# The design and construction of the MICE Electron-Muon Ranger

April 13, 2016


**Abstract**

The Electron-Muon Ranger (EMR) is a totally active scintillator detector installed in the beam of the Muon Ionization Cooling Experiment (MICE) [1]. The experiment will demonstrate ionization cooling, an essential technology needed for the realization of a Neutrino Factory and/or Muon Collider. The EMR is aimed at measuring the properties of the low energy beam composed of muons, electrons and pions, performing the identification particle by particle. The detector is made of 48 stacked layers alternately measuring the X- and the Y-coordinate. Each layer consists of 59 triangular scintillator bars. The read-out is based on FPGA custom made electronics and commercially available modules. This article will describe the construction of the detector, starting with the process of designing the detector up to its final commissioning with particle beam.


## 1 Introduction

### 1.1 Ionization cooling

The Neutrino Factory based on a high-energy muon storage-ring is the ultimate tool to study the neutrino mixing matrix and is established as the best facility to discover, and study the possible leptonic CP violation. It will produce the most intense, pure and focused neutrino beam ever achieved and is also the first step towards a $\mu^+\mu^-$ collider. The Neutrino Factory accelerator complex will use as a sources muons, produced as a tertiary beam. A proton beam bombarding a target will produce pions. These pions will be captured and focused in a high-field solenoid channel and will decay to muons, creating a low energy muon beam with very large emittance. The emittance of the muons needs to be reduced, i.e the muon must be cooled, so that the beam can be accelerated efficiently.

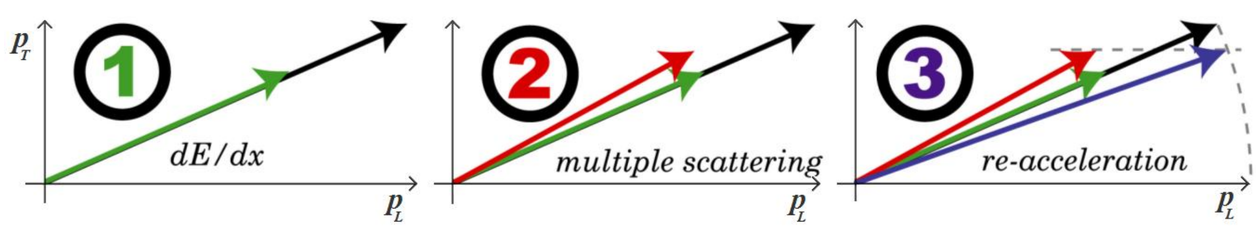


Figure 1: Ionization cooling principle: 1. Energy loss by ionization ($dE/dx$ reduces $P_L$ and $P_T$) 2. Heating from multiple scattering 3. $P_L$ restored by RF cavities

Ionization cooling [2] (Fig. 1) provides the only practical solution to this problem, because it is fast enough to cool the beam within the muon lifetime ($\tau_\mu \sim 2.2\ \mu s$). The cooling effect is accomplished by passing the muons through a low-Z materiall ("absorber"), in which they loses energy via ionization, reducing both the longitudinal and the transverse components of momentum. Later the longitudinal momentum is restored by accelerating cavities. The net effect is a reduction of the beam emittance. To maximize cooling we need the absorber to be placed at a position where the transverse momentum $P_T$ has a maximum (the transverse betatron function $\beta_\perp$ has a minimum).

### 1.2 MICE

The international Muon Ionization Cooling Experiment (MICE) [1] is under development at the Rutherford Appleton Laboratory (UK). The goal of the experiment is to build a section of a cooling channel that can demonstrate the principle of Ionization cooling and to verify its performance in a muon beam.

Since energy loss by ionization and multiple Coulomb scattering are momentum dependent, the ionization-cooling effect is momentum dependent. MICE (Fig. 2) uses variety of muon beams of limited intensity, having central momenta in the range $140-240\ MeV/c$ and a momentum spread of $\sim 20\ MeV/c$. These muon beams are generated using a titanium target [3] which is dipped into the ISIS proton beam [4]. Produced secondary and tertiary particles are captured, momentum-selected and transported to the cooling section by a system of magnets which includes: 5 $T$ superconducting pion decay solenoid, two dipole magnets, nine quadrupole magnets and a mechanism for inflation of the initial emittance called Diffuser.

The cooling section of MICE, is similar to the cooling channel for the International Design Study for the Neutrino Factory [5]. It consists of one primary lithium-hydride (LiH) absorber, two secondary absorbers, two focus coils and two 201 MHz RF cavities. The two superconducting focus-coil modules provide strong focusing at the absorber, ensuring that the transverse betatron function is minimised at this position and enhancing the cooling effect. All beam particles are detected individually by two identical Scintillating fiber trackers in 4T solenoids, situated upstream and downstream of the cooling section. The beam emittance is reconstructed, by measuring the spatial coordinates and momentum $(x, y, p_x, p_y, p_z)$ of each muon.

The particle content of the beam is measured by a dedicated system of detectors situated upstream and downstream of the cooling section and designed to provide precise muon, pion and electron identification. The upstream part includes two Time-of-flight hodoscopes (TOF0 and TOF1) and a Cherenkov detectors (Ckov). The downstream part combines another Time-of-flight hodoscope (TOF2) and a calorimeter system. The calorimeter system consists of the KLOE-Light (KL) lead-scintillator sampling calorimeter, similar to the KLOE design [30], but with thinner lead foils, serving as a preshower for the totally-active Electron-Muon ranger (EMR), situated behind him.

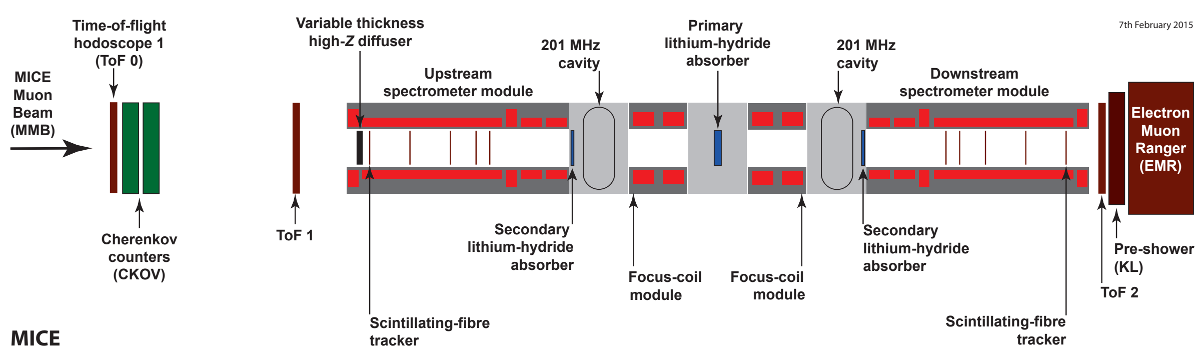


Figure 2: Schematic view of the MICE experiment.

MICE will measure the normalised transverse emittance $\epsilon_N$ with a precision of $\sigma_{\epsilon_N}/\epsilon_N \sim 0.1\%$ when 6% cooling effect is expected for a muon beam with a nominal momentum of 200 $MeV/c$ and 4D normalised emittance $\epsilon_N = 5.8\ \pi mm \times rad$ is .

### 1.3 Electron-Muon Ranger (EMR)

EMR is a fully active scintillator detector. It can be classified as tracking calorimeter, since its granularity allows for track reconstruction. The primary purpose of the detector is to distinguish muons from their decay products, rejecting events in which the muon decays in-flight along the cooling section [6]. This allows for the selection of a muon beam with a contamination below 1%. The range of the muon track can be measured, providing an estimate of the momentum of the muon.

The construction of the detector started in the early 2011 and in October 2013 the detector was fully commissioned with beam during one month of a dedicated data-taking at RAL. In 2014 the detector was upgraded, including a replacement of the single-anode photo-multiplier tubes and installation of a new high-voltage system.

## 2 Design

The EMR is built of triangular scintillator bars arranged in planes. One 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. A cross-section of bars and their arrangement in a plane is shown in Figure 3. With this configuration there is no dead area for particles crossing a plane with angles less than 45 degrees from the beam axis.

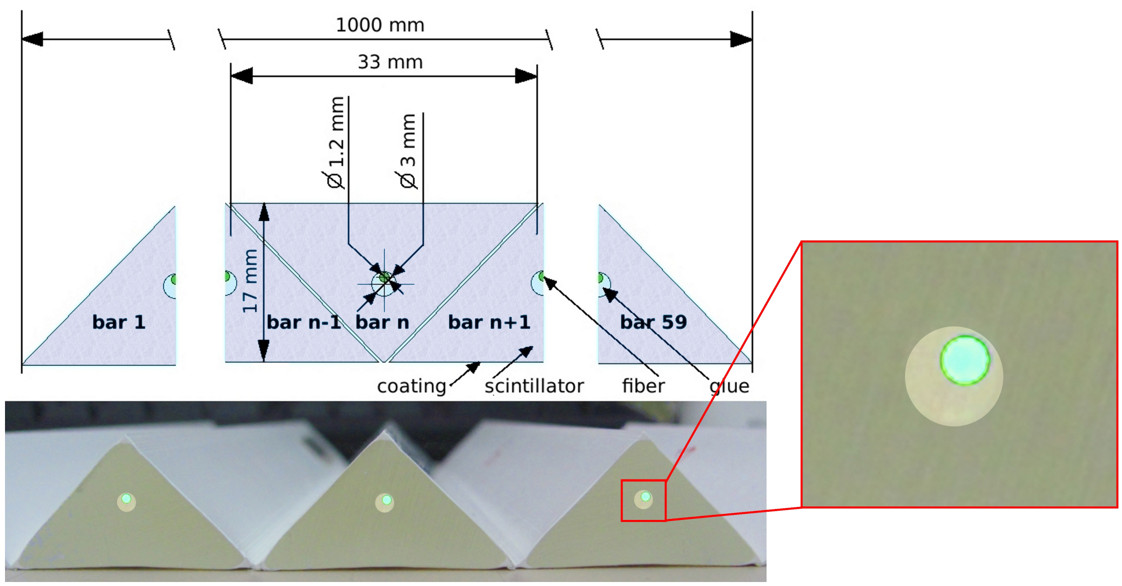


Figure 3: EMR bar cross-section and bars arrangement in a plane. There are 59 bars per plane.

The light, produced when a particle crosses a bar, is collected by a wave-length shifting (WLS) fiber glued inside the bar. Transparent epoxy[1] is used to glue the WLS fiber in order to increase the light collection efficiency. At both ends of a bar the WLS fiber is coupled to a clear fiber that transfers the light to a photo-multiplier (PMT). The clear fibers are protected with rubber sleeves and packed in aluminum fiber boxes as drawn in Figure 4. In order to reduce the bending radius, which affects light attenuation, each fiber has individual length. The two bunches of clear fibers coming from the two sides of a plane are glued into different types of connectors. One is designed to match a multi-anode PMT, when the other one matches a single-anode PMT.

[1] Prochima E30 water effect resin

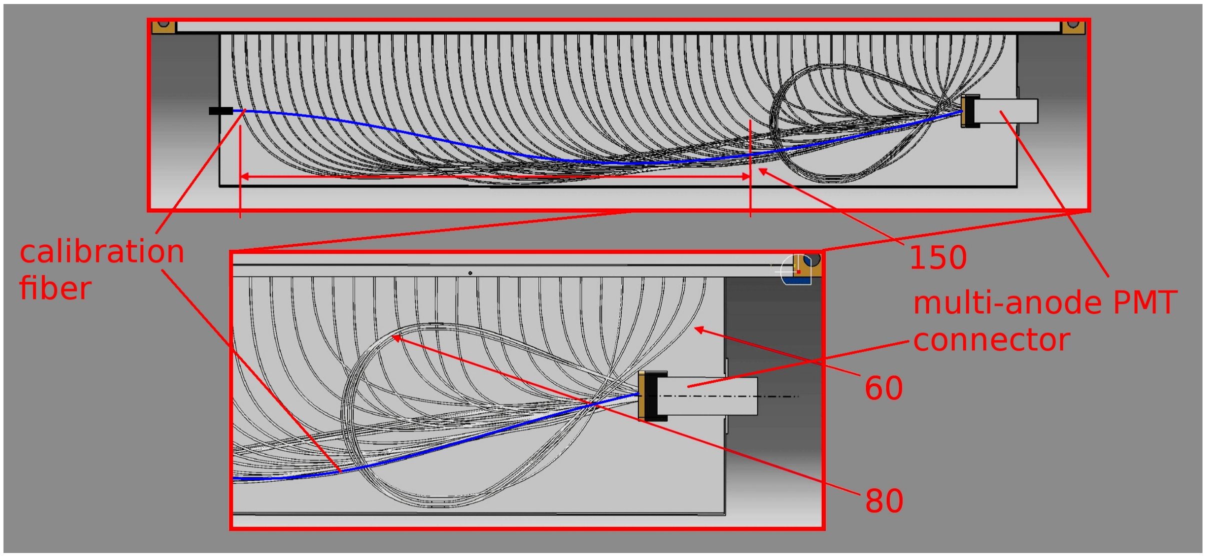


Figure 4: A package of clear fibers in a fiber box. Multi-anode PMT connector is shown. The fiber box for a single-anode PMT connector has similar structure. The last 5 fibers are looped in order to have largest possible bending radius. The bending radius of some of the fibers is indicate in red. The calibration fiber is also shown.

Two planes attached to each other via aluminum profiles form a rigid structure called module (Figure 5). The full detector contains 24 modules as shown in Figure 6. Panels cover all sides of the detector in order to insure a light-tightness. The signal coming from each multi-anode PMT is read-out and processed by a front-end board attached directly to the fiber box as shown in Figure 5. The single anode PMTs is equipped whit a voltage divider and the analog signal is sent outside the detector for digitization.

A calibration system was installed inside the enclosure of the detector in order to monitor the drift of the gain and the quantum efficiency of the PMTs. This system is made of a LED driver distributing light homogeneously to 100 fiber. Each fiber box is connected to one of the calibration fibers through a dedicated connector. Inside a fiber box a clear fiber connects the calibration fiber to the PMT (see Figure 4).

All cables inside the detector are feed through four patch-panels. There are 96 high-voltage, 6 low voltage, 48 analog, 48 digital, and one configuration cables in total. A support frame is designed to withhold the full weight of the sensitive volume with electronics ($\sim$ 1 tonne). In order to protect the front-end electronics from the magnetic field of the spectrometer solenoid, situated nearby the detector, a shielding plate is mounted on the side of the detector that faces the beam. The total weight of the detector is almost 2.5 tonnes.

### 2.1 Optical Elements

The scintillator bars were manufactured at extrusion facility at Fermilab [7]. This facility also produced scintillators of different shapes for other experiments like: DO preshower detector, MINOS [8], Minerva [9], SciBar (K2K/SciBoone), Star, Mayn Pyramid Mapping, Hall-B JLAB, T2K-ND280, Double-Chooz, Amiga - Piere Auger. Each bars is 110 cm long, 1.7 cm high and 3.3 cm wide with 3 mm hole along the bar for a wavelength shifting fiber. The scintillator is made of polystyrene

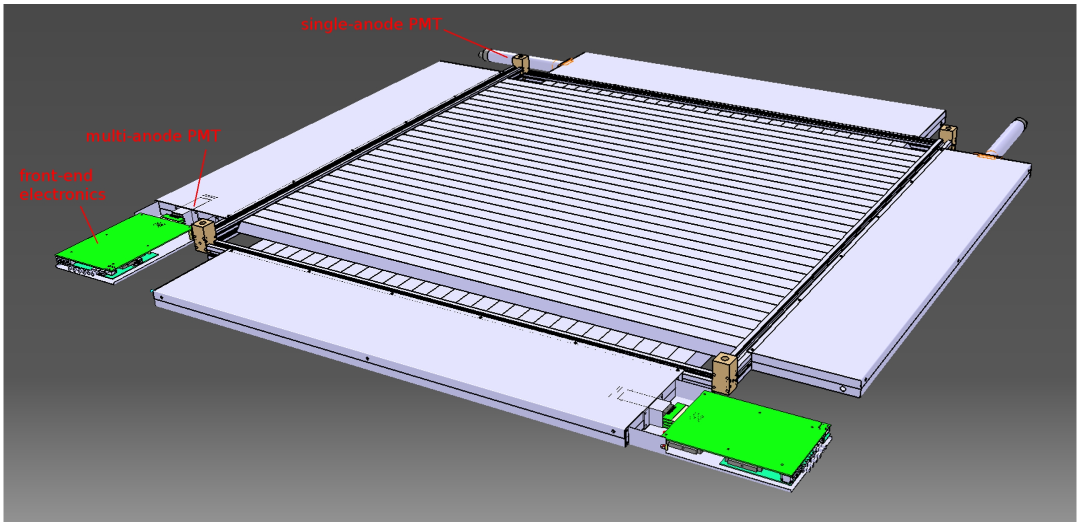


Figure 5: CAD drawing of one EMR module made of X and Y planes. There are two front-end boards per module.

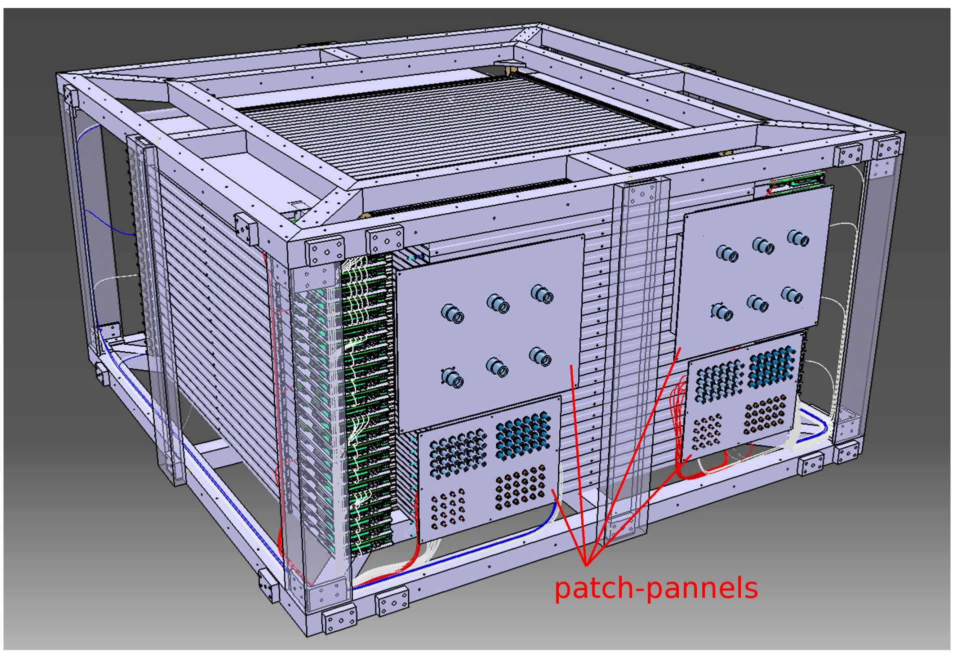


Figure 6: CAD drawing of the complete EMR detector. The external protective panels are not shown.

pellets[2] as base, 1% PPO[3] as primary and 0.03% POPOP[4] 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 [7] with a photo-multiplier (25% quantum efficiency) and it is around 17 photo-electrons.

The WLS fiber glued inside the bar is a double cladding 1.2 mm in diameter fiber, produced by

[2]Dow Styron 663 W

[3]scintillator, 2,5-diphenyloxazole, $C_{15}H_{11}NO$

[4]wavelength shifter, 1,4-di-(5-phenyl-2-oxazolyl)-benzene, $C_{24}H_{16}N_2O$, spectrum peaks at 410 nm (violet)

Saint-Gobain Crystals [10]. 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%. The light is absorbed in blue part of a visible spectrum and re-emitted in green.

The clear fiber, used to transfer light from the ends of scintillator bar to the PMTs, is a 1.5mm multi-cladding fiber produced by Kuraray [11] 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.

A special connector was designed to couple a clear fiber to a wavelength shifting fiber (see Figure 7). 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 a sharp edge of the connector would easily damage it. As shown in Figure 7 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 peaces are non-standard and could not be found on a market, therefore a special mold was designed to produce them using injection molding technique.

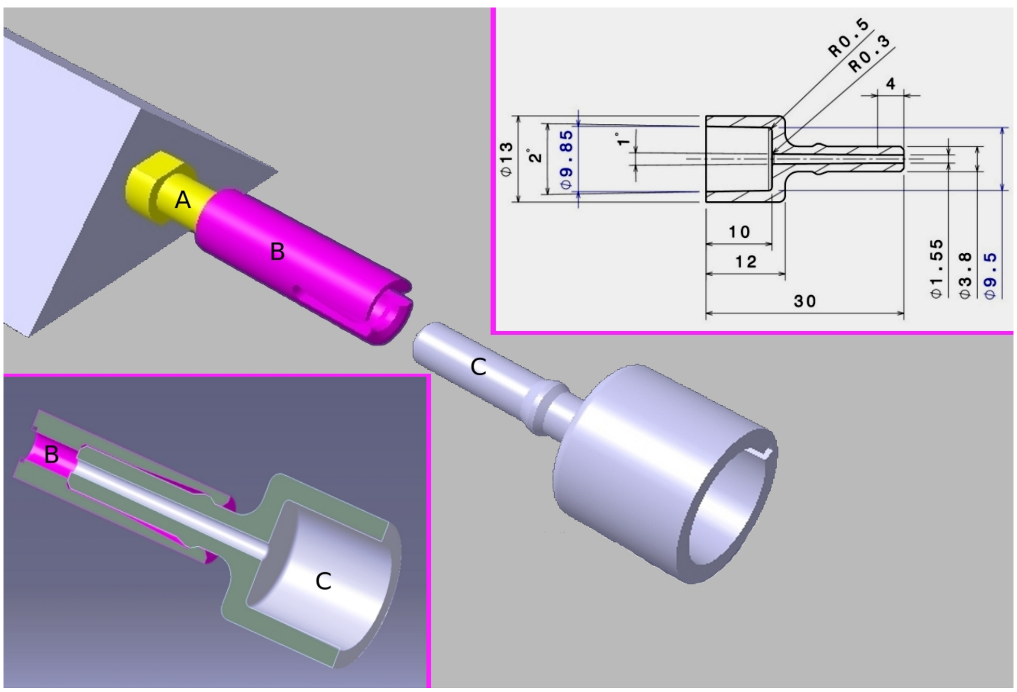


Figure 7: clear fiber connector (C) is attached to the wavelength shifting fiber connector (A) via retaining clip (B).

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. 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 8).

## 2.2 Photodetectors

As it was briefly mentioned earlier the EMR has a dual readout. Each scintillator plane is equipped with a multi-anode PMT, which collects the light from the individual bars and a single-anode PMT which detects the integrated response of all bars in the plane.

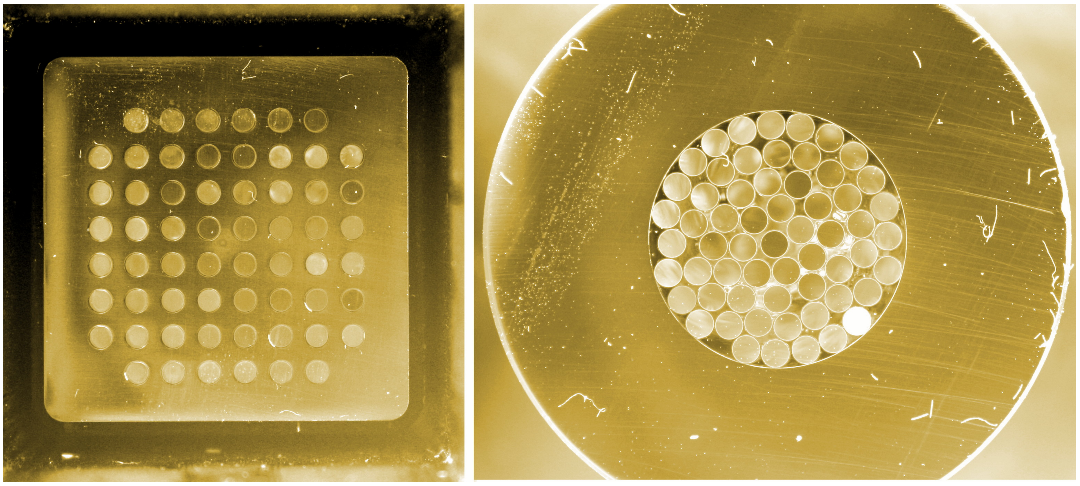

Figure 8: **Left:** multi-anode PMT connector. **Right:** single-anode PMT connector.

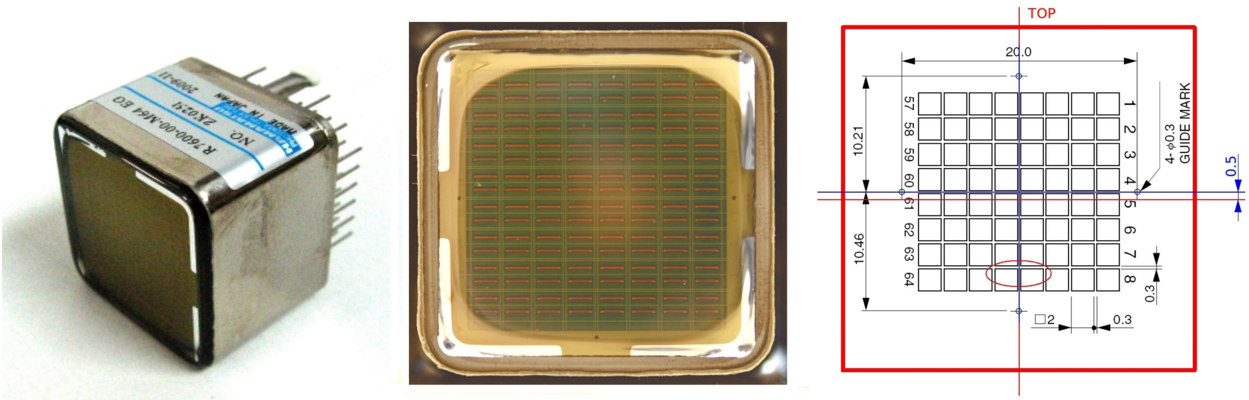


Figure 9: Multi-Anode PMT. **Left:** photo. **Center:** anode matrix. **Right:** anode matrix dimensions.

The multi-anode photo-multiplier tube (MAPMT) is a 64-channel PMT produced by Hamamatsu (model R5900-00-M64 [12], see Figure 9, left). The spectral sensitivity matches to the emission spectrum of the wavelength shifting fiber. It is placed in a $\mu$-metal tube which serves as additional shielding against the static magnetic filed. Inside $\mu$-metal tube, the PMT is aligned with respect to the fiber connector in such a way that each fiber shines only one channel. Therefor it was important to measure all dimensions of the PMT and especially position of the anode matrix with respect to the PMT case (Figure 9, centre). Figure 10 shows distributions of the measured dimensions (width and height) and displacements of the anode matrix for 53 MAPMTs. It was found that on average the matrix is shifted by 0.5 mm upwards (see Figure 9, right and Figure 10, bottom right). This was taken into account in the design of the MAPMT fiber connectors.

As for the MAPMTs, the single-anode photo-multiplier tube (SAPMT) is placed in a $\mu$-metal tube. The EMR detector was initially assembled by reusing old SAPMTs, available after the disassembly of the HARP experiment [13]. These were 10 stage linear focused PMTs produced by Philips (model XP2972). A special selection procedure was developed in order to select the best samples for the assembly of the detector [14]. In 2014, during the upgrade of the detector, all Philips SAPMT were replaced by new SAPMTs produced by Hamamatsu (model R6427 [12]).

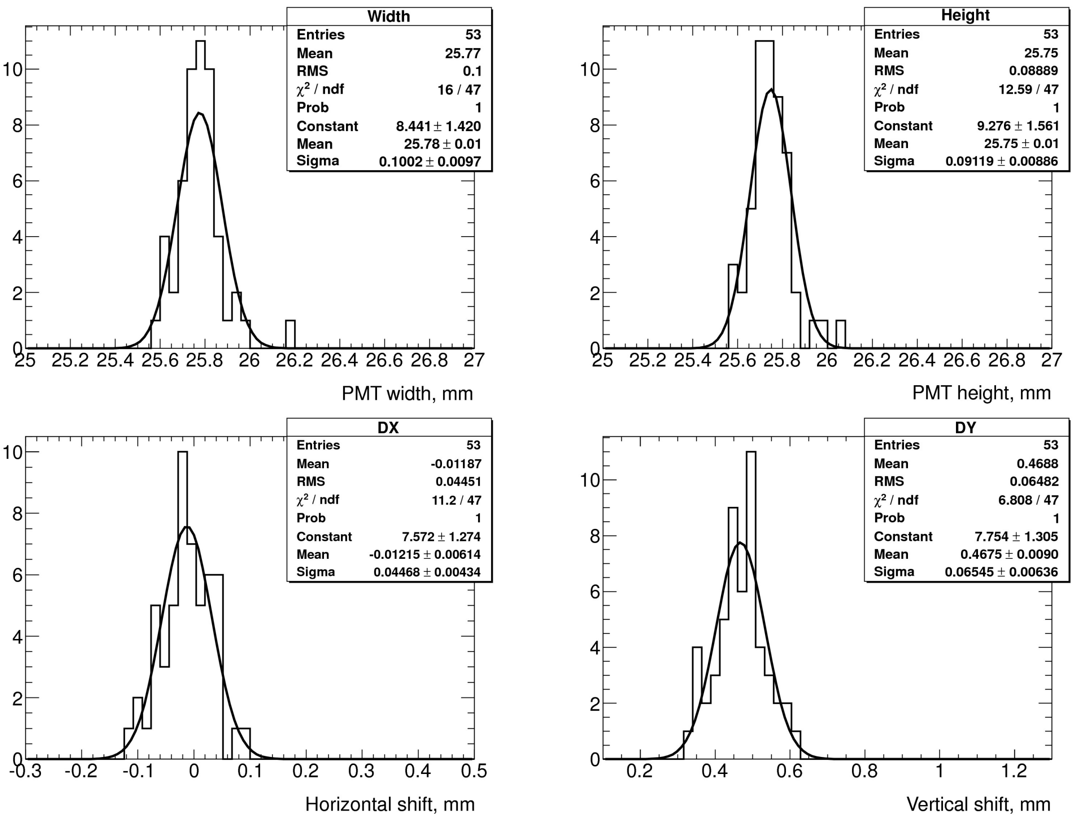


Figure 10: Distribution of Multi-Anode PMT dimensions.

### 2.3 Electronics Layout

In MICE the spill is defined as the period when the target crosses the ISIS proton beam. The maximum spill repeating rate allowed by the MICE target system is $\sim 0.75\ Hz$. The overall principle of the MICE Data Acquisition (DAQ) system is that during the spill the accumulated digital data is kept in local memory buffers and the readout is performed only at the end of the spill.

A schematic layout of the EMR electronics is shown in Figure 11. The multi-anode PMT connected via a flex cable to a front-end board (FEB) which processes the signal and sends it to a piggy-back digitizer-buffer board (DBB) for digitization and storage. The FEB is configured by the VME configuration board (VCB), which resides in the VME crate in the control rack. This board is able to configure up to 16 FEBs, therefore three of them are required for the full detector. The DBBs are readout by groups of six. In each group the first DBB 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 (VRB), which transfers all the data from the six DBBs to the DAQ computer. In the whole detector there are 8 groups of DBBs, i.e. 8 VRBs are installed in the control rack.

#### 2.3.1 Front-End and Digitizer-Buffer Boards

The multi-anode PMT is readout by a dedicated front-end board equipped with piggy-back digitizer-buffer board which stores hit information during a spill. Figure 12 show the full assembly that is mounted on every plane of the detector. It consists of a PMT attached to a voltage divider which is connected to a FEB through a flex cable. This cable also creates additional pressure between the

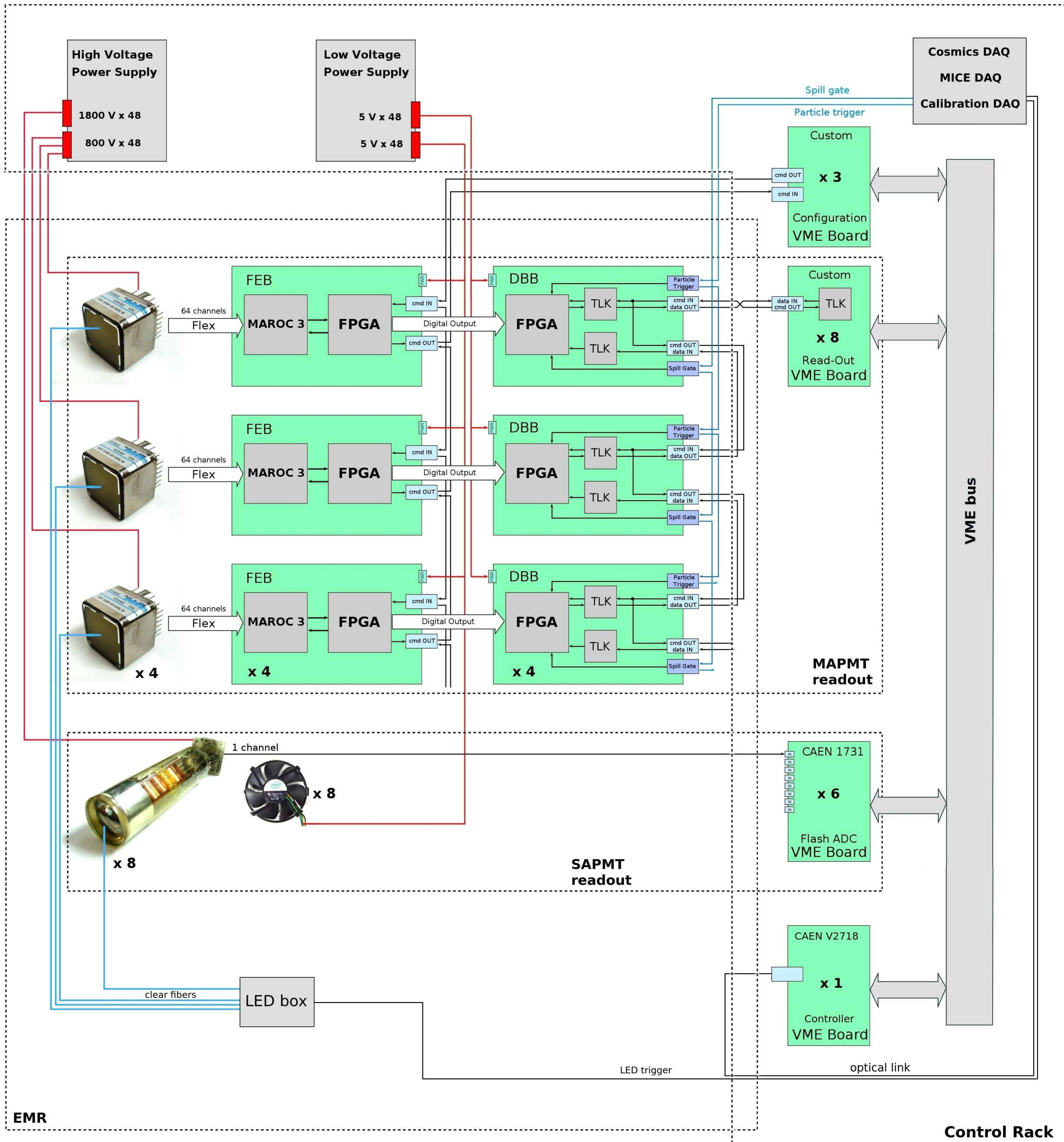


Figure 11: EMR electronics layout. **FEB:** front-end board for multi-anode PMT readout. **DBB:** digitizer-buffer board. **MAROC 3:** 64 channel readout ASIC for multi-anode PMT. **MAPMT:** multi-anode PMT. **SAPMT:** single-anode PMT.

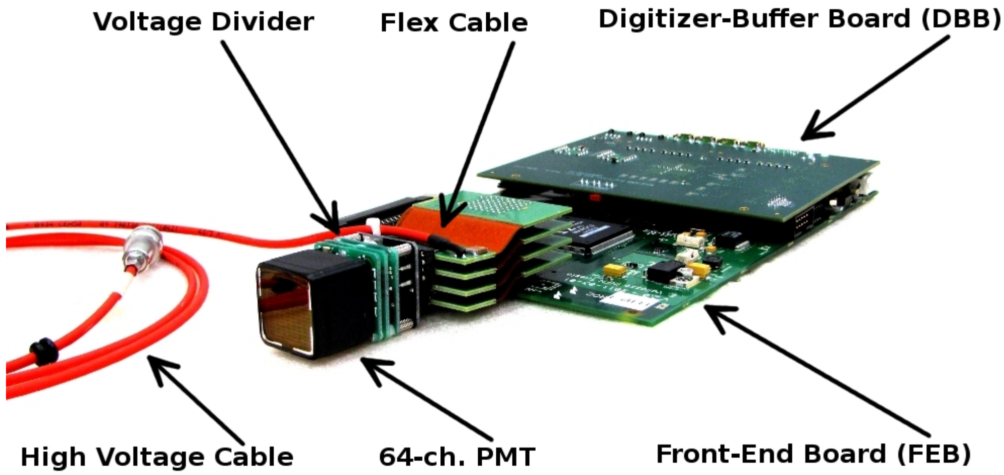


Figure 12: Front-end and Digitizer-Buffer board assembly.

PMT and fiber connector. The FEB is able to process all 64[5] signals of the MAPMT thanks to 64-channel ASIC[6] called MAROC[7]. The 64 analog signals are feed into the MAROC chip where they are shaped and discriminated. The discriminated signals are then forwarded to two high density connectors where a DBB is connected. The width of the discriminated signal represents a 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 function of the FPGA chip[8] is mainly to forward data from MAROC to the DBB and to send configuration signals from the VCB 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 two essential roles of the DBB are to sample the 63 channels (and external trigger) coming from the FEB and to transmit the event data upon request of the acquisition system. The digitization starts when the board receives the Spill Gate signal from an external LEMO connector. The number of clock ticks from the begging of the spill to the leading edge and trailing edge of every discriminated signal coming from the FEB is recorded. The difference between the two measurements represents the 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 DBB. The trigger signal is feed into one of the 64 input channel and is treated as any other signal. Therefore, only 63 channels are recorded from the FEB. 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[9] that performs the sampling, data buffering, and dataflow control functions of the board. Internal memory of the FPGA, configured as FIFO, is used to store the event data which is a collection of leading and trailing

[5]Each EMR plane contains 59 scintillator bars which results in having 5 redundant channels.
[6]Application-Specific Integrated Circuit
[7]Multi Anode ReadOut Chip
[8]Altera Cyclone II (EP2C35F484C8N)
[9]Altera Stratix II (EP2S30F484C3N)

edge timestamps that occurred on each channel during a specific spill. Two gigabit transceivers[10] 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 VRB - via four coaxial cables.

### 2.3.2 VME Configuration Board

The VCB is a single FPGA[11] board designed to perform configuration of the MAROC chip on the FEB. The communication between the boards is realized via LVDS[12] signals driven and received by LVDS drivers/receivers directly connected to corresponding FPGA's. As mentioned in the previous section, it can read analog signal (charge of the signal from every channel) from the FEB but this 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[13] signal composed of 830 bits which code the configuration parameters.

### 2.3.3 VME Read-Out Board

One VRB performs the readout of a group of six DBBs. It is a single FPGA[14] board with a gigabit transceiver[15], which drives the communication with the DBBs and four high-speed 16M-bit static RAMs[16], providing a local memory buffer. During the readout cycle, the transfer of the data between the DBBs and the DAQ computer is executed in two steps. First, after a request from the DAQ computer, the VRB starts transferring data from the 6 DBBs. The gigabit transceiver is used for this and the received data is temporarily stored locally. The four static RAMs, each organized as 16 bits data words, are grouped in two pairs, providing the record of the DBB data, which is originally structured in 32 bits data words. Once the first part of the transfer is completed, and all the data accumulated by the 6 DBBs during the spill is available in the local memory buffer of the VRB, the DAQ computer sends a second request which triggers the transfer of this data over the VME bus.

Additional LVDS input/output connector is available at the front pannel of the board. This connector does not have a specific function, and was used mostly for debugging.

### 2.3.4 Fast ADC Board

The Flash ADC Waveform Digitizer made by CAEN [15] is used to readout signals from single-anode PMTs. The ADC has a sampling frequency of 500 M 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.

## 2.4 Mechanics

Total wight 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

[10] TLK1501
[11] Altera Cyclone II (EP2C50F484C8N
[12] Low-Voltage Differential Signaling, communication protocol.
[13] Transistor-Transistor Logic
[14] Altera Cyclone II (EP2C50F484C8N)
[15] TLK1501
[16] IS61WV102416BLL-10TLI - SRAM, 16Mbit, 10ns, 48TSOP

in a truck over more then 1000 kilometers. Therefore a reinforced support frame (see Figure 13) 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.

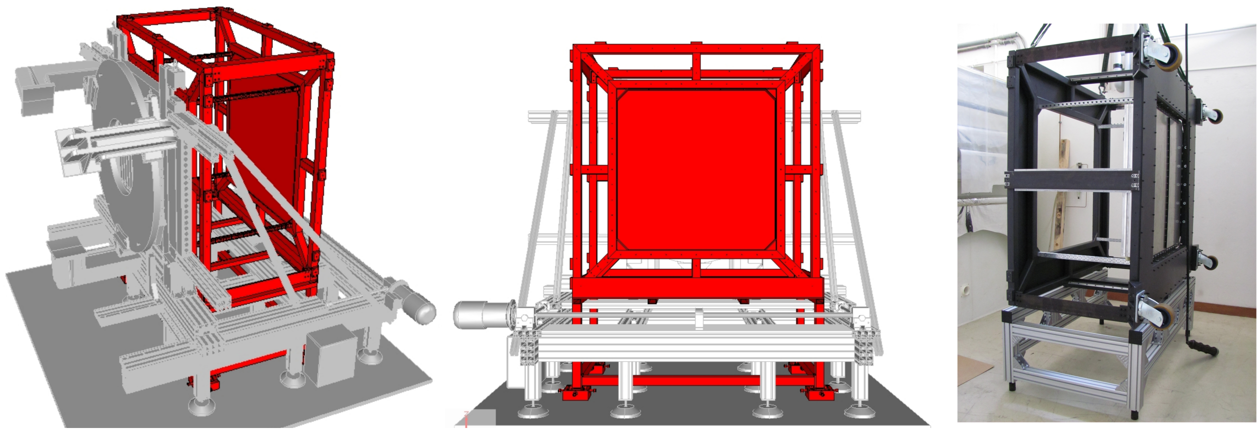

Figure 13: EMR support frame. When installed in the experimental hall the EMR is integrated into support structure of other detectors.

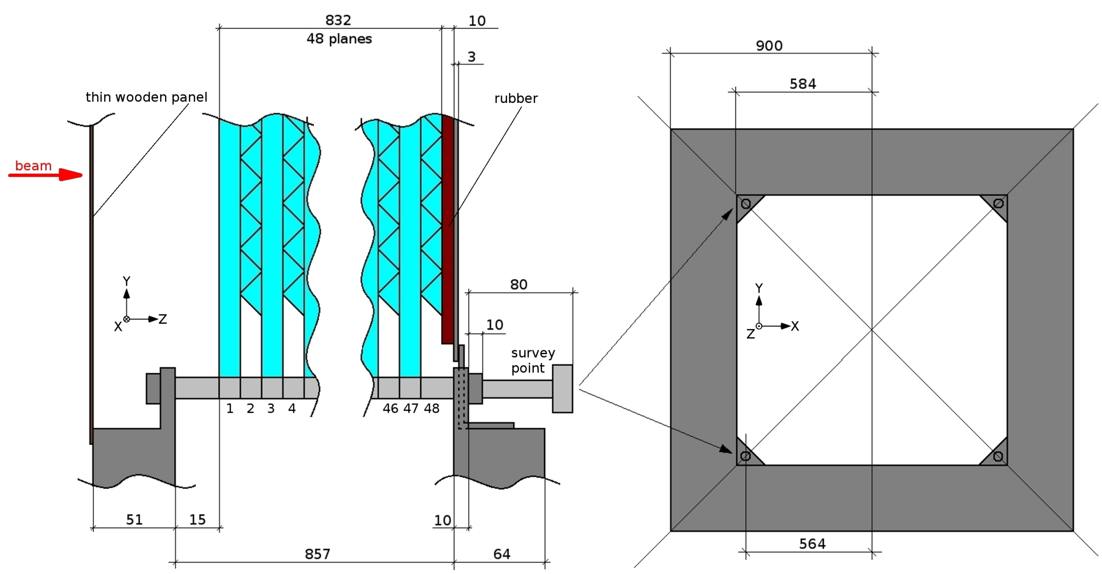


Figure 14: EMR dimensions (mm).

Figure 14 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 14, right) is made of 5 cm thick iron plates (total wight 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).

# 3 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. 2832 bars are required fro building the full detector. 3150 bars were glued and assembled with fiber connectors in order to provide enough spares available.

In the second step, each fiber connector (two per bar) was polished on a dedicated bench equipped with four different diamond sanding papers. 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 parallel with bar gluing fiber bundles (see Figure 15) 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 7, 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 **??**, bottom). In total there were 96 fiber bundles (48 for each type of the PMTs).

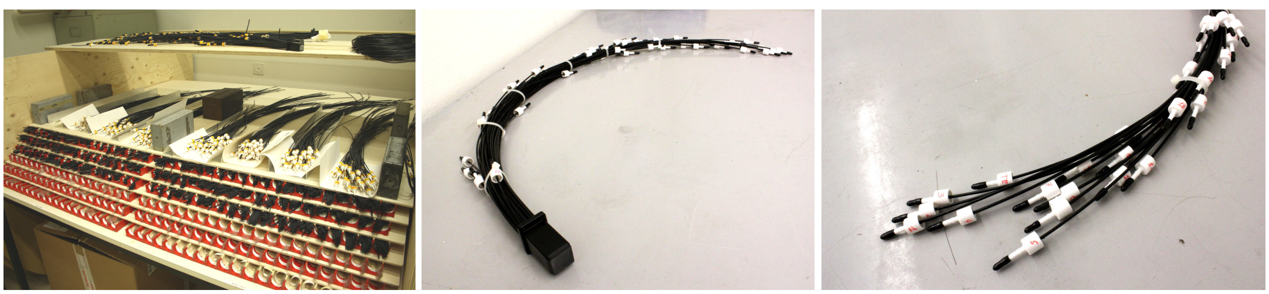

Figure 15: Clear fiber bundles. **Left:** fiber pre-cut to the specified length. **Center:** PMT connector. **Right:** fiber connector.

# References


[1] Mice web site. *http://mice.iit.edu*, contains detailed information about the experiment.

[2] D. Neuffer. Principles and applications of muon cooling. *Part. Accel.*, 14:75, 1983.

[3] C. N. Booth and et al. The design, construction and performance of the mice target. *Journal of Instrumentation*, 8:P03006, 2013.

[4] ISIS pulsed neutron and muon source at the Rutherford Appleton laboratory. web site. *http://www.isis.stfc.ac.uk*.

[5] S. Choubey et al. International design study for the neutrino factory. *Interim Design Report*, IDS-NF-20, 2011. arXiv:hep-ex/1112.2853.

[6] R. Asfandiyarov. Totally active scintillator tracker-calorimeter for the Muon Ionization Cooling Experiment. *University of Geneva, PhD thesis*, 2014.

[7] A. Pla-Dalmau, A. Bross, and K. Mellott. Low-cost extruded plastic scintillator. *Nucl. Instrum. Meth.*, A466:482–491, 2001. FERMILAB-PUB-00-177-E.

[8] A. Pla-Dalmau. Extruded plastic scintillator for the MINOS calorimeters. *Frascati Phys.Ser.*, 21:513–522, 2001. FERMILAB-CONF-00-343.

[9] A. Pla-Dalmau, A. Bross, V. Rykalin, and B. Wood. Extruded plastic scintillator for MINERvA. *Nuclear Science Symposium Conference Record, IEEE*, 3, 2005. FERMILAB-CONF-05-506-E.

[10] Saint-Gobain Crystals. Scintillating fiber brochure.

[11] Kuraray. Plastic scintillating fibers brochure.

[12] Hamamatsu. Multianode photo-multiplier tubes R5900-00-M64 datashee.

[13] M. G. Catanesi et al. [HARP Collaboration]. The HARP detector at the CERN PS. *Nucl. Instr. and Meth.*, (A 571):527, 2007.

[14] R. Asfandiyarov et al. Selecting philips xp 2972 photomultiplier tubes for the electron muon ranger (emr). *MICE internal note*, 2012. MICE-NOTE-DET-383.

[15] CAEN. V1731 4/8 ch. 8 bit 1000/500 ms/s Digitizer. Technical information manual.