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A totally active scintillator calorimeter for the Muon Ionization Cooling Experiment (MICE). Design and construction

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ABSTRACT

The Electron-Muon Ranger (EMR) is a totally active scintillator detector to be installed in the muon beam of the Muon Ionization Cooling Experiment (MICE) [1] – the main R&D project for the future neutrino factory. It is aimed at measuring the properties of the low energy beam composed of muons, electrons and pions, performing the identification particle by particle. The EMR is made of 48 stacked layers alternately measuring the X- and the Y-coordinate. Each layer consists of 59 triangular scintillator bars. It is shown that the granularity of the detector permits to identify tracks and to measure particle ranges and shower shapes. The read-out is based on FPGA custom made electronics and commercially available modules. Currently it is being built at the University of Geneva.

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1. MICE

1.1. Neutrino factory

A Neutrino Factory [2] based on a muon storage ring is the ultimate tool for studies of neutrino physics [3]. It is also a first step towards a muon collider. One of the challenges posed is the control of the large emittances possessed by muons from the decay of pions produced at the proton driver target. Ionization cooling is a proposed mechanism to reduce these emittances on a suitably short timescale. It has never been demonstrated in practice but it has been shown by simulations and design studies to be an important factor both for the performance and for the cost of a Neutrino Factory.

The MICE collaboration has designed an experiment [1] in which a section of the cooling channel is exposed to a muon beam, which would demonstrate and explore this technique for the first time in practice. MICE is being installed at the ISIS facility [4], at the Rutherford Appleton Laboratory (RAL). MICE is composed of a cooling cell (see Fig. 1) and of all the equipment necessary to measure the emittance of a muon beam before and after this cell through single particle measurements and to achieve 10% cooling of 200 MeV/c muons. The cooling cell will be sandwiched between two identical trackers inside the 4 T superconducting solenoids, complemented by upstream and downstream particle detectors.

1.2. Beam instrumentation

The ISIS synchrotron accelerates a high intensity 300 μ A proton beam up to 800 MeV/c at 50 Hz. To produce muons for MICE, an internal target is installed which provides a source of pions for a pion-muon decay channel. The muon beam line [5] makes use of existing dipole and quadrupole magnets, together with a superconducting solenoid contributed by the Paul Scherrer Institute. MICE requires muon momenta in the range of 140–240 MeV/c, with a $\pm 10\%$ momentum acceptance. Both muon signs can be obtained by switching the magnet polarities.

The beam line splits into three parts: a pion capture and selection section, a pion-muon decay section, and a transport line to convey muons to MICE. The last section also hosts a thick lead scatterer, and serves to generate the large emittances and to match the beam into the experiment. A schematic of the beam-line layout is shown in Fig. 2.

1.3. Calorimeter: Electron-Muon Ranger (EMR)

A fully active scintillator calorimeter (see Fig. 4) is located at the very end of the cooling channel. It will stop all muons and electrons and will give very distinct signatures for both. It has 1 m³ of active volume, 48 planes composed of 59 triangular scintillator bars with glued 1.2 mm wavelength shifting fibers. The dimensions of the triangular bars and the arrangement to form a plane are shown in Fig. 3.

For each plane the light is collected by a single-anode photo-multiplier tube (PMT) on one side, and by a 64-channel PMT on

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the other side: 3120 channels in total. The granularity of the detector allows for individual track reconstruction and for measurement of the energy deposition in every bar.

2. EMR design

The 48 stacked planes of the calorimeter (see Fig. 5) form 24 modules which allow for measurement of the X–Y coordinates of a traversing track, the Z coordinate being given by the module position. The read-out electronics is housed inside the support frame and is located next to the PMTs in order to minimize analog signal distortions.

Fig. 6 summarizes the layout of the triangular scintillator bar: the bars emit light in the blue region of the spectrum, the wavelength shifting fibers collect the light and shift it to green. Finally, light guides transfer the light to the PMTs. At both end faces, each bar has an individual connector which couples the wavelength shifting fiber to the corresponding light guide.

59 bars are assembled to form one plane (see Fig. 7) and the height of the triangular bars defines the thickness of the plane.

2.1. Construction

The following procedure is employed to construct the EMR planes (see Fig. 8). The wavelength shifting fibers are inserted into the triangular scintillator bars and glued with epoxy adhesive (60 bars at a time; 3300 bars have been produced to allow for a 15% rejection rate) as shown in Fig. 8A. Both faces of the bar's fiber connectors are polished with a special polishing machine (Fig. 8B). Four different grades of sand paper are used to achieve a mirror like quality of the polished surfaces. The last step is performed

Fig. 3. Scintillator bar dimensions, the arrangement in a plane, and a cross-section of a real bar. Imperfections in the bar dimensions can be clearly seen in the real bar cross-section photograph.

Fig. 4. EMR overview.

Fig. 1. MICE cooling channel overview.

Fig. 2. MICE beam instrumentation. The straight section at the end of the beam line contains the cooling channel from Fig. 1 and the Electron–Muon Ranger (EMR).

Fig. 5. EMR design.

Fig. 6. Scintillator bars. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

Fig. 7. Plane assembly.

using a 1 μm grade diamond-based polishing paper. Each bar is then tested with a LED and a digital camera (Fig. 8C). Bars with a light output below 85% of the average are rejected. The faults are mostly due to fiber damage during gluing and polishing. Only tested bars are used for plane assembly (Fig. 8D). And the last step is to clip the two clear-fiber bundles to the two sides of a plane (Fig. 7).

2.2. Electronics

The EMR has a dual read-out (see Fig. 9). Fibers from one side of a plane are bunched together and directed to a 1-channel PMT that

measures the total energy in the plane. Eight 1-channel PMTs are read out by one flash ADC (CAEN V1731), there are 6 fADCs in total. On the other side of the plane the fibers are coupled to a 64-channel PMT that is read out by custom-made FPGA-based electronics.

The Front-End electronics consists of the Front-End Board (FEB) and the Digitizer-Buffer Board (DBB) (see Fig. 10). The FEB is designed to read out the 64-channel PMT. It hosts a MAROC ASIC that amplifies, discriminates and shapes all input signals. Pulse height information can be extracted at low rate (during calibration with cosmics). Time-over-threshold information is directed to a piggy-back buffer board. The DBB receives signals from the FEB

Fig. 8. Construction procedure.

Fig. 9. EMR electronics layout.

and stores them in a buffer memory. The beam for MICE is composed of 1 ms spills at the rate of 1 Hz. Every spill contains several hundreds of particles. All interactions of these particles are stored in the DBB and transferred to a computer at the end of an accelerator spill.

Fig. 10. Front-End electronics.

3. Physics potential

The Electron–Muon Ranger was simulated with the help of the Geant4 package [6]. All the geometry details of the detector were implemented in the simulations, including the fibers and the glue. The Geant4 simulation of the EMR shows that muons, electrons and pions give very distinct signatures and event topologies (see Fig. 11): muons release most of their energy at the point where they stop, while electrons lose energy continuously along their tracks, and pions stop earlier than muons. The granularity of the detector allows for track identification which in turn will help to create very explicit patterns for the event reconstruction.

4. Summary

The Electron–Muon Ranger (EMR) is a fully active scintillator calorimeter to be used at MICE to distinguish electrons, muons and pions on an event-by-event basis. It employs FPGA electronics which allows for a flexible customization of the detector behavior.

Fig. 11. Shower shapes.

The installation of the detector at the Rutherford Appleton Laboratory is planned for summer 2013.

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