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MICE: The international Muon Ionization Cooling Experiment

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Abstract. The MICE collaboration has designed an experiment made by a section of an ionization cooling channel equipped with particle detectors used as beam diagnostics stations. The channel uses liquid-hydrogen absorbers to provide energy loss and high-gradient RF cavities to re-accelerate the particles; this setup is designed to reduce the beam transverse emittance by $> 10\%$ for muon momenta in the range 140MeV/c to 240MeV/c. The particle detectors, grouped in two spectrometers before and after the channel, are meant to measure the beam transmittance and emittance reduction with an absolute precision of $\pm 0.1\%$.

1 Introduction

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 [1] [2]. It is also the first step toward a $\mu^+\mu^-$ collider.

Ionization cooling of muons is straighforward in principle, but it has never been demonstrated in practice. It has been shown by end-to-end simulation and design studies to be an important factor for both performance and cost of a Neutrino Factory.

This motivates an international program of R&D, including an experimental demonstration. The aims of the 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

A proposal [3] has been submitted to Rutherford Appleton Laboratory (RAL) to mount the experiment at ISIS.

2 Measurement technique

Two techniques have been considered.

- The multi-particle method: emittance and number of particles are derived from measurements of global properties of the bunches.
- The single-particle method: each particle is individually measured to determine its properties.

There are several advantages in the choice of the single-particle method:

- Possible correlations are easily measured if the parameters are computed on a particle-by-particle base.
- Detailed understanding of the role of each beam parameter can be studied by making selection cuts on a set of measured particles.
- Any desired input beam condition can be reconstructed by appropriate weighting in a set of observed particles.

Additionally, measuring the 6-dimensional covariance matrix, from which the 6d-emittance can be easily computed [10], would be a very delicate task in a multi-particle experiment.

The previous considerations lead us to the choice of performing single-particle measurements; this technique, typical of particle physics experiments, can be based on well-proved and already existing experimental methods.

On the base of evaluations taking into account the resolution of the detectors and the pion contamination in the accepted muon sample, it is believed that MICE is able to achieve an absolute accuracy in the emittance measurement of 0.1% or better.

Several sources of systematic errors have been evaluated. The most important ones are the uncertainties in thickness or density of the liquid-hydrogen absorbers and of other materials in the beam line, the degree of control over the magnetic fields and the systematic differences (efficiency, alignment, uniformity of the magnetic field) in the measurement devices. Present estimates of the systematic errors on the ratio of output to input emittance indicate a value of $\pm 10^{-3}$.

3 Experimental setup

The experiment is sketched in Fig. 1. Cooling is made by two cells as designed in the Neutrino Factory "Study II"

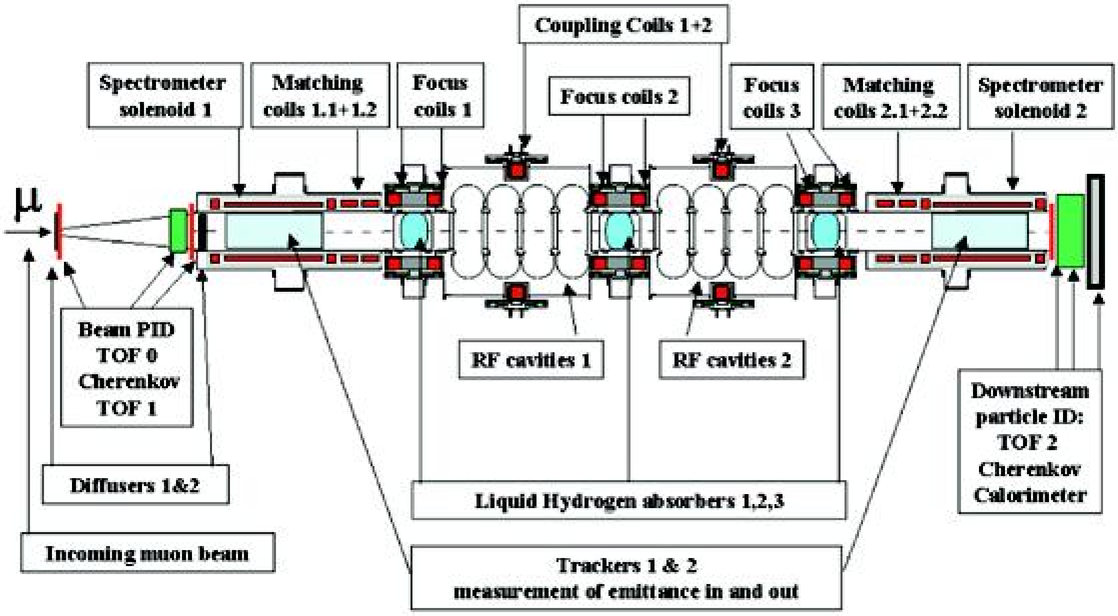

Fig. 1. Setup of the MICE Experiment

[4]; it has been necessary to apply some modifications to reduce the cost and to comply with RAL's safety rules.

At the entrance of the apparatus, diffusers are provided to generate a tunable, large input emittance; this first region is equipped with detectors able to assign a precise timing and identification to the incoming particles.

Before entering the lattice cell, the particles traverse a solenoid spectrometer equipped with tracking devices, in order to measure space coordinates, angles and momenta.

The cooling section is made by liquid hydrogen absorbers and RF cavities in a solenoid magnetic field provided by superconducting coils.

The track parameters of the outgoing particles are measured by a spectrometer identical to the first one. Timing and particle identification are again checked at the end of the apparatus.

3.1 The cooling channel

The channel has to achieve cooling of the transverse phase-space of the muon beam by reducing the kinetic energy of the muons in the absorbers, where the normalized emittance decreases; the kinetic energy than has to be replenished by accelerating RF cavities.

The magnetic channel is symmetric with respect with its center, where two focusing coils sit around an absorber. Moving away from the center, there are a coupling coil of rather large inner diameter ($0.69m$) around an RF cavity assembly, a set of absorber and focusing coils, than a set of matching coils preceding the uniform-field region ($4T$ $30cm$ diameter and $1m$ long) hosting the spectrometer. In the baseline configuration, the channel operates at an average momentum of $200MeV/c$ and $\beta = 42cm$ at the center of the absorber. Several operating parameter sets have been identified, with momenta ranging from $140MeV/c$ to $240MeV/c$ and β values from $5.7cm$ to $42cm$.

Each cavity assembly is made by 4 cavities, hence a total of 8 201-MHz RF cavities are needed in total. Due to financial limitations, the cavities will be operated at about $8MV/m$ instead of the $16MV/m$ of the "Study-II" design. The cavities must be normal-conducting to properly operate in strong magnetic field, and the iris must be large enough to accommodate the transverse size of the beam. In these conditions, using conventional open-iris cavities would be inefficient; to achieve high shunt impedance, the beam aperture is electromagnetically terminated with low-Z, very thin conductive windows.

The absorbers are made by very thin Aluminum windows enclosing liquid hydrogen. The absorber length is $35cm$ and the diameter is $30cm$. Their design had to cope with the conflicting requirements of minimizing the thickness of the windows while respecting the safety requirements. The material has been chosen to maximize the energy loss by ionization and minimize the multiple scattering probability.

3.2 The detectors

The core of the MICE detectors is represented by two spectrometers, one upstream and one downstream of the cooling section; they are complemented by Time-Of-Flight (TOF) and Particle Identification (PID).

It must be pointed out that, beside the need of precise tracking and high-purity particle identification, a MICE-specific challenge is the harsh environment of a particle accelerator; the particle detectors will have to be certified against electromagnetic noise from the RF system and high-intensity X-ray photon sources generated by RF dark currents.

The muons must be tagged and identified against the background of beam protons and pions, and the cases where the muons decayed along the cooling channel must be properly discarded. Precise timing and reliable particle identification are needed both upstream, by TOF and Cerenkov, and downstream, by TOF, Cerenkov and electromagnetic calorimetry.

The TOF system is made by three stations, two upstream and one downstream; its purpose is to provide the basic trigger for the experiment, measure muon timing (relative to the RF phase) for the measurement of the longitudinal emittance, and contribute to particle identification. It has been evaluated that a time resolution of about $70ps$ provides effective PID and adequate timing; such performances seem within reach, as similar performances have already been published for TOF systems of similar dimensions [5].

Additional redundancy in PID is provided by Cerenkov detectors, both upstream and downstream. To address the cases where the muons decay in flight along the cooling channel, redundancy in $e - \mu$ separation is provided by the downstream electromagnetic calorimeter.

Overall, the PID detectors must make sure that the contamination by wrong particles is kept below 1%.

The solenoids must be equipped with tracking devices providing adequate resolution in transverse and longitudinal momentum. Specific issues for the trackers are the minimization of the material budget, to keep the multiple scattering to the minimum and to reduce conversions of RF-generated photons, and the provision for enough redundancy to separate signals of real tracks from random hits due to the photon background.

Two options are being considered. Prototypes of both options are being intensively studied under all the relevant aspects, with the aim of taking a decision in late 2003.

The baseline choice is made by 5 planes of scintillating fibers, each plane consisting of three sets of fiber doubles arranged at 120° to each other. Each plane will have an active area of $30cm$. Very light construction will be achieved by the adoption of thin, $350\mu m$ diameter fibers. Scintillation light will be routed to high quantum efficiency Visible Light Photon Counters (VLPCs). The design is inspired by the D0 [6] fiber tracker. The adoption of $350\mu m$ fibers should provide large enough photon statistics, due to the reduced length of the clear fibers with respect to D0. Very good rejection of the background photon conversions is possible in such an intrinsically fast detector by exploiting the timing capabilities; by the addition of timing to the standard D0 readout electronics, resolutions or the order of $1ns$ are considered to be achievable.

The alternative option is a Time Projection Chamber (TPC) with GEM amplification [7], or TPG in short [8]. The proposed readout plane, called *hexaboard* [9], is made by hexagonal $300\mu m$ pads with a $450\mu m$ pitch and arranged to form three projections oriented at 120° to each other. The TPG technique offers the following advantages:

- Choosing a light gas mixture (He-based) keeps the multiple scattering and photon conversion probability down to exceptionally low figures.
- Thanks to the uniformity of the readout plane, the response is uniform, regardless of the track angles.
- A large number of space points (≥ 100) is generated per track, each with excellent resolution in the transverse plane, and offering exceptional pattern recognition and background rejection capabilities.
- The application of GEM technology has the advantage of minimizing the ion feedback in the drift volume as well as $\overrightarrow{E} \times \overrightarrow{B}$ effects.

These positive features are of course offset by the long drift time of about $50\mu s$, during which the detector will integrate, together with real hits from muon tracks, any photon conversion from RF dark currents.

4 Conclusions

The international Muon Ionization Cooling Experiment (MICE) collaboration, a team of 147 physicists drawn from 37 institutes in Europe, Japan and the US, proposes to demonstrate ionization cooling in a fully engineered section of cooling channel. The proposed schedule for MICE could establish the technical feasibility of muon cooling in 2007.

By demonstrating the feasibility and assessing its costs and performances, MICE would be a step forward to the provision of high-intensity stored muon beams, allowing to measure neutrino properties with unprecedented precision.

Last but not least, this effort is based on a strong interdisciplinary collaboration of accelerator and elementary-particle physicists.

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