PROGRESS IN THE CONSTRUCTION OF THE MICE COOLING CHANNEL

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On Behalf of the MICE Collaboration

Abstract

The international Muon Ionization Cooling Experiment (MICE), sited at Rutherford Appleton Laboratory in the UK, aims to build and test one cell of a realistic ionization cooling channel lattice. This comprises three AbsorberFocus-Coil (AFC) modules and two RF-Coupling-Coil (RFCC) modules; both are technically challenging. The Focus Coils are dual-coil superconducting solenoids, in close proximity, wound on a common mandrel. Each pair of coils is run in series, but can be configured with the coil polarities the same (solenoid mode) or opposite (gradient mode). At the center of each FC there is a 20-L liquid-hydrogen absorber, operating at about 14 K, to serve as the energy loss medium for the ionization cooling process. The longitudinal beam momentum is restored in the RFCC modules, each of which houses four 201.25-MHz RF cavities whose irises are closed with 42-cm diameter thin Be windows. To contain the muon beam, each RFCC module also has a 1.4-m diameter superconducting coupling solenoid surrounding the cavities. Both types of magnet are cooled with multiple 2-stage cryo-coolers, each delivering 1.5 W of cooling at 4 K. Designs for all components are complete and fabrication is under way. Descriptions of the various components, design requirements, and construction status is described.

INTRODUCTION

Neutrino Factory [1] (Figure 1) based on muon storage ring is the ultimate tool for studies of neutrino physics [2]. 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 produced from pion decay at the proton driver target. Ionization cooling is a proposed mechanism to reduce this on a suitably short timescale. It has never been demonstrated in practice but has been shown by simulation 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 [3] in which a section of cooling channel is exposed to a muon beam, which would demonstrate and explore this technique for the first time in practice. It is proposed to install MICE at the ISIS facility [4], at Rutherford Appleton Laboratory (RAL).

The MICE collaboration started in 2001 and now rallies about 140 people, engineers, accelerator and particle physicists from more than 40 institutes in Europe, USA, China and Japan. The MICE collaboration is working together with the US MuCool Collaboration with whom it shares several objectives.

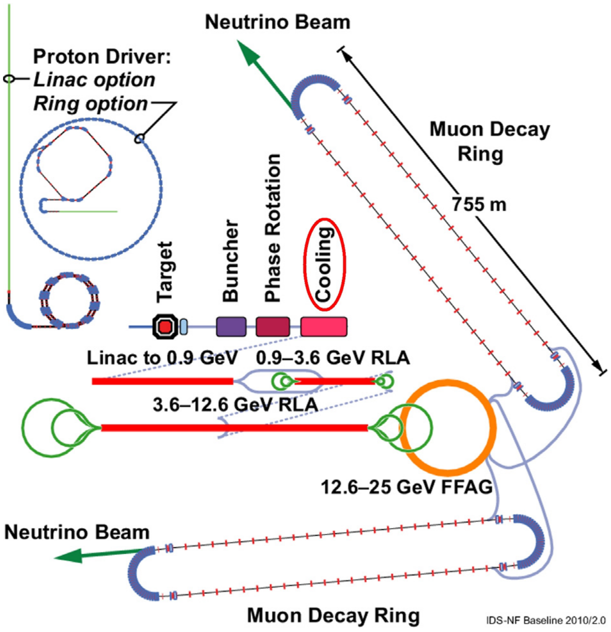

Figure 1: Neutrino Factory baseline scheme.

Ionization Cooling

The principle of ionization cooling relies on the cooling rate formula, expressing the emittance variation in a medium with thickness X $(g \cdot cm^2)$ due to ionization(cooling) and multiple scattering(heating):

$$\frac{d\epsilon_n}{dX} = -\frac{\epsilon_n}{\beta^2 E_\mu}\left\langle \frac{dE_\mu}{dX} \right\rangle + \frac{\beta_t (0.014GeV)^2}{2\beta^3 E_\mu m_\mu X_0} \qquad (1)$$

where ϵ_n is the normalized 4D emittance of the beam, β_t is the betatron function, and β is the velocity of the particle. The ideal cooling channel should produce the lowest possible emittance:

$$\epsilon_{eq} = \frac{\beta_t (0.014GeV)^2}{2\beta m_\mu X_0}\left\langle \frac{dE_\mu}{dX} \right\rangle^{-1} \qquad (2)$$

Hence, the goal is to minimize the β_t and maximize $X_0 \langle \frac{dE_\mu}{dX} \rangle$. Therefore liquid hydrogen has been chosen for the first realization of the absorber of a cooling channel.

Due to the short muon lifetime (2.2 μs), ionization cooling must be used. The cooling of the transverse phase-space coordinates of a muon beam can be accomplished

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by passing it through a light energy-absorbing material and an accelerating structure as shown in Figure 2, both embedded within a focusing magnetic lattice. Longitudinal and transverse momentum are lost in the absorber while the RF-cavities restore only the longitudinal component.

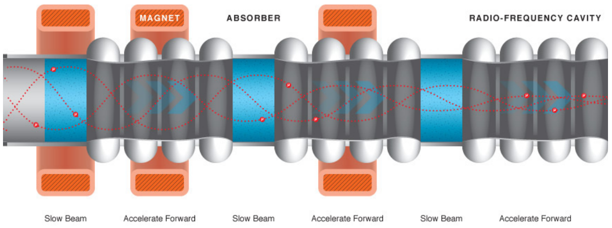


Figure 2: To create a narrow, uniform muon beam, particles are sent through a series of absorbers and cavities.

The MICE aims to construct a cooling cell (Figure 3) with all the equipment necessary to measure the emittance of a muon beam before and after this cell based on single particle measurements and achieve 10% cooling of 200 MeV/c muons. The cooling cell will be sandwiched between two identical trackers inside 4T superconducting solenoids, complemented by upstream and downstream particle detectors.

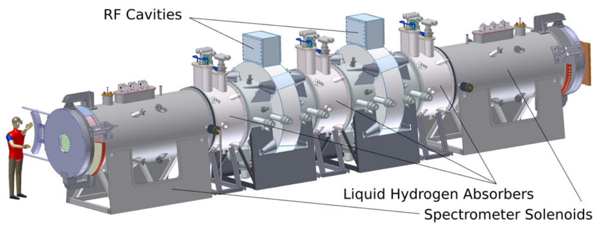


Figure 3: 3D view of the MICE cooling cell.

BEAM LINE

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

The beamline 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 match the beam into the experiment. A schematic of the beamline layout is shown in Figure 4.

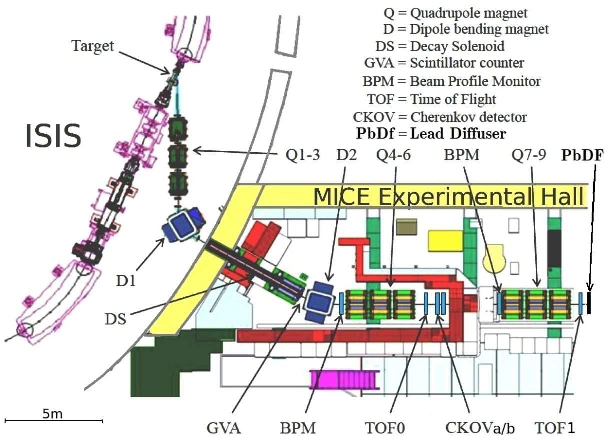


Figure 4: The layout of MICE muon beamline.

The beamline has been already installed: target, Q1, Q2, Q3, D1 inside ISIS synchrotron enclosure; decay solenoid, Q4, Q5, Q6, TOF0, CKOVa/b inside decay solenoid area and Q7, Q8, Q9, TOF2, KL in the MICE Hall (Figure 5).

Figure 5: Recent photo of the MICE Hall.

A dedicated system has been designed in Sheffield to dip the Ti target into the halo of the beam in the few milliseconds preceding the extraction of the primary proton beam. The main constraint was that the target should be completely out of the way when the injection of the next ISIS bunch starts. The acceleration of 80g m/s^2 necessary to meet this requirement has been achieved recently with the target attached to a leaded bronze shaft driven by induction coils. The system has been running reliably for more than 12 weeks at a rate of 1 Hz, producing more than 5 millions actuations.

The first section of the beamline is designed to capture as large a pion acceptance as possible from the target, and to momentum select the pions into the decay section. It has been designed to select high momentum pions, such that the muons are derived from backward decay in the pion rest frame. This has advantages in terms of the final muon flux and purity. The decay solenoid then serves to accumulate as large a flux of muons as possible. Muon extraction section consists of a large aperture dipole, to select muons of the desired momentum, and two sets of large aperture quadrupole triplets to transport the muon beam towards the experiment. The half-widths of the pion-muon beam profile are illustrated in Figure 6.

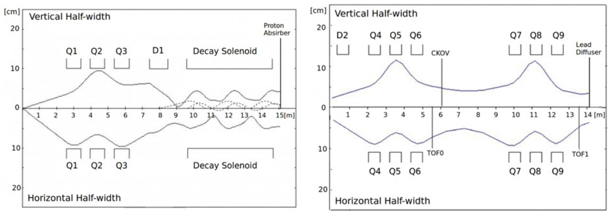


Figure 6: Beam profile for the pion injection, decay and extraction sections.

COOLING CHANNEL

The Layout of the MICE Cooling Cell is shown in Figure 7. It consists of three, 35 cm, liquid-hydrogen absorbers to achieve a 10% reduction in emittance and eight 201 MHz RF cavities to re-accelerate the muon beam. Trackers within 4 T solenoids make single particle measurements at each end of the cooling channel. Each tracker consists of five scintillating-fibre planes, measuring x, y, px, py, which are transverse coordinates to the beam, and the muon energy. A pair of match coils in each spectrometer tune the magnetic optics to match the muon beam into and out of the cooling lattice.

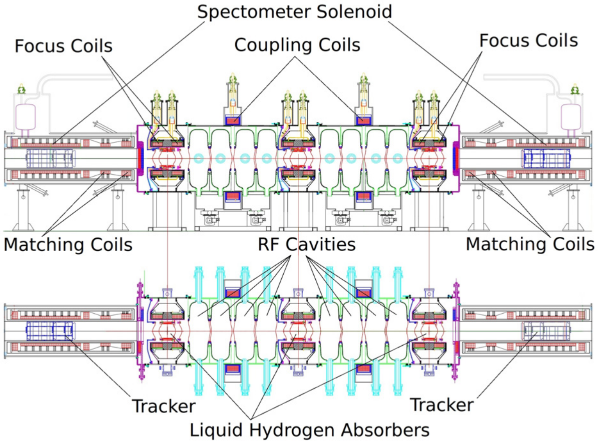


Figure 7: The Layout of the MICE Cooling Cell.

Liquid Hydrogen Absorber Module

The absorber module is made of two main components - the liquid hydrogen container and distribution system. It represents a considerable safety challenge. The container is 35 cm long for a volume of 20 litters. It is sealed by 0.18 mm, curved aluminum windows. The entire system is double walled for safety reasons. The 3D view of the module is shown in Figure 8. Each muon loses about 12 MeV in the absorber, i.e. 1 W for a beam of $5 \cdot 10^{11}$ muons per second. The absorbers have been built in KEK, Japan in 2010 and the first one has been already delivered to RAL (Figure 9, left). The set of two focus coils provides small β_t inside the absorber. The winding of the coils is complete (Figure 9, right) and installation in the Hall is scheduled for the end of this year.

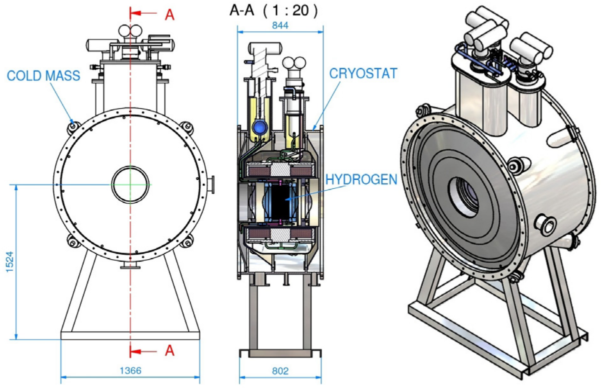


Figure 8: CAD drawings of the liquid hydrogen absorber module.

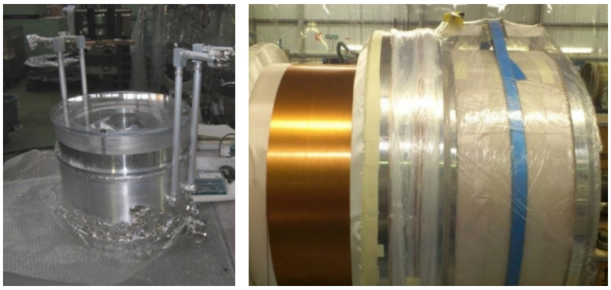


Figure 9: Progress in construction of the liquid hydrogen absorber module and focusing coils.

RF and Coupling Coil (RFCC) Module

RFCC module (Figure 10) has four 201 MHz normal-conducting RF cavities and one superconducting coupling coil (solenoid) magnet. Each RF cavity has a pair of curved Be windows and it operates in a few Tesla magnetic field at 8 MV/m.

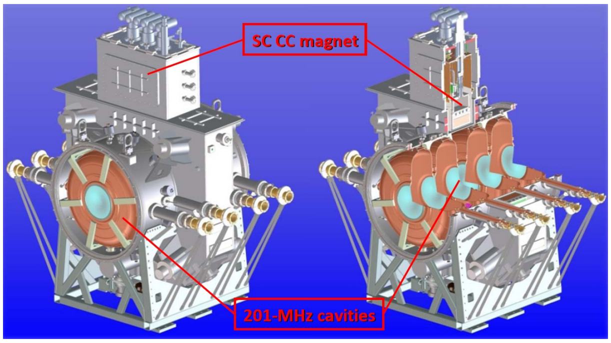


Figure 10: 3D view of the RFCC module.

Ten RF cavities (Figure 11, left) and nine berilium windows (Figure 11, middle) have been manufactured and received at BNL for further tests in 2010. First coupling coil winding is completed at Qi Huan Company already (Figure 11, right).

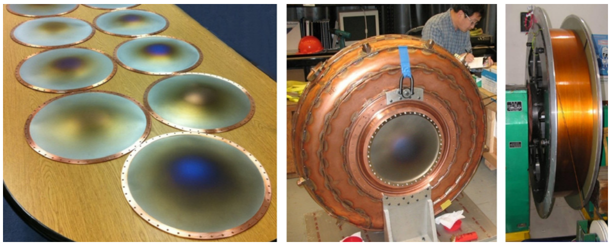


Figure 11: Progress in construction of the RFCC Module.

Spectrometer Solenoids

The two spectrometers modules (Figure 12) are fully symmetrical. Each is made of a cylindrical tracker immersed into a solenoid field of 4 T. The main solenoid coil is flanked by two correcting coils ensuring field uniformity. Two additional coils on the absorber side provide matching optics with the cooling cell. The three coils are connected in series and are powered by a single 300 amp power supply.

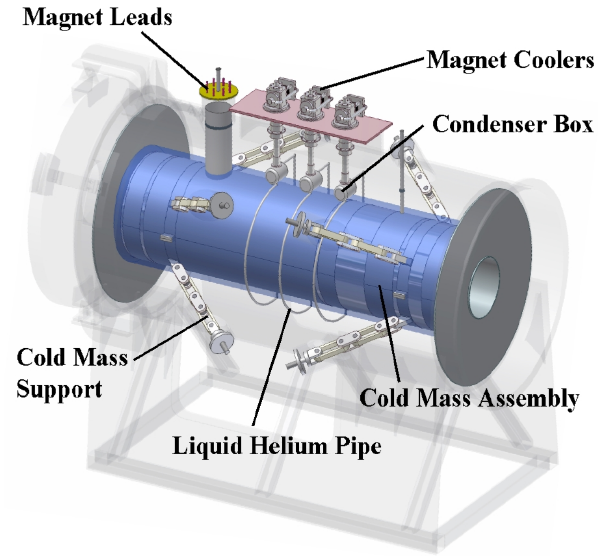


Figure 12: The layout of the spectrometer solenoid module.

The magnets have been produced in US (Figure 14). The first module is to be completed and ready for tests by the end of 2011 and the second one in three months. The modules will be delivered to RAL in 2012.

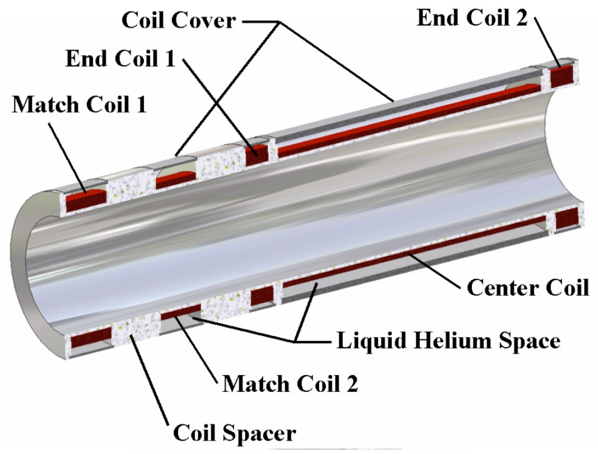


Figure 13: Composition of the spectrometer solenoid module.

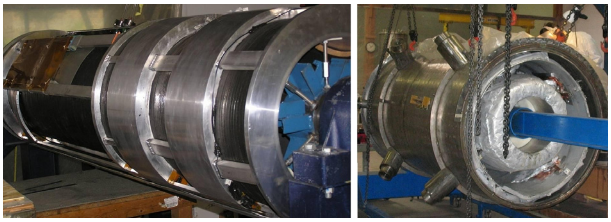


Figure 14: Progress in construction of the spectrometer solenoid modules.

Scintillating Fibers Tracker

The tracker (Figure 15) is 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 $\sim$9K.

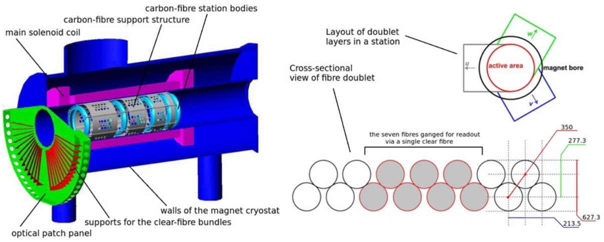


Figure 15: Scintillating fibers tracker layout.

Both of the upstream and downstream trackers have been constructed (Figure 16) and performance has been examined with cosmic-ray runs performed at RAL in 2008-2009: light-yield 11.23±0.01 photo electrons; RMS of the residual distributions 682μm$\pm 1\mu$m; channel resolution 470μm; space-point efficiencies 99.7% for each station.

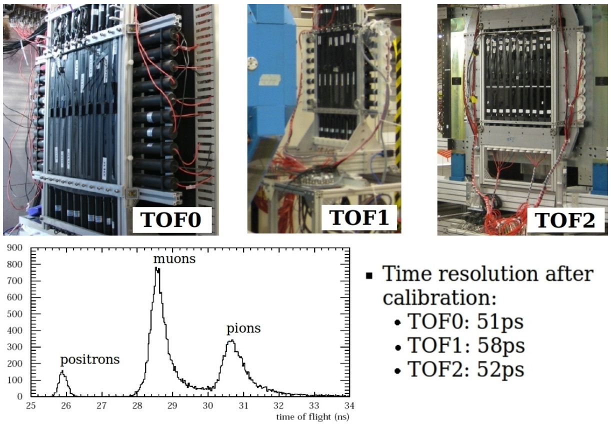
Figure 16: Progress in construction of the scintillating fibers tracker.

PARTICLE IDENTIFICATION (PID) DETECTORS

PID is obtained upstream of the first tracking solenoid by two TOF stations (TOF0/TOF1) [6] and two threshold Cherenkov counters (CKOVa/CKOVb), that will provide muon/pion/electron separation up to 300 MeV/c. Downstream the PID is obtained via a further TOF station (TOF2) and calorimeters (KL and EMR), to separate muons from decay electrons. All TOF detectors are used to determine the time coordinate in the measurement of the emittance.

Time of Flight Stations: TOF0, TOF1, TOF2

The TOF stations (Figure 17) are used in establishing a precision particle trigger which can be synchronized to within 70 ps of the RF cavity phase. TOFs are made of two crossed planes of plastic scintillator bars 2.54 cm thick and 4-6 cm wide and cover ~50 cm^2 active area. The signal is readout from both ends of scintillator bars by fast PMTs shielded against stray magnetic field which provide 50-60 ps intrinsic timing resolution. A trigger signal is given by the first dual coincidence of the PMTs connected to the same TOF0 bar.



- Time resolution after calibration:
  - TOF0: 51ps
  - TOF1: 58ps
  - TOF2: 52ps

Figure 17: Progress in construction of the time of flight stations.

Cherenkov Counters: CKOVa, CKOVb

The two Cherenkov counters share the same design (Figure 18). 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 can be used to complete the PID. CKOVs have been installed in the beamline (Figure 19).

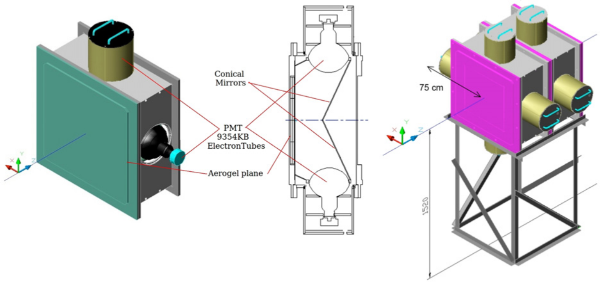


Figure 18: 3D view of the Cherenkov detectors.

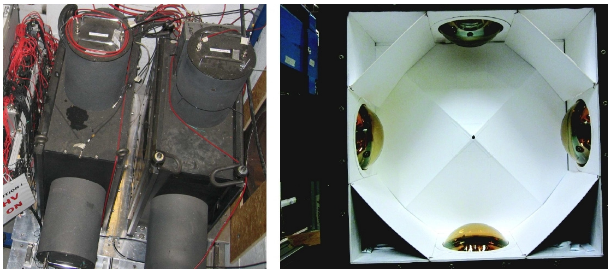


Figure 19: Progress in construction of Cherenkov Counters: CKOVa, CKOVb

Calorimeter: KL

The calorimeters are dedicated to the separation between the muons and the electrons produced by muon decaying in the cooling channel. A design study has demonstrated that a better particle identification is obtained with a detector made of two parts. The first part (KL) is a 4 cm thick conventional sampling calorimeter made of grooved lead foils interleaved with scintillating fibers. It forces the electrons to shower while most of the muons are going through. The second part is EMR.

The KL electromagnetic calorimeter was installed in the MICE Hall in June 2008 and operates successfully since then. It allows to distinguish between electrons, muons and pions at different energies. Muons/electrons/pions with momentum above 135/160/70 MeV/c at KL entrance will pass through KL.

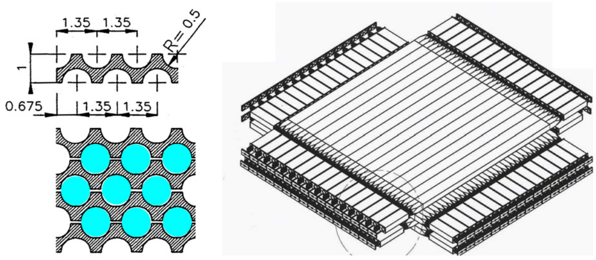


Figure 20: 3D view of KL detector.

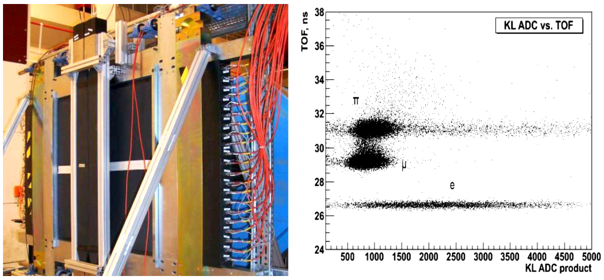


Figure 21: Progress in construction of KL calorimeter.

Calorimeter: Electron-Muon Ranger (EMR)

A fully active scintillator calorimeter (Figure 22) is located at the very end of the cooling channel. It will stop all muons and electrons and give very distinct signatures for both allowing to measure particle range. It has 1 m^3 of active volume, 48 planes composed of 59 triangular scintillator bars with glued 1.2 mm wavelength shifting fibers; light is collected by single-anode PMT on one side of a plane and by 64-channel PMTs - on the other: 3120 channels in total; the granularity of the detector allows it to reconstruct individual tracks and measure energy deposition in every bar.

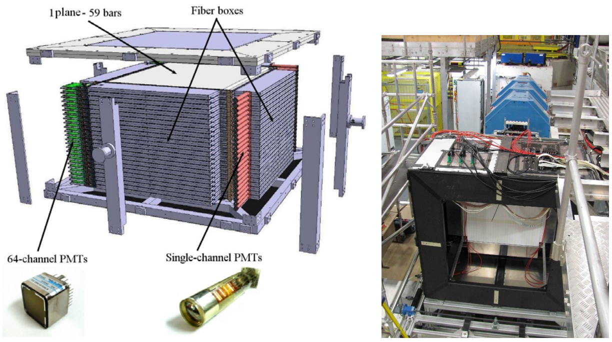


Figure 22: EMR detector design (left) and first tests at RAL (right).

EMR with 3 X-Y modules (6 planes) was installed in the MICE hall on June 16^{th} for preliminary tests. Electronics and DAQ have been successfully tested. Construction will be finished next year.

CONCLUSIONS

The installation of the MICE [7] experiment is underway at RAL, UK. The major challenge of the experiment is the operation of large gradient RF cavities in intense magnetic field and in the vicinity of liquid hydrogen cells. The beam line was commissioned in early 2008. Particle identification detectors have been installed in MICE hall and used for the first emittance measurements. Most of the components of the cooling channel have been produced and under commissioning. The first observation of ionization cooling with a partial setup is expected for October 2012, after the delivery of the first absorber. The setup with RF cavity is aimed for April 2014 (Figure 23).

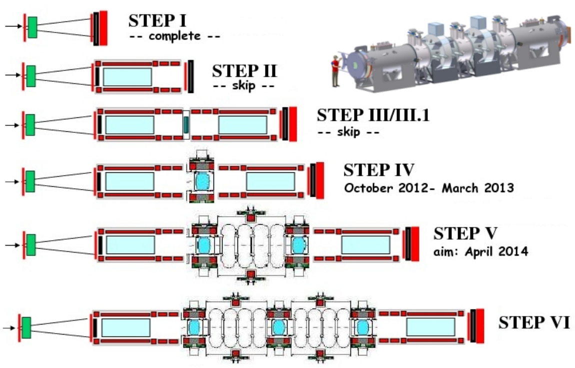


Figure 23: MICE Schedule.

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