TRIUMF

CONCEPTUAL DESIGN STUDY FOR THE TRIUMF CONTROL AND SAFETY SYSTEM

TRIUMF Controls Group

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Dilworth, Secord, Meagher and Associates Limited

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SUMMARY

A general philosophy for the control of the TRIUMF facility has been presented.

The hard-wired personnel safety system is based on a system of controlled access areas. Radiation levels throughout the facility are routed through area safety units to central control. Violation of a personnel interlock results in interruption of the beam delivery to the entire facility. A change in radiation levels beyond prescribed limits will also interrupt beam delivery. The machine safety system is based on beam characteristics. Both relative and absolute beam intensity limits are proposed. A beam shut-off time of about 300 μsec is adequate for machine protection, while personnel protection requires the shortest possible beam shut-off time.

A computer-based scanning and digitizing system permitting fast and flexible data processing is proposed for the ion source and injection system. The radio frequency will be a fixed reference to which the main magnet field is controlled. The main magnet is regulated by a current shunt and/or an NMR probe. Trim and harmonic coils are current regulated. A scanning system monitors temperatures by measuring the coil voltages and currents and calculating the coil resistance. Beam diagnostics probes will be mounted at 90 deg intervals. Two probes will measure beam current and two will be shadow probes. High energy beam transport optics will be set using one-word memories at power supplies. A slow scanning system will be used to log optics parameters. Diagnostic devices which are proposed include position, profile, and intensity monitors.

Computer control which is redundant in CPU and I/O capability has been proposed. Operator communication with devices will proceed through the central computer using CRT-keyboard-shaft-encoder stations. An integrated TV display system using standard TV monitors is proposed. TV camera output, computer graphics and analog signals from diagnostic devices will be handled by the same system.

Few if any control loops will be closed at commissioning. Data logging will be performed by a digital data acquisition system. Set points will be controlled by an operator using a digital link. As machine development progresses control loops will be closed.

CONTENTS

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1. INTRODUCTION

This report outlines an approach for centralized control of TRIUMF. There are many control schemes that can be used at TRIUMF. Though capital cost is an important aspect in assessing the control schemes, there are other important considerations.

The first consideration is reliability. If the control system were disabled regularly, the scientific output of the facility would be impeded. Hence, the control system reliability must be sufficient to gain maximum scientific return for the total investment over the life of the accelerator. Component failure rates affect the down-time of the accelerator, e.g. flow switches are notorious for their lack of fail-safe operation. Thus, a judicious choice of components and duplication, and even triplication, of some of the more important sensors will be required. In addition, the control system (in the words of the computer technology) is basically a man-machine interface and as such must be spatially oriented in such a way as to minimize human error. Precise human engineering will enhance the reliability of the accelerator.

The second aspect to be considered as a guideline is the flexibility of the control system. TRIUMF is a project engaged in original scientific research so by its very nature is a dynamic structure. The development and commissioning of the accelerator will involve adjusting to changing knowledge of the accelerator. In order to satisfy the demands of the experimental groups, continual updating of the facility will be required. The control system must not be the limiting factor.

The third factor is one of development time. The control system must be developed on a time scale which is commensurate with the development of the accelerator. Sophistication cannot be allowed if it interferes with the completion of any design or commissioning date for the facility. The control system must therefore represent a compromise between flexibility, sophistication and development time.

Bearing these guidelines in mind, a survey of the kinds of equipment that must be controlled at TRIUMF was performed. The data are not complete but have been updated when design group experience has added pertinent factors. For the purpose of this survey the facility was divided into a number of sections, each associated with a specific accelerator function. The groups are:

1. Ion source and inflection system
2. Cyclotron magnets and RF system
3. Beam probes, strippers, and diagnostics
4. High energy beam transport and diagnostics
5. Safety and communication systems
6. Ancillary services
    a) Tank vacuum
    b) Transport vacuum
    c) Power fan-outs
    d) Cooling systems

The survey gave an overall picture of equipment needs for each accelerator function and thus provided an indication of the extent to which similarities in instrumentation and techniques exist. Using this overview, control schemes consistent with an overall TRIUMF control scheme were developed on a group-by-group basis. The detail of control schemes has been limited, since this is a conceptual study. When a scheme seriously violated the guidelines, the detailing was stopped.

The conceptual design problem, as in the controls survey, was broken down according to the accelerator function. Each accelerator function was treated as an entity. It very quickly became apparent that these units could be best unified through a central control incorporating computer techniques, so greatest effort was directed along that line of approach. The philosophy recommended involves, in most cases, using the computer to act as an interested referee, informing operator and sub-unit of infractions or defining for a sub-unit its operational boundaries rather than to close control loops.

2. SAFETY SYSTEMS

The accelerator system consists of a vast array of sub-systems, all of which must be operating in order for the facility to produce accelerated ions. The sub-systems range from single devices (e.g. the RF power supply) to ubiquitous cooling water circuits. A failure in any one of these sub-systems will ultimately produce a beam excursion which if not terminated would produce high radiation levels and high residual activities in the facility, in addition to the possibility of damaging machine components.

A protection system is therefore necessary to guard both personnel and machine. It must be reliable, fail-safe and simple. An unnecessarily complex fail-safe system would tend to shut down the facility, due to protection system failure rather than accelerator failure, and consequently would encourage unauthorized "jumpering" of the system. The protection system must be as independent of the mode of operation as possible. In other words, the protection system must be operating both during and after commissioning, independent of any changes made in the operation of the machine.

As a general philosophy, the machine protection system will be based on beam characteristics. The personnel protection system will be based on a system of controlled access areas whose radiation levels are constantly monitored. The remainder of this section is a presentation of both personnel and machine safety details. Both systems employ hard-wired logic to give a short response time. An action taken via the hard-wired logic is annunicated through the central control display system.

2.1 Personnel Safety

2.1.1 General

The personnel safety system is designed to control the movement of staff between accessible, controlled access and inaccessible areas, and to monitor for radiation hazards. Within the facility radiation hazards consist of direct radiation, radioactive contamination, and the ingestion hazard of airborne activity. Effluents from the facility must be monitored to ensure that no radiation hazard is created beyond the controls exercised on the accelerator site.

These considerations lead to the provision of the following instrumented systems:

1) Access control
2) Direct radiation hazard control
3) Contamination control
4) Airborne hazard control
5) Site effluent hazard control

The facility is divided into defined areas for purposes of radiation hazard control, depending on whether the area is accessible, controlled access, or inaccessible. Inaccessible areas are those accessible only during shutdown and include:

1) Cyclotron vault
* 2) Beam line 1
* 3) Beam line 4
4) East, west and south service tunnels
5) Heat exchanger and storage area

The controlled access areas include:

1) The experimental areas associated with beam line 1
2) Thermal neutron experimental area
3) Proton experimental area

The accessible areas are then all other areas, except that some areas could have occasional or local hazards which will be controlled by roping or fencing off areas, such as in the main hall, the mechanical services area, the RF and ion source rooms, the chemistry laboratory, and the maintenance shop. The latter two areas require a form of contamination control.

Radiation instrumentation which indicates a potentially rapid change in radiation exposure conditions in the facility arising from misoperation or malfunction of the accelerator must actuate the machine shutdown system. Such signals include unauthorized access

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* Beam line 1 should be accessible when only beam line 4 is running and vice versa.

to any area, high direct radiation levels, and high airborne activity. In addition, personnel safety requires machine shutdown for beam misalignment.

Since equipment other than radiation monitors can more accurately sense beam misalignment, the radiation monitors are considered as a back-up to the primary beam misalignment detection systems along the beam line.

In certain areas, principally the experimental areas, some trip signals may occur during specific operations in an experimental area even though continued cyclotron operation is desired together with beams to other areas. It will be necessary in such cases to bypass or condition these trip signals. The designed-in bypass or conditioning circuit will have the same reliability as the normal trip circuit; otherwise a failure of the conditioning circuit could bypass the shutdown system during normal operating conditions. The conditioning circuit therefore is made up in all cases of two independent signals; generally a target or stripper position signal to confirm that this device is out of the beam line, backed up by an appropriate signal from a beam line current sensor to confirm that a beam is not being directed to the area in question.

Although some of the trip signals from an area can be conditional, as described above, there is one principal exception. High radiation level in an area and high airborne activity will be absolute trips, i.e., they cannot be conditioned out. A high radiation field could be the result of many causes, including cyclotron beam misalignment. High radiation level must always shut down the complete facility.

2.1.2 Access Control

The access control system is the primary system for allowing areas to be entered only under specific conditions. The system must therefore be the most reliable of all personnel safety controls. This reliability can be achieved either by the use of a suitable interlock method, by duplication or triplication of function, or by backing up one interlock method with another. It is proposed that the system be a very reliable interlock with back-ups. For inaccessible areas, opening the associated door should cause machine shutdown. For controlled access areas, opening the associated door should normally be allowed only after the operator terminates beam delivery to that area. As a back-up, improper opening of such a door should automatically terminate the beam. Subsequent closing of the door should not restart the beam. Beam restarting should be carried out in the control room.

A key interlock system, conforming to the principle of control only from the control room, is proposed. All access control points to inaccessible and controlled access areas are locked by key. The door lock is such that the key cannot be removed unless the door or gate is in the closed and locked position. After locking, the keys are inserted into an appropriate interlock panel. All door keys are required to be inserted in the interlock in order to allow removal of the master key in the control room master panel. The latter must be used to activate the cyclotron start-up panel.

The position of all doors is indicated in the control room by door microswitches. As a back-up to the key interlock system, the status of the door microswitches will be interrogated in the run-up sequence.

The controlled access areas need further provisions. Access must be allowed into these areas with the machine operating as long as beam delivery to the area is terminated by the operator, or in special cases while there is beam delivery but the general room radiation levels are below tolerance levels. An area access key will be defined which unlocks one access door to each experimental area. This key will not be used in the key system which controls the availability of the cyclotron master key. This area access key will be used to activate the following area control panels:

AREA		AREA
1a access key	-	1a target position
2a access key	-	2a target position
3a access key	-	3a target position
P area access key	-	P beam stripper controls
Neutron area access key	-	cyclotron control circuit

In each case, the key is required to adjust the associated controls. Removal of the key (for access to the area) will cause cyclotron shutdown, except for one condition. If the radiation monitors in the area show a below-tolerance radiation field, the key may be withdrawn without beam shutdown. This system will be a back-up to low level delivery interlocks in the accelerator control.

The operating procedure would be for an experimenter who wishes access to an experiment during beam delivery to request the operator to reduce the beam current to the area until the radiation monitor reads below 2.5 mR/h. The key may then be withdrawn and an operator and experimenter go to the access door. The door is interlocked by its door position microswitch so that if the key is turned to the normally-open position and the door is opened, the beam to the area is tripped. However, if the operator holds the key in a third position, against spring tension returning it to the normally-open position, the door can be opened, with continued beam delivery. This ensures that the operator remains at the door guarding against inadvertent access, while the experimenter makes his adjustment or reading.

If the key is not held in the third position, the cyclotron will be shut down. In addition, the beam start permissive (logic) circuit for that area will now need to be reset. This will also be the case after access into an experimental area with beam delivery shutdown, as would occur following the setup of the experiment. It is now necessary for the operator to reset the beam delivery permissive by going to a series of watchman stations in the room, as presented in Figures 2, 3 & 4 (pp.16-18). At each station which contains a beam interrupt switch, he must switch to "reset", then to "on". He is expected to view the surrounding area at this time to ensure that no experimenter is left in the room. When the first station is reset, a timer begins, and all stations must be reset and the access door closed before the timer times out. If this is done, the beam start permissive has been made operational, and the beam can be directed into the area by action from the control room.

In the case of access to an experimental area while there is no beam delivery to that area, the access door can be opened by the normal use of the access key. The cyclotron trip described above will be prevented in such cases by appropriate signals indicating target (or stripper) out and no beam. Opening the door, however, requires the beam start permissive circuit to be reset before beam delivery can be reinitiated.

Additional equipment will be required in each controlled access area. There will, for example, be manual beam interrupt switches which, when activated to the off position, prevent restart of beam without control room action. A number of other devices will be centralized at the local safety units. These units will contain a telephone set and a patch panel for telephone and TV outlets, as shown in Figure 1. The unit will also contain a large BEAM ON indicator and a klaxon. This klaxon will be actuated at a preset time (1 minute) before the beam is to be initiated into the area. Radiation area monitors will be required in these areas for reasons other than access control, and will act as a back-up to the access control system. The safety unit in the area will display the readouts of these fixed monitors and their alarms. A readout and alarm display on the safety unit will be provided for portable monitors which may be employed in the area occasionally. In addition to the above displays within the room, a display will be provided just outside the access door (outer safety unit) containing a large BEAM ON indicator and a readout of the fixed radiation monitor in the area. The unit may also contain a portable radiation monitor for use on access. A provision will also be made so that alarm signals pertaining to hazardous equipment of the experimentalists may be routed to central control via the area safety unit. The area safety unit will have a self-contained standby battery power supply to power it (but not a TV system), a fire alarm, and a personnel safety system. The unit also acts as a junction box

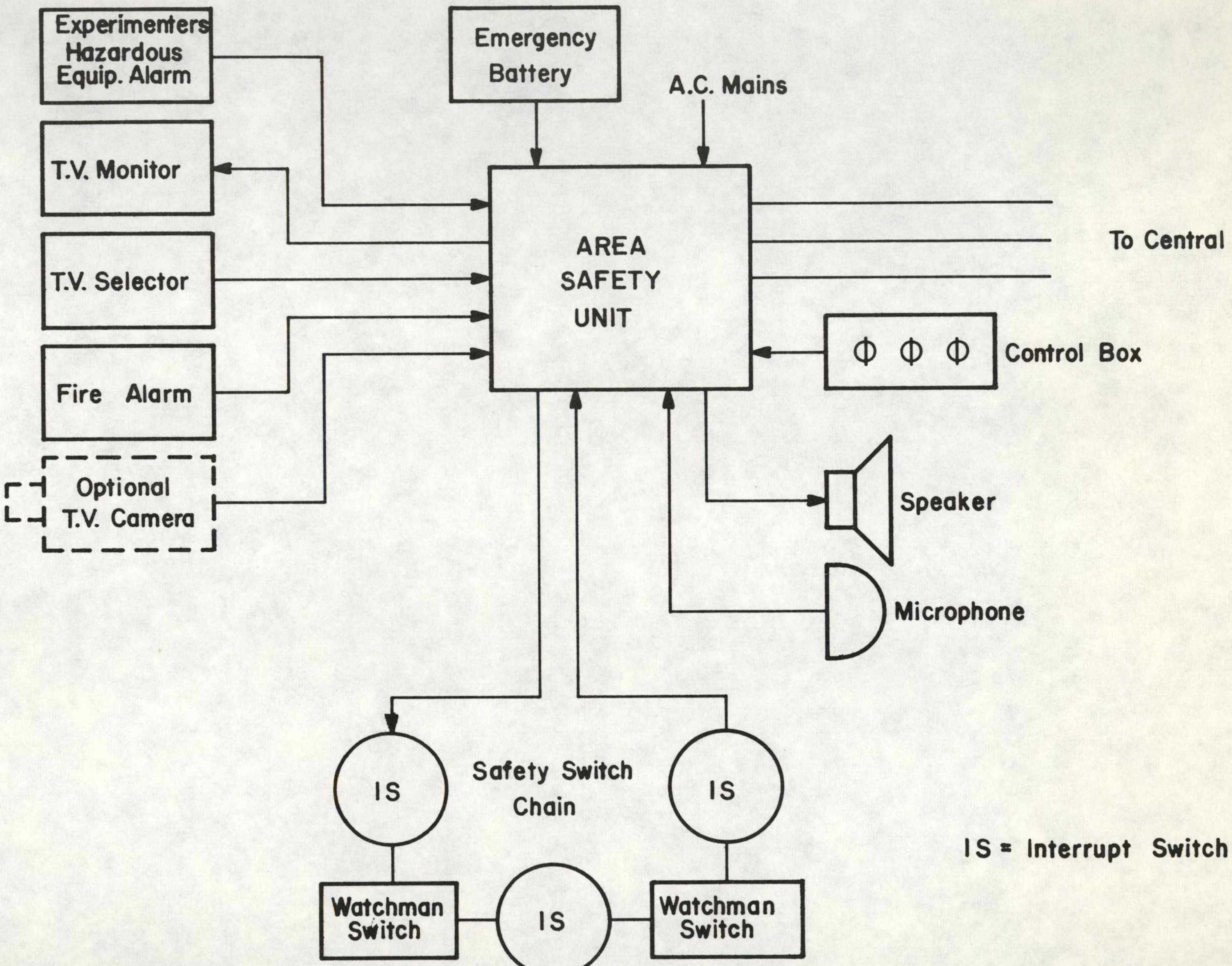


Fig. 1. AREA SAFETY UNIT. This panel provides interfacing to central control, emergency power, and a convenient termination for all communications and safety equipment in each area.

for connecting remote device cables to central control. (Items such as intercoms have all their active electronics located at central control.)

A special condition of access control would arise if the concrete beams or hatches were removed from above the cyclotron or experimental areas. If this is an abnormal condition, it is proposed that the operator's responsibility will include ensuring that these are in place before startup. If it is necessary to have a beam removed over the experimental area in order to locate instrumentation in the hall, it will be necessary to use special procedures. The beam removal infers local shielding of the experiment, so high fields near the opening at the main hall floor level would not be expected. The area having fields in excess of 2.5 mR/h could be closed off by barricades, with the operating field posted. It is proposed that complex access control would not be required, but that a personnel safety unit should be located at the opening, containing a BEAM ON indicator, beam start-up warning klaxon (muted during operation), and the output from a radiation monitor.

2.1.3 Direct Radiation Hazard Control

Fixed area monitors are required to indicate the occurrence of a direct radiation hazard in an area which could be occupied by personnel. The indirect hazard of ingestion of activity is demonstrated to some extent by area monitors but more specifically by airborne activity monitors. The location for area monitors must be evaluated, considering accessible, inaccessible and controlled access areas for normal, shutdown, and accident conditions.

2.1.3.1 Normal Operating Conditions

Accessible Areas:

Under these conditions, any area of radiation hazard would be roped off and posted. Any transport of radioactive material through these areas would be carried out in safe containers. No monitor is required.

Inaccessible Areas:

These areas are inaccessible during operation, so no direct monitor is required. Monitors in these areas might, however, indicate the degree of radiation which is creating activation products and therefore be of use in determining the difficulty of entry on shutdown. There are other measurements indicating the same information, and surveys can be made during shutdowns, so no monitoring equipment is required.

Controlled Access Areas:

These are areas of potential hazard where occupation is possible. All hazardous situations, however, cannot be covered by fixed monitors, even in large number. Portable monitors must be used. The actual number or requirement for fixed monitors is set by accident conditions. Monitors installed for this reason will serve as a back-up to the access control system, warning personnel not to enter an experimental area if a high field exists.

2.1.3.2 Shutdown Conditions

Accessible Areas:

No requirement.

Inaccessible Areas:

The hazard arises from induced activity and airborne activity. This will vary with the type of beam operation before shutdown and can be safely determined only by a survey with a portable monitor. Since the decay of activity with time is an important consideration in determining how long to wait before entering an inaccessible area, however, it is advisable to have one fixed area monitor in each area, located near the access door, with remote reading outside the door.

Controlled Access Areas:

See remarks under Normal Operating Conditions.

2.1.3.3 <u>Accident Conditions</u>

<u>Accessible Areas</u>:

Monitors are required in these areas primarily to indicate the presence of unauthorized radioactive materials which are allowed to enter such areas either by personnel error or machine accident. Excitation of such a monitor would cause local alarm signals and simultaneous annunciation in the control room.

The following areas require the presence of such monitors:

1) mechanical services area
2) maintenance shop
3) chemistry lab
4) main hall (two monitors)
5) ion source room
6) RF room
7) control room

<u>Inaccessible Areas</u>:

Monitors should be located close to access doors in order to provide access control in the following areas:

1) cyclotron vault at door
2) beam tunnel at hatch
3) P area at hatch
4) west service tunnel
5) east service tunnel

<u>Controlled Access Areas</u>:

Monitors are required during machine operation, when personnel are in these areas, to alarm on cyclotron or beam misalignment and trip the cyclotron. The monitors installed for this purpose can also be considered as a back-up to the access control system to indicate beam status.

For the accident conditions, the large experimental areas require a distribution of monitors:

1) area 1a - 2 monitor locations, one near access door
2) area 1b - 2 monitor locations, one near access door
3) area 1c - 2 monitor locations, one near access door

4) Thermal neutron area - 2 monitor locations, one near access door
5) Experimental P area - 3 monitors, one near each of 2 access doors

All fixed area radiation monitors will be provided with two alarm levels, annunciated on the device by an audible alarm and flashing lights. The alarm level and flash rate will increase on the high alarm setting. The alarm annunciation is transmitted to the room safety unit and thence to the control room.

In general, the low alarm level will be actuated when radiation is above background. The high alarm level will be set to an appropriate value, typically 10 times background. The actual levels will be defined during detailed design. The low alarm level will also be used as a permissive to allow entry to the associated experimental area under controlled conditions. A high alarm level in controlled access and inaccessible areas will, if the access door is opened, cause cyclotron shutdown. The equipment is listed on function list 3, Fixed Area Monitors, TRI-I-69-4, Section 4.

2.1.4 Contamination Control

Areas in which there is potential radioactive contamination will be zoned so that the contamination is not inadvertently spread throughout the building. Particulate (solid) activity should originate only in the chemistry laboratories, although it could possibly be present in the maintenance area if work were being done on an active component. Transport of active material between areas or to disposal should be done in a containing package. The chemistry laboratory will therefore have permanent contamination and a hand and foot monitor installation. The maintenance shop could employ ad hoc arrangements for contamination control (roped area and rubber station) when the need arises. A hand and foot monitor station will be located in the corridor outside this area. These two hand and foot monitors will be available for monitoring when personnel leave experimental areas.

2.1.5 Airborne Hazard Control

Airborne activity hazard will be minimized by designing the ventilation system so that active areas operate at a room pressure lower than that of inactive areas. Active areas will include the chemistry laboratories, maintenance area, experimental areas, and cyclotron vault. With this system, the air from active areas passes directly to the exhaust plenum. It is proposed that gaseous and particulate airborne activity monitors in this plenum will provide a sufficient continuous monitoring function. The monitors would be located ahead of the absolute filters and have two levels of alarm: the low level will alarm in the control room, and the high level will shut down the cyclotron.

In addition, the high level alarm will shut down the ventilation system and close the dampers in the ventilation exhaust. The high level alarm will initiate on accident conditions and probably would require some evacuation of the building. After an assessment of stack atmospheric dispersion conditions, the ventilation system would be restarted to purge the facility of active gases. A survey of activity dispersion around the site would probably have to be carried out coincidentally. In addition, a portable airborne activity monitor will be available to use in areas where high airborne activity is suspected.

2.1.6 Site Effluent Hazard Control

2.1.6.1 Gaseous

See the previous section.

2.1.6.2 Liquid

Liquid wastes that could become active will be treated as a separate waste system and taken to a holding tank. These wastes would include those from the chemistry laboratories. If target cooling circuits become highly active, and the secondary side cooling water becomes active through heat exchanger leakage, this water flow would also be taken to the decay tank. This low flow system should be monitored before entry to the decay tank. The effluent from the tank should also be monitored. The effluent is then mixed with the general site effluent before discharge off the site. In this way, a continuous measurement of liquid effluent activity can be made, with an alarm point at an easily measurable value, but well below the drinking water tolerance level for mixed general site effluent. The site effluent will be monitored by hand samples periodically.

2.1.6.3 Particulate

The monitoring for movement of particulate activity outside the site will consist of a personnel monitor at the main personnel gate and portable monitors at truck access gates.

2.1.7 Testing

The complete personnel safety control system will be tested at regular intervals. The shutdown system can be checked by actuating a trip and checking for proper operation of the shutdown device. The key interlock system can be tested by checking whether key removal in the control prevents cyclotron or experimental beam operation; the door microswitch system can be checked by opening controlled access doors. The fixed area monitors will be fitted with a test source to allow a check on the low and high alarm positions, and the safety unit should show the correct display during these tests. The hand and foot monitors can be checked by the use of a source. The airborne activity monitors, the liquid effluent monitors, and the personnel monitor will have source check facilities.

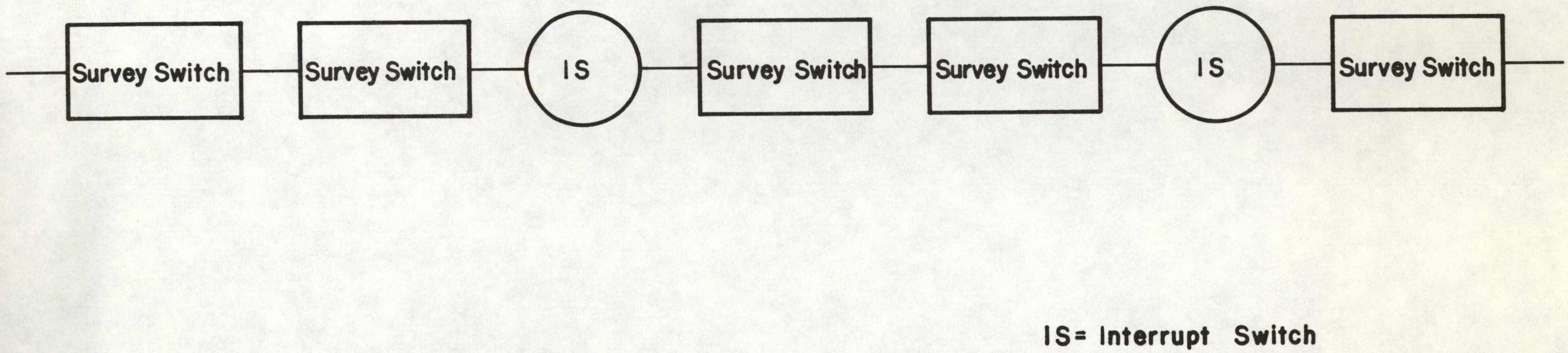


Fig. 2. PERSONNEL SAFETY SWITCH CHAIN. To obtain beam delivery to a controlled area this chain must first be operated, in order from the left. Operating any interrupt at any time halts beam operation, and survey switches to the right must be reset.

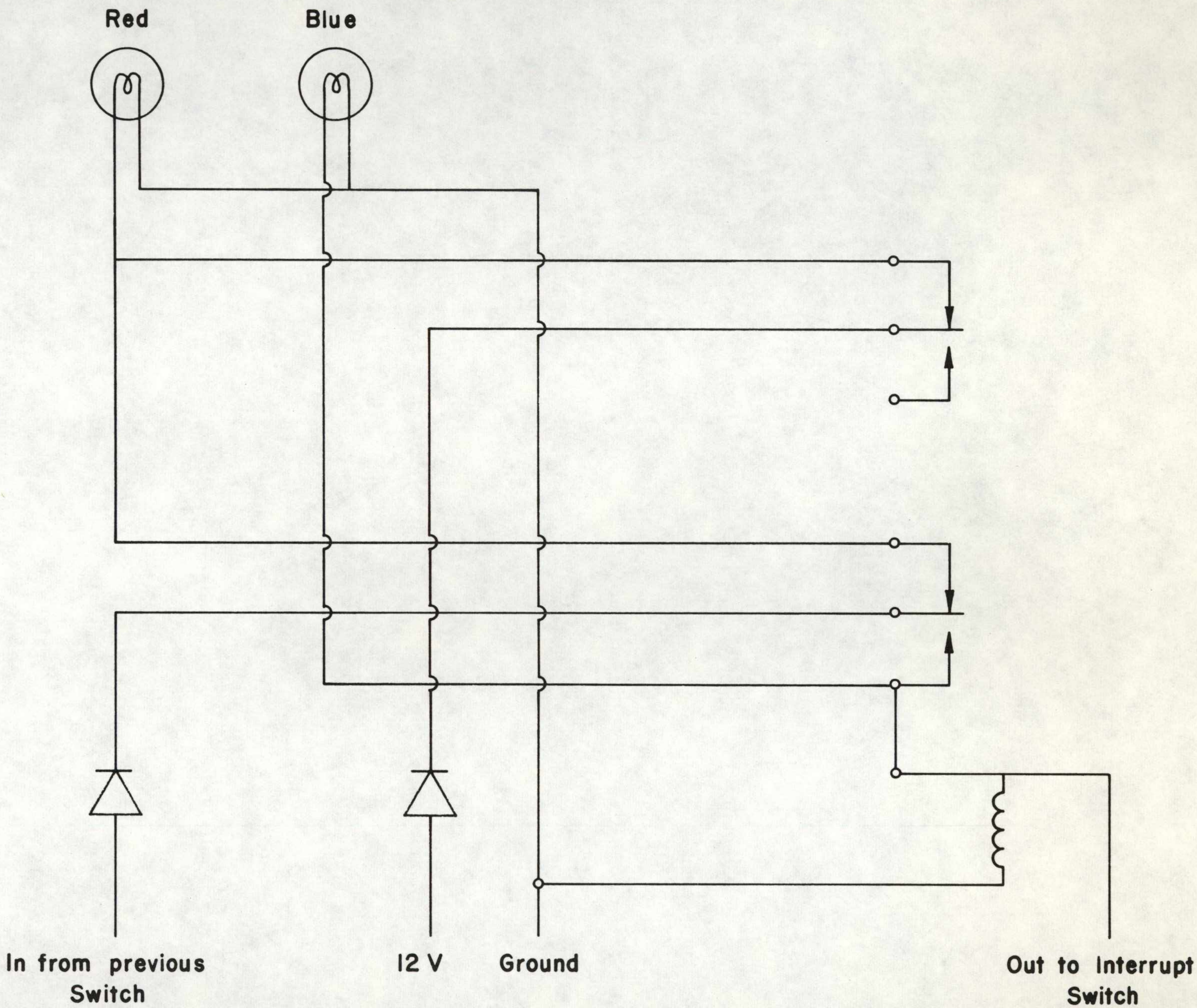


Fig. 3. SURVEY SWITCH. The switch is magnetically latching. Red and blue lamps indicate the status of the switch. Once operated, the switch will stay latched until reset by central control or until an interrupt switch to the left is operated.

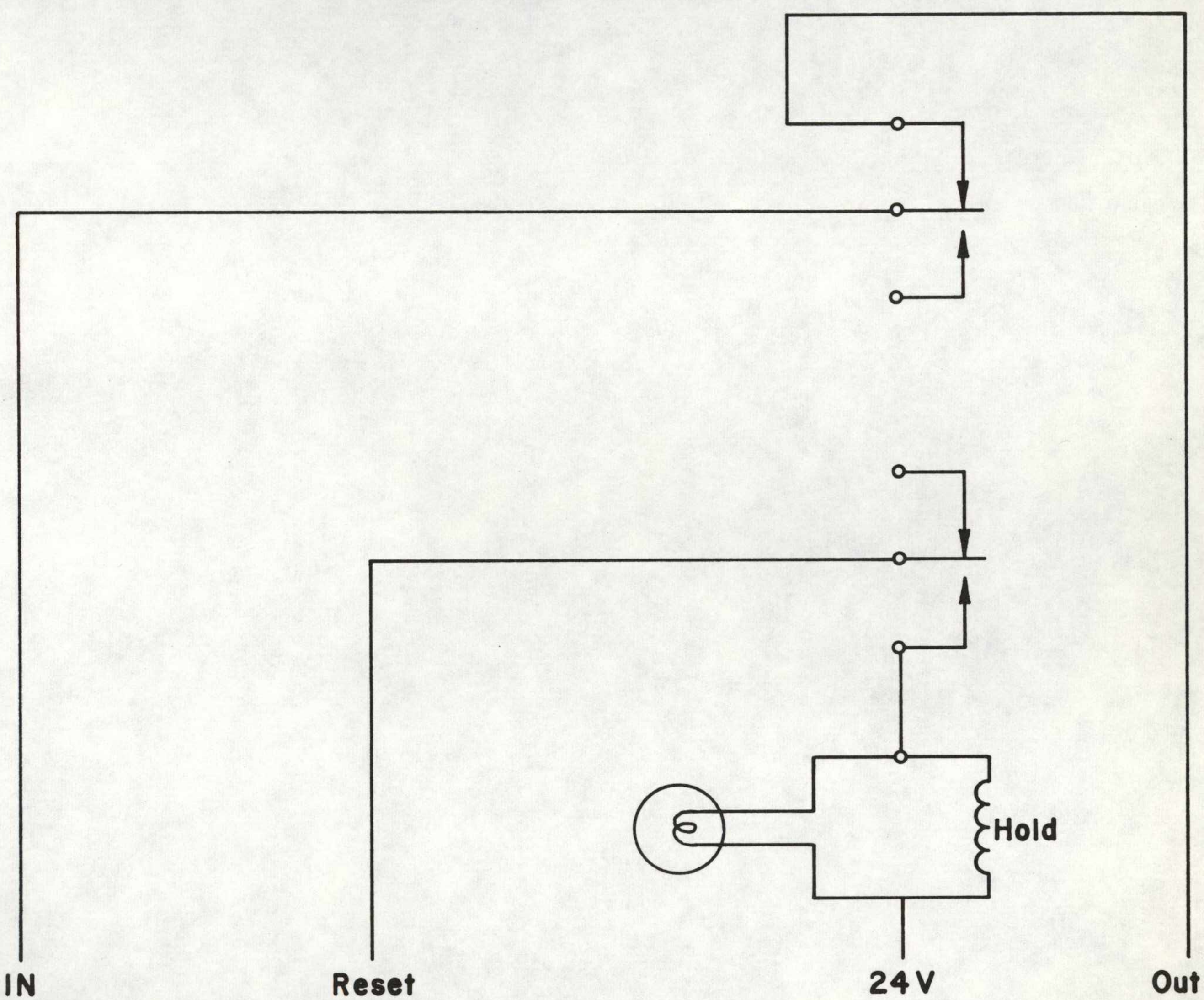


Fig. 4. INTERRUPT SWITCH. The switch is magnetically latching and holds the survey line open until reset by central control.

2.2 Machine Protection

The personnel safety system complements the machine protection system in the fail-safe operation of the facility. Excessive irradiation of accelerator components must be minimized. Consequently, a machine protection interrupt system must be developed.

Each sub-system will have its own array of operating permissives. Excessive coil temperatures, heat sink temperatures, power supply loading, etc., will cause the particular unit to shut down. A sub-system shutdown will, in general, alter the characteristics of the beam sufficiently that a complete facility shutdown would result. Two techniques will be employed to assist the operator in dealing with sub-system failure. A well-kept data log will be available for trend examination and a two-level alarm system will be used. For example, any temperature sensor indicating a value exceeding some predetermined value will annunciate this situation in the control room, even though the departure is not sufficient to warrant shutdown of the machine. If the operator is unable to correct the situation before the temperature reaches a second limit, the sub-system will shut down and announce the result to the control room.

Since the production of particle beams is the basic aim of the facility, their characteristics will be used to assess the operation of the accelerator and to signal an improper function. The nature of the beam must be monitored at a number of points. They include ion source output, injection system output, extracted beam current, and the beam current in each of the beam lines. The beam intensities at these stations will be measured and compared with non-intercepting monitors to determine whether the beam lost at each acceleration step is within specifications. Since the beam intensity is a parameter that will be varied regularly, the comparison will be on a relative basis.

2.2.1 Two-Level Alarm System

A two-level alarm system similar to that described for the sub-system shutdown procedure is proposed. Because of the need for a high degree of reliability, the basic components of this system will be triplicated and "voting majority" (two out of three) logic will be employed.

Beam position monitors will also be incorporated into the facility protection system. They will measure the displacement of a beam from its central design trajectory and indicate when the displacement is excessive.

Note that two levels of machine protection exist. The beam intensity monitors, which are always in operation, require the fractional beam loss to be less than a predetermined amount, whereas the beam position monitors act as an absolute limit on dangerous beam excursions.

Descriptions of these beam sensors are included in Sections 4.4 and 5.1.

In addition to activation by signals from beam monitors as discussed above, the hard-wired protection machine shutdown system will also be triggered by excessive pressure signals from the main cyclotron vacuum tank. Since many of the systems within the cyclotron tank (such as RF) require good vacuum for safe operation, it is anticipated that the hard-wired vacuum interlock would be actuated whenever the cyclotron equipment is turned on, independent of whether a beam was actually being accelerated.

Discussion of the monitoring system for the vacuum in the high energy beam lines is presented in Section 5.2.

Radiation monitors will be used as a back-up to the hard-wired machine safety logic, using the area safety unit described in the preceding section.

Alarm activation of the facility shutdown sequence causes termination of the beam, disabling those sub-systems which are intimately connected with the unit that failed. Other accelerator units will remain fully energized so that the facility may return to operation after remedial steps have been taken. For example, if a quadrupole in beam line 1 fails, beam sensors would indicate an excessive beam spray in beam tunnel 1, and if the second limit were passed would terminate beam delivery. On the other hand, all steering and focusing elements would still be fully energized, so that reduction of the total cyclotron beam current and repositioning stripping foil 4 to extract all cyclotron beam and retracting stripping foil 1 would allow experiments along beam line 4 to continue while line 1 repairs proceeded. As the facility develops, the positioning of stripping foils will be determined by the amount of spray along the beam lines as well as by the sharing requirements dictated by multiple extraction. An experiment along an intact beam line would therefore suffer little or no inconvenience because of unrelated failures.

A distinct advantage is realized by using a hybrid system of hard and soft control for machine protection. Hard-wiring optimizes personnel protection, minimizes component activation, and protects sensitive electronics from excessive radiation. Balancing this system with software, which will condition the operation of the facility within the hard-wire bounds, will allow maximum experimental use of the facility.

2.2.2 Shutdown Devices

An integral part of the safety system, machine and personnel, is an effective and rapid method for terminating the beam. The two major considerations in designing this system must be reliability and speed of response. System safety is increased by requiring the shutdown device to be fail safe, i.e., for the beam to be terminated if the shutdown device itself fails. The response time must be examined to determine which shutdown system offers adequate protection for the facility.

The speed of response needed for the shutdown device depends on the time it takes for continued operation of the machine to become dangerous. The following are estimates of such times for various types of system faults.

The failure of the stripping foil would mean that the beam would strike the outer wall of the vacuum chamber but in most cases would be distributed around the entire circumference. The area irradiated would be large (approximately 1000 sq.in.). The failure of a bending magnet power supply would cause the beam to be directed at the wall of the beam pipe. On failure, however, the decay of the magnetic field in a bending magnet would occur over a period of at least one second, so that during that time interval the beam would be swept along the sides of the beam pipe. The failure of a quadrupole lens would also have a long time constant, with the beam again striking the beam pipe over a fairly large area during the decay time. Failure of either the RF system or the main magnet would dissipate the beam around the circumference of the vacuum tank.

In the low energy ion source beam transport system the focusing devices will probably be electrostatic, so that failure will cause the beam to strike the beam pipe over a relatively large area, with the decay time again being seconds.

The temperature rise associated with traversal of the high energy proton beam through a material is relatively independent of the beam position along the proton track within the absorber. (Here we assume that the spread in beam size due to multiple scattering, as the energy is degraded, is roughly compensated for by the increased rate of energy loss of the slower protons. For example, in copper the rate of energy loss of 15 MeV protons is ten times larger than that of 500 MeV protons.) For an initial cross-sectional area of $\sim$0.1 cm^2 for the beam, the rate of temperature rise in an absorber along the beam path is $\sim$10°C per millisecond, assuming that 100 μA of 500 MeV protons are traversing material with a specific heat of 1 cal/cm^2 C°. Diffusion of heat from the beam area has been neglected. Allowing for an order of magnitude safety factor and a 100°C upper limit for the allowable temperature excursion, a maximum beam turn-off time of $\sim$1 msec is implied.

The beam may also be deflected, on particular accident conditions, to electronic instrumentation placed near beam pipes (beam monitor equipment, radiation monitors, etc.). Since many electronic components are damaged when subjected to fluxes in excess of $\sim 10^{13}$ particles/cm^2, beam turn-off times sufficiently shorter than this radiation limit are required. Again assuming a 100 μA proton beam of 0.1 cm^2 cross-sectional area, this restriction imposes a limit of $\sim$1 msec.

Since the cyclotron will continue to deliver a high energy beam for about 300 μsec (the residence time of an ion in the system) after beam termination at the ion source, the time required to turn off the beam at the ion source must be less than a few hundred microseconds to meet the overall turn-off time requirements.

In the present conceptual design of the low energy beam line an electrostatic dogleg is ahead of the inflector. To terminate the beam, the shutdown system would drive the dogleg deflector voltage to 0. This would deflect the beam sufficiently so that no beam would enter the cyclotron. The shutdown action operating in the dogleg would also initiate a shutdown of the ion injector system by reducing the extracting and accelerating voltages to 0.

An alternative fast shutdown system would involve crowbarring the RF system. In addition to fast beam shutdown, this method would eliminate the 300 μsec delay which characterizes the former system.

Either one (or both) of these methods could be used for machine shutdown. The equipment cost and design time for either approach will be similar. The RF crowbar shutdown is proposed as the primary shutdown mechanism with dogleg deflection as a back-up.

3. ION SOURCE AND INJECTION SYSTEM CONTROL MONITORING

3.1 The Ion Source and Injection System

The ISIS sub-system forms the first acceleration stages of the TRIUMF facility; thus its control-monitoring system is the first to be discussed in this report. The ISIS consists of an ion source that emits a 15 keV beam of H^- ions, an electrostatic accelerator that raises the beam energy to 300 keV, a chopper, a buncher, a dogleg beam dump for safety shutdown, a set of quadrupoles and bending magnets that transport the beam to the inflector, and appropriate diagnostic stations. Acceptable operating pressure and temperatures are maintained by ancillary vacuum and cooling systems.

During operation of the ISIS, the following parameters must be controlled:

In the ion source	- ion source filament current, extraction potential, extraction magnet current, H_2 gas supply, arc current, temperature The ion source is at high potential (the accelerating voltage), in order to obtain the extracted ion beam at ground potential.
Accelerator	- accelerating voltage
Chopper	- voltage and phase
Buncher	- buncher phase, peak voltage, bunching factor
Dogleg	- power supplies, fast switch off
Quadrupoles and bending magnets	- power supplies, temperature
Vacuum system	- pressure, overload indication in pumps, valve status
Cooling system	- temperature and flow
Beam diagnostics	- beam intensity, profile, and distribution

Although all elements of the ISIS sub-system contain power supplies, the type and manufacturer of the supplies have not been determined. For the purpose of this study, we have assumed power supplies with the following characteristics:

- local closed loop control of preset current or voltage
- remotely-settable operating points
- local metering on 0-50 μA meters provided with appropriate scales
- automatic overload and interlock protection with external status indicators

Control and monitoring of the ion source itself requires data to be transmitted to and from the source in the high voltage head. For manual control, insulated rods and mechanical linkages will be used. For remote signals, however, interfacing to the high voltage area must be provided. Techniques that may be used include a radio link or a light pipe link.[1]

The ISIS control system must be discussed in two stages. It will be one of the first phases of the TRIUMF project to be completed. The ISIS control system must, therefore, be capable of running ISIS independently of the central control (which will not be in operation until a year or more later) and yet be easily incorporated into the central control system when it is finally commissioned.

To meet requirements for the initial ISIS development phase, the control system must provide a flexible display of ISIS variables with data-logging capability. There must be a provision for manual control of variables to allow for initial optimal performance. The controls must provide sequential operations for start-up and shut-down as well as provision for steady-state operation.

Eventually, steady-state operation will be under the supervision of the central control system, in which case the ISIS system will be integrated into, or interfaced to, the central control system. If necessary, a dedicated digital computer for ISIS control, interfaced into the central control, could be considered.

3.2 Possible Control Techniques

The following section discusses five possible ways of supervising and controlling the ISIS. A brief description of each mode is given and the hardware requirements listed. The advantages and disadvantages of each are summarized. The same discussion applies to the control system for the complete facility.

3.2.1 Straight-through Analog System

The straight-through analog system is illustrated in Figure 5a. In this system, each parameter is compared with its analog limit. The comparator output may be binary (go, no go) for supervisory functions, or analog for control functions. The following comments indicate the dependence of the system on the number, n, of parameters:

a) Hardware : n comparators, n limit stores (references); possibly n signal amplifiers and n noise filters

b) Advantages : Speed; simplicity for small n; locatable at each device; reliability (for n small)

c) Disadvantages: Signal itself tends not to be available for display or logging; high accuracy and large n imply high cost; limit changes and computation are difficult to effect

d) Major Uses: : This system is used when speed is important, when signal-to-noise ratio is high, when limits are fixed and/or the number of inputs is very small, e.g. local control of power supplies, safety systems

3.2.2 Scanned Analog System

Figure 5b displays a schematic of a scanned analog system. The input parameters and associated limits are sequentially presented to a single analog comparator by means of dual scanners. In general, only $n' \ll n$ limits need be stored, because groups of inputs, for example pressure sensors, will have a common alarm level.

a) Hardware : 2 scanners; 1 comparator; 1 signal amplifier; possibly n noise filters, n' limit stores (assuming parameters can be grouped)

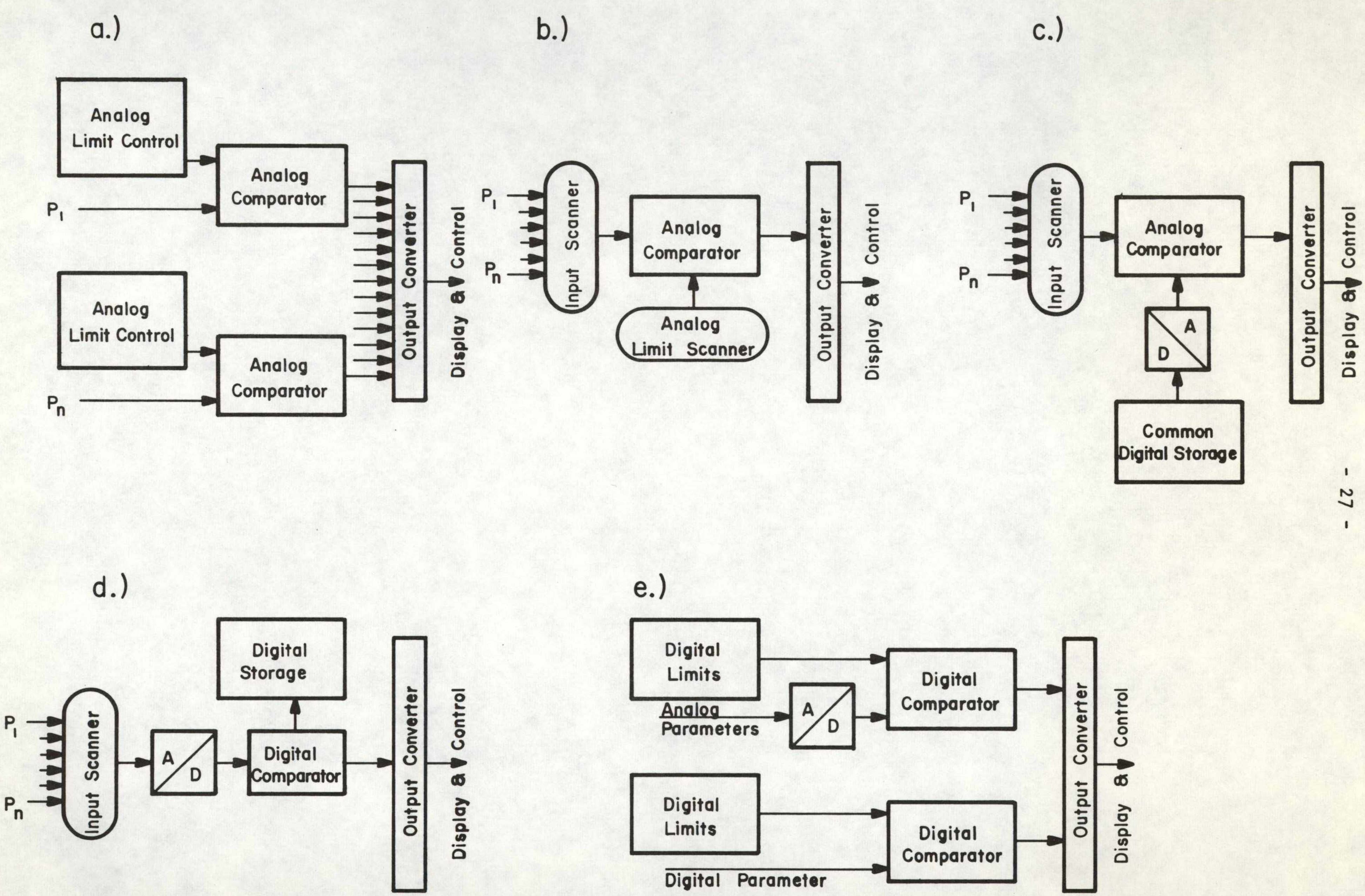


Fig. 5. DATA ACQUISITION METHODS. Possible data acquisition and control methods as detailed in Section 3.2

b) Advantages : Hardware saving for n large, because only 1 amplifier, one comparator, and n′ limit stores are required

c) Disadvantages : Slower than straight-through analog system; inflexible with respect to limit changes and computation; limited accuracy for high price

d) Major Uses : When large numbers of (slowly varying) parameters with identical fixed limits are to be monitored, this system may prove advantageous.

3.2.3 Hybrid System

The hybrid system, shown in Figure 5c, combines digital limit storage with analog comparison. The input parameters are scanned in synchronism with the digital limit store. The digital limits are converted to analog by a digital to analog (D/A) converter and sequentially fed, along with the appropriate input parameter, to a single analog comparator. A study of this arrangement gives the following results:

a) Hardware : 1 analog scanner; 1 comparator; 1 D/A, 1 digital store and scanner; 1 signal amplifier, possibly n filters

b) Advantages : The hybrid system has the advantages of the scanned analog system with respect to hardware saving. In addition, limits are easily changed and limits are available for digital display.

c) Disadvantages : It is slower than the straight-through analog system, is more expensive than the scanned analog, and has no facility for computation.

d) Major Uses : This system is useful when a large number of parameters with different, changeable limits are to be monitored.

3.2.4 Scanned-Digitized System

Figure 5d displays the scanned-digitized system where input parameters are sequentially routed by the scanner to an A/D converter. Their digital equivalent is then compared with digital references supplied synchronously from a common digital memory. With this system, excellent rejection (typically > 40 dB) of interference from 60 Hz lines can be realized through the use of an integrating A/D converter which averages the signal (plus noise) over one or more periods of the mains frequency. The following observations may be made:

a) Hardware : 1 analog scanner; 1 signal amplifier (auto-ranging perhaps); 1 A/D converter; digital memory, scanner, and comparator (can all be handled by computer)

b) Advantages : Those due to scanning; noise rejection; inclusion of a digital processor (computer) offers high degree of flexibility in acquisition and treatment of data

c) Disadvantages: Complexity

d) Major Uses : Complex processes with initially unknown characteristics and potentially controllable behaviour may advantageously utilize this system. Simpler systems with low level signals may also require its noise-rejection capability.

3.2.5 Straight-through Digital System

In the straight-through digital system, all analog systems are digitized. All signals are then processed digitally, as is indicated in Figure 5e. The following observations may be made:

a) Hardware : A/D converters for analog channels, digital logic for comparators

b) Advantages : If a large number of digital sensors or transducers exist in the system, simple hardware logic can be used.

c) Disadvantages : Not flexible; A/D without scanning is inefficient

d) Major Use : See b) above

3.3 Control Techniques on the ISIS

The ISIS variables will be processed by a combination of these systems.

a) Straight-through Analog - Because of the need for reliability, the high priority safety system falls into this category. This will include excess pressure and temperature detection wherein a violation of warning or safety limits requires immediate action independent of the rest of the control system. Subsequent steps can be performed under computer control.

b) Scanned Analog - This technique should be used for beam diagnostics because information displayed in analog form gives the most convenient picture of the beam position and distribution. During the initial stage, this method will also be used for filament power, arc current, etc., because these variables will be manually controlled and selected.

c) Hybrid - This system is applicable for remote control of power supplies. Each power supply will have a closed loop analog control with provision for remote setting. These settings will initially be performed manually but will eventually be made by direct digital control as part of a multivariable control and optimization scheme.

d) Scanned-Digitized - This flexible system should be used through the rest of the ISIS for every accessible analog signal in the system. Where highest accuracy is required, conversion from analog to digital should be done as close to the sensor as possible.

e) Straight-through Digital - This should be used for all inherently digital signals in the hard-wired protection system (status of the valves, flow switches, etc.).

Because of the experimental character of the ISIS system, the computer-based scanning-digitizing approach offers advantages over other systems discussed. Its computing, logging, and "learning" capabilities permit fast and flexible processing of data and enable control loops to be closed as system characteristics become well defined. On the basis of available specifications, it is clear that a computer-based system is able to handle all the variables which must be sensed. Its implementation can shorten the period of the experimental stage by a factor of about three in comparison with a system equipped with classical instrumentation requiring off-line processing of voluminous records.

3.4 Computer Control of the ISIS

Computer control of the ISIS system can be done two ways. The ISIS control and monitoring can be handled by a small computer while a central data processing system supervises the overall operation of the facility. Alternatively, when the central computer and control system is operating, its software system can be extended to include the ISIS control and monitoring previously performed by the separate, dedicated ISIS computer. If, at this stage, a smaller computer is retained as an ISIS supervisor, this dedicated computer will communicate with the central computer via standard parallel/serial data channels involving direct memory access.

For either of these approaches, the selection of peripheral equipment during development of the ISIS system should be as compatible as possible with the instrumentation needs of the central control. Thus as the central control system is developed, redundant ISIS peripherals can be included. It is advisable, then, that as far as possible the same manufacturer be employed for equipment used in both ISIS and central control. This applies to software as well as to hardware. If such an exchange is possible, the price for a complete multiprocessor can be reduced.

3.5 Injector Diagnostics

Beam diagnostic devices are necessary along the ion injector transport. The parameters of interest are the beam current and the size, position, and divergence of the beam. It is desirable to be able to tune up the injected beam independent of the cyclotron. To facilitate this, the cyclotron should have a beam dump, possibly in the shape of a Faraday cup, as close as possible to the inflector. Immediately upstream of the beam dump will be electrostatic deflection plates forming a dogleg. This dogleg, when energized, will deflect the beam into the entrance gap of the inflector or, when de-energized, permit the beam to run into the dump.

The beam intensity may be measured using the Faraday cup beam dump just ahead of the inflector. For the beam power involved (up to 150 W) cooling the Faraday cup will probably be necessary. With the beam chopper in operation, beam current measurements can also be made without interrupting the beam, by using a transformer technique.[2]

A beam profile monitor system is manufactured by Danfysik, Jyllinge, Denmark. The sensing element consists of a loop moved through the beam in an oscillatory fashion. One part of the loop scans the beam in the X direction, another part in the Y direction. Brookhaven National Laboratory uses a modification of this device for scanning a beam with a power density of up to 35 kW/cm^2.[3] Since the power density in the TRIUMF injector should be substantially smaller, the loop supplied by the manufacturer can probably be used as is. The addition of the fiducial mark system added by Brookhaven should also be adopted by TRIUMF.

Beam divergence can be measured with a slotted electrode probe in combination with a wire scanner. The slotted electrode has two positions, "in the beam" and "out of the beam". The probe can be driven by an electric motor or by a pneumatic actuator. The wire scanner is a thin vertical wire mounted on a carrier capable of moving the wire across the beam tube behind the slotted electrode, thereby picking up the beam emerging through the slots. The beam current is amplified and transmitted back to the control room. The wire can be driven by a reversible motor controlled by a switch in the control room.

3.6 Beam Interruption for Current Measurements

The general philosophical question of how often the beam to an experimental area should be interrupted for routine diagnostic checks is difficult to answer. Since the experimenters associated with such a facility desire as uniform a beam as possible, whereas the operating personnel would prefer frequent interruptions in order to provide good updating of the operational characteristics of the machine as well as to facilitate attempts at upgrading its performance, a compromise position must be adopted. There will, of course, be a large amount of diagnostic information available from non-beam-interrupting devices, and this data will be logged by the central control. During commissioning of the cyclotron, extensive beam diagnostics involving interruption of external beams will probably be required at least once per shift. Subsequently, when cyclotron development is complete, a programmed routine could perform periodic beam diagnostic measurements without interruption of the beam, perhaps once an hour, in order to keep an up-to-date log of beam quality. By this means, re-establishment of cyclotron operation to its previous conditions, following temporary shut-downs, would be facilitated.

4. CYCLOTRON

The second large sub-division, the cyclotron, involves the control aspects associated with a number of systems required for cyclotron operation. It covers the RF system, the magnet systems, beam diagnostics, and temperature and flow monitoring of the cyclotron components. This portion of the system is predicated upon the RF frequency being the fixed reference to which the main magnetic field is controlled. In driven RF systems it is feasible to maintain stabilities of the order of one part in 10^8 or better without undue problems or cost.

4.1 RF System

Recent investigations have shown the advantages and feasibility of "square wave" acceleration voltages. Introduction of the third harmonic of the main RF fundamental essentially relaxes magnetic/RF tolerances. Figure 6 illustrates the system proposed.

Basic requirements have been established in TRIUMF Preprint TRI-PP-69-8. These, in brief, are:

a) A frequency stability of ±1.25 parts in 10^6 for maximum duty factor and ±7.5 parts in 10^8 for single-turn extraction.

b) A time variation in voltage amplitude stability of ±2 parts in 10^4 for maximum duty factor and ±2.5 parts in 10^5 for single-turn extraction.

c) A peak cavity voltage of 100 kV.

d) A phase tolerance of approx. ±1.5° of the third harmonic with respect to the fundamental for maximum duty factor and ±0.15° at 0° for single-turn extraction.

e) A third harmonic voltage amplitude tolerance of approximately ±0.1% for single-turn extraction.

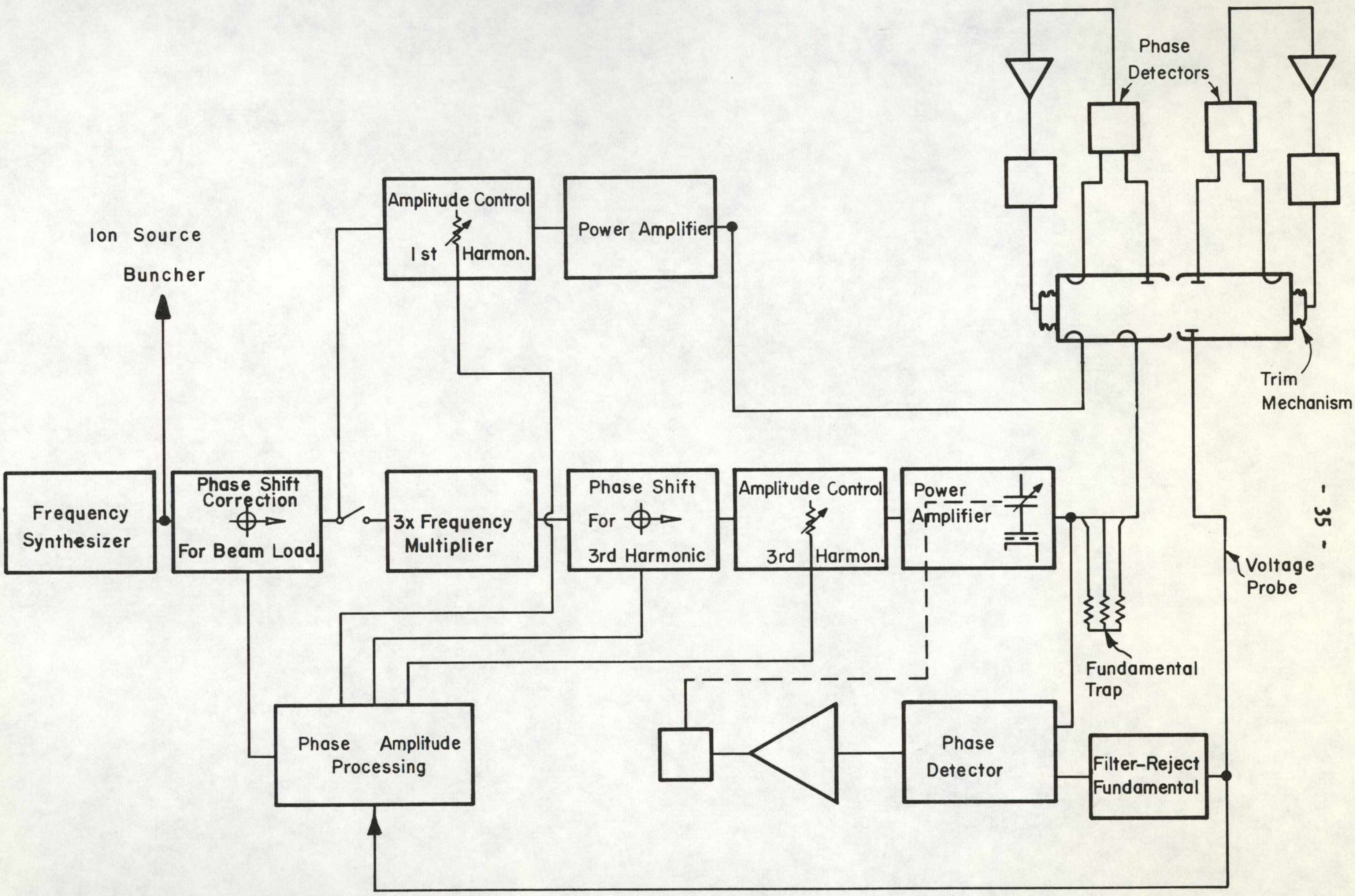


Fig. 6. RF CONTROL SYSTEM. Schematic representation of control loops within the RF system as detailed in Section 4.1.

The frequency source, a standard commercial synthesizer enabling coarse and fine variations, will be used to provide direct primary excitation. Following this will be an intermediate series of amplifiers generating sufficient power to drive the power amplifier. Through a 50 ohm wave transmission line the cavity will be excited directly at the approximate frequency of 22.8 MHz.

The third harmonic will be derived by frequency multiplication of the fundamental. Its phase will be 180° away or antiphase at the peak of the fundamental envelope. To compensate for discrete and fixed phase delays in both fundamental and third harmonic systems, an adjustable but preset delay is provided. Transmission and injection of the third harmonic signal into the resonator via a separate transmission line and loop permits more freedom of adjustment and less interaction between the two frequencies than other coupling systems would permit.

Resonance control of the cavity at the fundamental will be through a phase detector servo-controlled loop system actuating internal tuning panels. A phase comparison of either the magnetic flux at the root of the resonator or of the final amplifier plate voltage with the resonator tip voltage will be used to provide the error signal to control the tuning. Excess limits of phase error will be annunciated to the central control system. Resonance tuning for the third harmonic will not involve an active or live system at the cavity but will instead be obtained by capacitor trimming at the anode of the third harmonic power amplifier. In addition, there will be fixed or preset panels in the cavity adjusted "in situ" to obtain coarse optimum resonance conditions.

During high current operation of the cyclotron the asymmetry of the phase structure of the beam with respect to the RF results in an additional reactive load for the RF system. To prevent the development of a runaway situation, an additional control loop is included for adjusting the phase of the RF voltage with respect to that of the beam. Since the mechanical tuning system for the resonator operates by fixing the phase of the RF voltage in the cavity to that of the synthesizer, it can obviously handle reactive beam loading effects characterized by time constants that are appropriate to the mechanical system. Compensation of the effects of more rapid fluctuations in beam current must be handled by the non-mechanical control loop described.

4.1.1 RF Controls

The RF equipment in itself represents a considerable array of interlocks, adjustments, and status indicators that have but a minor role in cyclotron operation. The bulk of these details and control functions will be relegated to the RF equipment room. On the other hand, information concerning voltage and phase at the cavity will be directly available in the control room.

The location of the RF equipment room is one floor elevation below the main cyclotron control room. It will be completely shielded. During normal operation the frequency will be controlled from a stable frequency synthesizer, which should probably be located in the RF equipment room. Since major alterations of the resonator frequency involve significant mechanical motion of parts of the system, the need for control of the RF frequency from the control room should be relegated at most to one of minor trimming of the frequency. In general, changes in the tuning of the cyclotron can most simply be accommodated by altering the set point for the NMR reference probe for the current stabilizer of the main magnet. This facility should therefore be available in the control room.

4.1.2 RF Monitors, Set Points and Limits

Each of the upper and lower rows of a resonator will be equipped with a number of voltage probes or sensors built into the ground arm near its tip and distributed to enable maximum coverage. Although all the probes will be capable of being monitored in the RF equipment room, only one or two will form an integral part of the RF voltage feedback system.

The location of the reference or set points for voltage control will be in the RF equipment room. The set points, however, may be changed from the central control. Limits will be provided for several of the voltage probes on each resonator row, including one set of ±0.1% warning limits plus one set of ±0.2% shutdown limits. Basic on/off and RF start-up functions as well as RF voltage control will be available in the central control room. Summary warning limits of the equipment in the RF room will be annunciated in the main control room with indication of the particular RF sub-unit for which limit has been exceeded.

4.1.3 RF Start-up Procedures

In the RF equipment room, the initial procedures involve turning on filaments and power supplies, and activating the resonance tuning systems. Full power must be supplied to the resonator in order to approach the equilibrium operating conditions quickly.

As the change in resonant frequency of the cavity during warm-up is about 0.5% and only a 0.1% tuning range is available for control and voltage distribution tolerances, the following turn-on procedure is recommended. The system is initially excited at the cold cavity resonant frequency until the multipactoring region has been passed. The system is then connected in an oscillator configuration, allowed to warm up for five minutes, and then tuned to the main reference frequency. At this point, the system is transferred back to the driven mode, in which it is driven by the synthesizer. The third harmonic system, which has been on standby, is finally injected into the cavity. Observations of a phase error between the two signals would be trimmed manually if required.

4.1.4 RF Interlocks

Interruption of RF excitation will be achieved by simultaneously "pulsing off" the main plate supply series regulator and applying a "crowbar" across the final power amplifier. Thus, in the event of arc-over in the cavity or transmission line, the system will be unloaded for some 50 microseconds followed by immediate restoration of RF energy. During this time the ion source beam will be dumped at the dogleg. The system will also be shut down if the cavity voltage exceeds the limits allowed. Within the system are a number of interlocks capable of interrupting RF operation. Should any of them do so, the machine safety system would cause dumping of the injected beam.

4.1.5 Gross Frequency Changes

For those modes of operation of the cyclotron requiring a change in RF frequency of ±2% from the centre value, it will be necessary to shut down the RF system and carry out a manual adjustment of the resonator gaps. This is similar to the basic operation of initial set up and will have to be repeated for the new frequency setting. Third harmonic operation will also be affected and will have to be trimmed.

4.2 Main Magnet

The main field coil configuration of 30 turns consists of two equal groups, each distributed at the upper and lower regions of the return yoke. Since the required operating value of excitation is 720,000 ampere turns, the control system should be designed to handle up to 800,000. With third harmonic RF excitation, the tolerances in the control of the average magnetic field are ±5 parts in 10^6 for large duty factor operation and ±1.25 parts in 10^6 for single-turn extraction. Without third harmonic injection these tolerances would have to be tightened by almost an order of magnitude (TRI-PP-69-8).

Figure 7 displays an approximate power supply configuration. At least two stages of regulation are required. One will maintain 1% steady-state control. It will encompass the set point value, the change in power due to temperature rise in the load, and the slow time variations in the utility supply. This is achieved through use of an induction regulator (25% kVA range) in the primary of the rectifier transformer. It will permit a nominal system efficiency excluding the second stage regulator of about 95%. The second

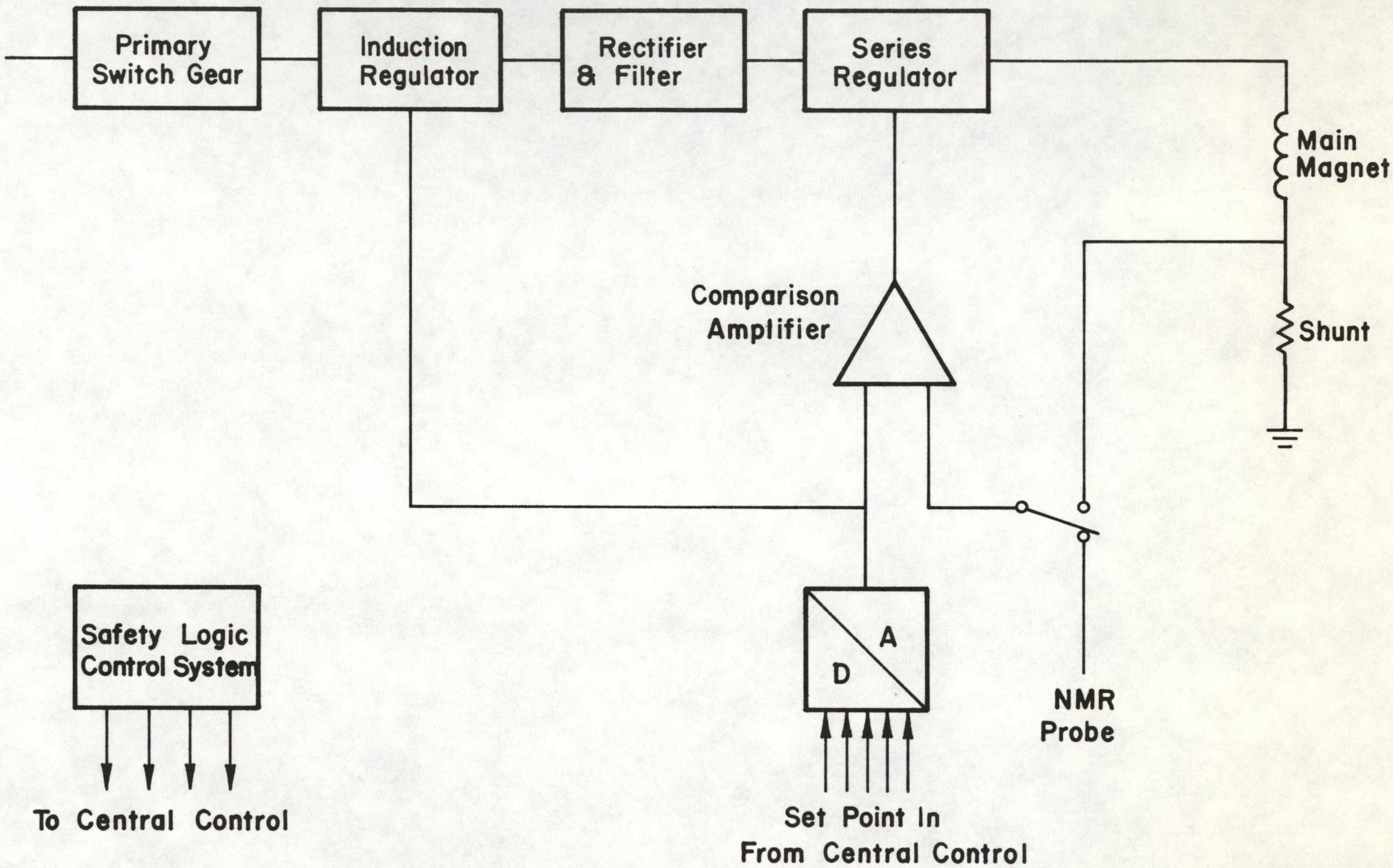


Fig. 7. MAIN MAGNET POWER SUPPLY. As detailed in Sections 4.2 and 4.2.1, the main magnet current is demanded by digital signals from central control and maintained by local feedback loops with reference to either magnet coil current or NMR probe.

stage regulator is more responsive and will look after the fast time voltage variations of the utility and supply the required steady current. No limitations are envisaged for the allowable rate of application or removal of power in the load. Thus the coil will be protected by both diode and zener diode units against back emf. To cover the complete range of zero to unity excitation, an increase by a factor of four in the induction regulator range would be necessary.

The power supply will be located in the mechanical equipment room of the building.

4.2.1 Main Magnet Controls

For a 25,000 ampere system the maximum current regulation performance that can be expected for a shunt or transducer sensing device is ± 1 part in 10^4. The power supply will be controlled from a self-contained reference (located in the control room) and shunt system to derive the error information. To achieve ± 2.5 parts in 10^6 performance, it will be necessary to use an NMR probe system to derive suitable error signals. A single NMR probe will be located in the outer radius of the magnet, situated in a magnetic field hill, just beyond the last trim coil. The control unit will be located in the control room to facilitate trimming the value of the magnetic field. Some care in the probe cable routing may be necessary as certain manufacturers specify limits of 100 to 150 feet between the probe and control unit (e.g. Varian Model F8-A). Digital remote referencing of the NMR control unit would be contemplated only if the cable length limitation prevented the control unit from being situated in the control room.

Associated with the power supply are a large number of protective interlocks. A summary of warning and shutdown functions would be available in the control room. Should the latter occur, the ion source would be interrupted. Diagnostic equipment used for power supply maintenance will be located with the supplies in the mechanical equipment room.

The following procedure is proposed for turning on the cyclotron:

a) Since RF frequency can be held stable to better than one part in 10^8, it is therefore assumed to be the primary reference, and set to the design value.

b) After the main magnet power supply has warmed up, the control loop involving the NMR probe would be switched in, and the NMR control unit adjusted to yield the appropriate value for the central magnetic field.

c) The trim and harmonic coils are set to their calculated values established from shimming and magnetic profile measurements.

d) The ion source is turned on at low current levels.

e) As subsequent trim and harmonic coil adjustments are made, care will be exercised to ensure that the net change in flux due to such adjustment is zero in order to keep the centre field constant. Long-term tracking of the magnetic field and RF would be checked during periodic beam diagnostic tests.

4.2.2 Trim and Harmonic Coils

The trim and harmonic coils contain 54 and 72 coil pairs, respectively. Each coil consists of two turns of mineral-insulated, water-cooled copper cable. The maximum expected exciting currents are 500 and 350 A, respectively. The voltage will vary between approximately 10 and 50 V depending on the nominal radius.

The stability of the magnetic field produced by the trim and harmonic coils must be at least ±5 parts in 10^4 (TRI-67-2 and TRI-69-6), in order for the overall magnetic stability to meet the requirements stated in the previous section (±2.5 parts in 10^6). This stability is easily obtained using current-regulated power supplies. Reference set points for these supplies will be located with the supplies in the mechanical equipment room. Reference errors will be annunciated in the central control room.

With the exception of the inner and outer trim coils, given coil pairs, i.e. the coil on the upper side and the one on the lower side of the vacuum tank at the same azimuth or radius, will be connected in series to a common power supply. A possibility for operation in an imbalanced operation will be provided, however. For the inner and outer trim coil systems, the upper and lower coils will be connected to separate power supplies to provide means for adjusting the position of the median plane. Power supplies, located in the mechanical equipment room, may be constructed in two parts. One part includes the transformer, rectifier, filter, and shunt. The second part includes the current regulator and the reference or set point system. The actual configuration must be deferred until detailed design begins. Remote on-off switching will also be provided. In the event that any one given coil or power supply system fails, as detected by a lack of output current or error indication from the reference comparator, the ion source would be turned off through the machine safety system. Again, the necessary diagnostic equipment required for power supply maintenance will be located in the mechanical equipment room.

4.3 Measurement of Component Temperatures

Since the temperatures of the sub-system components indicate whether the coolants are adequately removing the heat dissipated in the sub-systems, a suitable monitoring system must be incorporated. An interrupt initiated by an excursion of one of these temperatures would cause shutdown of the equipment associated with this sub-system, and initiate machine shutdown if necessary. The hard-wired protection system, operating in parallel with this process, would also terminate the beam if the sub-system which failed was a critical one in the acceleration process. The interrupt process will be a two-level system whereby temperatures passing the first level will announce a warning and temperatures which continue their excursion and pass the second level will initiate the sub-system shutdown sequence.

One of the more critical areas of concern is monitoring the resonator temperature to check the operation of the individual cooling circuits. The temperature sensor must be easily bonded to the outside skin of the resonator in a way that ensures good thermal coupling. Resistance spot welding of the thermocouple species of temperature detector to the cavity skin fulfils measurement requirements, robustness, and simplicity. It also has the advantage of an extremely low thermal resistance in the bonding. Five points in each of the resonator segments would be so attached with thermocouples, i.e., the tip and root area of each of the hot and cold arms, and the root itself. A measurement sensitivity of $\sim\pm 1°F$ can be expected in differential measurements between sensors, a sensitivity more than adequate for the needs of the system.

The monitoring of the temperatures of the many magnet coils can be accomplished conveniently and reliably without relying on a number of specific sensing units by utilizing the magnet coils themselves as resistance thermometers. Since the magnets are excited at constant current, a measurement of the IR drops across the coils (on the voltage supplied by the power supply) is adequate. By this means, no difficulty is anticipated in detecting a 50°C temperature rise, an increase within allowable limits. Each section will be compared with an appropriate preset standard or reference voltage, and upon detection of the excess limit, action is taken to warn the operator of an impending condition or shut down the associated power supply.

Internal component temperatures in sub-systems must be monitored. For many of the heavy current power supplies, protection of components (i.e., semiconductors mounted on water-cooled heat sinks) could involve use of a proprietary bimetallic thermal button directly wired into the system requiring primary protection.

A number of cases exist in which the performance of a heat exchanger or heat transfer process is inferred from measurements of inlet and outlet temperatures. Although many types of sensors would fulfil this requirement, a simple thermocouple is preferable, since it will satisfy the requirements and be compatible with the larger number of such sensors recommended for use with the resonators.

4.3.1 Temperature Alarm System

Signals from the temperature sensors described in the preceding paragraph must be handled by an error detection system. Two alternatives have been considered. One employs a multiplex-sequential scan process; the other involves interruption of central control only when an alarm situation occurs, as shown in Figure 8.

Because of the large number of sensors which must be scanned (about 650 temperatures in the cyclotron and beam lines), the scanning process is necessarily slower than interrupt alarms. For interrupt alarms, however, problems arise in supplying the large number of set points. Because of this, a synchronous scan system may be necessary.

Perhaps the major reason for favouring a scanning system, however, is the ease with which trend analysis can be accomplished. The value of any sensor, as it is read, can easily be compared with the corresponding values obtained during earlier scans. In this way, impending problems can be anticipated. The straightforward interrupt does not provide corresponding information.

Since most devices can withstand operation for several minutes under alarm conditions, it is proposed that a scanning system be employed in which the scan rate is sufficiently large that any sensor will be sampled at least once per minute. The outstanding advantage of such a technique is its flexibility. Thermocouples will be sampled on a schedule which assigns a higher sampling priority to sensitive devices. If an alarm signals, the scanning routine will shift the priority scan schedule to relate associated temperature points (e.g. 5 thermocouples are used on each element of the resonator system) and will monitor the temperature trends in the alarm area. The scanning routines can therefore decide if the alarm was caused by a temperature excursion or by a thermocouple failure, and either initiate a system shutdown plus operator warning or inform the

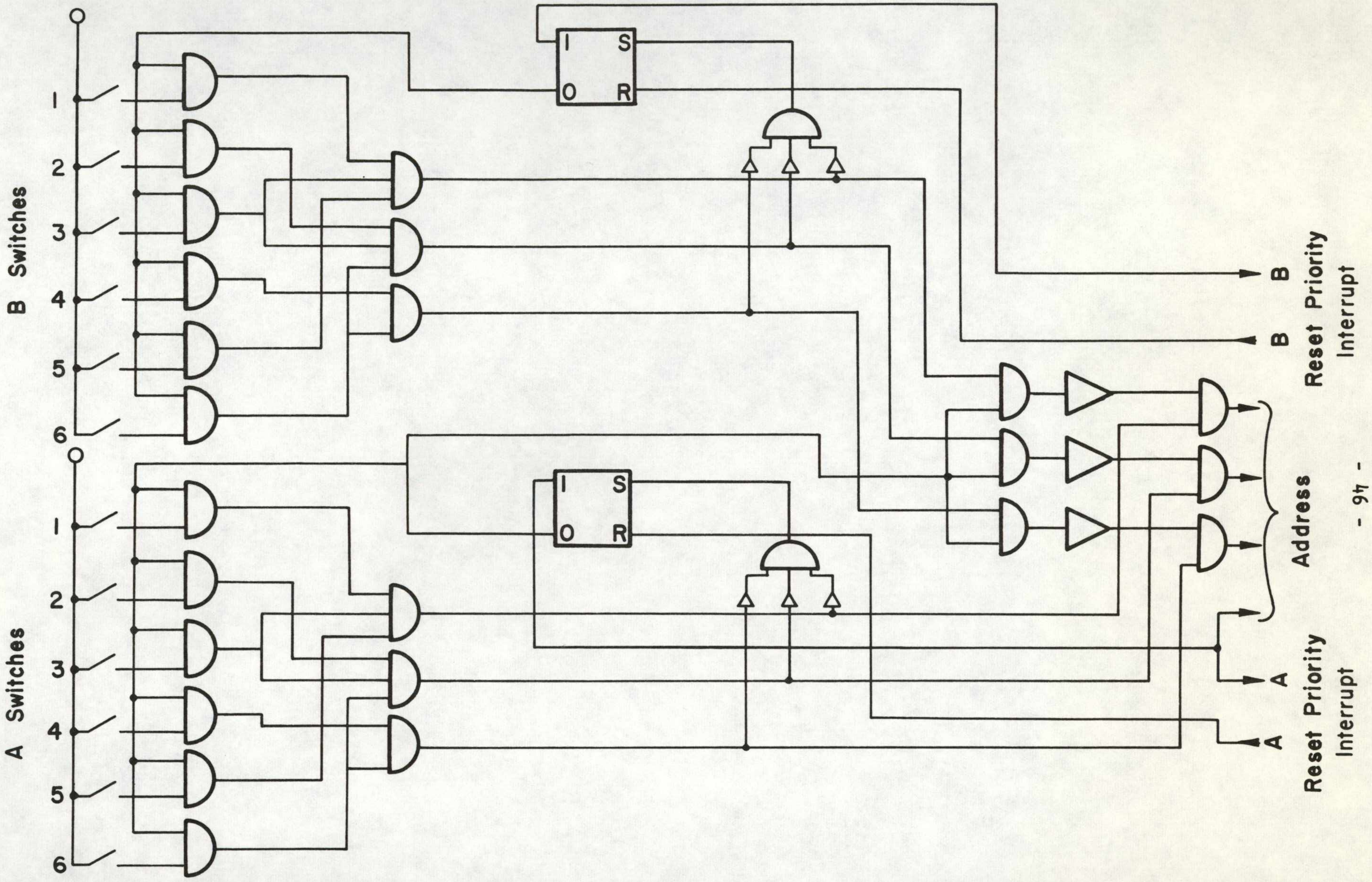


Fig. 8. HARD-WIRED SWITCH MONITOR. A system of logic gates provides an output when any input is switched. Two tenets of priority are provided. The address of the switch operated is presented directly to the computer.

operator of a thermocouple failure but to continue operation. Figure 9 presents a schematic outline of the signal transmission. Figure 10 shows the logic sequence used in the scanning technique. The detailed design of this portion will draw on both techniques, hard-wired for high priority safety devices and scanning for recording and updating detailed operating characteristics.

4.3.2 Coolant Flows

In nearly all cases involving component heating in high current circuits, the measurement of temperature will detect local cooling circuit malfunctions. To detect pump or supply failure, shut-off status, or other conditions impeding flow, a differential probe and differential pressure cell will suffice. Only one flow measurement in a given cooling circuit will be provided. Two measurements could be used (one for pump inlet, one for pump outlet), but the second measurement would yield redundant information except for the detection of major system leakages (greater than 10% flow). In case of leakage in the main vault, a system consisting of a drain pit and float switch backed up by another reservoir and float switch would detect any leakage in excess of evaporation rates (gpm). The first float switch would serve as an alarm, the second as a shutdown. Leakages in other areas are much less likely, and detection other than that provided by routine maintenance is not contemplated.

4.4 Beam Diagnostic Instrumentation

Since the principal product of TRIUMF is a high energy ion beam, the characteristics of the beam itself will provide the most reliable means for detecting process abnormalities. Aside from troubleshooting, beam monitors will also provide useful diagnostic information during start-up and tuning operations. The diagnostic devices can be divided into the following five groups:

a) Beam current measurement
b) Beam position detection
c) Beam size and orbit separation
d) Determination of phase relations between the beam and RF voltage
e) Beam extraction

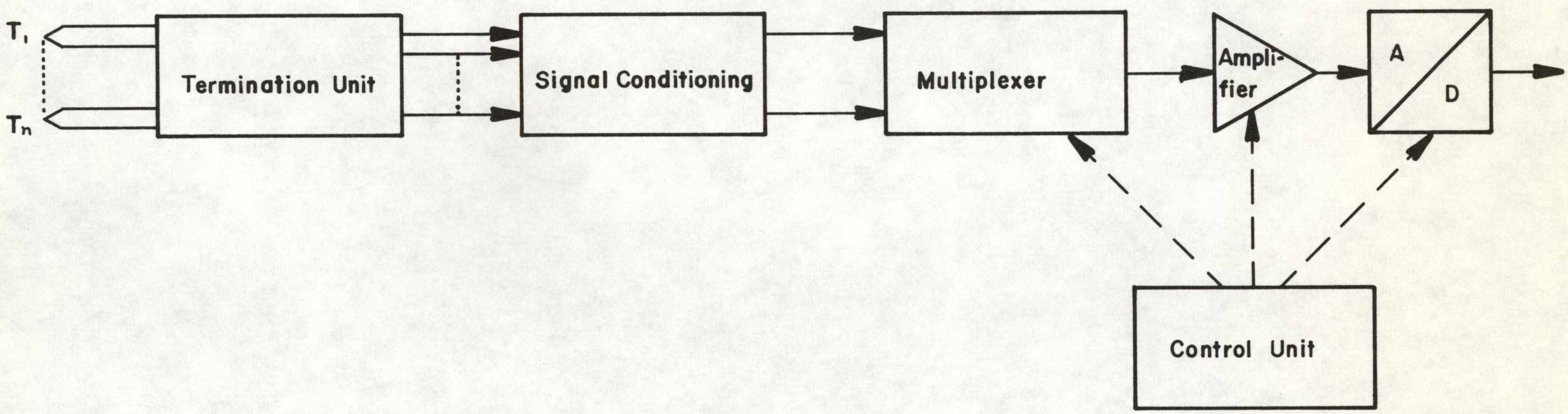


Fig. 9. LOW LEVEL SCANNER. Thermocouples are brought back to termination unit which contains the 'cold functions'. The multiplexer scans the thermocouples in a sequence and at a rate commanded by the central control computer through the multiplexer control unit. The thermocouple signals are amplified and digitized and fed to central control.

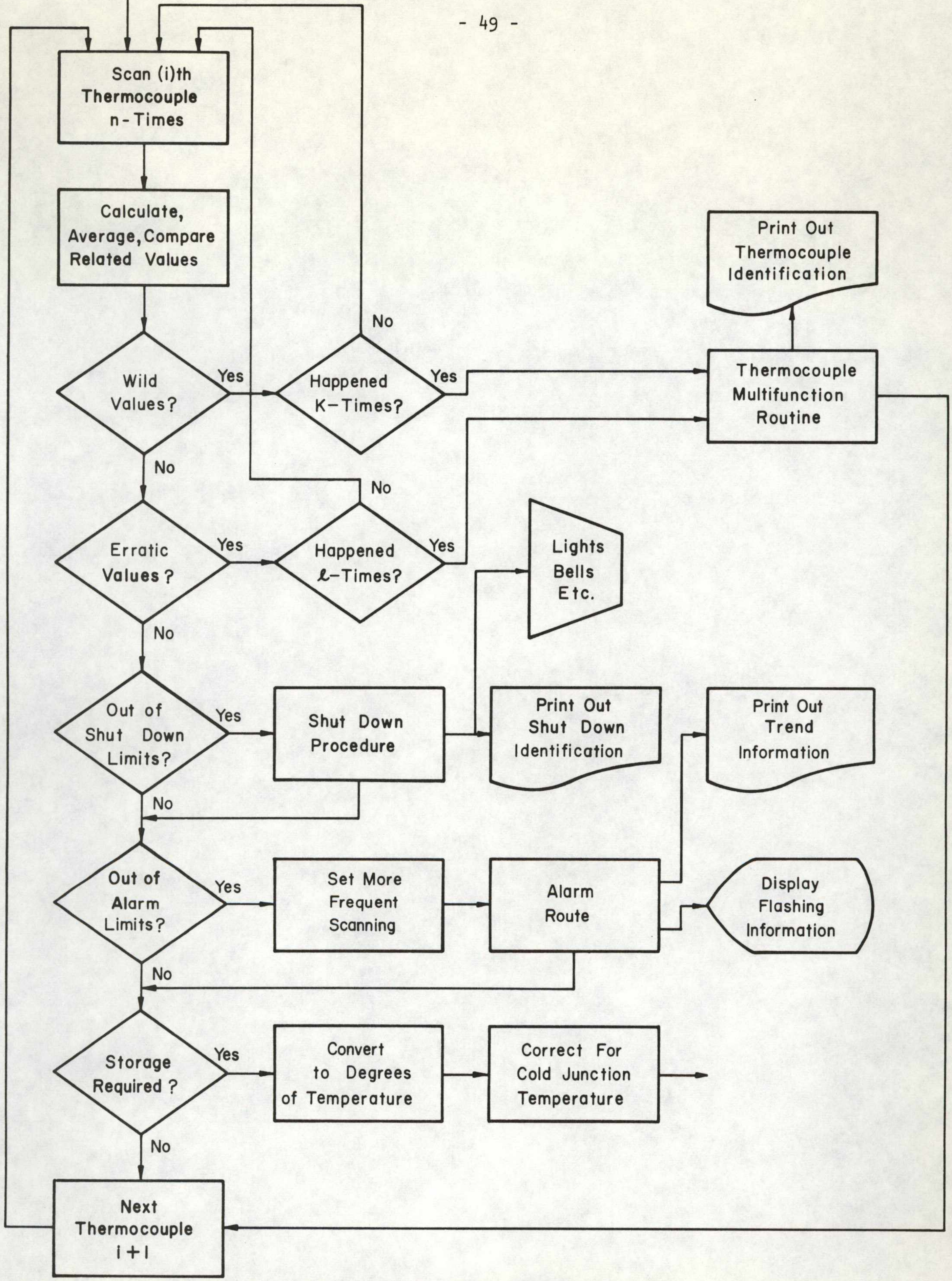


Fig. 10. TEMPERATURE MONITORING LOGIC

4.4.1 Beam Current Probes

The beam current probes proposed for TRIUMF are a combined beam-defining slit and current-measuring probe, diagnostic probes used for measuring low intensity beams during tuning of the cyclotron, and extraction probes which strip the energetic ions. Most of the ensuing discussion is based on the probe characteristics outlined in the TRIUMF notes, TRI-DN-69-2 and TRI-DN-69-25.

The beam-defining probe should have a radial adjustment range of 10 inches and be mounted somewhere between 72 inches of radius (15 MeV) and 150 inches of radius (30 MeV). The slit should be adjustable in width from 0 to 1 inch and be completely removable from the circulating beam. The slit may be a thin carbon foil which would strip off the electrons but allow the protons to pass through, or it may have thicker jaws capable of absorbing the protons and dissipating a beam power of about 3 kW. Three such slits are necessary. In the first case (stripping), the foil will not need cooling since the heat can be dissipated by radiation. In the second case (absorbing), water-cooling would be required. The probe would probably be at the root of the resonators diametrically opposite the phase probe assembly. The defining slit must be remotely controlled and requires three different drives. The slit width and its radial position can be adjusted by using either a stepping motor or a reversible single phase motor mounted outside the vacuum tank. The position readout is then obtained by counting the number of steps if a stepping motor is used, or by the use of an encoder and digital readout system if the reversible single phase motor is used. The "in-beam"/"out-of-beam" motion can be accomplished by a special solenoid mounted inside the vacuum tank or by an ordinary solenoid outside the vacuum tank.

The positioning accuracies desired are:

slit width	±0.010 in.
slit position	±0.005 in.

The low current probes will be in a line perpendicular to the resonators, accommodated in a corrugation in one of the centre resonator units, and will be driven by solenoid motors or stepping motors through appropriate shafts and gears in a manner similar to the beam defining probe. Each probe requires two different motions, one radial and the other vertical. From a mechanical point of view, it is desirable to break up each probe mechanism into two sections, one reaching from the back of the resonator to the minimum radius, and the other covering the rest of the radial travel. The positioning requirements are:

Range of travel, inner probe:	from about 22-inch radius to outside edge of resonator
outer probe:	from outside edge of resonator - 2 inches to last orbit
Speed of travel:	full travel in less than 3 minutes
Positioning accuracy:	$\delta R = \frac{0.010}{0.040}$ in.
	$\delta Z = \frac{0.010}{0.040}$ in.

During normal operation of the cyclotron, these probes would be withdrawn about 2 inches below the median plane.

The electronics for the low beam current probe will consist of a suitable preamplifier with appropriate connecting coaxial cable having RF filtering. The mechanical design must facilitate quick removal of the entire probe head assembly from the vacuum tank for servicing. Removal through an air-lock would minimize shutdown time for the facility.

4.4.2 Beam Position Probes

Sensing the position of the beam relative to the geometric centre of the cyclotron is done by a beam sharing and shadowing technique. During commissioning of the machine, both current sensitive and current insensitive probes would be used for this purpose.

The current sensitive probes would include the diagnostic current probes discussed in the preceding section as well as multi-element probes ("multi-finger" and "picket fence" configurations for measuring the cross-sectional distribution of the beam current perpendicular to and parallel to the machine radius. Electronic requirements for these probes will be similar to those presented in the preceding section, since such probes are used only when low beam currents ($\sim$100 nA) are involved. Mechanically, all such probes will be mounted on a common probe head providing radial travel perpendicular to the resonator structures.

The current insensitive probes are opaque to the beam. Beam characteristics such as centring of the orbits, single-turn separation, etc., are inferred from observations of the intensity of the extracted beams as the current insensitive probes move within the machine intercepting various portions of the internal beam. In most cases, the opacity of these objects results from the ions being stripped on traversing the material, and being lost from the circulating beam. Thus, thin wires or foils may be used. At low energies, the ions may be completely stopped. Both wire (0.010 to 0.030 inch diameter) and foil (about 2-inch radial extent) have been suggested. During the commissioning stage, these current insensitive probes will be required at four angular positions: two in the current sensitive probe heads at 90° and 270° and two in the electrical ground plane between the resonators at 0° and 180°. As the beam currents would be limited to about 0.1 μA in this stage, no cooling would be required. During full operation of the cyclotron, with beam currents greater than 1 μA, only the wire probes at the 90° and 180° positions are considered essential (TRI-DN-69-25).

The positioning system for the current insensitive probes will be similar to the low current probe positioning system. The positioning requirements are:

Range of travel:	from 22-inch radius to outermost orbit
Speed of travel:	full range in less than 3 minutes
Positioning accuracy:	$\delta R = \frac{0.020}{0.080}$ in.

4.4.3 Beam Extraction Probes

A thin carbon foil (approx. 4 mg/cm^2) is one type of beam extraction foil under consideration as an extraction probe mechanism. The beam current which may be handled by such a foil is tabulated below (TRI-DN-69-15):

Extraction Energy (MeV)	Maximum Currents High Resolution (50 keV FWHM)	Low Resolution (1 MeV FWHM)
200	220 μA	2400 μA
400	72 μA	870 μA
500	45 μA	530 μA

Heat produced in the foil will be removed by radiation. The stripped beam current is obtained by measuring the electron current deposited on the stripping foil assembly.

The extraction foils will be mounted on a trolley which will follow a track tailored to suit the calculated extraction position. The positioning requirements are as follows:

Range of travel:	Radial	- from 500 MeV extraction point to the back of the resonator
	Azimuth	- 4 inches
	Vertical	- 4 inches
Speed of travel:	Radial	- full travel in less than 3 minutes
	Azimuth	- full travel in less than 2 minutes
	Vertical	- full travel in less than 2 minutes

Positioning accuracy:

$$\delta R = \frac{0.010}{0.040} \text{ in.}$$

$$\delta\theta = \frac{2.0''}{R}$$

$$\delta z = \frac{0.060}{0.100} \text{ in.}$$

4.4.4 Phase Probes

Phase probes of a non-intercepting type are currently used in a number of cyclotron laboratories both in Europe and the United States. The Karlsruhe cyclotron uses a phase probe system developed by Hans-Helmut Feldmann of AEG-Forschungsinstitut, Germany.[4] This system consists of five sets of capacitive pick-up plates mounted at the outer edges of trim coils. The size of the pick-up plates is 9 x 39 mm, the larger dimensions being the azimuthal extent. Vertical distance between a pair of plates is 26 mm. The charge on the plates induced by the passing beam is sampled by a gate circuit near the plates, amplified, and displayed on a CRT whose time base is triggered by a signal derived from the main RF system. By displaying all five traces simultaneously, excellent information as to the isochronous condition of the beam is obtained.

The phase probe assemblies will contain radiation-resistant electronics. Because of the complexity of these devices, however, it is important that the probe assemblies be designed so that they can be readily removed and replaced. This in turn requires some kind of mechanical guide or rail system. In order not to impede the beam, the support structure should be as far away as possible from the midplane. The resonators are of a corrugated design and lend themselves to insertion of probe structures perpendicular to the accelerating gap.

Either a set of static phase probes or a single probe mounted on a movable arm can be used. If fixed in position, at least 10 probes are required to supply sufficient information. This arrangement provides a phase probe assembly independent of the movable probes discussed earlier. Because of problems associated with the lifetime of the probe circuitry in the radiation field, however, easy maintenance of the components is essential. Since providing easy mechanical access is difficult, an alternative scheme in which a phase probe mounted on the movable arm used for driving other current probes at the 270° position has been suggested (TRI-DN-69-25). During full operation of the machine, the phase probe would be the only mechanism mounted on the probe.

5. HIGH ENERGY BEAM LINES

At commissioning, two beam lines will be in operation. Meson and neutron experiments will be performed in the areas adjacent to beam line 1, while proton and neutron experiments will be performed with beams directed along beam line 4. Since at the time of writing preliminary design studies are available only for beam line 1, this line has been used as the model in developing a conceptual design for the diagnostic and control instrumentation for high energy beams. Provision of the experimental areas with suitable beams is assumed to be the responsibility of the machine operators. Thus in the beam line 1 facility, for example, production and transport of appropriate pion beams to the experimenters in Area 1 is as much the responsibility of the operating personnel as is producing and transporting high energy proton beams. This means that beam optics elements and interlocks along these beam lines will be routed through central control even if a particular device is actuated from an experimental trailer. In this way, interference between experimental groups can be minimized.

The beam line devices which must be controlled include bending magnets, a combination magnet, quadrupoles, pion targets, beam tube vacuum, and cooling systems. Many of these devices were discussed in Section 3 in conjunction with the low energy ion transport system. Scanning rates of one per minute should be adequate for those temperature sensors not interacting directly with the beam. Those requiring more immediate attention, e.g. sensors associated with pion production targets, will be serviced by a hard-wired system associated with the safety system. Excessive temperatures in the pion production targets will thus cause shutdown of a beam line until the faulty target can be mechanically removed from the beam.

All quadrupoles on beam line 1, with the exception of the quadrupole immediately before target 1, must be controlled to ±0.1%. For the quadrupole before target 1, the limits are ±0.01%. Set points for the 0.1% devices can be conveniently established using single word 10 bit memories at the power supplies (assumed to be digitally controlled). After machine commissioning, the output values of the current-controlled power supplies will be scanned and compared to the set-point values at least once every ten minutes. Those devices requiring 0.01% accuracy will be controlled by sensors sensitive to the magnetic field (e.g. Hall probes). The scan rate for these devices should be one per minute.

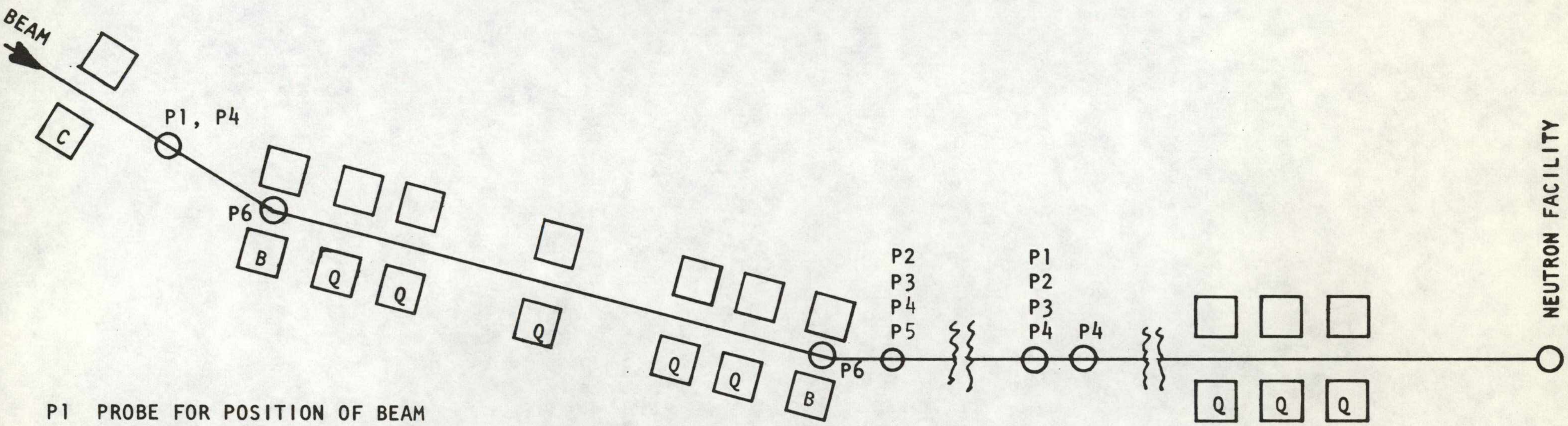
Relevant beam line information will be displayed in the experimental trailers as well as at central control. Routine maintenance of the beam line power supplies can be achieved using manual controls at the power supplies. Although these controls could be used to energize the power supplies in the event of a failure of the central computer, satisfactory operation of the complete facility in such a situation would be difficult to maintain. Figure 11 shows beam line 1 magnet and diagnostic configurations.

5.1 Beam Line Diagnostics

In order to check the performance of such beam transport elements as bending magnets, combination magnet, and quadrupoles, some beam diagnostic equipment is required. Such equipment includes devices for monitoring beam position, profile, divergence, and intensity.

A non-intercepting beam position sensor has been developed by K. Johnson and W.J. Rambler of Argonne National Laboratory.[5] This device is capable of locating the centre of a DC beam with an accuracy of ±0.1 mm at a beam current of only 0.03 μA. The system uses two sets of detection coils, one set for horizontal location of the beam and one set for vertical location. Three preamplifiers close to the detection coils are required. These in turn drive the final amplifier and a detector. Six such devices are proposed for beam line 1.

H.E. Wegner and I.L. Feigenbaum of Brookhaven National Laboratory in New York have modified a commercial oscillating beam scanner for measuring beam profiles of high current density.[3] The highest beam



P1 PROBE FOR POSITION OF BEAM

P2 PROBE FOR SPATIAL DISTRIBUTION OF BEAM

P3 PROBE FOR DIVERGENCE OF BEAM

P4 PROBE FOR INTENSITY OF BEAM

P5 PROBE FOR ENERGY RESOLUTION OF BEAM

P6 PROBE FOR MAGNETIC FIELD STRENGTH

C COMBINATION MAGNET

B BENDING MAGNET

Q QUADRUPOLE

Fig. 11. BEAM LINE SCHEMATIC. Beam line arrangement showing typical magnet target and diagnostic locations. Data inputs from central control set power supply currents and position targets. Data read back to central control are magnet currents, power supply and magnet temperature, diagnostics and target data.

power density so far scanned by this device is about 35 kW cm^{-2}. Heat transport calculations, however, have indicated that this type of scanner should be capable of handling beam power densities as high as 80 kW cm^{-2}. The scanner consists essentially of a water-cooled loop made out of 0.64 mm diameter stainless steel tubing. The loop oscillates through the beam with a frequency of between 10 and 15 Hz. The loop is shaped in such a way that one element scans through the beam in the X direction while another scans in the Y direction. A combination of light source and photocell provides fiducial marks which can be displayed with the signal on an oscilloscope. The fiducial marks show the centre of the beam pipe in the X and Y direction. For TRIUMF's beam line 1 four such devices would be required.

The beam envelope can be monitored using motor-driven jaws placed at appropriate places along the beam line. Each set of jaws would consist of one vertical and one horizontal pair of thin foils. Relative beam current will be determined by measuring the secondary electron current from the foils. By moving the jaws into the beam and recording the distance from the centre of the beam pipe when a certain integrated collected current is reached, a measure of the beam size can be obtained. Three sets of jaws along beam line 1 should be sufficient.

Hohbach and Mango working at CERN in Geneva, Switzerland have developed a beam current intensity monitor for the CERN Proton Synchrotron.[2] The device is a non-intercepting sensor with a band width from 10^{-4} Hz to several hundred MHz. The system consists of two transformers, their preamplifiers, a control unit, and the digital display unit in the control room. A simpler version of the CERN system could probably be employed for the TRIUMF beams which are characterized by 100% macroscopic duty factor. Figure 11 displays the positions of these diagnostic devices.

5.2 Beam Line Vacua

The vacuum requirements for the beam lines are less stringent than those for the cyclotron. Whereas the pressure requirements for the cyclotron itself involve considering the probability of electron stripping of the negative hydrogen ions, the pressure within the beam lines must satisfy the following criteria:

1) The Landau spread in energy loss of the beam while traversing the channel must be less than the energy resolution required of the beam (50 keV for separated-turn operation).
2) The degradation in optical properties of the beam due to multiple small-angle Coulomb scattering must satisfy the appropriate requirements (e.g. less than 10 mm-mr at the first pion production target in beam line 1).
3) The channels must not contribute significantly to the pumping load of the cyclotron vacuum system.

For the primary proton channels, criteria 1) and 2) are satisfied for air pressure of < 1 Torr. Mechanical pumps can easily provide pressure of $\sim 10^{-3}$ Torr. Pressure of such magnitude would, however, require a suitable window to protect the cyclotron vacuum system. Alternatively, the use of diffusion pumps throughout the beam line system (yielding pressures $\sim 10^{-6}$ Torr) could be coupled directly to the high vacuum system using a collimator system providing high impedance to gas flow.

Since a mechanical pumping system is undoubtedly simpler, some considerations about the necessary "window" are offered. In order not to degrade the optical quality of the beam, a light material window (e.g. beryllium) would have to be used. With a beam of 200 μA of protons, the maximum power dissipation would be $\sim$ 20 W/G cm^{-2} of material distributed over an area of ~ 0.1 cm^2. The mechanical problems arising from such a rate of energy deposition, not to mention those associated with radiation damage of the material itself, warrant consideration of the somewhat more complex approach. This would involve a collimator system larger than that discussed in connection with diffusion pumps. In this case, however, high capacity diffusion pumps would be inserted at the middle of the beam line unit to limit the gas flow into the cyclotron vacuum system.

For beam lines associated with secondary particles (such as meson beams), the beam currents are small enough so that no problems in the use of mechanical windows for isolation of vacuum systems are expected. In fact, such windows are recommended in order to allow modifications on a secondary beam line without affecting the vacuum of the primary beam line.

Considerations for the pion lines, similar to those for the proton line, indicate upper limits for the operating pressure of $\sim$0.1 Torr. Thus mechanical pumping systems like those described for the proton line should be adequate.

Beam line vacuum sensors will be distributed at various points throughout the system. They will be scanned a few times per hour and will be connected to the hard-wired machine safety system. They will also be coupled to a system for actuating "fast" vacuum valves to isolate various portions of the beam line if some vacuum component should fail. In general, the interaction of the various pumping stations with central control is similar to that of the cyclotron vacuum system.

6. VACUUM SYSTEM

As shown in Figure 12, the vacuum system can be subdivided into three sections, according to location. The primary equipment (vacuum gauge heads, cryopanels, etc.) is located in the cyclotron vault. Large mechanical devices (mechanical pumps, refrigerators, etc.) are in the mechanical services room. A "local" control panel will be at a third location. All data inputs to the central control system will come from the local control panel.

The local control panel is used for the vacuum system, since the large complete sub-systems commercially available - roughing and backing pump systems, helium refrigerator, and nitrogen liquefier - already have independent local controls capable of operating the sub-system. Consequently, the local control panel contains all the necessary status and alarm indicators as well as a complete sub-system safety arrangement. Some of the other sub-systems will have TRIUMF-designed controls (e.g., diffusion pumps, cold traps, vacuum gauges, and temperature sensors).

All the vacuum control sub-systems must be connected. Part of weekly maintenance will be devoted to recycling the cryopanels. It is proposed that operations of this sort be capable of being handled at the central control room as well as at the local control panels. This determines the vacuum system demands on central control. Central control must know whether the vacuum system is operating properly. Sensor alarm signals and vacuum system status signals must, therefore, be sent to central control. As in all bidding procedures for cyclotron and beam line equipment, the vacuum sub-system bids must contain specifications for logic levels of status indicators and on-off set points as options. Any change in the manual sub-system control to computer control is thereby simplified: a program of machine development is not hampered by sub-system logic incompatibility.

In total, 50 on-off indicators will service the helium refrigerator, the nitrogen liquefier, and the roughing and backing pump sub-systems.

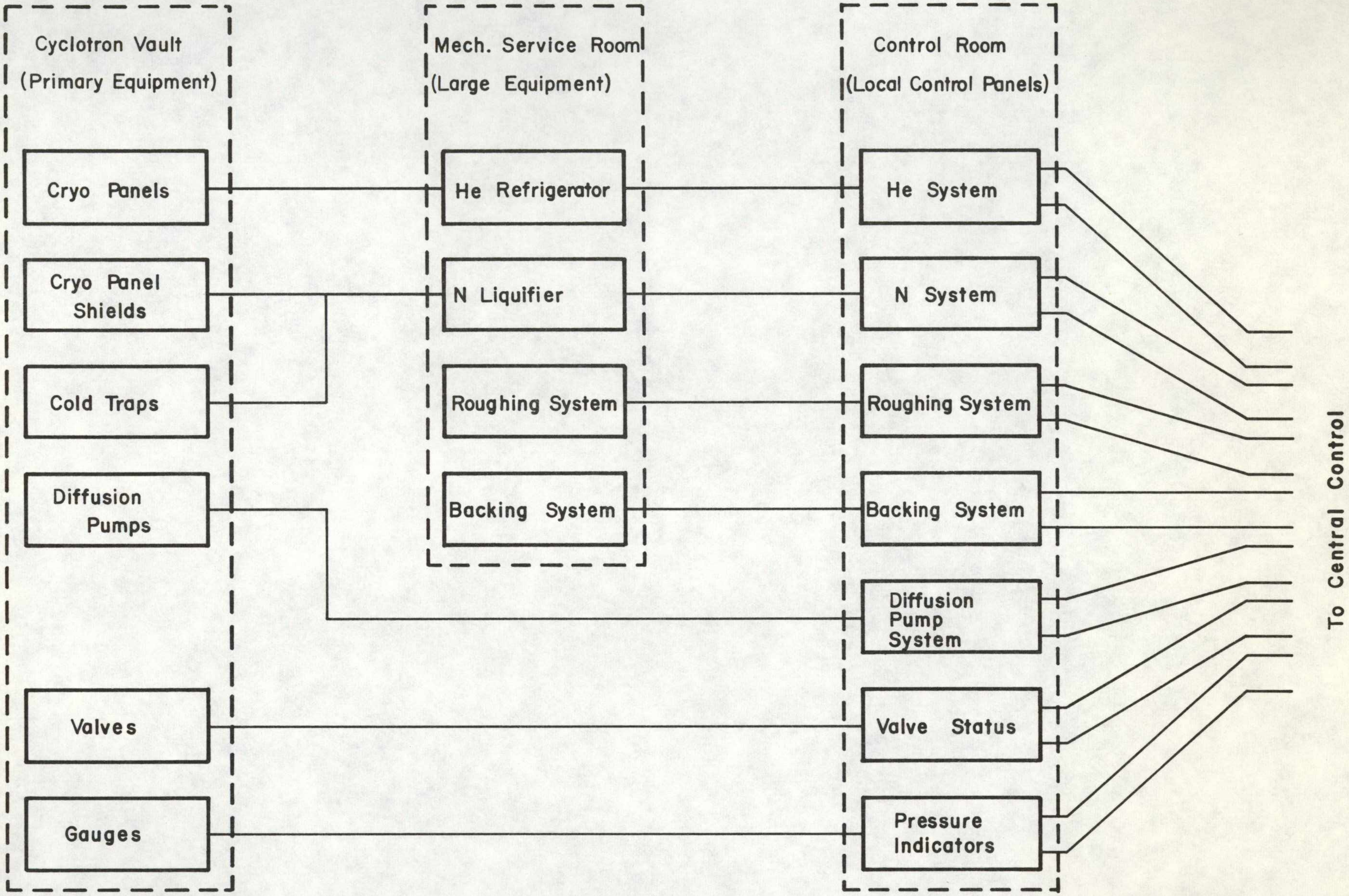


Fig. 12. VACUUM SYSTEM BLOCK DIAGRAM. The location of the vacuum system components are shown in schematic form. Control panels are provided to operate each sub-system and to interface that sub-system to central control.

About six of these indicators should be observable at central control. The diffusion pump sub-system will have 30 heaters interlocked to fore pump pressure with local on-off indicators. Five signals indicating a failure in any one of 15 heaters will be transmitted to central control.

Ion gauges for tank vacuum must be radiation hard and must perform reliably at 10^{-8} Torr. A gauge unit developed by W. Pierce[6] is being considered. Twelve such ion gauges will be installed, whose readings will be observable in the central control room as part of the scanned DAS. Seven thermocouple gauges will be used for monitoring tank pressure during the roughing process, and these readings will also be observable at central control. In addition, these signals will be compared with set points as part of the hard-wired machine safety system.

7. CENTRAL CONTROL

Central control must be capable of servicing about 300 set points and receiving data continuously from about 1200 sensors and reference points. Figure 13a is a schematic of such a system. Stored program devices are proposed as the central unit in this system. The operational parameters of the cyclotron are presented to the operating personnel so as to facilitate efficient monitoring of the operation of the cyclotron, including complete rapid indication of any abnormal situation. The controls must be arranged so that the operator can set the machine parameters quickly, yet with minimum chance for error. The control system should be flexible enough to facilitate independent operation of any of the cyclotron systems during commissioning of the cyclotron, yet sufficiently general to be adapted efficiently to the changing requirements of subsequent cyclotron development programs.

The traditional form of central control for cyclotrons, a totally manual central control console, is not recommended for the TRIUMF facility. This is not because the control functions are different, but because the size of the manual system required by TRIUMF would be both operationally inconvenient and prone to failure. A control console for the 300 set points would be about 18 ft long. An additional wall-mounted display rack of about the same length would be needed to monitor the 1200 display points. This console would require five alert operators per shift to manage the cyclotron. The setting of machine parameters would be a lengthy process. For example, about one hour would be needed to set the transport optics on beam line 1 alone. The large number of parallel systems required would also be a serious maintenance problem. The set point actuators (potentiometers and rotary switches) would contribute about 10 days per year of machine downtime. The larger operating staff required (compared to that needed for the stored program system recommended for the facility) would cost an additional $100,000 annually. Control room maintenance would require roughly $12,000 more annually than the alternate, computer-based system.

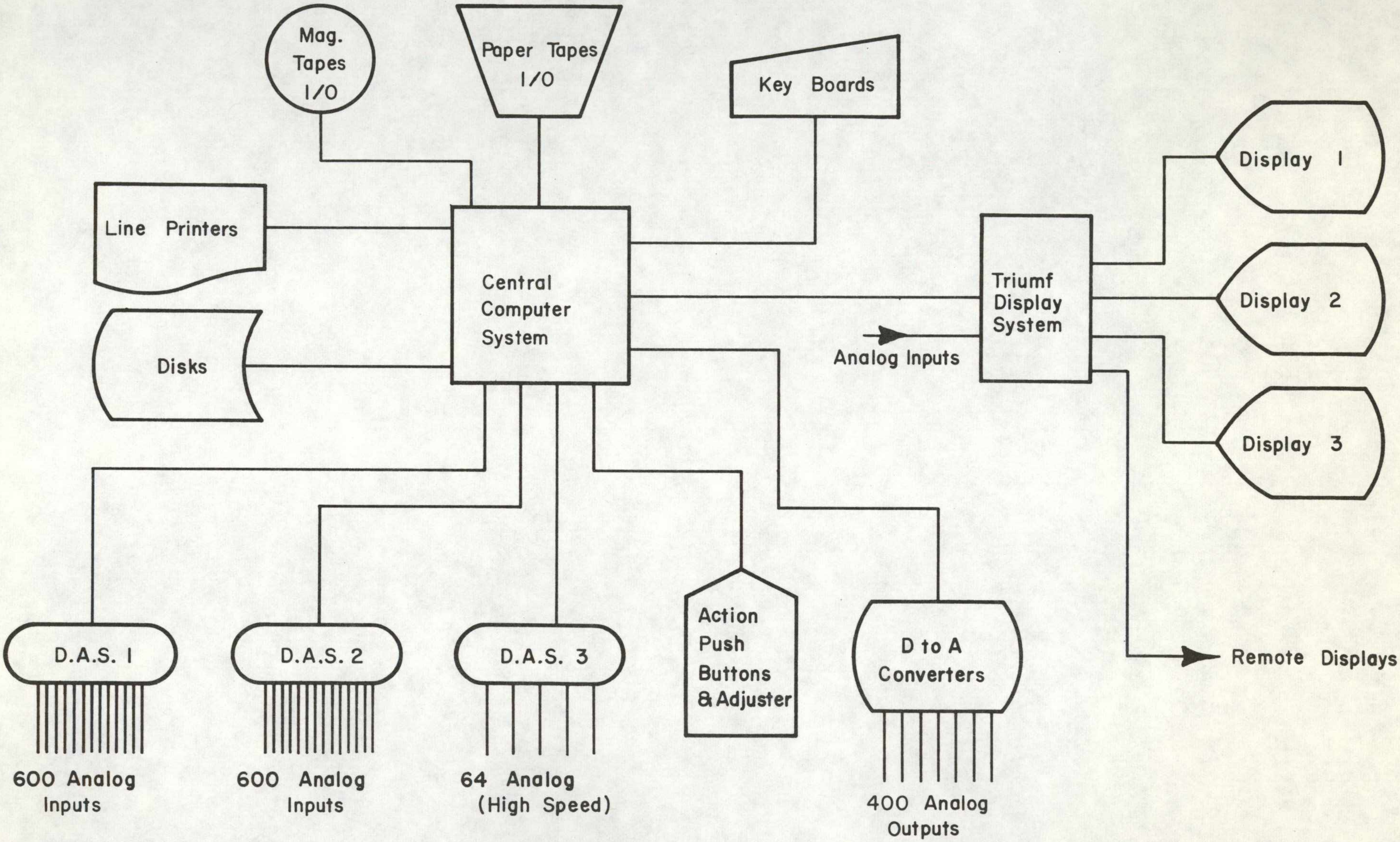


Fig. 13(a). CENTRAL CONTROL SYSTEM. The central computer system receives data from data acquisition systems (DAS) and operates remote power supplies, etc., through D to A converters. The operator communicates with the computer through knobs (shaft encoders), pushbuttons, and typewriter keyboards. The computers answer via CRT displays and printer hard copy.

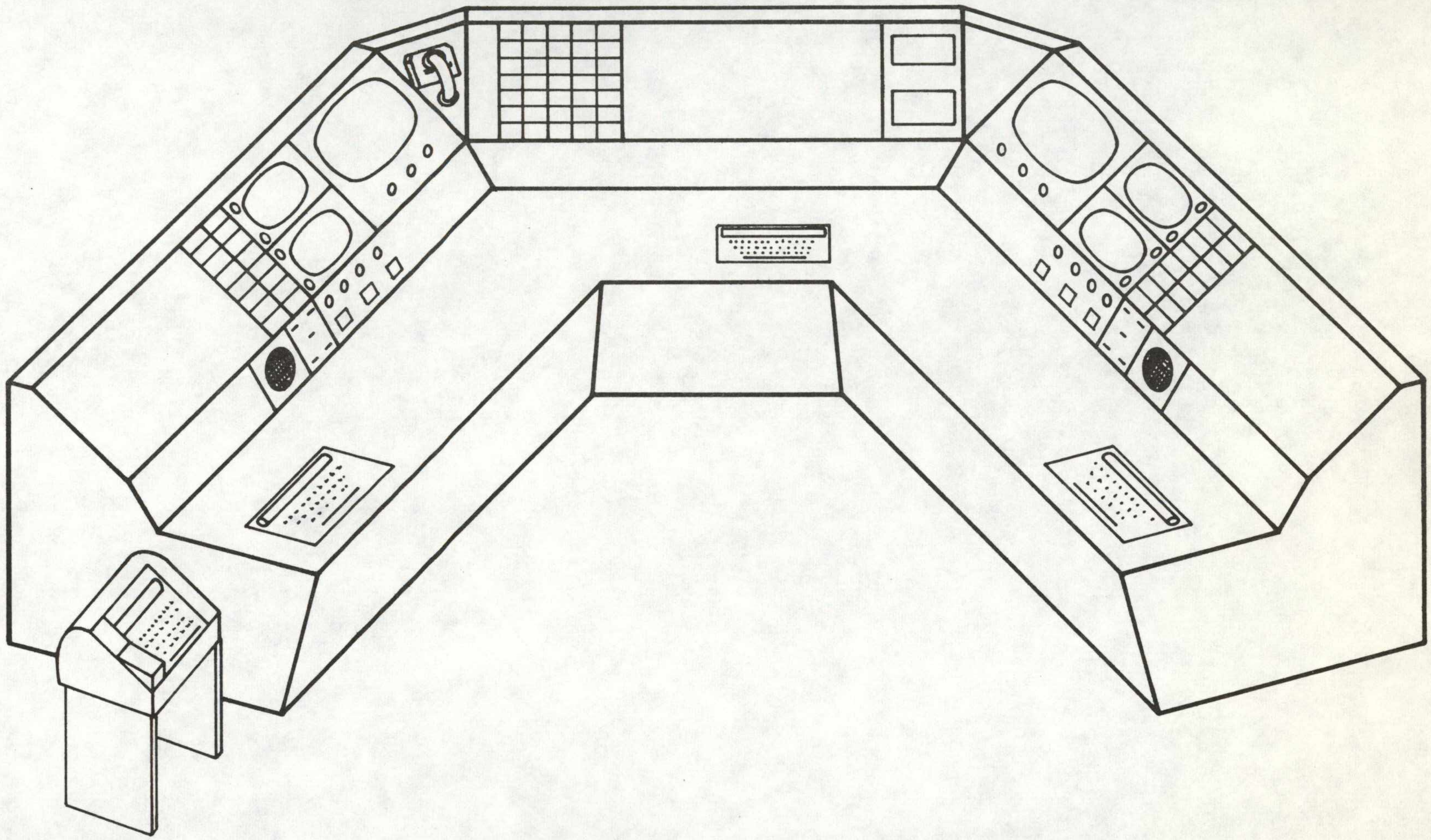


Fig. 13(b). AN ARTIST's VIEW OF CONTROL ROOM CONSOLE. Two identical operator stations are located between a central alarm station.

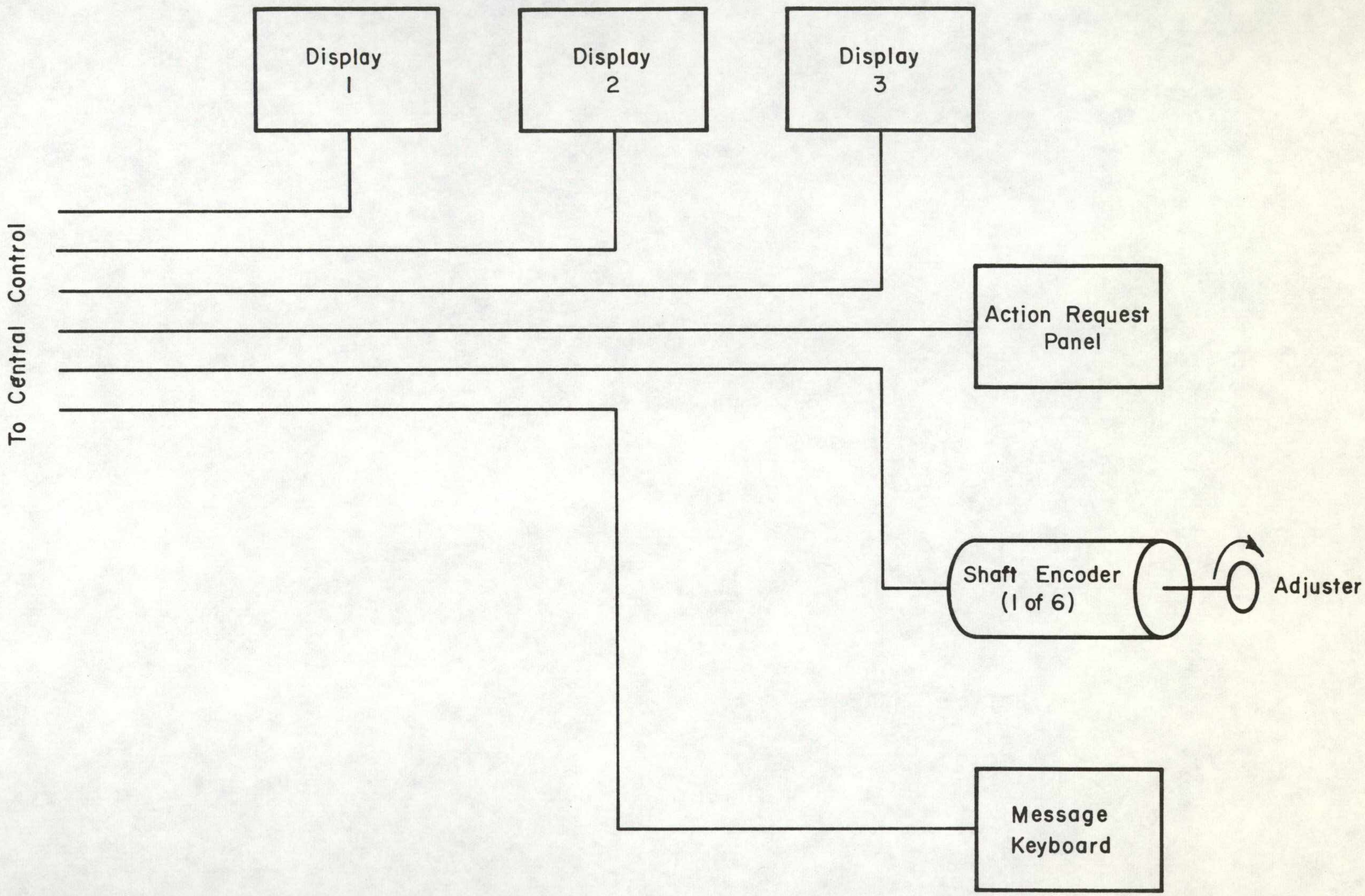


Fig. 13(c). OPERATOR STATION. Information required by the operator appears on the display CRTs. The operator can request information and other actions by the computer by pushbutton panel or typewriter keyboard. Tuning adjustments of power supplies, etc., are effected by six shaft encoders acting through the computer to the selected device.

7.1 Central Computer Approach

A system based on the use of central stored program devices is recommended. Some bunching would be performed by dedicated, hard-wired systems that would not be a part of the computer-based system. These would include the personnel safety and machine protection system. In addition, regulation of power supplies, etc., will be performed by local dedicated analog control systems. All other "control" functions in the facility, however, will be performed by central control.

For such a highly-centralized system to be successful, that is to operate reliably without extensive hard-wired back-up systems, the equipment must be very reliable. In this conceptual study, 99% availability (or 100 hours per year downtime) is assumed. This figure is reasonable, providing the following conditions are met.

In using TRIUMF personnel for computer maintenance, an average of one-half hour travel time per failure is assumed. Since most faults in a computer-based control system occur in the associated electro-mechanical equipment, two identical operator stations (consoles), interfaced to common processor and memory units, provide a large amount of instrumental redundancy. The system functions as long as either of these consoles is operating. In addition, none of the computer input-output equipment, such as the magnetic tape unit, the logging typewriter, or the programming typewriter, is essential for cyclotron operation. Magnetic discs, however, are an integral part of the control system during normal operation. Failure of a disc presumably would mean a shutdown. It is essential also that at least <u>one</u> of the two typewriters be working.

The cyclotron will be operating up to 80% of the time, 24 hours a day, seven days a week. Time will be scheduled, probably once a week, for repair and preventative maintenance of the whole facility. The computer-based control system should facilitate preventative maintenance by information recorded with appropriate programs. In addition, the redundant instrumentation described permits much of the maintenance to be performed while the overall installation is in operation.

Discussions with computer manufacturers reveal that a mean time between failure, which in one case includes failures of input channels as well, of better than 1000 hours can be assumed. This is fewer than eight failures per year. With a TRIUMF trouble-shooting staff, repairs should average no more than two hours. Although some failures will undoubtedly be more elusive, the design criterion of fewer than 100 hours per year downtime should be attainable.

From a programming standpoint, of course, any increase in complexity increases the possibility of software problems. With a reasonable time for control system debugging, however, and allowing for some debugging during machine conditioning, most software problems can be eliminated by the time the machine is operating. Development of appropriate flow programs for the control system should be one of the first areas in which effort is expended.

7.1.1 Functions of Control Computer

1) Data acquisiton - All static or quasi-static variables will be scanned in a sequence controlled by the computer. The variables include all magnet currents, quadrupole currents, beam diagnostic readouts, most temperatures, etc. At present, there are about 1200 inputs specified for the system, and by commissioning, this number will probably have increased to 1500-1800.

2) Monitoring - Monitoring temperatures is accomplished by using either thermocouples or resistance thermometers. Resonator temperatures are monitored with thermocouples, whereas all coil temperatures are determined by using the computer to read current and voltage in order to calculate magnet coil resistance. This temperature detection system will branch to alarm or shut-down sequences. Any other variables scanned, off normal limits, will be displayed without facility shutdown. The alarm and

shutdown system operates as follows: Within the computer each variable is compared with the normal operational value and possible deviations are compared to allow excursion limits. If a limit is exceeded, the operator is notified by a printout and/or CRT display, accompanied in some cases by an acoustic alarm signal. The scanning is then modified automatically to concentrate on the offending input, and related inputs, to determine if the abnormal condition is due to a sensor failure. If it is not, another program determines the seriousness of the alarm. It then informs the operator of necessary corrections, together with the time that will elapse before the condition becomes critical and hard-wired protection systems shut down the facility.

3) Remote Setting - Set points must be generated for the 250 - 300 power supplies in the system. It is assumed that in the initial stages of operation these will be set manually by the central control room operator. This will be accomplished by using twelve (six at each of two consoles) "control point set" potentiometers or push buttons. The computer will multiplex these stations so that they can operate any of the power supplies. Each power supply will contain a one-word buffer memory and a digital-to-analog converter for receiving and storing signals from the computer and for generating the analog set point to use as a reference level in a fast local control loop. It should be noted that if the computer fails, all power supplies will remain functioning at a level corresponding to the last set point signal transmitted to its one-word memory.

4) Remote Startup - All startup of remote equipment, where possible, will be initiated by the operator through the computer. While the operator can start and stop all devices, a group of devices, e.g. beam line 1 magnet power supplies, can also be automatically started. These would be timed to reduce the inrush on the power system. Sub-systems such as vacuum pump startup would also be initiated from the central control station. For vacuum tank

bakeout the central system would control the rate of temperature rise on the basis of vacuum tank pressure to ensure that the vacuum system is not overloaded.

5) Closed Loop Control - The extent to which primary control loops are closed through the computer during initial stages of operation is expected to be very small. With the configuration recommended, however, all important primary variables (beam diagnostics, etc.) as well as all secondary variables are available in memory, and all control point set values are initiated from the computer. Therefore, to close any primary loop one need only introduce the appropriate algorithm into the program. Although this may increase the rate of scan for those particular variables, no hardware changes are anticipated.

6) Machine Shutdown - Orderly and efficient shutdown of the cyclotron is facilitated by stored program control systems. At present, however, fast alarm shutdown will not be directly initiated by the computer. This is the function of a hard-wired protection system which will terminate the beam on abnormal operation. These systems will, in addition to terminating the beam, initiate a program interrupt in the computer. The computer will then shut down other parts of the system in an orderly fashion.

7) Data Logging - Two devices for logging data will be included. One is a printer which will produce hard copy. Logging information in this manner will be minimal so that information can be readily analyzed. Detailed operational data will be logged on magnetic tape. It will include all data read over a period of several hours. This historical information will be continuously updated with no editing, so whenever a failure occurs a detailed record of the previous several hours' operation will be available for analysis. This tape should be compatible with the IBM 360 tape drives so that routine analysis can be performed at the UBC Computing Centre.

7.1.2 Computer and Data Acquisition Equipment Configuration

Most of the computer hardware and peripherals and most of the data acquisition equipment will be located in the central control room close to the cyclotron operators.

The following equipment will be provided:

1) central control computers
2) paper tape input-output equipment
3) digital magnetic tape transport
4) disc bulk storage units
5) data acquisition equipment
6) teletype printer-keyboard
7) integrated display system

The central control room will have three stations: two operation stations and one alarm station. An overall view of the control room console is presented in Figure 13b. The two operation stations will be identical but will allow two different functions to be performed simultaneously (time-sharing) by two operators. For example, one operator could be checking the harmonic and trim coil settings while a second operator could be checking the beam line operation.

An abnormal or shutdown condition would be indicated at the alarm station by a flashing light and possibly by a horn, together with an appropriate printer output or CRT display. The operator would have to acknowledge the alarm to turn off the light and horn.

An operator station will include the following items. These items are displayed on the schematic drawing of the station, Figure 13c.

1) CRT displays programmed to display in digital form any group of variables. A display having up to 950 alpha numeric characters is available.
2) An alpha numeric keyboard will communicate with the computer.

3) Six remote set point stations.

4) A number of push buttons will, through interrupts, produce certain control station configurations. For example, pressing a button marked "Laboratory 1A" would show magnet currents for the group of magnets between pion production target #1 and the experimental area, target #1 position, stripper position, beam energy and current, etc. It would also connect to the appropriate magnet power supplies between the target and the experimental area the six control point set actuators.

   The number of pushbuttons will be determined as programming details evolve. Since the specific function for each button will be determined by the program associated with the button, their purpose can be changed at any time.

5) Three oscilloscopes to display dynamic variables will be connected directly to the sensor amplifiers. A matrix system should be included to allow any variable to be displayed on any of the oscilloscopes. Three oscilloscopes per station appear to be adequate, although as details evolve more may be preferable. On the other hand, this job may be handled by the integrated display system.

The alarm station will include the following:

1) An alarm printer

2) A logging printer which will become the alarm printer if the alarm printer is not operating

3) A CRT display

4) An alarm light and horn equipped with an acknowledge button

During an alarm the light will flash, the horn will sound when appropriate, and the printer will output the abnormal condition (including whether it is a warning alarm or shutdown, as well as timing information). Coincidentally, the relevant variable will appear on the CRT. "Acknowledging" the alarm will stop the horn and the light but will not affect the CRT display. When the variable returns to normal, the same process will repeat except that the CRT display will disappear. The CRT will therefore provide a summary display of all abnormal conditions. It will also be possible to print out at any time a summary of abnormal conditions.

All changes in major variables made by the operator could be included on the alarm printer. This hard copy then would become a shift report. Thus each operating shift would be provided with a printout of all abnormal conditions occurring in the previous shift. As each shift proceeds, a record is made of additional abnormal conditions as they occur. Repairs, the timing for facility shutdown and start-up, changes in beam current, stripper foil positions, target positions, etc., could also be included as part of this shift report.

Program Development Area

Since the computer system recommended involves "small" computers, a duplicate back-up unit to protect the system against long shutdown owing to computer failure is advantageous. The back-up computer would not normally be required in the control system, so it would be available for developing and debugging new control programs without erroneously affecting system control. If only control computers were available, all program testing would be postponed until facility shutdown, or else extensive software protection would be necessary. In either case, extra paper tape input/output equipment and a teletypewriter adjacent to the operating area would facilitate program development.

7.1.3 Proposed Computer Configuration

Control systems based on single-CPU, twin-CPU, and multi-CPU processing have been investigated, bearing in mind the necessity for considerable independence of the design groups during commissioning. The twin-CPU and the single-CPU configurations offer little independence. A computer system based on these two systems would be the limiting instrument for parallel development of accelerator functions.

On the other hand, a multi-CPU system offers a high degree of independence. Figure 14 shows the control system during its development phase. Set point control and data logging will be provided independently for facility functions.

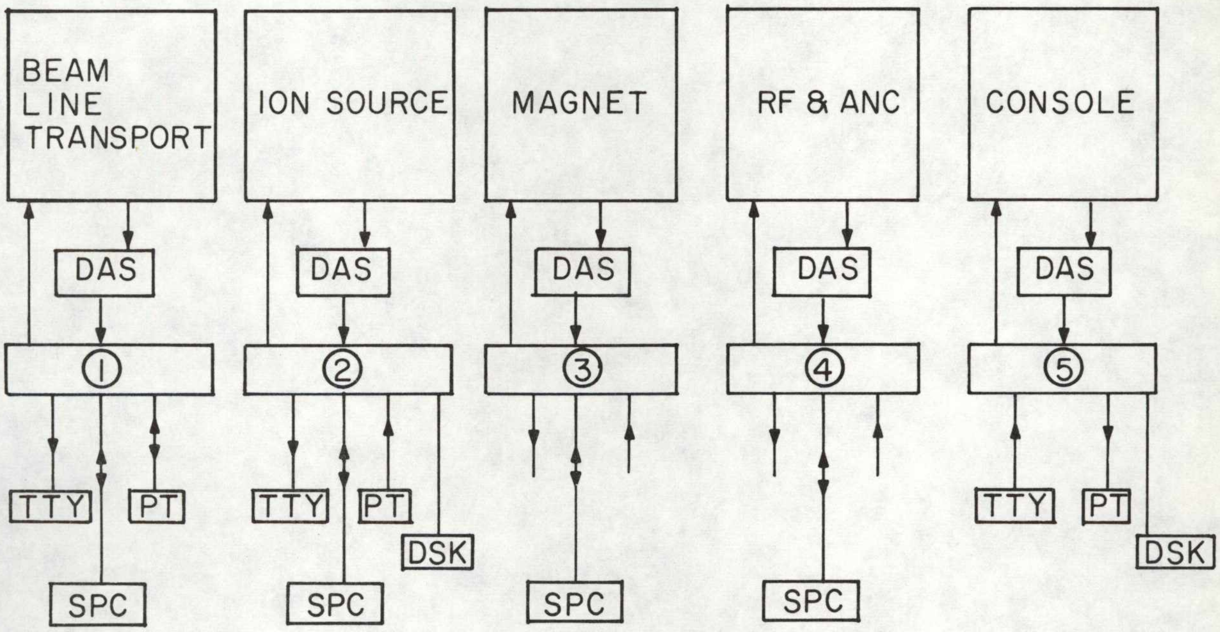
At commissioning, the accelerator functions will be unified into a control system operated from a central control console. Figure 15 shows the integrated control system. Computer 6 operates as a data log as well as a supervisory monitor.

7.2 Communication Systems and Experimenter Interface

To use high energy beams experimental personnel must have ready access to an updated summary of beam parameters and facility status. Similarly, efficient operation of the facility requires that central control be kept informed of the activities and needs of experimental groups.

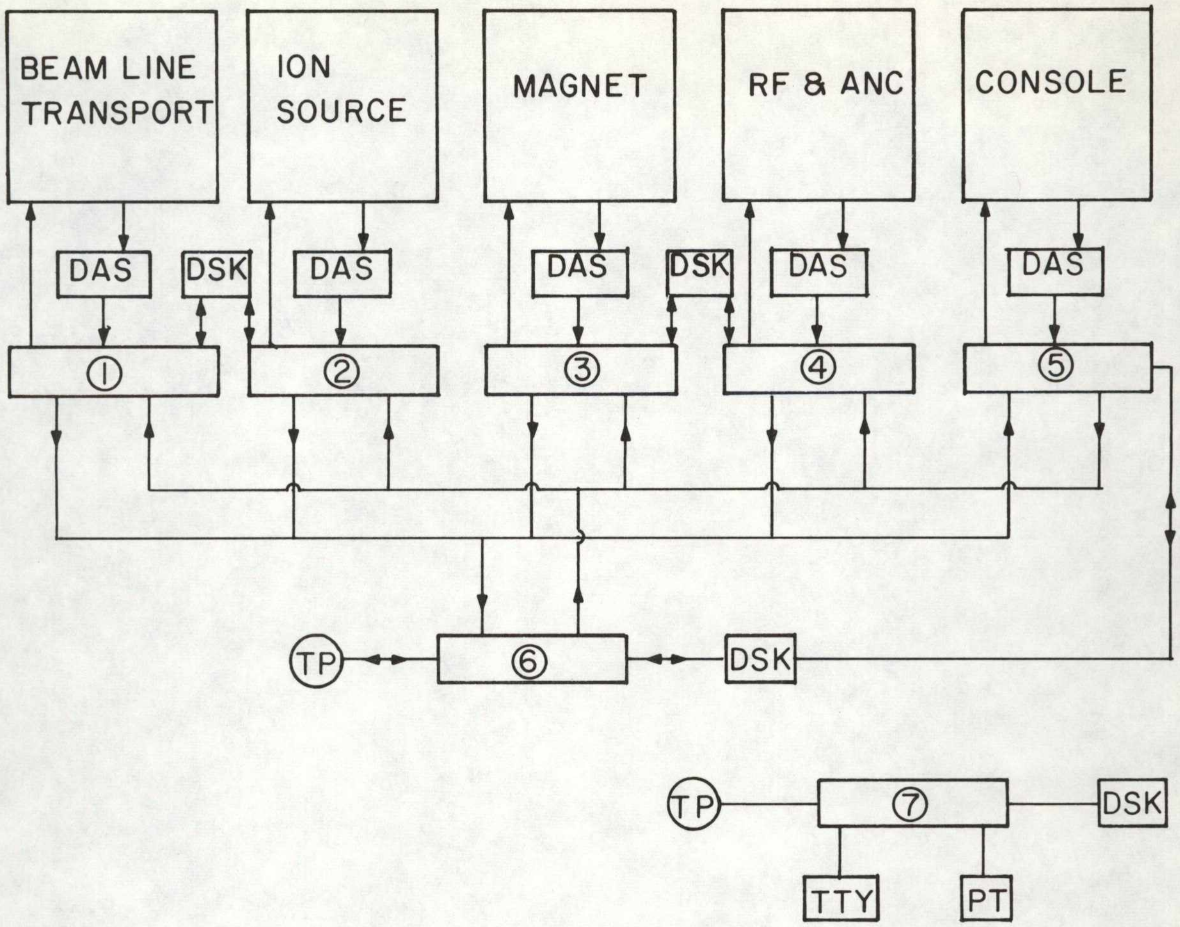
7.2.1 Communications

At present, two uses for TV are envisaged: remote monitoring of "hot" areas, especially experimental areas, by experimenters; and computer output display. Picture monitors suitable for both purposes will be located both at the main control desk ($\sim$3 monitors) and at the experimenters' locations ($\sim$10x1=10). At all locations a variety of signals can be displayed on the monitor. Remote adjustments of all cameras should be made from a central location containing a high-quality television waveform monitor. A convenient method of displaying a variety of signals is the use of conventional TV monitors together with a character generator to convert computer output signals into the appropriate video signal. At least five such computer-to-video generators, having a capacity to store input signals and to accept data for display as fast as the computer can deliver data are necessary. Two channels will contain up-to-the-minute tables of data pertaining to facility operation (beam



SPC - SET POINT CONTROL

Fig. 14. DEVELOPMENT CONTROL SYSTEM. Prior to machine integration of the various accelerator functions, the equipment configuration displayed above will allow each group to develop their system independently.



DAS - DATA ACQUISITION SYSTEM
DSK - DISK
TP - MAGNETIC TAPE
PT - PAPER TAPE
TTY - TELETYPE

Fig. 15. INTEGRATED CONTROL SYSTEM. The control system after commissioning is based on the sub-system central processors (1-4) in communication with a central control console (5) and an executive control (6).

statistics, present mode of operation, etc.), and three would provide additional information required by the operator. Such systems would also, of course, provide analog storage and display. The Tektronix 4501 analog-to-television converter is a currently available unit which performs the computer-to-video generator function described. Figures 16 and 17 show a schematic description of the TV system.

The computer output will consist of a two-channel (x and y) D/A converter and a character generator. The converter will display graphical data and the character generator, alpha-numerical data such as tables of operating conditions.

An intercom system containing a matrix of input and output lines in which connections of crosspoints performed by remote control operation is recommended. The input lines come from at least three sources: close-talking PA microphones (main control desk, experimenters' areas, etc.); wide-angle "loudspeaker" microphones (maintenance shop, etc.); and radio-telephone to the vault. Each input line will have a microphone preamp (high or low gain) at the intercom rack in the main control room. Outputs of two types are recommended: low power amplifiers ($\approx$0.1 watt) driving 4-inch speakers, and $\sim$5 watt amplifiers driving paging loudspeakers. The output amplifiers will also be located in the intercom rack. Crosspoint connections consisting of remotely controlled diode gates provide flexibility and room for expansion. Additional circuits are obtained by inserting appropriate crosspoint switches in the matrix.

"Walkie-talkie" sets will also be available. They will be connected to the intercom system via an appropriate base station.

No telephone units are recommended. The local telephone company should provide a telephone system for communication outside the facility as well as between local stations.

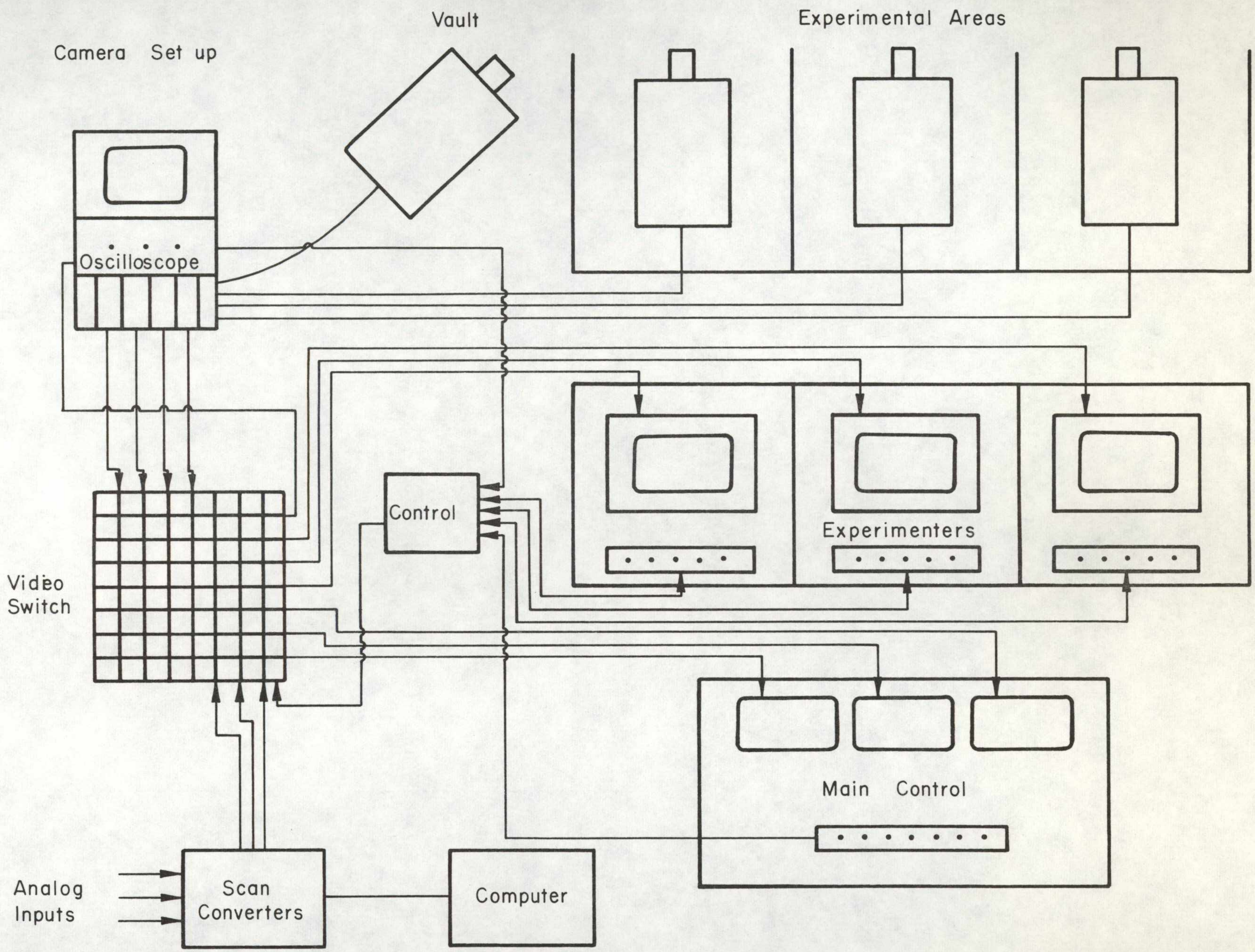


Fig. 16. TELEVISION DISPLAY SYSTEM. The television portion of the integrated display system includes monitors located anywhere in the facility viewing, by remote switching, any video source: TV cameras, computer outputs, or beam diagnostics.

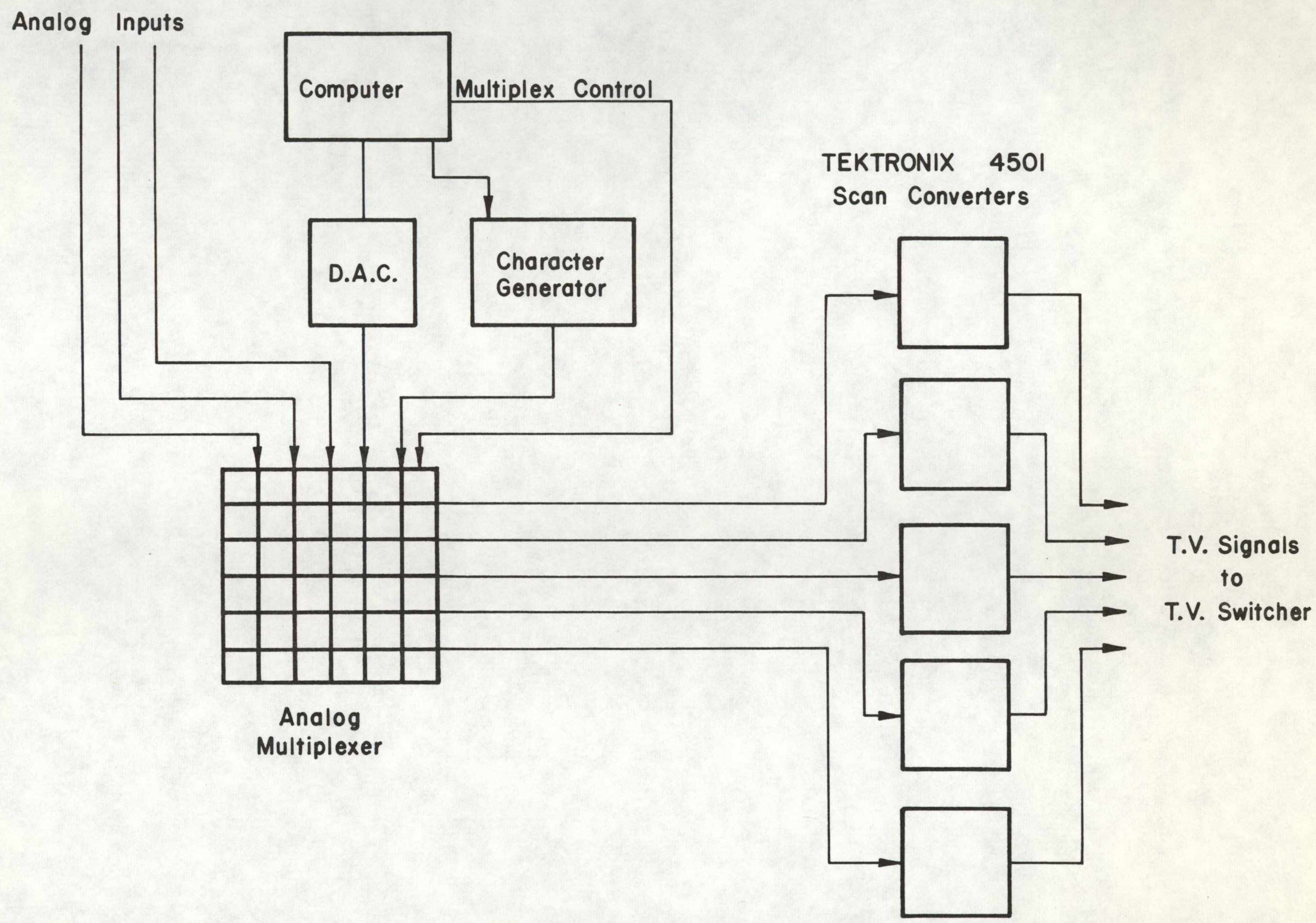


Fig. 17. SCAN CONVERTERS. The 4501 accepts input data as a conventional storage oscilloscope and converts this data to a TV image. The computer can plot graphs or write pages of tabular information.

7.2.2 Experimenter Interface

The experimenters will have two locations of concern to the control system. They will have their own "trailers" (portable local counting rooms) parked above the "experimental area" containing their equipment. Generally the experimental area will not be accessible when beam is being used. The trailers will contain standard intercoms, TV monitors and set point controllers, as shown in Figure 18. Initially the experimental area should have an intercom only to the associated local counting room. Since the local counting room will be connected with the overall communication system, any communication required between an experimental area and another part of the facility can be provided via the associated local counting room.

The TV monitor will receive data from the central control room and, if desired, from a TV camera in the experimental area. Set point controllers connected to the central control system will provide the experimenter with limited control. The TV monitor will be of standard broadcast quality. A video switcher will permit display of any of a number of video sources including two or three data outputs from the central control computer, any remote cameras in "hot" experimental areas, and several spare inputs for future use. The set point controllers will be the same as those used by the cyclotron operator at the central control room.

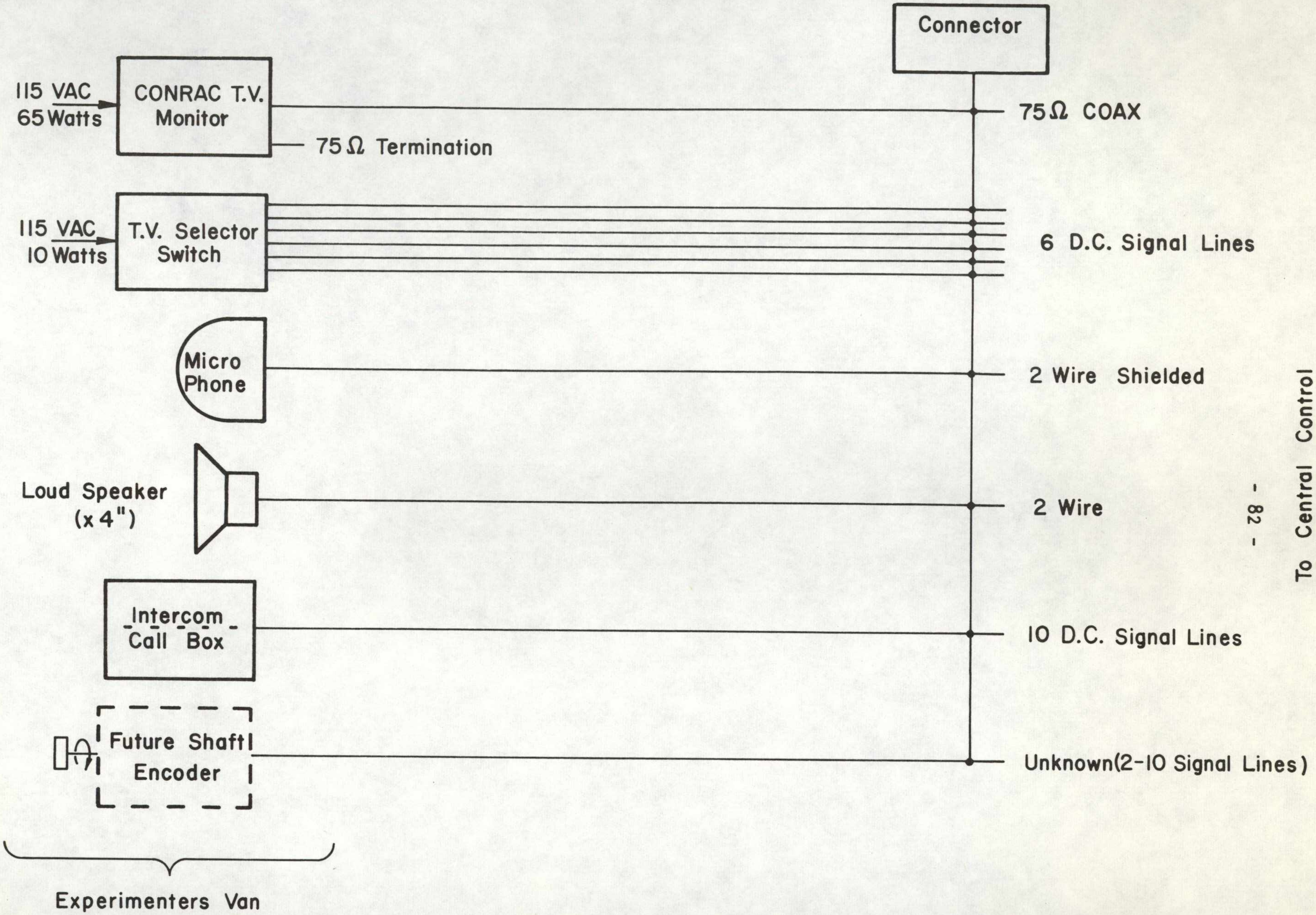


Fig. 18. EXPERIMENTERS INTERFACE. This equipment will be installed in the experimenters van and will be connected to the facility via a standard connection.

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