MICE: THE INTERNATIONAL MUON IONIZATION COOLING EXPERIMENT

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Abstract

An international experiment to demonstrate muon ionization cooling is scheduled for beam at Rutherford Appleton Laboratory (RAL) in 2008. The experiment comprises one cell of the neutrino factory cooling channel, along with upstream and downstream detectors to identify individual muons and measure their initial and final 6D emittance to a precision of 0.1%. Magnetic design of the beam line and cooling channel are complete and portions are under construction. This paper describes the experiment, including cooling channel hardware designs, fabrication status, and running plans. Phase 1 of the experiment will prepare the beam line and provide detector systems, including time-of-flight, Cherenkov, scintillating-fiber trackers and their spectrometer solenoids, and an electromagnetic calorimeter. The Phase 2 system will add the cooling channel components, including liquid-hydrogen absorbers embedded in superconducting Focus Coil solenoids, 201-MHz normal-conducting RF cavities, and their surrounding Coupling Coil solenoids. The goal of MICE Collaboration is to complete the experiment by 2010.

INTRODUCTION

The MICE experiment is part of the R&D programme towards a neutrino factory based on a muon storage ring, largely considered as the most precise tool to probe neutrino physics in the future. The cooling of muon beam is largely unexplored and is a major source of uncertainty on the cost and construction time of a neutrino factory. MICE has been designed to demonstrate that it is possible to engineer, build and operate safely and reliably a section of linear muon ionization cooling channel similar to the one proposed in the US Feasibility Studies [1].

The MICE collaboration started in 2001 [2] 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 also working together with the US MuCool Collaboration with whom we are sharing several objectives.

GENERAL DESIGN

An introduction to Ionization Cooling can be found in [3]. Basically, under certain conditions, cooling is obtained when the beam passes through some energy absorbing material where it loses energy by ionization. The conditions are 1) the Z of the material is low, in order to maximize the ratio between the stopping power, responsible for cooling, and the multiple scattering cross section, responsible for heating; 2) The transverse β function is small at the position of the absorber. Additionally, in order to avoid de-bunching effects, the energy loss in the forward direction should be compensated for. In line with these principles, the MICE cooling channel is made of three liquid hydrogen absorbers alternating with two linac sections, each composed of four RF cavities. Rapid evaluation has shown that this system should be able to cool a 6π mm rad beam by about 10% [4]. The aim of the experiment is to measure this cooling effect with a precision of 1%, requiring a precision of 0.1% on the emittance measurement before and after the cooling channel. Such a precision can't be obtained with standard beam diagnostic instrumentation hence we had to adopt a particle per particle tracking approach. It has been shown as well [5] that pion and electron contamination in the beam introduces a bias on the emittance measurement, imposing the presence of some detectors dedicated to Particle Identification (PID), both upstream and downstream. The tracker and PID detectors have been designed using a simulation code based on GEANT4 [6] but developed especially for MICE. This code, called G4MICE, after validation by precise experimental data, can be considered as one of the most important deliverable of the experiment since it should become a reliable tool for the design of future cooling channels.

THE BEAM LINE

MICE will be hosted by the Rutherford Appleton Laboratory (RAL) in the UK. A new muon beam line is under construction using the existing, 800 MeV, 300 μA, proton synchrotron, ISIS. The beam line components are shown in Figure 1 and detailed in [7]. A short description is given below.

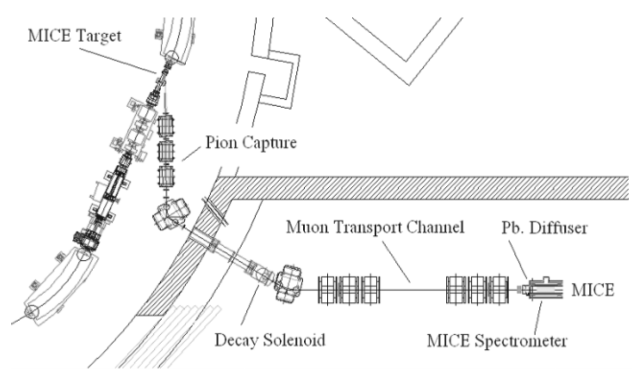

Figure 1: Schematic view of the MICE beam line at ISIS, Rutherford Appleton Laboratory, UK.

The Target System

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

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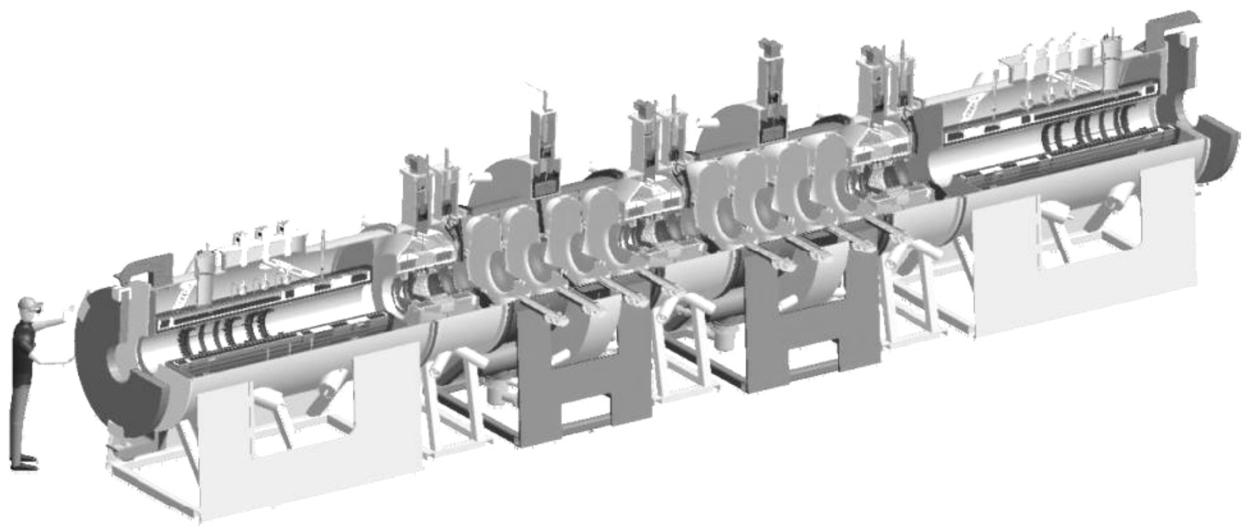

Figure 2: 3-D cutaway rendering of the MICE apparatus, showing, from left to right, the first spectrometer module, the first LH_2 absorber module, the RF module and, at the centre of symmetry, the second absorber module.

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. However, the observation of a small amount of dust produced by the wearing of the shaft and bearings has led to the decision to test a diamond-like carbon coated shaft.

Pion Collection and decay

The pions produced by the collision of the protons on the target are captured by a triplet of quadrupoles, followed by a dipole selecting the pion's momentum. The pions then decay in a 5 m long, 12 cm bore, supra-conducting (SC) solenoid (5 T) which is the contribution to the experiment from the Paul Scherrer Institute, Switzerland. All the magnetic elements in the ISIS vault have been put in place before the accelerator start-up in August 2007. Unfortunately, a vacuum leak in the cooling system of the solenoid prevented us to install it and forced us to add temporary radiation shielding in the hall, disturbing the plan for subsequent installations.

Muon optics

After the decay solenoid, a second dipole selects muons with half the momentum of the original pions (backward muons). This particular setting ensures a very large reduction of the pion content in the muon beam. Muon beam central momentum will be selectable from 140 MeV/c to 240 MeV/c. The entire beam line has been designed to obtain about 600 muons traversing the cooling channel per target shot.

The second dipole is already mounted on rails, allowing transverse translation and necessary clearance for the decay solenoid installation. After the second dipole, two triplets of quadrupoles transport the beam up to the entrance of the cooling channel where a lead diffuser distribution system provides variable beam emittance from less than 1π mm rad up to 10π mm rad.

THE COOLING CHANNEL

The MICE cooling channel is illustrated in Figure 2, together with the upstream and downstream trackers that are also part of the main magnetic channel.

Absorber Module

The absorber module (Fig. 3) is made of two main components. The first is the liquid hydrogen container and distribution system. It represents a considerable safety challenge. It has been designed and prototyped in KEK and is now under test at the MuCool Test Area (MTA) in Fermilab, USA. The container is 35 cm long for a volume of 20 litters. It is sealed by 0.18 mm, curved

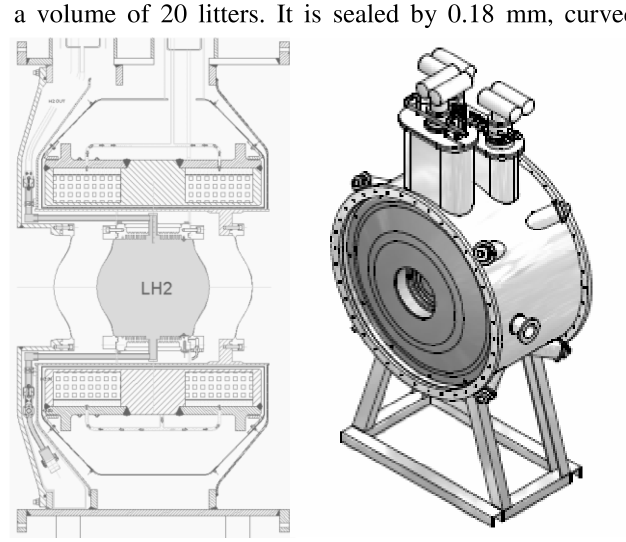

Figure 3: Left: a sketch of the LH_2 absorber. Right: 3D rendering of the Focus Coil Module.

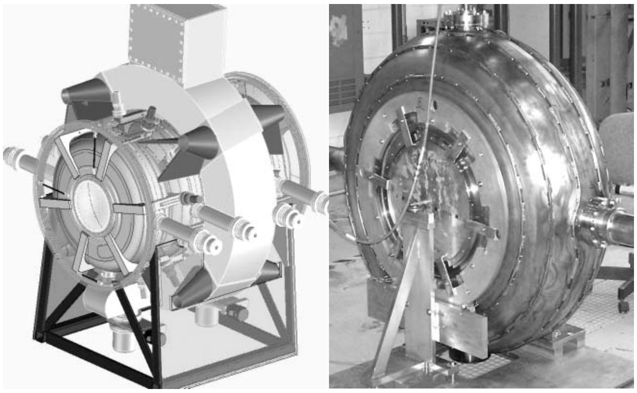

Figure 4: The RF and Coupling Coil Module. Left: three-dimensional rendering of the preliminary design. Right: The prototype 201 MHz RF Cavity.

aluminium windows. The entire LH2 system is double walled for safety reasons. Each muon looses about 12 MeV in the absorber, that is 1 W for a beam of 5 10^{11} muons per second. The system has been designed to absorb up to 15 W of power.

The second main component of the absorber module is the set of two SC focus coils, providing the required small β function inside the absorber. The two coils can be operated with identical or opposite polarities, allowing a rapid field flip inside the absorber. The absorber modules are now out for tender and should be delivered in mid 2009.

RF Module

Relatively low RF frequency (201 MHz) has been chosen to handle the extended muon beam. A large SC coil surrounds the cavities allowing for magnetic coupling with the neighbouring focus coils. The magnetic field inside the RF cavities reaches a few Tesla, precluding the use of SC cavities and enhancing field emission.

Large, water cooled, copper cavity has been prototyped and tested at the MTA. It has reached easily 16 MV/m without magnetic field. Further tests are needed to validate the pre-curved beryllium windows used to isolate the individual cavities and to study the behaviour under large magnetic field. Simulations have shown that the RF background stays at an acceptable level in the condition of the experiment. The RF and Coupling Coil Module (RFCC) is still in the design phase but the production of the coupling coils should start shortly, thanks to a fruitful collaboration with ICST in Harbin, China. The delivery of the first RFCC is scheduled for summer 2009.

THE PARTICLE DETECTORS

The particle detectors are based on standard particle physics techniques. Apart from the tracker, the data digitalization and readout use commercial VME electronics controlled by PCs running Linux.

Spectrometers

The two spectrometers modules are fully symmetrical. Each is made of a cylindrical tracker immerged 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 channel. These magnets are in the manufacturing process with delivery of the first coil expected for spring 2008.

The tracker inside has been optimized to minimize the amount of material in the beam. It is made of 5 stations of 350 μm scintillating fibres, exploiting the technology of the Fermilab-D0 tracker [8]. Each station is perpendicular to the beam axis and is made of three plans of fibres rotated by 60^{o} in order to resolve degeneracy in case of multiple hits. By recording hit positions in the five stations, it is possible to reconstruct the full helix track of the particle and obtain the longitudinal and transverse momentum. A four-station prototype has been constructed and tested in beam at KEK in 2005 with magnetic field. It has shown a spatial resolution better than 440 μm, allowing a momentum resolution of 1.5 Mev/c in p_T and 3 Mev/c in p_z for a typical muon at 200 MeV/c. The first tracker, completed with the fifth station will be tested with comics ray in November 2007 and installed in the beam early 2008. The two complete spectrometers are expected for summer 2008.

Time of Flight Stations

Three Time-of-Flight (TOF) stations are placed along the beam line in the experimental hall, respectively between the two triplets of quadrupoles, just before the diffuser and just after the downstream spectrometer. They are made of two crossed plans of plastic scintillator slabs, 1” thick and a few centimetres wide (Fig. 5). Each slab is equipped with standard light guides and Photomultiplier Tubes (PMT). Tests in beam have shown that this design

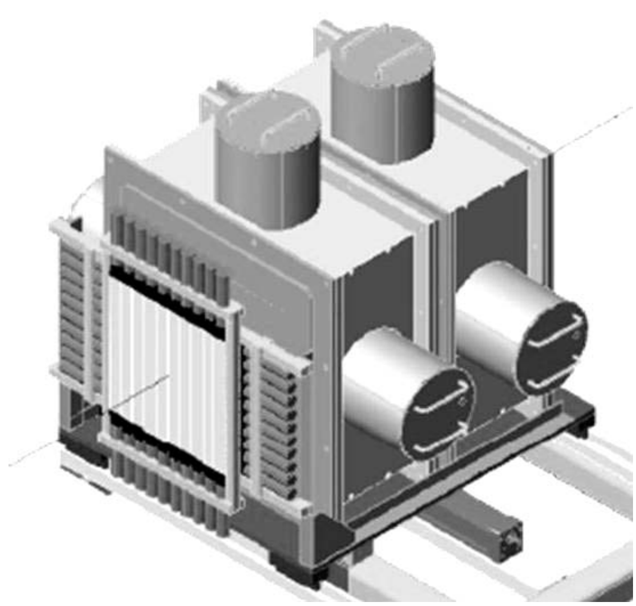

Figure 5: 3-D rendering of the upstream PID module, showing the first TOF station (foreground) and the two Cherenkov counters (background).

allows a resolution on the time of flight between two stations of 70 ps [9]. The first two stations provide a good muon/pion separation at low energy while the second two provide the time information needed for 6D emittance measurement as well as the time of arrival with respect to the RF phase. The main problem encountered with the design of the TOF stations is the intense fringe field coming from the solenoid coils and imposing a heavy iron magnetic shielding. The first two stations are under construction and will be delivered in November 2007.

Cherenkov Counters

The two Cherenkov counters share the same design. A three dimensional view is shown in Figure 5. 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 plans, ensuring a good muon/pion/electron separation at high momentum when electrons trigger both counters, muons only one and pions none. At lower momentum, the TOF counters can be used to complete the PID. The first Cherenkov counter is already assembled at RAL and will be tested in November 2007 together with the first tracker and the TOF stations. The second counter is under construction in the US and will be delivered to RAL later this year.

Electron Muon Calorimeter

The last particle detector is dedicated to the separation between the muons and the electrons produced by muon decaying in the cooling channel. A careful design study [10] has demonstrated that a better PID is obtained with a detector made of two parts. The first part is a 4 cm thick conventional sampling calorimeter similar to the one used for the KLOE experiment [11]. Grooved lead foils interleaved with scintillating fibres force the electrons to shower while most of the muons are going through. The second part is a fully active plastic scintillator wall, thick enough to stop all the muons and segmented along the beam axis (z axis) to allow range measurement. The layer thickness also increases along the z axis to improve the performance of the system for low energy muons, almost stopped in the first layer. Muons and electrons behave very differently in such a device. Electrons lose more energy in the first layer while muons exhibit the Bragg peak in the last layer. In general, the energy deposit of the muon is much larger than that of the electron for which a significant part of the kinetic energy is radiated as gamma rays and is not detected by the scintillator. Apart for the last layer, the energy deposit is also much more homogenous since the muon tack angle is conserved. Last but not least, for the muons, there is a well defined relation between the total energy deposit and the range which is less pronounced from the electron distribution.

A prototype of the first part, manufactured in Rome III has been tested in beam in the summer 2006. The final production is nearly finished. The second part is still at the prototyping stage in Trieste, Italy. The plan is to use extruded scintillator with individual wavelength shifter fibres coupled to standard or solid sate (Si) PMTs.

CONCLUSION

The installation of the MICE 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 commissioning will start in early 2008. In the meanwhile, the particle detectors will be commissioned with cosmic rays. The first observation of ionization cooling with a partial setup is expected for mid 2009, after the delivery of the first absorber. The complete setup should be operational by the end of 2009 and the final result, the first performance measurement of a realistic muon ionization cooling channel, delivered in 2010.

REFERENCES

[1] M. Zisman, "Review of U.S. Neutrino Factory Studies", Nuclear Physics B155-1, May 2006, pp. 336-338, and references there in.

[2] The MICE web site, http//mice.iit.edu offers very complete documentation links and references.

[3] R.P. Johnson, "Ionization Cooling", COOL07, Bad Kreuznach, September 2007, TUM2I04.

[4] P. Drumm, Proceedings of PAC'05, Knoxville, May 2005, pp. 398-400

[5] R. Sandström, "Background and Instrumentation in MICE", PhD Thesis, Geneva, 2007.

[6] GEANT4 Collaboration, Nuclear Instruments and Methods in Physics Research A 506 (2003) 250-303, and IEEE Transactions on Nuclear Science 53-1 (2006) 270-278.

[7] K. Tilley et al, Proceedings of EPAC'06, Edinburgh, WEPLS002, pp. 2397-2399

[8] T. Hart, "MICE Tracker Data Acquisition Using D0 Analog Front End IIt Boards", MICE Note 139, April 2006 and
The MICE tracker group, "Specification of the scintillating and clear fibre for the MICE scintillating fibre trackers", MICE Note 135, December 2005, http://mice.iit.edu/notes/notes.html

[9] M. Bonesini et al, "Study of the MICE TOF prototypes performance at the BTF test beam", MICE Note 163, February 2007, http://mice.iit.edu/notes/notes.html

[10] R. Sandström, "Comparison of two calorimeter designs", MICE Note 146, September 2006, http://mice.iit.edu/notes/notes.html

[11] J. Lee-Franzini, "The KLOE electromagnetic calorimeter", Nuclear Instruments and Methods in Physics Research A 360 (1995) 201-205