolute accuracy +/- 0.1 %</td>
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<td></td>
<td></td>
<td>Relative accuracy +/- 0.02 %</td>
</tr>
<tr>
<td>Flux Standard</td>
<td>LBL Model No. 43</td>
<td>Absolute accuracy +/- 0.02%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Relative accuracy +/- 0.01%</td>
</tr>
<tr>
<td>Hall Effect Gaussmeter</td>
<td>F.W. Bell Model 811</td>
<td>Absolute accuracy 0.25% of full scale</td>
</tr>
</tbody>
</table>

For determining transfer functions and effective length, a single pair of signals was acquired i.e., the integrator signal and the shunt signal for determining the transfer function waveform, and two integrator output signals for determining the effective length function.

One of the authors (Don Nelson) developed an AC measurement technique⁶ whereby variations in effective length (ΔL_eff) are determined from differential measurements as follows:

\[
\Delta L_{\text{eff}} = \frac{\left\{ B_y(x_0,o,o) \right\} - \left\{ B_y(x_0,x_0,o) \right\} \cdot L_{\text{eq}}(B^*)}{L_{\text{eq}}(B^*)} = \frac{L_{\text{eff}}(t) - L_{\text{eq}}(B^*)}{L_{\text{eq}}(B^*)}
\]

The numerator is the differential signal obtained by connecting the point coil in series opposition to the line coil. \(L_{\text{eq}}(\text{uiivalent}) (B^*)\) is numerically equal to \(L_{\text{eff}}(t^*)\), the effective length evaluated at \(t=t^*\) i.e., when \(\{B_y(x_0,o,o)\} (t=t^*) = B^*\). \(L_{\text{eq}}(B^*)\) is realized by adjusting the point-coil divider such that its divided signal precisely cancels the line coil's signal at \(t=t^*\). Dividing this differential signal waveform by the magnetic induction waveform yields the difference in effective length as shown by the equation. To compute \(L_{\text{eff}}(t)\) the effective length \(L_{\text{eff}}(t^*)\), determined independently, is added to \(\Delta L_{\text{eff}}\). This technique overcomes the accuracy limitation in determining the effective length by the ratio of two parametric functions whose resolution is limited by the resolution of the oscilloscope (see RESULTS - Effective Length).

For determining the field uniformity on the aperture midplane, a series of differential waveforms was acquired with a pair of matched coils electrically connected in series opposition. The acquired waveforms corresponded to the field at the \(x\)-position of one of the coils \((x = x_i)\) with respect to the field at an arbitrary, stationary, \(x\)-position of the second (bucking) coil \((x = x_0)\) i.e., \(\{\Delta B (x_i) = B (x_i) - B (x_0)\}\) for the local magnetic induction uniformity and \(\{\Delta Bds (x_i) = Bds (x_i) - Bds (x_0)\}\) for the integral uniformity. Each series started and ended with the first coil located on the aperture centerline \((x_i = 0)\). The averaged waveforms at \(x_i = 0\) were subtracted from each of the other waveforms. This process partially compensated for integrator drift between the first and last measurements, although this drift was negligible.
RESULTS

A detailed description of all measurements and results can be found elsewhere7.

Effective Length

Figure 3 displays the magnet’s effective length as a function of magnetic field. The measurements indicate that the effective length is 1.047 ± .001m up to 1.1 T and decreases to 1.044 m at 1.25 T. This decrease in effective length at higher field values is attributed to saturation effects. Although the effective length is somewhat shorter than the design length (1.05m), the resultant displacement of the accelerated electron beam will be negligible.

We have included data identified as unreliable in Fig. 3 in order to illustrate a limitation in the 1st method used for determining the effective length. The effective length is defined as: 
\[ \frac{\int B_y ds}{B_y(s=0)} \]. In the first method \(B_y(s=0)\) and \(\int B_y ds\) were measured as parametric functions of time over the magnet’s operating field range (.04 T to 1.25 T). The accuracy of the acquired data is limited by the 10 Bit resolution of the oscilloscope to 0.1% of the maximum signal size or 1.25 x 10^-3 T which is about 3% of the minimum field. By expanding the time scale the acquired waveform obtains increased accuracy at lower values and the computed effective length is more reliable as is illustrated by the curve labeled \(0.04 \leq B \leq 0.2\) T in Fig. 3.

The technique for determining variations in effective length from differential measurements eliminates the uncertainty in the effective length at low field as is indicated by the third curve in Fig. 3.

![Effective Length Graph](image)

Fig. 3. Effective length of the Booster Dipole from three different measurements at 2 Hz.

Field Uniformity

Field uniformity measurements were made with point coils, both with and without vacuum chamber sections and with integral coils in order to distinguish between eddy current induced effects, pole shape effects, and magnet end field effects on the field quality. Within the vacuum chamber (inserted between the poles) measurements were made at only three x-positions due to space restrictions. Data taken at three positions allowed determination of quadrupole and sextupole coefficients as is illustrated in Fig. 4.
For the multipole analysis, we assume that a function $\Phi(x)$ - either a vertical magnetic field, $B_y$, or its integral, $\int B_y \, ds$ - is composed of a linear and a quadratic term, identified as quadrupole and sextupole components, respectively i.e., $\Phi(x) = b_1 \cdot x + b_2 \cdot x^2 = \Phi_{\text{quad}}(x) + \Phi_{\text{sext}}(x)$

Symmetry relations dictate that: $\Phi(-x) = b_1 \cdot (-x) + b_2 \cdot x^2 = -\Phi_{\text{quad}}(x) + \Phi_{\text{sext}}(x)$

From combinations of these two equations we find:

$$\Phi_{\text{quad}}(x) = (\Phi(x) - \Phi(-x)) / 2; \quad \Phi_{\text{sext}}(x) = (\Phi(x) + \Phi(-x)) / 2;$$

$$b_1 = (\Phi(x) - \Phi(-x)) / 2x; \quad \text{and} \quad b_2 = (\Phi(x) + \Phi(-x)) / 2x^2$$

![Diagram](image)

**Fig. 4** Derivation of quadrupole and sextupole coefficients from magnet field data measured at three locations across the magnet.

The results obtained from 2 Hz and 10 Hz measurements are displayed in Figs. 5 - 8. Data that represent point coil measurements have to be multiplied by the effective length, to be compared to the integral data. Only those results are displayed that appear not to be affected by the discussed data acquisition accuracy problems.

Expressing the quadrupole term of the field integral as the linear change in effective length, $L_{\text{eff}}(x)$, we define wedge angles, $\alpha$, at each end of the magnet as:

$$\alpha = \arctan \left[ b_1 / 2B_y(o,o,o) \right] = \arctan \left[ (L_{\text{eff}}(x) - L_{\text{eff}}(-x)) / 4x \right]$$
In Fig. 5 the effective wedge angles derived from the integral uniformity measurements at 2 Hz are plotted for each end of the magnet. The average wedge angle equals -0.3 degrees which means that the magnet is effectively shorter at its outer side ($x>\alpha$).

The sextupole term of the field integral, normalized to the beam rigidity $B_p$, is given by:

$$m = \frac{1}{B_p} \frac{d^2 \Phi}{dx^2} = \frac{2b_2}{B_p}$$

The integrated sextupole values ($m$), measured at 2 and 10 Hz without a vacuum chamber are plotted in Fig. 6. The close agreement of the data taken at 2 and 3 cm means that up to 3 cm there is a uniform sextupole field. The stronger sextupole values at 4 cm may be interpreted as higher harmonics that could not be analyzed with the measurements made. In absolute terms, the 2 Hz data appear to be more accurate than the 10 Hz data.

In Fig. 7 the local sextupole strengths, measured near the magnet center without the vacuum chamber, are plotted for both 2 and 10 Hz excitations. The curves for 2.3 and 3.2 cm are essentially flat with negligible amplitude, showing slight saturation effects only at the highest field levels investigated. This means that the transverse pole contours, optimized with a 2-dimensional simulation code, fulfill the quality requirements outlined above.

Fig. 8 shows local sextupole strengths measured near the magnet center- at 2 Hz with a 0.8-mm thick stainless steel vacuum chamber and at 10 Hz with a 0.3 mm thick chamber. Strong eddy current effects are seen at the lower field levels as expected.

When the Booster Ring is operational, with vacuum chambers in place, the sextupole strength will be determined by three effects: eddy currents, end geometry, and saturation. The first and last of these are time-dependant, each one being significantly strong when the other one is negligible. Due to the opposite signs of eddy-current induced and geometrical sextupoles, the absolute value of the total sextupole strength for the entire excitation cycle is moderate.
CONCLUSION

The AC magnetic qualities of the ALS Booster Dipole were measured at 2 and 10 Hz frequencies. Many measurements, taken over the entire excitation range, showed intolerably high errors at low field values due to the resolution of the data acquisition hardware used. However, by combining measurements that were taken over narrower ranges and in one case by employing a differential measurement technique, these errors were compensated for. The magnetic length and field uniformity values obtained demonstrate that the magnet design meets the specifications and qualify it for production.

ACKNOWLEDGEMENTS

The authors wish to thank Klaus Halbach, LBL, for the idea of using a storage oscilloscope; Mike Lapolla, Tektronix, for making the Tektronix 11401 digital oscilloscope available to LBL; John Cerino and his staff at SSRL for making the SPEAR injector prototype 10 Hz power supply available; and to various members of the ALS project team for their help. We especially thank Sharon Fujimura and David VanDyke for their assistance in preparing this paper.

REFERENCES

LOSS MEASUREMENT PROGRAMS AT TRIUMF

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ABSTRACT

During the KAON Factory Project Definition Study year we plan to directly measure magnet losses at sinusoidal excitation and at the proposed dual frequency excitation of the booster and driver rings. The losses due to transverse fields in the conductors will be measured using the NINA magnets and core losses will be measured on steel samples using an Epstein Bridge method which allows dc bias levels to be applied. The proposed tests are described and some preliminary findings are presented. The aim of these tests is to allow us to understand the loss processes and to allow us to calculate these losses with greater accuracy and confidence.

EDDY CURRENT LOSSES IN CONDUCTORS

The power supply tests set up by Klaus Reiniger using the NINA dipoles give us an opportunity to install varying size conductors in the magnet aperture and to measure the eddy current losses directly by the temperature rise of the cooling water.

For a square hollow conductor, as shown in Fig. 1, subject to a transverse alternating field $B \cos \omega t$, the estimated loss $^1$ is

$$\omega_e = \left[ \frac{a^4}{24} - \frac{\pi d^4}{128} \right] \frac{B^2 \omega^2}{\rho} \quad \text{W/m}.$$  (1)

For standard hollow conductors in a field of 0.4 T we estimate the losses at 50 Hz to be...
Conductor size & Power loss \\ 0.162 × 0.090 in. (411 × 2.3 mm) & 22 W/m \\ 0.3648 × 0.204 in. (9.27 × 5.18 mm) & 580 W/m \\ 0.650 × 0.363 in. (16.51 × 9.22 mm) & 5824 W/m 

It should be possible to measure the power loss to about 5%. It is planned to measure at both sinusoidal and dual frequency excitation. It is expected that calculating losses at an average frequency of 50 Hz for the booster magnets will be very inaccurate. We anticipate that the dual frequency loss will be given by the average of the 30 Hz and 100 Hz losses.

Straight square hollow copper conductors of varying size will be installed in the gap. Thermocouples will be used for temperature measurement and flowmeters for the flow. We also intend to make measurements on a stranded cable conductor which has been loaned to us by Los Alamos. This particular conductor was made by Brown Bovari and is in transit.

CORE LOSSES IN STEEL SUBJECT TO NON-SINUSOIDAL EXCITATION

Manufacturers data on core losses are invariably given at sinusoidal excitation and specific excitation levels. There does not appear to be any simple method described in the literature of extrapolating this data to our proposed dual frequency excitation waveform superimposed onto a dc bias field. We have therefore decided to measure core losses using an Epstein bridge modified to accept a dc bias winding. We propose to use an ASTM procedure so that we can relate our measurements to manufacturers published data. The Epstein bridge is being made and in the meantime we have tried out the method in UBC’s Department of Electrical Engineering using a 1 kVA transformer core. The results which we have obtained are preliminary because some of the details of the transformer are not accurately known. We will describe only our general findings.

Conventional electrical engineering splits the total core loss into two components:

\[ W = \omega_h + \omega_e, \]

where

\[ \omega_h = k_h \cdot B_m^2 \cdot f \]
\[ \omega_e = k_e B_m^2 t^2 f^2, \]

where

\[ k_h \quad \text{hysteresis loss coefficient} \]
\[ B_m \quad \text{maximum flux density, T} \]
\[ f \quad \text{frequency} \]
\[ k_e \quad \text{eddy current loss coefficient} \]
\[ t \quad \text{lamination thickness} \]

We can write

\[ \frac{W}{f} = k_h B_m^2 + k_e B_m^2 t^2 f. \]
So if the loss/cycle is plotted against frequency a straightline with a slope of $k_e B_m^2 t^2$ is expected. The intercept at $f=0$ gives the value of the hysteresis term and hence the value of $x$ can be determined. In practice the curve becomes nonlinear below 20 Hz and the intercept is difficult to determine.\(^2\)

Figure 2(a–c) shows the transformer circuit and the results obtained at various amplitudes of the field. The value of the hysteresis coefficient appears to vary with field amplitude, as shown in Fig. 2(c).

---

**Fig. 2(a).** Circuit used for ac loss measurements.

**Fig. 2(b).** Measurements of total loss per cycle for sinusoidal fields.

**Fig. 2(c).** Determination of $x$ exponent.
We have also used the circuit of Fig. 3(a) to look at the effect of superimposing a dc bias field. It was necessary to use two back-to-back transformers to reduce the value of the induced ac current in the dc bias circuit. The results, Fig. 3(b), show that the loss/cycle above 30 Hz is linear and that the dc bias increases the losses, so that they must be estimated from the peak field rather than only the ac component.

Fig. 3(a). Circuit used for measurement of total loss due to an ac bias field.

Fig. 3(b). Measurement of total loss per cycle for an ac bias field.

SUMMARY

These results are preliminary and are incomplete. In time it is our aim to complete them with all three conditions:

a) Sinusoidal ac excitation only
b) Sinusoidal ac excitation with a dc bias
c) Dual frequency sinusoidal excitation with a dc bias

We hope when these measurements are completed to be able to extrapolate data from steel manufacturers to our dual frequency excitation with a good degree of accuracy.

REFERENCES

METHODS OF ESTIMATING IRON LOSSES AND FIELD ERRORS IN AC MAGNETS

P.A. Reeve
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ABSTRACT

Some semi-empirical formulas for estimating the iron losses due to hysteresis and eddy currents are presented. Also a method of estimating the field error or phase lag caused by eddy currents in components of magnets is given.

INTRODUCTION

Ac magnets have hysteresis and eddy current losses in the steel. In order to reduce these losses, the iron in the magnet is generally laminated silicon steel. Manufacturers of laminated steels quote the steel losses referenced to a fixed field, typically 1 T, and a fixed frequency, typically 60 Hz. The magnets to be designed for the KAON Factory will be operated at varying fields and frequencies. The formulas presented here enable the manufacturers data to be extrapolated to the fields and frequencies to be used for the KAON Factory magnets. The formulas are based on very simple models, assume no saturation occurs, the laminations are thin and the frequencies are modest. These formulas can be used to see if a potential problem exists in the magnet design. If a problem does exist and is unavoidable, then some more sophisticated techniques must be used to study it, such as the computer program PE2D.

POWER LOSSES

Hysteresis Losses

From Boyajian and Camilli\textsuperscript{1} the hysteresis losses can be estimated using

\[ P_h = k_h f (B_m)^n, \]

where \( P_h \) is the power loss, \( k_h \) is a material constant, \( f \) is the frequency, \( B_m \) is the maximum magnetic field, and \( n \) is the Steinmetz exponent, which can vary from 1.6 to 2.6. For example, silicon steel laminations at 1 T, 60 Hz, with a Steinmetz exponent of 2, would typically have a hysteresis loss of about 0.5 W/kg.

Eddy Current Losses

Again from Boyajian and Camilli\textsuperscript{1} the eddy current losses can be estimated from

\[ P_e = k_e f^2 B^2 t^2, \]

where \( k_e \) is a constant for the material, \( f \) is the frequency, \( B \) is the rms value of the magnetic field, and \( t \) is the lamination thickness. For example, for SiFe at 1 T rms, 60 Hz and a lamination thickness of 0.36 mm, the losses are typically about 1 W/kg. This loss becomes the dominant one at higher frequencies but the losses can be readily reduced by using thinner laminations.
PHASE LAG AND FIELD ERRORS

Eddy currents produced in components of a magnet will produce local magnetic fields, which have an amplitude of opposite sign to the main field. The net effect is to produce a local phase lag in the rise of the field. This phase lag can also be thought of as a local field error. The phase lag can be estimated using the theory of Lammeraner and Stafal, modified to the form

\[ \tau_0 = \frac{\mu_0 l \gamma ab}{\pi^2 \delta (a/b + b/a)} \]

where \( \mu_0 \) is the space permeability, \( l \) is the magnetic path length around the component (Fig. 1), \( \delta \) is the magnet air gap size, \( a \) is the component dimension normal to the field and parallel to the beam, i.e. into the paper in Fig. 1, \( b \) is the thickness normal to the field and the beam, \( \gamma \) is the conductivity, and \( \tau_0 \) is the phase lag. In cgs units \( \mu_0 \) is \( 0.4\pi \times 10^{-8} \). Therefore, Eq. (3) becomes

\[ \tau_0 = \frac{1.27 \times 10^{-9} l \gamma ab}{\delta (a/b + b/a)} \]  

For a linear ramp of length \( \tau \) and field \( B \) the phase lag is given by

\[ \frac{\delta B}{\tau_0} = \frac{B}{\tau} \]

and as

\[ \tau = \frac{1}{2f} \]

Therefore,

\[ \frac{\delta B}{B} = \frac{2.55 \times 10^{-9} l \gamma f ab}{\delta (a/b + b/a)} \]
BOOSTER DIPOLE EXAMPLE

As an example for the above equations, a possible design for a booster dipole was done using MAGDES. The magnet had a gap of 10.68 cm, a pole width of 25.16 cm, a length of 318 cm, a maximum field of 10.6 kG, and a current of 1000 A. With SiFe laminations, 0.027 cm thick and a frequency of 100 Hz, the hysteresis losses are 12 kW and the eddy current losses are 25 kW. The field errors caused by the laminations are very small, $2 \times 10^{-5}$ but if a stainless steel vacuum box were used, which is 1 cm thick, it would introduce an error of about one per cent.

REFERENCES

REPORT ON KICKERS WORKING GROUP DISCUSSION


Questions considered

1. Can a 10 ns electric field deflector be made for the Accumulator?
2. B versus I rise time. Lag?
3. Rise, ∫Bdl, magnet length trade-offs
4. Coupling impedance questions
5. KAON Factory needs
   a) Are they within existing technology?
   b) Cost/risk of shorter than 80 ns rise times
   c) How to build something in a year
   d) How much tunnel space needed?
   e) How can the kickers be monitored/controlled?
   f) How does a test facility get set up?
6. What do the new lattices mean for the kickers?

Electric field deflector

1. 10 ns looks impossible for 4 mrad. (Would need many >100 kV switches and even then, doubtful!!)
2. Empty bucket scheme allowing ≥30 ns rise looks interesting.
3. Job easier if deflector can be shorted to switch beam.
4. Precise calculations needed to determine number of switches/voltage for 30 ns beam hole.

B-I tracking

1. Experience differs CERN/SLAC.
2. Need to verify ∫Bdl rise by both probe and voltage difference methods.
3. CERN/SLAC differences may result from different ferrite grades/path length.

Kicker design

1. Take as high a voltage as can be comfortably handled.
2. Use as much length as possible.
3. Keep Z₀ high – better frequency response
   - lower switch current
4. Avoid complications wherever possible – use matched magnets.

5. Watch rise time definition for $\int B dt$ – take 1–99% as limits (can add 20 ns to usual rise with 5–95% limits).

**Coupling impedance**

1. Topic where we have least knowledge.

2. DESY designs for electron machines cost a lot of vertical aperture (lowers $Z_0$!!).

3. CERN PS still OK at $2.4 \times 10^{13}$ in 20 bunches, but for how much longer.

4. At least try to make kicker return conductor(s) continuous and make direct connections to vacuum tank flanges.

5. Do not believe delay line kickers to be worse than lumped ones.

**KAON Factory kicker needs**

1. Within existing technology

2. Should not go for shorter rise(fall) times! Don’t forget:
   - 50 Hz
   - low losses
   - cost
   - thyratron life

3. Building prototypes in a year – not possible even in labs with existing infrastructure. Instead,
   a) borrow from other labs
   b) start calculations, design and measurements on borrowed equipment

4. Tunnel space – no problem

5. Monitoring/control – existing systems present no problems; much to learn

6. HV and monitoring facilities needed (but also a dedicated team of staff)

**The new lattices**

1. A kicker designer’s dream

2. All is now much easier:
   - fewer modules 23 versus 45
   - total kV down 1377 versus 2477
   - higher $Z_0$ 25 versus 15
   - stored energy down 31% versus 100%
## Preliminary proposals for kickers for KAON factory - Version 2

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<th>Function</th>
<th>Angle (mrad)</th>
<th>Overall length needed (m)</th>
<th>Kicker aperture w × h (cm²)</th>
<th>Needed No/Z₀ of modules (#–Ω)</th>
<th>Module active length (m)</th>
<th>Module τₘ (ns)</th>
<th>Current rise 10–90% (ns)</th>
<th>Kick rise (fall) 1–99% (ns)</th>
<th>Needed PFN voltage (kV)</th>
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<td>82</td>
<td>52.1</td>
<td>1.04</td>
</tr>
<tr>
<td>Collector</td>
<td>Ejection 50 Hz</td>
<td>1.5</td>
<td>1.20</td>
<td>15×7</td>
<td>2 – 25</td>
<td>0.53</td>
<td>55</td>
<td>30</td>
<td>82</td>
<td>52.1</td>
<td>1.04</td>
</tr>
<tr>
<td>Driver</td>
<td>Injection 10 Hz</td>
<td>1.5</td>
<td>1.20</td>
<td>15×7</td>
<td>2 – 25</td>
<td>0.53</td>
<td>55</td>
<td>30</td>
<td>82</td>
<td>52.1</td>
<td>1.04</td>
</tr>
<tr>
<td>Driver</td>
<td>Ejection 10 Hz</td>
<td>1.0</td>
<td>4.00</td>
<td>15×6</td>
<td>8 – 25</td>
<td>0.44</td>
<td>53</td>
<td>30</td>
<td>80</td>
<td>72.9</td>
<td>1.46</td>
</tr>
<tr>
<td>Extender</td>
<td>Injection 10 Hz</td>
<td>1.0</td>
<td>3.20</td>
<td>6×4</td>
<td>4 – 25</td>
<td>0.73</td>
<td>53</td>
<td>30</td>
<td>80</td>
<td>58.3</td>
<td>1.17</td>
</tr>
</tbody>
</table>

23 modules @ 25 Ω (Total kV = 1377)

---

*Version 1 required 34 modules @ 15 Ω, total kV = 2322 + accelerator ejection. Version 2 has only 31% of stored energy of Version 1.*
REPORT ON FAST CYCLING MAGNETS WORKING GROUP DISCUSSION


Questions considered

1. Considerations determining peak field in fast cycling magnets
   - How to achieve optimum field quality over a full range of excitation
   - Relative importance of factors such as yoke flux density, cost optimization, acceptable loss limits and magnet size

2. Considerations on eddy current losses and conductor design
   - How accurately can iron and copper losses be calculated and how accurate are estimates of inductance, etc. with a nonsinusoidal waveform?
   - What type of conductor should be used, directly or indirectly cooled?
   - Is it better to use grain-oriented or nongrain-oriented steel?

3. Considerations on fabrication techniques
   - Advantage/disadvantages of one-piece lamination vs. split lamination with bolted assembly
   - Procedures for fabrication curved magnets

4. Considerations on combined function magnets
   - Variations from flat pole design
   - Gradient tolerances achievable
   - Practicality of gradient control with pole face windings

5. Considerations on tolerances and tracking
   - Should dipoles and quadrupoles be excited in series, so that they track together, or separately?
   - Will quadrupoles with the same current but different field strengths track together?
   - What tolerances can reasonably be expected?
   - What correction or tuning windings should be provided?

6. Considerations on magnet installation in the tunnel
   - Location of chokes and other power supply components
   - Effect of stray magnetic field from one ring, e.g. cycling magnets on dc magnets.

1. Optimum field quality will be achieved over full excitation range by:
   - 1) Using good quality (high $\mu$) steel
   - 2) Low, wide shims

   Advantage should be taken of beam damping. Average yoke flux density at peak field should be kept modest, so that the permeability does not drop below a high value (~1000). This will help in tracking, should dipoles and quadrupoles be in series. Probably the peak air gap field should not exceed about 1.3 T. Cost optimization is secondary to tracking and field quality.
2. Copper losses can be calculated to ~5%, inductances to ~2%. Iron loss estimations may be more inaccurate, but can be measured on prototypes. Indirectly cooled conductors are apparently available at current densities of up to 8 A/mm². These will considerably reduce losses compared with directly cooled conductors, and should be seriously considered. The radiation resistance of the copper strand insulation might be a drawback.

Grain-oriented steel is expensive and probably not necessary.

3. A one-piece lamination will make the achievement of assembly tolerances easier, but restricts coil design and implies a vacuum chamber which can be inserted.

Curved dipoles similar to the KAON dipoles have been successfully made in various laboratories, and these should be assessed to find a technique best suited to the manufacturer.

4. In a combined function magnet the peak field is significantly higher than that at the edge of the good field region. In addition, to achieve the same good field width in a CF magnet probably requires a wider pole than is necessary in a pure dipole.

Gradients to 1% or better are achievable.

Control of gradient with pole face windings is difficult due to induced emf's. Forces on the windings must be taken into consideration, and of course they consume aperture.

5. The problem of tracking will be eased by placing quadrupoles in series with the dipoles, but if significant changes of tune are envisaged then separate circuits are indicated. Putting taps on the quadrupole coils is probably impractical.

The linearity of quadrupole effective length with energization can be optimized by careful design of the pole ends. Nevertheless at some level saturation will set in and this regime should be avoided. As a very approximate guide, pole tip fields should not exceed 0.9 T, but this assumes a well rolled-off pole end.

Tracking of gradients to better than 1% should not be too difficult.

For tune variation about one particular working point, \( \Delta \nu = \pm 0.2 \) should be enough.

6. If possible chokes should be centralized with 100% coupling.

Design of magnets should prevent long-range stray fields, but these may still be a problem with two rings close to one another. They may, for instance, induce vibration. Stray fields from prototype magnets should be measured and their effects assessed.

Natural vibration frequencies of both magnets and supports should be taken into account.
REPORT ON MAGNET POWER SUPPLY SYSTEM WORKING GROUP DISCUSSION

Klaus Reiniger, TRIUMF
Walter Praeg, ANL
Hirochi Sasaki, KEK
Neil Marks, ESRF/DL

The discussion considered various features of the dual frequency resonant circuits needed for the fast cycling machines. The 50 Hz repetition rate system was mainly discussed, but many conclusions are relevant to the 10 Hz system.

1. POSITION AND NUMBER OF DC BIAS SUPPLIES

The present proposal used twelve separate dc supplies, one for each cell, around the distributed system. This would lead to a significant increase in the cost of this supply, as twelve small units are a factor of between three and four times more expensive than a single supply.

A large single unit would be rated at about 2 kA, 1 kV and would require stabilization to $1 \times 10^4$ or better ($2$ or $3$ in $10^5$ should be possible). There was doubt whether Canadian industry could manufacture the big unit, whereas the multiple units, with the lower ratings, could certainly be manufactured. However, it was agreed that this may be more a matter of confidence than inability. Politically, buying 'modular' components from different manufacturers may be seen to be advantageous, but it was pointed out that this could lead to technical problems.

A major technical advantage of the single system is that it allows one of the choke/capacitor cells to be modified to separate the alternating current in the choke from the dc source. Diagram is given below:

At each choke/capacitor cell there is sufficient capacitance to resonate the magnets in series, and the choke in parallel:

$$C_M = \frac{1}{\omega^2 L_M} \quad C_{ch} = \frac{1}{\omega^2 L_{ch}}.$$ 

At the modified cell, the choke secondary is split, each half being separately resonated. The bias supply, with a central earth, is connected between the two half windings; because these
are separately resonated, no reactive current flows in the dc supply. Resistive power, if made up from the choke primaries, will flow through the supply, but this will only require a modest capacitor, and the large 2–10 F capacitors can be dispensed with.

This modification is possible with 12 separate dc supplies, but leads to the complexity being present in all cells.

The two capacitors required for dual circuit operation will be necessary in each of the three banks at the modified cell.

The final decision on this problem will clearly involve political and commercial considerations as well as technical arguments.

2. CIRCUIT RESONANCE AND CHOKE CONSTRUCTION

The multiple resonances, possible in a circuit with distributed inductors and capacitors, are eliminated by ensuring that there is strong (i.e. ~100%) coupling between choke secondaries. In practice, this involves having a primary winding strongly coupled magnetically to each secondary, and then strongly coupling the primaries, electrically in parallel. The circuit then oscillates at a single resonant frequency, irrespective of inductor/capacitor distributions.

Component imbalance then leads to voltage differences in the circuit. To obtain the required ‘sawtooth’ voltage distribution to earth, which is needed to balance capacitative leakage currents and prevent over-voltages to earth, magnet inductances must have similar values, and the values of the individual capacitor banks are ‘trimmed’, during commissioning, to give a balanced distribution.

Choke construction should reflect the high coupling required between the primary and secondary coils in one cell, and interleaving appears to be a reasonable solution.

A number of choke constructions are possible. A single large air gap will give a large choke with very linear behaviour. The flux density in the air gap will vary down the axis of the choke, and the number of turns in each primary/secondary pair must be varied to give the same inductance. In this circumstance, the use of an eddy-current shield around the coil would be very advantageous, and should lead to uniform flux densities in the coil stack. Praeg also believed that this could lead to an overall reduction in eddy losses.

A multiple air gap design, using steel packets between insulated, nonmagnetic spacers in the centre of the coil stack, gives a more compact, more economical design. This would possibly be less linear (leading to higher harmonics in the magnet) and also leads to mechanical problems of securing the steel packets.

A completely steel-free design would be highly linear, and have less ac losses. However, it would be large, expensive, have high fringe fields, and is possibly not optimum in terms of dc resistance.

It is felt that the single large air gap, steel-clad design is the best approach.

Separate chokes in each cell had been discussed previously. They would be more expensive (by up to a factor of 3), but would reduce cable lengths, cable losses, and capacitance to earth. Discussions with industry would be useful to establish the true situation relating to costs.

3. AC ENERGY MAKE-UP SYSTEM

The present proposal uses a ‘pulse power supply’ invertor (as at CEA and NINA) for maintaining ac excitation. The current pulse enters the network through the choke primaries,
and is a half sine wave, with a frequency of between three and five times the network fundamental. The second integral of this current, i.e. \( \frac{1}{\omega_p^2} (\sin \omega_p t) \) appears in the magnet circuit.

This system is not necessarily the best available, and produces a number of problems:

(i) The disturbance in the magnets is quite large, and is a source of tracking inequality between dipole and quadrupole circuits. This is due to the phase of the pulse varying when a circuit is driven off resonance, leading to pulse phase differences being present between the free cycling dipole and forced quadrupole circuits.

(ii) The pulse will excite the delay line mode in the magnet network, the capacitor volts having a cosine waveform, with sharp edges:

(iii) When 'forcing' a circuit (the quads will be driven at the dipole frequency), and there is an appreciable difference between the resonant and forced frequency, there is a large increase in the pulse current amplitude.

Recently, ESRF had commissioned a study on inverter circuits for 'White Circuit' applications from Holec, and the report had recommended the use of a single phase 'PWM' circuit using 'GTO's to generate the square waves from a dc rectifier. Holec had shown that by controlling the waveform, lower-order harmonics could be eliminated, leading to better tracking between the different circuits. Information on this study was provided to TRIUMF.

The degree of decoupling from the supply was considered. Whilst the pulse power supply appears to be well decoupled, other circuits also use a series inductor, and the use of a fast voltage servo at the rectifier should produce good isolation from mains transients. However, all the circuits considered will be susceptible to disturbance by supply fundamental (due to phase imbalance) and harmonic (from the rectifiers) contamination. These will appear (heavily attenuated) in the magnet, and should be examined as a source of servo instability and tracking error.

4. TIMING AND FREQUENCY STABILITY

One circuit – probably the network with the highest stored energy – would be the frequency master for the machines. All other supplies will then be frequency locked to this system. As this results in the other networks being driven off frequency, phase differences will result, and as \( \partial \phi / \partial \omega \) is maximum at resonance these can be appreciable for even small frequency shifts. These effects should be minimized by maintaining a reasonable temperature control on ring tunnels and capacitor/choke buildings. Tighter control is achieved by switching small capacitance into/out of circuits automatically. This will minimize the reactive power that is needed from the supplies powering the driven systems, and should result in the rating increase needed for reactive power being small.

Some phase drift will occur, and phase control servos will be essential, holding all driven systems in phase with the frequency master system.
5. FAULTS AND FUTURE INVESTIGATIONS

The circuit can clearly have some interesting fault conditions associated with switch malfunctions, capacitor breakdowns, etc. It is not clear what features these will have, and investigation will be necessary. Circuit protection, as at ANL, where power is dumped into shorting switches when a fault is detected, should be considered.

Reiniger indicated his intention to extend his existing single cell high current tests to a dual cell experiment. It was also suggested that a low voltage/current tabletop network, with all twelve cells present, could give valuable information on normal and fault behaviour in the multicell situation.
REPORT ON INDUSTRIAL PARTICIPATION WORKING GROUP DISCUSSION

A total of 15 participants attended these discussion. These broke down into:

- Canadian manufacturers representatives: 5
- U.S. manufacturers representatives: 2
- French manufacturers representatives: 1
- U.S. laboratory employees: 4
- TRIUMF employees: 3

Questions considered

1. Establishing industrial capacity for magnet production:
   - Methods for getting companies interested in a new product line
   - Present capability of Canadian industry to manufacture magnets
   - Are the quantities and schedules feasible for a fabrication period of 3–4 years?

2. Production technology
   - Can the tolerance requirements on tooling and lamination stamping be met?
   - The coils will be vacuum impregnated with insulation of fibreglass, mica and either epoxy or polyester and a voltage insulation requirement of 10 kV. Is this a problem for most companies?

3. Design assistance
   - Can companies assist TRIUMF in detailed design studies such as eddy current losses and in providing cost estimates?

The discussion was free ranging with a lot of time spent discussing current practices in making magnets. The questionnaire was not followed rigidly but was used as a guide. Summary answers to the questions listed in it are given below:

1. Industrial Capacity for Magnet Production

   There is always interest in new product lines, but they have to be sold to company management as being beneficial to the company. A product which does not lead to repeat orders is especially hard to sell. TRIUMF is planning continued involvement with companies during the PDS year.

   At the present, Canadian capacity does not exist to manufacture all the KAON Factory magnets. There was a feeling that it could be generated if the manufacturers are convinced that it is worth their while to be involved in the project. It is to be noted that excess transformer manufacturing capacity which was present 2–3 years ago is now much reduced as a benefit of the improved economy. The response from industry cannot be predicted for two years time which is the earliest we anticipate orders will be placed for the main KAON Factory production. It will depend on the economy at that time.

   The size of potential contracts was discussed. Manufacturing facilities will have to be in the range of 100,000–200,000 square feet to handle the larger contracts. Production will have to be done on an assembly line basis to meet the schedules. No one manufacturer could handle the production and we expect to have at least 60 different contracts spread amongst the suppliers. If Canadian companies do not accept the challenge we would have to look to
offshore suppliers. There is also the possibility that International Participation in the project may reduce the number of magnet orders to be placed in Canada.

2. Production Technology

Tooling can be built to meet the tolerances on our magnets, obviously the tighter the tolerances the higher the cost. It was pointed out that some tolerances are relative and not absolute, but our aim will be to produce magnets identical to a few parts in $10^4$.

The fact that we will require vacuum impregnation and voltage levels of 10 kV to ground did not appear to be a problem. The large transformer manufacturers work with higher levels than this and all are familiar with vacuum impregnation.

3. Design assistance

Companies were very interested in becoming involved with the design of our magnets. AC machine designers are much more experienced than TRIUMF staff in calculating eddy current and core losses especially for non-sinusoidal excitation.

There was a feeling that participation by industry engineers would be mutually beneficial. However, there might be a problem in finding engineers who would be willing to come to Vancouver for a period of time. This aspect will have to be followed up individually with the companies.

Finally, we gave photographs of typical TRIUMF magnets and photographs of DESY magnets plus a copy of a typical specification to Canadian manufacturers. We will also send them a copy of the Economic Impact Study by Coopers & Lybrand. Three of the representatives are having meetings with their company management to report on the workshop in the week following the workshop. We told them that if they need further help or special visits we will do all that we can to assist them.
A SHIELDED ENERGY - STORAGE CHOKE FOR RAPID CYCLING SYNCHROTRONS

W.F. Praeg

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ABSTRACT

The conventional design of energy storage chokes with a picture frame iron enclosure is briefly reviewed. Eddy current losses in the coil windings caused by transverse leakage flux are calculated. Eddy current shielding is proposed for the coil assembly to protect it from leakage flux and to eliminate the need for stranded conductors. The eddy current shield forces nearly 100% coupling between the coils, permitting designs with an H-frame iron enclosure and multiple air gaps.

INTRODUCTION

Large rapid cycling synchrotrons (RCS) comprise many resonant cells. Each cell has an energy storage choke that carries the ring magnet dc current and an ac current. These chokes may be constructed as separate units or they may use one iron structure common to all of them. In either case, the design usually consists of pancake coils with an air core and a "picture frame" iron enclosure to confine the return path of the magnetic flux. For such a structure the main flux is transverse to the axis of the coil windings and rises linearly from zero, at the outside of the coil to a maximum on the inside of the coil as illustrated in Fig. 1. The flux distribution is not the same for each of the pancake coils since the coil turns are at different distances from the top and bottom of the enclosure. Effective uniformity of flux linkage of the different choke coils is enhanced by coupling all coils with an auxiliary winding. This is more effective if all chokes are in one common iron frame as compared to widely space individual chokes. To reduce eddy current losses, the coils are wound from conductors comprising many small insulated wires in parallel. These wires are cooled either by inserting the choke assembly in oil or by providing a water cooled heat sink at the center of the wires.

The major criteria for the choke design are:

a. uniform flux linkage in the choke coils of all resonant cells,

b. small eddy current losses in the coil assembly,

c. cost and simplicity of construction.

The purpose of this paper is to stimulate interest in exploring whether these design criteria can be satisfied more efficiently by enclosing the choke coils with eddy current shields. Of special interest are designs that have the chokes of the resonant cells in one structure.
CONVENTIONAL DESIGNS

Energy storage chokes with a common magnetic structure have been analyzed. Figure 1 illustrates the design of a recently developed prototype choke.

Eddy Current Losses in the Coil Winding

Each of the twelve pancakes of the choke in Fig. 1 has seven turns of 58 stranded wires as shown in Fig. 2. With a 50 Hz current of 880 A per turn, the field at the center of the choke is \( \approx 2140 \, \text{G} \). The average flux density in the seven conductors of the pancake coil rises in steps of 305.6 G from 153 G for the turn on the outside to 1987 G for turn No. 7 on the inside. Eddy current losses per unit length of a wire with radius \( r \) in a field \( H \) transverse to the wire axis are

\[
P = 2 \pi \rho \left| \frac{B}{\mu_0} \right|^2 \mathcal{F} \left( \frac{r}{\delta} \right) = 2 \pi \rho \left| \frac{B}{\mu_0} \right|^2 \mathcal{F} \left( \frac{r}{\delta} \right). \tag{1}
\]

where

\[\rho = \text{resistivity}\]
\[\mu_0 = \text{permeability of free space}\]
\[\delta = \left( \frac{\rho \mu_0}{\pi f^2} \right)^{1/2} = \text{skin depth}\]
\[f = \text{frequency}\]

The function \( \mathcal{F}(\frac{r}{\delta}) \) is given by

\[
\mathcal{F} \left( \frac{r}{\delta} \right) = -\text{Re} \left( \sqrt{2} j \frac{r}{\delta} \frac{J_1 \left( \sqrt{2} \frac{r}{\delta} \right)}{J_0 \left( \sqrt{2} \frac{r}{\delta} \right)} \right), \quad \text{where } J_0 \text{ and } J_1 \text{ are Bessel Functions.} \tag{2}
\]

Figure 3 shows \( \mathcal{F}(\frac{r}{\delta}) \) with its approximations.

\[
\mathcal{F} \left( \frac{r}{\delta} \right) = \begin{cases} \frac{1}{4} \left( \frac{r}{\delta} \right)^4 & \text{for } r < \delta \\ \frac{r}{\delta} - \frac{1}{2} & \text{for } r > \delta \end{cases} \tag{3}
\]

With \( 2r = 0.26 \, \text{cm} \) and a skin depth of \( 0.93 \, \text{cm} \) for copper, we have \( r < \delta \) and the power losses per unit length can be calculated by combining eqs. (1) and (3) which gives

\[
P = \frac{\pi}{2} \rho \left| \frac{B}{\mu_0} \right|^2 \left( \frac{r}{\delta} \right)^4. \tag{4}
\]

The losses per cm length in a single wire and in the 58 parallel strands of a conductor are given below for the seven turns of a pancake.
<table>
<thead>
<tr>
<th>Turn</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Field</td>
<td>153</td>
<td>459</td>
<td>764</td>
<td>1071</td>
<td>1376</td>
<td>1682</td>
<td>1988</td>
</tr>
<tr>
<td>Single Wire</td>
<td>0.0151</td>
<td>0.136</td>
<td>0.3755</td>
<td>0.738</td>
<td>1.22</td>
<td>1.82</td>
<td>2.54</td>
</tr>
<tr>
<td>58 wires</td>
<td>0.874</td>
<td>7.86</td>
<td>21.8</td>
<td>42.8</td>
<td>70.7</td>
<td>105.5</td>
<td>147.8</td>
</tr>
</tbody>
</table>

There is also a horizontal field component in each of the pancake coils due to the current flowing in all other pancakes as illustrated in Fig. 4 by the dashed bars. With $7 \times 880A = 6160$ amperturns per pancake, the horizontal fields and eddy current losses for the conditions as shown in Fig. 1 are shown below.

<table>
<thead>
<tr>
<th>Pancake No.</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>XII</td>
<td>XI</td>
<td>X</td>
<td>IX</td>
<td>VIII</td>
<td>VII</td>
</tr>
<tr>
<td>horizontal field</td>
<td>1442</td>
<td>1051</td>
<td>709</td>
<td>405</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td>single wire</td>
<td>1.34</td>
<td>0.711</td>
<td>0.324</td>
<td>0.106</td>
<td>0.011</td>
<td>0.011</td>
</tr>
<tr>
<td>58 wires</td>
<td>77.7</td>
<td>41.22</td>
<td>18.8</td>
<td>6.11</td>
<td>0.611</td>
<td>0.611</td>
</tr>
</tbody>
</table>

These losses must be added to the losses caused by the vertical field. The losses per turn depend on the wire length which is a function of the twist of the stranded wires.

**Eddy Current Losses in the Water Cooled Heat Sink**

The time average eddy current power losses in a conducting cylinder due to a transverse sinusoidal field have been calculated as

$$P = \text{Re} \left( \frac{1}{2} \int_0^{\pi/2} \int_{r_1}^r |J|^2 \rho r dr d\theta \right) = \text{Re} \left( \frac{\omega^2}{2\rho} \int_0^{\pi/2} \int_{r_1}^r |A_z|^2 r dr d\theta \right)$$

where

- $J$ = current density
- $r, \theta, z$ = cylindrical coordinates ($\chi$ axis at $\theta = 0$)
- $A$ = magnetic vector potential.

The losses in the $1.5 \text{ cm O.D.}$ copper heat sink with a wall thickness of $0.15 \text{ cm}$ are given below for the design shown in Figs. 1 and 2.
The losses in the 84 copper heat sinks due to the vertical fields are 14.9 kW. Additional losses are caused by the horizontal fields shown dashed in Fig. 4. They are tabulated below and amount to 3.6 kW.

<table>
<thead>
<tr>
<th>Pancake No.</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>XII</td>
<td>XI</td>
<td>X</td>
<td>IX</td>
<td>VIII</td>
<td>VII</td>
</tr>
<tr>
<td>horizontal field</td>
<td>1442</td>
<td>1031</td>
<td>709</td>
<td>405</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td>losses/cm</td>
<td>0.94</td>
<td>0.502</td>
<td>0.228</td>
<td>0.0745</td>
<td>0.007</td>
<td>0.007</td>
</tr>
<tr>
<td>losses/turn</td>
<td>3.75</td>
<td>31.8</td>
<td>82.8</td>
<td>152</td>
<td>234</td>
<td>324</td>
</tr>
<tr>
<td>12 pancakes</td>
<td>45</td>
<td>383</td>
<td>994</td>
<td>1828</td>
<td>2809</td>
<td>3887</td>
</tr>
</tbody>
</table>

The total eddy current losses in the heat sink are \( \sim 18.5 \) kW. They could be reduced by replacing the copper tube with one made from stainless steel. However, this would also reduce the efficiency of the heat sink.

**PROPOSED DESIGNS WITH THE COILS ENCLOSED BY AN EDDY CURRENT SHIELD**

**Picture Frame Iron Core**

By enclosing the pancake coils with copper, except for a small vertical gap to avoid that the enclosure becomes a shorted turn, the vertical transverse flux is prevented from entering the coil area by means of eddy current shielding. The vertical flux distribution is now as shown in Fig. 5 for one quarter of the choke assembly of Fig. 1. With the transverse flux excluded from the coil conductors, there is no longer a need for stranded wires. The pancakes can now be wound from conventional water cooled copper conductors suitable for the operating frequency. With a copper shield 0.9 cm thick and for a 2140 G, 50 Hz field at the center of the choke the eddy current losses in the shield were calculated with PE2D as 96.6 W/cm. With a median circumference of 290 cm, the losses in the water cooled shield would be \( \sim 28 \) kW. These losses can be reduced with a thicker shield wall, a more compact pancake design, or by using an H-Frame core as described below. More importantly, the shield forces a more uniform flux throughout the coil assembly; this improves the mutual coupling between the
chores of different resonant cells without large equalizing currents in the auxiliary windings.\textsuperscript{1,2}

The eddy current pattern of a simple shield as shown in Fig. 6, can be improved with thin contact making copper sheets between the pancakes at the air gap location as shown in Fig. 7 (i.e., sheet 1/16" x 2" x width of shield).

Flux Within Shielded Volume

The magnitude of the horizontal fields to which each of the 12-pancakes is exposed due to the 6160 amp-turns in each of the other 11 pancakes is illustrated by the solid bars of Fig. 4. These fields can be eliminated with copper shield plates between each pancake as shown in Fig. 8. These plates make electrical contact with the walls and have one gap to prevent a shorted turn for the main choke flux.

H-Frame Iron Core

With the shield excluding external transverse flux from entering the space occupied by the choke coils, it is no longer necessary to have an air core design. A multi-air-gap iron-core choke can now be considered as illustrated by Fig. 9 which has the same inductance as the choke of Fig. 1. The losses in the eddy current shield should be much smaller than for a shielded picture frame because the iron guides the flux around the shielded area and the field strength around the multiple air gaps is small. Each of the twelve pancake coils has 10 turns. The core comprises twelve 2.12 cm thick G-10 plates separated by thirteen 4.27 cm high sections of grain oriented silicon steel. This design will be analyzed at a later date. Of course, the eddy current shields could also be made from aluminum.

Acknowledgment

I am grateful to R. Lari of Vector Fields, Inc., who calculated the losses in the eddy current shield with PE2D.

References


Fig. 1 Picture-frame choke assembly and flux distribution.

Fig. 2 Stranded conductors of pancake coil.

Fig. 3 $F(\frac{T}{a})$ for calculating the losses in solid round conductors.

Fig. 4 Horizontal fields in pancake coils.

Fig. 5 Flux distribution in one quadrant of choke with shielded coils.
Fig. 6 Eddy current pattern of a simple shield.

Fig. 7 Eddy current pattern of shield with thin contact making sheets between shield walls.

Fig. 8 Shield plates between pancake coils to eliminate horizontal field.

Fig. 9 H-frame choke with multi-air-gap iron-core and shielded pancake coils. Choke has same inductance as choke in Fig. 1.
DUAL VERSUS SINGLE FREQUENCY RING MAGNET POWER SUPPLIES FOR RAPID CYCLING SYNCHROTRONS

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ABSTRACT
Features of dual and of single frequency ring magnet power supplies for rapid-cycling synchrotrons are compared.

INTRODUCTION

Ring magnets of rapid-cycling synchrotrons (RCS) are usually excited in a resonant circuit by a dc-biased cosine wave current. Particle acceleration takes place during the rise time of the current. After beam extraction, the magnets are reset during the fall time of the cosine wave. Only 50% of the cycle is used for acceleration. A significant reduction in peak radio frequency (rf) power can be achieved by making the magnetic field rise slowly and fall rapidly. This can be done by adding harmonics to the fundamental cosine wave or by using a dual frequency circuit. The B and \( \dot{B} \) waveshapes associated with the various circuits are shown in Fig. 1. Adding a 2nd harmonic (\( f_Q, 2f_Q, \ldots \)) reduces the peak value of \( \dot{B} \) by 33% as compared to a single frequency wave (\( f_Q, \ldots \)). By adding a 2nd and a 3rd harmonic (\( f_Q, 2f_Q, 3f_Q, \ldots \)) \( \dot{B} \) can be made to remain practically constant during most of the acceleration time. Note that at the beginning (injection) and end (extraction) of acceleration, \( \dot{B} \) is about the same as with a single frequency circuit. Analysis of a 2nd harmonic circuit shows that the voltages on the additional components are larger than the magnet voltages and the control of the amplitude and phase of the various circuit currents is difficult. This may be the reason why this circuit is not in use.

These difficulties can be avoided with a circuit that has the magnet and choke in one core assembly. A second harmonic (\( 2f_Q \)) and a dc bias field can be added to a first harmonic (\( f_Q \)) as shown in Fig. 2. Figure 3 illustrates the phase-relation and magnitudes of the magnetic fields. Desirable features of this circuit, which is especially suitable for combined function magnets, are:

1. No dc flows through the first harmonic ring magnet coils.
2. No 1st harmonic magnet current flows through the dc coil or through the 2nd harmonic coil.
3. With the inductances of the magnet and choke connected in series, the circuit needs only a fraction of the tuning capacitance required for a conventional circuit. For \( L_M = L_{CH} \), the circuit requires 1/4 of the capacitance of a conventional circuit.

In 1980, the writer developed, for an upgrade of a 30 Hz, 500 MeV synchrotron, a dual frequency circuit. For a reduction of \( \dot{B} \) by 1/3 as
compared to a single frequency circuit, the frequencies during acceleration and during magnet reset must have a ratio of 1:3 as shown in Fig. 1. Note also the reduction in B during injection and extraction as compared to all other circuits. The resonant frequency is changed by adding or removing a capacitor bank $C_2$ in parallel to a capacitor bank $C_1$ with a solid state switch. Switching takes place when all the circuit energy is in the magnet and choke of the circuit, thereby keeping switching transients to a minimum. The design curves of Fig. 4 show a ratio of $f_0/f_1 = 1.5$ as optimal. This ratio corresponds to values of $f_1/f_0 = 0.667$, $f_2/f_0 = 2$, $C_2/C_0 = 2$, $C_1/C_0 = 0.26$ and $C_1 + C_2 = 2.26 C_0$. Any further increase in $f_0/f_1$ will decrease B during acceleration by a much smaller percentage ($f_1/f_0$) than it will increase the magnet voltage during reset ($f_2/f_0$). For example with $f_0/f_1 = 1.6$, B during acceleration will decrease by 6.2% and the magnet reset voltage will increase by 25% as compared to the corresponding values for $f_0/f_1 = 1.5$.

In the early 1980's, there were no suitable gate-turn-off (GTO) thyristors available and, therefore, silicon controlled rectifier (SCR) turn-off circuits were required for practical circuit applications. Recently large power GTO's have become available and the solid state switching circuit can now be simplified by using a combination of GTO's, SCR's, and diodes. Dual frequency circuits with flat bottoms and with flat tops utilizing GTO's have been described, as well as circuits with only dual frequency operation. For a comparison of dual frequency and single frequency operation, the circuits of Fig. 5 and 6 will be referred to.

**BRIEF COMPARISON OF FEATURES OF DUAL FREQUENCY VERSUS SINGLE FREQUENCY RING MAGNET POWER SUPPLIES**

**Economics**

For a high rate of pulses per second (pps), the reduction in peak rf power with a dual frequency ring magnet circuit is 56% and the savings far outweigh the increase in cost over a single frequency ring magnet power supply. Cost comparisons have not yet been made to establish the lower limit for the pps, which may be near 10 pps (6.6 Hz and 20 Hz).

**Circuit Reliability**

The addition of the dual frequency switching circuit adds relatively few thyristors to the overall power supply and the switching stress on these components is relatively low. The dv/dt and di/dt stress on these thyristors is much smaller than the stress on conventional power supply thyristors. For example, the thyristors of the 24-phase power supply of the 500 MeV, 30 Hz RCS at Argonne National Laboratory (ANL) are continually phase controlled to generate a unidirectional current $i = 2300 A - 1300 A \cos 188 t$. Every 1.39 ms a thyristor is switched, it must commutate half the magnet current, and must hold off voltages that rise at $< 100 V/\mu s$ to generate a biased 30 Hz wave from the 60 Hz commercial power source. This circuit has operated satisfactorily for over 10 years. The addition of a capacitor switch as shown in Fig. 5 for dual frequency operation would add only one high voltage (HV) switch to the existing 24 thyristor switches. This would not degrade the overall circuit reliability by much because the HV switch operates when its voltage is zero.
With reference to Fig. 6, the switching modes are as follows:

1. At time $t_1$ (the switch closes, connecting $C_2$ in parallel with $C_1$).

All the circuit energy is in the choke and in the magnet. The capacitor voltage is zero and the current in $C_1$ is at its negative peak. As the voltage on capacitor $C_1$ increases, the diode begins conducting and capacitors $C_1$ and $C_2$ share the current while the choke discharges its energy into the magnet and the capacitors. The current transfer into $C_2$ is determined by the inductance of the interconnections; transmission lines rather than bus bars should be used for this purpose to keep the inductance and the duration of transients low. The reverse voltage on the thyristor assembly is limited to the diode voltage drop.

2. At time $t_2$ (the capacitor current goes through zero).

At time $t_1$, the capacitor current goes through zero; the capacitors are at their peak energy (voltage). Diode D turns off as the magnet voltage begins to fall and the thyristor assembly must be turned on. After $t_1$, the choke and capacitors discharge into the magnet. As the capacitors discharge, the thyristor current increases at a rate of $\frac{dI}{dt} = \omega I_2 \cos \omega t$. With $I_2 < 6$ kA the $\frac{dI}{dt}$ rating is $\leq 2\pi 33 \frac{1}{3}$ s $\times 6$ kA $\leq 1.25$ A/µs which is small compared to typical thyristor ratings of $< 800$ A/µs. The slow current rise necessitates gate drives for the thyristors long enough to go past the thyristors holding currents.

3. At time $t_2$ (the switch opens, disconnecting $C_2$)

The capacitors are discharged (zero voltage), the capacitor current is at its positive peak. All the circuit energy is stored in the magnet and in the choke. A hard gate drive to the GTO turns it off and the current in the series connected chain of one GTO and several SCR's goes to zero with the aid of parallel connected snubber circuits (not shown in Fig. 5). The forward voltage on the thyristor assembly rises at a rate of $< 18.8$ V/µs which is negligible when compared to the assembly rating. The peak forward voltage at time $t_3$ is three times larger ($< 30$ kV per cell) than the peak voltage during acceleration. The design rating of the switch assembly for blocking a peak forward voltage of $30$ kV would be about $60$ kV peak.

Power Supply

The number of resonant cells and power supply feed points depends on what peak voltage to ground can be used. The major considerations are capacitive currents through the coil insulation and resistive currents through the cooling water circuits. The capacitive currents are determined by the magnet voltage and by the coil insulation. During acceleration, the magnitude of the magnet voltage in a dual frequency circuit is only 66% of the magnitude that a single frequency accelerator with the same repetition
rate would have. During magnet reset, the voltage is twice as large as for a single frequency accelerator. However, by then the beam has been extracted and capacitive currents are of little consequence. Coil insulation make up less than 10% of the magnet cost. A peak magnet cell voltage to ground of ±15 kV should cause no problems for an insulation system based on mica tape and a coil and core design that prevent corona discharges. In principle, power can be supplied continuously\(^3\),\(^6\) or pulsed.\(^9\),\(^10\) The continuous 24-phase power supply at ANL mentioned earlier provides for the ac and dc losses of around 500 kW with a peak power demand of about 1.4 MVA. This relatively inexpensive power supply operates from the 480 V, 3-phase, 60 Hz power line without causing noticeable interference with other circuits.\(^7\) Power supplies for much larger loads should be connected to a 13 kV or 60 kV power line. A more expensive but most likely better solution is a pulsed power supply as shown in Fig. 5.\(^7\) It provides complete isolation from the power line during the make-up pulse. In this circuit, power losses are made up by a current pulse on the primary winding of the choke. This pulse is usually applied during magnet reset.\(^9\),\(^10\) However, applying the pulse during acceleration with its peak occurring at time \(t\) is better. The peak power supply and magnet voltages are smaller and the pulse can be made longer. Tests in 1984 at ANL showed negligible disturbance in the magnet current due to a make-up pulse during acceleration.

CONCLUSION

Table 1 is a summary of some of the features of a single versus a dual frequency power supply. For a synchrotron operating at 50 pps, I recommend a dual frequency power supply.

Table 1: Comparison of Single and Dual Frequency Ring Magnet Power Supplies

<table>
<thead>
<tr>
<th>Circuit Function Compared</th>
<th>(f_0 )</th>
<th>(f_1 = \frac{f_0}{1.5} ); (f_2 = 2f_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>peak rf power</td>
<td>1.0</td>
<td>0.44</td>
</tr>
<tr>
<td>(B) at injection and extraction</td>
<td>1.0</td>
<td>0.66</td>
</tr>
<tr>
<td>capacitive and resistive ground currents during acceleration</td>
<td>1.0</td>
<td>0.66</td>
</tr>
<tr>
<td>phase shift between I &amp; B in cores</td>
<td>small</td>
<td>smaller</td>
</tr>
<tr>
<td>peak magnet and choke voltages</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>circuit losses</td>
<td>1.0</td>
<td>(\geq 1.0)</td>
</tr>
<tr>
<td>capacitor switching</td>
<td>none</td>
<td>takes place at zero voltage. (\frac{dv}{dt} &lt; 20 \text{ V}, \frac{di}{dt} &lt; 3 \text{ A/\mu s}.)</td>
</tr>
</tbody>
</table>
REFERENCES


Fig. 1:
B AND B WAVESHAPES FOR VARIOIARI
RESONANT RING MAGNET POWER
SUPPLY CIRCUITS.

Fig. 2:
TWO RINGS WITH COMMON
WINDINGS, MAGNET CORE,
AND POWER SUPPLIES.

Fig. 3:
FLUX DENSITIES IN TWO-RING
CORE WITH FIRST ($f_0$) AND
SECOND (2 $f_0$) HARMONIC AND
DC EXCITATION.
Fig. 4: RESPONSE OF DUAL FREQUENCY CIRCUIT VERSUS $f_o/f_1$.

Fig. 5: DUAL FREQUENCY RING MAGNET CIRCUIT AND PULSED POWER SUPPLY.

Fig. 6: WAVESHAPES OF THE CIRCUIT OF FIG. 5.
CALCULATING THE FREQUENCY RESPONSE OF MAGNETS WITH LAMINATED CORES

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ABSTRACT

A method is described for calculating the frequency response of magnets with laminated ferromagnetic cores energized from alternating current (ac) with a direct current (dc) bias. This is useful during the design of magnets and their power supplies for regulation and ripple studies and to estimate magnet losses and the circuit response to transients.

INTRODUCTION

The ring magnets for rapid cycling synchrotrons are often energized with a unidirectional current that comprises a single or dual frequency cosine wave superimposed on a direct current bias. During the design stage, knowledge of power losses and the frequency response of the magnets is essential for studies of transient response, power supply regulation, etc., of the overall ring magnet circuit.

This paper shows how the inductance and the resistance due to core losses can be calculated for any magnet based on measurements on a small core sample. The capacitance of the magnet, transformed to the coil terminals, is calculated from the coil and core geometry. Finally, from this data the frequency response of the magnet is calculated.

MAGNET RESISTANCE DUE TO CORE LOSSES AND MAGNET INDUCTANCE

Complex Permeability

Neglecting capacitive effects, the impedance of a coil containing a ferromagnetic core is \( Z = R + j\omega L \). After subtracting the coil resistance \( R_{Cu} \) from \( R \), we have

\[
Z = R_{Fe} + j\omega L
\]

Resistance \( R_{Fe} \) is due to core losses (hysteresis and eddy currents). Both the core losses and the inductance are dependent on the properties and the geometry of the core, and Eq. (1) can be written as

\[
Z = j\omega \mu\frac{n A}{\ell} \tag{2}
\]

where \( \omega = 2\pi f \),

\( f = \) frequency,

\( \mu = \mu_L - j\mu_R \) = complex permeability of core material,

\( n = \) number of coil turns,
\[ A = \text{effective core area}, \]
\[ \ell = \text{length of core}. \]

From Eqs. (1) and (2), the real and imaginary parts of the complex permeability are

\[ \mu = \mu_L - j\mu_R = \frac{L}{\omega n^2 A} \ell - j \frac{R_{Fe}}{\omega n^2 A} \ell. \quad (3) \]

For a defined core and coil geometry as, for example, a toroidal core shown in Fig. 1, and for a controlled core magnetization, the complex permeability can be calculated from an impedance measurement.

The toroidal test core has a \( B \)-coil to measure the dc and the ac magnetic fields. This one layer coil is made from thin (i.e., flat) wire and wound close to the core to reduce errors due to flux in the space between the \( B \)-coil and the core. The ac excitation winding is wound over the \( B \)-coil and has a relatively large cross-section to keep the copper losses small in comparison to the iron losses. The dc magnetization coil can be a few turns through the center of the hole of the toroid with the return far enough away in order not to effect the core material.\(^2\)

Before taking measurements on core samples with the appropriate ac and dc magnetization, it is essential that the core laminations be demagnetized. The dc magnetization is than slowly increased until the desired dc bias field (i.e., 6.75 kG) is reached; thereafter the ac magnetization is increased from zero to its maximum value (i.e., 3.85 kG). For some core material, including silicon steel, it takes time before a final impedance value is obtained for a given ac and dc magnetization. This effect (NACHWIRKUNG), which causes changes in the permeability of several percent, can be eliminated by operating the sample at a given magnetization for about half an hour before the impedance measurement is made.

Figures 2 and 3 show the complex permeability, \( \mu \), and its components \( \mu_r \) and \( \mu_i \) of 0.35 mm thick silicon steel (96\% Fe, 4\% Si) measured at 50 Hz without dc magnetization.\(^3\) These values were calculated with Eq. (3) from impedance measurements with an inductance bridge on a coil containing core laminations. A sinusoidal excitation current was forced by connecting a relatively large resistor in series with the bridge and by making the coil impedance and the impedance of the comparison arm of the bridge small as compared to the other two bridge arms.

The reason that, in the above figures, the maximum permeability is only \( \mu = 3200 \mu_0 \) as compared to the usually quoted values of \( \mu = 7000 \mu_0 \) for 4\% silicon steel is the sinusoidal excitation. When the sinusoidal excitation drives the core into saturation, the corresponding flux contains large harmonics; the amplitude of the fundamental frequency of the flux is considerably smaller than its peak value. The curves in Figs. 2 and 3 illustrate the effect of hysteresis because at 50 Hz eddy current effects are small. At higher frequencies both hysteresis and eddy currents affect the complex permeability. In eddy current problems, it is convenient to make use of the equivalent skin depth, \( \delta \), where the field...
strength has a value \( e^{-1} = 0.37 \) of the field on the surface of the lamination.

\[
\delta = \left( \frac{\rho}{\pi \mu f} \right)^{1/2}
\]  

(4)

where

\[ \rho = \text{resistivity}. \]

\[ \mu = \mu_0 \mu_r \]

\[ \mu_0 = \text{permeability of free space} \]

\[ \mu_r = \text{relative permeability} \]

It is common to distinguish between low frequencies where the field distribution in the laminations is approximately uniform and the lamination thickness \( d < 2\delta \), and high frequencies where skin effects are pronounced, \( d > 2\delta \). The boundary between these two frequency ranges has been defined so that

\[ d = 2\delta \]  

(5)

The cut-off frequency defined by (5) is

\[
f_c = \frac{4\rho}{\pi \mu d^2}
\]  

(6)

For 0.35 mm thick, 4% silicon steel with an initial permeability of 330 \( \mu \), and a peak permeability of 3200 \( \mu \), the cut off frequency is 13 kHz and 1.73 kHz respectively; well above 50 Hz.

The effects of hysteresis and eddy currents on 4% silicon steel are shown in Fig. 4 for sinusoidal excitation. For \( f \ll f_c \), only hysteresis effects are present; the 50 Hz curve shows a change in permeability from \( |\mu| = 330 \mu \) for \( H_{ac} = 0 \) to \( |\mu| = 1150 \) for \( H_{ac} = 100 \text{ mA/cm} \). For \( f \gg f_c \) and \( H_{ac} = 0 \) only eddy current effects are present as shown on the lower curve for the range from 50 Hz to 9 kHz with a corresponding change in \( |\mu| \) from \( \sim 330 \) to \( \sim 265 \). All other curves show the combined effect of hysteresis and eddy currents.

Figure 5 shows how a dc magnetization of 1 A/cm reduces the permeability values of Fig. 4.

**Equivalent Magnet Circuit**

In order to calculate the eddy current and hysteresis losses of an ac magnet from measured values of the complex permeability of the core material, we need an equivalent magnetic circuit. With reference to the magnet cross-section shown in Fig. 6, the ac excitation current \( i \), the ac field strength \( H \), various lengths of the flux path \( l \), the number of turns of the magnet coil \( n \) and the ac magnet flux \( \phi \) are related by:
\[ \int H_\ell \, dl = i \, n = H_{g g} + H_{1 l} + \ldots + H_{N N} \]  
\[ H = \frac{B}{\mu} = \frac{\phi}{\mu A} \]  
(7) into (8) gives

\[ i \, n = \phi \left( \frac{l_g}{\mu A g} + \frac{l_1}{\mu A_1} + \ldots + \frac{l_N}{\mu A_N} \right) \]  
multiplying both sides by \( \frac{1}{j \omega n^2} \) and rearranging results in

\[ \frac{i}{j \omega n \phi} = \frac{l_g}{j \omega n^2 \mu A g} + \frac{l_1}{j \omega n^2 \mu A_1} + \ldots + \frac{l_N}{j \omega n^2 \mu A_N} \]  
with \( Z = \frac{j \omega n^2 \mu A}{\phi} \), equation (10) can be written

\[ \frac{i}{j \omega n \phi} = \frac{1}{Z} = \frac{1}{Z_g} + \frac{1}{Z_1} + \ldots + \frac{1}{Z_N} \]  

Equation (11) illustrates that the total magnet impedance \( Z \), neglecting the ohmic resistance and the capacitance of the coil, can be thought of as being the parallel connection of \( N \) impedances, each having \( n \) turns and the electromagnetic properties of its path length. Such an equivalent circuit allows one to compute separately the impedance of the various magnet sections as a function of frequency. The total magnet response being the parallel connection of the various sections. The complex permeability \( \mu \) of each section is measured on the one core sample by magnetizing it with the ac and dc fields corresponding to this section. The equivalent circuit for the magnet of Fig. 6, neglecting coil resistance and capacitance, is shown in Fig. 7.

**EQUIVALENT CAPACITANCE OF MAGNET COIL**

The magnet coil turns have turn-to-turn and turn-to-ground capacitances. An equivalent capacitance, connected across the coil terminals can be found by transforming the individual capacitors to the coil terminals and adding them up. For example, Fig. 8 shows the coil conductor arrangement of the magnet coils of the former 12 GeV Zero Gradient Synchrotron (ZGS). From the geometry of the coil and the electrical properties of the insulation an equivalent circuit of the coil turns and associated capacitances can be drawn as shown in Fig. 9. For this circuit, the terminal capacitance was computed as 0.075 \( \mu F \).

**FREQUENCY RESPONSE OF MAGNET**

The equivalent magnet circuits of Fig. 10 are obtained by connecting in parallel with the terminal capacitance, \( C \), the \( R_e \) and \( L \) values calculated from the equivalent magnet circuit of Fig. 7 and adding the coil
resistance $R_{Cu}$. Figure 11 illustrates the $R_{Pe}$ and $L$ values calculated for
an octant of the ZGS. Figure 12 shows the frequency response of the octant
during injection and with a dc magnetization of 21.5 kG. After the ZGS was
built, the actual measured frequency response of an octant agreed very well
with the calculated values.

For the ZGS, response to power supply ripple was of interest. For the
50 Hz synchrotron of the KAON-factory, the response to much larger fields
must be known. The field values should start from rated values at 33 and
100 Hz and decrease to a few gauss at $< 10$ kHz. A family of curves with
different rates of field decay with frequency may be desirable.

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$A = a \times b \times$ stacking factor

Fig. 1: Toroidal Test Core
Cross-Section

Fig. 2: Complex Permeability $\bar{\mu}$ of
Silicon Steel at 50 Hz

Fig. 3: Components of $\bar{\mu}$ for 4%
Silicon Steel at 50 Hz
Fig. 4: Complex Permeability of 4% Silicon Steel without dc Magnetization

Fig. 5: Permeability of 4% Silicon Steel with 1 A/cm dc Magnetization

Fig. 6: Illustration of Flux Path and Excitation in a Magnet

Fig. 7: Equivalent Circuit of Magnet of Fig. 6
Fig. 8: Coil Conductor Arrangement of ZGS Magnet Coil

Fig. 9: Capacitance Network of ZGS Magnet Coil

Fig. 10: Equivalent Circuits of Magnet
Fig. 11: ZGS Ring Magnet Inductance and Resistance as Function of Frequency for 1 Gauss ac-Magnetization with and without dc-Magnetizations

Fig. 12: Impedance of ZGS Ring Magnet as Function of Frequency for 1 Gauss ac-Magnetization with and without dc-Magnetizations
Several kicker magnet systems are required for the KAON Factory. The most critical requirements with respect to rise time and kick strength are for the kickers for ejection of the Booster ring and the Driver ring. The performance requirements are listed in Table 1. In the following we look at a possible prototype magnet for either case.

### Magnet Design - Driver Extraction

#### Driver Extraction Kicker

For protons the magnetic deflection is:

\[ \alpha = 0.3 \frac{\int B d\ell}{p} \]

where \( \alpha \) is the deflection angle in mrad, \( \int B d\ell \) the kick strength in T·m, \( p \) is the momentum in GeV/c. For 30 GeV protons \( p = 30.9 \text{ GeV/c} \) and for \( \alpha = 1 \text{ mrad} \) we get

\[ \int B d\ell = 0.103 \text{ Tm} \]

which is the required kick strength for the ejection kicker.

### Table 1

Performance requirements

<table>
<thead>
<tr>
<th></th>
<th>Booster ejection</th>
<th>Driver ejection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum (GeV/c)</td>
<td>3.82</td>
<td>30.9</td>
</tr>
<tr>
<td>Deflection angle (mrad)</td>
<td>2.5</td>
<td>1</td>
</tr>
<tr>
<td>Kick strength (Tm)</td>
<td>0.032</td>
<td>0.103</td>
</tr>
<tr>
<td>Kick flat top duration (( \mu \text{s} ))</td>
<td>0.66</td>
<td>3.5</td>
</tr>
<tr>
<td>Kick rise time (1 to 99%) (ms)</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Kick fall time (99 to 1%) (ms)</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>Aperture (width ( \times ) height) (cm)</td>
<td>15 ( \times ) 8</td>
<td>15 ( \times ) 7</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>Gas pressure in vacuum tank (Torr)</td>
<td>( 5 \cdot 10^{-9} )</td>
<td>( 5 \cdot 10^{-9} )</td>
</tr>
</tbody>
</table>

#### Rise Time

The kick rise time depends on the current rise of the pulse generator and the travelling time of the current wave in the delay line-type magnet. We have
where $\tau_r$ is the kick rise time, i.e. the rise time of $\int B \cdot d\ell$,
$\tau_g$ is the current rise time of the pulse generator, and
$\tau_M$ is the travelling time of the magnet.

To get the specified value
$\tau_r = 30$ ns
and assuming
$\tau_g = \tau_M$,
we get
$\tau_M = 56$ ns

**Number of Magnet Module N**

High kick strength and short rise time are conflicting requirements. Therefore the magnet has to be split in $N$ modules such that the total magnetic length $l$ of the magnet is

$$l = N \cdot l_M \quad (1)$$

where $l_M$ is the magnetic length of a magnet module, and

$L = N \cdot L_M$

where $L$ is the total magnet inductance and $L_M$ is the inductance of a magnet module.

From (1) we get

$$\int B \cdot d\ell = N \cdot B \cdot l_M \quad (2)$$

Assuming a single turn excitation coil and a high relative permeability of the yoke ferrite, the flux density $B$ in the gap is:

$$B = \frac{1}{w \cdot l_M} \cdot L_M \cdot I \quad (3)$$

where $w$ is the horizontal aperture and $I$ is the magnet current on the kick flat top. We assume a horizontal beam deflection.

The magnet current $I$ is given by the generator voltage $V_g$ and the characteristic impedance of the magnet module $Z_M$. We get

$$I = \frac{1}{Z} \cdot \frac{V_g}{Z_M}$$
since the wave travelling along the magnet module has half the voltage of the generator voltage. With

\[ Z_M = \sqrt{\frac{L_M}{C_M}} \]

where \( C_M \) is the matching capacitance of the magnet module, and

\[ \tau_M = \sqrt{L_M C_M} \]

using (2) and (3) we get:

\[ \int_B d\ell = N \cdot \frac{1}{\ell_M} \cdot \tau_M \cdot \frac{V}{Z} \]

For a maximum generator voltage of 60 kV (see below) and \( \ell = 0.15 \text{ m} \) we find the number of modules must be:

\[ N > 9.2 \]

which means:

\[ N = 10 \]

**Maximum Generator Voltage**

To limit the maximum generator voltage to 60 kV has the advantage that standard coaxial cable RG 220/U can be used as a transmission cable between the pulse generator and the magnet module. This cable has a characteristic impedance of 50 Ω. Several cables can be connected in parallel which gives impedances of

\[ Z_M = 50 \text{ Ω/m} \]  

with \( m = 1, 2, \ldots \)

**Magnetic Length of a Module**

From (2) we get

\[ \ell_M = \frac{\int_B \ell d\ell}{N \cdot B} \]

With (3) and the module inductance

\[ L_M = \mu_0 \cdot \frac{w \cdot \ell_M}{h} \]

where \( h \) is the gap height, we get

\[ L_M = \mu_0 \cdot \frac{1}{\ell_M} \cdot h \cdot \frac{2}{V_B} \cdot Z_M \]

We choose a high magnet impedance:

\[ Z_M = 25 \text{ Ω} \]

i.e. 2 coaxial cables of 50 Ω in parallel. A higher impedance would result in an unnecessarily long magnet.
The operating generator voltage is

\[ V_g = \frac{22}{10} \cdot 60 \text{ kV} = 55.2 \text{ kV} \]

which gives a magnet current

\[ I = \frac{55.2 \text{ kV}}{2 \times 25 \mu \text{H}} = 1.1 \text{ kA} \]

and a flux density in the gap of

\[ B = 19.7 \text{ mT} \]

for a gap height \( h = 0.07 \text{ m} \).

The (magnetic) length of the magnet module is then

\[ \ell_M = 0.52 \text{ m} \]

**Module Design**

The module inductance is:

\[ L_M = \mu_0 \cdot \frac{w \ell_M}{h} = 1.4 \mu \text{H} \]

Thus the total matching capacitance is

\[ C_M = \frac{L_M}{Z_M} = 2.24 \text{ nF} \]

The magnet module as well as the pulse forming network (PFN) is split in several cells. The optimum number of cells can be determined by computer simulation.

Choosing 20 cells with a magnet module we get a ferrite thickness of 26 mm. The capacitance per cell is thus 112.5 pF. They could be built by ground plates interleaved with the high voltage plates at a distance of 6 mm. The effective area of the plates is 19.5 cm².

A Ni-Zn ferrite (like the Philips type 8C11) having a high saturation induction (<0.3 T) and a low coercitive force should be used. The flux density in the yoke should be calculated by a magnet program (like POISSON).

The main parameters are summarized in Table 2.
Table 2
Main parameters

<table>
<thead>
<tr>
<th></th>
<th>Booster ejection</th>
<th>Driver ejection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum generator voltage (kV)</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Characteristic impedance</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Maximum magnet current (kA)</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Number of magnet modules</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Number of vacuum tanks</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Magnetic length of magnet module (m)</td>
<td>0.59</td>
<td>0.52</td>
</tr>
<tr>
<td>Module inductance (μH)</td>
<td>1.40</td>
<td>1.4</td>
</tr>
<tr>
<td>Module filling time (ns)</td>
<td>56</td>
<td>56</td>
</tr>
</tbody>
</table>

**Booster Extraction Kicker**

The main parameters have been determined also for a maximum generator voltage of 60 kV and for a module travelling time of 56 ns. The results are summarized in Table 2.

**Conclusion**

A possible design for a prototype kicker magnet module for the Booster and Driver ejection has been studied. It is well within the limits of today's technology. Further investigation of the electrical circuit in conjunction with a pulse generator is necessary along with a more detailed study of the mechanical engineering.
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