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From: K. Long (MICE spokesman), C. Whyte (MICE Project Manager)

February 6, 2017

Brief specification of the MICE cooling demonstration

To deliver intense muon beams of high brightness requires that the muon-beam phase space is reduced (cooled) prior to acceleration and storage. Ionization cooling, in which the beam is caused to pass through a material (the absorber), in which it looses energy, and is subsequently accelerated, is the technique by which it is proposed to cool the beam. The international Muon Ionization Cooling Experiment (MICE) collaboration seeks to demonstrate the principle of ionization cooling by measuring the performance of a realistic ionization-cooling cell as a function of muon-beam energy, initial emittance and the optics of the lattice. The configuration that was proposed for the demonstration of ionization cooling is shown in figure 1 [1]. It contains a cooling cell sandwiched between two spectrometer-solenoid modules. The cooling cell is composed of two 201 MHz cavities, one primary (65 mm) and two secondary (32.5 mm) LiH absorbers and two superconducting "focus-coil" (FC) modules. Each FC has two separate windings that can be operated either with the same or in opposed polarity.

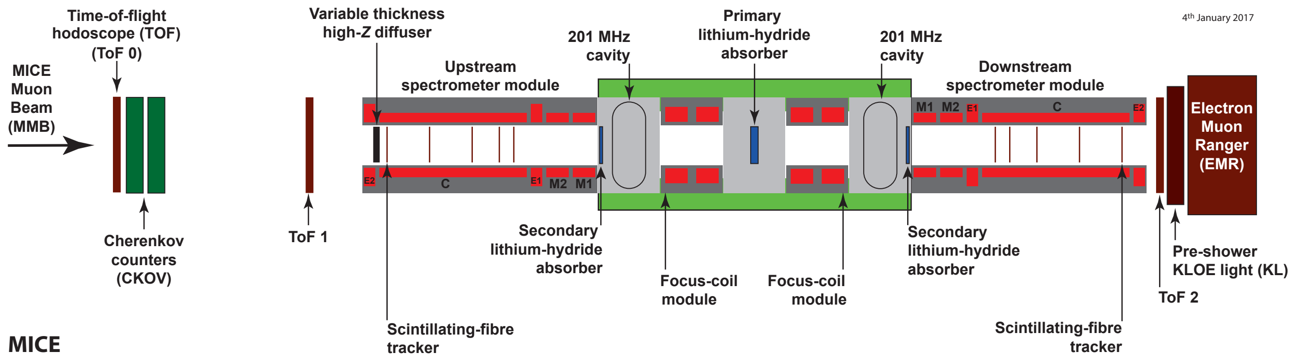

Figure 1: Layout of the lattice configuration for the cooling demonstration. The red rectangles represent the solenoids. The individual coils in the spectrometer solenoids are labelled E1, C, E2, M1 and M2. The ovals represent the RF cavities and the blue rectangles the absorbers. The various detectors (time-of-flight hodoscopes [2, 3], Cerenkov counters [4], scintillating-fibre trackers [5], KLOE Light (KL) calorimeter [6, 7], electron muon ranger [8]) used to characterise the beam are also represented. The green-shaded box indicates the cooling cell.

The MICE programme is executed in "Steps". The MICE collaboration is now executing "Step IV" of its programme. Step IV is optimised for the study of the factors that determine the size of the ionization-cooling effect and consists of the two spectrometer modules sandwiching a central lithium-hydride or liquid-hydrogen absorber (see figure 2). Each spectrometer solenoid is instrumented with a scintillating-fibre tracker [5]. The spectrometers have been designed such that the change in the properties of the beam as it passes through the absorber (for example $\epsilon_\perp^{\rm n}$) can be measured with a relative precision at the per-cent level [5]. Upstream of the first spectrometer, time-of-flight (ToF) hodoscopes and Cherenkov (CKOV) counters are used to reject the small residual pion contamination in the beam [9]. The ToF system will also be used to trigger the experiment and, combined with the upstream spectrometer, measure the longitudinal phase-space of the incoming beam.

Downstream of the experiment, a ToF hodoscope, a lead-scintillator calorimeter (the KL) and a totally active scintillator calorimeter (the Electron Muon Ranger, EMR) will reject electrons (positrons) from muon decay and determine the longitudinal phase-space of the beam as it emerges from the absorber [10, 11]. Both LH_2 and LiH absorbers will be used at Step IV [12, 13].

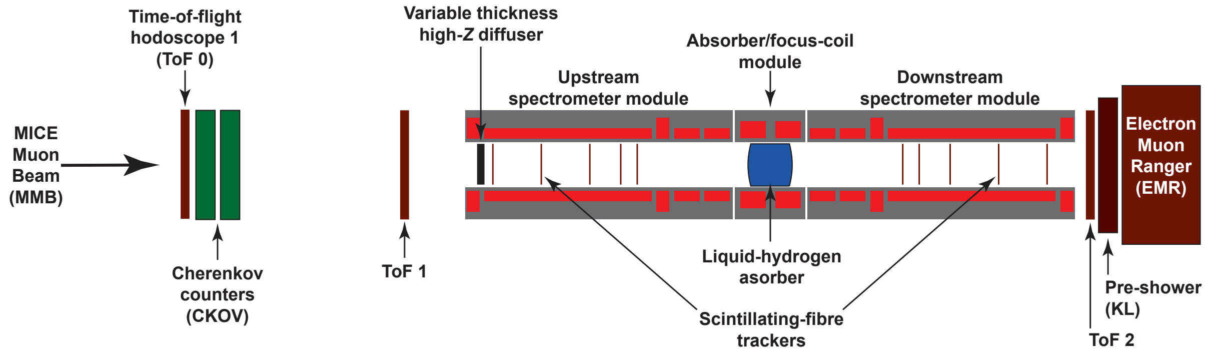

Figure 2: Schematic diagram of the Step IV configuration of MICE. The muon beam enters from the left of the figure. The beam-line instrumentation (the time-of-flight, ToF, hodoscopes, the Cherenkov (CKOV) counters, the pre-shower, KL, detector and the Electron Muon Ranger, EMR) are indicated. The spectrometer solenoids, and the scintillating-fibre trackers they contain are shown upstream and downstream of the central absorber/focus-coil (AFC) module.

Recently, one of the coils (labelled "M1" in figure 1) in the spectrometer solenoid placed downstream of the absorber module failed. Analysis of the failure indicates a possible weakness in the one remaining match coil (M2). As a result, the collaboration is preparing a proposal to upgrade the Step IV configuration to complete the ionization-cooling lattice cell and to reconfigure the instrumentation downstream of the cooling cell as shown in figure 3. Four scintillating-fibre stations from the unused downstream spectrometer will be used to measure the beam emerging from the cooling cell. The performance of the revised configuration is sufficient to prove the principle of ionization cooling and no longer relies on the damaged downstream solenoid.

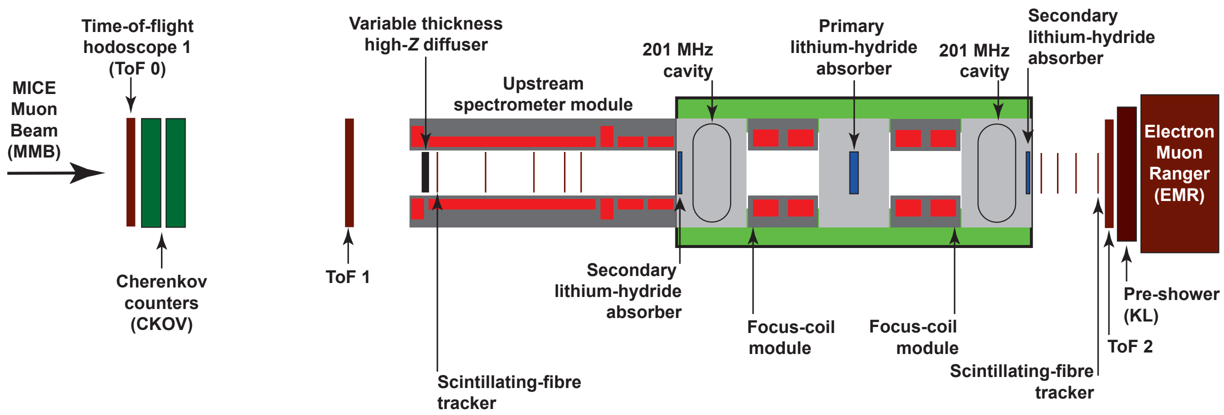

Figure 3: Schematic of the configuration prepared to deliver the demonstration of ionization cooling in the light of the issues related to the downstream solenoid.

The following paragraphs summarise the specification of the MICE Muon Beam on ISIS at the Rutherford Appleton Laboratory, the detector systems that are in use to measure each muon as it passes through the experiment and the infrastructure that is required to support the revised ionization-cooling demonstration. The time table for the elements of the MICE collaboration's programme that are presently approved and the desirable timescale for the proof of the principle of ionization cooling using the equipment that is presently available to the collaboration is also summarised.

1 MICE Muon Beam

The muons for MICE come from the decay of pions produced at an internal target dipping directly into the circulating proton beam in the ISIS synchrotron at the Rutherford Appleton Laboratory (RAL) [14, 15]. A beam line of 9 quadrupoles, 2 dipoles and a superconducting "decay solenoid" collects and transports the momentum-selected beam into the experiment [6]. The beam momentum can be varied over the range 140 MeV/c to 240 MeV/c [16]. A diffuser is installed in the upstream spectrometer to vary the initial normalised transverse emittance of the beam over the range 1–10 mm.

The bulk of data taking will be performed using positive beams. Negative beams can be delivered to study systematic uncertainties. The beam-line instrumentation, which consists of the time-of-flight hodoscopes and Cherenkov counters, installed upstream of the first spectrometer module can be used to select muons and reject pions with high efficiency [9].

A "muon beam tune" corresponds to setting the second dipole to select particles with momentum $\sim 50\%$ of the momentum selected by the first dipole. A muon beam tune yields a beam with a pion contamination of less than 1.4% at the 90% confidence level [17]. "Pion beam tunes" correspond to settings in which the momentum selected by the two dipoles are similar. The beam-line instrumentation is able to select a muon sample with a purity that exceeds 98.6% [18] from the data collected using a pion-beam tune. Since the rate of muons is larger when using a pion beam tune that it is when using a muon beam tune, pion beam tunes are preferred.

The principal parameters of the muon beam delivered to MICE are summarised in table 1.

Table 1: Principal parameters of the MICE Muon Beam.

Parameter	Unit	Value or comment
Δp	MeV/c	20
Vertical angular spread	rad	0.02–0.05
Horizontal angular spread	rad	0.02–0.05
Vertical emittance	mm	2–3
Horizontal emittance	mm	2–3
Intensity	μ/s	30–50 (depending on momentum)

2 Detectors

The specification of the MICE instrumentation is presented in the collaboration's original proposal to RAL [16]. Table 2 summarises the principal parameters that determine the performance of each detector system. In each case, the performance of the detector system quoted meets the specifications defined in [16].

Table 2: Principal parameters that determine the performance of each of the detectors used in MICE.

Detector system	Number	Measured performance	Reference
Time of flight hodoscopes	3	Timing resolution: $\approx$ 60 ps per hodoscope	[2]
Threshold Cherenkov counters	2	Momentum threshold: 210 MeV/c and 270 MeV/c	[19]
Scintillating-fibre trackers	2	Space-point resolution 470 μm	[5]
		$p_\perp$ resolution $\sim$ 1 MeV/c	[20]
		p_z resolution $\sim$ 4 MeV/c	[20]
Lead-scintillator calorimeter (KL)	1	Muon efficiency 98% for momenta $>$ 150 MeV/c	[21]
Electron Muon Ranger (EMR)	1	Electron identification efficiency: 98.6%	[18]
		Muon selection purity: 99.8%	

3 Infrastructure

Physical:
The Mice Hall is a concrete structure with a floor area of 50 m $\times$ 12 m, the ceiling height is 8 m. There are two 8 t overhead gantry cranes that cover essentially all of the floor area. The two cranes can be used in tandem when required. When used in tandem the maximum load is 15 t.

Experimental:
The MICE experiment in its current configuration is 12 m long by 4 m wide by 3 m in height. It is constructed on a steel false floor with aluminium top plates and translation stages.

Electrical:
The electrical power needs of the experiment are summarised in table 3.

Table 3: Power consumption of elements of the MICE Muon Beam and MICE experiment.

Component	Power consumption	Comment
MICE Muon Beam	200 kW	Nominal
Cryo-coolers	200 kW	Nominal
Helium fridge	100 kW	
Air conditioning	350 kW	Five units, each of 70 kW
Roof mounted chiller/air blast cooler	350 kW	500–1000 l/min
Secondary chiller	175 kW	500 l/min
Pumps, heaters and services	100 kW	

Weight:
The weight of the principal components of the experiment is summarised in table 4.

Gases:
Helium gas is provided to flush the tracker volume. Nitrogen is used to purge the hydrogen containment volumes. Helium is used to “top up” the magnet cryogenic volumes.

Table 4: Weight of the principal components of the MICE Muon Beam and MICE experiment.

Component	Weight	Comment
Soft iron magnetic flux return	30 t	
Spectrometer solenoid	8 t	Two off, weight per module
Focus coil magnet	4 t	Two off, weight per module
RF module	2 t	Two off, weight per module
Cryo compressor	0.1 t	20 off, weight per compressor

4 Time schedule

The experiment is approved to take data in the Step IV configuration until the end of summer 2017. At the international review of the project that will take place at RAL on the 7^{th} and 8^{th} March 2017 the collaboration plans to bring forward a proposal for the implementation of the revised cooling-demonstration configuration sketched in figure 3. Our schedule shows that this configuration could be implemented at RAL by February 2018.

To develop a project plan for the implementation of the cooling demonstration at IHEP that includes the timetable for the preparation of the necessary proposals will require further discussion between us. The timetable should take into account the recent announcement that nuSTORM will be studied within the CERN Physics Beyond Colliders workshop and the opportunity to develop a 6D-cooling experiment that would build on the results of MICE.

References

[1] **MICE** Collaboration, M. Bogomilov *et al.*, “Design and expected performance of the MICE demonstration of ionization cooling,” `1701.06403`.

[2] **Mice Collaboration** Collaboration, R. Bertoni *et al.*, “The design and commissioning of the MICE upstream time-of-flight system,” *Nucl.Instrum.Meth.* **A615** (2010) 14–26, `1001.4426`.

[3] R. Bertoni, M. Bonesini, A. de Bari, G. Cecchet, Y. Karadzhov, and R. Mazza, “The construction of the MICE TOF2 detector.” `http://mice.iit.edu/micenotes/public/pdf/MICE0286/MICE0286.pdf`, 2010.

[4] L. Cremaldi, D. A. Sanders, P. Sonnek, D. J. Summers, and J. Reidy, Jr, “A Cherenkov Radiation Detector with High Density Aerogels,” *IEEE Trans. Nucl. Sci.* **56** (2009) 1475–1478, `0905.3411`.

[5] M. Ellis *et al.*, “The design, construction and performance of the MICE scintillating fibre trackers,” *Nucl. Instrum. Meth.* **A659** (2011) 136–153, `1005.3491`.

[6] **MICE collaboration** Collaboration, M. Bogomilov *et al.*, “The MICE Muon Beam on ISIS and the beam-line instrumentation of the Muon Ionization Cooling Experiment,” *JINST* **7** (2012) P05009, `1203.4089`.

[7] F. Ambrosino *et al.*, “Calibration and performances of the KLOE calorimeter,” *Nucl. Instrum. Meth.* **A598** (2009) 239–243.

[8] R. Asfandiyarov *et al.*, "The design and construction of the MICE Electron-Muon Ranger," *JINST* **11** (2016), no. 10, T10007, `1607.04955`.

[9] **MICE** Collaboration, D. Adams *et al.*, "Characterisation of the muon beams for the Muon Ionisation Cooling Experiment," *Eur. Phys. J.* **C73** (2013), no. 10, 2582, `1306.1509`.

[10] **MICE Collaboration** Collaboration, M. Bogomilov, "The MICE particle identification system," *Nucl.Phys.Proc.Suppl.* **215** (2011) 316–318.

[11] **MICE** Collaboration, R. Asfandiyarov, "A totally active scintillator calorimeter for the Muon Ionization Cooling Experiment (MICE). Design and construction," *Nucl.Instrum.Meth.* **A732** (2013) 451–456.

[12] G. Kafka, P. Snopok, J. Cobb, and C. Rogers, "Solid Absorber Program Status for MICE Step IV," *Conf.Proc.* **C110904** (2011) 859–861.

[13] S. Ishimoto, S. Suzuki, M. Yoshida, M. Green, Y. Kuno, *et al.*, "Liquid Hydrogen Absorber for MICE," *Conf.Proc.* **C100523** (2010) 421–423.

[14] C. N. Booth *et al.*, "The design, construction and performance of the MICE target," *JINST* **8** (2013) P03006, `1211.6343`.

[15] C. N. Booth *et al.*, "The design and performance of an improved target for MICE," *JINST* **11** (2016), no. 05, P05006, `1603.07143`.

[16] The MICE collaboration, "MICE: An International Muon Ionization Cooling Experiment." `http://mice.iit.edu/micenotes/public/pdf/MICE0021/MICE0021.pdf`, 2003. MICE Note 21.

[17] **MICE** Collaboration, M. Bogomilov *et al.*, "Pion contamination in the MICE muon beam," *JINST* **11** (2016), no. 03, P03001, `1511.00556`.

[18] **MICE** Collaboration, D. Adams *et al.*, "Electron-Muon Ranger: performance in the MICE Muon Beam," *JINST* **10** (2015), no. 12, P12012, `1510.08306`.

[19] L. Cremaldi, D. Sanders, M. Drews, , D. Kaplan, and M. Winter, "Progress on Cherenkov Reconstruction in MICE." `http://mice.iit.edu/micenotes/public/pdf/MICE473/MICE473.pdf`, 2015.

[20] A. Dobbs, C. Hunt, K. Long, E. Santos, M. A. Uchida, P. Kyberd, C. Heidt, S. Blot, and E. Overton, "The reconstruction software for the MICE scintillating fibre trackers," *JINST* **11** (2016), no. 12, T12001, `1610.05161`.

[21] R. Bertoni, M. Bogomilov, M. Bonesini, A. de Bari, G. Cecchet, Y. Karadzhov, D. Orestano, F. Pastore, L. Tortora, and R. Tsenov, "Analysis of PID detectors (TOF and KL) performances in the MICE 2010 Run,".