Totally Active Scintillator Tracker-Calorimeter for the Muon Ionization Cooling Experiment

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29 July 2014

The research leading to these results has received funding from the European Commission under the FP7 Research Infrastructures project AIDA, grant agreement no. 262025.

This work is part of AIDA Work Package 8: Improvement and equipment of irradiation and test beam lines.

The electronic version of this AIDA Publication is available via the AIDA web site or on the CERN Document Server at the following URL:
Totally Active Scintillator Tracker-Calorimeter
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THÈSE

présentée à la Faculté des sciences de l’Université de Genève
pour obtenir le grade de Docteur ès sciences, mention physique

par

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de la Russie

Thèse N° 4701
Doctorat ès sciences
Mention physique

Thèse de Monsieur Ruslan ASFANDIYAROV

intitulée :

"Totally Active Scintillator Tracker-Calorimeter for the Muon Ionization Cooling Experiment"

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Résumé

Les récentes découvertes en physique des particules, notamment du boson de Higgs et des oscillations des neutrons, ont révélé le besoin de nouvelles machines offrant des performances accrues en terme d'intensité, d'énergie et de précision. Pour étudier de manière complète les oscillations de neutrons et sonder la possible existence de nouvelle physique, une usine à neutrons se présente comme un outil puissant qui offre un faisceau de neutrons de haute intensité et aux caractéristiques comprises avec précision. D'autre part, un collisionneur de muons est un outil unique pour une meilleure compréhension de la physique du Higgs. Les deux instruments partagent des éléments similaires, en particulier le refroidissement des faisceaux, qui est essentiel pour atteindre une haute brillance. La seule méthode connue pour obtenir le refroidissement d'un faisceau de muons est basé sur le principe d'ionisation. Un projet de R&D a été créé pour vérifier la possibilité d'un tel refroidissement, la Muon Ionisation Cooling Experiment (MICE). Son but est de construire une chaîne de refroidissement capable de diminuer l'émission d'un faisceau de muons de 10% et de mesurer l'effet avec une précision absolue de ~0.1%. Ceci est réalisé en utilisant des détecteurs de différentes technologies: traceurs à fibres scintillantes, détecteurs de temps de vol et calorimètres. Un des calorimètres, visant à identifier les muons traversant la chaîne de refroidissement sans désintégration, est un scintillateur traceur-calorimètre entièrement actif appelé Electron-Muon Ranger (EMR). La construction et la mise en service de ce détecteur est le sujet principal de cette thèse.

L'introduction et le premier chapitre sont consacrés aux motivations physiques pour une usine à neutrons et un collisionneur à muons. Le deuxième chapitre décrit l'expérience MICE de refroidissement par ionisation des muons. Le dernier chapitre constitue la partie principale de la thèse contenant une description du travail effectué.

Le projet de la construction de l'EMR a été lancé en 2008 ; mais en 2010 un défaut majeur dans la conception a été découvert. Lors de l'assemblage du détecteur, des forces excessives étaient appliquées sur les fibres optiques à décalage de longueur d'onde transmettant le signal du scintillateur au photomultiplicateurs, ce qui provoquait des craquelures sur celles-ci. Plus de 10% des canaux étaient ainsi endommagés. Il a été décidé de modifier la conception du détecteur en ajoutant de nouvelles fibres optiques reliant les fibres à décalage de fréquence aux photomultiplicateurs, grâce à des connecteurs spécifiquement conçus. De plus, de nombreux tests de qualité ont été mis en œuvre afin d'assurer le meilleur assemblage et éviter la détérioration de canaux lors de cette étape. Ceci a permis de n'avoir aucune fibre endommagée mécaniquement une fois le détecteur monté (à l'exception de cinq canaux morts au niveau de l'électronique).

Une simulation complète de l'EMR a été effectuée et sa performance a été étudiée à l'aide de logiciel Geant4. Il était important de prendre en compte toutes les interactions de faible énergie comme les particules qui s'arrêtent dans le détecteur et se désintègrent. Un système complet de numérisation Monte Carlo a été développé puis validé à l'aide de rayons cosmiques. Même sans aucun réglage des paramètres de la numérisation, l'accord entre la simulation et les données réelles est remarquable.

La construction du détecteur du point de vue de l'ingénierie et de l'électronique a été la plus grande partie de l'effort constituant le travail décrit dans cette thèse. A cela s'ajoute que tous les logiciels nécessaires pour produire des résultats de physique ont été codés: la reconstruction, l'étalement, l'analyse de données et la numérisation Monte Carlo. Les données réelles sont traitées par les mêmes codes de reconstruction et d'étalement. Le logiciel reproduit la longueur de pénétration et l'énergie des
événements ainsi que d'autres variables, telles que la présence d'électrons issus de désintégration et leur longueur de pénétration, et le taux de décroissance de l'énergie le long de la trajectoire d'une particule et la détection du pic de Bragg. Toutes ces mesures permettent de distinguer clairement les électrons des muons et des pions, et permettent une séparation correcte des muons par rapport aux pions.

Il peut être conclu avec un grand degré de confiance que les performances du détecteur sont bien dans les objectifs prévus et qu'il possède même un potentiel significatif d'amélioration.

Afin de mesurer l'émittance d'un faisceau de muons avec une grande précision, il est important de choisir un échantillon très propre de muons qui ont traversé la chaîne de refroidissement sans se désintégrer. L'EMR fournit les moyens d'effectuer une telle sélection, et permet de déterminer sans ambiguïté la nature des particules le traversant lorsqu'il est utilisé conjointement avec des mesures de quantité de mouvement d'autres sous-détecteurs de MICE. Les premiers résultats de MICE sont attendus en 2015 quand une partie de la chaîne de refroidissement sera achevée. L'EMR sera une partie de l'instrumentation du faisceau et il fournira des données précieuses qui permettront des mesures précises des quantités physiques nécessaires pour prouver la faisabilité du refroidissement par ionisation des muons.
Rapport préliminaire concernant la thèse présentée par
Monsieur Ruslan Asfandiyarov

“ Totally Active Scintillator Tracker-Calorimeter 
for the Muon Ionization Cooling Experiment”

Ruslan ASFANDIYAROV presented a preliminary version of his thesis on 25 June 2014 to 
the Jury nominated by the DPNC. This thesis was performed from November 2010 until 
spring 2014 in the Neutrino Group of the DPNC, in the framework of the Muon Ionization 
Cooling (MICE) experiment, the goal of which is to establish the method of cooling muon 
beams for neutrino factory and muon colliders. More specifically his assignment was the 
construction and commissioning of the Electron Muon Range (EMR). EMR is a totally active 
scintillator detector designed and built almost entirely at the DPNC, in collaboration with 
Milano/Como/Trieste and Fermilab. Its purpose is to select particles that are muons at the exit 
of the cooling channel, so as to ensure that the cooling measurement is not affected by 
backgrounds coming from pions or electrons from muon decays. Ruslan rose to the challenge 
beautifully and assumed almost by himself the full management of the detector quality 
assurance and construction, demonstrating a level of maturity and organization that goes well 
beyond that normally expected of a PhD student.

The DPNC is strongly involved in the MICE experiment since its inception in 2001, with 
Prof. Blondel leading the collaboration as spokesperson from 2001 till October 2013. The 
EMR was an idea by Jean-Sebastian Graulis to perform the downstream particle 
identification of MICE, which was previously unsatisfactory. That EMR fulfills the 
requirements was shown in simulations by Rikard Sandström in his PhD thesis in 2007.

The work reported in the thesis describes the final design, quality assurance, construction and 
commissioning of the EMR, as well as a first investigation of its particle identification 
performance. It is almost entirely the work of Ruslan. It is worth noting that Ruslan has 
explained with great clarity the operation of the EMR to a Master student, François Drielsma, 
who will take over the EMR responsibility.

The first chapter of the thesis is a short recall of the physics of massive neutrinos and, while it 
is brief, it goes to the main points, with a very good understanding of two main issues, namely
that three-flavour mixing leads to CP violation, and that the presence of both Dirac and Majorana mass terms in the Lagrangian could lead to heavy sterile neutrinos, potentially responsible for dark matter and the baryon asymmetry in the Universe.

The second chapter presents a summary of long and short baseline neutrino oscillation experiments, with a good description of the LBNO, T2HyperK and LBNE projects as well as of some of the short-baseline sterile neutrino searches. It then goes to describe the neutrino factory and the muon collider, as a basis for the motivation of the MICE experiment. As always, Ruslan is to the point and quite accurate, given the rapidly evolving situation.

Chapter three describes the principle of cooling, and the goals and the design of the MICE experiment in the amount of detail relevant to understand the need for the EMR and its role in the experiment.

The fourth chapter is the main chapter of the thesis. It is constituted of seven sub-chapters and in all, can be considered as 1) a thorough reference for the construction and geometry, 2) a complete user manual of the EMR, including online and offline software, 3) a first look at the performance using cosmics and MICE beam data.

The chapter 4.1 describes the construction of the EMR, and the principle of its operation as a particle detector. This includes: i) a geometrical description of all components; ii) a description of how they function: scintillation, wave-length shifting, light collection, connectors, description of both types of photo-multipliers, purpose and operation of the three levels of electronics. This is remarkable because the author knows the details but also understands the underlying detector physics and electronic science very well.

Chapter 4.2 describes the construction process which he has thoroughly supervised and in many ways masterminded. Probably the most remarkable part is the gigantic amount of quality assurance that has led to having essentially zero (out of 2500) faulty detector elements. This was done by designing and operating several levels of quality control, one for the scintillator bars, one for the individual connectors, one for the PMTs, one for the electronics, one for the assembled planes, one to determine the cross-talk, and finally one final cosmic test. Ruslan designed and imagined several clever methods for this quality assurance, and made very much the absolute best with the available funds and in great connection with the engineers and technicians. Because the quality tests were made in parallel with the construction, they were almost never on the critical path of the project, which was dominated by the assembly of the bars and detectors by the technicians.

The cosmic test was performed twice, once at ‘home’ in Geneva, once at RAL before beam data taking. It continues on a regular basis. These data have allowed to characterize the response of the scintillators and readout to a homogeneous flux of cosmic particles and allowed to spot one pair of inverted channels, and a set of four dead
electronics channels. All else is perfect. A careful study of the cross-talk was also performed. Given the foreseen voltage balance campaign and exchange of the old single anode PMTs, the detector will be nearly flawless.

Section 4.3 describes the electronics. The basic design was performed by our colleagues from Trieste and Como, but the supervision of the construction and of the final needs was done at Geneva, largely under Ruslan’s supervision. The principle and design of each of the components, from the front-end boards all the way to the data acquisition and data structure is reviewed in detail, including the essential discussions on the signal shape and on the time structure of the signals, trigger, events and beam spill. Once one reads this, one has the (rare) impression of having understood how it all works.

Chapter 4.4 discusses the analysis software, which was designed to work within the MICE framework and was used in conjunction with the other detectors in MICE. Starting from the data structure, we explore the event selection, the clean-up of data and the hit reconstruction, then the reconstruction of tracks and their connection in space and time. It is a characteristic of the EMR to have to connect in space and time the pions and muons with their decay products, which are separated in time by typically the pion lifetime ($20\text{ms}$) and the muon lifetime ($2.2\mu\text{s}$). An important aspect of the analysis is the calibration.

Chapter 4.5 describes the simulation, performed with Geant4 within the MICE software framework. It is obvious that Ruslan has enjoyed himself in witnessing what happens in the details of the simulation for various particle types, and in the way it is reproduced in the real life of the detector.

Chapter 4.6 describes the analysis of the cosmic data sets, what one learns of the noise, cross-talk, detector response uniformity, timing and MIP signal. Once the cosmics are well understood, they can be used as a powerful means of calibration and monitoring, that Ruslan has put together efficiently. He even had time to admire some of the high energy cosmic rays and the pulse-heights (and cross-talk) that they generate.

Finally chapter 4.7 describes the results obtained in a MICE beam exposure taken in October 2013. Ruslan explains very carefully the various beam settings: monochromatic electron/muon/pion beam with specific enhancement in electrons or pions, broad band muon beam, coming in several momenta and in both negative and positive polarities. Ruslan acted effectively as the data taking “champion” and the data taking was very effective. The results are excellent and show to which extent the detector is very powerful at separating muons from their electron decay products, a mission that was its original goal.

During this work, performed in three and a half years, Ruslan has demonstrated a very deep and detailed understanding of detectors, their underlying physics and their purpose; he also possesses an excellent judgment and knowledge of the big picture in particle
physics. He has also demonstrated remarkable ability at quality assurance and project management, delivering an essentially perfect detector, complete with electronics, DAQ, software and analysis.

A number of small corrections and complements will be communicated to the candidate to be incorporated before the thesis is publication-ready, but it is already in excellent shape. The jury unanimously agrees that the thesis merits to be defended publicly.

Geneva, 30 June 2014

[Signature]

Prof. Alain Blondel PO
DPNC Université de Genève
Rapporteur, Directeur de Thèse
Abstract

The recent discoveries in particle physics, the Higgs Boson and neutrino oscillations, voiced the need for new machines that can provide higher intensities, energy and precision. To study the neutrino oscillations in great details and to access new physics, a Neutrino Factory stands as an ultimate tool that offers a high intensity, well understood neutrino beam. On the other hand, a Muon Collider is indispensable for better understanding of a Higgs physics. Both machines share similar ingredients and one of them, that is essential to achieve high luminosity of the beams, is beam cooling. And the only feasible method to achieve cooling of a muons beam is based on ionization. An R&D project was established to verify a possibility of such a cooling, Muon Ionization Cooling Experiment (MICE). Its purpose is to build a cooling cell capable of cooling a muon beam by 10% and measure the effect* with an absolute precision of ±0.1%. This is achieved by utilizing detectors of different technologies: scintillating fiber trackers, time-of-flight stations and calorimeters. One of the calorimeters, aimed to tag muons traversing the cooling cell without decay, is a fully active scintillator tracker-calorimeter. Construction and commissioning of this detector is the main subject of this thesis.

Introduction and the first chapter are dedicated to physics motivation of Neutrino Factory and Muon Collider. The second chapter describes the Muon Ionization Cooling Experiment. And the last chapter constitutes the main part of the thesis containing the original work.

*The cooling effect is attributed to a reduction of beam emittance.
Acknowledgements

The worked presented in this thesis was performed entirely at Département de physique nucléaire et corpusculaire (DPNC) of the University of Geneva under supervision of Professor Alain Blondel and financially supported by Fonds National Suisse. Construction and assembly of the detector was carried out by technicians at University’s electronics and mechanics workshops and external companies. Some of the work related to the tests of electronics was performed at CERN.

The primary user of the results of this work is Muon Ionization Cooling Experiment based at Rutherford Appleton Laboratory in the UK. The MICE Collaboration provided extensive technical and managerial support that allowed for successful completion of the project.

AIDA (Advanced European Infrastructures for Detectors at Accelerators)* is also gratefully acknowledged for supporting the work especially during construction and commissioning phase.

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* AIDA is co-funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, under Grant Agreement no. 262025. Project website: http://cern.ch/aida
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Chapter 1

Introduction

For more than forty years the Standard Model\cite{22} of particle physics has been an unprecedented success. Since mod-1970s it was able to explain a wide variety of experimental results and predict a number of new particles. In the current formulation it describes twelve elementary particles called fermions, one scalar particle (Higgs boson) that generates masses of some fermions and three fundamental interactions (strong, week and electromagnetic) mediated by four different gauge bosons as shown in Figure 1.1\cite{40}.

![Figure 1.1: The Standard Model particles (table) and interactions (diagram). On the right diagram lines represent interactions between particles: red - electromagnetic, green - week, blue - strong interactions and yellow is a Higgs field indicating massive particles.](image)

The recent discovery of the Higgs boson\cite{2} at the LHC is consistent with the Standard Model. Moreover there are no signs of any physics beyond the Standard Model in the data collected by four CERN LHC experiments. Nevertheless, from a theoretical point of view there are a few unresolved questions in the Standard Model:

- **Hierarchy problem**: At any energy scale $\mu$ above 1 TeV the Standard Model is not natural\cite{26} due to a presence of a small dimensionless parameter $\chi^2 = (m_H/\mu)^2$ which is not associated

*Also called *naturalness* problem.*
to any symmetry in the limit $\chi = 0$. If the Standard Model is valid up to the Plank scale $\Lambda_{Pl} \sim 10^{19}$ GeV, then it has to be tuned to a precision of $(m_H/\Lambda_{Pl})^{-2} \sim 10^{34}$. The naturalness principal favors parameters of the order of 1. And there are two possible solutions that that problem. The first one is associated to the existence of new fermion-boson symmetry called supersymmetry\[25\] that introduces new heavy articles which are partners of the Standard Model particles but with a spin that differs by a half-integer. The other solution is related to the new interactions\[28\] at TeV scale which induce strong breaking of the electroweak symmetry.

- **Dark matter and dark energy:** According to the Standard Cosmological model\[39\] and the recent data\[3\] our Universe is geometrically flat with density parameters of different matter species $\Omega_i$ and a cosmological constant $\Omega_\Lambda$ summed into unity: $\sum_i \Omega_i + \Omega_\Lambda = 1$, where the matter density $\sum_i \Omega_i$ typically includes baryons ($\Omega_b$, electron density is included into this term), photons ($\Omega_\gamma$), neutrinos ($\Omega_\nu$) and cold dark matter ($\Omega_c$). Global fits of the cosmological parameters based on variety of observations\[3, 21\] give estimations of some density parameters: $\Omega_b \approx 0.05$, $\Omega_\nu \approx 0.25$ and $\Omega_\Lambda \approx 0.7$. In other words, 70% of the density of the Universe is mathematically described by a cosmological constant that is typically attributed to a new scalar field (Dark Energy) which is responsible for the acceleration of the universe; and other 30% are different types of matter only 17% of which is ordinary particles described by the Standard Model and the rest 83% are Dark Matter particles. There are plenty of theoretical explanations\[22\] of the Dark Matter but none of them has been proven experimentally so far.

- **Baryon asymmetry in the Universe:** There is no doubt that the Universe is exclusively populated with matter but not untimatter. The latter is only observed in cosmic rays or produced in accelerators. In the early Universe most of the untimatter annihilated with matter but some tiny fraction of baryon matter survived. It is understood\[18\] that this happened due to baryon number violating interactions, C and CP violation and fluctuations from thermal equilibrium that all lead to the present baryon asymmetry. And there are several mechanism that may be responsible for the baryon asymmetry which all formulated outside the Standard Model.

- **Neutrino masses and mixing:** It was well established that neutrinos are able to change their types (oscillate) between three available flavors (electron, muons and tau) while they travel through space. These oscillations imply non-zero masses of the neutrinos. The latter is not compatible with the Standard Model and therefore requires new physics phenomena.

During this decade the Large Hadron Collider at CERN will explore physics at TeV scale and may reveal new phenomena. There might be new gauge bosons, additional fermion families, new fundamental scalars, new dynamics or even extra dimensions. Nevertheless, the above mentioned questions likely to remain unanswered or not fully answered even after the LHC program is complete. In order to understand the origin of fermion masses, mixing and CP violation, the nature of dark matter, or to study in details the spectrum, dynamics and symmetries of the observed new physics, a new generation multi-TeV lepton collider would be required. Given the absence of new physics at the
Chapter 1. Introduction

LHC data so far and if nothing will discovered, a Muon Collider will be one of the most attractive option to fully explore any new physics.

The neutrino flavor oscillations, and hence the existence of massive neutrinos, is one of the undeniable evidences of the new phenomena outside the Standard Model. The neutrino mixing matrix $U$ translates there neutrino mass eigenstates into three flavor states: $(\nu_e, \nu_\mu, \nu_\tau)^T = U \times (\nu_1, \nu_2, \nu_3)^T$. The mixing matrix is parametrized using three mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$), Dirac CP phase $\delta$ and two Majorana CP phase ($\alpha_{21}, \alpha_{31}$). The mixing matrix can be written as follows:

$$U = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix} = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix} \begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{-i\delta} & 0 & c_{13}
\end{pmatrix} \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix} \begin{pmatrix}
1 & 0 & 0 \\
0 & e^{i\alpha_{21}/2} & 0 \\
0 & 0 & e^{i\alpha_{31}/2}
\end{pmatrix} \quad (1.1)
$$

where $s_{ij} = \sin(\theta_{ij})$ and $c_{ij} = \cos(\theta_{ij})$. The probability of a neutrino of given energy to oscillate from flavor $\alpha$ to $\beta$ at distance $L$ for a source as it propagates in vacuum can be expressed as:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j}^3 \text{Re}[U^*_{\alpha i} \cdot U_{\beta i} \cdot U_{\alpha j} \cdot U^*_{\beta j}] \sin^2 \left( \frac{\Delta m_{ij}^2}{4} \cdot \frac{L}{E} \right) + 2 \sum_{i>j}^3 \text{Im}[U^*_{\alpha i} \cdot U_{\beta i} \cdot U_{\alpha j} \cdot U^*_{\beta j}] \sin \left( \frac{\Delta m_{ij}^2}{2} \cdot \frac{L}{E} \right) \quad (1.2)
$$

where $\Delta m_{ij}^2 = m_i^2 - m_j^2$, $\delta_{\alpha\beta}$ is the Kronecker’s delta. Figure 1.2 shows survival ($P_{\alpha\alpha}$) and appearance ($P_{\alpha\beta}$) probabilities[17]. And Table 1.1 summarizes the current status[22] of measured oscillation parameters. The sign of the difference of the squares of the neutrino masses $\Delta m_{ij}^2$, Dirac CP phase $\delta$ and two Majorana CP phase $(\alpha_{21}, \alpha_{31})$ are not known. In addition, it is not clear whether $\theta_{23}$ is more or less than 45°.

![Figure 1.2: Appearance and survival probabilities in vacuum for electron and muons neutrinos as a function of L/E (arbitrary units).](image)

*The probability for anti-neutrinos is described by the same expression replacing $U$ to $U^*$. 3
<table>
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<td>$\sin^2 \theta_{12}$</td>
<td>$0.312^{+0.032}_{-0.047}$</td>
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<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>$0.42^{+0.22}_{-0.08}$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>$0.0251^{+0.0109}_{-0.0101}$</td>
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<tr>
<td>$\Delta m^2_{21}$</td>
<td>$(7.58^{+0.60}_{-0.59}) \times 10^{-5}$ eV$^2$</td>
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<td>\Delta m^2_{32}</td>
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Table 1.1: Measured neutrino oscillation parameters

The small mass and the large flavor mixing of the neutrinos could be a consequences of new physics at energies ranging from a few keV to the GUT scale*. In contrast to all fundamental particles the neutrino is the least understood and its properties are poorly measured. Moreover, the effects responsible for the neutrino masses and mixing are very small either because couplings are very small, as in low energy, or they energy scales are very high and therefore the effects are strongly suppressed. Therefore the new neutrino facilities are essential to allow for high precision measurements of the oscillation parameters and neutrino properties. They are complimentary to high energy colliders in terms of physics capabilities.

The accelerator based neutrino oscillation experiments are the major tools to study neutrino physics. They provide the only possible means to study precisely both neutrino and anti-neutrino transitions between all there neutrino flavors and they are essential to resolve the outstanding issues:

- **Neutrino mass hierarchy:** The probability of the neutrino oscillation depends on mass squared difference of the neutrino eigenstates. The masses of the eigenstates can be ordered in two different ways and the order is defined by three observables: $\Delta m^2_{21}$, $|\Delta m^2_{31}|$, the sign of $\Delta m^2_{31}$; and a few conditions: $m_2^2 > m_1^2$ and $\Delta m^2_{21} < |\Delta m^2_{31}|$. If $\Delta m^2_{31} > 0$ then the neutrino mass hierarchy is normal, otherwise - inverse. The two possibilities are shown in Figure 1.3.

![Figure 1.3: Neutrino mass hierarchy. The color indicate fractions of each flavor: electron (red), muon (green) and tau (blue).](image)

*Grand Unification Theory energy scale is the energy above which the four known forces (electromagnetic, weak, strong and gravitational force) become equal in strength and unify in one force. The exact value of the unification energy depends on precise physics model and can be as high as $10^{16}$ GeV.
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Figure 1.4: The bi-probability plot of $\mu - e$ neutrino oscillations for a baseline 810 km[32].

The oscillation probabilities are modified if neutrinos propagate through matter due to coherent forward scattering of neutrinos with the electrons present in the medium. Moreover, the matter effect is different between neutrinos and antineutrinos since there are no positrons in the ordinary matter. Besides that it can be used to determine the mass hierarchy due to the fact that it depends on whether the electron neutrino is made of the heaviest or lightest mass eigenstates. These two competing effects contribute to the oscillation probability and their relative strength can be visualized via bi-probability plots as shown in Figure 1.4.

- **CP-invariance violation:** As shown in Figure 1.4, measurement of the neutrino and antineutrino appearance oscillation probabilities $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ would allow for determination of the CP-violation phase. In order to enhance the sensitivity to the CP violation, it is required to place neutrino detectors at some distance from the source where the difference between the oscillation probabilities is maximal (see Figure 1.2).

- **Octant ambiguity:** The current experiments are able to determine $|\theta_{23} - 45^\circ|$ but not sensitive to the sign of $(\theta_{23} - 45^\circ)$. Therefore the octant in which the value of $\theta_{23}$ lies is not known. This question can be resolved by thorough analysis of the $\nu_\mu \rightarrow \nu_e$ oscillation pattern where the first order terms in the oscillation probability is proportional to $\sin^2\theta_{23}$ which enhances the transition if $\theta_{23} > 45^\circ$ relative the the corresponding value if $\theta_{23} < 45^\circ$.

The three effects (mass hierarchy, CP invariance violation and $\theta_{23}$ ambiguity) are closely related as seen in Equation 1.2. The impact of each effect can be varied systematically by studying the oscillations at different baselines and energies and comparing neutrino and antineutrino
• **The nature of the neutrino:** All the fermions in the Standard model are known experimentally to be Dirac particles, i.e. its antiparticle is a different fermion, except for neutrinos which could be either Dirac or Majorana. The latter is a fermion that is its own antiparticle. One of the ways to identify the neutrino type is to search for neutrinoless double-beta decay \((0\nu\beta\beta)\), a weak nuclear decay process in which a nucleus decays is accompanied by two beta electrons and no neutrinos, which is possible only if the neutrinos are Majorana fermions. This process violate the lepton number conservation by two units and, therefore, if experimentally observed, requires significant revision of the Standard Model. In addition, in Quantum Field Theory two distinct mass terms are allowed for neutrinos in the Lagrangian of electroweak interactions. They are called Dirac and Majorana mass terms and should not be confused with the fermion types. These mass terms are also related to the lepton number conservation and for Dirac fermions it is not conserved if the Majorana mass term is present in the Lagrangian while for Majorana fermions the lepton number is not conserved regardless of which term exists in the Lagrangian. There are many possible theoretical scenarios for the neutrino mass. In the one of the most accepted explanations of the relative sizes of the neutrino masses, the seesaw mechanism, the neutrino is described by the Lagrangian with both Dirac and Majorana mass terms and it still can be either Dirac or Majorana fermion. Table 1.2 summarizes possible combinations of fermion and mass term types and their relation to possibility of neutrinoless double-beta decay, seesaw mechanism, leptogenesis and dark matter. The neutrinoless double-beta decay experiments, besides studying the nature of the neutrino, offer sensitivity to the absolute neutrino mass scale, and potentially to the neutrino mass hierarchy and the Majorana phases appearing in the mixing matrix. The summed energy of electrons emitted in \(0\nu\beta\beta\) decays should have a single value and, therefore observation of the sharp peak in energy spectrum would quantify \(0\nu\beta\beta\) decay rate and demonstrate that the Majorana nature of neutrinos. The half-life of the \(0\nu\beta\beta\) decay is related to an effective Majorana mass \(\langle m_{\beta\beta}\rangle\):

\[
\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G_{0\nu}|M_{0\nu}|^2 \langle m_{\beta\beta}\rangle^2
\]

where \(\langle m_{\beta\beta}\rangle^2 = |\sum_i U_{ei}^2 m_i|^2\), \(G_{0\nu}\) is the phase space vector, \(m_i\) is the mass of \(\nu_i\) eigenstate, \(M_{0\nu}\)

<table>
<thead>
<tr>
<th>Mass term</th>
<th>Dirac</th>
<th>Majorana</th>
<th>Dirac and Majorana</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino nature</td>
<td>Dirac</td>
<td>Majorana</td>
<td>Majorana</td>
</tr>
<tr>
<td>Seesaw mechanism</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Number of neutrino states</td>
<td>4 per family</td>
<td>2 per family</td>
<td>4 per family</td>
</tr>
<tr>
<td>Sterile neutrinos</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Possibility of (0\nu\beta\beta)</td>
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<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Leptogenesis</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Dark matter</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>

Table 1.2: Dirac and Majorana fermion types and mass terms.
is the transition nuclear matrix element. The effective Majorana mass term can be expressed via oscillation parameters $\theta_{12}$, $\theta_{13}$, masses of the neutrino eigenstates $m_1$, $m_2$, $m_3$, two Majorana CP-violation phases $\alpha_{21}$ and $\alpha_{31}$ and Dirac CP-violation phase $\delta$ as follows:

$$\langle m_{\beta\beta} \rangle = |\cos^2\theta_{12}\cos^2\theta_{13}e^{-2i\alpha_{21}}m_1 + \sin^2\theta_{12}\cos^2\theta_{13}e^{-2i\alpha_{31}}m_2 + \sin^2\theta_{13}e^{-2i\delta}m_3|$$  \hspace{1cm} (1.4)$$

Figure 1.5 show the allowed area of the effective Majorana mass as a function of the lightest neutrino mass for the inverted and normal mass hierarchies[17]. In order to be explore these regions experiments should be sensitive to half-lives above $10^{27}$ years. The current and next generation $0\nu\beta\beta$ decay experiments use 100kg scale isotopes to reach sensitivity up to $10^{26}$ years.

• The absolute mass scale of neutrinos can not be measured in the oscillation experiments which only provide information about mass differences. The neutrino’s rest mass does not depend on whether it is a Dirac or Majorana particle, but it has a measurable effect on kinematics in low-energy nuclear beta decay. Tritium is the major nuclide that is used in current neutrino mass determination experiments, it decays to Helium, electron and neutrino: $^3\text{H} \rightarrow ^3\text{He} + e^- + \bar{\nu}_e$.

The energy spectrum of the decay electron can be described as:

$$\frac{dN}{dE} \propto F(Z,E)p_e(E + m_e)(E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2}$$ \hspace{1cm} (1.5)$$

where $E, p_e$ are electron energy and momentum, $E_0$ is the Q-value of the beta decay and $F(Z,E)$ is the Fermi function. The spectrum is shown in Figure 1.6 with the zoom of the endpoint. Massless neutrino would give a parabolic spectrum around $E_0$ while massive neutrino creates a
cut off around the value of the neutrino mass\[19\]. Since the electron neutrino flavor state is a combination of three mass states, the spectrum is a superposition of three spectra and it can be approximated by a single neutrino spectrum with an effective mass $m_{\beta}^2 = \sum_i |U_{ei}|^2 m_i^2$. The current limit from Tritium experiments gives $m_{\beta} < 2$ eV\[4\]. The direct mass measurements based on beta decay can also provide an unambiguous determination of the neutrino mass hierarchy (see Figure 1.7\[17\]).

- **Consistency of three-neutrino mixing model:** All of the neutrino oscillation data collected so far can be consistently described by a three-neutrino mixing model, except for a few anomalies that are not compatible with the this paradigm and which implies new physics. Namely, there is an evidence of the oscillation phenomena around $\Delta m^2 \sim 1$ eV$^2$ that is not consistent with well-
established solar and atmospheric scales of $\Delta m^2$. This effect is often attributed to an existence of a new additional neutrino state called sterile. Precise measurements of the standard neutrino phenomena is sensitive to new neutral-current interactions that modify neutrino production and detection effects and neutrino propagation through matter. In addition, studies of the neutrino magnetic moment is an attractive place for new physics.

Most of the above mentioned question related to neutrino physics can only be addressed if neutrino and antineutrino oscillations can be measured with very high precision, especially in appearance channels where the final and initial flavors of neutrinos are different. Several neutrino facilities have been designed to achieve high sensitivity and to allow the range of measurements required to remove all ambiguities in the determination of oscillation parameters. The Neutrino Factory, where intense $\nu_e(\bar{\nu}_e)$ beams are produced from the decays of muons confined in a storage ring, is the ultimate tool to study numerous neutrino physics subjects. It give the best performance for CP invariance violation measurements over the entire parameter space. Another possibility is use high power cyclotrons to produce muon neutrinos from the decays of muons brought to rest in a large detector to study CP violation parameters from the dependence of the oscillated neutrino beam on the distance from the source. In addition to the neutrino facilities a mutli-TeV Muon Collider provides a very attractive possibility for studying various new physics scenarios. Supersymmetry, extra dimensions, new strong dynamics are among those.
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Muon-Based Machines

The accelerator-based neutrino-oscillation program is international in both scope and engagement. The approved program will improve our knowledge of the mixing angles and the mass-squared differences and may be able to determine the neutrino mass hierarchy. In the medium term, the Long-baseline Neutrino Experiment (LBNE) in US and the Tokai (J-PARC) to Hyper-Kamiokande experiment in Japan offer complementary approaches to searching for the violation of the matter-anti-matter symmetry in neutrino oscillations. A design study of an alternative wide-band beam facility, the Long-baseline Neutrino Observatory (LBNO), is underway in Europe.

A Neutrino Factory, in which electron- and muon-neutrino beams are produced from the decay of muons confined within a storage ring, has been shown to offer the ultimate sensitivity and precision. The staged implementation of the facility has been studied in US. The attractive first stage (muSTORM) has the potential to make detailed and precise studies of electron- and muon-neutrino-nucleus scattering and to make exquisitely sensitive searches for sterile neutrinos. The Neutrino Factory will allow establishing the technology of using intense bunched muon beams. The complex could then evolve towards Muon Colliders, starting at 126 GeV with measurements of the Higgs resonance to sub-MeV precision, and continuing to multi-TeV colliders for the exploration of physics beyond the Standard Model.

2.1 Long-Baseline Neutrino Experiments

2.1.1 European Project - LBNO

The next generation neutrino observatory proposed by the LBNO collaboration will address fundamental questions in particle and astroparticle physics. The experiment consists of a far detector, in its first stage a 20 kton Liquid Argon Large Electron Multiplier Time Projection Chamber (LAr LEM-TPC)[37] and a 35 kton magnetised iron calorimeter (MIND)[15], placed in one of two large underground caverns[23] the Pyhäsalmi mine in Finland at a distance of 2300 km from CERN, and a near detector based on a high-pressure argon gas TPC. The MIND calorimeter collects an independent neutrino sample and serves as a tail catcher for CERN beam events occurring in the LAr target. It
provides a clean muon momentum and charge determination, important to ascertain the properties of the neutrino and antineutrino beams at the far site. It improves the neutrino energy determination of muon charged current events occurring in the LAr. A schematic view of the far detectors is shown in Figure 2.1.

![Figure 2.1: LBNO far detectors: LAr(left) and MIND(right).](image)

The long baseline provides a unique opportunity to study neutrino flavor oscillations over their first and second oscillation maxima exploring the L/E behavior, and distinguishing effects arising from CP violation and matter. The 2300 km baseline is adequate to have an excellent separation of the $\nu - \bar{\nu}$ asymmetry due to the matter effect (i.e. the mass hierarchy measurement) and the CP asymmetry due to the $\delta_{CP}$ phase. This is optimized to break the parameter degeneracies and provide a definitive resolution of mass hierarchy and a significant exploration of CP violation in the neutrino sector. These measurements are performed without over-relying on theoretical modeling and assumptions and the standard neutrino paradigm. This is different from extracting the mass hierarchy and $\delta_{CP}$ value from global fits of all available data.

The probabilities of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations for different values of $\delta_{CP}$ and normal hierarchy (NH) and inverted hierarchy (IH) are shown in Figure 2.2 as they are expected in LBNO at the 2300 km baseline. The plots illustrate qualitatively that the spectral information provides an unambiguous determination of the oscillation parameters and allows discriminating between the two CP-conserving scenarios. The $\delta_{CP}$-phase and matter effects introduce a well-defined energy dependence of the oscillation probability. As a consequence, the neutrino energy spectrum of the oscillated events need to be experimentally reconstructed with sufficiently good resolution in order to distinguish first and second maximum, and extract unambiguous information on the oscillation parameters. The spectral measurement will in addition verify the PMNS model, with possible unexpected differences between neutrinos and antineutrinos than those predicted by $\delta_{CP}$, or other non-standard deviations from the predicted L/E dependence. At the same time, the matter effects at 2300 km are large and
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Figure 2.2: Oscillation probabilities of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ in LBNO at the 2300 km baseline for normal (top row) and inverted (bottom row) hierarchy.

The normal and inverse hierarchy scenarios induce to an almost complete swap of behaviors between neutrinos and antineutrinos.

Figure 2.3: Neutrino and anti-neutrino flux for the CERN to Pyhäjsalmi beam.

Several options for CERN high-intensity and high-energy proton sources used for producing conventional neutrino beams have been considered[38]. In the initial phase of LBNO, it is assumed that the neutrino beam will be produced from high-energy protons fast extracted from the CERN SPS at an energy of 400 GeV. The unoscillated neutrino and anti-neutrino beam flux is shown in Figure 2.3. The reconstructed neutrino energy for neutrino and antineutrino beams for various values of $\delta_{CP}$ and for normal and inverse mass hierarchy are shown in Figure 2.4.

The $\Delta \chi^2$ of the mass hierarchy discriminant is presented as a function of true $\delta_{CP}$ in Figure 2.5(left). The sensitivity to determine mass hierarchy assumes a 50%-50% sharing of the running time between neutrino and antineutrino beams, and a total of $2.25 \times 10^{20}$ p.o.t. The obtained significance is above 5$\sigma$ over the entire range of $\delta_{CP}$ values.

The $\Delta \chi^2$ of CP-violation discriminant is presented as a function of true $\delta_{CP}$ in Figure 2.5(middle).
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Figure 2.4: Reconstructed event energy for neutrino (left) and antineutrino (right) for different values of true $\delta_{CP}$ and for normal (top) and inverse (bottom) mass hierarchy. A 25%-75% sharing between neutrino and antineutrino running mode and a total of $1.5 \times 10^{21}$ proton-on-target are assumed.

It exhibits the expected double peak structure with two zero values at $\delta_{CP} = 0$ and $\pi$, coming from the definition of the $\Delta \chi^2$, which defines the CP-violation discovery as the exclusion of 0 and $\pi$.

The $\Delta \chi^2$ with all sources of systematic errors included (blue curve) is transformed into a CP-violation discovery potential probability defined in terms of the $\delta_{CP}$ coverage as a function of the integrated SPS protons-on-target is shown in Figure 2.5(right). With $1.5 \times 10^{21}$ p.o.t., the existence of CP-violation can be demonstrated at the 90% C.L. for 60% of the $\delta_{CP}$ parameter space. This CP-violation sensitivity improves further with the increased exposure resulting from longer running periods and/or an increase in beam power and far detector mass. For example, the dashed red curve shows the $3\sigma$ C.L. sensitivity to CP-violation dependence as a function of p.o.t. assuming an increase of the far detector mass up to 70 kton. Under this upgraded scenario, the $3\sigma$ C.L. discovery for CP-violation reaches a coverage of 70% by doubling the number of p.o.t. Another option to reach the same CP-violation sensitivity would be to keep the 20 kton far detector but increasing significantly the beam power to the 2 MW level (HP-PS option). Ultimately the implementation of the Neutrino Factory[1] will provide a coverage of 85-90% at $3\sigma$ C.L.

Three upgrade scenarios are being considered for the LBNO neutrino beam. These involve the upgrade or alternative scenarios for the proton injector to the same target area: (i) use of an upgraded high-energy PS or SPS machines discussed in the high intensity LHC option[9], (ii) use of a new dedicated HP-PS synchrotron[24], (iii) use of a Neutrino Factory beam concept[1]. The realization of
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Figure 2.5: Mass hierarchy and CP-violation sensitivity in LBNO. **Left:** Mass hierarchy sensitivity as a function of $\delta_{CP}$, the upper solid curve corresponds to the fit of both distributions of reconstructed energy and missing momentum and dashed one corresponds to the fit of reconstructed energy only; in this case, the significance is reduced mainly because of the assumed 50% uncertainty on the tau production normalization. **Middle:** CP-violation sensitivity as a function of $\delta_{CP}$; the blue curve corresponds to the case with all systematic errors included, the dashed brown curve is the case when all energy correlated errors are set to zero and the average Earth density error is reduced to 1%. **Right:** CP-violation discovery potential probability defined as $\delta_{CP}$ coverage as a function of the integrated SPS p.o.t.

The HP-PS accelerator with MW power would expand the capability of the LBNO facility and provide an interesting way to increase the exposure by a significant factor. The chosen baseline of 2300 km is suitable to implement a Neutrino Factory[1], opening the path towards an ultimate exploration and an era of high-precision oscillation studies.

2.1.2 American Project - LBNE

The LBNE Project was formed to design and construct the Long-Baseline Neutrino Experiment. The experiment will comprise a new, high-intensity neutrino source generated from a megawatt-class proton accelerator at Fermi National Accelerator Laboratory (Fermilab) directed at a large far detector at the Sanford Underground Research Facility in Lead, South Dakota (US). A near detector will be located about 500m downstream of the neutrino production target. LBNE is currently planned as a phased program, with increased scientific capabilities at each phase. The experimental facilities are designed to meet the primary scientific objectives of the experiment:

- fully characterize neutrino oscillations, including measuring the value of the unknown CP-violating phase $\delta_{CP}$ and determining the ordering of the neutrino mass states
- significantly improve proton decay lifetime limits
- measure the neutrino flux from potential core-collapse supernovae in our galaxy

The LBNE beamline, based on the existing Neutrinos at the Main Injector (NuMI) beamline design, is designed to deliver a wide-band, high-purity $\nu_\mu$ beam with a peak flux at 2.5 GeV, which optimizes the oscillation physics potential at the 1300 km baseline. The beamline will operate initially
at 1.2 MW and will be upgradable to 2.3 MW utilizing a proton beam with energy tunable from 60 to 120 GeV. The full-scope LBNE far detector is a liquid argon time-projection chamber (LArTPC) of fiducial mass 34 kt. The TPC design is modular, allowing flexibility in the choice of initial detector size. The LBNE far detector will be located 1478 meters underground, a depth favorable for LBNE’s search for proton decay and detection of the neutrino flux from a core-collapse supernova. The high-precision near detector and its conventional facilities can be built as an independent project, at the same time as the far detector and beamline, or later. The 1,300–km baseline has been determined to provide optimal sensitivity to CP violation and the measurement of $\delta_{CP}$, and is long enough to enable an unambiguous determination of the neutrino mass hierarchy.

The horn current polarity can be changed to selectively focus positive or negative hadrons, thus producing high purity ($\sim 90\%$ in oscillation region) $\nu_\mu$ or $\bar{\nu}_\mu$ beams. Each beam polarity will have a $\sim 10\%$ contamination of neutrinos of the "wrong sign" in the oscillation energy region ($\bar{\nu}$’s in the $\nu$ beam and vice-versa) from decays of "wrong-sign" hadrons that propagate down the center of the focusing horns - where there is no magnetic field - into the decay volume. In addition, a $\sim 1\%$ contamination of $\nu_e$ and $\bar{\nu}_e$ in the $\nu_e$ appearance signal region is produced by the decays of tertiary muons from pion...
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Figure 2.7: The neutrino beam fluxes (left) and antineutrino beam fluxes (middle) produced in the LBNE beamline. The horn current assumed is 200 kA, the target is located 35 cm in front of horn 1, the decay pipe is air-filled, 4m in diameter and 204m in length. Event interaction rates (right) at the LBNE far detector in the absence of oscillations and due to neutrinos produced by a 120 GeV proton beam for several target positions relative to Horn 1.

decays, and decays of kaons. The neutrino flux components are shown in Figure 2.7. The beamline design provides a wide-band neutrino beam with a peak flux at 2.5 GeV, which matches the location of the first $\nu_\mu \rightarrow \nu_e$ oscillation maximum. The NuMI reference target design used for LBNE allows the target to be moved with respect to Horn 1. The location of the upstream face of the target with respect to the upstream face of Horn 1 can be varied from 35 cm (default location) to 2.85 m, thus the LBNE beamline can produce a wide range of beam spectra. Three possible far-site beam spectra, produced by moving the target from 35 cm (low-energy) to 1.5 m (medium-energy) to 2.5 m (high energy) are shown in Figure 2.7(right).

Figure 2.8: The LBNE near (left) neutrino detector reference design with the dipole magnet open to show the straw-tube tracker (grey) and electromagnetic calorimeter (yellow). RPCs for muon identification (red squares) are embedded in the yoke steel and up- and downstream steel walls. Schematic of a 34 kton Liquid Argon TPC design (right). The far detector comprises two 17 kton LArTPC vessels.
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A high-resolution near neutrino detector located approximately 500 m downstream of the LBNE neutrino production target as shown in Figure 2.6. The reference design for the near neutrino detector is a fine-grained tracker, illustrated in Figure 2.8(left). It consists of a $3 \times 3 \times 7.04 \text{m}^3$ straw-tube tracking detector (STT) and electromagnetic calorimeter inside of a 0.4 T dipole magnet and resistive plate chambers for muon identification (MuID) located in the steel of the magnet and also upstream and downstream of the tracker. High-pressure argon gas targets, as well as water and other nuclear targets, are embedded in the upstream part of the tracking volume. The nominal active volume of the STT corresponds to eight tons of mass. The STT is required to contain sufficient mass of argon gas in tubes (Al or composite material) to provide at least a factor of ten more statistics than expected in the far detector. The full-scope LBNE far detector is a liquid argon time-projection chamber (LArTPC) of fiducial mass 34 kton (see Figure 2.8, right) located at the 1478 meter level of the Sanford Underground Research Facility. The Liquid Argon TPC technology allows for high-precision identification of neutrino flavors, offers excellent sensitivity to proton decay modes with kaons in the final state and provides unique sensitivity to electron neutrinos from a core-collapse supernova. The full detector size and its location will enable LBNE to meet the primary scientific goals, in particular, to find evidence for CP violation over a large range of $\delta_{CP}$ values, and to significantly advance proton-decay lifetime limits.

Figure 2.9: The significance with which the mass hierarchy and CP violation ($\delta_{CP} \neq 0$ or $\pi$, can be determined by a typical LBNE experiment with a 34-kton far detector as a function of the value of $\delta_{CP}$ for normal (NH) and inverted hierarchy (IH). The width of the red band shows the range of sensitivities that can be achieved by LBNE when varying the beam design and the signal and background uncertainties.

Figure 2.9 shows the sensitivities for determining the mass hierarchy and CP violation as a function of the true value of $\delta_{CP}$ after six years of running in the LBNE 34-kton configuration under in a 1.2 MW beam. Across the overwhelming majority of the parameter space for the mixing parameters that are not well known (mainly $\delta_{CP}$ and $\sin^2\theta_{23}$), LBNE’s determination of the mass hierarchy will be definitive, but even for unfavorable combinations of the parameter values, a statistically ambiguous outcome is highly unlikely (see Figure 2.10).

If CP is violated maximally with a CP phase of $\delta_{CP} \sim -\pi/2$ as hinted at by global analyses of recent data[14], the significance would be in excess of $7\sigma$. This opportunity to establish the paradigm of leptonic CP violation is highly compelling, particularly in light of the implications for leptogenesis.
Figure 2.10: The square root of the mass hierarchy discrimination metric $\Delta \chi^2$ is plotted as a function of the unknown value of $\delta_{CP}$ for the full-scope LBNE with 34 kt, 3+3 ($\nu + \bar{\nu}$) years of running in a 1.2 MW beam, assuming normal hierarchy. The plot on the left is for an assumed value of $\sin^2 \theta_{23} = 0.39$ (based on global fits and assuming worst-case $\theta_{23}$ octant), while that on the right is for $\sin^2 \theta_{23} = 0.5$ (maximal mixing). In each plot, the red curve represents the median experimental value expected ($\sqrt{\Delta \chi^2}$), estimated using a data set absent statistical fluctuations, while the green and yellow bands represent the range of $\Delta \chi^2$ values expected in 68% and 95% of all possible experimental instances, respectively. For certain values of $\Delta \chi^2$, horizontal lines are shown, indicating the corresponding confidence levels with which a typical experiment correctly determines the mass hierarchy.

as an explanation for the Baryon Asymmetry of the Universe. With tight control of systematic uncertainties, additional data taking beyond 2035 would provide an opportunity to strengthen a marginally significant signal should $\delta_{CP}$ take a less favorable value. Similarly, the typical LBNE data set will provide evidence for a particular mass ordering by 2030 and will exclude the incorrect hypothesis at a high degree of confidence by 2035, over the full range of possible values for $\delta_{CP}$, $\theta_{23}$ and the mass ordering itself. In addition to the implications for models of neutrino mass and mixing directly following from this measurement, such a result could take on even greater importance.

2.1.3 Japanese Project - Hyper-K

Hyper-Kamiokande (Hyper-K) detector is a next generation underground water Cherenkov detector. It will serve as a far detector of a long baseline neutrino oscillation experiment envisioned for the upgraded J-PARC, and as a detector capable of observing proton decays, atmospheric neutrinos, and neutrinos from astronomical origins. The baseline design of Hyper-K is based on the highly successful Super-K, taking full advantage of a well-proven technology.

The Hyper-K detector (see Figure 2.11) consists of two cylindrical tanks lying side-by-side, the outer dimensions of each tank being $48(W) \times 54(H) \times 250(L)$ m$^3$. The total (fiducial) mass of the detector is 0.99(0.56) million metric tons, which is about 20(25) times larger than that of Super-K. A proposed location for Hyper-K is about 8 km south of Super-K (and 295 km away from J-PARC).
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Figure 2.11: Schematic view of the Hyper-Kamiokande detector.

at an underground depth of 1750 meters water equivalent (m.w.e.). The inner detector region of the Hyper-K detector is viewed by 99,000 20-inch PMTs, corresponding to the PMT density of 20% photo-cathode coverage (one half of that of Super-K).

Figure 2.12: Expected neutrino flux at Hyper-K. **Left:** neutrino mode. **Right:** anti-neutrino mode.

A proton beam energy of 30 GeV is provided by J-PARC neutrino beamline. Figure 2.12 shows the expected neutrino flux at Hyper-K for neutrino and anti-neutrino mode running. Thanks to the off-axis method, the spectrum has a narrow peak around the energy where oscillation probability is the maximum, with small high energy tail. Contamination of $\nu_e$($\bar{\nu}_e$) in the beam is well below 1% at the peak for both cases.

The Hyper-K presents unprecedented potential for precision measurements of neutrino oscillation parameters and discovery reach for CP violation in the lepton sector. With a total exposure of 5 years to a 2.5°off-axis neutrino beam produced by the 1.66 MW J-PARC proton synchrotron, it is expected
Figure 2.13: **Left:** Allowed regions in the space of $\sin^2\theta_{23}$ and $\delta$ near the known value of $\sin^2\theta_{23}$. Blue, green, and red lines represent 1, 2, 3 $\sigma$ allowed regions with the mass hierarchy known to be normal. **Right:** The sensitivity to the mass hierarchy as a function of $\theta_{23}$ with $\theta_{12}$ fixed at $\sin^2\theta_{13} = 0.098$. Normal hierarchy is assumed.

that the CP phase $\delta$ can be determined to better than 18 degrees for all possible values of $\delta$ and CP violation can be established with a statistical significance of 3$\sigma$ for 74% of the $\delta$ parameter space and the mass hierarchy is known as shown in Figure 2.13(left). The mass hierarchy can be determined with more than 3$\sigma$ statistical significance for 46% of the $\delta$ parameter space. With a full 10 year duration of data taking, the significance for the mass hierarchy determination is expected to reach 3$\sigma$ or greater if $\sin^2\theta_{23} > 0.4$ (Figure 2.13, right). In addition, a high statistics data sample of atmospheric neutrinos will allow us to extract the information on the mass hierarchy and the octant of $\theta_{23}$. 
2.2 Short-Baseline Neutrino Experiments

2.2.1 nuSTORM

A new facility was proposed that would utilize a 3-4 GeV/c muon storage ring to study eV-scale oscillation physics and, in addition, could add significantly improve our understanding of $\nu_e$ and $\nu_\mu$ cross sections. In particular the facility can:

- address the large $\Delta m^2$ oscillation regime and make a major contribution to the study of sterile neutrinos
- make precision $\nu_e$ and $\nu_\mu$ cross-section measurements
- provide a technology ($\mu$ decay ring) test demonstration and $\mu$ beam diagnostics test bed
- provide a precisely understood neutrino beam for detector studies

The facility is the simplest implementation of the Neutrino Factory concept. 60 GeV/c protons are used to produce pions off a conventional solid target. The pions are collected with a focusing device (horn or lithium lens) and are then transported to, and injected into, a storage ring. The pions that decay in the first straight of the ring can yield a muon that is captured in the ring. The circulating muons then subsequently decay into electrons and neutrinos. The storage ring design that is optimized for 3.8 GeV/c muon momentum. This momentum was selected to maximize the physics reach for both oscillation and the cross section physics. Figure 2.14 show a schematic of the facility.

![Figure 2.14: nuSTORM facility layout.](image)

Muon decay yields a neutrino beam of precisely known flavor content and energy. In addition, if the circulating muon flux in the ring is measured accurately (with beam-current transformers, for example), then the neutrino beam flux is also accurately known. Near and far detectors are placed along the line of one of the straight sections of the racetrack decay ring. The near detector can be placed 20-50 meters from the end of the straight. A near detector for disappearance measurements will be identical to the far detector, but only about one-tenth the fiducial mass. It will require a muon catcher, however. Additional purpose-specific near detectors can also be located in the near hall and will measure neutrino–nucleon cross sections. nuSTORM can provide the first precision measurements of $\nu_e$ and $\bar{\nu}_e$ cross sections that are important for future long-baseline experiments. A far detector at approximately 2000 m will study neutrino oscillation physics and be capable of performing searches.
in both appearance and disappearance channels. The experiment will take advantage of the "golden channel" of oscillation appearance, $\nu_e \rightarrow \nu_\mu$, where the resulting final state has a "wrong-sign" muon, of opposite sign as those from interactions of the $\bar{\nu}_\mu$ in the beam (e.g., in the case of $\mu^+$ stored in the ring, this would mean the observation of an event with a $\mu^-$). The detector will thus need to be magnetized in order to identify the wrong-sign muon appearance channel, as is the case for the current baseline Neutrino Factory detector. A number of possibilities for the far detector exist. However, a magnetized iron detector ("MIND") similar to that used in MINOS is likely to be the most straightforward approach. For the purposes of nuSTORM oscillation physics, a detector inspired by MINOS, but with thinner plates and much larger excitation current (larger B field), is assumed ("SuperBIND") as shown in Figure 2.15.

![SuperBIND detector concept for nuSTORM. The iron plates are disks with an overall diameter of 6 m and thickness of 1.5 cm.](image)

In nuSTORM, the neutrinos are produced by the purely leptonic, and therefore well understood, decay of muons, and thus the neutrino flux can be known with very high, sub-percent, precision. The signals are wrong-sign muons that can be identified quite easily in a magnetized iron detector. The precise knowledge of the neutrino flux and the expected very low backgrounds for the wrong-sign muon search allow one to reduce systematic effects to a negligible level, hence permitting a precise measurement of the new physics that may be behind the short-baseline anomalies. The possible exclusion regions for sterile-neutrino oscillation parameters obtained from 5 years of nuSTORM running are shown in Figure 2.16.

Advanced R&D for the high-intensity 6D ionization cooling channel required for a Muon Collider could be pursued using the nuSTORM facility, which provides a muon source with significant intensity ($10^{10} \mu/\text{pulse}$ in the 100-300 MeV/c momentum range). This beam can be produced simultaneously with the neutrino physics program at little additional cost. This is possible because nuSTORM requires an absorber to absorb pions remaining (about 60% of those injected into the ring) after the first straight. Pions in the momentum range 5 GeV/c±10% are extracted to the absorber. There are also many muons in the same momentum window (forward decays) that will be extracted along with the pions. The absorber will act as a degrader for these muons, producing the desired low-energy
Figure 2.16: Contour in sterile parameter space associated with $\nu_e \rightarrow \nu_\mu$ appearance. Assumed is $1.8 \times 10^{18}$ stored $\mu^+$ at $p = (3.8 \pm 0.38)$ GeV/c and a detector at 2 kilometers with a fiducial mass of 1.3 kilotonne. A smearing matrix is used corresponding to 2 cm steel plates. The orange/shaded areas show the combined 99%-confidence level allowed regions from MiniBooNE and LSND.

Muon beam. In addition, nuSTORM will present the opportunity to design, build and test decay ring instrumentation (BCT, momentum spectrometer, polarimeter) to measure and characterize the circulating muon flux.
### 2.3 Neutrino Factory

The Neutrino Factory concept is attractive since it provides very high intensity neutrino and antineutrino beams which are exact CP conjugates. The flavor content and energy spectrum as well as the total flux can be determined to better than 1%, which, combined with the great flexibility in neutrino energy, makes a Neutrino Factory the ideal source for precision neutrino physics. Moreover, the beam contains equal numbers of muon and electron flavors and therefore, it is possible to directly measure the relevant cross sections, including nuclear effects, in the near detector. As a result it is widely recognized that the Neutrino Factory is the only concept that will allow an accuracy in the determination of leptonic mixing parameters that can compete with that in the quark sector.

![Figure 2.17: Accuracy on the CP phase vs. the true value of the CP phase at 1σ confidence level. Light-blue bands depict the accuracy expected from LBNE using the various beams Project X (MW-class proton driver for muon generation) can deliver. Left: the thick blue curves represent what a Neutrino Factory beam can do using a magnetized Liquid Argon detector. Right: the gray bands illustrate the accuracy of a Neutrino Factory using a non-magnetized detector.](image)

Neutrino Factories were originally designed to cover the smallest possible values of $\theta_{13}$, but in response to the measurement of large $\theta_{13}$, the Neutrino Factory design was re-optimized to a stored muon energy of 10 GeV and a single baseline of 2000 km using a 100 kt magnetized iron detector. It is possible to further reduce the energy to around 5 GeV and concomitantly the baseline to 1300 km without an overall loss in performance if one changes the detector technology; possible choices include a magnetized liquid argon or fully active plastic-scintillator detector to improve efficiency around 1-2 GeV. Once one of these technology choices is shown to be feasible, there is no strong physics-performance reason to favor the 10 GeV over the 5 GeV option, or vice versa. The low-energy option is attractive due to its synergies with planned super-beams such as LBNE and because the detector technology would allow a comprehensive physics program in atmospheric neutrinos, proton decay and supernova detection. For the low-energy option detailed studies of intensity staging have been carried out which indicate that even at $1/20^{th}$ of the full-scale beam intensity and starting with a 10 kt detector, significant physics gains beyond the initial phases of a pion-decay based experiment, such as
LBNE, can be realized. At full beam intensity and with a detector mass in the range of 10-30 kt, a 5 GeV Neutrino Factory offers the best performance of any conceived neutrino oscillation experiment (see Figures 2.17 and 2.18).

The Neutrino Factory uses a high-energy proton beam to produce charged pions. The majority of the produced pions have momenta of a few hundred MeV/c, with a large momentum spread, and transverse momentum components that are comparable to their longitudinal momentum. Hence, the daughter muons are produced within a large longitudinal and transverse phase-space. This initial muon population must be confined transversely, captured longitudinally, and have its phase-space manipulated to fit within the acceptance of an accelerator. These beam manipulations must be done quickly, before the muons decay ($2.2\mu s$). Finally, muons are stored in the decay ring to produce neutrino beams in the ring’s straight sections. The figure of merit describing performance of the various stages is the neutrino flux generated by decaying muons in the storage ring straights.

The functional elements of a Neutrino Factory, illustrated schematically in Figure 2.19, are as follows:

- a proton source producing a high-power multi-GeV bunched proton beam
- a pion production target that operates within a high-field solenoid; the solenoid confines the pions radially, guiding them into a decay channel
- a solenoid decay channel
• a system of RF cavities that captures the muons longitudinally into a bunch train, and then applies a time-dependent acceleration that increases the energy of the slower (low energy) bunches and decreases the energy of the faster (high-energy) bunches.

• a cooling channel that uses ionization cooling to reduce the transverse phase space occupied by the beam, so that it fits within the acceptance of the first acceleration stage

• an acceleration scheme that accelerates the muons to 5 GeV

• a 5 GeV "racetrack" storage ring with long straight sections

The cooling channel consists of a sequence of identical 1.5 m long cells. Each cell contains two 0.5 m long RF cavities, with 0.25 m spacing between the cavities and 1 cm thick LiH blocks at the ends of each cavity (4 per cell). The LiH blocks constitute the energy absorbing material for ionization cooling. Each cell contains two solenoid coils of alternating signs; this yields an approximately sinusoidal variation of the magnetic field in the channel with a peak value of $\sim 2.5$ T, providing transverse focusing with $\beta_\perp = 0.8$ m. The total length of the cooling section is 75 m (50 cells). The cooling channel is expected to reduce the RMS transverse normalized emittance from $\varepsilon_{N,rms} = 18$ mm-rad to $\varepsilon_{N,rms} = 7$ mm-rad. The resulting longitudinal emittance is $\varepsilon_{L,rms} \approx 70$ mm/bunch. Consequently, about a factor 2 improvement of neutrino flux is expected from implementation of the 4D cooling.

A high-intensity Neutrino Factory can be obtained from NuMAX by upgrading the proton driver to the nominal power of 3 MW at 3 GeV as planned for Project X Stage IIb. The corresponding target and muon capture sections would need to be modified accordingly. Performance would benefit from the 4D cooling validated as R&D at NuMAX. This facility does not require any longitudinal cooling but would be used as a muon source and an R&D platform to test and validate transverse and longitudinal (6D) cooling to full specification and nominal muon bunch intensity ($10^{12}$/bunch) as required by Muon Colliders.
2.4 Muon Collider

A Higgs Factory is an attractive first stage in the development of a high-energy Muon Collider. Because the Muon Collider has the possibility of very precise energy resolution and an enhanced coupling to the Higgs ($4 \times 10^4$ larger than in an $e^+e^-$ collider), a large cross section for s-channel Higgs production is possible. For a beam spread of 4.2 MeV the Higgs cross section on resonance is 17 pb when taking into account Initial State Radiation (ISR). This allows unparalleled precision in the measurement of the Higgs mass ($\delta M = 0.1$ MeV) and a direct measurement of its width ($\delta \Gamma = 0.24$ MeV) with integrated luminosity of 100 pb$^{-1}$. Precision measurements of branching ratios are also possible. Access to second-generation Higgs couplings is assured because of the entrance channel: the branching-ratio product $B(h \rightarrow \mu^+\mu^-) \times B(h \rightarrow W^+W^-)$ will be determined to 2%. Precise measurement of $B(h \rightarrow b\bar{b})$ is also possible. In the (unlikely) event that the 126 GeV boson is actually a nearly degenerate doublet of states, only the MC could disentangle these states. More plausible is the two-Higgs-doublet model in which as the mass of the A increases it becomes more and more degenerate with the $H^0$. Here too the MC could disentangle the physics up to nearly $M_A = 900$ GeV.

In addition to direct production of a Higgs boson at a Higgs Factory, the Higgs boson can be studied in a number of other ways at a multi-TeV Muon Collider:

- in associated production where $\mu^+\mu^- \rightarrow Z^* \rightarrow Z^0 + h^0$ has a cross section ratio $R = 0.12^*$. One can measure the b-quark-Higgs Yukawa coupling and look for invisible decay modes of the Higgs boson.

- Higgstrahlung $\mu^+\mu^- \rightarrow t\bar{t}h^0$ has a cross section ratio $R = 0.01$. This process could provide a direct measurement of the top-quark-Higgs Yukawa coupling. However such a study is very challenging requiring at least 5 ab$^{-1}$ of integrated luminosity.

- WW fusion $\mu^+\mu^- \rightarrow \nu_\mu\bar{\nu}_\mu W^+W^- \rightarrow \nu_\mu\bar{\nu}_\mu h^0$ has a cross section ratio $R = 1.1s^2\ln(s)$ (for $m_h = 120$ GeV). It allows the study of Higgs self-coupling and certain rare decay modes. Its rate grows with $s = E_{CM}^2$, an advantage for a Muon Collider.

The Muon Collider is first and foremost an energy frontier machine. It offers both discovery, as well as precision, measurement capabilities. The physics goals of a Muon Collider are for the most part the same as those of a linear electron-positron collider (ILC/CLIC) at the same energy. The main advantages of a Muon Collider are the ability to study the direct (s-channel) production of scalar resonances, a much better energy resolution (because of the lack of significant beamstrahlung), and the possibility of extending operations to very high energies. At ILC/CLIC, however, significantly greater polarization of the initial beams is possible.

A multi-TeV Muon Collider is required for the full coverage of Terascale physics. The physics potential for a Muon Collider at $\sim$3 TeV and integrated luminosity of 1 ab$^{-1}$ is outstanding. Particularly strong cases can be made if the new physics is SUSY or new strong dynamics. Furthermore, a staged

\[ R = \frac{\sigma(\mu^+\mu^- \rightarrow X + \bar{X})}{\sigma(\mu^+\mu^- \rightarrow e^+e^-)} \]
Muon Collider can provide a Higgs Factory with unique abilities as well as a Neutrino Factory to fully disentangle neutrino physics. If narrow s-channel resonance states exist in the multi-TeV region, the physics program at a Muon Collider could begin with less than $10^{31} \text{cm}^{-2}\text{sec}^{-1}$ luminosity.

Figure 2.20: Functional elements of a Higgs Factory/Muon Collider complex.

The functional elements of a Higgs Factory/TeV-scale Muon Collider complex are illustrated schematically in Figure 2.20. They can be listed as follows:

- a proton driver producing a high-power multi-GeV bunched proton beam
- a pion production target operating in a high-field solenoid; the solenoid confines the pions radially, guiding them into a decay channel
- a "front end" consisting of a solenoid $\pi \rightarrow \mu$ decay channel, followed by a system of RF cavities to capture the muons longitudinally and phase rotate them into a bunch train suitable for use in the cooling channel
- a cooling channel that uses ionization cooling to reduce the longitudinal phase space occupied by the beam by about six orders of magnitude from the initial volume at the exit of the front end; the first stages of the cooling scheme include 6D cooling and a bunch merge section; for a Higgs Factory, cooling would stop before entering a "Final Cooling" section which trades increased longitudinal emittance for a ten-fold improvement in each transverse emittance as required for a high luminosity TeV-scale Muon Collider.
- a series of acceleration stages to take the muon beams to the relevant collider energies; depending on the final energy required, this chain may include an initial linac followed by recirculating linear accelerators (RLA) and/or fixed-field alternating gradient (FFAG) rings; at present, the multi-TeV collider designs utilize rapid-cycling synchrotrons (RCS) as the baseline for achieving the highest beam energies.
- a compact collider ring, having a circumference of $\sim 300$ m for a Higgs Factory and several kilometers for a TeV-scale collider, along with the associated detector(s); at present, the baseline Higgs Factory design assumes one detector while the TeV-scale colliders can readily accommodate at least two detectors.
The Higgs Factory takes advantage of the s-channel resonance specific to muons with a cross-section 40,000 times larger than for electron-positron collisions. As a consequence, the required luminosity to produce 13,500 Standard Model Higgs events during a typical $1 \times 10^7$ sec operating year is only $8 \times 10^{31}$ cm$^{-2}$s$^{-1}$. This can be compared with luminosities in the $10^{34}$ cm$^{-2}$s$^{-1}$ range, which are required to provide similar numbers of Higgs events with an electron-positron collider via associated production. In order to probe the narrow s-channel resonance, the rms beam momentum spread should not be larger than a few $\times 10^{-5}$, which requires a small longitudinal emittance and a collider ring with excellent beam energy stability and corresponding control of the injection energy. A plot of the emittance reduction through the planned muon ionization cooling channel is shown in Figure 2.21. In order to achieve the small longitudinal momentum spread required for a Higgs Factory, the cooling process will stop at the end of the 6D cooling system.

The Higgs Factory could be upgraded in luminosity by increasing the proton power on target and/or improving the transverse cooling while preserving the longitudinal emittance. It represents a logical stage towards a multi-TeV collider which would reuse a number of its systems, in particular:

- the proton driver injector complex including the proton linac, accumulator and compressor
- the high power target
- the front end, including the decay channel, buncher and phase rotator
- the 6D ionization cooling stages
- the initial stages of the acceleration chain

The most significant technical feasibility issue on the critical path is the design and performance of an ionization cooling channel. The basic principles of 4D (needed for the NuMAX+) and 6D (needed...
for a collider) ionization cooling are being studied in the Muon Ionization Cooling Experiment (MICE) at Rutherford Appleton Laboratory (RAL) in the UK with Step IV (one cooling station without acceleration) to be completed by 2016 and Step VI (one full cooling cell including acceleration) by the end of the decade. MICE results, in combination with the MAP* Feasibility Assessment, will enable an informed decision on Neutrino Factory capabilities by 2020.

Advanced R&D for the high-intensity 6D ionization cooling channel required for a Muon Collider could be pursued using a facility such as nuSTORM to provide a muon source with significant intensity (\(\sim 10^{10} \mu /\text{pulse in a 100-300 MeV/c momentum slice}\)) and in the FNAL/ASTA facility with protons at intensities of \(10^{12} - 10^{13} /\text{bunch}\) for the study of collective effects with possible results on the timescale of the early 2020s. These results, in combination with the output from the conceptual/technical design report effort, would enable an informed decision about a Muon Collider by around 2025.

\*Muon Accelerator Program
Chapter 3

Muon Ionization Cooling Experiment

A Neutrino Factory based on a muon storage ring is the ultimate tool for studies of neutrino oscillations, including possibly the discovery of leptonic CP violation. It is also the first step towards a Muon collider. Ionization cooling of muons has never been demonstrated in practice but has been shown by end-to-end simulation and design studies to be an important factor both for the performance and for the cost of a Neutrino Factory. This motivates an international program of R&D, including an experimental demonstration. The aims of the international Muon Ionization Cooling Experiment are:

- to show that it is possible to design, engineer and build a section of cooling channel capable of giving the desired performance for a Neutrino Factory
- To place it in a muon beam and measure its performance in various modes of operation and beam conditions, thereby investigating the limits and practicality of cooling

The MICE collaboration have designed an experiment in which a section of an ionization cooling channel is exposed to a muon beam. This cooling channel assembles liquid-hydrogen absorbers providing energy loss and high-gradient radio frequency (RF) cavities to re-accelerate the particles, all tightly contained in a magnetic channel. It reduces the beam transverse emittance by \(\sim10\%\) for muon momenta between 140 and 240 MeV/c. Spectrometers placed before and after the cooling section perform the measurements of beam transmission and emittance reduction with an absolute precision of \(\pm0.1\%\).

3.1 Ionization Cooling

A reduction of the phase-space of a beam of charged particles passing through some material, where it loses momenta in all directions, accompanied by an accelerating structure that restores longitudinal momenta, is called ionization cooling. The principal of the ionization cooling is shown in Figure 3.1. The cooling takes places along particle trajectories and therefore can be achieved in relatively short timescale. And hence it is primarily envisaged for muon beams due to short muon lifetime. Conventional cooling techniques (radiation, electron, stochastic and laser cooling) can not produce sufficient
phase-space compression of a beam within a muon lifetime and therefore are not applicable to muon beams.

Figure 3.1: The principal of the ionization cooling.

Cooling is discussed quantitatively in terms of emittance $\varepsilon$, defined as the volume occupied by a beam in phase space. This can be expressed as $\varepsilon = \sqrt{D}$, where $D$ is the determinant of the 6-dimensional covariance matrix of the beam particles in the 6D coordinates $(x, y, t, dx/dz, dy/dz, cdt/dz)$. Normalized emittance $\varepsilon_n$ is obtained by using the coordinates $(x, y, t, p/m \cdot dx/dz, p/m \cdot dy/dz, p/\cdot dt/dz)^*$. The same calculation performed in the 4D space of spatial coordinates yields the transverse 4D emittance. The transverse emittance is defined as the emittance in one 2D plane $(x, dx/dz)$; in a solenoid channel, the cylindrical symmetry argues for this to be calculated as the square-root of the transverse 4D emittance. The longitudinal emittance is defined similarly in the time-energy dimensions.

Within an absorber, normalized transverse emittance $\varepsilon_n$ behaves approximately as:

$$\frac{d\varepsilon_n}{ds} = -\frac{1}{\beta^2} \left\langle \frac{dE_\mu}{ds} \right\rangle \frac{\varepsilon_n}{E_\mu} + \frac{1}{\beta^3} \frac{\beta_\perp(0.014)^2}{2E_\mu m_\mu X_0}$$

where $s$ is path length, angle brackets denote mean value, muon energy $E_\mu$ is in GeV, $X_0$ is the radiation length of the absorber medium, $\beta_\perp$ is the optical beta-function in the magnetic channel, and $\beta$ is the particle velocity. This expression is appropriate to the cylindrically symmetric case of solenoid focusing, where $\beta_x = \beta_y = \beta_\perp$. The first term in this equation is the cooling term and the second is the heating term.

To minimize the heating term, which is proportional to $\beta_\perp$ and inversely proportional to radiation length, it has been proposed to use liquid hydrogen as the energy absorbing medium, with $dE/ds = 30$ MeV/m and $X_0 = 8.7$ m, and to use superconducting solenoid focusing to give a small value of $\beta_\perp \sim 10$ cm, rather than quadrupoles; this corresponds to large beam divergence at the location of the

*With the last three phase-space coordinates scaled with momentum, normalized emittance takes account of the natural decrease of beam size with acceleration, which does not constitute cooling.
absorbers, so that scattering in the absorbers gives a relatively small contribution to the emittance. Key issues in absorber R&D include coping with the large heat deposition by RF dark currents and the intense (10^{14} muons per second) muon beam of the Neutrino Factory, while minimizing scattering in absorber vessel windows, which are by necessity of higher-Z material.

An additional technical requirement is high-gradient re-acceleration of the muons between absorbers to replace the lost energy, so that the ionization-cooling process can be repeated many times. Ideally, the acceleration should exceed the minimum required for momentum replacement, allowing "off-crest" operation. This gives continual rebunching, so that even a beam with large momentum spread remains captured in the RF bucket. Even though it is the absorbers that actually cool the beam, for typical accelerating gradients (around 10 MeV/m), the RF cavities dominate the length of the cooling channel. The achievable RF gradient determines how much cooling is practical before an appreciable fraction of the muons have decayed or drifted out of the bucket.

It follows from the above equation that the percentage decrease in normalized emittance is proportional to the percentage energy loss. Low beam energy is favored because it requires less re-accelerating voltage. The negative slope of \( (dE/dx)/E \) at low energies leads to longitudinal heating, while the positive slope at high energies comes with an increase in straggling. So, most muon-cooling designs and simulations to date have used a momentum near the ionization minimum, between 150 and 400 MeV/c. This is also the momentum range in which the pion-production cross-section of thick targets tends to peak, and is thus optimal for muon production as well as cooling.

Calculations using linear ionization cooling theory and detailed simulations indicate that the process, if effected in a homogeneous magnetic field, will decrease the transverse momentum of the muons, but not the beam size itself. In order to convert the reduction of angles into a reduction of beam size, a change in optical functions is necessary. This can be done in various ways, the most drastic one being to perform a magnetic field reversal, which can also be used as a way to reduce the beta function. The beta function can be squeezed in a periodic way by repeated field reversals (FOFO or SFOFO cooling cells), or only a few times during the cooling process (single- or double-flip cooling channel). The difficulty in the design of a cooling channel is to integrate the three basic elements - low-Z absorbers, RF cavities and solenoid focusing - in the most compact and economical way.

### 3.2 Cooling Channel Design

A cooling device desirable for experimental test is a section of a cooling channel from a viable high-performance Neutrino Factory design. It is defined by a few important characteristics:

- **The cooling factor.** The transverse emittance reduction in a short cooling section is at best a factor \( \Delta \varepsilon/\varepsilon = \Delta E/E \), where \( \Delta E \) is the average energy loss in the absorbers (and restored in the RF cavities) and \( E \) is the average particle kinetic energy. For muons of 200 MeV/c, a "10% cooling experiment" requires an energy loss of about 20 MeV and a similar gain in the RF system.
• **The RF system**, characterized in particular by its frequency. There are several existing scenarios: in the scheme developed for the US Study II, cooling is performed with 201 MHz cavities; in the scheme developed at CERN the cooling is performed at 88 MHz. These differences in Neutrino Factory design are motivated by the different preparation of the beam prior to the cooling section. Another crucial parameter to consider for the cooling channel is of course the gradient that can be achieved with such RF systems. Cooling experiment designs have been developed in which the frequency is 88 MHz or 201 MHz.

• **The beam to be cooled**. It is characterized by its average energy, energy spread, beam size and angular divergence. In a Neutrino Factory design, the beam has properties that vary along the cooling channel. One should vary the beam characteristics in a test experiment to reproduce this variety of conditions all the way down to the equilibrium emittance. Here is an example of typical beam properties:

- momentum 200 MeV/c
- momentum spread ±10%
- beam size 5 cm rms in both projections
- beam angular divergence 150 mrad rms in both projections

One of the characteristics of a cooling channel is the equilibrium emittance. A beam at equilibrium emittance would traverse the channel without net reduction or increase of its emittance. A precise measurement of this quantity for various configurations of magnetic field and beam momentum, and comparison with that expected from simulation, given approximately by:

\[
\varepsilon_{\text{eq}} = \frac{\beta_\perp (0.014)^2}{2\beta m_\mu \frac{dE}{ds} X_0}
\]

is one of the quantitative aims of the experiment.

The main components of MICE are outlined in Figure 3.2. The incoming muon beam encounters first a beam preparation section, where a pair of high-Z (lead) diffusers generates a tuneable input emittance. In this section, a precise time measurement is performed and the incident particles are identified. There follows a first spectrometer, in which momentum, position and angles of each incoming particle are measured by means of tracking devices embedded in a uniform-field solenoid. Next comes the cooling section itself, with hydrogen absorbers and RF cavities, the focusing optics being provided by superconducting coils. The default magnetic configuration is such that the magnetic field changes sign at the center of each absorber. The momentum, position and angles of the outgoing particles are measured in a second spectrometer, identical to the first one. At the downstream end of the experiment, another time-of-flight (TOF) measurement is performed, and particle identification by means of two calorimeters eliminate muons that have decayed in the apparatus.

The cooling experiment consists of two complete cooling channel cells. One additional absorber finishes the cooling section, both for reasons of symmetry and to protect the trackers against dark
Figure 3.2: The main components of MICE.
currents emitted by the RF cavities. To avoid emittance growth, the magnets in these two cells must be matched to the spectrometer solenoids. This is done using two sets of matching coils situated between the solenoids and the focus pairs. Correction coils around each spectrometer solenoid ensure a uniform field of 4 T for a length of 1 m.

### 3.3 Simulation

The whole MICE cooling channel was simulated using ICOOL package, which includes energy loss, multiple scattering, straggling in the hydrogen absorbers and realistic descriptions of all magnetic fields. The simulation includes 0.5 mm thick aluminium absorber windows and stepped beryllium RF windows. The RF fields used are those from perfect pillbox cavities. The limiting apertures are found to be located at the central iris of each 4-cavity RF assembly. The RF gradients are 8.3 MV/m and the phase is such that maximum acceleration is obtained in each cavity. An illustration of the elements of the experiment is given in Figure 3.3.

Figure 3.4 shows the expected behavior of the beam for a large input emittance. The kinetic energy of the beam is reduced at each passage through an absorber, and increased in the RF cavities. At the location of each of the absorbers, the normalized emittance decreases. (It does not decrease through the accelerating section, but the un-normalized emittance would.) As an extra absorber has been included, the momentum of the outgoing beam is reduced with respect to the incoming. This could be avoided by emptying the central absorber. The experiment must measure the emittances of the incoming and outgoing beams and, most importantly, their ratio, with a precision much better than the expected 10% reduction in emittance.

Figure 3.5(left) shows how the output emittance varies with that of the input beam. For very large input emittance, the output emittance is reduced substantially, but the transmission decreases, large-amplitude particles being lost in the channel. Nevertheless, this may not be a sign of poor
Figure 3.4: Properties of the beam along the experiment. The narrow vertical lines depict the locations of the hydrogen absorbers. From top to bottom: the experiment layout, the average muon kinetic energy showing the typical saw-tooth, the particle losses which occur mostly at the central RF cavity iris and the 2D normalized transverse emittance, which is seen to decrease in the absorbers. These are all plotted for an input emittance of $6.1\pi \cdot mm$ rad and muons of 200 MeV/c average momentum.
3.4 Beamline

The MICE muon beam line is designed to generate and transport muons with tunable momentum from 140 to 240 MeV/c and with sufficient flexibility to generate beams of variable emittance in the MICE lattice ($\varepsilon_n = [3, 10] \text{ mm-rad}$), while maximizing intensity and keeping a low pion contamination. Both muon signs can be obtained by switching magnet polarities, however a $\mu^+$ beam line shows a higher production rate and will be used in MICE. The production of unwanted protons as associated with a positive beam line can be mitigated by means of a plastic absorber as demonstrated. The beam line can be conceptually split into two parts (upstream and downstream sections), tuned to transport two particle species: pions, in the upstream section, and muons in the downstream one (see Figure 3.6).

In the upstream section, a hollow cylindrical titanium target dips into the ISIS proton beam, generating secondaries via hadronic interactions. The dip depth and timing with respect to the ISIS beam cycle determine the secondary production rate. Secondary pions and protons produced from
the hadronic interactions in the target are transported along the upstream section of the MICE beam. Protons are then filtered out by plastic sheets of various thickness. The MICE target has the secondary effect of generating increased levels of beam loss in the ISIS accelerator, so the hollow cylindrical target design minimizes beam loss that might induce radioactivity in the synchrotron, while maximizing secondary particle yield. A first quadrupole magnet triplet (Q1-Q2-Q3) close to the production point is used to capture pions and direct them towards a dipole (D1) where the first momentum selection is carried out, which includes a 60° bend in the reference trajectory of the particles.

In the upstream section, particles travel in a vacuum pipe, to reduce the rate of hadronic interactions. A superconducting decay solenoid (DS) with 5T maximum field, 5 m length and 12 cm diameter enclosed in the radiation-interlocked Decay Solenoid Area (DSA) is used to collect pions with a momentum selection around 440 MeV/c. Muons from pion decays are contained and transported through this element and subsequently selected in momentum by means of another dipole (D2), which is the first element of the downstream section and produces a bend of 30°. After D2, the downstream section of the beam line consists of two further quadrupole triplets (Q4-Q5-Q6 and Q7-Q8-Q9), with 17.6 cm pole tip radius, which are used to transport the muon beam towards the diffuser, which inflates the emittance of the beam before the MICE cooling channel.

3.5 Beam Instrumentation

The MICE detector system as sketched in Figure 3.6. The major criteria of the detectors are: i) robustness, in particular of tracking detectors, to potentially severe background conditions in the vicinity of RF cavities and ii) redundancy in particle identification (PID) to keep contamination below 1%. Two spectrometers of very similar design, one upstream and one downstream of the cooling section, each measure the full set of six muon parameters. Each of them provides a high resolution measurement of the five parameters of the muon helix in a tracker embedded in a 4T solenoid, as
well as a precise time measurement. In addition, muon/pion/electron identifiers are situated in front of the upstream detectors (TOF and Cherenkov) and muon-electron identifiers (two electromagnetic calorimeters) are situated beyond the downstream spectrometer.

The trackers are made of 5 stations of 350µm scintillating fibers perpendicular to the beam axis. The station is made of three planes of fibers rotated by 120°. This allows to reconstruct the full helix track and obtain the momentum. The optical connectors on the station mates seven scintillating fibers to 1.05 mm clear-fiber light guide which transports the light from the stations to an optical patch panel mounted on the end flange of the magnet cryostat. The scintillation light is detected by Visible Light Photon Counters - low band-gap silicon avalanche detectors operated at ∼9K.

Three fast time-of-flight (TOF) stations are installed along the MICE beamline and after the cooling channel. The first two stations (TOF0 and TOF1), upstream of the cooling section and separated by about ∼8 m, provide the basic trigger for the experiment, in coincidence with the ISIS clock. These two stations have precise timing (around 70 ps) and pr

The overall detector dimensions, including magnetic shielding and housing of photomultiplier tubes and voltage dividers, is approximately 1204160 cm³ provide muon identification by time. The second of these stations will also provide the muon timing (relative to the RF phase) necessary for the measurement of the input longitudinal emittance. The coincidence with a third scintillator station of similar nature (TOF2), downstream of the second measuring station, will select particles traversing the entire cooling section. The variation of emittance due to losses and decays will thus be distinguishable from cooling. The TOF2 station also records the muon timing for the measurement of the output longitudinal emittance. 70 ps resolution provides both effective (99%) rejection of beam pions and adequate (5°) precision in the measurement of the muon RF phase. The three TOF stations are 40 × 40, 42 × 42 and 60 × 60 cm² respectively. Each slab is read out at both ends by a fast photomultiplier through a plexiglas light guide. The time-of-flight measurement is achieved by combining leading-edge time measurements from a TDC with pulse-height information from an ADC.

The two Cherenkov counters provide µ/π separation up to 365 MeV/c. The Cherenkov light produced in a 2.3 cm thick layer of hydrophobic aerogel is collected by four intersecting conical mirrors reflecting it on four 8” PMTs. Refractive indices of 1.07 and 1.12 are used respectively for the two aerogel planes, ensuring a good muon/pion/electron separation at high momentum: electrons trigger both counters, muons - only one and pions - none. At lower momentum, the TOF counters are used to complete the PID.

A combination of a sampling Pb-scintillating fibre calorimeter and a fully active active scintillator tracker calorimeter installed at the end of the cooling channel provides a final electron-muon. The sampling calorimeter is composed of extruded Pb foils in which scintillating fibers are placed in a volume ratio - scintillator:Pb=2:1. The overall detector dimensions, including magnetic shielding and housing of photomultiplier tubes and voltage dividers, is approximately 120 × 4 × 160 cm³. The sampling calorimeter acts as a pre-shower for electrons and enhances particle identification done in the following calorimeter which performs the identification based on range measurements. The latter is the subject of this thesis and fully covered in the next chapter.
Chapter 4

Electron-Muon Ranger

The main focus of this work was on construction and commissioning of the electromagnetic tracker-calorimeter for the Muon Ionization Cooling Experiment. It is named Electron-Muon Ranger (EMR) since its primary purpose is to measure a range of muons and reject electrons which appear from muons decaying inside the cooling channel.

This work included almost all possible aspects involved in a particle physics detector development. Firstly, the design was revisited in order to identify possible flaws that may affect the performance of the detector. These were found and several tests were performed to find the best solutions. Secondly, the construction procedure was optimized in order to avoid construction faults and increase production success rate. Thirdly, numerous quality checks were implemented by means of dedicated setups the aim of which was to assure that only the best components are selected for the final assembly of the detector. Forth, electronics readout had to be done from scratch. While some parts of the readout were based on commercially available modules, most of the signal processing is done by custom-made electronics boards within the detector enclosure. These boards house modern ASIC’s* and FPGA’s† which made it possible to configure the boards for specific purposes and create an integral system made of components performing different functions. The configuration of the FPGA’s was realized by means of VHDL‡. The FPGA’s also allows for future customization. Besides that, DAQ§ software was developed to control the equipment and readout binary data. Fifth, the detector was assembled with utmost caution that resulted in no dead channels. Also transportability and overall rigidity was insured to allow for safe transportation in a truck. Sixth, the full system (the detector and readout electronics) was tested with cosmics rays which confirmed full functionality. Seventh, the detector was installed in the beam line of the Muon Ionization Cooling Experiment followed by one month of beam tests during which all the systems were debugged and tuned. And finally, the collected data was analyzed. The results reviled an exceptional performance of the detector and confirmed its designed functionality.

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* Application-Specific Integrated Circuit
† Field-Programmable Gate Array
‡ VHSIC (Very High Speed Integrated Circuit) Hardware Description Language
§ Data Acquisition
4.1 Design

This section contains a description of the design of the detector with an emphasis on mechanics and general characteristics of all of the components.

The EMR can not be strictly called a calorimeter since its granularity allows for track reconstruction. Therefore it can be called a tracker-calorimeter. The granularity is achieved by employing triangular scintillator bars arranged in a plane as shown in Figure 4.1.

Figure 4.1: CAD drawing of one EMR plane. 59 triangular scintillator bars arranged in a plane held by aluminum profiles. Fiber boxes house clear fibers and PMT connectors. Each fiber box has a connector to couple a calibration fiber.

Physical and geometrical properties of the bars are described in section 4.1.1.

One EMR plane contains 59 bars and covers an area of 1.27 m$^2$. Each even bar is rotated by 180 degrees with respect to the odd one. With this configuration there is no dead area for particles crossing a plane with angles less than 45 degrees from a beam axis. The light produced by an interaction is collected by a wave-length shifting (WLS) fiber glued inside a bar. At both ends of a bar the WLS fiber is coupled to a clear fiber that transfers light to photo-multipliers (PMTs). The clear fibers are protected with rubber sleeves and packed in aluminum fiber boxes as drawn in Figure 4.2. In order to reduce bending radius, which affects light attenuation, each fiber has individual length. Bunches of clear fibers from from both sides of a plane are glued into two different types of connectors. One is designed to match multi-anode PMT, another - single-anode PMT.
Figure 4.2: Package of clear fibers in a fiber box. Multi-anode PMT connector is shown. Fiber box for single-anode PMT connector has similar structure. Last 5 fibers are looped in order to have largest possible bending radius. Numbers next to arrows indicate bending radii of corresponding fibers. Calibration fiber is also shown.

Two planes attached to each other via aluminum profiles form a rigid structure - one module (Figure 4.3). A module defines 2D coordinates (X,Y) of an interaction. Z coordinate is given by a module number. Multi-anode PMT is read-out by front-end electronics attached to a fiber box. Single anode PMT only has a voltage divider, analog signal is sent outside the detector enclosure.

Figure 4.3: CAD drawing of one EMR module made of X and Y planes. There are two front-end boards per module.

Full detector contains 48 planes as shown in Figure 4.4. Panels cover all sides of the detector to insure a light-tightness. All cables are feed through four patch-panels. There are 96 high-voltage, 48 analog, 48 digital, 6 low voltage and one configuration cables. A support frame is designed to withstand
Figure 4.4: CAD drawing of the complete EMR detector. External protective panels are not shown.
the full weight of the sensitive volume with electronics - 1 tonne. In order to protect front-end boards from a magnetic field from spectrometer solenoids installed in the cooling channel, a shielding plate is mounted on the side of the detector that faces a beam. The total weight of the detector is almost 2.5 tonnes.

It is known that gain and quantum efficiency of PMTs drift in time. And to monitor those drift a calibration system were installed inside the detector enclosure. This system is made of LED driver that distributes light homogeneously to 100 fiber. Each fiber is connected to a fiber box through a dedicated connector. Inside a fiber box a clear fiber connects the calibration fiber to a PMT. In case of multi-anode PMT the calibration fiber helps to characterize cross-talk and possible misalignment as described in section 4.2.4.

4.1.1 Scintillator Bars

![Figure 4.5: Scintillator extrusion facility at Fermilab [34]. Left: extrusion line. Right: extruder.](image)

Scintillator bars were manufactured at extrusion facility at Fermilab [34] (see Figure 4.5). This facility also produced scintillators of different shapes other experiments: DO preshower detector, MINOS [33], Minerva [35], SciBar (K2K/SciBoone), Star, Mayn Pyramid Mapping, Hall-B JLAB, T2K-ND280, Double-Chooz, Amiga - Pierre Auger. The scintillator is made of polystyrene pellets as base, 1% PPO as primary and 0.03% POPOP as secondary fluor. Each bar is coated with TiO$_2$ reflector to increase light collection by a wavelength shifting fiber inserted inside the scintillator. Light output of the scintillator was measured [34] with a photo-multiplier (25% quantum efficiency) and it is around 17 photo-electrons. Figure 4.6 shows relative transmittance and fluorescence spectra.

In the EMR detector the scintillator bars are 110 cm long, 1.7 cm high and 3.3 cm wide with 3 mm hole along a bar for a wavelength shifting fiber. A cross-section of bars and their arrangement in a plane are shown in Figure 4.7. The wavelength shifting fiber (see section 4.1.2) is glued with

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* Dow Styron 663 W
† scintillator, 2,5-diphenyloxazole, C$_{15}$H$_{11}$NO
‡ wavelength shifter, 1,4-di-(5-phenyl-2-oxazolyl)-benzene, C$_{24}$H$_{16}$N$_2$O, spectrum peaks at 410 nm (violet)
4.1. Design

Chapter 4. Electron-Muon Ranger

Figure 4.6: Light transmittance and fluorescence spectra of the extruded scintillator [20].

transient epoxy* inside a hole in the scintillator bar in order to increase light collection efficiency.

Figure 4.7: EMR bar cross-section and bars arrangement in a plane. There are 59 bars per plane.

4.1.2 Fibers

A scintillator emits violet light with wavelengths peaking around 410 nm. Photo-multipliers are most sensitive to green light. Therefore it was decided to use a wavelength shifting fiber to match scintillation light spectrum with photo-multiplier’s spectral sensitivity. The fiber is double cladding 1.2 mm in diameter produced by Saint-Gobain Crystals [16]. The core material of the fiber is polystyrene with acrylic cladding. It has very large numerical aperture of 0.58 compared to 0.2-0.3 of graded-index multimode fiber used in data communications. Trapping efficiency is 3.5%. Emission and absorption spectra are shown in Figure 4.8 [16]. The light is absorbed in blue part of a visible spectrum and re-emitted in green.

*Prochima E30 water effect resin
The fiber is characterized by quite high attenuation. It was measured in a dedicate test setup schematically shown in Figure 4.9 made of one scintillator bar with glued wavelength shifting (WLS) fiber which is readout on both ends by photo-multipliers (PMT). As a light source a light emitting diode (LED) was used, it was moved along the bar and signals from both PMTs were recorded for several positions. A ratio between the two signals as a function of the position of the LED (see Figure 4.10) characterizes fiber attenuation. It is 48% over 1 meter, that corresponds to an attenuation coefficient 3.2 dB/m.

In the original design of the EMR planes a single wavelength shifting fiber was used to transfer light to both PMTs. That is 1.1 meter of the fiber was glued inside a bar and 1 meter was outside the bar at both ends. A few planes were assembled following that design. And it was discovered [7] that many channels (10%) are damaged during production and assembly. Figure 4.11 shows multi-anode and single-anode PMT connector masks for a plane with a few broken channels (top row) and for a plane without any damaged fibers (bottom row).

A few faulty planes were examined and it was found that fibers are damaged at the exit of a scintillator bar (see Figure 4.12). It happens mainly during final assembly when fiber bundle is packed inside a fiber box. During that manipulation some fibers are twisted above acceptable limits. Therefore it was decided to change the design and to use clear fiber to transfer light from the ends of scintillator bar.
Figure 4.10: Ratio of signal from two PMTs showing attenuation along a bar. The two PMTs have different gain, therefore the ratio is not centered at 1.

Figure 4.11: Multi-anode and single-anode PMT connectors of a plane with a few dead channels (top raw) and without any dead channels (bottom raw). Histograms show residuals of luminosity of each channel with respect to an average channel luminosity. Faulty channels are below 0.2. In this plane (top row) there are 9 broken channels.
Figure 4.12: **Left:** damaged wavelength shifting fiber, white scratches are clearly seen. **Right:** example of a well functioning fiber.

Figure 4.13: Test setup to compare light transmission through wavelength shifting (WLS) fiber only (top) and WLS plus clear fiber (bottom). A - light loss in PMT connector, B - attenuation in fiber, C - insertion loss in fiber connector. For WLS Fiber Only configuration: A1 is unknown, B1 = 48%. For WLS+Clear Fiber: A2 - unknown, B2+C2 = 38%. Assuming A1 loss is similar to A2, the light gain due to change to clear fiber is B1-(B2+C2)=10%
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Figure 4.14: Light guide characteristics.

to PMTs. This modification has numerous advantages. Firstly, it simplifies construction and assembly due to the fact that scintillator plane and fiber bundles can be assembled separately. Secondly, the clear fiber is more rigid than wavelength shifting fiber. Thirdly, due to larger attenuation length more light can be transferred up to the PMT. And finally, optimization of fiber lengths (see Figure 4.2) allows for even higher gains in light transmission. The two configurations (wavelength shifting (WLS) fiber only and WLS coupled to clear fiber) were compared and for equal fiber lengths the light gain in the new configuration is 10%. The results of this test summarized in Figure 4.13.

Parameters of a clear fiber are shown in Figure 4.14. It is 1.5mm multi-cladding fiber produced by Kuraray[31] with special structure (S-type) that allows for better rigidity against bending. The aperture of this fiber matches to the one of WLS fiber so that insertion loss is minimal.

4.1.3 Connectors

A special connector was designed to couple a clear fiber to a wavelength shifting fiber (see Figure 4.15). It has a small cylindrical enlargement which is meant to be filled with glue to fix the fiber in the connector. Thanks to that configuration it is possible to avoid crimping the fiber since the latter can easily damage it. As shown in Figure 4.15 the retaining clip (B) is screwed into the wavelength shifting fiber connector (A) so that clear fiber connector can be easily and safely attached. All these pieces are non-standard and could not be found on a market, therefore a special mold was designed to produce them using injection molding technique.

Both faces of the bar’s fiber connectors are polished with a special polishing machine. Four different
grades of sand paper are used to achieve a mirror like quality of the polished surfaces (see Figure 4.16). The last step is performed using a 1\(\mu\)m grade diamond-based polishing paper. The same procedure is applied to the clear fiber connectors and PMT connectors (see Figure 4.17).

4.1.4 Read-Out and Control Electronics

The EMR has dual readout. Each plane is equipped with two PMTs: single-anode and multi-anode. Single-anode PMT registers light from all the bars in a plane and therefore provides signal proportional to the total energy deposition in a plane. Multi-anode PMT has 64-channels and reads all bars
4.1. Design

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4.1.4.1 Single-Anode Photo-Multipliers

The single-anode PMT (see Figure 4.18) is 10 stage linear focused photo-multiplier tube produced by Philips (model XP2972). It is most sensitive to wavelengths around 400 nm what matches to emission spectrum of the wavelength shifting fiber. The PMT is placed inside a $\mu$-metal shielding...
tube which protects it from static magnetic filed as shown in Figure 4.1. 48 PMTs are required for the full detector. Since these PMTs are not brand-new a special selection procedure was developed in order to select the best samples for the final assembly, the results of this selection is described in Section 4.2.1.3. Table 4.1 contains general characteristics of this PMT. Typical gain and spectral characteristics are shown in Figure 4.19.

Figure 4.19: **Left:** typical spectral characteristics. **Center:** typical gain curves. **Right:** dimensions.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode luminous sensitivity ($\mu$A/Im)</td>
<td>90</td>
</tr>
<tr>
<td>Cathode radiant sensitivity (mA/W)</td>
<td>85</td>
</tr>
<tr>
<td>Supply voltage (V) / gain</td>
<td>$1800 / 10^7$</td>
</tr>
<tr>
<td>Supply voltage (V) / gain</td>
<td>$1300 / 9.3 \times 10^5$</td>
</tr>
<tr>
<td>Anode dark current typical / maximum (nA)</td>
<td>5 / 20</td>
</tr>
<tr>
<td>Time response rise / FWHM (ns)</td>
<td>1.9 / 3</td>
</tr>
<tr>
<td>Pulse amplitude resolution for $^{137}$Cs (%)</td>
<td>7.7</td>
</tr>
</tbody>
</table>

Table 4.1: Single-Anode PMT general characteristics

### 4.1.4.2 Multi-Anode Photo-Multipliers

The multi-anode PMT (see Figure 4.20) is a 64-channel photo-multiplier tube produced by Hamamatsu (model R5900-00-M64). The spectral sensitivity matches to the emission spectrum of the wavelength shifting fiber. It is also placed in a $\mu$-metal tube in which PMT is aligned with respect to a fiber connector in such a way so that each fiber shines only one channel. Therefore it was important to measure all dimensions of the PMT and especially position of the anode matrix with respect to the PMT case. Figure 4.21 show distributions of the dimensions (width and height) and displacement of the anode matrix. Clearly the matrix is shifted by 0.5 mm upwards as shown if Figure 4.20, right. This was taken into account in the design of the PMT fiber connectors. Typical spectral characteristics are shown in Figure 4.22. And Table 4.2 summarizes all general characteristics of the multi-anode PMT [27].
4.1. Design

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Figure 4.20: Multi-Anode PMT. **Left:** photo. **Center:** anode matrix. **Right:** anode matrix dimensions.

Figure 4.21: Distribution of Multi-Anode PMT dimensions.
Figure 4.22: Multi-Anode PMT typical spectral characteristics [27]. **Left:** spectral response. **Right:** gain and dark current.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Response (nm)</td>
<td>300 to 650</td>
</tr>
<tr>
<td>Wavelength of Maximum Response (nm)</td>
<td>420</td>
</tr>
<tr>
<td>Photocathode Material</td>
<td>Bialkali</td>
</tr>
<tr>
<td>Photocathode Minimum Effective Area (mm$^2$)</td>
<td>18.1x18.1</td>
</tr>
<tr>
<td>Window Material</td>
<td>Borosilicate</td>
</tr>
<tr>
<td>Number of Stages</td>
<td>12</td>
</tr>
<tr>
<td>Anode Size (mm$^2$)</td>
<td>2x2</td>
</tr>
<tr>
<td>Weight Approx. (g)</td>
<td>30</td>
</tr>
<tr>
<td>Maximum Supply Voltage Between Anode and Cathode (V)</td>
<td>1000</td>
</tr>
<tr>
<td>Average Anode Current in total (mA)</td>
<td>0.1</td>
</tr>
<tr>
<td>Luminous Cathode Sensitivity (mA/Im)</td>
<td>70</td>
</tr>
<tr>
<td>Quantum Efficiency (%)</td>
<td>20</td>
</tr>
<tr>
<td>Anode Sensitivity Luminous (A/Im)</td>
<td>21</td>
</tr>
<tr>
<td>Gain at 800V</td>
<td>3.0x10$^5$</td>
</tr>
<tr>
<td>Anode Dark Current per channel (nA)</td>
<td>0.2</td>
</tr>
<tr>
<td>Anode Pulse Rise Time (ns)</td>
<td>1.5</td>
</tr>
<tr>
<td>Transit Time Spread (ns)</td>
<td>0.3</td>
</tr>
<tr>
<td>Pulse Linearity per Channel (mA)</td>
<td>0.6</td>
</tr>
<tr>
<td>Cross-talk with 1mm Optical Fiber (%)</td>
<td>2</td>
</tr>
<tr>
<td>Uniformity among all anodes</td>
<td>1:3</td>
</tr>
</tbody>
</table>

Table 4.2: Multi-Anode PMT general characteristics [27].
4.1.4.3 Front-End and Buffer Board

The multi-anode PMT is readout by a dedicated front-end board equipped with piggy-back buffer board which stores hit information during a spill. Functionality of the boards is explained in section 4.3. Figure 4.23 show the full assembly that is mounted on every plane. It consists of a PMT attached to a voltage divider which is connected to the front-end board through a flex cable. This cable also creates additional pressure between the PMT and fiber connector.

![Figure 4.23: Front-end and buffer board assembly.](image)

4.1.5 Mechanics

Total weight of the sensitive volume of the detector is almost 1 tonne. During construction and installation it is required to rotate and move the detector; besides that it is meant to be transported in a truck over more then 1000 kilometers. Therefore a reinforced support frame (see Figure 4.24) was design so that it can withhold the weight of the sensitive detector and all the stress that may happen during the transportation and installation. In its final position the EMR is installed in such a way so that planes are located vertically perpendicular to a beam direction.

Figure 4.25 shows location of the sensitive volume with respect to the support frame. The frame is covered with panels so that the whole volume is light-tight. A panel which faces the beam (see Figure 4.25, right) is made of 5 cm thick iron plates (total weight 755 kg) and plays a role of global shielding for electronics. The back panel is made of metal profiles and thin aluminum panels. The opening in the shielding front panel is closed with a thin wooden end cap and in the back panel - with metal end cap (since it holds the weight of the detector during assembly when it is in horizontal position).
Figure 4.24: EMR support frame. When installed in the experimental hall the EMR is integrated into support structure of other detectors.

Figure 4.25: EMR dimensions (mm).
4.2 Construction

All the construction work of the detector were done at University of Geneva and it involved many steps. As it was mentioned in the previous section the scintillator bars were produced at Fermilab. The first step in the construction was to glue wavelength shifting fibers into the bars (see Figure 4.26, top right). 60 bar were glued in a row on a stand designed to allow safe insertion of WLS fiber into the bar and rapid filling of bars with glue. Production rate was 60/day due to time required for glue to harden. For the full detector 2832 bars are required but 3150 bars were glued to make sure that there are enough spares available (see Figure 4.26, top left). In the second step, each fiber connector (two per bar) was polished on a dedicated bench equipped with four different diamond sanding papers (see Figure 4.26, bottom).

Figure 4.26: Top Left: a pile of glued and polished bars. Top right: scintillator bar gluing bench. Bottom: bar connector polishing bench.

Core material of fibers and scintillators is polystyrene. It is known that ultra-violet (UV) light and high temperature damaged polystyrene molecules and it becomes less transparent. This is especially important for fibers because the damage decreases light transmission. Therefore all activities related to fibers and scintillators were performed in a UV clean room, i.e. lights and windows were covered with UV-protective films, with air conditioning that kept temperature around 25°C.

In parallel with bar gluing fiber bundles (see Figure 4.27) were manufactured. Each fiber bundle is made of 60 clear fibers (clear fibers): 59 - to readout scintillator bars and 1 - calibration fiber. Each
fiber has an individual length so that when it is connected to a bar the bending radius is minimal. A fiber connector (see Figure 4.15, bottom right) is glued at one end of each fiber, at the other end all fibers are glued either in multi-anode or single-anode PMT connector. Once glued, both fiber and PMT connectors are polished on a bench similar to one used to polish bar connectors (see Figure 4.26, bottom). In total there were 96 fiber bundles (48 for each type of the PMTs).

Figure 4.27: Clear fiber bundles. **Left:** fiber pre-cut to the specified length. **Center:** PMT connector. **Right:** fiber connector.

The construction was organized in such a way so that all the steps until the plane assembly are as independent as possible. This allowed more efficient distribution of manpower. Once all the necessary components needed to build planes were ready (see Figure 4.28), plane construction began. First 59 bars placed to form a plane. Second, they are fastened by aluminum profile with half fiber boxes attached. Third, fiber bundles were attached to bars and fiber boxes could be closed. The planes were assembled directly on a final support frame as shown in Figure 4.29.

Figure 4.28: From left to right: scintillator bars with glued wavelength shifting fibers and polished fiber connectors, fiber bundles with polished connectors, fiber boxes, aluminum support profiles, retaining clips to attached clear fibers to wavelength shifting fibers.

Figure 4.29: From left to right: clear fibers attached to bars, x and y planes with fiber boxes open, single-anode PMT tubes, multi-anode PMT tubes.
4.2.1 Quality Tests

In order to assure the best possible performance of the detector, numerous quality test were implemented. They are described in the following subsections.

4.2.1.1 Scintillator Bars

At the moment when it was discovered that there was a flaw in the design (see Section 4.1.2) more than 1000 bars were already glued with the fibers. Those bars were refurbished, namely loose fiber ends were cut and a small adapter (seen in Figure 4.26, bottom right) glued on top of the existing aluminum connector. Some of those bars were damaged during this operation, therefore it was necessary to test all of them. Besides that it was important to check quality of polishing. That is why new bars were tested as well.

Figure 4.30: Scintillator bar quality test bench. From left to right: LED box, bar connectors, bars attached to the LED box, camera taking photos of bar connectors.

Bar quality test bench consists of LED* box, 4 scintillator bars and a digital camera placed in a light-tight box as shown in Figure 4.30. The LED box contains blue LED, light mixing box and diffusers so that the light is homogeneous at four output holes which are used to attach 4 bars. The camera takes a photo of four bar connectors. Out of four bars one is a reference and the measurements are normalized to it in order to correct the effect of LED instability and to have a possibility to compare different measurements. A program analyzes the photo and calculates light intensity of each bar. Figure 4.31 shows distributions of relative residuals of the light intensity† Only bars with the relative residual intensity above -0.15 were accepted for plane assembly. Out of 3150 tested bars 305 bars (9.7%) did not pass that requirement and were rejected.

4.2.1.2 Planes

Each assembled plane was tested in a similar way as bars. An LED tube attached to a single-anode PMT connector sends light through all the fibers (wavelength shifting and clear) all the way up to a multi-anode PMT connector where a camera is setup to take a picture of the PMT mask.

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*Light Emitting Diode
†The difference between the measured value and the average value divided by the average.
Figure 4.31: Bar quality test measurements. **Top left:** an example of one measurement, bottom bar is a reference. **Top right:** values of the relative residual intensity of all 3150 bars. **Bottom left:** distribution of the relative residual intensity. **Bottom right:** values of the relative residual intensity sorted in ascending order.
Figure 4.32). During this test not only fiber bundles are verified but also a quality of interconnections between wavelength shifting fiber and clear fiber is tested.

Figure 4.32: Plane quality tests. **Left:** LED tube with blue light to be attached to single-anode PMT connector. **Center:** multi-anode PMT connector inside shielding. **Left:** PMT mask.

Figure 4.33: Example of plane quality test for two planes. **Left:** PMT mask. **Right:** relative residual intensity values for 60 channels, the last value is for a calibration channel.

A photo of the multi-anode PMT mask is analyzed and light intensity of every channel is measured. Figure 4.33 shows examples of such measurements for two planes. If the relative residual intensity of all 60 channels is above -0.4 then the plane is accepted. All 48 planes have been tested and only 2 channels in two different planes were below -0.4. 95% of channels (out of 2832) are above -0.2 (see Figure 4.34). In other words, when all the planes were assembled no dead channels were found.

### 4.2.1.3 Photo-Multipliers

Brand-new multi-anode PMTs were tested in a factory, therefore there was no need to verify them individually. They were tested together with front-end-boards (see next subsection). On the contrary,
single-anode PMT were previously used in another experiment and that is why they had to be tested one by one [8]. A test bench to study the PMTs was set up (see Figure 4.35, left). It consists of a small plane (20×30 cm) made of the EMR triangular bars with wavelength shifting fibers, the fibers are gathered in two single-anode PMT connectors to one of which a single PMT with shielding tube is connected and to another - an LED tube (the same as for plane tests, see previous subsection). Two scintillators are placed above and below the plane to create a trigger signal when a cosmic muon crosses both of them. The trigger rate was a few hertz, and it was taking more than an hour to collect a few thousand triggers to minimize statistical errors on the measurements. It was needed to test more than 200 PMTs. Therefore the LED tube was installed the purpose of which was to mimic light that is produced by a cosmic muon crossing the scintillator plane and to use the LED to test the PMTs instead of cosmic muons. The LED tube was connected to a 10 kHz pulser (see Figure 4.35, center) and in one second there were enough statistics to characterize the PMT in terms of response to cosmic muon like signal.

Figure 4.35: Single-anode PMT test bench. **Left:** cosmic trigger setup. **Center:** LED setup. **Right:** setup to test dark noise.

Typical cosmic muon signal (waveform) is shown in Figure 4.36. The acquisition window is chosen
so that the signal pulse is clearly visible and positioned in the second part of the window. And integral of the signal in this part give a charge in ADC counts. The first part if the acquisition windows is used to calculate a pedestal charge.

![Waveform of a typical cosmic muon signal](image1)

**Figure 4.36:** A waveform of a typical cosmic muon signal. First part (gray) of the acquisition window is used to calculate pedestal charge and the second - signal charge.

The LED is driven by a variable amplitude pulser. The amplitude has to be selected in such a way so that the amount of photons produced by the LED is close to the number of photons produced by the scintillator when a muon crosses it. The amount of generated photons proportional to the measured charge of a signal. Therefore the appropriate voltage can be found by comparing charge distribution from cosmic muons and from LED signals at different voltages. The charge distribution from the muons is shown in Figure 4.37.

Another setup (see Figure 4.35, right) was used to characterize PMTs in terms of dark noise. In this setup the readout electronics were working in self-triggering mode, i.e. when the signal crosses a threshold the trigger is generated. An amplitude of the dark noise signal (see Figure 4.38, left) and dark noise rate are the parameters measured for each PMT. The dark noise rate evolves in time and
it is very high during the first few minutes, therefore the measurements are taken after 30 minutes when it becomes relatively stable (see Figure 4.38, right).

In total 217 PMTs were tested. Distributions of measured parameters for all of the tested PMTs are shown in Figure 4.39. According to this distributions selection criteria were chosen:

1. mean value of the LED signal charge distribution: \(8 < P1 < 25 \text{ ADC}\)

2. RMS\(^*\) of the LED signal charge distribution: \(P2 < 8 \text{ ADC}\)

3. signal resolution \((P2/P1\times100\%): 25 < P3 < 40\%\)

4. RMS of the pedestal distribution: \(P4 < 0.5 \text{ ADC}\)

5. dark noise rate: \(P5 < 5000 \text{ Hz}\)

6. mean value of the dark noise charge distribution: \(P6 < 28 \text{ ADC}\)

Out of 217 PMTs only 56 passed these selection criteria which was enough to equip the detector with 48 PMTs and to have 8 spares.

### 4.2.1.4 Electronic Boards

Readout of the multi-anode PMTs involves many stages. The signal from PMTs is processed by the front-end board, saved in a buffer board and then copied to a VME\(^\dagger\) controller who transfers the data to a computer (see Section 4.3 for more details). The front-end boards and buffer boards are custom made FPGA-based electronics boards and they are installed within the detector enclosure. Therefore it was important to test all the boards before their final installation in the detector. Once installed it is considerably difficult to replace a faulty equipment.

---

\(^*\) Root Mean Square

\(^\dagger\) VERSA module Eurocard - a flexible open-ended bus (computer data path) system based on the Eurocard standard
Figure 4.39: Selection parameters for PMTs.
A test bench (see Figure 4.40) has been setup to verify functionality of three major components of the EMR electronics: the multi-anode PMTs, front-end boards and buffer boards. It reproduces the full electronics chain used to readout the detector with the only difference that the light is generated by LED power by a variable amplitude pulser. The LED is attached to the PMT and lights all the channels at the same time. The final measurement that is provided by the system is a time-over-threshold of the PMT signal. During the tests this measurement is used as a figure of merit to characterize the electronics chain (PMT, front-end and buffer boards). Figure 4.41 shows an example of a fully functional electronics chain (top) and an example of a faulty electronics (bottom). Boards which exhibit behavior as in Figure 4.41(top) are excepted for the final installation into the detector. In the course of these tests 10 front-end-boards were rejected. Fully functional 48 multi-anode PMTs, front-end boards and buffer boards required for the full detector were found [6].

4.2.2 Final Assembly

Scintillator planes assembly (see Figure 4.42) was completed in six months, i.e. 48 planes made of 2832 bars equipped with 96 fiber bundles totaling 5760 fibers and 11520\textsuperscript{*} polished connectors. All the bars, connectors and planes used in the construction passed all the quality tests described earlier.

During the assembly the planes were equipped with electronics modules tested beforehand. One module is made of the multi-anode PMT, front-end and buffer boards. Each module is attached to

\textsuperscript{*}48 planes \times (59 \text{ bars} \times 2 \text{ fiber connectors per bar} + 2 \text{ fiber bundles per plane} \times 60 \text{ fibers per bundle} + 2 \text{ PMT connectors})
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Figure 4.41: Electronics quality tests. **Top:** functional board. **Bottom:** faulty board. **Left:** Time-over-threshold as a function of the channel number. Typical response to LED signal is around 40 ADC. Pedestal signal is around 5 ADC. Any faulty channel does not produce an adequate signal as seen in the bottom plot (channels 38 to 45). **Right:** Distribution of the time-over-threshold for all channel in a given board.

Figure 4.42: Scintillator planes assembly. **Left:** March 2013, 2 planes. **Center:** May 2013, 24 planes. **Right:** August 2013, 48 planes.
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Figure 4.43: EMR electronics modules. **First and second:** 24 modules are attached to each side of the detector. **Third:** power distribution boards provide 5V to 6 electronics modules. **Forth:** cooling fans provide necessary airflow between the modules.

Figure 4.44: Single-anode PMTs. 24 tubes on each side. Cooling fans blow the air to perforations in the tubes to remove hot air from PMT voltage dividers.
a corresponding multi-anode fiber box as seen in Figure 4.43. Cooling fans were installed between the electronics modules and adjacent single-anode fiber boxes to ensure proper air flow between the electronics modules. Electrical and signal connections of the modules are explained in Section 4.3.

Each signal-anode fiber box was equipped with the single-anode PMT housed in a shielding tube (see Figure 4.44). Cooling fans were also installed between the shielding tubes and adjacent multi-anode fiber boxes.

Figure 4.45: EMR patch-panels. **Bottom left:** configuration signal for front-end boards, low voltage power for trigger distribution board, trigger and spill gate signals. **Bottom center:** low voltage power for front-end and buffer boards. **Bottom right:** single-anode PMT high voltage power and signal, multi-anode digital signal.

Figure 4.46: Full EMR system. **Left:** all cables connected to the control rack. **Center:** control rack with power supplies and control electronics. **Right:** detector light-tight enclosure.

All the signal and power cables from electronic modules and PMTs are connected to four patch-panels installed on one side of the detector frame. (see Figure 4.45). There are 96 high voltage cables,
Figure 4.47: First cosmic muons seen by the EMR. **First row:** number of hits. **Second row:** time-over-threshold measurement. **Third row:** time difference between the trigger and the hits. **First column:** X planes. **Second column:** Y planes.
48 analog signal cables from single-anode PMTs, 48 digital signal cables from multi-anode PMTs, 6 low voltage power cables for front-end and buffer boards, three high density twisted pair cables for front-end board configuration, trigger and spill gate signals, power for trigger distribution board and LED calibration system. 48 front-end boards and 48 buffer boards draw more than 50 Amp of current and at power on the inrush current can go up to 70 Amp. All this current is transferred through six thick multi-wire cables attached to one of the patch panels (see Figure 4.45, bottom center). On the back of that patch-panel there is a board which distributes the power to 8 distribution boards (see Figure 4.43, third) each of which is connected to 6 front-end and 6 buffer boards. This allows for proper current distribution among the cables and minimizes heat dissipation. Trigger and spill gate signals (see Section 4.3 for details) are distributed to corresponding buffer boards via fan-out board attached to one of the patch-panels (see Figure 4.45, bottom left).

After the assembly was completed the detector was connected to a control rack and fully powered (see Figure 4.46) to verify the functionality of all the systems at the same time. During a few days it was collecting cosmosis data. Even without calibration and adjustment of any parameters the performance of the detector was outstanding. Cosmic muons (Figure 4.47) and showers (Figure 4.48) were clearly visible.

4.2.3 Fiber Mismatch

During assembly of the detector 5664 clear fibers had to be connected to bars and properly placed into the PMT connectors. Each fiber (in a given bundle) has individual length and has to be connected to a specific bar and placed into specific position in the PMT connector. This work was performed by technicians and there was a certain probability that a fiber is connected to a wrong bar or placed improperly. Therefore after the detector was assembled it was important to verify if there is any mismatch in fiber position [5]. This was done with the help of cosmic ray. A muon from cosmosis typically has momentum around 4 GeV and when it crosses the detector it leaves a straight track (see Figure 4.47). If there is no mismatch in any of the channels, all bars affected by the muon should lay on a straight line. And if there is a mismatch in a particular channel, then this channel will be systematically displaced from the straight muon track. Moreover, if there is a mismatch, there should be always even number of channels displaced by the same distance. One of the variable that was used to identify the mismatch was a ratio between the number of times a given channel is hit by a cosmic muon (only clean tracks were chosen) and displaced by a certain distance and the number of times it is hit. For a mismatched channel this ratio should be closer to one and for correctly placed channel it should be closer to 0. Results of this analysis are shown in Figure 4.49.

4.2.4 Alignment and Cross-Talk

The multi-anode PMT should is aligned with respect to the fiber connector by means of shielding tube. The fiber connector base and the PMT voltage divider have the same dimensions as the internal dimensions of the shielding tube minus 0.5 mm. But these dimensions are not precise and small
Figure 4.48: Cosmic showers seen in the EMR. Each row show different events (number of hits).
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Figure 4.49: Clear fiber mismatch analysis results. In plane 44 channels 47 and 48 are clearly mismatched. **Left:** the mismatch ratio (see definition in the text) for all the channels. **Right:** distribution of the ratio, for the mismatched channels the ratio is above 0.5. The rest of the channels are correctly placed.

variations are possible. Besides that a hole for a fiber in the connector is 0.1 mm larger then the diameter of the fiber. In addition there are variations in position of the PMT anode mask with respect to the PMT enclosure. All these factors add up to a misalignment of a fiber and corresponding PMT channel. This misalignment leads to a cross-talk since a given fiber shines to a neighboring PMT channel. The amount of the cross-talk was measured [5] for each PMT/fiber connector interface with the help of the calibration fiber (see Figure 4.50). This fiber is placed at the center of the PMT mask and connected to the LED driver box which send light to all the fibers at the same time. The cross-talk can be characterized as a ratio (cross-talk ratio) of the signal amplitude in a channel neighboring the calibration channel to the signal amplitude in the calibration channel.

The signal amplitude can not be directly measured by the existing EMR electronics, instead time-over-threshold (TOT) is calculated for each signal. The TOT is not linearly proportional to the signal amplitude, therefore it can not be directly used to estimate the cross-talk. But if this relation is known than the TOT can be converted to the amplitude and used for the cross-talk estimation.

The LED driver box sends light to all of the PMTs including single-anode PMTs. Therefore the same signal that is recorded by the multi-anode PMT is measured by the single-anode one. The single-anode PMT measures a pulse shape of a signal, thus an amplitude of the signal or charge*. In this way, a correlation between TOT and amplitude can be found (see Figure 4.51, left). An amplitude of voltage pulse for the LED driver was varied to obtain signals with different amplitudes (see Figure 4.51, right).

It was found that a level of the cross-talk depends on signal amplitude: the higher the amplitude

---

* an area of the signal pulse with respect to the pedestal
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Figure 4.50: LED calibration system. **Left:** LED driver box with a bundle of 100 fibers. **Center:** calibration fibers attached to fiber boxes. **Right:** multi-anode PMT fiber connector with a calibration fiber at the center.

Figure 4.51: **Left:** time-over-threshold as a function of signal amplitude. **Right:** time-over-threshold as a function of LED voltage, green area corresponds to signals with amplitude similar to once produced by cosmic muons.
the lower the cross-talk (see Figure 4.52, left). This can be explained by the nature of the time-over-threshold measurement and by the single photo-electron response. Typically one photo-electron produces a TOT signal of 3 ADC counts. Therefore lower signals are less likely to produce a signal in the neighboring channels and if it is produced (which is statistically possible) an amplitude is relatively high. This was confirmed by measuring the cross-talk rate*: at lower amplitude signal the rate is dramatically decreased.

![Figure 4.52: Left: cross-talk ratio as a function of signal amplitude in the calibration channel. Right: cross-talk rate as a function of TOT measurement in the calibration channel.](image)

When the cross-talk rate is 100% (TOT ≥ 40 ADC) the value of cross-talk ratio represents a real cross-talk not affected by the nature of the TOT measurements. The cross-talk ratio and rate was measured for all of the PMTs and summarized in Figure 4.53 where the charge ratio is given for signals with TOT ≥ 40 ADC and the rate is for TOT~10 ADC (MIP\(^\dagger\)-like signal). As it is clearly seen, the cross-talk is around 4% and at typical MIP signals the rate is negligible - 0.1%. This level of cross-talk is acceptable and does not require any special treatment.

The calibration channel can also be used to measure misalignment of the PMT with respect to fiber connector. A shift of the fiber connector is calculated based on weighted average of signals in 8 channels surrounding the calibration channel. The results of this measurement are shown in Figure 4.54. The misalignment ranges from -0.8 to 0.6 mm in X-direction and from -0.2 to 1 mm in Y-direction with most of the PMTs grouped around (-0.3,-0.3).

### 4.2.5 Transportation

The total weight of the EMR detector is 2.5 tonnes. Therefore a special care was taken to insure safety and shock-free transportation of the detector. Namely, the detector was attached to special shock absorbers (see Figure 4.46, right) designed to withstand this weight and allow for shock absorption in all three directions. The shock absorbers were then attached to a pallet by which the detector was

---

*a probability of a signal in the neighboring channel of the calibration channel is lit

\(\dagger\)Minimum Ionizing Particle. Cosmic muon is a MIP.
Figure 4.53: **Left:** cross-talk ratio (charge ratio) distribution for all multi-anode PMTs, the ratio is measured for high amplitude signals at which the cross-talk rate is 100%. **Right:** cross-talk rate distribution for MIP-like signals.

Figure 4.54: Misalignment shift of PMT mask with respect to the fiber connector.
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handled. It was placed in a truck (see Figure 4.55) and transported from University of Geneva to Rutherford Lab (Didcot, Oxfordshire, UK) over more than 1100 kilometers.

Figure 4.55: EMR transportation. Left: the detector and the control rack were wrapped with polyethylene foil to protect the equipment against humidity and with bubble paper. Center and Right: all the equipment was safely attached to the truck’s trailer.

4.2.6 Installation at Rutherford Lab

Once delivered to the Rutherford Lab the EMR detector was installed in the MICE hall (see Figure 4.56) and positioned vertically at the end of existing beamline (see Figure 4.57). At the time of the installation the cooling channel was not in the beamline only particle detectors: three time-of-flight stations, two Cherenkov detectors and the sampling calorimeter.

Figure 4.56: EMR positioning in the MICE hall. The detector was placed vertically so that planes are perpendicular to the beam.

In addition, cooling fans were installed onto the detector enclosure to insure air exchange with the internal volume.

To verify that transportation went well and none of components were damaged, all the detector systems were re-installed in exactly the same way as it was before the transportation at University of Geneva (see Figure 4.46), except for the orientation of the detector, and cosmic data was collected during a few days. The analysis of the data showed exactly the same behavior as before the transportation.
Figure 4.57: EMR installation in the MICE beamline. Left: patch-panels. Center: control rack (not in its final position). Right: cabling.

Figure 4.58: EMR cooling fans. Left: 8 fans installed (4 - air intake, 4 - air exhaust), temperature and humidity sensors are also placed on the panel. Right: light-tight filters are installed in the fan trays.
4.3 Electronics Layout

As it was briefly mentioned earlier the EMR has a dual readout. Each scintillator plane has a multi-anode PMT which collects light from individual bars and a single-anode PMT which records response from all the bars at the same time. A schematic layout of the EMR electronics is shown in Figure 4.59.

![Electronics Layout Diagram](image)

Figure 4.59: EMR electronics layout. **FEB**: front-end board for multi-anode PMT readout. **DBB**: buffer board. **MAROC 3**: 64 channel readout ASIC for multi-anode PMT. **MAPMT**: multi-anode PMT. **SAPMT**: single-anode PMT.
The multi-anode PMT connected via a flex cable to a front-end board (see Section 4.3.1) which digitizes the signal and sends it to a piggy-back buffer board for storage (see Section 4.3.3). The front-end board is configured by the VME configuration board (see Section 4.3.2) which resides in the VME crate in the control rack. This board is able to configure up to 16 front-end boards, therefore three of them are required for the full detector. The buffer boards are readout by groups of six. In each group the first buffer board is a master and other five are slaves. All six boards are daisy-chained via ethernet cable and the master is connected to a VME readout board (see Section 4.3.4) which transfers all the data from the six buffer boards to the DAQ* computer. In the whole detector there are 8 groups of buffer boards, i.e. 8 VME readout boards are installed in the control rack.

The single anode PMTs are readout by fast ADC boards (see Section 4.3.5). Each ADC board is connected to 8 single-anode PMTs. Therefore to readout 48 PMTs 6 ADC boards are used.

Three front-end configuration boards, eight buffer readout boards, six fast ADCs reside in a single VME crate controlled by CAEN V2718 VME controller which is connected to a computer via optical link. The VME crate is a part of the control rack (see Figure 4.46, center) which is placed at some distance from the detector where it is not affected by either beam or magnetic field from the spectrometer solenoid. The control rack also contains high and low voltage power supplies and a NIM crate with trigger logic, pulse generator and counters.

Inside the detector enclosure there are photo-multipliers, front-end and buffer boards, LED calibration system (see Figure 4.50), trigger and spill gate distribution board (see Figure 4.45, bottom left).

### 4.3.1 Front-End Board

The main purpose of the front-end board is to process analog signals from the 64-channel multi-anode PMT. It is able to process all 64 signals thanks to 64-channel ASIC† called MAROC‡. Figure 4.60 schematically shows main components of the board. 64 analog signals are feed into the MAROC chip where they are shaped and discriminated (see Figure 4.60, bottom), the discriminated signals are then forwarded to two high density connectors where buffer boards are connected. The width of the discriminated signal represents time over threshold measurement. The MAROC ASIC also provides analog measurement - signal charge. This measurement is based on a slow shaper and is multiplexed from all the channels and it requires a trigger (either external or internal) to produce a measurement. It takes tens of microseconds (depending on MAROC configuration) to process all the multiplexed signals and this dead time is not acceptable for the MICE DAQ duty cycle (a few hundred triggers per 1 ms spill). Therefore only time-over-threshold measurement is used since it is practically dead-timeless. The analog signal can be used with cosmics where particle rate is small but this requires development of a dedicate FPGA code.

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*Data acquisition
†Application-Specific Integrated Circuit
‡Multi Anode ReadOut Chip
Figure 4.60: Front-end board. **Top left:** schematics of the board with major components. **Top right:** photo of the board. **Bottom:** time-over-threshold measurement.
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4.3. Electronics Layout

The function of the FPGA chip∗ is mainly to forward data from MAROC to the buffer board or to send configuration signals from the VME configuration board to the MAROC and verify their status. The board has separate power for analog and digital part (both 5 V). The total power consumption of the board is 0.6 Amp.

The board ID is hard coded in the FPGA firmware and it is unique between all 48 boards.

4.3.2 Configuration Board

![Diagram of the VME configuration board](image)

Figure 4.61: VME configuration board. **Left:** schematics of the board with major components. **Right:** photo of the board [missing].

The VME configuration board is a single FPGA†Altera Cyclone II (EP2C50F484C8N)) board designed to perform configuration of the MAROC chip on the front-end board. The communication between the boards is realized via LVDS‡ signals driven and received by LVDS drivers/receivers directly connected to corresponding FPGA’s. Major components of the board are shown in Figure 4.61. As mentioned in the previous section, it can read analog signal (charge of the signal from every channel) from the front-end board but it is not implemented in the current design. The board is connected to VME bus through which it communicates with the VME controller and the DAQ computer.

The MAROC chip is configured by TTL§ signal composed of 830 bits which code the configuration parameters.

---

∗Altera Cyclone II (EP2C35F484C8N)  
†Altera Cyclone II (EP2C50F484C8N)  
‡Low-Voltage Differential Signaling, communication protocol.  
§Transistor-Transistor Logic
A DIP* switch is used to set the board ID which is unique between all the board in the VME crate.

4.3.3 Buffer Board

![Buffer board schematics](image)

Figure 4.62: EMR buffer board. **Top left:** schematics of the board with major components. **Top right:** photo of the board. **Bottom:** measurements.

The two essential roles of the buffer board (see Figure 4.62) are to sample the 63 channels (and external trigger) coming from the front-end board and to transmit the event data (see Figure 4.62, bottom) upon request of the acquisition system. The digitization starts when the board receives the Spill Gate signal from an external LEMO connector and it calculates the number of clock ticks from the begging of the spill to the leading edge and trailing edge of every signal coming from the front-end.

---

*manual electric switch packaged with others in a group in a standard dual in-line package*
board. The difference between the two measurements represents time over threshold of the original signal. The clock sampling rate is 400 MHz (2.5 ns resolution). An external trigger is also recorded by the buffer board. The trigger signal is feed into one of the 64 input channel and treated as any other signal. Therefore, only 63 channels are recorded from the front-end board. The board also calculates the width of every spill, counts the number of spills, number of triggers in the spills, and number of hits in every channel.

The general architecture of the DBB is organized around a single FPGA* that performs the sampling, data buffering, and dataflow control functions of the board. Internal memory of the FPGA - configured as FIFOs - is used to store the event data which is a collection of leading and trailing edge timestamps that occurred on each channel during a specific spill. Two gigabit transceivers† are interfaced to the FPGA to provide the physical transmission channels and form an upstream command link and a downstream data link. Six DBB’s are grouped together and daisy-chained with upstream and downstream links via ethernet cable. The first DBB in each group is directly connected to the acquisition system - the VME readout board - via four coaxial cables.

### 4.3.4 VME Read-Out Board

One VME readout board (see Figure 4.63) performs the readout of one group of six buffer boards. It is a single FPGA‡ board with a gigabit transceiver§ which drives the signals to and from the buffer boards. During the readout cycle the board should store the data from 6 buffer boards, therefore it is equipped with four high-speed 16M-bit static RAMs¶ each organized as 1024K words by 16 bits. It communicates with the DAQ computer via VME bus through the VME controller. Additional LVDS input/output connector is available but not used. A DIP switch sets the board ID.

### 4.3.5 Fast ADC Board

The Flash ADC Waveform Digitizer made by CAEN [11] is used to readout signals from single-anode PMTs. The ADC has a sampling frequency of 500M samples per second (2 ns resolution timing resolution). A pulse shape of each input signal is digitized by 8 bit ADC and continuously written in a circular memory buffer. When a trigger arrives the FPGA writes certain number samples defined by the pre- and post-trigger settings into a buffer which then is available for readout via VME bus. The data acquisition does not stop when trigger occurs and continues without dead-time in a new buffer. Each channel has a memory divided into pre-defined number of buffers of programmable size. The input signal dynamic range is 1V and can be adjusted by the programmable 16-bit DAC (DC offset). A block diagram of the board is shown in Figure 4.64.

---

* Altera Stratix II (EP2S30F484C3N)
† TLK1501
‡ Altera Cyclone II (EP2C50F484C8N)
§ TLK1501
¶ IS61WV102416BLL-10TLI - SRAM, 16Mb, 10ns, 48TSOP
Analog signals from the single-anode PMTs are not amplified and therefore special care was taken to control noise which can affect the measurements.

4.3.5.1 Noise Suppression

The flash ADC has many configurable parameters. One of them controls 16-bit DAC which allows to add up to ±0.5V offset to the input signal to preserve the full dynamic range with unipolar positive or negative input signals. This parameter directly affects the measurements by altering noise level - pedestal position. Moreover, the DC offset changes randomly after the power cycle of the board. Therefore, it was necessary to find a method that can be used to identify an optimal value of the DC offset that gives the lowest possible noise level. A simple test bench has been made to study the V1731 board (see Figure 4.65).

An example of a waveform recorded by the flash ADC is shown in Figure 4.66(Top). An acquisition window is 60 samples (120 ns). This window is divided into two regions. The first (red) one is used to calculate a pedestal charge (an integral of the distribution within this region). A signal charge is calculated in the next (blue) region. A distribution of the pedestal and signal values in 5000 events is shown in Figure 4.66(Bottom).

In order to study a dependency of these values on the DC offset, a scan (200 runs) over DC offset values was performed with a step of 0.5µV. For each run (5000 triggers) the distributions of signal and pedestal charges were acquired and their mean and standard deviation (sigma) are calculated.
Figure 4.64: Fast ADC block diagram.
4.3. Electronics Layout

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Figure 4.65: Schematic view of V1731 test bench. A pulser generates short square pulses that create light flashes in LED. The LED lights a single-anode PMT enclosed in a metal tube in order to reduce the electromagnetic peak-up noise. A signal from the PMT is readout by the flash ADC. Data from the ADC is transferred to a computer by an optical link. This configuration of the PMT readout is identical to the final EMR DAQ of single-anode PMTs. Therefore, the results acquired in these tests directly applicable to the final configuration.

Examples of the sigma of the signal and pedestal distributions in 200 runs are shown in Figure 4.67. Clearly the DC offset affects significantly the spread of both signal and pedestal values. The four plots in Figure 4.68 show the difference between distributions of signal and pedestal charges in runs with different values of the DC offset. The difference between signal and pedestal values is affected as well (see Figure 4.69).

This dependence is expected and can be explained by the relative position of the input signal baseline with respect to the ADC levels. Schematically this is shown in Figure 4.70.

Evidently, the optimal value of DC offset corresponds to the minimum of pedestal sigma distribution. It is important to notice that this minimum does not conserve if the ADC board undergoes a power cycle. Figure 4.71 shows the standard deviation of the signal and pedestal distributions after a power cycle. Therefore, the same value of the DC offset does not guarantee the same result during long term operation of the ADC board. Moreover temperature variations can affect the DC offset in the same way. But if the DC offset is selected such that the sigma of the pedestal distribution is minimal then the measurements are stable. Table 4.3 shows the mean value of signal minus pedestal before and after a power cycle for the runs with DC offset which correspond to the minimum of a pedestal sigma distribution. The mean value remains stable within statistical uncertainty.

A stability of ADC level was also checked. 170 runs were taken over 2 days with the same value of the DC offset. The corresponding plots of pedestal and signal sigma and mean values are shown in Figure 4.72. No significant change of the mean value was observed during these two days. An average
Figure 4.66: Top: an example of a waveform of the PMT signal recorded by the flash ADC. Bottom: distribution of the charge for signal and pedestal.

Figure 4.67: The standard deviation of the signal and pedestal distributions as a function of the DC offset value.
Figure 4.68: Distribution of signal and pedestal charges in runs with different values of the DC offset. Run IDs correspond to the Figure 4.67.

Figure 4.69: The mean and median of signal minus pedestal charge distributions as a function of the DC offset value.

<table>
<thead>
<tr>
<th>DC offset in minimum of pedestal sigma</th>
<th>Before power cycle</th>
<th>After power cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean value of signal charge</td>
<td>45 / 113</td>
<td>76 / 142</td>
</tr>
<tr>
<td></td>
<td>18.35 / 18.18</td>
<td>18.62 / 17.93</td>
</tr>
</tbody>
</table>

Table 4.3: Mean value of a signal charge distributions before and after power cycle for selected DC offset value that corresponds to the minimum of the distribution of the pedestal sigma.
Figure 4.70: A schematic explanation of DC offset dependence.

Figure 4.71: The standard deviation of signal and pedestal distributions as a function of the DC offset value after a power cycle. Should be compared with Figure 4.67. The positions of minimums are shifted.
value is $20.3 \pm 0.7$. All the fluctuations can be attributed to the ADC internal noise.

This analysis showed the importance of the proper DC offset selection.

4.3.6 Read-Out Scheme

This section describes the overall EMR readout scheme and communication between its three major components: front-end, buffer and VME readout boards.

The DAQ Software resides in a computer equipped with a PCI interface card (CAEN A2818 PCI CONET Controller[10]) allowing communication with the VME bus via VME controller (CAEN V2718 VME-PCI Optical Link Bridge[12]) connected to the PCI card by an optical fiber. The VME crate contains 19 modules:

- VME controller $\times$ 1
• Trigger Receiver module × 1

• VME Readout Boards (VRB) × 8

• VME Configuration Boards (VCB) × 3

• Flash ADC (FADC) × 6

The Trigger Receiver module (CAEN V977 16 Channel Input/Output Register[13]) receives a signal arriving about 100 microseconds after the end of the spill and triggers the readout of all the equipment associated to the crate. The DAQ trigger is different from the Particle Trigger which marks the passage of a particle through the detectors in MICE. According to the MICE specifications, one can expect a maximum of 500 particle triggers per spill. A typical muon crossing a plane generates 2 hits (2 bars crossed) but electrons, pions and stopping muons can generate more.

The Digitization and Buffer Board (DBB) digitizes the data from the front-end board (FEB) and stores it in memory for the entire duration of the spill. The DBBs are configured by a DIP switch to have a BOARD ID that is unique between all DBBs. 6 bits are used to store the BOARD ID. Considering the maximum duration of the MICE spill (10 ms) and the clock rate of the DBB FPGA (400 MHz), the time stamp corresponding to a hit can always be stored in a 22 bits word. The DBB stores both times corresponding to the leading edge and the trailing edge of the signal.

There are 8 VRBs in the VME crate. Each one is connected to a serial chain of 6 DBBs. The connection between the VRB and the first DBB of the chain is done via 4 coaxial cables with SMA connectors on the DBB side and LEMO connectors on the VRB side. One pair of coax cables carries the output command (CMD line) signals and the second pair carries the input data (DATA line) signal. Each pair forms a differential transmission line. The DBBs in the chain are connected to each other by CAT 5 cables equipped with RJ-45 connectors. A DBB in the middle of the chain receives DATA IN signals from the DBBs upstream* and transmits DATA OUT signal to the DBBs downstream (or to the VRB). It also receives CMD IN signals from the DBBs downstream (or from the VRB) and transmits CMD OUT signal to the DBBs upstream.

The FEB essential task is to discriminate the signal from the multi-anode PMTs (MAPMT). The FEB performs this task in a continuous way, regardless of the status of the system. The DBB receives the 64 discriminated outputs from the FEB. It also receives two additional Low Voltage TTL signals: the Spill Gate signal and the Particle Trigger signal.

The DBB works essentially as a TDC†, counting the clock ticks between the beginning of the Spill Gate signal and the arrival of the leading edge of a hit signal from the FEB. Each time a hit signal is detected, the DBB stores this time information in a local memory until the end of the spill. It also records the same way the trailing edge of the hit signals. Hence there are two measurement per each hit - leading and trailing edge time stamps - each measurement is a 32 bit (or 4 bytes) word. The

*Since the DBBs are the data sources, the one connected to the VRB is downstream and the DBB situated the farthest from the VRB is the most upstream.

†Time-to-Digital Converter
DBB firmware is organized such that each channel is treated the same way. The digitized data is first stored in a Level 1 FIFO buffer which is 128 words deep per channel. These buffers are read in a continuous way and the data is transferred to a unique Level 2 FIFO buffer which is 16000 words deep. The transfer time depends on the occupancy and is around 50 ns per DBB hit. The maximum data size per DBB is 64 kB. This should be compared to the rough estimation of the expected data size. Considering that a muon typically hit only 3 channels (2 bars plus the trigger channel) and adding a few more hits due to stopping muons, electrons or pions (hits in two additional bars), it is reasonable to assume that there are 5 channels fired per DBB for every particle crossing a plane. Therefore an estimation of the data size per spill per board can be done:

\[
\text{500 particles per spill} \times 2(\text{words per channel}) \times 4(\text{bytes per word}) \times 5(\text{channels per DBB}) \times \text{particles per spill} = 20 \frac{\text{kB}}{\text{DBB} \times \text{spill}}
\]  

In other words, the Level 2 FIFO buffer is over-sized by a factor of 3 which is believed to be safe enough.

The DBB also counts the number of hits it has recorded (HIT COUNT). This is inserted in the data header (see Figure 4.73). The Particle Trigger signal is treated the same way as ordinary hit signals*, only the format of the input signal is different (LVDS for FEB signals and Low Voltage TTL for the Particle Triggers). The Particle Triggers are counted separately (TRIGGER COUNT). The DBB also counts the total number of clock ticks during the Spill. This number is called the SPILL WIDTH and is used to cross calibrate the DBB clocks off-line.

### 4.3.6.1 DAQ Readout Procedure

At the beginning of each run, the DAQ software will send instructions to the VME Configuration Board (VCB) to check the status and configure all the FEB. At start of run, the DAQ software starts polling the Trigger Receiver board, looking for a DAQ trigger. Upon the arrival of the DAQ Trigger, which happens at the end of every spill, the following readout procedure begins:

1. The DAQ software loops over all the VME readout Boards (VRB) and asks to start the readout of the DBBs attached to it. It is done by performing a single VME write cycle in a register of the VRB which already knows the number of DBBs attached to it and their Board IDs. The list of Board IDs is sent to the VRBs at the beginning of each run.

2. Each VRB sets its TRANSMISSION STATUS FLAG to busy and starts collecting data from its DBBs. The data from the 6 DBBs is stored in the VRB’s memory called the VRB’s EVENT FIFO. The VRB keeps count of the size of the data it has received and writes it in a dedicated register (READOUT DATA SIZE). When all the data is collected, the VRB re-sets its TRANSMISSION STATUS FLAG.

3. While the 8 VRBs are receiving data from the DBB, in parallel, the DAQ software reads out the FADCs sequentially. The FADC readout request is sent just after the request to readout VRBs.

*This reduces the number of effective channels to 63 while only 60 are used (59 bars plus the calibration channel)
4. When the readout of the flash ADCs is completed, the DAQ software starts looping over the VRBs again polling on the VRB’s **TRANSMISSION STATUS FLAG**. As soon as this flag is reset, the DAQ software reads the **TIGGER COUNT** and asserts that it is correct (all the TRIGGER COUNTS should be identical, including those from the FADCs).

5. If the TIGGER COUNT is correct, the DAQ software reads the register containing the **READ-OUT DATA SIZE** and then performs a block transfer* of the VRB’s EVENT FIFO for this data size. When a given number of words is read by the DAQ software in the VRB’s EVENT FIFO, the **READOUT DATA SIZE** is reduced accordingly.

6. When all the data is read out from one VRB, the DAQ software goes to the next VRB until it has read all the VRBs in the chain. The DAQ software then releases its global busy, allowing for the next spill gate to be generated.

### 4.3.6.2 DBB - VBR Data Transfer

Communication between DBB and VRB is realized via TLK1501† chip. The TLK transmits 16 bits words, therefore the 32-bit words from DBB memory are encoded into two 16-bit words and transferred in DATA of CMD lines. The data on the DATA line when transfered through the chain of 6 boards is retransmitted by each DBB but is never decoded in the DBB. The DBB sends CMD data on request from the VRB which knows how many data words to expect in reply. This is not the case for HIT data for which the number of hits is not known in advance. That is why the HIT data is embedded inside a header/trailer structure as shown in Figure 4.73. The header contains four 16-bit words:

1. header type identifier coded in 4 bits followed by 6 bits of a board ID, i.e. the board ID can range from 0 to 63 ($2^6 - 1$) but only 48 are used
2. spill number coded in 16 bits, i.e. up to 65535 spills per run can be counted
3. trigger count coded in 10 bits, i.e. up to 1023 trigger per spill can be recorded
4. hit count coded in 13 bits, i.e. up to 8191 hits per spill can be saved

Other words code the data in the similar way.

One channel ID is reserved for the Particle trigger hits. It is not excluded that data from one channel appears in between the Leading Edge (LE) and the Trailing Edge (TE) of a hit in another channel, therefore the LE and TE measurements may not be next to each other. In case the Trailing Edge arrives after the end of the Spill Gate, it is not recorded by the DBB. Similarly, in the case the Leading Edge arrives before the beginning of the Spill Gate, it is not recorded either.

The definitions of the types used in the DBB data are given in Table 4.5.

The trailer not only indicated the end of the data stream but it also contains information about the DBB status. There are five possible status codes as shown in Table 4.4. If any of these codes

---

*The instruction how to copy certain number of words from memory to memory.
†Multigigabit transceiver for ultrahigh-speed bidirectional point-to-point data transmission.
Figure 4.73: DBB data structure is organized in a set of 16-bit words. It starts with 4 words of a Header, followed by Hit data made of leading edge (LE) and trailing edge (TE) measurements composed of two words each, and finishes with 4 words of a Trailer.
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is received, the data acquisition must be topped. If it happens occasionally (due to busy events or glitches in the system), it is sufficient to re-start the DAQ and launch a new run, but if the errors come regularly, further data acquisition should stop and the cause of the errors has to be investigated.

<table>
<thead>
<tr>
<th>Error</th>
<th>hexadecimal</th>
<th>binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timestamp overflow</td>
<td>0x01</td>
<td>000001</td>
</tr>
<tr>
<td>L1 FIFO overflow</td>
<td>0x02</td>
<td>000010</td>
</tr>
<tr>
<td>L2 FIFO overflow</td>
<td>0x04</td>
<td>000100</td>
</tr>
<tr>
<td>New command received while busy</td>
<td>0x08</td>
<td>001000</td>
</tr>
<tr>
<td>Data received while busy</td>
<td>0x10</td>
<td>010000</td>
</tr>
</tbody>
</table>

Table 4.4: DBB status codes.

4.3.6.3 DBB - VBR Communication

In contrast to the DATA line, every word sent over the CMD line is always decoded by all the DBBs in the chain but only the board with ID that matches to the one specified in the command will respond. Commands (see Figure 4.74,top) are sent from the VRB to the DBB and once received the addressed board answers with appropriate reply to acknowledge the reception of the command. Some commands have arguments (see Figure 4.74,bottom) that are sent together with commands. That is each individual 16-bit word has a well defined structure to allow the DBB to tell if it is a genuine command or an argument of a previous command, possibly addressed to another board. This is done by requiring that each word sent on the CMD line has their 4 most significant bits \(^*\) starting with either the CMD TYPE or the CMD ARGUMENT TYPE bit mask. The CMD TYPE and the CMD ARGUMENT TYPE are completely independent from the types defined for the DATA format and do not overlap.

One special board ID is reserved for commands that can be broadcasted to all the DBBs in the chain (e.g. Failsafe Reset or Set Enable Mask). The general format of the command, with optional argument is given in the previous Tables. The list of the commands to be implemented is given in section

There is no command sent from the DAQ Software to the VRB. The DAQ Software can only request the sending of a command sequence by the VRB by performing a write cycle to the START DBB READOUT register. The sequence of commands is defined in the firmware of the VRB. The

\(^*\)In case of 16-bit word, the four most significant bits are the bits 12 to 15 inclusively.
VRB ignores the requests from the DAQ Software when its TRANSMISSION STATUS FLAG is enabled. Additional commands are defined to trigger the readout of DBB status, firmware version etc.

The DBB readout procedure is performed by the VRB. Due to the TLK, the communication between DBB and VRB is based on 16 bits words. This readout procedure is triggered upon the request from the DAQ software and during all the procedure the VRB’s TRANSMISSION STATUS FLAG is set. The same following procedure is applied to all the DBBs in a chain sequentially:

1. The VRB sends the TRIGGER COUNT Command with the target DBB’s BOARD ID.

2. The DBB replies with two 16-bit words containing the BOARD ID (6 bits) and the TRIGGER COUNT (10 bits). The VRB checks that BOARD ID is correct and, if yes, it stores the TRIGGER COUNT in a dedicated register.

3. The VRB sends the SPILL WIDTH Command with the target DBB’s BOARD ID.

4. The DBB replies with two 16 bits words containing the BOARD ID (6 bits) and the SPILL WIDTH (22 bits). The VRB checks that BOARD ID is correct and, if yes, it stores the SPILL WIDTH in a dedicated register.

5. The VRB sends the SEND DATA Command with the target DBB’s BOARD ID.

6. The DBB replies with data organized as four Header words, a variable number of Hit Data words and four Trailer words (as shown in Figure 4.73). The 4 most significant bits of the 16-bit words (odd words) define the word type (Header, Hit Data or Trailer). The VRB decodes those word type bits, checks that the structure is correct and counts the words until the Trailer is received. The reception of the Trailer signals the end of the transmission for that DBB.

When all the DBBs are read out, the VRB re-sets its TRANSMISSION STATUS FLAG.

A command can generate a reply from the DBB. In case of a reply is sent, the four most significant bits of the first word always contain the type of the reply and are checked by the VRB for validation. The number of words of the reply is fixed and is known by the VRB to check that the expected reply is complete. Below a list of VRB commands is given.

**TRIGGER COUNT command**

This command has no argument:

```
<table>
<thead>
<tr>
<th>15</th>
<th>14</th>
<th>13</th>
<th>12</th>
<th>11</th>
<th>10</th>
<th>9</th>
<th>8</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cmd type: Board ID | TC Cmd
```

The expected reply is made of two words:

```
<table>
<thead>
<tr>
<th>15</th>
<th>14</th>
<th>13</th>
<th>12</th>
<th>11</th>
<th>10</th>
<th>9</th>
<th>8</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TC type: Board ID | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 Trigger Count
```
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**SPILL WIDTH command**

This command has no argument:

```
<table>
<thead>
<tr>
<th>Cmd type</th>
<th>Board ID</th>
<th>SW Cmd</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

The expected reply is made of two words:

```
<table>
<thead>
<tr>
<th>SW type</th>
<th>Board ID</th>
<th>Spill Width [21-16]</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Spill Width [15-0] |
```

**SEND DATA command**

This command has no argument:

```
<table>
<thead>
<tr>
<th>Cmd type</th>
<th>Board ID</th>
<th>Send Data Cmd</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

The expected reply is made of a variable number of words as described already in Section 4.3.6.2.

**FIRMWARE VERSION command**

The DBB sends its firmware version in a single word. This can be useful for testing communication. It is used at the beginning of the run when the DAQ software configures the VRB with the addresses of the DBB it is attached to. This command has no argument:

```
<table>
<thead>
<tr>
<th>Cmd type</th>
<th>Board ID</th>
<th>FWV Cmd</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

The expected reply is made of one single word:

```
<table>
<thead>
<tr>
<th>FWV type</th>
<th>Board ID</th>
<th>FWV</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

The Firmware version is coded so that the 2 most significant bits give the major revision number (X from 0 to 3) and the 4 least significant bits give the minor revision number (Y from 0 to 15). The revision number is X.Y

**BOARD RESET command**

This command has no argument:

```
<table>
<thead>
<tr>
<th>Cmd type</th>
<th>Board ID</th>
<th>Reset Cmd</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

It causes the reset of the board. It is possible to broadcast it to all boards at the same time. No reply is expected*. After sending this command, the VRB should wait a specified amount of time (???) before sending additional commands.

---

*A command accepting broadcast should never generate a reply since that would cause several boards to transmit data at the same time what will jam the communication line.
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**BOARD FS RESET command**

This command is the fail safe reset. It is executed in all cases, whatever is the state of the DBB. This command has no argument:

<table>
<thead>
<tr>
<th>Cmd type</th>
<th>Board ID</th>
<th>FS Reset Cmd</th>
</tr>
</thead>
</table>

It is possible to broadcast it to all boards at the same time. No reply is expected. As for the BOARD RESET after sending this command, the VRB should wait before sending any new commands.

**READ STATUS command**

Each board can report on its current error status. The detailed coding of the status word is given in Table 4.4. Six bits are reserved. The status is reset automatically at the beginning of the spill. This command has no argument:

<table>
<thead>
<tr>
<th>Status type</th>
<th>Board ID</th>
<th>Status</th>
</tr>
</thead>
</table>

The expected reply is made of one single word:

The status codes are shown in Table 4.4.

**SET ENABLE MASK command**

It is possible to allow enable/disable individual channels in the DBB (in case of noise problem). This command has six arguments. It can be broadcasted to all the boards at the same time:

<table>
<thead>
<tr>
<th>Cmd type</th>
<th>Board ID</th>
<th>SEM Cmd</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Cmd Arg type</th>
<th>EM [63-60]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cmd Arg type</td>
<td>Enable Mask [59-48]</td>
</tr>
<tr>
<td>Cmd Arg type</td>
<td>Enable Mask [47-36]</td>
</tr>
<tr>
<td>Cmd Arg type</td>
<td>Enable Mask [35-24]</td>
</tr>
<tr>
<td>Cmd Arg type</td>
<td>Enable Mask [23-12]</td>
</tr>
<tr>
<td>Cmd Arg type</td>
<td>Enable Mask [11-0]</td>
</tr>
</tbody>
</table>

No reply is expected.

**READ ENABLE MASK command**

This command is used to read the enable mask. It has no argument:

<table>
<thead>
<tr>
<th>Cmd type</th>
<th>Board ID</th>
<th>REM Cmd</th>
</tr>
</thead>
</table>
The expected reply is made of five words containing the enable mask:

![Enable Mask Table]

The expected reply is made of five words containing the enable mask:

**DBB data and communication format types**

Table 4.5 summarizes the DBB data and communication format types.

<table>
<thead>
<tr>
<th>Type</th>
<th>hexadecimal</th>
<th>binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE Hit Data</td>
<td>0x2</td>
<td>0010</td>
</tr>
<tr>
<td>LE Hit Data</td>
<td>0x3</td>
<td>0011</td>
</tr>
<tr>
<td>Header</td>
<td>0xD</td>
<td>1101</td>
</tr>
<tr>
<td>Trailer</td>
<td>0xE</td>
<td>1110</td>
</tr>
<tr>
<td>CMD Type</td>
<td>0x5</td>
<td>0101</td>
</tr>
<tr>
<td>CMD Argument Type</td>
<td>0x6</td>
<td>0110</td>
</tr>
<tr>
<td>Trigger Count Type</td>
<td>0x8</td>
<td>1000</td>
</tr>
<tr>
<td>Spill Width Type</td>
<td>0x9</td>
<td>1001</td>
</tr>
<tr>
<td>Firmware Version Type</td>
<td>0xA</td>
<td>1010</td>
</tr>
<tr>
<td>Status Type</td>
<td>0xB</td>
<td>1011</td>
</tr>
<tr>
<td>Enable Mask Type</td>
<td>0xC</td>
<td>1100</td>
</tr>
<tr>
<td>Send Data (SD) Command</td>
<td>0x21</td>
<td>100001</td>
</tr>
<tr>
<td>Trigger Count (TC) Command</td>
<td>0x23</td>
<td>100011</td>
</tr>
<tr>
<td>Spill Width (SW) Command</td>
<td>0x25</td>
<td>100101</td>
</tr>
<tr>
<td>Firmware version (FWV) Command</td>
<td>0x27</td>
<td>100111</td>
</tr>
<tr>
<td>Status Command</td>
<td>0x29</td>
<td>101001</td>
</tr>
<tr>
<td>Set Enable Mask Command</td>
<td>0x2A</td>
<td>101010</td>
</tr>
<tr>
<td>Read Enable Mask Command</td>
<td>0x2B</td>
<td>101011</td>
</tr>
<tr>
<td>Reset Command</td>
<td>0x3C</td>
<td>111100</td>
</tr>
<tr>
<td>Failsafe Reset Command</td>
<td>0x3E</td>
<td>111110</td>
</tr>
</tbody>
</table>

Table 4.5: DBB data and communication format types.

**4.3.6.4 VRB registers**

The VRB registers are implemented in FPGA code and summarized in Table 4.6. The absolute maximum data size can be calculated as follows:

$$6^{DBBs}_{VRB} \times 16^k_{words} \times 4_{bytes}^{word} = 384kB$$  \hspace{1cm} (4.2)
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<table>
<thead>
<tr>
<th>Register name</th>
<th>access</th>
<th>size</th>
</tr>
</thead>
<tbody>
<tr>
<td>READOUT OUTPUT BUFFER</td>
<td>read/write</td>
<td>384 kB</td>
</tr>
<tr>
<td>START DBB READOUT</td>
<td>write only</td>
<td>????</td>
</tr>
<tr>
<td>TRANSMISSION STATUS FLAG</td>
<td>read only</td>
<td>????</td>
</tr>
<tr>
<td>READOUT DATA SIZE</td>
<td>read only</td>
<td>20 bits</td>
</tr>
<tr>
<td>NUMBER OF DBBS</td>
<td>read/write</td>
<td>4 bits used</td>
</tr>
<tr>
<td>Nth DBB ID</td>
<td>read/write</td>
<td>6 bits</td>
</tr>
<tr>
<td>Nth DBB TRIGGER COUNT</td>
<td>read only</td>
<td>10 bits</td>
</tr>
<tr>
<td>Nth DBB SPILL WIDTH</td>
<td>read only</td>
<td>22 bits</td>
</tr>
<tr>
<td>Nth DBB FIRMWARE VERSION</td>
<td>read only</td>
<td>6 bits</td>
</tr>
<tr>
<td>Nth DBB STATUS</td>
<td>read only</td>
<td>6 bits used</td>
</tr>
<tr>
<td>Nth DBB ENABLE MASK MSB</td>
<td>read/write</td>
<td>32 bits</td>
</tr>
<tr>
<td>Nth DBB ENABLE MASK LSB</td>
<td>read/write</td>
<td>32 bits</td>
</tr>
</tbody>
</table>

Table 4.6: VRB FPGA registers. N ranges from 1 to 6. MSB - Most Significant Bit. LSB - Least Significant Bit.

Figure 4.75: VRB data structure.

### 4.3.6.5 VRB - DAQ computer Data Transfer

Communication between the VRB and the DAQ computer is based on 32-bit words. Therefore 16-bit data received from the DBBs is merged into 32-bit as shown in Figure 4.75.

### 4.3.6.6 DBB response time

The time between the moment the VRB sends a command to the DBB (the moment when the VRB’s FPGA released the command) and the moment it starts receiving the corresponding data (in the VRB’s FPGA) is estimated as follows. The CMD line and the DATA line are connected in a very different way reflecting essential features. The CMD line is made of a single source (VRB) with multiple receivers (6 DBBs) while the DATA line is made of several sources (6 DBBs) with a unique receiver (VRB). Therefore the CMD signals can be simply repeated at the entrance of each DBB with one output going to the CMD IN of the DBB and the second output going to the CMD IN of the next DBB upstream* in the chain. On the contrary, the DATA signal coming to a DBB from upstream

*Upstream means farther from the VRB.
has to go through one TLK of the DBB and be re-transmitted by a second TLK to the next DBB downstream (or to the VRB). For technical reasons the connection between the two TLKs is made through the FPGA of the DBB. The following times are involved:

- $T_{\text{long}}$ - transmission time in the long cable connection between the VRB and the first DBB. The communication between the VRB and the DBB is realized by four coaxial cables, a delay in this type of cables is 5 ns per meter.
- $T_x$ - emission latency in the TLK[29]: between 23 ns and 25 ns.
- $T_r$ - reception latency in the TLK[29]: between 51 ns and 71 ns.
- $T_{\text{CMD FPGA}}$ - latency introduced in the CMD line by the DBB’s FPGA: 53 ns (simulation*)
- $T_{\text{short}}$ - transmission time in the short cable connection between two DBBs: 2 ns
- $T_{\text{rep}}$ - latency of the repeater in the CMD line: 1 ns
- $T_{\text{DATA FPGA}}$ - latency introduced in the DATA line by the DBB’s FPGA: 140 ns (simulation)

For the first DBB, the total response time is given by:

$$T_{\text{tot resp}} = 2 \times T_{\text{long}} + T_{\text{CMD FPGA}} + 2 \times (T_x + T_r)$$

For the $N_i$ DBB ($i = 2..5$) the FPGA is present in the processing line which introduces additional delay. Therefore a total response time is:

$$T_{\text{tot resp}} = 2 \times T_{\text{long}} + T_{\text{CMD FPGA}} + 2 \times (T_x + T_r) + (n - 1) \times [(T_x + T_r) + T_{\text{rep}} + T_{\text{DATA FPGA}} + 2 \times T_{\text{short}}]$$

Results of this calculation for all six DBBs are given in Table 4.7

At the time of construction the length of DBB-to-VRB cables was 15 meters. Therefore the maximum delay of a reply from the last DBB in a chain is 1.6 $\mu$s. This time has to be set in the DAQ software as a minimum delay between the a command that is sent to a VRB and command which reads the reply.

### 4.3.7 Trigger and Spill Gate

As it was explained earlier the EMR readout is based on the Spill Gate signal. This signal is generated differently depending on the operation mode of the detector. There are three modes in which the

*Made with QSim of Altera Quartus software package
detector can be operated: beam acquisition, cosmics acquisition and LED calibration. The trigger generation also depends on the operation mode. During the data taking the EMR records all the triggers and hits that arrive within the Spill Gate. No matching is done on-line between the trigger and hit signals, the matching is performed during the event pre-selection (see Section 4.4.2) and reconstruction (see Section 4.4.3) where timing and position of hits is used.

### 4.3.7.1 Beam Acquisition mode

During this mode the Spill Gate signal is provided by the target system which is operated in the proton beam. When the target dips into the beam, after a certain delay of a few milliseconds, the Spill Gate is generated. The width of the Spill Gate can be set manually and usually it is up to 10 ms and period is about 1 second. Triggers are generated within the the Spill Gate by one of the TOF detectors installed in the beam line (usually it is TOF1).

### 4.3.7.2 Cosmics Acquisition mode

During the Cosmics Acquisition mode the detector is operated as standalone, i.e. no signals provided by other systems. The trigger signal is generated by the signal from the EMR planes. Any trigger configuration can be chosen and typically the first and the last planes are used. Signals form the single-anode PMTs are discriminated and fed into coincidence unit which generates the trigger. The Spill Gate is provided by a pulser located in the EMR control rack and it is generated in such a way so that the trigger rate is maximal. Only triggers that are within the Spill Gate are recorded. Therefore to achieve the highest possible rate the Spill Gate should be the largest and the period is the smallest, typically it is 10 ms for both.

### 4.3.7.3 LED Calibration mode

In the LED calibration mode both the Spill Gate and the Triggers are provided by a pulser. The trigger signal is also used to drive the LED pulser which provides light flashes for PMTs. The size and rate of the signals are only limited by the DBB memory size and the DBB/VRB readout rate and can go up to thousand triggers per spill of 10 ms each with period down to 15 ns.

<table>
<thead>
<tr>
<th>$t_{c}^{long}$</th>
<th>0 m</th>
<th>15 m</th>
<th>50 m</th>
<th>100 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBB ID min</td>
<td>max</td>
<td>min</td>
<td>max</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>201</td>
<td>245</td>
<td>701</td>
<td>745</td>
</tr>
<tr>
<td>2</td>
<td>420</td>
<td>486</td>
<td>920</td>
<td>986</td>
</tr>
<tr>
<td>3</td>
<td>639</td>
<td>727</td>
<td>1139</td>
<td>1227</td>
</tr>
<tr>
<td>4</td>
<td>858</td>
<td>968</td>
<td>1358</td>
<td>1468</td>
</tr>
<tr>
<td>5</td>
<td>1077</td>
<td>1209</td>
<td>1577</td>
<td>1709</td>
</tr>
<tr>
<td>6</td>
<td>1296</td>
<td>1450</td>
<td>1796</td>
<td>1950</td>
</tr>
<tr>
<td>1</td>
<td>351</td>
<td>395</td>
<td>1201</td>
<td>1245</td>
</tr>
<tr>
<td>2</td>
<td>570</td>
<td>636</td>
<td>1420</td>
<td>1486</td>
</tr>
<tr>
<td>3</td>
<td>789</td>
<td>877</td>
<td>1639</td>
<td>1727</td>
</tr>
<tr>
<td>4</td>
<td>1008</td>
<td>1118</td>
<td>1858</td>
<td>1968</td>
</tr>
<tr>
<td>5</td>
<td>1227</td>
<td>1359</td>
<td>2077</td>
<td>2209</td>
</tr>
<tr>
<td>6</td>
<td>1446</td>
<td>1600</td>
<td>2296</td>
<td>2450</td>
</tr>
</tbody>
</table>

Table 4.7: DBB response time. First row: length of the cable which connects DBB and VRB. Time is given in nanoseconds.
4.3.8 EMR DAQ

The EMR can work either as a standalone detector or as a part of the MICE cooling channel. The EMR DAQ software allow for both operational modes with no modifications to the codes when switching from one to another. When the detector is operated within MICE, the readout code is enabled inside the MICE DAQ software, while in the standalone operation the rest of the experiment is disabled.

A block diagram in Figure 4.76 shows the main components of the EMR DAQ software and its connection to the EMR hardware.
The hardware connection between different parts of the readout electronics is realized by means of the VME bus which is governed by the VME controller. The controller is responsible for the communication between the boards in the VME crate and the DAQ computer. The communication between the boards in the VME crate is based on the 32-bit asynchronous TTL signaling with a bandwidth up to 80 Mb/s. The DAQ computer is equipped with a PCI interface card which is connected to the VME controller via an optical link. CAEN proprietary communication protocol called CONET is used for data transfer over the link.

The major component of the DAQ software is CAEN VME Dynamic Library (CAENVMELib) which is a set of C++ functions used to access the VME bus through CAEN VME controller. The library is situated between the C++ readout code and the PCI interface card driver. The library allows for the direct access to all available memory locations (registers) on all of the electronic boards. In the readout software these functions are used to initiate communication commands (start/stop readout, enabled/disable equipment, configure the boards, verify status etc.) between the VME boards and the EMR front-end electronics by writing a binary data (according to the readout scheme, see Section 4.3.6) into specific registers and to readout the replies or collected data by accessing registers containing the data. Configuration of the MAROC chip of the front-end board is also realized via the CAENVMELib.

Once the data is retrieved from the hardware it is available in binary format for the subsequent processing. The next step is a conversion of the binary data (based on the readout scheme) into the detector measurement quantities implemented in C++ data classes (see Section 4.4.1). After the conversion the data is saved in a ROOT * tree which is used for the data analysis (see Section 4.4).

*A data analysis framework developed at CERN.
Chapter 4. Electron-Muon Ranger

4.4 Analysis Software

The analysis software written on C++ performs all the required data treatment to produce final physics measurements. It starts with event cleaning and pre-selection (see Section 4.4.2) followed by track reconstruction, calibration and data correction. After the last step the data contains the measurements which can be used to perform a particle identification and characterization. The software is modular and each part performs a specific function (reconstruction, calibration etc.) and can be executed either sequentially or individually. It can also run within MICE software framework* and be used alongside the analysis code of the other detectors.

4.4.1 Data Structure

After conversion from the binary format the data is saved in an organized structure that naturally follows the detector physical organization (see Figure 4.77).

A Data Set contains information about run conditions, trigger condition, the time it was taken and a set of runs. The run conditions summarize beam settings (beam type, magnet currents and corresponding momentum, proton absorber thickness etc.). When the detector is in a standalone operation (cosmics or LED calibration) the run conditions are not effective. The trigger condition also depends on the operation mode and can based on one of the MICE detectors (beam mode), on signals from the EMR planes (cosmics mode) or on a pulser (LED calibration).

The Data Set is made of a set of Runs. The beginning and the end of the run are marked by the start and stop of the DAQ. Each Run consists of an array of Spills and its identifier - Run ID. The number of the Spills is usually set in the Run Conditions. The Spill is a container of an array of Trigger Events plus the Spill identifier. The number of triggers depends on the operation mode. Each Trigger Event is made of 48 EMR Plane hit containers, trigger identifier, total charge (measured by 48 single-anode PMTs) and particle range measurements. The EMR Plane hit container is an arrays EMR Bar containers plus plane ID, charge per plane and plane pulse shape (given by the single-anode PMT connected to a given plane). There are 60 elements inside the EMR Bar container: 59 scintillator bars and one calibration channel. Each EMR Bar contains three arrays of Bar Hits, the bar identifier and a set of measurements (given by the multi-anode PMT) that fully characterize the interaction of the particle with a given bar: time-over-threshold, hit time with respect to (w.r.t.) the start of the Spill, hit time with respect to the Trigger time, 3D coordinate of the hit and a charge measurement per bar.

The three Bar Hit arrays are raw hits, primary and secondary hits. The raw hits arrays is made of all the hits associated to a given trigger, the primary hits are those used for coordinate (track) reconstruction and associated to a primary (hardware) trigger, the secondary hits are not associated to any primary trigger but matching in space to the primary tracks (these are coming from muon-decay electrons). Hits from the primary and secondary collections are used to reconstruct primary

* MICE Analysis User Software (MAUS) is a framework for tracking, detector reconstruction and accelerator physics analysis.
Figure 4.77: EMR data structure.
Figure 4.78: Bar hits data structure.
and secondary tracks. The length of these tracks is called Range.

Figure 4.78 shows how the three bar hit collections are filled. Firstly, the raw data hits are associated to initial triggers and those which are not associated to the triggers are placed in two additional events at the end of the events container. Hits in the first of the two events are coming from electronics noise and hits in the second one are the rest of the hits not associated either to noise or the primary triggers (see Section 4.4.2 for more details). Secondly, the hits from the last event are grouped in time, i.e. if the hits are within 500 ns and separated from others by at least 1 µs, they are placed into subsequent events. At the next step, 3D coordinates of the grouped hits and the hits from the initial triggers are constructed. The set of these hits form the primary hits array. At the last step, the end points of each track reconstructed from the primary grouped hits are matched to the end point of the track from primary initial trigger hits, and if they match, the corresponding hits are placed into the secondary hit collection in the event that corresponds to the matching track.

### 4.4.2 Event Pre-selection

The EMR stores all the particle interactions during the entire spill (up to 10 ms). That is not only hits coming from particles associated to triggers are recorded but all other interactions that may happen between the triggers: decay electrons from muons and pions (muon track from pion decay is not visible), cosmics, noise. Therefore it is important to sort the hits, reject noise and remove unwanted events.

Each hit has a unique time stamp which is used to identify which trigger it comes from. Hits from the same trigger are coming always at the same time interval with respect to the trigger. The time difference between the trigger and corresponding hits depends on which trigger is used since different equipment generates the trigger which gives different delays. For cosmics trigger it is around 225±25 ns and hits come before the trigger, for beam trigger - 575±25 ns (before the trigger), for the LED calibration trigger - 75±25 ns (after the trigger). Electrical signals in the electronics circuits induce electromagnetic noise withing the boards. This noise is linked to triggers and typically comes withing 100 ns after the corresponding hits associated to triggers. All other hits are not linked to any trigger and come randomly within the Spill gate. Among those are the hits from decay electrons. Figure 4.79 shows an example of hits timing association for the case of 4 real (initial triggers). Hits coming from the noise signals are placed in the fifth events, and all the rest (including decays) - in the last event. If a trigger is close to the edge of the Spill gate, the decay may not be recorded (event 4).

### 4.4.3 Hit Coordinates Reconstruction

3D coordinates of hits can be reconstructed if an event (trigger) is composed of a single track. If two or more particles cross the detector at the same time, there is ambiguity of the track position due to the fact that the adjacent planes are orthogonal to each other. The case of multiple simultaneous tracks is not treated here.

Each plane can provide a 2D coordinate of a hit: (X,Z) or (Y,Z). The Z coordinate is given by
Figure 4.79: Raw data event pre-selection. Four triggers are shown
plane ID and X or Y - by bar ID. Typically, there are more than one bar hit in a single plane due to the triangular shape of the bars, but only one bar is used for the track reconstruction - the one with the highest time-over-threshold (TOT) signal. This is very good approximation of an average position of a hit in a given plane. Thus, the following procedure (refer to Figure 4.80 for the reduced example) is applied to calculate missing coordinates (X coordinate for Y planes and Y coordinate for X planes):

- only bars with the highest TOT are saved (primary hits)
- for a given hit in X (Y) plane two neighboring hits in Y planes are used to calculate the extrapolated position for corresponding Z coordinate
- for the plane 1 (X,Z) coordinates are known - (1,1), and Y coordinate needs to be reconstructed
- linear function is calculated between (Y,Z) points of planes 2 and 4
- the function is used to calculate Y coordinate for Z position of plane 1
- for the plane 2 (Y,Z) coordinates are known - (6,2), and Z coordinate needs to be reconstructed
- linear function is calculated between (X,Z) points of planes 1 and 3
- the function is used to calculate X coordinate for Z position of plane 2
- the procedure continues for all intermediate points
- for the plane 6 (Y,Z) coordinates are known - (1,6), and Z coordinate needs to be reconstructed
• linear function is calculated between (X,Z) points of planes 3 and 5

• the function is used to calculate X coordinate for Z position of plane 6

After this procedure is applied all the primary hits have 3D coordinates. By definition the primary hits belong to a single track, therefore the coordinates are used to calculate the particle range by simply summing the distances between adjacent primary hits along the particle track.

### 4.4.4 Calibration

If the same energy is deposited in two different scintillator bars, the resulting signal measured by PMTs will be different and the difference will change from one bar to another. This difference has to be corrected so that the signal measured by the PMTs is the same for interactions leaving the same energy in the scintillators. There are many factors that contribute to the distortion of a signal on its way from the interaction point to the memory buffer of the electronics board. Schematically they are shown in Figure 4.81.

There are nine major factors that affect a signal (i - channel ID, it ranges from 1 to 2832; j - single- or multi-anode PMT):

1. \( \delta_{ij}^{scint} \) - non-uniformity of scintillator response due to fluctuations of the amount of scintillator components during production (extrusion) process, the scintillator light yield may differ between different production batches

2. \( \delta_{ij}^{glue} \) - non-uniformity of glue transparency due to altered amount of hardener added to epoxy before gluing

3. \( \delta_{ij}^{WLS} \) - non-uniformity of WLS fiber response appeared during manufacturing (different thickness of cladding, altered amount of dopants, etc.)

4. \( \alpha_{ij}^{WLS}(x/y,z) \) - WLS fiber attenuation, it depends on the hit position in (X,Z) or (Y,Z) planes

5. \( \beta_{ij}^{Bcon} \) - light loss in the bar connector due to misalignment of the WLS fiber and clear fiber, imperfections of polishing, reflections on the fiber faces, etc.

6. \( \alpha_{ij}^{clear} \) - attenuation in the clear fiber, it depends on channel ID since each channel has individual length of the clear fiber

7. \( \beta_{ij}^{Fcon} \) - light loss in the fiber connector due to misalignment of the clear fiber and PMT focusing electrode mask, imperfections of polishing, reflections on the fiber and PMT faces, etc.

8. \( \delta_{ij}^{PMT} \) - non-uniformity of PMT photo-cathode and internal accelerating dynode structure

9. \( \gamma_{ij}^{ADC} \) - non-uniformity of the conversion of the analog signal to the digital representation
Figure 4.81: EMR calibration parameters. 1 - non-uniformity of scintillator response, 2 - non-uniformity of glue transparency, 3 - non-uniformity of WLS fiber response, 4 - WLS fiber attenuation, 5 - light loss in bar connector, 6 - attenuation in clear fiber, 7 - light loss in fiber connector, 8 - non-uniformity of PMT photo-cathode and internal accelerating dynode structure, 9 - conversion of the analog signal to digital representation.
Each signal recorded by a PMT is characterized by its charge. Therefore, a measured charge can be related to a true charge as follows:

\[
Q_{\text{meas}}^{ij} = \delta_{\text{scint}}^{ij} \times \delta_{\text{glue}}^{ij} \times \delta_{WLS}^{ij}(x/y, z) \times \beta_{\text{con}}^{ij} \times \\
\alpha_{\text{clear}}^{ij} \times \beta_{\text{con}}^{ij} \times \delta_{\text{PMT}}^{ij} \times \gamma_{\text{ADC}}^{ij} \times Q_{\text{true}}^{ij} \tag{4.5}
\]

Removing the term that depends on a hit position (attenuation in WLS fiber) and replacing all the other terms by single calibration factor, we have:

\[
Q_{\text{meas}}^{ij} = \alpha_{WLS}^{ij}(x/y, z) \times \epsilon_{\text{calib}}^{ij} \times Q_{\text{true}}^{ij} \tag{4.6}
\]

After the first step of the reconstruction all the primary hits have coordinates, therefore it is possible to calculate the following value:

\[
q_{\text{meas}}^{ij} \equiv \frac{Q_{\text{meas}}^{ij}}{\alpha_{WLS}^{ij}(x/y, z)} = \epsilon_{\text{calib}}^{ij} \times Q_{\text{true}}^{ij} \tag{4.7}
\]

where \( Q_{\text{meas}}^{ij} \) is a charge measured by either single- \((j = 1)\) or multi- \((j = 2)\) anode PMT in channel \(i\). If the energy deposition of a particle in a given bar is the same, the value \( q_{\text{meas}}^{ij} \) will have a certain distribution due to statistical nature of processing involved in the signal generation and propagation along the acquisition channel. A mean (or median) value \(<q_{\text{meas}}^{ij}>\) of this distribution for a given channel can be used to estimate a corresponding calibration factor \( \epsilon_{\text{calib}}^{ij} \) for that channel. There are 2832 channels in the EMR and a mean value \(<<q_{\text{meas}}^{ij}>>\) of the distribution of \(<q_{\text{meas}}^{ij}>>\) for all the channels should be related to a true charge corresponding to initial energy deposition, i.e. :

\[
q_{\text{meas}}^{ij} \sim <q_{\text{meas}}^{ij}> \tag{4.8}
\]

and

\[
Q_{\text{true}}^{ij} \sim <<q_{\text{meas}}^{ij}>> \tag{4.9}
\]

Therefore, the calibration factor for each channel can be estimated as follows:

\[
\epsilon_{\text{calib}}^{ij} = \frac{<q_{\text{meas}}^{ij}>}{<<q_{\text{meas}}^{ij}>>} \tag{4.10}
\]

Cosmics can be used to perform the calibration of the channels since muons from the cosmics deposit on average the same energy (around 3.5 MeV) each time they cross a scintillator bar. In case of the single-anode PMT, \( Q_{\text{meas}}^{i1} \) is directly give by the flash ADC, while for the multi-anode PMT the time-over-threshold (TOT) measurement has to be converted into charge using empirical function found during cross-talk studies (see Figure 4.51). But in order to calibrate each channel on both single- and multi-anode PMTs only one bar must be hit in a given plane. If more than one bar is hit, it is not possible to calibrate individual channels (fibers) of the single-anode PMTs, since the signals
are summed. Typically in a single muon track crossing all 48 planes around 5 planes have only one bar hit by the track and signals from these bars are used to estimate the calibration factors for all the channels. To calibrate all the channels with sufficient statistics, more than half a million cosmic tracks covering the detector homogeneously is required.

Once the calibration is completed, the data is corrected according to the calibration factors: two for each channel (one for multi-anode PMT and another one for the single-anode PMT). For the multi-anode PMT \( j = 2 \) it is a simple conversion of a measured charge for each channel \( i \):

\[
Q_{\text{true}}^i = \frac{Q_{\text{meas}}^i}{\varepsilon_{\text{calib}}^i \times \alpha_{WLS}^i(x/y, z)}
\]

(4.11)

In case of the single-anode PMT \( j = 1 \), signals from different bars are summed together at the photocathode of the PMT. But it is still possible to apply the calibration factors by using measurements from multi-anode PMT. The following procedure is applied. The total charge measured by the single-anode PMT can be expressed as:

\[
Q_{\text{meas}}^1 = \sum_i Q_{\text{meas}}^{i1} = \sum_i [\alpha_{WLS}^{i1}(x/y, z) \times \varepsilon_{\text{calib}}^{i1} \times Q_{\text{true}}^{i1}]
\]

(4.12)

Since the signal for both single- and multi-anode PMT is generated by the same source (scintillation) the following relation should be valid:

\[
\frac{Q_{\text{true}}^1}{\sum_i Q_{\text{true}}^i} = \frac{Q_{\text{true}}^2}{\sum_i Q_{\text{true}}^i} \equiv \psi^i
\]

(4.13)

The total true charge measured by the single-anode PMT can be denoted as \( Q_{\text{true}}^1 \) and therefore:

\[
Q_{\text{true}}^i = Q_{\text{true}}^1 \times \psi^i
\]

(4.14)

Hence, if \( \psi^i \) is calculated based on the multi-anode PMT measurements, from the equation 4.12 we can derive an expression for the corrected charge measured by the single-anode PMT:

\[
Q_{\text{true}}^1 = \sum_i [\psi^i \times \alpha_{WLS}^{i1}(x/y, z) \times \varepsilon_{\text{calib}}^{i1}]
\]

(4.15)

Application of the calibration factors and calculation of the true charges make a separate step in data processing called Data Correction (as shown in the Section 4.4.5).

### 4.4.5 Data Flow

There are four types of data sources:

- Monte Carlo simulation based on Geant4*

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* A toolkit for the simulation of the passage of particles through matter.
• cosmics
• particle beam from the accelerator
• LED calibration signals

The first data source is purely virtual while the other three involve real hardware. Seven steps can be distinguished in the data flow regardless of which source is used (see Figure 4.82):

1\textsuperscript{st} Step: Physics Event Generation

- **Geant4** simulates particle interaction with matter and generates energy depositions according to a particle type and physics process involved. All low energy electromagnetic processes were enabled in order to reproduce real interactions as close as possible. Muons, electrons and pions were generated with momentum in the range from 100 to 400 MeV/c. Muons with momentum up to 290 MeV/c and pions with momentum up to 320 MeV/c stop in the EMR and decay.

- **Cosmics** provide a stable source of muons with mean energy around 4 GeV. Most cosmics muons cross the detector leaving straight tracks. This is an ideal source for channel calibration.

- **Beam** particles are typically electrons, muons and pions with momentum from 100 to 400 MeV/c.
4.4. Analysis Software

The **LED** driver box generates the same amount of photons as a scintillator crossed by a cosmic muon. A voltage on LED can be changed to allow for higher or lower signals.

2nd Step: Detector Response

- **Geant4** provides energy deposition for every particle interaction. Typically there up to 5 interactions per bar. During that hits generated by the Geant4 are converted into detector hits; step energy from all the hits in one bar (within 10 ns) is summed and assigned to one bar hit and hits from all the bars - to a plane hit. Therefore, this step is called ”Conversion”.

- **Cosmics** muons, **Beam** particles and **LED** signals are processed by the detector DAQ which provides raw binary data as an output.

3rd Step: Raw Data Processing

- **Geant4** generates energy depositions. This energy is converted into the detector related quantity, ADC counts. This step is called ”Digitization” and explained in Section 4.5.5. Some information acquired during calibration of the cosmics data is used during this step.

- The binary data from **Cosmics**, **Beam** or **LED** signals is converted into measured quantities - charge, time, bar or plane identifiers. After that step the data format is the same regardless of the initial source.

4th Step: Reconstruction

- During that step coordinates of all primary hits are reconstructed. It is done with data from **Geant4**, **Cosmics**, **Beam**.

- For data from **LED** signals this step is irrelevant since there are no tracks.

5th Step: Calibration

- **Cosmics** data is used to calibrate the detector, i.e. to find calibration constants $\varepsilon_{ij}^{calib}$ (see Section 4.4.4). Cosmics can be simulated with **Geant4** and corresponding data can be used to calibrate the virtual detector in the same way as the real one. The latter is used to test the calibration procedure.

- **Beam** or **LED** signal can not be used for calibration.

6th Step: Data Correction

- The **Geant4** calibration constants derived in the previous step are applied only to **Geant4** data.

- The calibration constants derived from **Cosmics** are applied both th Cosmics and **Beam** data.

- **LED** signal are not corrected.
7th Step: Analysis

- After the Geant4, Cosmics, Beam data is corrected with the calibration constants, it can be used for physics analysis.

- LED data is used for performance studies, PMT gain calibration, PMT alignment, etc.
4.5 Simulation

The full volume of the detector was simulated with the help of Geant4 toolkit. Geometrical details of all volumes which affect the passage of particle through the detector were implemented: scintillator bars, wavelength shifting fibers (core and claddings) and glue. Energy deposited in the sensitive (scintillator) is used to simulate the detector response, energy loss other materials (fibers, glue and air) are not tracked.

Figure 4.83: EMR Geant4 geometry: 48 planes of 59 triangular scintillator bars each with glued wavelength shifting fiber.

Figure 4.83 shows the overall geometry implemented in Geant4. An elementary volume (triangular bar with glued fiber) is replicated 2832 time to form 48 planes of 59 bars each with alternating orthogonal orientation.

All known low energy physics interactions were included in the simulation as well as processes for intermediate and high energies while the latter were practically not effective but were added for completeness. QGSP_BIC_HP_EMY physics list was used (see Appendix A for details).

A simple particle gun∗ was used as a particle source. Three types (electrons, muons and pions) of both signs were simulated with momentum from 100 to 400 MeV/c what matches to particles produced in the MICE beam-line. Also muons with 4 GeV momentum were simulated to be compared

∗One particle of a specific type per event with a predefined energy and direction
Figure 4.84: Typical event display. 200 MeV/c negative muon stops in plane 21. After 2.2 microseconds (muon lifetime) it decays into an electron (green track) and electron anti-neutrino (cyan track) and muon-neutrino (magenta track). Red points are hits. Plane, bar ID and orientations are also shown.

with cosmics. Typical event display of a stopping muon with momentum of 200 MeV/c is shown in Figure 4.84.

### 4.5.1 Event Topologies

Figure 4.85 show interactions of 200 MeV/c protons in the detector. Typically all the protons are stopped by a proton absorber installed in the beam-line but if they reach the EMR they will stop within a few millimeters of the scintillator.

Figure 4.85: Interaction of 200 MeV/c protons in the EMR. **Center:** Z-Y view. **Right:** X-Y view. **Left:** zoom of Z-Y view.

Interactions of negative (see Figure 4.86) and positive (see Figure 4.87) electrons, muons and pions exhibit different topologies which are used to identify a particle type and measure their characteristics.

Difference between positive and negative electrons and muons is marginal. Only a few negative
4.5. Simulation

Figure 4.86: Interactions of 200 MeV/c negative particles in the EMR. Beam particles come from the left in Y-Z projections or toward a viewer in X-Y projections. 1\textsuperscript{st} column: single event display, Y-Z projection. 2\textsuperscript{nd} column: 10 events, Y-Z projection. 3\textsuperscript{rd} column: 10 events, X-Y projection. 1\textsuperscript{st} row: electrons. 2\textsuperscript{nd} row: muons. 3\textsuperscript{rd} row: pions.
Figure 4.87: Interactions of 200 MeV/c positive particles in the EMR. Beam particles come from the left in Y-Z projections or toward a viewer in X-Y projections. 1\textsuperscript{st} column: single event display, Y-Z projection. 2\textsuperscript{nd} column: 10 events, Y-Z projection. 3\textsuperscript{rd} column: 10 events, X-Y projection. 1\textsuperscript{st} row: electrons. 2\textsuperscript{nd} row: muons. 3\textsuperscript{rd} row: pions.
muons are captured by a nucleus. Most of muons are stopping in the detector and then decay. Positive pions behave like muons but stop earlier due to hadronic interactions. While negative pions undergo nuclear captures in almost all of the cases. This is clearly seen in the Figure 4.88. Interactions of positive pions and positive and negative muons are accompanied by neutrinos coming from pion/muons decays. And interactions of negative pions are characterized by a presence of neutrons which is a sign of a nuclear capture.

Figure 4.88: Charge difference of pion/muon interactions of 200 MeV/c muons and pions. 10 events in each Y-Z projections are shown. 1st column: muons. 2nd column: pions. 1st row: positive particles. 2nd row: negative particles.
4.5.2 Energy Loss in Planes

Figure 4.89 shows an average energy deposited in every plane for electrons, muons and pions at six different momenta (100, 150, 200, 250, 300 and 350 MeV/c). The plots represent Bragg curves of corresponding particles in the plastic scintillator. Moreover, the Bragg peaks are clearly visible for muons and pions which indicate the place where they stop. Energy deposition in the peak is approximately five times larger than along a track before a stopping point. The Bragg curves for momenta from 100 to 400 MeV/c in steps of 10 MeV/c are shown in Appendix B.1.

![Figure 4.89: Simulation: average energy loss per plane for $e^\pm$, $\mu^\pm$, $\pi^-$. Dashed lines correspond to negative particles and solid lines to positive.](image)

Muons, both negative and positive, stop mainly due to electromagnetic interactions (multiple
scattering and ionization) while pions exhibit different behavior depending on a sign. As it was mentioned earlier negative pions are captured by a nucleus and do not decay into muons. This is visible in the tail of the distributions where electrons from decays contribute mostly for positive pions which stop and decay similarly to muons. Electrons and positions do not exhibit a Bragg peak since they create electromagnetic showers.

The position of the Bragg peak for muons and pions as a function of the particle incident momentum is shown in Figure 4.90. According to that plot muons with momenta above 300 MeV/c and pions with momenta above 350 MeV/c cross the detector.

![Figure 4.90: Bragg peak position for muons (green), pions (blue) and maximum energy loss for electrons (red). Dashed lines correspond to negative particles and solid lines to positive.](image)

Distributions of energy loss in the first plane for electrons, muons and pions at lowest and highest momenta are shown in Figure 4.91. The second peak in the distributions for muons and positive pions is due to decay electrons. Distributions for momenta from 100 to 400 MeV/c in steps of 10 MeV/c

![Figure 4.91: Energy loss distributions in the first plane for electrons (red), muons (green) and pions (blue) at 100 MeV/c (left) and 400 MeV/c (right). Dashed lines correspond to negative particles and solid lines to positive.](image)
are shown in Appendix B.2.

Due to a statistical nature of physics interactions energy loss has relatively wide distributions. RMS$^*$ of the Bragg curves are shown in Figure 4.92 for seven different momenta and all particle types. As expected at higher momenta distributions become wider.

![Bragg curves for electrons, muons, and pions.](image)

**Figure 4.92:** RMS of Bragg curves for electrons (**first row**), muons (**second row**) and pions (**third row**). **First column:** negative particles. **Second column:** positive particles. Bragg curves are calculated for particles at 100 MeV/c (violet), 150 MeV/c (cyan), 200 MeV/c (black), 250 MeV/c (orange), 300 MeV/c (green), 350 MeV/c (blue), 400 MeV/c (red).

$^*$Root-Mean-Square
4.5.3 Shower Shapes

Event topologies are clearly visualized when Bragg curves are shown in a form of 2D histograms (shower shapes) as in Figure 4.93 (in log scale) or Figure 4.94 (in normal scale).

Figure 4.93: Shower shapes (in log scale) of 250 MeV/c electrons (first row), muons (second row), pions (third row). **First column:** negative particles. **Second column:** positive particles.
Electrons and positions as well as positive and negative muons exhibit similar behavior. But pion shower shapes differ due to the nuclear capture. The Bragg peak is more pronounced and sharper in case of negative pions but becomes less and less visible at higher momenta (see Appendix B.3). Many secondary interactions are visible around pions while muon tracks are much cleaner.

![Shower shapes](image.png)

Figure 4.94: Shower shapes (in normal scale) of 250 MeV/c electrons (first row), muons (second row), pions (third row). First column: negative particles. Second column: positive particles.
4.5.4 Total Energy Loss

Most of the volume of the detector is active except for the glue and wavelength shifting fibers. Therefore the total energy deposited in the detector can be evaluated by summing all the signal from single and multi anode PMTs. Figure 4.95 shows the total energy deposited in active volume of the detector for six different momenta.

Figure 4.95: Total energy loss in the detector for $e$(red), $\mu$(blue), $\pi$(green). Dashed lines correspond to negative particles and solid lines to positive.

Both the range and the total energy loss measurements allow for good particle identification and momentum estimation (see 4.6).
4.5.5 Digitization

A purpose of the Monte Carlo digitization is to convert simulated energy depositions into real-like signals as the once produced by single- and multi-anode PMTs. The EMR DAQ produces several measurements:

- **single-anode PMT**
  - plane ID of a hit
  - charge of a signal in a plane
  - trigger count

- **multi-anode PMT**
  - bar ID of a hit
  - time-over-threshold of a signal in a bar
  - time of a hit with respect to the beginning of a spill gate
  - trigger time

All the above measurements are calculated from the energy deposition, bar ID and the time of a hit generated by Geant4. The energy is converted and sampled several times according to the geometry of the detector and according to propagation media. Conversion takes place at each step where a signal undergoes a transformation. These places are schematically shown in Figure 4.81 and can be summarized as follows:

1. convert a deposited energy given by Geant4 into the number of scintillation photons (nsp) according to Birks’ law:
   \[ N_\gamma = \frac{\alpha \cdot \Delta E}{1 + \frac{k_B}{\lambda} \cdot \Delta E} \quad (4.16) \]
   where \( \alpha = 2000 \text{ photos/MeV} \), \( k_B = 0.126 \text{ mm/MeV} \) (Birks’ constant), \( \lambda = 17 \text{ mm} \)
   (average path length)

2. sample nsp according to Poisson distribution

3. covert nsp to the number of trapped photons (ntph): trapping efficiency 4%

4. sample ntph according to Poisson distributions

Half of the photons go to the multi-anode PMT which signal simulated according to the following procedure:

5. reduce ntph according to the length of wavelength shifting fiber (naph): 2.0 dB/m

6. reduce ntph according to the length of clear fiber (naph): 0.35 dB/m
7. apply channel attenuation map: **light loss in connectors is up to 30%**

8. sample naph according to Poisson distribution

9. convert naph to the number of photoelectrons (npe): **PMT quantum efficiency - 25%**

10. sample npe according to Poisson distribution

11. correct npe for photocathode non-uniformity: **up to 40%**

12. convert npe to the number of ADC counts (nADC): **6 ADC/pe**

13. simulate electronics response: **Gaussian smearing of nADC with width of 10 ADC**

14. convert nADC to TOT:

   $$\text{TOT} = a + b \cdot \ln \left( \frac{n\text{ADC}}{c + d} \right)$$

   where $a = -60.5$, $b = 15$, $c = 70$, $d = 2$

15. convert hit time to ADC counts (T): **2.5ns/ADC**

16. delay T according to fiber length: **10 ns/m**

The other half of trapped photons is directed towards single-anode PMT and signal is simulated as follows:

5. reduce ntph according to the length of wavelength shifting fiber (naph): **2.0 dB/m**

6. reduce ntph according to the length of clear fiber (naph): **0.35 dB/m**

7. apply channel attenuation map: **light loss in connectors is up to 30%**

8. sample naph according to Poisson distribution

9. convert naph to the number of photoelectrons (npe): **PMT quantum efficiency - 11%**

10. sample npe according to Poisson distribution

11. correct npe for photocathode non-uniformity: **up to 40%**

12. convert npe to the number of ADC counts (nADC): **2 ADC/pe**

13. simulate electronics response: **Gaussian smearing of nADC with width of 1 ADC**

14. set signal baseline (8bit ADC): **130 ADC**

15. simulate noise level - number of fluctuations within acquisition window: **from 0 to 200**

16. set noise position: **upwards or downwards fluctuations**

17. simulate negative voltage pulse with random noise
After all the above conversions the data from simulation has exactly the same format and dimension (ADC counts) as the data coming from the real detector. To make the simulation as realistic as possible, the virtual geometry should correspond to the real one, namely position fibers, bars, planes, PMTs and the orientation with respect to a beam should be as in the real experiment. The implemented virtual geometry is shown in Figure 4.96.

![Figure 4.96: EMR virtual geometry: EMR fibers, bars, planes, PMTs mapping.](image)

Validation of the digitization is done with cosmics and explained in Section 4.6.3.
4.6 Detector Performance with Cosmic Rays

Cosmic rays present an ideal source of particles that can be used to characterize, debug and tune the detector. Cosmic rays are composed of particles of different type but mostly muons reach the detector. To trigger the cosmic muons single-anode PMT signal from the first and the last planes were used. The two signal were taken out from the readout and directed to a coincidence unit which generated the trigger.

A typical cosmic muon is shown in Figure 4.97. Cosmic muons have momentum around 4 GeV and leave approximately the same energy in all the planes but due to difference in gain and sensitivity between different PMTs the measured charge varies quite significantly as it can be seen on two right most plots in the Figure 4.97. Similar behavior is seen for time-over-threshold measurements. After calibration the measurements should be more homogeneous. But already before calibration it can be seen that a typical time-over-threshold value for cosmic muon signal is around 10 ADC counts, time difference between bar hit and a trigger is around \( -80^* \) ADC counts\(^\dagger\) and plane charge is around 15 ADC counts.

![Figure 4.97: Raw cosmic muon event display. First row: X planes. Second row: Y planes. 1\(^{st}\) column: number of hits. 2\(^{nd}\) column: time-over-threshold measurements. 3\(^{rd}\) column: hit time minus trigger time. 4\(^{th}\) column: plane charge measurements. X axis: plane ID. Y axis: bar ID.](image)

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\(*\) The trigger comes later due to the trigger selection logic.

\(\dagger\) The time of bar hits is measured by buffer boards which has resolution of 2.5 ns per ADC count.
4.6.1 Multi-Anode PMT Readout

The multi-anode PMT readout provides information about hits in bars in particular time-over-threshold measurement, hit time and trigger time.

4.6.1.1 Electronics Noise

Usually a muon hits two bars in a plane and as all other hits come either from cross-talk or noise (see hits in plane 8, bars 1 to 10 in Figure 4.97). Hits from a muons should have approximately the same time with respect to a trigger and it is around 80 ns before a trigger. Figure 4.98 show a distribution of time difference between bar hits and triggers in all bars and planes (see Appendix C.1 for individual planes). A peak around -80 corresponds to hits from cosmics, other peaks correspond to electronics noise induced by initial signal in a PMT.

![Figure 4.98: Bar hit time minus trigger time. All bars and planes.](image)

![Figure 4.99: Hit-trigger time difference in bars. All planes. Left: logarithmic scale. Right: normal scale.](image)

The noise hits are not only grouped in time but also they appear in certain channels (see Figure 4.99) and typically they have time-over-threshold value around 4 ADC counts (see Figure 4.100). See Appendix C.2 and C.3 for these distributions in individual planes.
To clean the events from the noise hits a cut on time difference between bar hit and trigger is applied. According to Figure 4.98 hits that come between 80 and 100 ADC units before a trigger are coming from real cosmics signals while hits between 80 and 35 before a trigger are associated to electronics noise.

During construction phase all channels (2832) have been optically tested and none of them was broken. After cosmic tests five dead channels were discovered (plane 14, channels 2,3,4,9,10; see Appendix C.2 and C.3). Hence the dead channel appeared somewhere in the electronics circuits during assembly or transportation.

4.6.1.2 MIP Signal

Average momentum of muons from cosmic rays is approximatively 4 GeV. Muons at this energy deposit minimum possible energy via ionization and, therefore, called minimum ionizing particles (MIP).

As explained in the previous section, in order to remove noise signals a cut on time difference between bar hit and a trigger should be made. Once applied only hits coming from real MIP interaction are left. Figure 4.101 shows time difference between bar hits and a trigger for all planes (left) and, as an example, for third plane. A specific pattern of this dependency (shown by a black line) can be explained by the fact that light from different bars transmitted to PMTs via clear fibers with different lengths, the shorter the fiber the closer hit signal to a trigger. The last five fibers are looped and their length is about 0.7 m. Bar 27 is matching to a channel on FEB which has shorter electrical path then other channel hence the shorter hit time. Distributions of hit-trigger time difference in plane 3, 21 and all planes are shown in Figure 4.102. Position of hits along bars also contributes to the spread of these distributions.

Time-over-threshold after noise cleaning is shown in Figure 4.103(in bars) and in Figure 4.104(as a function of hit-trigger time difference). In the latter figure it can be noticed that lower amplitude (5 ADC) signals come 10 ns earlier on average than more energetic ones (15 ADC). A distinctive spike at 15 ADC counts in the time-over-threshold distribution is explained in Section 4.6.3.

Detector occupancy in cosmic events is shown in Figure 4.105.
Figure 4.101: Hit-trigger time difference in bars after noise is removed. **Left:** all planes. **Right:** plane 3, length of clear fibers is shown.

Figure 4.102: Distribution of Hit-trigger time difference for all channels in plane 3, 21 and all planes.

Figure 4.103: Time-over-threshold (TOT) in bars after noise is removed. **Left:** distribution of TOT in all planes VS bar ID. **Right:** distribution of TOT in all bars and planes.
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Figure 4.104: Time-over-threshold (TOT) in all planes and bars as a function of hit-trigger time difference after noise is removed. **Left:** 2D distribution of TOT VS hit-trigger time (log scale). **Right:** 3D distribution of TOT VS hit-trigger time (normal scale).

Figure 4.105: Detector occupancy (number of hits in bars) in cosmic events. **Left:** X planes. **Right:** Y planes.
4.6.2 Single-Anode PMT Readout

The single-anode PMTs measure total charge in planes. The readout boards store waveforms of signals associated to triggers within a certain acquisition window. These waveforms (see Figure 4.106) are then integrated in a signal window off-line taking into account baseline positions and this integral represents the total plane charge. An integral of the waveform in the pedestal window gives the pedestal charge.

Figure 4.106: Single-anode PMT signal waveforms. Signal and pedestal interaction windows are shown. Integrals of the waveforms in these windows minus baseline give corresponding plane charges.

4.6.2.1 Electronics Noise

Eight flash ADCs read out 48 single-anode PMT. The flash ADC has 8 bit precision and 1 V dynamic range, therefore one ADC count represents a change of voltage by 3.9 mV. Input voltage pulse as a response to a MIP signal is typically 20 to 100 mV of negative polarity. A baseline of a signal is slightly different for each channel and can vary withing a few ADC counts as seen in Figure 4.106. The baseline position can be set by a parameter on the flash ADC and, at the same time, this parameter* significantly affect noise and must be calibrated after every power cycle or once in a few days (see Section 4.3.5.1). Figure 4.107 shows pedestal charges for noisy and clean signals. The pedestal charges for all 48 single-anode PMTs are summarized in

4.6.2.2 MIP Signal Plane Charge

An integral of the waveform in the second window shown in Figure 4.106 gives a charge of a single-anode PMT signal. Distributions of the charge in planes 3, 21 and 44 are shown in Figure 4.108. The single-anode PMTs are known to have wide variations of the gain and quantum efficiency due to which the charge measurements are different (distributions for all PMTs are shown in Appendix C.5).

*It is called DC_OFFSET and it control position of 1 V dynamic range in the window from +1 to −1 V
Figure 4.107: Single-anode PMT noise and pedestal charge.

Figure 4.108: Signal charge of signal-anode PMTs in plane 20, 21 and all planes.
Figure 4.109: Plane hit-trigger time difference in plane 20, 21 and in all planes.

Figure 4.109 contains distributions of plane hit time within ADC acquisition window and, similar to the time of bar hits, the distributions are characterized by wide spread due to different cable and fiber lengths and hit positions along bars.

### 4.6.3 Validation of the Monte Carlo Digitization

![Diagram](image)

**Figure 4.110: Comparison of Monte Carlo simulation and real cosmics data.**

The simplest way to validate Monte Carlo digitization is to compare data collected with cosmics and simulated 4 GeV muons since most of the particles in cosmic ray at sea level are muons with mean energy around 4 GeV. The digitization procedure described in Section 4.5.5 was applied to the simulated data and a comparison is shown in Figure 4.110. Simulated energy deposition in bar is
converted into time-over-threshold measurement and energy deposition in a plane - into plane charge. Some discrepancies between real data and Monte Carlo can be mostly due to two facts. Firstly, most of the digitization parameters were taken from data-sheets and most likely they are slightly different from real values. Secondly, only muons with mean momenta of the cosmics spectrum were simulated and not the full spectrum. But even with these assumptions an agreement between the simulation and the real cosmics data is more than acceptable.

Not only the energy is digitized but also a pulse shape and noise of single-anode PMT signals are simulated. Figure 4.111 shows examples of waveforms of signal-anode PMT signal from simulation (left) and cosmics (right).

![Monte Carlo Simulation](image1) ![Cosmic Data](image2)

Figure 4.111: Single-anode PMT signal pulse shape and noise from simulation (left) and cosmics (right).

After the digitized Monte Carlo data looks like real data, it has exactly the same format and dimensions (ADC counts, plane and bar ID). For the subsequent steps (calibration, reconstruction, data correction analysis) there is no difference whether the data comes from the simulation and the real detector.

To make the digitization as precise as possible calibration constants derived from cosmics data are used to alter simulated PMT signals by correcting number of photoelectrons what simulates a photocathode non-uniformity (see step 11 in Section 4.5.5). Figure 4.112 shows event displays of a muon from cosmics and simulation before and after digitization.
Figure 4.112: Event display (X planes only) of a cosmosics muon in data and simulation.
4.6.4 PMT Calibration

According to the calibration procedure described in Section 4.4.4, in order to get calibration constants one has to know median (or mean) of charge distributions for every channel. These distributions were derived from cosmics data and shown in Figure 4.113. Only clean and straight cosmic tracks are selected for calibration. And among all the hits along a track, only hits appearing in one bar in a plane are used for charge distributions. Number of selected hits in all the bars are shown in Figure 4.114.

![Figure 4.113: Distribution of median and mean of charge distributions for all channels.](image)

![Figure 4.114: Calibration hits statistics. (Global bar ID)=(local bar ID [0-58])+59x(plane ID [0-47]).](image)
4.6.5 Energetic Cosmic Rays

Most of the events associated to triggers are muons (see Figure 4.112) but there are a few events which exhibit quite busy interactions. Some of them are clearly high energy single particle events (see Figure 4.115), deep-inelastic scattering (see Figure 4.116) or massive electromagnetic showers (see Figure 4.117). Once energy calibration is available*, it will be possible to measure energy of these events and possibly momentum of the particles.

Typical plane charge of a cosmic muon is from 10 to 40 ADC counts (depending on PMT). In those high energy events the plane charge reaches 2000 ADC counts. Taking into account that the amount of light generated in a scintillator does not depend linearly on the deposited energy (Birks’ law), the particle energy could be up to a few TeV. More event displays of high energy cosmic rays can be found in Appendix C.6.

![Figure 4.115: High energy cosmics: single particle.](image)

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*Energy calibration is outside the scope of this thesis.
Figure 4.116: High energy cosmics: deep-inelastic scattering.

Figure 4.117: High energy cosmics: massive electromagnetic shower.
4.7 Detector Performance with MICE beam

In September 2013 the EMR detector was installed in the MICE beamline at Rutherford Appleton Laboratory in the UK. During next month it was exposed to a beam which parameters were varied in order to achieve different beam composition and momenta. This data was used to verify the designed functionality of the detector, i.e. an ability to distinguish different particle types (muons, electrons and pions) and to measure their range. In this analysis there was no attempt to do precise measurement of the particle beam and its characteristics (e.g. emittance) since the goal was to commission the detector.

4.7.1 MICE Beamline Configuration

During the beam tests all of the components of MICE beamline were installed and operational except for the decay solenoid and Cherenkov detectors*. None of the components of MICE cooling channel were in the beamline at the time of the tests. Figure 4.118 shows beamline configuration during the tests.

![MICE beamline configuration during EMR run](image)

Figure 4.118: MICE beamline configuration during EMR run. MICE cooling channel was not in the hall at the time of the tests.

Protons from ISIS accelerator hit target and create hadrons (mostly pions) which are captured by quadrupole magnets (Q1-Q3) and first dipole magnet (D1). D1 selects pion momentum. Most pions decay to muons between first and second dipole magnets (D2). The D2 selects muon momentum followed by quadrupole magnets (Q1-Q9) which direct particles to MICE experimental hall. Beam instrumentation was composed of 5 detectors: three Time-of-Flight (TOF) stations, sampling calorimeter (KL) and the EMR. Geometrical orientation of the detectors is shown in Figure 4.119. A

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*The decay solenoid and Cherenkov detectors were not in operation due to technical reasons.
global trigger was given by TOF1 detector. All three TOF detectors were used to characterize the beam in terms of particle composition and momentum (see Section 4.7.4). Data from KL was not used in this analysis.

Figure 4.119: Position of MICE beamline detectors. Cherenkov detector was present in the beamline but not in operation.

### 4.7.2 Beam Settings

Momentum and particle composition of the MICE beam can be configured via setting appropriate currents on magnets. There are nine quadrupole magnets, two dipole magnets and one decay solenoid. The beamline can be operated with or without the decay solenoid. If the decay solenoid is operational, the particle rate is increased significantly in comparison when it is turn-off. Due to technical reasons the decay solenoid was out of operation during the beam tests.

There are 6 types of beams that can be configured in MICE: positive and negative electron, muon and pion beams. Name of the beam indicates which type of particles is enhanced and the corresponding magnet configuration parameters insure that at given momentum particle rate of that type is the highest possible among three types of given polarity. At any beam configuration all three types of particles are present.

The magnet currents have been calculated for all beam types and summarized in tables shown in Figures 4.120, 4.121 and 4.122 where according to a preset momentum at target all other values are calculated. Variation of momentum of a given particle type along the beamline is also shown.

When the decay solenoid is off, the particle rate of a muon beam is too low and it is not practical to use that beam setting. Therefore only electron and pion beams were collected (see Section 4.7.3).

Therefore a MICE beam can be defined by polarity (positive negative), momentum at target (from 100 to 400 MeV/c) and a particle type \((e, \mu, \pi)\): \(\mu^+ @ 200\) MeV/c.

Particles lose tens of MeV/c along the beamline. Figure 4.123 shows the momentum loss (difference between initial momentum and momentum just after TOF1) for electrons, muons and pions. Figure 4.124 represents the same curves in terms of momentum loss fraction. At momentum higher than 300 MeV/c electrons lose around 55% of their momentum, muons and pions - around 10%.
Figure 4.120: Electron beam settings.
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Figure 4.121: Muon beam settings.

INSTRUCTIONS:
- a) insert initial momentum
- b) adjust the momentum to match at D1 (red box)
- c) read the currents out of the relevant final column (SOLENOID / NO SOLENOID)

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</tbody>
</table>

Distance from target, mm
INSTRUCTIONS:
a) insert initial momentum
b) adjust the momentum to match at D1 (red box)
c) read the currents out of the relevant final column (SOLENOID / NO SOLENOID)
Figure 4.123: Particle momentum loss in MICE beam. **Left:** electrons. **Center:** muons. **Right:** pions.

Figure 4.124: Particle momentum loss fraction.
4.7.3 Data Sets

One of the purposes of the beam tests was to study a response of the EMR to electrons, muons and pions at different momentum. Therefore it was decided to scan the momentum at target (for electron and muon beams) from 280 to 540 MeV/c as shown in Figure 4.125. This range of the momentum at target corresponds to the following ranges at TOF1: electrons - from 100 to 250 MeV/c, muons and pions - from 200 to 500 MeV/c.

![Figure 4.125: Particle momentum at TOF1 as a function of momentum at target.](image)

Collected data sets are summarized in Table 4.8 where the number of recorded spills and triggers are shown. The last column contains the number of triggers for which particles crossed all three TOF detectors. Since the last TOF is in front of the EMR and has a smaller active area, all particles crossing the tree TOFs will definitely hit the EMR (Figure 4.126, left). And Figure 4.126(right) shows trigger rate (number of beam particles per spill) in the EMR. The trigger rate is around 1 particle per spill for negative beams and it rises up to 8 for positive beams.

4.7.4 Beam Characterization with TOF Detectors

There are three time-of-flight detectors in the MICE beam line. These detectors can be used to measure particle momentum assuming that particle type (mass) is known. Distributions of the time-of-flight values exhibit three-peak pattern and, from simulation\cite{30}, it is known that the first peak corresponds to electrons, second - to muons and the last one - to pions. Therefore, the shape of the time-of-flight distributions can be used to identify particle type and calculate momentum based on simple relation: \( p/E = s/t \) where \( s \) is a path length between two TOFs and \( t = t_{TOFi} - t_{TOF(i-1)} \).

For the purposes of the beam characterization it is enough to adopt a few assumptions that simplify calculations. Firstly, momentum \( p \) is configured to be constant, i.e. no energy loss in the air and
### Table 4.8: MICE beam data sets.

<table>
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<tr>
<th>beam type</th>
<th>momentum, MeV at target</th>
<th>spills</th>
<th>number of triggers (TOF1)</th>
<th>trigger (all TOFs)</th>
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<tr>
<td>e+</td>
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<td>143</td>
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<td>24847</td>
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<td>77454</td>
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<td>193</td>
<td>2151</td>
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<tr>
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<td>430</td>
<td>402</td>
<td>4110</td>
<td>100299</td>
</tr>
</tbody>
</table>

Figure 4.126: Total number of beam particles (left) and rate (right) in the EMR.
detector materials. Secondly, the path length $s$ is simply a geometrical distance between TOFs (as shown in Figure 4.119). A rigorous calculation[36] takes into account multiple scattering and energy loss along particle’s track and a proper path length.

Figure 4.127 contains examples of time-of-flight distributions (histograms) for three pairs of TOF detectors: 0 and 1, 0 and 2, 1 and 2. First, the three histograms are filled for each dataset (given momentum at target). Second, they are fitted with three Gaussian functions for each peak ($F_{e}^{ij}(\text{tof}_{ij}, p_{t})$, $F_{\mu}^{ij}(\text{tof}_{ij}), F_{\pi}^{ij}(\text{tof}_{ij})$) as shown in Figure 4.127. Third, the datasets are processed again and TOF fit functions are used to calculate probabilities that a given particle is an electron, muon or pion based on the following expression:

$$\text{Prob}(\text{tof}_{ij})_{\alpha} = \frac{F_{\alpha}^{ij}(\text{tof}_{ij})}{F_{e}^{ij}(\text{tof}_{ij}) + F_{\mu}^{ij}(\text{tof}_{ij}) + F_{\pi}^{ij}(\text{tof}_{ij})}$$

(4.18)

where $\alpha = e, \mu, \pi$ and $ij = 01, 02, 12$ - the three combinations of TOF detectors. For each couple of TOF detectors (01, 02 and 12) the three probabilities and momenta are calculated. Figures 4.128 and 4.129 show the fitted parameters (mean and sigma of Gaussian distributions) of the TOF distributions as a function of beam momentum at target for all collected beams. It can be noticed that positive beams have larger time-of-flight at lower momenta, at higher momenta there is no difference in time-of-flight between negative and positive particles.

The fitted parameters of the TOF distributions can also be used to calculate relative particle rates as shown in Figures 4.130 and 4.131. Electron beams have higher electron/positron rate at low momenta than pion beams while the latter have more pions. Above 400 MeV/c electron/positron rate drops below 5%. Pion rate increases with momenta for all beam settings.

A particle is considered as having a specific type if corresponding probabilities calculated based on TOF fitted functions are greater than 0.9 for all three combinations of TOFs, i.e. a particle is an electron if:

$$\text{Prob}_{e}^{01} > 0.9 \text{ and } \text{Prob}_{e}^{02} > 0.9 \text{ and } \text{Prob}_{e}^{12} > 0.9$$

(4.19)

Once a particle type is known corresponding momentum is calculated as follows:

$$p_{ij}^{\alpha} = \frac{m_{\alpha} \cdot c}{\sqrt{\left(\frac{c \cdot \text{tof}_{ij}}{s_{ij}}\right)^{2} - 1}}$$

(4.20)

The reconstructed momentum as a function of the beam momentum at target is shown in Figure 4.132. Thus all the particles in beams were characterized, i.e. type of particles and momentum were identified and used to study responses of the EMR detector.
Figure 4.127: Time-of-flight distributions in electron beam (277 MeV/c at target) between TOF0 and TOF1 (top), 0 and 2 (center), 1 and 2 (bottom). Gaussian fits for each peak are also shown.
Figure 4.129: Time-of-flight as a function of beam momentum (at target) of particles in "pion" beam. 

Figure 4.130: Relative particle rate in "electron" beam. **1st column:** negative particles. **1st column:** positive particles. **Red:** electrons. **Blue:** muons. **Green:** pions.
Figure 4.132: TOF reconstructed momentum as a function of beam momentum at target for all types of beams.
Figure 4.133: Beam particle event display: electron shower.

Figure 4.134: Beam particle event display: pion nuclear capture.
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4.7. Detector Performance with MICE beam

Figure 4.135: Beam particle event display: muon/pion decay.

Figure 4.136: Detector occupancy in 200 MeV/c electron beam.
4.7.5 Beam Characterization with the EMR Detector

To characterize a performance of the EMR, beam particles were first identified at TOF detectors and, if all selection criteria are satisfied\(^*\), the particles are matched to the EMR hits using trigger and spill counts since the EMR records triggers produced by TOF1 detector.

Electron shower with a gamma conversion is shown in Figure 4.133. Negative pion nuclear capture, Figure 4.134 is identified by a significant energy loss at the end of the track and a lack of a decay products. In Figure 4.135 one can see a positive muon (or pion) decay where the decay electron is clearly identified by timing (third column).

Figure 4.136 shows the detectors occupancy in 200 MeV/c electron beam where it is clearly seen that the detectors is misaligned with respect to a beam direction, namely it is shifted by 15 cm in horizontal direction\(^†\).

4.7.5.1 Primary and Secondary Tracks

For each beam particle a track in EMR is reconstructed if the timing of the track is related to the trigger time. These track is called a primary track. If a particle is a muon or pion and below certain energy, it may stop and decay. Tracks from the decay electrons (muon tracks from pion decays are too short to be visible) are not associated to triggers but they are close to end points of parent muons or pions. Figure 4.137 shows a relative number of reconstructed primary and secondary tracks in the EMR for four different momenta (170, 210, 250 and 290 MeV/c). For majority of positive muons, positive pions and negative muons, both primary and secondary tracks are found and reconstructed. Secondary tracks can be missed if a primary particle stops close to the edge of the detectors and the decay electron leaves the sensitive volume. The decay electron can also be ignored by the reconstruction algorithm if its track is along a plane in which case only one transverse coordinate can be reconstructed and it can not be matched to a primary track. In case of negative pions, the majority of particles do not have secondary tracks since they are captured by nuclei and there are no charged decay particles that originate from the stopping point. This behavior clearly confirms the simulation.

Figure 4.138 summarizes the relative number of the reconstructed tracks for all momenta. For muons above 300 MeV/c there are no secondary tracks since they penetrate the detector without stopping.

Distance between primary and secondary tracks is used to identify a parent muons or pion for decay electrons. Distributions of that distance at four different momenta are shown in Figure 4.139 and for all momenta in Figure 4.140. A secondary track can be considered as coming from a given primary one if the distance between them is below 2 bar units\(^‡\). In these performance studies a cut of 5 bar units was applied.

\(^*\)A particle should have a hit in all three TOF detectors and be identified as the same type in all of them.

\(^†\)A precise alignment of the detectors was not required and, as a results, enough attention was not paid to the position of the detector with response to a beam.

\(^‡\)One bar unit equals to half bar width, i.e. 1.65 cm.
Figure 4.137: Relative number of reconstructed primary and secondary tracks in the EMR at 170, 210, 250, 290 MeV/c. In each plot Y axis contains three numbers: (top) the number of beam particles with only reconstructed primary tracks in the EMR, (middle) the number of beam particles that have reconstructed secondary tracks in addition to the primary once, (bottom) sum of the two previous cases.
Figure 4.138: Relative number of reconstructed primary and secondary tracks in the EMR: from 150 to 350 MeV/c
Figure 4.139: Secondary to primary track distance in the EMR at 170, 210, 250, 290 MeV/c.
Figure 4.140: Secondary to primary track distance in the EMR: from 150 to 350 MeV/c.
4.7.5.2 Range of Primary Particles

Figure 4.141: Distributions of the primary range reconstructed in the EMR at 170, 210, 250, 290 MeV/c.

Figure 4.141: Distributions of the primary range reconstructed in the EMR at 170, 210, 250, 290 MeV/c.
Positive particles

Negative particles

Figure 4.142: Distributions of the primary range reconstructed in the EMR: from 150 to 350 MeV/c
According to the Geant4 simulation (and hence the name of the detector), the range is the main parameter that is used for particle identification. The range was measured for each beam particle as a function of momentum reconstructed in TOF detectors. Distributions of the range for four different momenta are shown in Figure 4.141. Figure 4.142 contains scatter plots of the range for electrons, muons and pions for all momenta. All three types of particles grouped in distinct areas of \((\text{range}, \text{momentum})\) phase-space and therefore can be efficiently identified. Even without thorough efficiency analysis these plots show that the detector confirms its designed functionality aimed at separating electrons from muons and pions.

Figure 4.143 shows RMS of range distributions as a function of the reconstructed momentum.

### 4.7.5.3 Range of Secondary Particles

Positive and negative muons and positive pions which stop in the detector decay and produce electrons (through muon for pions). Most of these decays are recorded and analyzed off-line. Since muons and pions decay at rest, the range of the decay electrons should be independent of the momentum of the initial particle as shown in Figure 4.144 and Figure 4.145. Due to the fact that a cut applied to the distance between primary and secondary tracks was relatively large (5 bar units), track matching algorithm was not quite efficient. Therefore some random tracks were associated to primary tracks of negative pions. According to the simulation there should not be secondary particles from negative pions. According to the simulation there should not be secondary particles from negative pions.

### 4.7.5.4 Total Reconstructed Charge

The whole sensitive volume of the detector is fully readout. Single-anode PMTs collect light from individual planes and multi-anode PMTs from individual bars. A sum of all the signals give total
Figure 4.144: Distributions of the secondary range reconstructed in the EMR at 170, 210, 250, 290 MeV/c.
Figure 4.145: Distributions of the secondary range reconstructed in the EMR: from 150 to 350 MeV/c
Figure 4.146: Distributions of the total charge reconstructed in the EMR at 170, 210, 250, 290 MeV/c.
Figure 4.147: Distributions of the total charge reconstructed in the EMR: from 150 to 350 MeV/c
charge deposited in the sensitive volume. Figure 4.146 shows distributions of the total charge for four different momenta and Figure 4.147 for all momenta.

Charge measurements from single-anode PMTs correspond to only primary particles since only signals close to initial triggers are recorded, while multi-anode PMTs can provide charge information about all interactions happened within a spill gate. The charge measurements here correspond to primary particles only.

Figure 4.148 shows mean and RMS values of the total charge distributions. One can see that for muons the resolution is relatively good (around 15%), while for electrons and pions it is greater than 50%.

4.7.5.5 Reconstructed Charge Ratio

The detector is able to measure a charge deposited at the place where muon or pion stops, this corresponds to a Bragg peak energy. Electrons do not have the Bragg peak. Therefore, the following variable can be useful for particle identification:

\[
R_Q = \frac{\frac{1}{n_1} \sum_{i=0}^{n_1-1} Q_{pl}^i/(n_1 - 1)}{\frac{1}{n_2} \sum_{i=n_1}^{n_2} Q_{pl}^i/(n_2 - n_1)}
\] (4.21)

where \(Q_i\) is a charge in plane \(i\), \(n_1 = \lfloor n_2 \cdot 4/5 \rfloor\) and \(n_2\) is an ID of the plane with the last hit from a primary track. Since muons and pions release most of their energy at the end of a track and electrons release more at the beginning of a track, this ratio should be less than one for muons and pions and more than one for electrons. Distributions of the charge ratio \(R_Q\) for four different momenta (Figure 4.149) and for all momenta (Figure 4.150) confirm that this variable is very effective.
Figure 4.149: Distributions of the charge ratio reconstructed in the EMR at 170, 210, 250, 290 MeV/c.
Figure 4.150: Distributions of the charge ratio reconstructed in the EMR: from 150 to 350 MeV/c
in separation between electrons and muons or pions. Mean and RMS values of $R_Q$ are shown in Figure 4.151 and it can be clearly seen that for positive and negative muons and positive pions the ratio is close to 0.7, for electrons and positrons it is around 1.5, while for negative pions it is close to 0.8 and RMS is wider.

4.7.6 Discussion of the Beam Test Results

The main objective of the beam tests was to verify the functionality of the detector, namely its ability to measure the range of particles and clearly separate electrons from muons. It is known from a simulation that muons, electrons and pions produce very distinct signal patterns in the detector: muons and pions below certain energy stop in the detectors and the energy deposition exhibit a clear Bragg peak which position defines the range, while electrons gradually lose energy along their tracks. In order to verify that a beam with all three types of particles was collected with different momenta from 100 to 400 MeV/c. And, as expected, electrons, muons and pions produce substantially different signal. Moreover, separation between electrons and muons can be established with high efficiency.

It should be noted that the detector was not tuned and optimized. There are plenty of hardware parameters that significantly affect the performance of the detectors: configuration of the ASIC of the front-end board, high voltage of the PMTs, parameters of the readout/buffer boards. These parameters were set to the most reasonable values but they were never optimized. Nevertheless, the detector showed excellent performance. Its ability to separate electrons from muons was confirmed.

The detector provides tracking and calorimetric information about particle interactions. Tracks can be clearly reconstructed and identified as being muons, electrons or pions. Muon or pion decay products can be identified and matched to its originating particles. A presence of the decay electron is one of the powerful discriminating signatures. A Bragg peak at the end of muon and pion tracks.
mark the place where a particle stops and, therefore, helps to measure the range. It was shown that
the range can be used to infer particle's momentum.

The detector has a potential to discriminate muons from pions. The range and total deposited
energy show different behavior in case of muons and pions. Due to hadronic interactions pions stop
earlier than muons and release more energy on average along their tracks. In addition, it was confirmed
that negative pions produce significantly different signals than positive pions due to a nuclear capture.
Chapter 5

Conclusions

The EMR detector is an essential part of the Muon Ionization Cooling Experiment. It allows one to measure emittance with required precision by identifying muons that crossed the whole cooling channel and rejection muons that decayed inside the channel and pions.

The EMR project was initiated in 2008. But in 2010 a major flaw in the design was discovered. During the detector assembly excessive force was applied to fibers causing them to crack. More than 10% of channel were damaged. It was decided to modify the design introducing clear fibers coupled to corresponding fiber connectors on scintillator bars. In addition, numerous quality tests have been implemented in order to insure the best quality of the assembly and to exclude any broken channels. Thanks to that, after the completion, the detector did not have any broken channels.

The detector was fully simulated and its performance was studied with the help of Geant4 simulation package. It was important to take into account all low energy interactions since particles stop in the detector and decay. A comprehensive Monte Carlo digitization scheme was developed. Most of the digitization parameters were set to values from data-sheets. The digitization was validated with cosmics and even without tuning the parameters an agreement between the simulation and real data is outstanding.

The construction of the detector from the engineering and electronics points of view was the major part of the effort constituting the work described in this thesis. Besides that all the necessary software have been written required to produce the relevant physics measurements. It includes reconstruction, calibration, data analysis and Monte Carlo digitization. After the digitization the Monte Carlo data and real data are processed by the same reconstruction and calibration codes. The code produces the range and energy measurements together with additional variables: presence of the decay electronic and its range, energy ratio along a particle track that is sensitive to Bragg peak. All these measurements allow one to clearly distinguish electrons from muons and pions, and have relatively good separation between muons and pions. It is clear that a more sophisticated reconstruction and particle

---

*After first cosmic tests five dead channels have been found. All five channel belong to one front-end-board and appear on the electronics circuit level. Once the board is replaced there will be no dead channels (out of 5664, dual readout of 2832 scintillator bars) in the whole detector.

†The digitization parameters (light yield, fiber attenuation, photo-efficiency etc.) will be measured in dedicated test setups. This should significantly improve the digitization.
identification algorithms are required but their development is outside the scope of this thesis. They should take into account all possible correlations between variables and possibly combine them with measurements from other detectors in MICE.

The calibration of the detector is performed with the help of cosmic muons. All 5664 channels are calibrated individually which typically requires three weeks of data taking. Once completed it can be monitored with a dedicated LED calibration system installed inside the detector enclosure.

It can be concluded with a great degree of confidence that the detector performance is well within the designed parameters and it has a significant potential for improvement.

In order to measure the emittance of a muons beam with high precision it is important to select a very clean sample of muons that traveled all the way until the end of the cooling channel with decaying. The EMR provides the means to perform such a selection. If combined with momentum measurements from other detectors the EMR gives unambiguous determination of a particle type.

The first results from MICE are expected in 2015 when one cooling station (liquid hydrogen absorber) without re-acceleration (RF cavities) will be completed*. As shown in Figure 5.1 the EMR will be a part of the beam instrumentation and it will provide valuable data that will for precise measurements of physical quantities required to prove the feasibility of muon ionization cooling.

![Figure 5.1: Configuration of MICE in Step IV scheduled for 2015. It includes one liquid hydrogen absorber fully equipped with all beam instrumentation detectors. The EMR is the rightmost.](Image)

*It is named Step IV.
Appendix A

Geant4 Physics Lists

Physics lists contain all the necessary information to model particle interactions with matter. Typically they cover specific energy range and applicable to specific particle type depending on the physics involved. Table A.1 summarizes physics lists available in Geant4 as of version 10.0 (February 2014). An explanation* of all the abbreviations follows the table.

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<th>Hadronic physics</th>
<th>Electromagnetic physics</th>
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<td>QGSC</td>
<td>BERT</td>
</tr>
<tr>
<td>QGSP</td>
<td></td>
</tr>
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</table>

Table A.1: Geant4 physics lists.

PRECO

**Particle:** proton, neutron

**Energy:** 0 - 170 MeV

This model generates the final state for hadron inelastic scattering. For details, see the chapter on the Precompound Model in the Geant4 Physics Reference Manual.

LEAD

**Particle:** pi+, pi-, K+, K-, K^0_L, K^0_S, proton, neutron, anti-proton, gamma

**Energy:** 0 - 5 GeV

This model generates the final state for hadron inelastic scattering using leading particle biasing techniques. For details, see the chapter on the Leading Particle Bias Model (G4Mars5GeV) in the Geant4 Physics Reference Manual.

BERT

**Particle:** $\pi^+, \pi^-, K^+, K^-, K^0_L, K^0_S$, proton, neutron, lambda, $\sigma^+, \sigma^-, \chi^-, \chi^0$

**Energy:** 0 - 10 GeV

The Bertini model generates the final state for hadron inelastic scattering by simulating the intra-nuclear cascade. This model is a re-engineered version of the INUCL code in which incident hadrons collide with protons and neutrons in the target nucleus and produce secondaries which in turn collide with other nucleons. The final state of each collision is sampled according to free-particle cross section data. The target nucleus is treated as an average nuclear medium to which excitons (particle-hole states) are added after each collision. At the end of the cascade the excited nucleus is represented as a sum of particle-hole states which is then decayed by pre-equilibrium, nucleus explosion, fission and evaporation methods. This model reproduces detailed cross section data for nucleons, pions and kaons in the region below 1 GeV and is expected to do reasonably well in the multi-GeV region. An alternative model, the Binary cascade, also does well for protons, neutrons and pions in the same energy region.

BIC

**Particle:** $\pi^+, \pi^-$, proton, neutron

**Energy:** 0 - 1.3 GeV ($\pi^+, \pi^-$), 0 - 10 GeV (proton, neutron)

This model generates the final state for hadron inelastic scattering by simulating the intra-nuclear cascade. The target nucleus is modeled by a 3-D collection of nucleons, as opposed to a smooth nuclear medium. The propagation through the nucleus of the incident hadron and the secondaries it produces is modeled by a cascading series of two-particle collisions. These collisions occur according to the particles’ total interaction cross section. Between collisions the hadrons are transported in the field of the nucleus by a Runge-Kutta method. Secondaries are created during the decay of resonances formed during the collisions. The decay of the excited nucleus is handled by G4PrecompoundModel. This model reproduces detailed proton and neutron cross section data in the region below 10 GeV, but due to its dependence on resonances, should not be used for pions above 1.3 GeV. An alternative model, the Bertini cascade, also does well for these particles.

HP

**Particle:** neutron; **Energy:** all

For energies below 20 MeV this model generates the final state for neutron-induced fission, neutron capture, elastic and inelastic neutron scattering using the high precision neutron model when sufficient high precision data is available for the selected element or isotope. When there is insufficient data, calculation is performed using the less precise Low Energy Parameterized model. For energies above 20 MeV final state for fission and capture are generated using GHEISHA model.
LHEP

**Particle:** all  **Energy:** all

The LHEP Physics lists are based on a parametrised modeling for all hadronic interactions for all particles. The parametrised model is an improved version of the Gheisha model. These lists combine the high energy parameterised (HEP) and low energy parameterised (LEP) models describing inelastic interactions for all hadrons. The modeling of elastic scattering off a nucleus and of capture of negative stopped particles and neutrons proceeds via parameterised models. Cross sections used are based on Gheisha parameterisations.

FTFC

**Particle:** $\pi^+$, $\pi^-$, $K^+$, $K^-$, $K^0_L$, $K^0_S$, proton, neutron  
**Energy:** 15 GeV - 100 TeV

The FRITIOF CHIPS (FTFC) model is built from several component models which handle various parts of a high energy collision. The FRITIOF part handles the formation of strings in the initial collision of a hadron with a nucleon in the nucleus. String fragmentation into hadrons is handled by the Lund fragmentation model. The Chiral Invariant Phase Space (CHIPS) part handles the de-excitation of the remnant nucleus.

FTFP

**Particle:** $\pi^+$, $\pi^-$, $K^+$, $K^-$, $K^0_L$, $K^0_S$, proton, neutron  
**Energy:** 15 GeV - 100 TeV

The FRITIOF Precompound (FTFP) model is built from several component models which handle various parts of a high energy collision. The FRITIOF part handles the formation of strings in the initial collision of a hadron with a nucleon in the nucleus. String fragmentation into hadrons is handled by the Lund fragmentation model. The precompound part handles the de-excitation of the remnant nucleus.

QGSC

**Particle:** $\pi^+$, $\pi^-$, $K^+$, $K^-$, $K^0_L$, $K^0_S$, proton, neutron  
**Energy:** 8 GeV - 100 TeV

The Quark-Gluon String CHIPS (QGSC) model is built from several component models which handle various parts of a high energy collision. The quark-gluon string (QGS) part handles the formation of strings in the initial collision of a hadron with a nucleon in the nucleus. String fragmentation into hadrons is handled by the Quark-Gluon String fragmentation model. The Chiral Invariant Phase Space (CHIPS) part handles the de-excitation of the remnant nucleus.
QGSP

**Particle:** $\pi^+, \pi^-, K^+, K^-, K^0_L, K^0_S$, proton, neutron

**Energy:** 12 GeV - 100 TeV

The Quark-Gluon String Precompound (QGSP) model is built from several component models which handle various parts of a high energy collision. The quark-gluon string (QGS) part handles the formation of strings in the initial collision of a hadron with a nucleon in the nucleus. String fragmentation into hadrons is handled by the Quark-Gluon String fragmentation model. The precompound part handles the de-excitation of the remnant nucleus.

EM

**Particle:** all; **Energy:** all

Default electromagnetic standard physics.

EMV

**Particle:** all; **Energy:** all

Electromagnetic standard physics using set of options allowing speed up simulation. Results for simulation in thin layers of materials with different density may be biased.

EMX

**Particle:** all; **Energy:** all

Electromagnetic standard physics using set of options allowing to utilize sub-cutoff option for ionization processes and higher production threshold than in default EM physics.

EMY

**Particle:** all; **Energy:** all

Electromagnetic standard physics using set of the most advanced options allowing precise simulation at low and intermediate energies.
Appendix B

EMR Simulation

This Appendix contains the following sections:
B.1: Average Energy Loss in Planes
B.2: Distribution of Energy Lost in a Plane
B.3: Shower Shapes
B.4: Total Energy Loss
Figure B.1: Average energy loss per plane for $e$(red), $\mu$(green), $\pi$(blue). Dashed lines correspond to negative particles and solid lines to positive.
Figure B.2: Average energy loss per plane for $e$ (red), $\mu$ (green), $\pi$ (blue). Dashed lines correspond to negative particles and solid lines to positive.
Figure B.3: Average energy loss per plane for $\epsilon$ (red), $\mu$ (green), $\pi$ (blue). Dashed lines correspond to negative particles and solid lines to positive.
Figure B.4: Average energy loss per plane for $e$(red), $\mu$(green), $\pi$(blue). Dashed lines correspond to negative particles and solid lines to positive.
Figure B.5: Energy loss distributions in the first plane for electrons (red), muons (green) and pions (blue). Dashed lines correspond to negative particles and solid lines to positive.
Figure B.6: Energy loss distributions in the first plane for electrons (red), muons (green) and pions (blue). Dashed lines correspond to negative particles and solid lines to positive.
Figure B.7: Energy loss distributions in the first plane for electrons (red), muons (green) and pions (blue). Dashed lines correspond to negative particles and solid lines to positive.
Figure B.8: Energy loss distributions in the first plane for electrons (red), muons (green) and pions (blue). Dashed lines correspond to negative particles and solid lines to positive.
B.3 Shower Shapes

Figure B.9: Shower shapes (in log scale): 100 MeV/c electrons (first row), muons (second row), pions (third row). First column: negative particles. Second column: positive particles.
Figure B.10: Shower shapes (in log scale): 150 MeV/c electrons (first row), muons (second row), pions (third row). First column: negative particles. Second column: positive particles.
Figure B.11: Shower shapes (in log scale): 200 MeV/c electrons (first row), muons (second row), pions (third row). First column: negative particles. Second column: positive particles.
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B.3. Shower Shapes

Figure B.12: Shower shapes (in log scale): 250 MeV/c electrons (first row), muons (second row), pions (third row). First column: negative particles. Second column: positive particles.
Figure B.13: Shower shapes (in log scale): 300 MeV/c electrons (first row), muons (second row), pions (third row). **First column**: negative particles. **Second column**: positive particles.
Figure B.14: Shower shapes (in log scale): 350 MeV/c electrons (first row), muons (second row), pions (third row). First column: negative particles. Second column: positive particles.
Figure B.15: Shower shapes (in log scale): 400 MeV/c electrons (first row), muons (second row), pions (third row). First column: negative particles. Second column: positive particles.
B.4 Total Energy Loss

Figure B.16: Total energy loss in the detector for $e$ (red), $\mu$ (blue), $\pi$ (green). Dashed lines correspond to negative particles and solid lines to positive.
Figure B.17: Total energy loss in the detector for $e$ (red), $\mu$ (blue), $\pi$ (green). Dashed lines correspond to negative particles and solid lines to positive.
Figure B.18: Total energy loss in the detector for $e$ (red), $\mu$ (blue), $\pi$ (green). Dashed lines correspond to negative particles and solid lines to positive.
Figure B.19: Total energy loss in the detector for $e$ (red), $\mu$ (blue), $\pi$ (green). Dashed lines correspond to negative particles and solid lines to positive.
Appendix C

Detector Performance with Cosmics

This Appendix contains the following sections:
C.1: Bar Hit and Trigger Time Difference in Planes
C.2: Bar Hit and Trigger Time Difference in Bars
C.3: Time-Over-Threshold in Bars
C.4: Pedestal Charge of Single-Anode PMTs
C.5: Signal Charge of Single-Anode PMTs
C.6: High Energy Cosmic Rays
C.1 Bar Hit and Trigger Time Difference in Planes

Figure C.1: Bar hit time minus trigger time: planes 0 to 14.
Figure C.2: Bar hit time minus trigger time: planes 15 to 29.
Figure C.3: Bar hit time minus trigger time: planes 30 to 47.
Figure C.4: Bar hit time minus trigger time in bars: planes 0 to 14. In plane 14 five dead channels are clearly visible: 2,3,4,9,10.
Figure C.5: Bar hit time minus trigger time in bars: planes 15 to 29.
Figure C.6: Bar hit time minus trigger time in bars: planes 30 to 47.
Figure C.7: Time-Over-Threshold in bars: planes 0 to 14. In plane 14 five dead channels are clearly visible: 2,3,4,9,10.
Figure C.8: Time-Over-Threshold in bars: planes 15 to 29.
Figure C.9: Time-Over-Threshold in bars: planes 30 to 47.
C.4 Pedestal Charge of Single-Anode PMTs

Figure C.10: Pedestal charge of single-anode PMTs: planes 1 to 15, plane 0 is a trigger plane.
Figure C.11: Pedestal charge of single-anode PMTs: planes 16 to 30.
Figure C.12: Pedestal charge of single-anode PMTs: planes 31 to 46, except for 44 (shown in Figure 4.107) and 47 (trigger plane).
C.5 Signal Charge of Single-Anode PMTs

Figure C.13: Signal charge of signal-anode PMTs: planes 1 to 15, plane 0 is a trigger plane.
Figure C.14: Signal charge of signal-anode PMTs: planes 16 to 30
Figure C.15: Signal charge of single-anode PMTs: planes 31 to 46, except for 44 (shown in Figure 4.108) and 47 (trigger plane).
C.6 High Energy Cosmic Rays

Figure C.16: High energy cosmics: event 1

Figure C.17: High energy cosmics: event 2
Figure C.18: High energy cosmics: event 3

Figure C.19: High energy cosmics: event 4
Figure C.20: High energy cosmics: event 5

Figure C.21: High energy cosmics: event 6
Figure C.22: High energy cosmics: event 7

Figure C.23: High energy cosmics: event 8
Figure C.24: High energy cosmics: event 9

Figure C.25: High energy cosmics: event 10
Figure C.26: High energy cosmics: event 11

Figure C.27: High energy cosmics: event 12
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C.6. High Energy Cosmic Rays

Figure C.28: High energy cosmics: event 13

Figure C.29: High energy cosmics: event 14

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Figure C.30: High energy cosmics: event 15

Figure C.31: High energy cosmics: event 16
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C.6. High Energy Cosmic Rays

Figure C.32: High energy cosmics: event 17

Figure C.33: High energy cosmics: event 18
Figure C.34: High energy cosmics: event 19

Figure C.35: High energy cosmics: event 20
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C.6. High Energy Cosmic Rays

Figure C.36: High energy cosmics: event 21

Figure C.37: High energy cosmics: event 22
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Figure C.38: High energy cosmics: event 23

Figure C.39: High energy cosmics: event 24
Bibliography


[29] Texas Instruments. TLK1501, 0.6 to 1.5 Gbps Transceiver, Datasheet.


