STUDIES OF A
LEAD-SCINTILLATOR CALORIMETER
WITH FAST RESPONSE

By
JEAN ROY
B.Sc., Université de Montréal, 1986

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

in
THE FACULTY OF GRADUATE STUDIES
Department of Physics

We accept this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA
October 1988
© Jean Roy, 1988
In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the head of my department or by his or her representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Department of PHYSICS

The University of British Columbia
Vancouver, Canada

Date 10/14/88
Abstract

We describe in detail a fast photon calorimeter for the endcap region of the BNL (Brookhaven National Laboratory, U.S.A.) experiment 787 detector. The experiment, conducted by a collaboration of physicists from BNL, Princeton University (U.S.A.) and TRIUMF (Canada), studies the rare kaon decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and aims at measuring its branching ratio with a sensitivity of $2 \times 10^{-10}$, almost three orders of magnitude better than the current best measurement. A short description of the physics involved is given as well as a description of the overall detector.

The endcap calorimeter is formed of two almost identical systems, one at each end of the cylindrical detector. Several requirements must be met: compact design, high efficiency of photon detection, low energy threshold and fast counting ability. This is achieved with a segmented lead-plastic scintillator sampling calorimeter with wavelength shifter read out system. Each endcap is formed of 24 individual modules tightly assembled to minimize non-active areas. The scintillator-wavelength shifter combination used, NE-104 and BBOT, was found to give very fast pulses of approximately 10 ns FWHM. The light output obtained is about 10 photoelectrons per MeV deposited in the scintillator. A detailed description of the modules and their working principle is given.

Since the endcaps will operate in a high rate environment, radiation damage to NE-104 scintillator was studied. It was found that the light output diminishes by a factor of two for a dose of about $18 \times 10^6$ rad. However, with an expected dose in the endcaps for the whole duration of the experiment of about $1 \times 10^6$ rad, we find that radiation damage is not a cause of concern.
Two endcap modules were tested in a particle beam at TRIUMF to
determine the linearity of the energy response and the resolution as a function of
energy. The linearity was found to be excellent over the energy interval 30 to
140 MeV. The energy resolution can be well represented by

\[ R = \frac{(6.2 \pm 0.1)\%}{\sqrt{E}} \]

where \( E \) is the energy in GeV. This is comparable with the results obtained for a
similar calorimeter, used in the ARGUS detector at DESY, which uses a
wavelength shifter (BBQ) with a much slower decay time.

The energy calibration of the endcaps was done using monoenergetic muons
from the decay \( K^+ \rightarrow \mu^+\nu_\mu \). Doing the calibration in the experimental conditions
insures that the systematics will be the same as for the physics data. The
expected energy in the endcaps for this decay was determined by a Monte Carlo
calculation using a programme called UMC, specifically designed for E787. A
verification of the calibration could be done by measuring the energy of the two
photons coming from the decay of the monoenergetic \( \pi^0 \)'s of the \( K^+ \rightarrow \pi^+\pi^0 \)
decay. The value obtained is consistent with what is expected.

The latter decay is also used to calibrate the endcaps' TDC's. It is achieved
by selecting events with well identified decay products, including one photon in
the endcaps. Offsets which make the time of the endcaps events the same as the
time of the positive pion are calculated using this data set. Both the energy and
time calibration are described in details. Online random vetoing by the endcap,
i.e. events rejected by the endcap energy veto because of random background hits,
is calculated to be about 1 %, using a clean sample of \( K^+ \rightarrow \mu^+\nu_\mu \). This rate is
also found to be dependent on the kaon beam intensity.

Finally, we found that the calorimeters described here performed very
satisfactorily for an extended data collection period. Nothing at the moment
indicates that they could be a limitation to the photon detection efficiency required to attain the ultimate goals of the E787 experiment.
Table of Contents

Abstract ii
List of Tables vii
List of Figures viii
Acknowledgements x

I Introduction 1

I.1 Experiment 787 at BNL ........................................ 1
I.1.1 The Standard Model .......................................... 2
I.1.2 \( K^+ \rightarrow \pi^+ \nu \bar{\nu} \) ...................................... 4
I.2 Kinematics and background ..................................... 6
I.3 The Detector .................................................... 7

II The Endcap Photon Veto 16

II.1 Description .................................................. 16
II.1.1 Design and Working Principle .............................. 16
II.1.2 Physical Description ....................................... 20
II.2 Choice of scintillator and wavelength shifter and tests .......... 25
II.3 Radiation Damage .............................................. 30
II.4 Construction of Endcap Modules ............................... 34

III Beam Test 37

III.1 Experimental setup and data taking .......................... 38
III.2 Results ...................................................... 40
## List of Tables

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Endcaps dimensions</td>
<td>20</td>
</tr>
<tr>
<td>II</td>
<td>Endcap modules’ dimensions</td>
<td>23</td>
</tr>
<tr>
<td>III</td>
<td>NE-104 scintillator tests</td>
<td>28</td>
</tr>
<tr>
<td>IV</td>
<td>Corrected beam energies for electrons</td>
<td>52</td>
</tr>
<tr>
<td>V</td>
<td>Energy resolution for electrons</td>
<td>52</td>
</tr>
<tr>
<td>VI</td>
<td>Final statistics for Monte Carlo simulation of the endcap $K_{\mu 2}$ calibration trigger</td>
<td>62</td>
</tr>
<tr>
<td>VII</td>
<td>Analysis result for run 1154 (Endcap $K_{\mu 2}$ trigger)</td>
<td>75</td>
</tr>
<tr>
<td>VIII</td>
<td>Endcap gains calculated with runs 1148 to 1154</td>
<td>77</td>
</tr>
<tr>
<td>IX</td>
<td>Analysis result for run 2235 (Endcap $K_{\mu 2}$ trigger)</td>
<td>80</td>
</tr>
<tr>
<td>X</td>
<td>Endcap gains valid for runs 2235 and above</td>
<td>81</td>
</tr>
<tr>
<td>XI</td>
<td>Analysis result for run 2444 ($K_{\pi 2}$ trigger)</td>
<td>90</td>
</tr>
<tr>
<td>XII</td>
<td>Time offsets check using the first set determined</td>
<td>93</td>
</tr>
<tr>
<td>XIII</td>
<td>Time offsets check using refined values</td>
<td>98</td>
</tr>
<tr>
<td>XIV</td>
<td>Analysis result for runs 2823 and 3026 ($K_{\mu 2}$ trigger)</td>
<td>98</td>
</tr>
</tbody>
</table>
# List of Figures

1. Highest order Feynman diagrams contributing to the \( K^+ \rightarrow \pi^+\nu\bar{\nu} \) decay .................................................. 8
2. Range distribution in scintillator for \( K^+ \rightarrow \pi^+\nu\bar{\nu} \) and its main background sources ........................................ 9
3. Side view of the E787 detector ........................................ 11
4. End view of the scintillating fibers segmented target .................. 15
5. Schematic diagram of working principle for endcap photon veto .... 19
6. Endcap photon veto .................................................. 21
7. Endcap module ....................................................... 24
8. Light output of scintillator for each large sheet received ............ 30
9. Light attenuation in BBOT ........................................... 31
10. Relative light output of NE-104 as a function of radiation acquired dose .................................................. 33
11. Schematic diagram of the online trigger for endcap beam test ...... 41
12. Pulse shape from module U16 ........................................ 43
13. S1 counter pulse height versus time of flight for beam momentum of 140 MeV/c .................................................. 44
14. S1 counter pulse height versus time of flight for beam momentum of 30 MeV/c .................................................. 45
15. Module U16 energy spectrum for 140 MeV/c pions ................. 46
16. Module U16 energy spectrum for 140 MeV/c muons ................ 47
17. Module U16 energy spectrum for 140 MeV/c electrons .............. 48
18. Example of least squares fit to 50 MeV/c electrons peak ........... 50
19. ADC peak value for electrons in module U16 as a function of beam energy .................................................. 51
20. Energy resolution of module U16 as a function of energy .......... 55
21. Y position versus X position of stopped kaons in the target ...... 59
<table>
<thead>
<tr>
<th>Page</th>
<th>Image/Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>Z position of stopped kaons in the target</td>
<td>60</td>
</tr>
<tr>
<td>23</td>
<td>Occupation plot of the endcap modules (Monte Carlo)</td>
<td>64</td>
</tr>
<tr>
<td>24</td>
<td>Energy distribution in one endcap module for $K_{\mu2}$ trigger (Monte Carlo)</td>
<td>65</td>
</tr>
<tr>
<td>25</td>
<td>Energy deposition in target live material for muons in the upstream endcap</td>
<td>66</td>
</tr>
<tr>
<td>26</td>
<td>Energy deposition in target live material for muons in the downstream endcap</td>
<td>67</td>
</tr>
<tr>
<td>27</td>
<td>Sum of muons energy distribution for all upstream modules</td>
<td>68</td>
</tr>
<tr>
<td>28</td>
<td>Sum of muons energy distribution for all downstream modules</td>
<td>69</td>
</tr>
<tr>
<td>29</td>
<td>Endcap $K_{\mu2}$ online trigger logic diagram</td>
<td>72</td>
</tr>
<tr>
<td>30</td>
<td>Endcap module spectrum for endcap $K_{\mu2}$ trigger (Module # 15)</td>
<td>74</td>
</tr>
<tr>
<td>31</td>
<td>Endcap module spectrum for endcap $K_{\mu2}$ trigger (Module # 9 with amplifier splitter box)</td>
<td>75</td>
</tr>
<tr>
<td>32</td>
<td>Percentage of events rejected versus beam intensity</td>
<td>78</td>
</tr>
<tr>
<td>33</td>
<td>Occupation plot of the endcap modules for runs 2882 and 2883</td>
<td>80</td>
</tr>
<tr>
<td>34</td>
<td>Range-momentum distribution of $K_{\pi2}$ events with one photon in the barrel veto and one in the endcaps</td>
<td>84</td>
</tr>
<tr>
<td>35</td>
<td>Visible energy measured for the photon in the barrel veto</td>
<td>85</td>
</tr>
<tr>
<td>36</td>
<td>Visible energy measured for the photon in the endcaps</td>
<td>86</td>
</tr>
<tr>
<td>37</td>
<td>Reconstructed $\pi^0$ energy</td>
<td>87</td>
</tr>
<tr>
<td>38</td>
<td>Time offset for endcap module # 47 (50 ch. endcap threshold)</td>
<td>91</td>
</tr>
<tr>
<td>39</td>
<td>A counter time minus endcap time</td>
<td>93</td>
</tr>
<tr>
<td>40</td>
<td>Scatterplot of pulse height against time offset (module # 47)</td>
<td>94</td>
</tr>
<tr>
<td>41</td>
<td>Random hits for each upstream endcap module as a function of time</td>
<td>99</td>
</tr>
<tr>
<td>42</td>
<td>Random hits for each downstream endcap module as a function of time</td>
<td>100</td>
</tr>
<tr>
<td>43</td>
<td>Random rate as a function of beam intensity (upstream endcap)</td>
<td>101</td>
</tr>
<tr>
<td>44</td>
<td>Random rate as a function of beam intensity (downstream endcap)</td>
<td>102</td>
</tr>
<tr>
<td>45</td>
<td>TINA function shape</td>
<td>112</td>
</tr>
</tbody>
</table>
Acknowledgements

First and foremost, I would like to thank my supervisor, Dr. Jean-Michel Poutissou, whose expert guidance and infinitely patient explanations gave me the inspiration to pursue this work to its conclusion and the urge to continue research in the same field. Special thanks also to all members of the E787 collaboration, from whom so much can be learned, in particular the TRIUMF contingent with whom I interacted the most. I wish I had enough space to thank them all individually.

Numerous people at TRIUMF were a great help during the endcap construction phase, in particular Chris Stevens and Steve Chan from the scintillator shop and André Fougères, summer student from the Université de Montréal.

At UBC, special thanks to Dr. David Measday who kindly accepted to be the formal link between TRIUMF and the University.

Moral support during the dark periods came from the graduate student “Tuesday-Thursday after 528 lunch” club. Many discussions about life, the universe and the latest hockey scores added the fun ingredient to grad school. Many thanks also to all my other friends who kept encouraging me.

On a more serious side, thanks to Jennifer who suffered through my long days tied to the terminal in the past few months. Your understanding was much appreciated. Et finalement, je remercie sincèrement mes parents, Louise et Gilles, ainsi que ma soeur Line qui malgré la distance m’ont toujours supporté pleinement.

This work was supported in part by an NSERC post-graduate scholarship.
Chapter I
Introduction

I.1 Experiment 787 at BNL

Over the years, kaon decays have been the source of several important discoveries, of which parity and charge-parity violation, weak neutral currents and the existence of charm are the prime examples. These discoveries helped to elaborate and refine the theory describing an increasingly large number of “elementary” particles and their interactions with each other, a theory now known as the standard model of weak and electromagnetic interactions (electroweak). Presently, calculations and predictions based on the standard model agree very well with the experimental values. Substantial effort is now being made to testing predictions of the model to a high degree of precision, to look for discrepancies and hunt for possible new phenomena. Studies of rare kaon decays are at the center of this effort.

Experiment 787 at the Brookhaven National Laboratory (U.S.A.) is one of the current major searches for rare kaon decays. It is conducted by a collaboration of physicists from Brookhaven, Princeton University (U.S.A.) and TRIUMF (Canada). The main goal of the experiment is to study the decay

\[ K^+ \to \pi^+ \nu \bar{\nu} \]  

and to measure its branching ratio with a sensitivity of about \(2 \times 10^{-10}\), almost three orders of magnitude better than the current upper limit of \(1.4 \times 10^{-7}\) [1]. Before we describe this decay any further, let us first briefly discuss the standard
I.1.1 The Standard Model

Presently, elementary particles can be subdivided in two groups: quarks and leptons, all fermions of spin $\frac{1}{2}$. The leptons are the electron ($e$), the muon ($\mu$) and the tau ($\tau$), all of unit charge, and their associated neutral massless neutrinos, $\nu_e$, $\nu_\mu$, and $\nu_\tau$. There are six different quarks (flavours): down ($d$), strange ($s$), and bottom ($b$), all of charge $-1/3$, and up ($u$), charm ($c$) and top ($t$), of charge $+2/3$. The existence of the top has yet to be confirmed, but is supported strongly by the framework of the model. All particles have their anti-particle counterparts, of exactly the same mass and spin angular momentum but of opposite magnetic moment, charge, and other quantum numbers (e.g. the anti-quark $\bar{u}$ has charge $-2/3$).

The particles interact via the four basic forces: gravity, electromagnetism, strong and weak. The interactions are mediated by vector bosons of spin 0. Gravity, described by Einstein’s general relativity, is experienced by massive particles and assumed to be mediated by a hypothetical boson called the graviton. The strong force, described by quantum chromodynamics, is experienced only by the quarks and the gluons, massless mediators of the force. Electromagnetism, mediated by massless photons, is felt by all charged particles. Already well described by quantum electrodynamics, it has been unified with the weak force in a common framework proposed by Weinberg, Glashow and Salam (WGS).

In this framework, based on the mathematical group $SU(2)_L \times U(1)$, quarks and leptons are grouped in left-handed doublets and right-handed singlets as
Each family, or generation, is treated identically. There does not seem to be any reason for having three seemingly redundant generations [2]. In fact, it is not even clear how many generations there are. This is one of the main puzzle particle physicists have to solve.

Weak interactions are mediated by three massive intermediate vector bosons, $W^+$, $W^-$ and $Z^0$. The WGS framework, presented in the late '60s, predicted these bosons; it was a triumph for this theory when they were discovered in an experiment at CERN in 1983. In the early history of weak decays, when only three quarks were known ($u,d,s$), it was observed that the decay rate of $\Lambda$ hyperons (quark content $uds$) was much smaller than the neutron ($udd$) decay rate. This lead Cabibbo to suggest that the physical $d$ and $s$ quarks were in fact linear combinations of the $d$ and $s$ quarks of the theory. Later, it was found experimentally that strangeness changing neutral currents (i.e. an $s$ quark decaying into a $d$ quark) were strongly suppressed. This led Glashow, Iliopoulos and Maiani (GIM)[3] to predict the existence of a fourth quark, charm. In particular, this explained the very small branching ratio of the reaction $K_L^0 \rightarrow \mu^+\mu^-$. The confirmation of the existence of charm in 1975 completed the second generation.

With the discovery of a fifth quark flavour, bottom, and the postulated top quark, the number of generations of quarks was brought up to three. Then, Kobayashi and Maskawa realized that the physical charge -1/3 quarks could be described by rotated states of the theoretical quarks, simply as an extension of the
Cabibbo scheme. The rotation is operated by a $3 \times 3$ unitary matrix:

$$
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix} =
\begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix} \tag{2}
$$

They parametrized the matrix, now known as the Cabibbo-Kobayashi-Maskawa (CKM) matrix, with three real angles and one complex phase:

$$
\begin{pmatrix}
  c_1 & s_1 c_3 & s_1 s_3 \\
  -s_1 c_2 & c_1 c_2 c_3 - e^{i \delta} s_2 s_3 & c_1 c_2 c_3 + e^{i \delta} s_2 s_3 \\
  s_1 s_2 & -c_1 s_2 c_3 - e^{i \delta} c_2 s_3 & -c_1 s_2 s_3 + e^{i \delta} c_2 s_3
\end{pmatrix} \tag{3}
$$

where $c_i = \cos \theta_i$ and $s_i = \sin \theta_i$. The very important point suggested by Kobayashi and Maskawa is that the complex phase $\delta$ could be the source of CP violation. The four parameters of the matrix are not predicted by the theory and must be determined experimentally.

### I.1.2 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

The $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay occurs via a flavour changing weak neutral current, since the positive kaon is formed of an $\bar{s}$ quark with a $u$ quark and the positive pion is formed of a $\bar{d}$ quark with a $u$ quark. As mentioned in the previous section, these decays are strongly suppressed in the standard model. They occur only via second order processes or higher. A reliable calculation can be performed to determine the expected branching ratio. Figure 1 shows the three highest order Feynman diagrams contributing to the decay. The process is very similar to the decay $K^0_L \rightarrow \mu \mu$, but does not suffer as much from long range effects, such as $K^0_L \rightarrow \gamma \gamma \rightarrow \mu \mu$. Therefore, $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is a "natural laboratory" to study high precision calculations for the weak interactions.

The branching ratio per neutrino flavour has been calculated [4] for a three generation model and is given by:

$$
BR(K^+ \rightarrow \pi^+ \nu_i \bar{\nu}_i) = 0.71 \times 10^{-6} \left| \frac{\sum_{i=e,\mu,\tau} V_{i3}^* V_{i2} D(x_i)}{|V_{us}|^2} \right|^2 \tag{4}
$$
where \( D(x_i) \) is a function of \( x_i = m_{q_i}^2/m_W^2 \), \( m_{q_i} \) being the quark masses and \( m_W \) the mass of the W boson. \( V_{q_i q_i'} \) are the CKM matrix elements introduced in the previous section. In the calculation, the mass of the \( u \) quark was taken to be zero and its contribution was eliminated because of the unitarity of the CKM matrix. The expression can be reduced furthermore to

\[
BR(K^+ \to \pi^+ \nu_i \overline{\nu_i}) = 0.71 \times 10^{-6} |D(x_c) + s_2(s_2 + s_3 e^{i\delta})D(x_t)|^2
\]  

(5)

The value of \( s_2 + s_3 e^{i\delta} \) is fixed by the value of the \( b \) quark lifetime \( \tau_b \). Recent observation of \( B^0 - \overline{B^0} \) mixing allows the determination of \( s_2 \) as a function of the mass of the yet to be confirmed top quark, using \( \tau_b \) and the \( B_d \) decay constant. With reasonable values for those parameters, the authors in [4] determine a branching ratio of

\[
BR(K^+ \to \pi^+ \nu_i \overline{\nu_i}) = (1 - 8) \times 10^{-10}
\]  

(6)

for a range of top quark masses of \( m_t = 100 - 200 \) GeV/c\(^2\). Hence, the decay could be observed by experiment 787 and a determination of the branching ratio would place further constraints on the top quark mass and the \( V_{td} \) matrix element and validate the standard model. Observation of a signal significantly larger than this prediction would be the signature of new physics. The simplest explanation for this would be the existence of new generations of quarks and leptons. A recent calculation of charged Higgs contributions [5] predicts an enhancement of about 1.5 times the standard model contribution. Other more exotic possibilities, such as supersymmetric particles, could also contribute.

The experiment is also sensitive to the two body decay

\[
K^+ \to \pi^+ X^0
\]  

(7)

where \( X^0 \) is any light, weakly interacting particle. Candidates for this hypothetical particle include axions and familons. As well, decays yet to be
observed, such as $K^+ \rightarrow \pi^+\mu^+\mu^-$ and $K^+ \rightarrow \pi^+\gamma\gamma$ can be studied. Also, the decay $K^+ \rightarrow \pi^+\pi^0$ ($K_{\pi 2}$), with a branching ratio of 21%, provides a copious source of tagged $\pi^0$'s (by precise identification of the positive pion) which allows for the study of rare $\pi^0$ decays, although this might be more difficult to accomplish.

1.2 Kinematics and background

The detector used for experiment 787 has to be optimized for $K^+ \rightarrow \pi^+\nu\bar{\nu}$. The signature of such an event is quite simple: a kaon decaying into a pion and nothing else since the neutrinos escape detection. To identify the initial kaon as best as possible, a design with an active target in which the kaons stop and decay at rest is desirable. Also, this allows the use of the low energy high intensity kaon beam lines available at Brookhaven. Therefore, the detector has to identify accurately a pion leaving the kaon stopping point. However, since it comes from a three body decay, it will have a non discrete energy. More importantly, the background sources mimicking this decay are numerous. Figure 2 shows the range distribution of pions or muons in scintillator for $K^+ \rightarrow \pi^+\nu\bar{\nu}$ and its most important background sources.

The decay $K^+ \rightarrow \mu^+\nu\mu$ ($K_{\pi 2}$) where the muon is misidentified as a pion is a possible source, although the large difference in range (see figure 2) with the maximum possible range for $K^+ \rightarrow \pi^+\nu\bar{\nu}$ reduces this background substantially. Another possible source is the $K_{\pi 2}$ decay, where the two photons from $\pi^0$ decay leave undetected. To cut down this source, only the pion momentum region above the $K_{\pi 2}$ monoenergetic peak will be considered, this region consisting of 21% of the $K^+ \rightarrow \pi^+\nu\bar{\nu}$ phase space. Yet, the tails of the range distribution of this decay might still have an effect. To get rid of the $K_{\pi 2}$ background events, the $\pi^0$ detection inefficiency must be less than $10^{-5}$; hence, a single photon detection inefficiency of less than $10^{-3}$ for photons of energy greater than 50 MeV must be
attained. The decay $K^+ \rightarrow \mu^+ \nu\mu\gamma (K_{\mu\nu\gamma})$ where the muon is misidentified and the low energy photon goes undetected is another serious background source. A detection inefficiency of less than 10% for photons of energy greater than 20 MeV is necessary in order to keep the background at the level needed for a sensitivity to $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ of $2 \times 10^{-10}$. Therefore, a highly precise identification of the positive pion, using measurements of momentum, range in scintillator, kinetic energy and decay sequence ($\pi^+ \rightarrow \mu^+ \rightarrow e^+$) is necessary, as well as a highly efficient full solid angle (4\pi sr) photon detection coverage.

I.3 The Detector

Even though E787 is a fixed target experiment, the design philosophy of the detector is more along the lines of the modern collider beam detectors with a central region identifying the decay vertex and full solid angle coverage to detect the outgoing particles. This is mainly because the $K^+$ is at rest in the laboratory frame when it decays. The detector is located at the end of the Low Energy Separated Beam Line I (LESB I) of BNL’s Alternating Gradient Synchrotron (AGS). About 1 \mu A of proton beam is slowly extracted pulsed proton beam impinges on a production target at the start of the LESB I beam line to produce pions and kaons. The line, equipped with an electrostatic separator, delivers a beam with a momentum of \sim 785 MeV/c and a ratio of $K^+/\pi^+$ of 1/4. The kaon stopping rate in the detector could be as high as $3 \times 10^5$ kaons per second. The tune of the beam line’s magnets is such that the kaons are focused at the center of the live target, where they will come to rest and decay.

In the following paragraphs, the detector will be described. The reader is referred to figure 3 for a side view of the overall detector. The coordinate system used in all references made to the detector has its origin at the center of the detector. The $z$ axis is along the beam direction, pointing downstream. The $y$ axis
Figure 1: Highest order Feynman diagrams contributing to the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay in a three generations standard model.
Figure 2: Range distribution in scintillator for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and its main background sources
is vertical pointing upwards and the z axis is horizontal, pointing left when looking in the +z direction.

To monitor the incoming particles, an array of beam counters precedes the target. A first one, B1, 17.5 cm wide and 4 cm high, is located at the exit of the last magnet. It is followed by two 20 cm wide by 4 cm high segmented counters, B2X and B2Y. B2X is segmented vertically (eight segments) while B2Y is segmented horizontally (four segments). They are followed by a Čerenkov counter, to do the pion/kaon identification. Next is a fast multiwire proportional chamber consisting of three wire planes, one vertical and the other two at ±45° from the vertical, to distinguish multiple particles entering the detector simultaneously, a possible source of background. A 12 cm wide square counter, B3, follows; it is slightly larger than the beryllium oxide degrader it precedes. Just before B3 is the smaller B3S counter, only 5 cm wide and 3.8 cm high, used exclusively for beam tuning purposes.

The cylindrical BeO degrader is 11.43 cm in diameter and 45.1 cm long. The material used for the degrader has to have several properties. It must be dense enough to be compact but at the same time not made of high atomic number (Z) materials so that the loss of kaons due to multiple scattering is small. Materials of low Z are also important to reduce photon detection inefficiencies (see section IV.4). Beryllium oxide was found to be the best option, even though it is a toxic material and dangerous to machine.

The beam, slowed down by the degrader, finally goes through the square B4 hodoscope counter, formed of two planes, one vertical and one horizontal, just before entering the target. Each plane of B4 is made of four 10 cm long by 2.5 cm wide segments. All counters described above are made of $\frac{1}{8}$ inch (0.32 cm) thick plastic scintillator (Bicron BC-412), except for B4, which is $\frac{1}{4}$ inch (0.64 cm) thick and the Čerenkov counter, made of 1 inch thick Lucite plastic.
Figure 3: Side view of the E787 detector
Immediately following the B4 counter and at the very center of the detector is the live target. It is an array of 378 bunches of aluminum coated cylindrical scintillating fibers. The bunches are triangular in shape and are formed of six fibers, each 2 mm in diameter and over 3 meters long. The bunches, viewed by photomultipliers, are arranged in a hexagon of 10.5 cm in diameter (flat face to flat face). Figure 4 shows an end view, along the $z$ direction, of the target geometry. Only the first 20 cm of the array are used as the actual target. This part is covered by six flat scintillating counters (I counters), each covering one face of the hexagonal target, in order to identify charged particles exiting the target.

In a similar way, six more counters (V counters) cover part of the tail of the target's fibers, to veto any charged particle originating from that part. This combination of beam counters, Čerenkov counter, wire chamber and segmented active target allows one to identify an incoming kaon and locate its stopping position. It also helps to identify beam pions scattered in the target which mimic the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay.

Surrounding the target is a cylindrical drift chamber to measure the momentum of particles and obtain position information. The chamber must be of the minimum possible mass and possess very little non-active area, again to reduce photon detection inefficiencies. It has an inner and outer radius of 9.5 cm and 43.2 cm respectively and covers about half of the total solid angle. The active volume, 50.8 cm in length, is filled with a gas mixture of argon, ethane ($C_2H_6$) and alcohol and is occupied by five layers of wire cells. Layers 1, 3 and 5 are axial while layers 2 and 4 are at stereo angles to allow for $z$ position measurements. Each cell is 4.6 cm high and its half width can vary from 1.2 cm to 1.7 cm, depending on the layer. A cell contains 8 sense wires 5 mm apart. This allows for small drift times and therefore fast operation. A solenoidal magnet coil surrounding the whole detector provides a 10 kgauss magnetic field in the
chamber area parallel to the beam direction. The chamber allows for a position resolution in the $x$ and $y$ direction of 150 $\mu$m.

Next in radius is the range stack. It is designed to cover a range up to the $K_{\mu2}$ peak (see figure 2) and give good position resolution. This dictated a segmentation of 24 azimuthal sectors covering one half of the solid angle. Each sector consists of 21 layers of plastic scintillator (NE-110) 1.905 cm thick, except for the innermost layer, called T counter, only 0.635 cm thick. Layers 2,3,4 and 5, numbered from the inner to the outer radius, are grouped together to form what is called the A counter. Similarly, layers 6, 7 and 8 form the B counter and layers 9 and 10 the C counter. Hence, each range stack sector is formed of 15 counters, each of them viewed at both ends by phototubes.

In addition to the standard electronic readout system (FERA ADC’s, FASTBUS TDC’s), the phototubes of the most interesting layers (where most pions will stop, layers $\sim$11-17) are instrumented by 500 MHz transient digitizers. These digitizers allow the observation of the decay chain of a particle stopping in a layer of the range stack. To improve the position resolution and get a refined range measurement, each range stack sector contains two fast proportional wire chambers, one between the C counter and layer 11 and one between layers 14 and 15. The chambers cover the same length as the scintillator counters and allow for position measurements in $z$ as well as in azimuth. Their fast readout by flash ADC’s allows them to be used in the online trigger. A stainless steel structure supports each of the 360 scintillator modules and the 48 proportional chambers individually.

Surrounding the range stack is the barrel photon veto, designed to cover the largest possible solid angle, detect photons with fast response and obtain some position information about them. To achieve this, a modular lead-scintillator calorimeter divided in 48 azimuthal sectors, which in turn are divided in 4 layers,
is used. Each module consists of alternating sheets of 5 mm plastic scintillator (Bicron BC-408) and 1 mm lead, all 190 cm long. Layers 1 through 4 contain 16, 18, 20 and 21 sheets of scintillator respectively; with the lead this gives a total of 13.5 radiation lengths for one sector. Both ends of each module are viewed by photomultiplier tubes, allowing for a determination of the energy deposited with little sensitivity to the attenuation length of light in the scintillator. Knowledge of this attenuation length along with the pulse heights from both ends provides z position information. As for the range stack, each barrel veto module is supported individually by a stainless steel frame. The sectors are not radial to prevent photon detection inefficiencies due to cracks.

To complete the photon veto coverage, two endcap arrays are installed around the beam area, covering together about 37% of the solid angle. These components are the subject of this thesis and will be described fully in the following chapters.
Figure 4: End view of the scintillating fibers segmented target
Chapter II

The Endcap Photon Veto

II.1 Description

II.1.1 Design and Working Principle

As explained in the previous chapter, highly efficient and reliable photon detection is of utmost importance for experiment 787. Full solid angle coverage is needed with no cracks where a photon might escape. The range of detection goes from 20 to 220 MeV for photons from $K_{\pi 2}$ decay and up to 236 MeV for photons from $K_{\mu \nu \gamma}$. Also, a low detection threshold of about 1 MeV has to be attained. Finally, to keep up with the high counting rates expected, the photon detectors need to have a fast response: less than 50 nanoseconds (ns) for the full pulse width, or a full width at half maximum of the order of 10 ns.

The cylindrical range stack and barrel veto leave two uncovered regions, around the beam pipe and around the target fiber tails, before and after the drift chamber respectively. This means that, as for the barrel veto, the photon detector in that region has to operate in a 10 kgauss magnetic field. Along with the expected performance specifications of the preceding paragraph, this defined the endcaps' physical parameters. Several different designs were considered. In the end, a lead and plastic scintillator sandwich with light collection by a fluorescent wavelength shifter bar was chosen. This compact design has been used before, and was studied in details by Keil [6,7].

The principle, shown on figure 5, is as follows: a charged particle goes through one of the scintillator plates, exciting the special chemical compounds
mixed in the plastic and causing them to emit light isotropically. In the case of photons, direct excitation is negligible. Instead, they will interact with atomic electrons via the photoelectric effect or Compton scattering or will undergo pair creation in the electric field of the atomic electrons or of a nucleus. The latter process is possible only if the energy of the electrons is greater than the threshold for pair production of $1.022$ MeV (twice the electron mass) in the vicinity of a nucleus. In turn, the resulting electrons from these processes will cause excitation in the scintillator. The response to excitation is very fast: the rise time of the light pulse is of the order of a few nanoseconds. This is one of the main reasons for using plastic scintillator; other important reasons are the ease with which it is produced, the number of various shapes in which it can be obtained, and its relatively low cost.

The amount of light produced by an incident particle in plastic scintillator is approximately proportional to the kinetic energy of the particle, a feature necessary in order to have a calorimeter with linear energy response. This response is not linear for protons, deuterons, α-particles, etc. but we do not detect such particles. The scintillator is also highly transparent to its own emitted light, i.e. only a small fraction of it will get reabsorbed. A good fraction of the light will be trapped by total internal reflection; to recuperate the fraction not trapped, reflective aluminized mylar is applied on all surfaces except the one coupled to the wavelength shifter bar, perpendicular to the scintillator. A thin air gap is maintained between the exit end of the scintillator and the wavelength shifter. A good fraction of the light entering the wavelength shifter gets absorbed and is re-emitted isotropically at a longer wavelength. In turn, a fraction of this light will be trapped in the bar by total internal reflection and be transported to the phototube, coupled to the wavelength shifter bar via an adiabatic light guide. This is the reason for the air gap coupling; in the case of a direct coupling, such as
optical grease, a larger fraction of the light from the scintillator would get in the wavelength shifter but the light re-emitted by the latter would re-enter the former and be lost.

As mentioned above, photons interact via the photoelectric effect, Compton scattering and pair creation. The cross section for all these processes increases with some power of the atomic number $Z$ of the medium in which the photon interacts. Hence, by adding a heavy material such as lead in the calorimeter we increase the chances of detecting photons. Positrons from pair creation will annihilate with electrons in the medium. Electrons, in addition to losing energy by collision with other electrons, will lose energy by radiating photons (bremsstrahlung). The cross section for this process increases as a function of $Z^2$. Therefore, a single incident photon or electron will create a cascade, known as electromagnetic shower [8]. The shower will develop from the first interaction point until the photons have an energy less than the pair creation threshold and the electrons have slowed down to the point where they do not radiate significantly anymore. Heavier charged particles, such as muons, pions and protons tend not to radiate very much. They lose energy through collisions with electrons in the media and come to rest, traveling more or less in a straight line. By alternating layers of scintillator and lead, we can “sample” the energy deposited by the particles. Obviously, the energy deposited in the lead will not be seen by the calorimeter; the fraction of visible energy over incident energy has to be determined by a Monte Carlo calculation and is expected to be independent of the energy.

The “sampling” (the number of scintillator and lead plates and their thickness) is what ultimately determines the energy resolution of such a calorimeter. In our case, the design is also constrained by photon detection efficiency considerations. Monte Carlo studies with the electromagnetic shower
simulation programme EGS [9] showed that the optimum values for the endcap photon calorimeter was 66 plates of 5 mm thick scintillator alternated with 1 mm lead plates. The energy resolution of the present design was investigated and will be discussed in chapter III. Also discussed in the same chapter is the linearity of the energy response. If the calorimeter is to have a linear dependence on energy, the amount of light reaching the phototube has to be proportional to the energy of the incident particle. Furthermore, the phototube has to produce an electric pulse proportional to the amount of light incident on the photocathode. And finally, the electronic readout system (ADC) needs to have a linear dynamic range.

Figure 5: Schematic diagram of working principle for endcap photon veto. Only a part of the calorimeter is shown here
II.1.2 Physical Description

The scintillator and lead plates are oriented perpendicular to the beam direction with the wavelength shifter bars running parallel to the beam. The endcaps, as they will now be designated, are of cylindrical shape, with a central region left open for the beam and the target fiber tails. Mechanical considerations as well as physics requirements of photon position measurements dictated a segmented design; the optimum segmentation was found to be 24 radial sectors, each occupied by a single module read by a single phototube. Figure 6 shows one endcap assembly. The dimensions, position and angle covered, for upstream (around the beam region, \(-z\)) and downstream (around the fiber tails, \(+z\)) are indicated in table I. From these numbers we get the solid angle covered by each endcap from the center of the target. For the upstream endcap we get \(0.77\pi\) sr while for the downstream one we find \(0.69\pi\) sr, for a total of \(1.46\pi\) sr or 36.5% of the full solid angle.

Table I: Endcaps dimensions.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Upstream</th>
<th>Downstream</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance from target center to front face</td>
<td>32.4 cm</td>
<td>34.6 cm</td>
</tr>
<tr>
<td>Overall length of modules</td>
<td>39.7 cm</td>
<td>39.7 cm</td>
</tr>
<tr>
<td>Inner radius</td>
<td>10.3 cm</td>
<td>10.3 cm</td>
</tr>
<tr>
<td>Outer radius</td>
<td>42.7 cm</td>
<td>40.8 cm</td>
</tr>
<tr>
<td>Minimum angle from z axis covered ((\theta_{\text{min}}))</td>
<td>8.1°</td>
<td>7.9°</td>
</tr>
<tr>
<td>Maximum angle from z axis covered ((\theta_{\text{max}}))</td>
<td>52.8°</td>
<td>49.7°</td>
</tr>
<tr>
<td>(\cos \theta_{\text{min}})</td>
<td>0.990</td>
<td>0.991</td>
</tr>
<tr>
<td>(\cos \theta_{\text{max}})</td>
<td>0.604</td>
<td>0.646</td>
</tr>
</tbody>
</table>

The 24 modules in each endcap are all identical and enclosed in a 0.029 inch (0.7 mm) thick stainless steel frame. The frames, of the same wedge shape as the modules, are assembled together to form the endcaps. Their dimensions fit the modules as tightly as possible except for a 3 mm gap left between the wavelength
Figure 6: Endcap photon veto. Note: not to scale.
shifter bar and the frame so that no excessive pressure is applied on the wavelength shifter. A detailed view of a module is shown on figure 7. They consist of 66 plates of plastic scintillator 5 mm thick alternated with 1 mm thick plates of lead, for a total of 12.4 radiation lengths. Two ~ 1 mm thick plates of aluminum, of the same dimensions as the lead and scintillator pieces, are placed at the end and beginning of the stack for construction purposes. They add a negligible contribution to the total radiation length. All dimensions except thickness are the same for the lead and the scintillator. Between each lead and scintillator plate is a layer of aluminized mylar as well as on every other scintillator surface except the one coupled to the wavelength shifter. The air gap between the scintillator and the wavelength shifter is maintained by two 0.3 mm diameter copper wires extending for the full length of the module. The wavelength shifter bar, 6.5 mm thick, is slightly narrower than the scintillator-lead end to accommodate two adjustable aluminum support wedges, one on each side of the bar. They are inserted once the module is wrapped in light tight and protective black tape and sits in its stainless steel can, in order to hold it firmly in place. Since a gap exists between the wavelength shifter and the stainless steel can, small springs are inserted in it to help maintain the 0.3 mm air gap, between the wavelength shifter and the module, as constant as possible.

The last part remaining is the coupling between the wavelength shifter and the phototube. Physical constraints from the other parts of the detector dictated that the light guides connecting the modules to the phototubes, mounted outside of the magnet to be in a region with a magnetic field of small magnitude, be at a smaller radius than the maximum endcap radius. Therefore, a short bent adiabatic light guide, called the gooseneck, connects the wavelength shifter to a 1.3 m long cylindrical light guide. The coupling between these last two components is through a soft disk made of silicone dielectric gel (SYLGARD 527
from Dow Corning Corporation). This soft disk, a few millimeters thick, allows for the possibility of a small misalignment of the light guides with the holes made through the magnet end plug. Around the aluminum disks fitted around the ends of the gooseneck and the cylindrical rod, a non-magnetic metal clamp is used to keep a tight coupling. All light guides are covered with reflective aluminized mylar and wrapped in light tight black tape.

The phototube is coupled to the light guide with optical grease. It is surrounded by a cylinder of magnetic shield alloy to eliminate, as much as possible, any residual magnetic fields that could hamper its operation. It is expected that residual fields of about 100 gauss, mostly transverse, will be present in the area where the phototubes are mounted. The bases supplying the high voltage required by the phototubes were made by the Princeton collaborators. The whole phototube array is enclosed in a thick iron cylinder, tightly fitted around the light guide. The endcap modules' dimensions are summarized in table II.

Table II: Endcap modules' dimensions. All measurements are in cm.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Upstream</th>
<th>Downstream</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of scintillator plates</td>
<td>66</td>
<td>66</td>
</tr>
<tr>
<td>Number of lead plates</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>Height of module (distance between parallel sides)</td>
<td>31.3</td>
<td>29.4</td>
</tr>
<tr>
<td>Width at narrow end</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Width at wide end</td>
<td>10.7</td>
<td>10.2</td>
</tr>
<tr>
<td>Thickness of air gap coupling</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Thickness of wavelength shifter</td>
<td>0.65</td>
<td>0.65</td>
</tr>
<tr>
<td>Width of wavelength shifter</td>
<td>10.1</td>
<td>9.6</td>
</tr>
<tr>
<td>Length of wavelength shifter</td>
<td>41.6</td>
<td>41.6</td>
</tr>
<tr>
<td>Length of gooseneck</td>
<td>12.7</td>
<td>12.7</td>
</tr>
<tr>
<td>Length of cylindrical light guide</td>
<td>130</td>
<td>130</td>
</tr>
</tbody>
</table>
Figure 7: Endcap module
II.2 Choice of scintillator and wavelength shifter and tests

An important step in the endcap design consisted in choosing the scintillator-wavelength shifter combination. Several companies produce materials with similar properties; performance, availability and cost were the main points considered in choosing the right combination. After considering many different options, the scintillator chosen was NE-104 from Nuclear Enterprises. According to the company’s technical notes, its wavelength of maximum emission is 406 nm and its pulse width (FWHM) is 2.2 ns, with a decay time of 1.8 ns. The wavelength shifter chosen was an acrylic based doped with BBOT from Bicron. Its wavelength of maximum absorption is 398 nm and its maximum emission is at 432 nm, with a decay time of 1.6 ns, substantially faster than the 10 ns for BBQ, a popular wavelength shifter with an absorption peak at 430 nm and emission peak at 505 nm, offering a better match with the scintillator. The most important consideration in choosing the scintillator-wavelength shifter combination is the overlap between the emission spectrum of the scintillator and the absorption spectrum of the wavelength shifter. However, care must be taken when considering the spectra supplied by the manufacturers. For instance, scintillators such as Pilot-U and BC-420, with emission peaks around 390 nm, might seem to be a better combinations with BBOT than NE-104. However, it was found that this is not the case. The self-absorption in the scintillator is more important at short wavelengths, effectively reducing the amount of overlap between the emission and absorption spectra (see for example figure 32 in reference [10]). Therefore, for its good light output performance and fast response, the NE-104-BBOT combination was chosen.

To help in choosing the scintillator and later monitor the quality of the material received to build the endcap, a special setup was used to determine the
light output of scintillator pieces. The piece to be tested, cut and machined to standard dimensions, is installed perpendicular to a bar of wavelength shifter which is connected at one end to a light guide similar to the “gooseneck” of the final design; a short cylindrical light rod links the gooseneck to a phototube. An air gap is maintained between the scintillator and the wavelength shifter by two thin copper wires. Also, the scintillator is wrapped in aluminized mylar, to simulate as best as possible the proposed design. The scintillator is irradiated perpendicular to its surface by a collimated ruthenium ($^{106}\text{Ru}$) radioactive source. The source undergoes the following decay sequence:

$$^{106}_{44}\text{Ru} \xrightarrow{\beta^-} ^{106}_{45}\text{Rh} \xrightarrow{\beta^-} ^{106}_{44}\text{Pd}.$$ (8)

The first beta decay of the sequence has a half-life of approximately one year with an end-point energy of the $\beta^-$ ray spectrum of 39 keV while the second one has a half life of about 30 seconds with an end-point energy of 3.54 MeV. The latter will traverse the scintillator plate with minimum ionizing energy and deposit approximately 2 MeV per cm on average. According to section II.1.1, the phototube will produce an electric pulse proportional to the energy of the incident particle. To tag the particle, two thin counters, S1 and S2, are installed behind the scintillator in line with the source. The signals from these two counters are discriminated and sent to a coincidence unit. The output is sent to a gate generator that sends its output to a QVT multichannel analyzer. The input to the QVT is the analog signal from the phototube connected to the wavelength shifter. If a pulse occurs during the gate opened by an $S1 \cdot S2$ coincidence, its charge is integrated by the QVT, the sum is digitized and then added to the spectrum that can be seen on an oscilloscope receiving the QVT output.

To compare the scintillators accurately, the testing conditions have to be well controlled. First, the same wavelength shifter-light guide-phototube
combination is used for all scintillators. Next, the source is always impinging at the same distance from the wavelength shifter. Finally, the thickness of the scintillator, upon which depends the deposited energy, is carefully measured using a micrometer at the point where the source will impinge. A convenient measure of the performance of the scintillator is the number of photo-electrons produced by the phototube per MeV of energy deposited in the scintillator. This number is determined with the following formula:

\[
\frac{\text{# p.e.}}{\text{MeV}} = \frac{N_{\text{peak}} - N_{\text{ped}}}{N_{\text{spe}} - N_{\text{ped}}} \times \frac{1}{\frac{dE}{dx}} t
\]  

where

- \(N_{\text{peak}}\) is the channel number of the spectrum peak
- \(N_{\text{spe}}\) is the number of channels for one photo-electron
- \(N_{\text{ped}}\) is the channel number of the pedestal
- \(\frac{dE}{dx}\) is the energy deposited per unit thickness by an electron in the scintillator and
- \(t\) is the scintillator thickness.

The channel number of the peak for a single photo-electron is determined by placing a mask made of black light tight material, in which a small hole has been pierced, between the scintillator and the wavelength shifter; the hole lets out only enough light to produce a single photo-electron. The pedestal value is easily determined using noise. These values are measured immediately before taking a full spectrum measurement for every scintillator tested.

The NE-104 scintillator was received in large sheets (typically 2 m \(\times\) 0.7 m) of 5 mm thickness. Our requested tolerance for thickness was ± 10% . To control the quality of the material, small square samples taken from the corners of the sheets were tested using the setup described above. If the sheet proved to be good enough, it was roughly cut in pieces slightly larger than the final dimensions; each piece was numbered according to what sheet it came from and its location in the sheet. Typically, a sheet would give about 50 pieces, not quite enough for one
endcap module. The pieces were then machined to the precise dimensions using a diamond tool. The machined surfaces were not polished afterwards; it was found, using the test setup once again, that polishing the diamond-cut surfaces did not increase the light output significantly.

A number of pieces from various areas of each sheet were chosen and tested for light output. Figure 8 shows the average result for each sheet, in the order in which they were received. The dotted lines delimit the batches, or groups of sheets produced together. We see that huge light output fluctuations within batches occurred at first but that the results get much better for the later batches. As a result of this, several sheets from the early shipments had to be rejected, some on the sole basis of the small square samples light output tests and some according to more conclusive tests on cut pieces. For the latter tests, the criteria of rejection was a light output of 4.5 photoelectrons per MeV, as indicated on figure 8. The improvement in quality for the later batches is explained by the fact that the company supplying the material improved its production technique along the way. None of the scintillator received to construct the downstream endcap was rejected. The overall results of light output and thickness measurements are summarized in table III. We note that the results are poorer for the material used for the upstream endcap not only in light output but also in thickness. In fact, the thickness average fluctuation is not quite up to our requested tolerance, although not by much. Taking all this in consideration, we might expect the performance of the upstream endcap to be somewhat worse than the downstream one.

Table III: NE-104 Scintillator tests

<table>
<thead>
<tr>
<th></th>
<th>Upstream</th>
<th>Downstream</th>
</tr>
</thead>
<tbody>
<tr>
<td># of photo-electrons per MeV</td>
<td>8.4 ± 1.5</td>
<td>11.6 ± 1.3</td>
</tr>
<tr>
<td>Thickness (cm)</td>
<td>0.49 ± 0.06</td>
<td>0.48 ± 0.03</td>
</tr>
</tbody>
</table>
Another factor affecting the performance of the system is the attenuation length of the wavelength shifter and scintillator. If their values are small, fluctuations in the light output of the system dependent on the location of the electromagnetic shower in the module could occur, especially for photons which in principle could convert in the deepest parts of the calorimeter. Tests were done with the BBOT-NE-104 combination using the setup geometry as described above but with a particle beam at TRIUMF instead of the radioactive source. To measure the BBOT attenuation length, the light output was measured (in units of photoelectrons per MeV) as a function of the position of the scintillator piece with respect to the end of the wavelength shifter connected to the light guide. Figure 9 shows the results obtained along with a fit to

\[ I = A \exp \left( -\frac{d}{L_0} \right) \]  

where \( I \) is the light output, \( d \) the distance, \( L_0 \) the attenuation length and \( A \) a normalization factor. The obtained fit value of the attenuation length is \( L_0 = 78.9 \pm 19.3 \); despite the fact that is not very accurate, we at least have a good estimate. Considering the length of the BBOT (41.6 cm), we see that fluctuation up to a factor of two in the light output could occur from one end to another.

In the case of the scintillator, it was found to be very difficult to measure the attenuation length since fluctuations in light output due to the geometry mask the effects of attenuation. Estimates of about 40 cm were found. Again, this will possibly introduce non-uniformities in the energy response of the endcaps, although the geometry effects (focusing, see section II.4) might be as important and cancel in part the attenuation effect.

Finally, a phototube had to be chosen to match the emission spectrum of the wavelength shifter. The one chosen is model 9954B from Thorn EMI, with a diameter of 52 mm (2.05 inches). Its rise time is typically 2 ns; the maximum
sensitivity of its bialkali photocathode is at a wavelength of about 390 nm. The light guides (gooseneck and cylindrical) are made of UVT Lucite (UltraViolet Transmitting) to keep as much light as possible from the wavelength shifter to the phototube.

Figure 8: Light output of scintillator for each large sheet received. The dotted lines delimit batches and the horizontal line indicates the rejection threshold

II.3 Radiation Damage

One source of concern in long running particle physics experiments such as 787 is how stable will the quality of detector parts be; will certain subsystems deteriorate with time and have to be replaced? The major source of damage to the quality of
Figure 9: Light attenuation in BBOT. The distance is the position of the scintillator plate with respect to the BBOT bar end coupled to the light guide. The curve shown is a least-squares fit to an exponential function.
scintillator is radiation. Long exposure to intense radiation causes the properties of scintillator to change; in particular, the light output diminishes. Since the endcaps are close to the beam region, it was necessary to investigate how NE-104 might respond to radiation exposure.

Two cut and machined pieces coming from the same area of a scintillator sheet were chosen. One was kept as a standard and the other one was exposed to radiation. The latter was installed about 3 meters away from the end of a beam line of the 42 MeV cyclotron operated by Atomic Energy of Canada Limited at TRIUMF. At that location, the scintillator received a substantial dose of radiation from neutrons. The flux was approximately $4.4 \times 10^8$ neutrons/s/cm$^2$ for a beam intensity of 100 $\mu$A. In addition to charged particles, the endcaps are expected to receive a large neutron flux from the beam when they are in position in the detector at Brookhaven.

The piece was removed periodically and the light output was measured using the test setup described in section II.2. Figure 10 shows the relative light output as a function of acquired dose. The deterioration is quite drastic. Direct observation of the piece compared to the non-irradiated one showed that no major macroscopic physical changes occurred; only a change in the hue of the clear plastic (from a normal bluish tint to a yellowish one) was observed. It is therefore conceivable that the peak of the emission spectrum has been shifted to longer wavelength.

However, we have to ask what dose we can expect in the endcaps for the duration of the experiment. Assuming a flux of $\sim 5 \times 10^6$ particles per second in each module (see section IV.3) and 2000 hours of operation, we can estimate a total dose of less than $1 \times 10^6$ rad. From the graph of figure 10, we see that for such a dose, the light output is still more than 80% of its original value. Therefore, we do not expect any significant effect on the endcaps due to radiation damage.
Figure 10: Relative light output of NE-104 as a function of radiation acquired dose
II.4 Construction of Endcap Modules

With the physical parameters of the modules well defined, it was necessary to develop an assembly procedure. The most important aspect is to insure that the assembly is mechanically stable enough so that a module can be handled and slid into its stainless steel can. Several different techniques were tried using a prototype in which the scintillator was replaced by plexiglass. Some of those techniques involved gluing a small fraction of the area of the scintillator pieces directly to the lead pieces. However, any dark surface in optical contact with the scintillator is a potential light absorber, reducing the light output accordingly. Simulations were made using a photon tracking program from the CERN Library called GUIDE 7. With these studies, it was found that the surface near the wavelength shifter is crucial. The non-parallel sides create a focusing effect causing most of the photons emitted in the scintillator to reach the widest of the parallel sides and exit from that side. This is a very welcome feature, increasing the amount of light obtainable compared to a rectangular piece of scintillator. This also means that any light absorber near that edge will have important effects. On the other hand, because of the same focusing effect, areas near the small edge of the scintillator pieces could be glued with no significant loss of light output. However, this proved not to be sufficient to provide good stability. Thus, a technique in which the scintillator surfaces were not glued to the lead had to be developed.

It was eventually found that simple light tight wrapping was sufficient, as long as the wrapping tape could be well anchored at the front and end faces of the module. For this reason, a plate of aluminum 0.030 inch (0.8 mm) thick with the same dimensions as the scintillator and lead pieces was used to start and end the stacks. The light tight tape is not in direct contact with the scintillator; a layer of aluminized mylar is placed in between.
When all the scintillator and lead pieces required for the upstream endcap were available, the assembly process was started. The first step consisted in classifying each large sheet of scintillator according to the average light output performance (number of photo-electrons per MeV) and thickness of samples (see section II.2). Three categories were made, each consisting of about one third of the total number of scintillator pieces used for the upstream endcap. Then, 22 pieces from each category were picked to form each module. Care was taken to choose the pieces so the overall length of each module would remain roughly constant. The pieces were to be stacked so the ones with the largest light output were the furthest away from the phototubes, and vice-versa. This would hopefully help to render the modules more uniform since the amount of light reaching the phototube can vary depending on the depth at which a photon starts to convert in a module (see section II.2).

Both sides of each piece of lead were carefully covered with a sheet of aluminized mylar for light reflection. Each piece of scintillator and lead was carefully checked prior to use and any imperfect one was discarded and replaced (in the case of scintillator pieces, a piece with similar light output and thickness was chosen). The BBOT bar, resting on the copper wires providing the air gap, was covered with a piece of light tight plastic folded to provide room for the support wedges on both sides of the bar. The "goose neck" light guide, glued to the BBOT bar with optical cement, was covered with thin aluminized mylar and wrapped with light tight black tape. All sharp edges were carefully taped for protection.

The stainless steel cans were welded together to form the modules' support and the assembly was slid into an aluminum support cylinder. A special trolley was made to support the cylinder while the modules were loaded, and allowed it to be rotated. The modules were loaded carefully in the cans with the BBOT bar
always free of any pressure, and the aluminum support wedges were then inserted and adjusted so the module was solidly in place in the can. A specially designed crate was then installed around the endcap and allowed it to be crane lifted and rotated in order to have it rest on the flat side opposite to the light guides. In this position, each module could be easily tested with cosmic rays; this showed that all modules were in good working order and had similar light outputs (the same phototube was used to check all modules). The endcap was then shipped to Brookhaven. On arrival, each module was tested with a radioactive source to make sure none of them had been damaged during the trip. All modules were still working properly. The procedure described above was repeated exactly for the downstream endcap. The endcaps were then installed in their final position in the detector.
Chapter III

Beam Test

In March 1987, while the construction of the upstream endcap’s modules was still under way, two of the completed modules were tested in a particle beam at TRIUMF, a nuclear and particle physics facility on the UBC campus. TRIUMF’s particle accelerator, a sector focused cyclotron, produces a high intensity (\(\sim 100 \mu A\)) proton beam of a maximum kinetic energy of 500 MeV. The beam is directed onto a solid target to produce beams of pions and other particles; typical production reactions are:

\[
\begin{align*}
p(p) & \rightarrow p n \pi^+ \\
p(p) & \rightarrow p p \pi^0 \\
p(n) & \rightarrow p p \pi^-
\end{align*}
\]

where \(\pi, p\) and \(n\) indicate a pion, a proton and a neutron respectively and parenthesis indicate a particle bound in a nucleus.

The neutral pions quickly decay into two photons (the lifetime of the \(\pi^0\) is \(\tau_{\pi^0} \approx 10^{-16}\) seconds). The latter convert in the target and surrounding material to form electrons and positrons which contaminate all the beams. The charged pions, with a lifetime of \(\tau_{\pi^\pm} \approx 26\) ns, decay into a muon and a neutrino; the muon in turn decays into an electron and two neutrinos with a lifetime of \(\tau_{\mu^\pm} \approx 2.2\mu s\). The decay chain is then

\[
\begin{align*}
\pi^+ & \rightarrow \mu^+ \nu_\mu \\
\mu^+ & \rightarrow e^+ \nu_e \overline{\nu_\mu}
\end{align*}
\]
with the conjugate reactions for the negative particles, i.e. change all + signs for
− signs and all neutrinos (νᵢ) for anti-neutrinos (νᵢ̄).

The charged particles can be channeled from the production target to an
experimental area via a beam line that will also select their momentum; hence we
have a beam consisting of a mixture of pions, muons and electrons (or positrons¹).
Several of these beam lines are available to experimenters at TRIUMF. The beam
line used for the tests described in this section is called M13. Its characteristics
are well described elsewhere [11,12]. The object of the tests was to verify first if
the modules worked properly and according to the design specifications and
second to measure their resolution in energy and verify to what degree their
performance matched those of an idealized calorimeter.

III.1 Experimental setup and data taking

The modules were exactly as they were going to be in the completed endcaps, as
described in section II.1.2; same light guides, same kind of phototube and same
coupling at the interfaces. The two modules tested were for the upstream endcap
and were designated U1 and U16. One module was tested at a time; it was
installed perpendicular to the beam so that particles would impinge at the center
of the module, parallel to the wavelength shifter and about 16 cm away from it.
Two successive thin scintillator counters were placed in the beam path in front of
the module to identify incoming particles. The two counters, which we will
designate by S1 and S2, were both \( \frac{1}{8} \) inch thick; S1 was a 2 inches (5.08 cm)
diameter circular counter while S2 was a 1 inch by 1 inch (2.54 cm) square
counter. The particles would go through the two counters and then deposit energy
in the module. The M13 beam line can be set up to provide positive or negative

¹In the rest of this essay, the terms pions, muons and electrons will refer to all charged states of
those particles.
particles. Since ultimately the modules are destined to detect the predominantly positive decay products of positive kaons, the positively charged particles were chosen. At the time of the tests, the proton beam intensity had been diminished to a value of less than 100 nanoamperes, in preparation for a maintenance shutdown, and was polarized. These last two conditions did not affect the results of the tests in any way.

Since the beam is a mixture of different particles, we need to record information allowing us to differentiate them. Two properties of the particles are exploited. First, since electrons, muons and pions have different masses, they have different speeds for the same momentum and therefore different time of transit from the production target to the module. And second, the amount of energy deposited per unit length by each particle as a function of energy \( (dE/dx) \) is characteristic of each particle. Therefore, recording the time of flight of the particles and their energy deposition in the S1 and S2 counters should allow us to select the different particles.

The online electronic trigger was quite simple. A schematic diagram of it is shown on figure 11. The analog signals from S1 and S2 were both sent to a separate fan in/fan out module; these modules sum their input signals and offer several identical outputs of the sum. In our case, since only one input is present, the outputs are simply copies of the input. For both S1 and S2, one output was sent to a discriminator module. If the input voltage presented to this module exceeds a certain preset adjustable threshold, a square output pulse of standard height and adjustable duration is produced. A second output of the fan in/fan out modules was sent to an ADC (Analog to Digital Converter) housed in a standard CAMAC (Computer Aided Measurement And Control) crate controlled by the online computer, a PDP-11/34 (Digital Equipment Corporation). The outputs of the discriminators were sent to a coincidence unit. If a coincidence between the S1
and S2 discriminated signals occurred, a square gate signal was sent to a trigger module in the CAMAC crate. The gate was also sent to an ADC and started a TDC (Time to Digital Converter). The trigger module would warn the computer of an event occurrence via a LAM (Look At Me) signal. In the mean time, the ADC would integrate in separate channels the pulse heights of the S1 and S2 counters and the endcap module for a time equal to the duration of the gate pulse. The same gate pulse also started the TDC which was stopped by a signal derived from the radio frequency of the cyclotron. This periodic signal, of a frequency of 23 MHz, is directly related to the time at which the protons from the cyclotron hit the production target. Therefore, the TDC will digitize the time of flight of a particle from the production target to its arrival in the endcap module. The computer then reads in the digital values from the three ADC channels and the TDC and sends them to a tape drive to be recorded on magnetic tape.

Data was taken at several different beam momenta: 30, 50, 70, 100 and 140 MeV/c. A separate data set, called run, was created for every case with different experimental conditions.

III.2 Results

The first important observation from the test is the shape of the pulses produced by the modules. Figure 12 shows an oscilloscope picture of a pulse obtained with module U16. From this we can see that the full pulse width at half maximum is about 10 ns. Therefore, the module meets its fast counting requirements. Also, the pulse height shows to be adequate. At 30 MeV/c, when most of the particles reaching the module are electrons of kinetic energy $T_e \approx 30$ MeV, the pulse height is about 120 mV for a very reasonable high voltage of 2200 volts applied to the phototube. Hence, the NE-104-BBOT scintillator-wavelength shifter provides enough light to detect the low energy photons expected in experiment 787.
Figure 11: Schematic diagram of the online trigger for endcap beam test. RF represents the signal derived from the cyclotron's radio frequency.
Module U1 showed very similar pulses.

The data taken could be analyzed offline on a VAX 8650 using a program called MULTI. By doing a two dimensional plot of the time of the events relative to the cyclotron radio frequency signal versus the energy deposited in the S1 and S2 counters, the different particles could be identified, as explained in the previous section. An example is shown on figure 13. Using this plot, tight constraints can be applied to the data to select subsets of well identified particles. The boxes shown on figure 13 are an example of the constraints chosen. The data is analyzed a second time using those constraints to histogram the energy spectrum of the module for each particle. Figures 15,16 and 17 show the spectra obtained for module U16 at a beam momentum of \( \approx 140 \) MeV/c for pions, muons and electrons respectively.

From this we note a difference in the shape of the spectra of the pions and the muons. The difference in the width can be explained by the fact that the integration time of the ADC is long enough to accept the decay energy of the pion to a muon (\( \approx 4 \) MeV). Depending on whether the pion stops in a lead plate or a scintillator plate, this decay energy will be seen or not, therefore broadening the width of the energy spectrum in the pion case. The difference in the tails is due to the nuclear reactions of the pions, which can deposit more or less than their kinetic energy, depending on the reaction.

To determine the performance of the module, electrons were chosen. There are two reasons for that : first, the endcaps calorimeters are designed to detect photons; electrons produce electromagnetic showers very similar to the ones produced by photons. And second, at low momentum (\( \approx 30-50 \) MeV/c), the muons and pions have very little kinetic energy and since their energy loss per unit length of material increases as their energy decreases, most of them would stop in the S1 and S2 counters. In fact, this is observed in the time versus energy plots for
Figure 12: Pulse shape from module U16. One horizontal division represents 10 ns and one vertical division represents 50 mV
Figure 13: S1 counter pulse height versus time of flight for beam momentum of 140 MeV/c
Figure 14: S1 counter pulse height versus time of flight for beam momentum of 30 MeV/c. The wide background strip is probably due to electrons from muon decay that are not in time with the radio frequency signal.
Figure 15: Module U16 energy spectrum for 140 MeV/c pions
Figure 16: Module U16 energy spectrum for 140 MeV/c muons
Figure 17: Module U16 energy spectrum for 140 MeV/c electrons
the counters; only the electron peak is present (see figure 14). Each electron peak
is fitted, using a least squares method, to a gaussian function of the form

\[ y(x) = \frac{A}{\sigma \sqrt{2\pi}} \exp \left\{ -\frac{1}{2} \left[ \frac{x - \mu}{\sigma} \right]^2 \right\} \]  

(16)

where \( \mu \) is the peak position and \( \sigma \) the standard deviation. The gaussian function
reproduces well the monoenergetic peak of the electrons broadened by statistical
fluctuations in the calorimeter and by the resolution of the instruments. The
fitting algorithm uses the Gauss-Newton method to find the values of the
parameters of the hypothetical function that minimize the sum of the squares of
the differences between the data points and the fitted function \[13\]. Weights are
associated with each data point; they are expressed by

\[ w_i = \frac{1}{\sigma_i^2} \]  

(17)

where \( \sigma_i \) is the standard deviation of the dependent variable of each data point. In
our case, according to Poisson statistics, \( \sigma_i \) will be given by

\[ \sigma_i = \sqrt{N} \]  

(18)

where \( N \) is the number of counts in each histogram bin. Figure 18 shows an
example of a fit.

Measurements were taken on module U16 at 5 different beam energies.
Table IV shows the corrected values of beam energy for electrons calculated using
the DAC (Digital to Analog Converter) values of magnet B1 in the beam line. It
is scaled so that a DAC value of 8195 corresponds to a momentum of 91 MeV/c.
Also in table IV is the correction for the energy lost in the trigger counters S1 and
S2. It is calculated assuming that the stopping power \( (dE/dx) \) is constant in the
two counters, and by using the formula

\[ E_{\text{lost}} = \frac{dE}{dx} \rho t \]  

(19)
Figure 18: Example of least squares fit to 70 MeV/c electrons peak. The $\chi^2$ value is per degree of freedom.
where $\rho$ is the density of the scintillator counters and $t$ the total thickness. The density is taken to be $\rho = 1.032 \, g/cm^3$ and $t = 0.25$ inch (0.635 cm). The stopping power values are taken from reference [14]. Table V shows the results of the fits to the electron peaks at the various beam energies. Also indicated are the $\chi^2$ per degree of freedom values for each least squares fit. The errors shown are statistical. Using the values for the peaks in table V, we can verify the linearity of the module as a function of energy. Figure 19 shows the distribution of data points. We see that the response is extremely linear for the first four points. The last point, at an energy of about 140 MeV, is lower than we would expect it. This

![Figure 19: ADC peak value for electrons in module U16 as a function of beam energy. The line shown is the result of a least squares fit to a straight line using the first four points.](image)
Table IV: Corrected beam energies for electrons

<table>
<thead>
<tr>
<th>Approximate beam momentum</th>
<th>MeV/c</th>
<th>30</th>
<th>50</th>
<th>70</th>
<th>100</th>
<th>140</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1 magnet DAC value</td>
<td></td>
<td>2561</td>
<td>4610</td>
<td>6403</td>
<td>9092</td>
<td>12806</td>
</tr>
<tr>
<td>Real beam momentum</td>
<td>MeV/c</td>
<td>28.4</td>
<td>51.2</td>
<td>71.1</td>
<td>101.0</td>
<td>142.2</td>
</tr>
<tr>
<td>Electron kinetic energy</td>
<td>MeV</td>
<td>27.9</td>
<td>50.7</td>
<td>70.6</td>
<td>100.5</td>
<td>141.7</td>
</tr>
<tr>
<td>Stopping power in S1,S2</td>
<td>MeV cm²/g</td>
<td>2.50</td>
<td>3.00</td>
<td>3.45</td>
<td>4.09</td>
<td>5.00</td>
</tr>
<tr>
<td>Energy loss in S1,S2</td>
<td>MeV</td>
<td>1.64</td>
<td>1.97</td>
<td>2.26</td>
<td>2.68</td>
<td>3.28</td>
</tr>
<tr>
<td>Corrected electron kinetic energy</td>
<td>MeV</td>
<td>26.3</td>
<td>48.7</td>
<td>68.3</td>
<td>97.8</td>
<td>138.4</td>
</tr>
</tbody>
</table>

Table V: Energy resolution for electrons in module U16. The peak ($\mu$) and standard deviation ($\sigma$) values are from a least squares fit to a gaussian function

<table>
<thead>
<tr>
<th>Electron Energy ($T_e$) (MeV)</th>
<th>Peak ($\mu$) (channels)</th>
<th>Standard deviation ($\sigma$) (channels)</th>
<th>$\chi^2$</th>
<th>Resolution ($\sigma/\mu$) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>138.4</td>
<td>725.0 ± 2.3</td>
<td>103.5 ± 2.3</td>
<td>1.23</td>
<td>15.3 ± 0.4</td>
</tr>
<tr>
<td>97.8</td>
<td>542.2 ± 0.7</td>
<td>98.0 ± 0.6</td>
<td>1.06</td>
<td>19.9 ± 0.2</td>
</tr>
<tr>
<td>68.3</td>
<td>395.1 ± 0.5</td>
<td>85.4 ± 0.4</td>
<td>1.35</td>
<td>24.7 ± 0.3</td>
</tr>
<tr>
<td>48.7</td>
<td>295.5 ± 0.9</td>
<td>71.3 ± 0.8</td>
<td>1.20</td>
<td>29.0 ± 0.7</td>
</tr>
<tr>
<td>26.3</td>
<td>181.6 ± 0.9</td>
<td>48.5 ± 0.7</td>
<td>1.45</td>
<td>36.8 ± 1.5</td>
</tr>
</tbody>
</table>
could be caused by the fact that at higher energies, the electromagnetic showers might not be fully contained by the module. This effect should be reduced in the full endcap array, since energy leaking out laterally of a module will end up in an adjacent one. However, the stainless steel support structure will introduce other non-linear effects. A least squares fit to a straight line was made using the first four points. The result is

\[ P_{ADC} = (5.043 \pm 0.002) E_{beam} + (49.9 \pm 1.4) \]  

where \( P_{ADC} \) is the ADC value in channels and \( E_{beam} \) is the beam energy in MeV. The \( \chi^2 \) value of the fit is 1.81. This result gives us the value of the pedestal, the amount by which the “zero” of the ADC is offset. In an ideal case, a beam energy of zero should correspond to channel zero for the ADC. However, DC levels present in the electronics trigger system shift the origin of the ADC scale by a certain amount. The fit value of 49.9 ± 1.4 will be used in subsequent calculations instead of the more ambiguous value that can be obtained by direct observation in the spectra. The line drawn on figure 19 corresponds to the fit. As can be seen from this, the linearity is adequate. Non-linearities introduced by the phototube and the electronics read out system should be negligible.

The last column in table V indicates the energy resolution, defined as

\[ R = \frac{\sigma}{(\mu - Ped)} \]  

where \( Ped \) is the pedestal value of the ADC. The resolution as a function of energy is shown in figure 20. As stated in section II.1.1, the resolution is limited by sampling fluctuations. It can be parametrized by [10]:

\[ \frac{\sigma(E)}{E} = \frac{A}{\sqrt{E}} \]  

where \( A \) is a constant of the order of 5 to 10% and \( E \) is in GeV. A least squares fit
assuming this function was performed (the curve in figure 20). A value of

\[ A = (6.2 \pm 0.1)\% \]

is obtained, with a \( \chi^2 \) per degree of freedom of 4.9. Even though the agreement between the data and the hypothetical function is not very good, we see that the behaviour of the resolution is very close to the ideal situation of equation 22. The deviation might be caused by energy leakage effects although these effects seemed negligible according to the linearity test. Systematic uncertainties, which were not controlled very well in this test, might cause the deviation observed. The value of the resolution is for particles incident at the center of the module. Averaging over the entire area of the module would certainly worsen the resolution.

We can compare the results of this test with the results obtained with a very similar calorimeter built for the ARGUS detector on the DORIS II electron-positron storage ring at DESY [15,16]. Tests similar to the one described in this section were conducted very carefully and thoroughly. Looking at figure 6 of reference [15], we see that the \( 1/\sigma(E) \) behaviour holds more or less over the 30-140 MeV energy range but is not perfect. They attribute the deviation to energy leakage, this being supported by a Monte Carlo calculation using the EGS routines. Their measured value of about 6.5 \% for the constant agrees quite well with the value measured here.
Figure 20: Energy resolution of module U16 as a function of energy. The curve shown is a least squares fit of the data to $R = A/\sqrt{E}$. 

Electrons
Module U16
Chapter IV

Endcap Calibration

IV.1 Energy Calibration

Once the endcaps are installed in the detector, the two most important tasks are to first calibrate them in energy, i.e. find the gains for each module and second do a balance of the modules, i.e. adjust the high voltages on the phototubes so that all modules give more or less the same pulse height for the same energy deposition. The latter has to be done because the hardware energy thresholds for photon veto apply to the sum of the pulses of all modules in each endcap; a pulse of a certain height has to represent the same energy in every case in order for the veto to be uniform. Another reason for that is the fact that the TDC’s threshold is the same for all modules.

In order to calibrate, a source of particles of known energy deposition in the calorimeter is required. The simplest and most obvious one is of course cosmic ray muons, provided they can be cleanly identified as penetrating completely through the modules. But the geometry and orientation of the endcaps in the detector makes their use quite difficult. Since the scintillator and lead plates of the endcaps’ modules are oriented vertically, we do not know how much live material an almost vertically incident particle goes through. Therefore, we cannot calculate the proper expected energy deposition. Horizontal cosmics would be suitable but the rate is considerably lower. Also, since one cannot install additional counters once the detector is closed, we are forced to require a coincidence between the upstream and downstream endcaps to identify an event properly, reducing the rate
furthermore. However, horizontal cosmic rays could be used to do a first approximation high voltage balance, since high statistics precision is not needed. Indeed, this method was used to do a first balance of the endcaps.

The next logical choice for the energy calibration is to use a well known kaon decay. This has the disadvantage that the calibration can be done only when the beam is on, which is not always desirable considering how precious beam time is for this experiment. On the other hand, this is probably the best conditions in which to do the calibration since the ever present background due to the beam and DC offsets in the electronics switched on and off by the pulsed beam could affect the phototubes' gains. The gains in experimental running conditions is what we really need.

A special trigger was designed to use the monoenergetic muons from the $K_{\mu 2}$ reaction

$$K^+ \rightarrow \mu^+\nu_\mu.$$  \hspace{1cm} (23)

These muons have a momentum of 236 MeV/c ($T_{\mu^+}=152$ MeV) and are expected to stop in the endcap. However, the fact that the muons start in the target and have to traverse it before reaching the endcap degrades their energy and results in a broader spectrum in the endcap. On average, the muons will deposit about 20 MeV in the target. Also, the muons have to traverse the drift chamber end plates; in particular, the downstream side, with all the chamber pre-amplifiers, could degrade the energy even more. And finally, those muons coming at a very small angle with respect to the beam direction will have to travel quite a distance in the degrader and the target fiber tail, upstream and downstream respectively. We can expect the muons to stop within the first third of an endcap module, which should be the part where the scintillator with the best light output quality is.

The trigger should select events for which the muon energy is contained
mostly in only one module in order to provide an easily recognizable peak in each
module. The expected visible energy deposited by the muons had to be
determined by a Monte Carlo calculation using the geometry of the E787 detector
to try to simulate the effects mentioned in the previous paragraph. This
calculation also helped to show the feasibility of the calibration method. It is
discussed in the next section.

IV.1.1 Monte Carlo Calculation

The Monte Carlo simulation of muons from the $K_{\mu 2}$ reaction depositing energy in
the endcaps was done using the programme UMC, specifically written for
experiment 787 (see appendix A). As a first step, a distribution of kaons stopping
positions in the target was obtained. Kaons were started at the entrance of the
BeO degrader with a momentum of 783 MeV/c with a momentum bite ($\Delta p/p$) of
2.0 %. The kaon beam was assumed to be focused in the $x$ direction and on the
centre of the target. The $x$ and $y$ axis directional cosines of the initial momentum
vector were smeared out by the appropriate beam angular distributions. The
event was rejected if the kaon decayed in flight or was scattered outside of the
degradert-beam counter-target area. To be accepted, the kaon had to stop in the
target. All dimensions used were as close as possible to the actual ones. A total of
117 445 stopping kaons coordinates were generated. Figures 21 and 22 show the $y$
versus $x$, and $z$ stopping distributions respectively. Looking at the figures, we
notice that the stopping distribution in $x$ and $y$ is very good as we can expect
since the kaons are started with normally distributed directional cosines along
those axis. The distribution clearly shows the hexagonal shape of the target. The
$z$ distribution, on the other hand, is a bit off center, towards the downstream end
of the target. A fit to a gaussian distribution gives a mean of 0.46 cm. There
could be several causes to this; the beam momentum is too high, the degrader too
Figure 21: Y position versus X position of stopped kaons in the target generated by Monte Carlo
Figure 22: Z position of stopped kaons in the target generated by Monte Carlo
short, the BeO density used in the program too low or the target too short. Of course, a combination of several of the above is possible. Nevertheless, this small offset should not affect the final result and therefore this stopping distribution was used as a starting point for the $K_{\mu 2}$ calculation.

The calculation simulating the $K_{\mu 2}$ endcap calibration used the exact dimensions and positions in the detector for the endcaps. As in the experimental situation, a magnetic field of 10 kgauss was included. One important difference between the Monte Carlo and the real detector is the absence of any material simulating the devices installed on the end plates of the drift chamber. This could introduce a systematic shift in the energy calibration, since it relies on the calculation described in this section. $K_{\mu 2}$ decays were generated in the target. If the muon's original direction vector pointed outside of the endcaps' solid angle, the event was rejected immediately. The muon was followed until it stopped or decayed. The decay energy was not included in the calculation since in the experimental case, the integration time of the ADC's is relatively short (~ 50 ns) compared to the muon lifetime (~ 2.2 μs) and the effect should not be very significant. This saved a lot of computer time since the electron coming from the muon decay is a showering particle and therefore very time consuming. After the muon had stopped, the following conditions were required:

- The visible energy deposited in the endcap is greater than 1 MeV
- No energy is deposited in the range stack
- No energy is deposited in the barrel veto
- The energy of the two immediate neighbours of the module with the most energy is less than 0.1 times that of the maximum

These constraints should select events for which the energy is well confined to only...
one endcap module. The variable parameter in the last constraint is used because a large energy deposition in a module will tend to give a larger energy deposition in its immediate neighbours. Using a fixed energy constraint would tend to bias towards the events with a small energy deposition. The results of the calculation are given in table VI. From this we make a few observations: first, the percentage of muons reaching each endcap agrees very well with the fraction of solid angle covered by each, as is expected. Second, the fraction of events rejected because of the energy constraints is much larger for the upstream endcap. This seems to be caused by the fact that the range stack is much closer to the upstream endcap than the downstream one; this explains the large difference in rejects because of the range stack energy constraint. Also, the larger solid angle covered by the upstream endcap is at cause; the muons just catching the outer edge of the endcap arrive at a steeper angle upstream. They are therefore more likely to deposit very little energy and/or end up in the range stack. Finally, we see that only about 14% of the total number of events survive. But because of the large branching ratio of the $K_{\mu 2}$ decay, this is not a cause of concern for the experimental case.

Table VI: Final statistics for Monte Carlo simulation of the endcap $K_{\mu 2}$ calibration trigger

<table>
<thead>
<tr>
<th>Constraint</th>
<th>$Upstream$</th>
<th>$Downstream$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of $K_{\mu 2}$ events generated</td>
<td>117445</td>
<td></td>
</tr>
<tr>
<td>Muon not in endcaps solid angle</td>
<td>71712</td>
<td></td>
</tr>
<tr>
<td>Constraint</td>
<td>$Upstream$</td>
<td>$Downstream$</td>
</tr>
<tr>
<td>Number of events</td>
<td>23567</td>
<td>22166</td>
</tr>
<tr>
<td>Energy deposited in endcap &lt; 1 MeV</td>
<td>2060</td>
<td>1641</td>
</tr>
<tr>
<td>Range stack energy &gt; 0</td>
<td>5859</td>
<td>4118</td>
</tr>
<tr>
<td>Barrel veto energy &gt; 0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Adjacent module(s) with energy &gt; 0.1 $\times$ maximum</td>
<td>7864</td>
<td>7892</td>
</tr>
<tr>
<td>Good events</td>
<td>7784</td>
<td>8515</td>
</tr>
</tbody>
</table>

Figure 23 shows an occupation plot of the endcap modules. We see that the
events are distributed very uniformly. We also notice the upstream- downstream difference in the number of events. Figure 24 shows the energy distribution in one module. We see a clear peak although it is definitely smeared at low energy because of the material degrading the muon energy, as explained earlier. In figures 25 and 26, we show the energy deposited in the target. As expected, the peak is around 16 MeV, a bit less than the 20 MeV expected if the target was solely made of scintillator; the target includes a certain amount of dead material to hold the fibers together. The tail at larger energies for the events in the downstream endcap is caused by the tails of the fibers; the energy deposited in them is included in the target energy.

Since the background is inexistent in Monte Carlo and because of the perfect symmetry of the modules of each endcap, a sum of the histograms of each module was done for each endcap. The results are shown in figures 27 and 28. We notice a small bump at about 35 MeV for the downstream end. The cause of this was not found. To find the position of the peak, a function called TINA (see appendix B) was fitted to the data using a weighted least squares method. The fits are shown on the figures. From the fit parameters, the values obtained for the peaks are:

$$\text{Upstream} \ 54.6 \pm 0.4 \text{ MeV} \quad (24)$$
$$\text{Downstream} \ 51.6 \pm 0.7 \text{ MeV} \quad (25)$$

We observe a large difference between the two ends. A priori, there doesn’t seem to be any major difference between them. It is possible that the veto counters installed around the target fiber tail contribute in degrading the muons energy. However, only an experimental verification of the accuracy of the calibration using these figures will tell if this calculation is correct. But, if the experimental uncertainties proved to be larger than the \(\sim 5\%\) discrepancy observed here, no solid conclusions could be drawn.
Figure 23: Occupation plot of the endcap modules (Monte Carlo). The modules numbered 1-24 and 25-48 are for the upstream and downstream end respectively.
Figure 24: Energy distribution in one endcap module for $K_{\mu 2}$ trigger (Monte Carlo)
Figure 25: Energy deposition in target live material for muons in the upstream endcap.
Figure 26: Energy deposition in target live material for muons in the downstream endcap
Figure 27: Sum of muons energy distribution for all upstream modules. The curve shown comes from a least squares fit to a TINA function.
Figure 28: Sum of muons energy distribution for all downstream modules. The curve shown comes from a least squares fit to a TINA function.
IV.1.2 Endcap $K_{\pi 2}$ Online Trigger

Since the branching ratio for the $K_{\pi 2}$ decay is the predominant one (63.5%), the rate of events is more than we need. Also, the basic idea for the trigger is quite simple: we are looking for a kaon in the target, an event in one endcap and nothing in the rest of the detector. Figure 29 shows a schematic diagram of the online trigger logic. The signal cables from the endcaps’ phototubes are brought into the counting room and connected to individual splitter boxes. These boxes passively split the signal in three outputs. One is sent to the FERA (Fast Encoding and Read out ADC) ADCs, one to the TDC’s discriminators and one to the summing units (to form the upstream and downstream endcaps veto signals). The diagram shows one of the splitter boxes.

Three CAMAC controlled discriminators (LeCroy model 4413) are used to present signals to the endcaps’ FASTBUS TDCs. Each has sixteen endcap modules’ signals as inputs (via cables from the splitter boxes). These units have a backplane output that gives an electrical current proportional to the multiplicity of hits. In a 100 ohms load, one hit gives a signal of 100 mV. The three outputs were ORed in a fan in/ fan out and this sum was sent to a discriminator (Philips Scientific model 710) set at 75 mV. The sum was also sent to a second discriminator (same model), set at 125 mV. The output of this second discriminator was used to veto the output of the first one in a coincidence unit (Philips Scientific model 755). This selects events where only one endcap module is above the TDC threshold, which was set at 400 mV, corresponding to about 20 MeV of total deposited energy. This endcap signal is sent to a coincidence unit along with the “Kbeam” signal, which insures that a kaon hit the target. The Kbeam signal is formed by the coincidence of a kaon Čerenkov signal, a B4 beam counter signal and a signal identifying an energy deposition in the target. As an
additional precaution, a coincidence of the upstream and downstream endcaps is made and used as a veto in this unit. In principle, this should not be necessary since the logic previous to that step selects events where only one endcap module is hit. Then, in yet another coincidence unit, the OR sum of the coincidence between the range stack T and A counters (T·A), barrel veto energy sum and range stack energy sum signals vetoes this endcap signal. The output of this last coincidence unit is sent to an ECL-NIM-ECL unit which sends the final signal to the trigger board. The trigger board takes no further decisions and initiates the sequence to record the event on tape. All discriminators and coincidence units used are operated in “update” mode, which means that their output pulses are extended beyond the preset width until the input pulse drops below the unit’s threshold. Also, all units are capable of handling high counting rates (up to 150 MHz).

IV.1.3 Analysis and Results

A programme was written to analyze the data written to tape using the trigger described in the previous section. Constraints similar to the ones described in section IV.1.1 were used along with some additional ones since in the experimental case, a large background arises from beam particles and other decays, especially $K_{π2}$. The optimum constraints were found to be:

1. The sum of the energy deposited in all T,A and B layers of the range stack is less than 2 MeV
2. There is at least one endcap module hit
3. The pulse height of the module with the largest pulse exceeds 100 ADC channels
Figure 29: Endcap $K_{\mu 2}$ online trigger logic diagram. Only one splitter box corresponding to one module is shown. Each fan in/fan out used to form the upstream and downstream sums has 24 inputs. Each CAMAC discriminator has 16 inputs.
• The two modules adjacent to the one with the largest pulse have a pulse less than 0.1 times that of the module with the largest pulse

• All other modules except the one with the largest pulse and its two immediate neighbours have a pulse height less than 100 ADC channels

• There is at least one TDC hit within the full range of the TDC for the module with the largest pulse

• The pulse height of the pion Čerenkov is less than 40 ADC channels

For every successful event, the ADC value of the module with the largest pulse is added to a histogram corresponding to that particular module. Using this, the muon peaks could clearly be recognized in each module. An example is given in figure 30. There is an excellent qualitative agreement between the experimental spectrum’s shape and the one from the Monte Carlo calculation (figure 24). The first task was then to adjust the high voltage on the endcaps’ phototubes so the peaks identified with the offline analysis would all correspond to the same pulse height. Since according to the Monte Carlo calculation the peak corresponds to about 50 MeV of energy deposited in the endcaps, and that the energy range expected to be covered by the endcaps goes up to about 100 MeV, the peaks were positioned at about half of the FERA ADC’s dynamic range. Several iterations were necessary to get a good alignment. It was found that several of the upstream modules (number 3, 6, 9, 11, 12, 13, 16 and 17\footnote{The modules are numbered clockwise starting from the +x axis when looking downstream. The downstream modules have numbers 25 to 48 (i.e. module 1 faces module 25, etc.)}) had output pulses not large enough to align them with the others, even when the high voltage on the phototube was pushed up to 2500 volts, the maximum voltage allowed by the high voltage power supplies. Therefore, new splitter boxes containing amplifiers had to be installed. Unfortunately, the active splitters slightly deform the shape of the energy spectra
(see figure 31). This is a bit of a problem since it introduces a different cutoff at low energy. Solutions to this will be discussed later.

Once the high voltages were fixed, several data sets were made. The kaon stopping rate was approximately $3.5 \times 10^4$ per particle burst from the synchrotron. Analysis results of a typical run are shown in table VII.

We see from this that the constraints rejecting the most events are the range stack energy sum and the modules adjacent to the one with the largest pulse. It seems that the online range stack energy veto is not extremely efficient. We will see below that it is a major problem for the calibration. The analysis results of all the data collected at that point were summed together (runs 1148 to 1154). The
Figure 31: Endcap module spectrum for endcap $K_{\mu 2}$ trigger (Module # 9 with amplifier splitter box)

Table VII: Analysis result for run 1154 (Endcap $K_{\mu 2}$ trigger)

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Events rejected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range stack energy sum</td>
<td>11611</td>
</tr>
<tr>
<td>Some energy in the endcaps</td>
<td>0</td>
</tr>
<tr>
<td>Maximum pulse height &gt; 100 channels</td>
<td>0</td>
</tr>
<tr>
<td>Immediate neighbour(s) pulse &lt; 0.1× maximum</td>
<td>10646</td>
</tr>
<tr>
<td>Other module(s) pulse &lt; 100 channels</td>
<td>1423</td>
</tr>
<tr>
<td>At least one TDC hit for maximum module</td>
<td>1</td>
</tr>
<tr>
<td>Pion Cerenkov pulse height &lt; 40 channels</td>
<td>2459</td>
</tr>
<tr>
<td>Good events</td>
<td>12883</td>
</tr>
</tbody>
</table>
spectrum of each module was fitted individually to a TINA function in the same way the Monte Carlo peaks were fitted. Then the gain for each module, expressed in units of channels per unit of visible energy deposited in the endcap (MeV), is given by the ratio of the peak value and the expected energy determined by the Monte Carlo calculation (section IV.1.1). Table VIII lists the values obtained. We note that, as expected, the gains are all very close to each other. It was then decided to accumulate two full magnetic tapes of data using this trigger twice a week during the data taking period, to monitor the stability of the calibration. This started about one month after the first calibration described above was done. The first tapes taken showed that the online trigger was disastrously ineffective. Table IX shows the analysis result of one of those runs. First, we note that the total number of events on tape is much smaller. This is explained by the fact that more information was written for each event compared to earlier data, since so many of these events have large energy depositions in the range stack. However, nothing explains this extremely large number of rejects because of energy in the range stack. The online trigger was verified several times but nothing wrong was found. As a result of this, the two tapes of data acquired twice a week did not provide enough statistics to verify the calibration. Much time was spent trying to solve this problem without disrupting the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ data collection, but without success. However, it was eventually noted that the number of events rejected by the offline analysis' range stack energy constraint was dependent upon the beam intensity, which was increased in the latter stages of the data collection period. Figure 32 shows the percentage of events rejected by that constraint as a function of the number of incident kaons. This clearly shows why this problem was not originally detected. The source of the problem is then logically the online range stack energy veto. It is possible that the discriminators operated in update mode cannot cope with the high counting rates and are inefficient. This will be
Table VIII: Endcap gains calculated with runs 1148 to 1154

<table>
<thead>
<tr>
<th>Module #</th>
<th>Gain</th>
<th>Module #</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>10.377</td>
<td>13</td>
<td>10.587</td>
</tr>
<tr>
<td>2</td>
<td>10.036</td>
<td>14</td>
<td>10.730</td>
</tr>
<tr>
<td>3</td>
<td>10.156</td>
<td>15</td>
<td>10.723</td>
</tr>
<tr>
<td>4</td>
<td>10.104</td>
<td>16</td>
<td>10.626</td>
</tr>
<tr>
<td>5</td>
<td>9.906</td>
<td>17</td>
<td>10.267</td>
</tr>
<tr>
<td>6</td>
<td>10.093</td>
<td>18</td>
<td>10.944</td>
</tr>
<tr>
<td>7</td>
<td>10.351</td>
<td>19</td>
<td>10.202</td>
</tr>
<tr>
<td>8</td>
<td>10.293</td>
<td>20</td>
<td>10.899</td>
</tr>
<tr>
<td>9</td>
<td>10.368</td>
<td>21</td>
<td>11.141</td>
</tr>
<tr>
<td>10</td>
<td>11.642</td>
<td>22</td>
<td>11.449</td>
</tr>
<tr>
<td>11</td>
<td>9.724</td>
<td>23</td>
<td>10.894</td>
</tr>
<tr>
<td>12</td>
<td>9.930</td>
<td>24</td>
<td>10.331</td>
</tr>
<tr>
<td>Downstream</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>10.552</td>
<td>37</td>
<td>10.761</td>
</tr>
<tr>
<td>26</td>
<td>10.468</td>
<td>38</td>
<td>10.776</td>
</tr>
<tr>
<td>27</td>
<td>10.256</td>
<td>39</td>
<td>10.434</td>
</tr>
<tr>
<td>28</td>
<td>10.857</td>
<td>40</td>
<td>10.386</td>
</tr>
<tr>
<td>29</td>
<td>11.114</td>
<td>41</td>
<td>11.471</td>
</tr>
<tr>
<td>30</td>
<td>9.842</td>
<td>42</td>
<td>11.797</td>
</tr>
<tr>
<td>31</td>
<td>9.729</td>
<td>43</td>
<td>10.092</td>
</tr>
<tr>
<td>32</td>
<td>10.486</td>
<td>44</td>
<td>10.503</td>
</tr>
<tr>
<td>33</td>
<td>9.387</td>
<td>45</td>
<td>11.182</td>
</tr>
<tr>
<td>34</td>
<td>11.160</td>
<td>46</td>
<td>9.968</td>
</tr>
<tr>
<td>35</td>
<td>10.648</td>
<td>47</td>
<td>11.375</td>
</tr>
<tr>
<td>36</td>
<td>10.710</td>
<td>48</td>
<td>9.724</td>
</tr>
</tbody>
</table>
investigated since an improvement to this trigger is imperative for the next data collection period at the start of 1989.

![Percentage of events rejected versus beam intensity. The intensity is given in terms of number of $K_T$ counts per particle burst](image)

Figure 32: Percentage of events rejected versus beam intensity. The intensity is given in terms of number of $K_T$ counts per particle burst.

Even though the statistics were not good enough to do a calibration for every pair of data tapes, we could still determine if any major gain change had occurred. No such change was observed so the analysis results of all the data tapes recorded after the first calibration were added together. The spectra had the same shape as previously, indicating that the gains had remained fairly stable over the last month or so of data collection. The spectra were fitted to TINA functions and a new set of gains applying to runs 2235 and beyond were calculated. They
are shown in table X. Comparing with the results of table VIII, we note that some of the gains changed substantially, but that no systematic shift occurred. The change occurred during the one month period between runs 1154 and 2235. Nothing happening during that period seems to be related to that change. The systematic uncertainties on the gains are estimated to be about 10%. Therefore a shift of less than that value would not be significant. Nonetheless, a calibration monitoring procedure must be devised to keep good control of the gains.

We can wonder how uniformly distributed the events are. Figure 33 shows an occupation plot of the good events selected from two runs. The profile is definitely not as uniform as the Monte Carlo was. An interesting observation is that the upstream modules with the largest number of counts are the modules with active splitter boxes. This probably stems from the fact that in the active splitters, the outputs all have the same voltage ratio with respect to the input voltage while for the passive splitters they are different. More importantly, the ratio of the output connected to the discriminators with respect to the input is larger in the case of the active splitters. The result is that these modules will be favored since they will produce more large pulses. This also means that it introduces non-uniformities in the photon veto. The downstream endcap is more uniform, although a few modules have small occupancies.

**IV.1.4 Reconstruction of $\pi^0$**

The calibration described in the previous sections relies on a Monte Carlo calculation. It is therefore natural to seek an independent way to verify its accuracy. The most obvious one is to try to reconstruct the energy of the neutral pion of the $K_{\pi 2}$ decay, $K^+ \rightarrow \pi^+ \pi^0$, by measuring the energy of the two photons produced by its decay,

$$\pi^0 \rightarrow \gamma \gamma.$$  

(26)
Table IX: Analysis result for run 2235 (Endcap $K_{\mu2}$ trigger)

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Events rejected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range stack energy sum</td>
<td>12480</td>
</tr>
<tr>
<td>Some energy in the endcaps</td>
<td>0</td>
</tr>
<tr>
<td>Maximum pulse height &gt; 100 channels</td>
<td>3</td>
</tr>
<tr>
<td>Immediate neighbour(s) pulse &lt; 0.1$\times$ maximum</td>
<td>2298</td>
</tr>
<tr>
<td>Other module(s) pulse &lt; 100 channels</td>
<td>944</td>
</tr>
<tr>
<td>At least one TDC hit for maximum module</td>
<td>0</td>
</tr>
<tr>
<td>Pion Cerenkov pulse height &lt; 40 channels</td>
<td>1187</td>
</tr>
<tr>
<td>Good events</td>
<td>2557</td>
</tr>
</tbody>
</table>

Figure 33: Occupation plot of the endcap modules for runs 2882 and 2883
Table X: Endcap gains valid for runs 2235 and above. Expected visible energy calculated using UMC version 2.0

<table>
<thead>
<tr>
<th>Endcap Gains (ch./MeV visible)</th>
<th>Upstream</th>
<th>Downstream</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Module #</td>
<td>Gain</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>10.217</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>9.256</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>11.332</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>11.592</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>9.748</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>10.021</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>12.223</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>8.290</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>9.758</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>11.299</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>9.343</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>10.239</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>9.853</td>
</tr>
<tr>
<td></td>
<td>26</td>
<td>11.989</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>9.049</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>11.179</td>
</tr>
<tr>
<td></td>
<td>29</td>
<td>12.461</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>9.838</td>
</tr>
<tr>
<td></td>
<td>31</td>
<td>10.295</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>12.205</td>
</tr>
<tr>
<td></td>
<td>33</td>
<td>10.018</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>10.510</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>11.674</td>
</tr>
<tr>
<td></td>
<td>36</td>
<td>11.174</td>
</tr>
</tbody>
</table>
A trigger dedicated to the $K_{\pi 2}$ reaction was used at frequent intervals during the data collection period. The only requirement for this trigger was for a charged track in the range stack not reaching any further than layer 18. The angle between a photon’s direction and the direction of the monoenergetic positive pion (momentum $p_{\pi^+} = 205$ MeV/c) is strongly correlated with the energy of that photon. The energy spectrum of the photons is flat, with a minimum at about 20 MeV and a maximum at 225 MeV. The photon of minimum energy will be in the same direction as the positive pion while the one of maximum energy will be opposite to it. At the minimum angle of separation between the two photons, $66.7^\circ$, the energy of the two photons is equal at 122 MeV. Since we are forced to have the positive pion in the range stack, it is rare to find events where both photons are in the endcaps, one upstream and one downstream. Indeed, a Monte Carlo calculation showed that only a little more than 1 % of all $K_{\pi 2}$ decays where the positive pion goes in the range stack will have both photons in the endcaps, rendering this option virtually impossible to use. However, since the barrel veto is a calorimeter of the same design as the endcaps and that its calibration is done using a fairly reliable method (cosmic rays), it is possible to identify events where one photon is in the barrel veto and one in an endcap, and add their measured energies to reconstruct the $\pi^0$ energy of 245.55 MeV. We must remember that the energy measured will be the visible energy, i.e. the energy deposited in the scintillator, and that the fraction of the incident energy can only be computed by means of a Monte Carlo calculation.

To select the appropriate events, the following constraints were applied when analyzing data collected using the $K_{\pi 2}$ trigger:

- The incoming particle is identified as a kaon by the Cerenkov counter
- There is only one track in the range stack
• There is at least 5 MeV of energy in the barrel veto

• There is only one "cluster" in the barrel veto (a cluster is defined as a group of adjacent modules containing energy)

• The same constraints as the previous two are applied to the endcaps

• There is no confusion in the target, i.e. the tracks of the incoming kaon and the outgoing positive pion are well identified

• The ratio of the energy of the pion track in the range track to the total range stack energy is greater than 90%.

The last constraint eliminates the numerous events where one of the photons has converted in the range stack. Figure 34 shows the range-momentum correlation for the $\pi^+$, which is very good. Figures 35 and 36 show the individual energies of the photons in the barrel veto and the endcaps respectively, which when added together give the result shown on figure 37. Fitting this peak to a gaussian function gives a value of

$$E_{\pi^+}^{\text{vis}} = 76.5 \text{ MeV}$$ (27)

with a standard deviation of $\sigma = 11.6$ MeV. Dividing this number by the $\pi^0$ expected energy, we get the fraction of visible energy over incident energy,

$$f_{\text{vis}} = 0.312.$$ (28)

We can compare this last number to the result of a Monte Carlo calculation done by the ARGUS group at DESY for a calorimeter of the same design (reference [15] figure 5). We see that the number found here corresponds almost exactly to the calculation. The analysis of other data sets collected using the $K_{\pi^2}$ trigger gave very similar results. Therefore, we can be confident that the endcap calibration is quite accurate.
Figure 34: Range-momentum distribution of $K_{\pi 2}$ events with one photon in the barrel veto and one in the endcaps. The range is the measured range in scintillator and the momentum is measured by the drift chamber, with corrections for energy lost in the target and I-counter.
Figure 35: Visible energy measured for the photon in the barrel veto
Figure 36: Visible energy measured for the photon in the endcaps
Figure 37: Reconstructed $\pi^0$ energy. The curve shown is a fit to a gaussian function.
IV.2 Time Calibration

To be able to place cuts on the timing of events, it is necessary to evaluate the timing offsets of the FASTBUS TDC’s of the different subsystems so they all refer to the same origin, or “zero”.

Since most triggers of physics interest require a range stack T·A coincidence to define the event, the timing of the A counters has been very carefully adjusted via short delay cables, so that they are within one nanosecond of each other. Thus, we take the time of the A counters to be the time of an event, since in most cases, they will have been triggered by a minimum ionizing pion or muon, giving pulses of similar heights every time. Then, for each detector element equipped with a TDC, we must determine the offsets that will realign its measured time with the time of the A counter.

In the case of the endcaps, each one of the forty-eight modules is equipped with a TDC. In order to determine the time offsets, we need a decay allowing for a clean event in the range stack as well as a simultaneous hit in an endcap. The $K_{\pi2}$ decay where the $\pi^+$ goes in the range stack, one photon goes in the barrel veto and the other photon hits an endcap is perfectly suited for this task. We can also make use of the runs taken with the $K_{\pi\gamma\gamma}$ trigger, since most of the events recorded on tape for this trigger are $K_{\pi2}$ events.

The offline analysis selected events as follows:

1. The kaon Čerenkov signal ($\mathcal{C}_K$) is greater than the pion Čerenkov signal ($\mathcal{C}_\pi$)

2. There is only one charged track in the range stack

3. The total barrel veto visible energy is more than 5 MeV

4. There is some energy in the endcaps
5. The endcap module with the largest energy has an ADC hit greater than 50 channels (~5 MeV)

6. All other endcap modules except the two immediate neighbours have ADC hits less than 10 channels (~1 MeV)

7. There are no multiple TDC hits in the A counter which is part of the pion track within a time window of 0 to 100 ns (the prompt time is at about 12 ns)

8. Both ends of the A counter have a TDC hit

9. There are no multiple TDC hits in the endcap module with the maximum energy deposition

Constraint # 1 ensures that the incoming particle is a kaon. Constraints # 2 and 3 improve the $K_{\pi 2}$ event selection, helped furthermore by cuts # 4, 5 and 6 which select events with one cluster of hits in the endcaps. Constraints #7, 8 and 9 are necessary to get the time unambiguously. Constraints # 3, 5 and 6 were chosen considering the fact that the lowest energy photon from a $K_{\pi 2}$ decay is approximately 20 MeV and that the visible energy in the lead-scintillator stacks is expected to be about 0.3 times the incident energy (see previous section). Table XI shows the analysis result of a typical run where we indicate the number of events eliminated by the constraints along with the percentage of events remaining. The constraints were applied in the order shown in the table, an event being rejected as soon as it did not satisfy a condition. If an event satisfied all the above mentioned conditions, the A counter time was subtracted from the raw time of the endcap module with the maximum energy deposition. The resulting time difference was then histogrammed, one histogram being made for each endcap module. In this discussion, “time” always refers to the “leading edge” time, i.e. the time when the
pulse height from the detector element exceeds the threshold of the TDC, which was 50mV for the endcaps. Because we are using the leading edge, a pulse height correction should be made. In the case of the A counters, this correction is assumed to be negligible. The correction for the endcaps will be discussed below.

Table XI: Analysis result for run 2444 ($K_{π2}$ trigger)

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Events rejected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incoming particle not a kaon</td>
<td>168</td>
</tr>
<tr>
<td>Not only one range stack track</td>
<td>1715</td>
</tr>
<tr>
<td>Barrel veto energy &lt; 5 MeV</td>
<td>6667</td>
</tr>
<tr>
<td>No energy in the endcaps</td>
<td>2631</td>
</tr>
<tr>
<td>Maximum endcap hit &lt; 50 channels</td>
<td>1265</td>
</tr>
<tr>
<td>Other module &gt; 10 channels</td>
<td>1499</td>
</tr>
<tr>
<td>Multiple TDC hits in A counter</td>
<td>605</td>
</tr>
<tr>
<td>Not both ends of A counter with TDC hit</td>
<td>128</td>
</tr>
<tr>
<td>Multiple TDC hits in the endcap module</td>
<td>164</td>
</tr>
<tr>
<td>Good events</td>
<td>920</td>
</tr>
<tr>
<td>Percentage of good events</td>
<td>5.8%</td>
</tr>
</tbody>
</table>

For the first calibration, two runs were used, 2238 and 2239, both taken with $K_{πγγ}$ trigger. These two runs were chosen because they offered a reasonably large number of events with good, stable and unchanged data taking conditions. The histograms of both runs were added together. Figure 38 shows a typical histogram for one endcap module. We see that even though the statistics are poor, the peaks can be easily determined, even by eye.

To get a more accurate value for the peaks, a least squares fit to a gaussian function was performed on each histogram. A more sophisticated chi-square minimization fit was performed on some histograms using the MINUIT minimization routines from the CERN library. The values found with MINUIT agreed very nicely with the values from the least squares fits. The MINUIT one
Figure 38: Time offset for endcap module # 47 (50 ch. endcap threshold).
standard deviation errors are less than 0.5 ns for the peaks ($\mu$). But, the fit value of $\sigma$ is between 1 and 2 ns, depending on the histogram, for both MINUIT and the least squares fit. This is to be expected since the TDC's were operated with a bin width of 2 ns for the whole 1988 data collection period.

To check the quality of the time calibration, a second analysis was made on runs 2238 and 2239, this time using the endcaps' calibrated times. The event selection was the same as the one detailed above. Only one histogram was made of all the differences between the A counter time and the endcap time. The result is shown on figure 39. A fit to a gaussian function gives a mean of 0.129 ns with a standard deviation of 1.86 ns. This confirms that the calibration is limited by the size of the TDC bins. Then, to see how stable the time calibration is, several $K_{x2}$ runs were analyzed in the same way using the offsets determined with runs 2238 and 2239. The results are shown on table XII. From those results we first notice that the calibration is quite stable. We also notice that runs 2400 to 2978 all have very similar results. Therefore, all these runs were analyzed in order to get the time offsets. The histograms from runs 2444 to 2978 were all added together and fitted to gaussians to produce a second set of time offsets. As a final check, all runs were re-analyzed using those new time offsets. The results are shown in table XIII. Excellent values of the mean are obtained. The values are all very close to zero, as expected.

As said earlier, these results do not include pulse height corrections. Since the TDC's record the leading edge, a large pulse height will be seen as arriving earlier than a smaller pulse, this for the same event time. To see if such a correction is important in the case of the endcap, the $K_{x2}$ runs 2400 to 2978 were analyzed in the same way as before except that this time, for each module, a scatterplot was made of the pulse height against the time offset. Figure 40 shows a typical scatterplot for one module. There is indeed a correlation as expected, the
Figure 39: A counter time minus endcap time for runs 2238 and 2239. The curve comes from a gaussian least squares fit. The resulting fit parameters are indicated.

Table XII: Time offsets check using the first set determined

<table>
<thead>
<tr>
<th>run number</th>
<th>Mean</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2238-2239</td>
<td>0.129</td>
<td>1.86</td>
</tr>
<tr>
<td>2400</td>
<td>-0.347</td>
<td>1.92</td>
</tr>
<tr>
<td>2444</td>
<td>-0.484</td>
<td>1.98</td>
</tr>
<tr>
<td>2460</td>
<td>-0.391</td>
<td>1.91</td>
</tr>
<tr>
<td>2802</td>
<td>-0.423</td>
<td>1.89</td>
</tr>
<tr>
<td>2842</td>
<td>-0.461</td>
<td>1.89</td>
</tr>
<tr>
<td>2904</td>
<td>-0.481</td>
<td>1.84</td>
</tr>
<tr>
<td>2978</td>
<td>-0.462</td>
<td>1.99</td>
</tr>
</tbody>
</table>
large pulses arriving earlier. This finer correction would be needed if the exact time of arrival of an event in the endcap was required in order to veto events recorded using the $K^+ \rightarrow \pi^+\nu\bar{\nu}$ trigger.

![Figure 40: Scatterplot of pulse height against time offset (module # 47)](image)

**IV.3 Random Vetoing**

One important characteristic of the photon veto system is how many times it will reject events because of random hits due to accidental background. For the $K^+ \rightarrow \pi^+\nu\bar{\nu}$ online trigger, the endcap veto is applied in the following way: for every event, a sum of the pulse heights of all 24 modules of each endcap is made. Those two sums are sent to a discriminator whose threshold is set at a level
equivalent to about 10 MeV. If a sum exceeds that level, the output of the discriminator is latched into a standard signal (bit) presented to the trigger board. The procedure is identical for the barrel veto. If one of those bits is present, the event is rejected.

The discriminator’s level is purposely set at a relatively high level (e.g. the lowest energy photons from $K_{\pi 2}$ decay are $\approx 20$ MeV) in order to reduce the rate of random vetoing; with the help of other constraints from other detector components, the background events can be rejected in offline analysis. However, there is still the possibility of a beam particle hitting the endcaps and depositing enough energy to veto an event otherwise perfectly clean. To estimate the rate of random vetoing, we used data runs collected using a special $K_{\mu 2}$ trigger. For this trigger, the only requirement is that there be a charged track in the range stack reaching layer 21. Even though the photon veto is not included in that trigger, the veto bits are still recorded for each event. A $K_{\mu 2}$ decay where the muon is well identified in the drift chamber should not deposit any energy in the endcaps. Then by isolating a subset of the data consisting of a very pure sample of $K_{\mu 2}$ decays, we can determine the random veto rate by verifying the photon veto bits for those events.

To select $K_{\mu 2}$ events, the following constraints were applied to the data:

- The initial particle is identified as a kaon by the Cerenkov counter
- There is no confusion in the target
- The ratio of the muon track energy in the range stack to the total range stack energy is greater than 0.95
- The total barrel veto energy is less than 1 MeV
The muon measured range in scintillator is within the bounds $45\,\text{cm} < R_{\mu^+} < 60\,\text{cm}$

The muon measured momentum is within the bounds $220\,\text{MeV}/c < P_{\mu^+} < 245\,\text{MeV}/c$

The data had gone through a pre-selection process where only events with a single charged track in the drift chamber and a matching single charged track in the range stack were kept. These tight constraints should be sufficient to isolate an extremely pure sample of $K_{\mu2}$ decays. Table XIV shows the results of the analysis of two runs. From these results, we can determine the total endcap random veto rate for those two runs; we get:

Run 2823: 1.3% (29)
Run 3026: 1.0% (30)

Therefore, about 1% of the time, the online $K^+ \rightarrow \pi^+\nu\bar{\nu}$ trigger will reject true events because of random hits in the endcaps.

The kaon stopping rate for run 2823 was $1.9 \times 10^5$ per burst and $1.3 \times 10^5$ for run 3026. We might wonder if the random rate has any dependence on the beam intensity. Unfortunately, few data sets collected using the $K_{\mu2}$ trigger are available and most were recorded with similar beam intensities. Hence, a different method giving the endcaps random rate independent of the online trigger was necessary. Such a method was found using the endcaps FASTBUS TDC's. The TDC's sampling time range of 1024 ns is more or less centered on the prompt time, i.e. the time at which the trigger fired. Therefore, by counting the number of hits per unit time in the TDC's at times earlier than the prompt time, we obtain a number related to the random rate. We expect this number to be greater than the "real" random rate found using the $K_{\mu2}$ method since in this method events where
several endcap modules fire simultaneously will be counted individually. Also, this
method counts hits in the endcaps which give pulse heights higher than the TDC
discriminator’s threshold, set at 50 mV for all the runs considered. This threshold
corresponds to about 1 or 2 MeV deposited in the modules. Nevertheless, the rate
found by this method will be proportional to the random veto rate.

Figures 41 and 42 show the number of events as a function of time for each
module for a typical run. From this we see the flat background as a function of
time, as is expected when we are away from the prompt time. This also shows the
TDC occupation. For the downstream endcap, we note a larger occupation for
modules around the x axis of the detector. This seems to indicate a spreading of
the beam in that direction beyond the target. Figures 43 and 44 show the random
rate as a function of the number of stopped kaons per particle burst, for the
upstream and downstream endcap respectively. We see a clear linear dependence
of the random rate upon the beam intensity. This means that increasing the beam
intensity for the next data taking run (1989) will increase the figure of ~ 1 %
random vetoing, although this should not be an important factor in limiting the
acceptance of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ events of experiment 787.

IV.4 Photon Detection Inefficiency

One of the main concerns about the background effects for experiment 787 is the
photon detection efficiency. As explained in the introduction, high levels of
efficiency are required in order to attain the goal of a sensitivity of $2 \times 10^{-10}$ to
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ . A limitation to photon detection with the design used for the
endcaps and the barrel veto occurs because of photo-nuclear reactions, where the
photon is absorbed by a nucleus. In general, this leads to $(\gamma, n)$ or $(\gamma, p)$ reactions,
where a neutron or proton is ejected from the nucleus [17]. The residual nucleus
may be left in an excited state and can return to a more stable state via $\gamma$, $n$ or $\alpha$
Table XIII: Time offsets check using refined values

<table>
<thead>
<tr>
<th>run number</th>
<th>Mean</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2400</td>
<td>-0.058</td>
<td>1.86</td>
</tr>
<tr>
<td>2444</td>
<td>-0.064</td>
<td>1.87</td>
</tr>
<tr>
<td>2460</td>
<td>0.005</td>
<td>1.82</td>
</tr>
<tr>
<td>2802</td>
<td>-0.050</td>
<td>1.81</td>
</tr>
<tr>
<td>2842</td>
<td>-0.018</td>
<td>1.83</td>
</tr>
<tr>
<td>2904</td>
<td>-0.004</td>
<td>1.81</td>
</tr>
<tr>
<td>2978</td>
<td>-0.072</td>
<td>1.89</td>
</tr>
</tbody>
</table>

Table XIV: Analysis result for runs 2823 and 3026 ($K_{\mu2}$ trigger) used to determine the endcaps random vetoing rate

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Events rejected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run number</td>
<td>2823</td>
</tr>
<tr>
<td>Events analyzed</td>
<td>12410</td>
</tr>
<tr>
<td>Incoming particle is a kaon</td>
<td>194</td>
</tr>
<tr>
<td>No confusion in the target</td>
<td>219</td>
</tr>
<tr>
<td>Barrel veto energy &lt; 1 MeV</td>
<td>1759</td>
</tr>
<tr>
<td>Ratio of track/total range stack energy &gt; 0.95</td>
<td>3246</td>
</tr>
<tr>
<td>Range-momentum constraints</td>
<td>2335</td>
</tr>
<tr>
<td>Events left</td>
<td>4657</td>
</tr>
<tr>
<td>The upstream endcap fired</td>
<td>26</td>
</tr>
<tr>
<td>The downstream endcap fired</td>
<td>26</td>
</tr>
<tr>
<td>Both endcaps fired</td>
<td>8</td>
</tr>
</tbody>
</table>
Figure 41: Random hits for each upstream endcap module as a function of time. The time of the prompt events would be approximately 600 ns on this scale.
Figure 42: Random hits for each downstream endcap module as a function of time. The time of the prompt events would be approximately 600 ns on this scale.
Figure 43: Random rate as a function of beam intensity (upstream end-cap). The line shown is from a least squares fit to a straight line.
Figure 44: Random rate as a function of beam intensity (downstream end-cap). The line shown is from a least squares fit to a straight line.
decay. The ground states may also decay via $\beta$ or $\alpha$ decay but this would occur much later. Also, at high energy ($E_\gamma > 140$ MeV), pion production can occur via the reactions

\begin{align*}
\gamma p &\rightarrow p \pi^0 \\
\gamma p &\rightarrow n \pi^+ \\
\gamma n &\rightarrow p \pi^- \\
\gamma n &\rightarrow n \pi^0
\end{align*}

(31) \hspace{1cm} (32) \hspace{1cm} (33) \hspace{1cm} (34)

where the protons and neutrons are bound in the nucleus.

It is possible that the energy liberated by the photo-nuclear reactions goes undetected, especially if the reaction products are of low energy and if the reaction occurred in non-active material. At low photon energies, the cross section for photo-nuclear reactions is dominated by the giant dipole resonance. The peak position of the resonance decreases as the mass number of the nucleus increases; for instance, carbon peaks at about 23 MeV while lead peaks at about 13 MeV. Also, the total cross section increases with mass number. Therefore, the presence of inactive lead in the detectors might limit the photon detection capability, compared to more expensive totally active designs using materials such as barium fluoride crystals with a gas chamber read out system. Monte Carlo simulations incorporating photo-nuclear interactions were made [18], and it was found that the lead-scintillator still allowed sufficient photon detection efficiency.

Finding the experimental value of the efficiency is a very important and difficult task. One way to determine the one photon detection efficiency would be to select $K_{\pi2}$ decays, measure the direction of the positive pion and one of the photons and verify if the other photon was detected at the expected location according to the kinematics of the decay. However, the position resolution using the barrel veto or the endcaps is not sufficient to determine with certainty if the
photon should have been seen by the detector. In particular, the hole in the middle of the endcaps introduces an uncertainty of several percent. Therefore, it becomes very difficult to determine the efficiency of one particular subsystem.

It is possible to obtain the global $\pi^0$ detection efficiency by looking at the analysis results of the $K^+ \rightarrow \pi^+\nu\bar{\nu}$ data in the phase space region of the $K_{\pi2}$ decay. Events in that region not rejected by the analysis can be attributed to $K_{\pi2}$ decays since the contribution of $K^+ \rightarrow \pi^+\nu\bar{\nu}$ events should be very small. A calculation of the efficiency using this method was performed by a member of the E787 collaboration [19]. The number obtained is

$$I_{\pi^0} < 6 \times 10^{-6} \quad (35)$$

where $I_{\pi^0}$ is the inefficiency, defined as

$$I_{\pi^0} = 1 - \mathcal{E}_{\pi^0} \quad (36)$$

where $\mathcal{E}_{\pi^0}$ is the efficiency. This was calculated for a veto energy threshold of 1 MeV. This number is not only the barrel veto and endcaps inefficiency but also includes contributions from the range stack, the target and any cracks or inactive material. More studies of this will be done in the future.
Chapter V

Conclusion

In this thesis, it has been shown that it is possible to construct a lead-scintillator sampling calorimeter using a wavelength shifter readout system for fast photon detection operation in the endcap region of the E787 detector. The scintillator-wavelength shifter combination used (NE-104+BBOT) gives a light output of the order of 10 photo-electrons per MeV deposited in the scintillator. Beam tests at TRIUMF showed that its energy resolution is relatively well represented by a $1/\sqrt{E}$ energy dependence, as is expected from such a calorimeter. The energy resolution is comparable to the resolution of a very similar calorimeter built for the ARGUS detector, using a wavelength shifter called BBQ. Hence, BBOT has a performance similar to BBQ while being able to sustain high counting rates. Also, the linearity of the energy response was showed to hold fairly well over the energy interval 30-140 MeV.

The calibration of the completed assembly was done using monoenergetic muons from the $K_{\mu 2}$ decay. This method has the major advantage that it gives the calibration for the exact experimental conditions, eliminating a possible systematic error. The online trigger used for the calibration did not perform as well as expected and will have to be investigated. The veto on range stack energy will have to be improved so that a sufficient amount of calibration data can be quickly accumulated at frequent intervals to monitor short term variations in the gains of the modules. The operation of the electronic modules at high counting rates, also a possible cause of trigger inefficiency, will have to be thoroughly tested.
The endcaps performed well and without failure for several months of data collection. At the moment, there is no indication that the endcaps' photon detection inefficiency is a limitation to the ultimate goals of the experiment. A completely active calorimeter, using novel techniques with barium fluoride or pure cesium iodide, might be considered to complement or even replace the actual photon detectors. However, the very high cost of such an improvement might not justify the gain obtained in photon sensitivity, since all designs are ultimately limited by photo-nuclear absorption of photons.
Bibliography


A computer code, called UMC, has been written specifically for the 787 experiment. Several members of the E787 collaboration contributed to its elaboration [20]. This programme defines a detector geometry as close as possible to the actual detector. To treat photons’ and electrons’ energy depositions, use is made of routines from the EGS Monte Carlo programme, a well known and extensively used code [9]. For heavy charged particles (muons, pions, kaons and protons) it calculates the energy deposition by adding the energy losses of each ionization and excitation events along the steps taken by the particles. The number of ionization and excitation events is determined by dividing the total average energy deposited along the step, obtained using the Bethe-Bloch formula [21], by the minimum energy a particle loses because of an event, taken to be 65 eV.

The programme includes photonuclear reactions for photons. They are handled by a code called PICA [22], integrated with UMC. Also, an option allows the user to turn on nuclear absorption reactions for strongly interacting particles (pions, kaons, protons). The flow of the programme is handled by several user supplied subroutines, giving access to the output variables generated by the code at every step. In this way, a significant amount of computer time can be saved by generating only interesting events.
Appendix B

TINA function

The TINA function was developed at TRIUMF to reproduce the energy response of a large sodium iodide crystal called TINA. A typical shape is shown in figure 45. It is given by:

\[
TINA(x, B, C, D) = e^{(\frac{x-B}{D})} \frac{[1 - \text{erf}(\frac{x-B}{D})]}{2D e^{(\frac{C^2}{4D^2})}}
\]  \hspace{1cm} (37)

where

\[
\text{erf} = \frac{2}{\sqrt{\pi}} \int_{0}^{\infty} e^{-t^2} dt
\]  \hspace{1cm} (38)

is the error function. The numerator in (37) is a normalization factor. The parameters \( C \) and \( D \) determine the width of the curve on the right and left side of the peak respectively. The parameter \( B \) determines the peak position, but \( C \) and \( D \) also have an effect. In fact, there is no analytic expression for the peak position, as we will now see.

Taking the derivative of equation (37) with respect to \( x \) yields:

\[
\frac{\partial TINA}{\partial x} = \left\{- \frac{2}{\sqrt{\pi}} \frac{1}{C} e^{(\frac{x-B}{D})} e^{-(\frac{x-B}{D})^2} + \frac{1}{D} e^{(\frac{x-B}{D})} \left[ 1 - \text{erf} \left( \frac{x-B}{C} \right) \right] \right\}
\times \frac{C^2}{2D e^{(\frac{C^2}{4D^2})}}^{-1}
\]  \hspace{1cm} (39)

where use is made of

\[
\frac{d \text{erf}(z)}{dz} = \frac{2}{\sqrt{\pi}} e^{-z^2}
\]  \hspace{1cm} (40)

To find the peak, we equal this result to zero. This gives:

\[
\frac{2}{C \sqrt{\pi}} e^{-(\frac{x-B}{D})^2} - \frac{1}{D} \left[ 1 - \text{erf} \left( \frac{x-B}{C} \right) \right] = 0
\]  \hspace{1cm} (41)
This leaves us with a transcendental equation to be solved numerically. We use the Newton-Raphson iterative method, where for a function $f(x)$, the value of $x$ satisfying the equation $f(x) = 0$ is given by:

$$x_{k+1} = x_k - \frac{f(x_k)}{f'(x_k)}$$

where the $x_i$ are successive values of $x$ and $f'(x_k)$ is the derivative of $f(x_k)$ with respect to $x_k$. Iterations are made until the difference between two successive values of $x$ is small enough. For our specific case, $f(x) = 0$ becomes equation (41), while $f'(x)$ will be given by

$$f'(x) = \frac{2}{C\sqrt{\pi}} e^{-\left(\frac{x-B}{C}\right)^2} \left[ \frac{1}{D} - \frac{2}{C^2(x-B)} \right]$$

where again use is made of equation (40).

A short program to perform this algorithm on a computer was written. For every case considered, convergence was rapid and the peak value could be obtained to a high degree of precision, provided the initial value was suitably chosen.
Figure 45: TINA function shape. The axes are arbitrary.