MUON IONIZATION COOLING EXPERIMENT: CONTROLS and MONITORING

P. Hanlet[*], Illinois Institute of Technology, Chicago, IL, USA 60616,
C. Booth[†], University of Sheffield, Sheffield S102TN UK for the MICE Collaboration[‡]

Abstract

The Muon Ionization Cooling Experiment (MICE) is a demonstration experiment to prove the viability of cooling a beam of muons for use in a Neutrino Factory and Muon Collider. The MICE cooling channel is a section of a modified Study II cooling channel which will provide a 10% reduction in beam emittance. In order to ensure a reliable measurement, we intend to measure the beam emittance before and after the cooling channel at the level of 1%, or an absolute measurement of 0.001. This renders MICE as a precision experiment which requires strict controls and monitoring of all experimental parameters in order to control systematic errors. The MICE Controls and Monitoring system is based on EPICS and integrates with the DAQ and data monitoring systems. A description of this system, its implementation, and performance during recent muon beam data collection will be discussed.

MOTIVATION

Muons, for a neutrino factory or muon collider[1, 2], are produced as tertiary particles $p+N \rightarrow \pi+X$ with subsequent decay $\pi \rightarrow \mu\nu$, and hence have too large an inherent emittance (beam volume in the 6D position and momentum phase space) for a cost-effective accelerator. They must therefore be "cooled" to reduce the beam spread both transversely and longitudinally. Due to the short muon lifetime, the only feasible technique is ionization cooling, which has as yet only been studied in simulations. The international **M**uon **I**onization **C**ooling **E**xperiment (MICE) at the ISIS accelerator at Rutherford Appleton Laboratory (UK), will demonstrate the viability of muon ionization cooling with a variety of beam optics, muon momenta (140-240 MeV/c), and emittances.

MICE will measure a 10% reduction in beam emittance with a 0.1% resolution, making it a precision experiment in which it is imperative that the systematic errors be minimized and well understood. For this reason, as well as budget constraints, MICE is a staged experiment in which the parameters of the beam, detectors, tracking, and cooling channel components are studied in detail in each step.

Emittance is given by $\varepsilon = \sigma_r \sigma_p/(mc)$, where σ_r and σ_p are the RMS spatial and momentum spread, respectively, and mc is the product of the particle mass and speed of light[1, 3]. The *normalized* emittance $\varepsilon_n = \varepsilon\gamma\beta$, where γ and β are the usual relativistic factors, is used to remove the energy dependence (a higher energy beam has smaller transverse emittance due to boosting).

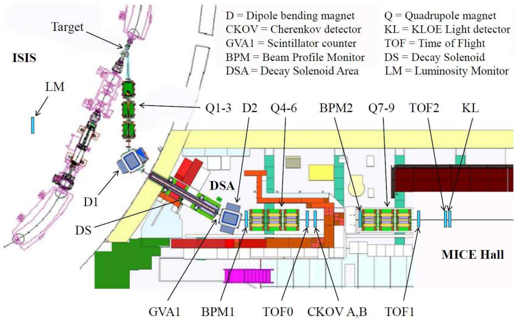


Figure 1: MICE beamline schematic.

In ionization cooling, the muons lose energy traversing a low-Z absorber and have the longitudinal component of momentum restored in accelerating cavities, all while being focused in a magnetic lattice. In traversing the absorber, muons lose energy in all directions–"cool"–while Coulomb scattering tends to increase emittance –"heat". The rate of change of ε_n thus has both a cooling and a heating term when traversing a path length s, as given in Eq. 1:

$$\frac{d\varepsilon_n}{ds} = -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\varepsilon_n}{E_\mu} + \frac{1}{\beta^3}\frac{\beta_\perp(13.6\ \mathrm{MeV})^2}{2E_\mu m_\mu X_0} \qquad (1)$$

Here $\beta = v/c$, $\langle dE_\mu/ds \rangle$ is the average rate of energy loss, E_μ and m_μ are the muon energy and mass, $\beta_\perp$ is the transverse beta function (focal length) evaluated at the absorber, and X_0 is the radiation length of the absorber. Note that heating is reduced by strong focusing in the absorber (low $\beta_\perp$), and use of a low-Z absorber to increase X_0.

MICE DESCRIPTION

A more complete description of MICE can be found in these preceedings and also in the MICE technical design report[4].

The muon beam is created using a titanium target, dipped at ~ 1 Hz with acceleration ~ 90g into the ISIS beam during the last 3 ms of the acceleration cycle. The pions are transported to the MICE Hall and momentum selected using conventional quadrupole triplet (Q1-3) and dipole (D1) magnets. Muons from pion decay within the superconducting Decay Solenoid (DS) are then momentum selected and transported to the cooling cell with a dipole (D2) and quad triplets (Q4-6 & Q7-9), see Fig. 1.

Particle Identification (PID) is performed with two threshold Cherenkov counters and two time-of-flight scintillator hodoscopes (ToF0 & ToF1) surrounding the last

---

[*] hanlet@fnal.gov, Work supported by NSF PHY0842798

[†] C.Booth@sheffield.ac.uk, Work supported by STFC

[‡] http://mice.iit.edu

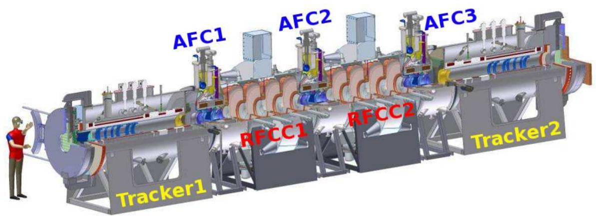


Figure 2: MICE Cooling Channel: 2 trackers sandwiching cooling channel of 3 AFC modules and 2 RFCC modules.

triplet. Decayed muons are rejected using the last ToF plane (ToF2), KLOE-light calorimeter (KL), and electron-muon ranger (EMR) downstream of the cooling channel. Calibration data were collected for all detectors (except EMR). The ToF detectors were calibrated to have time resolutions of 51 ps/58 ps/52 ps for ToF0/ToF1/ToF2, respectively[5].

Future stages of MICE will introduce components of the cooling channel and tracking systems to measure particle emittance, see Fig. 2. The cooling channel consists of 3 Absorber/Focusing Coil stations–AFC–interleaved with 2 RF/Coupling Coil stations–RFCC. This cooling channel is sandwiched between two identical tracking spectrometers which measure muon trajectories upstream and downstream of the cooling channel. In this way, the particle emittance, which is calculated as an ensemble of individual measurements, will be measured before and after cooling, such that the difference in measurements directly measures the cooling effect.

CONTROLS AND MONITORING

MICE is a precision experiment. It is imperative that we tightly control systematic errors, requiring careful monitoring of pertinent experimental parameters. MICE also has a wide variety of hardware components. These considerations require a mature Controls and Monitoring (C&M) framework.

EPICS[6] (Experimental Physics and Industrial Control System) platform was chosen for all of MICE C&M because of its reliability, existing support for a wide variety of hardware devices, flexibility to add new hardware devices, large selection of existing user applications, and a worldwide support network. It is open source software and can be accessed from [6].

EPICS's backbone is a local area network (LAN) to which hardware components are connected via hardware drivers interfacing with EPICS Input/Output Controllers (IOCs). A wide variety of user interfaces to the EPICS IOCs are performed using EPICS Channel Access (CA). In this way IOCs can interact to share information, feedback loops can be implemented, and tasks can be correctly sequenced. see Fig. 3.

C&M systems are generally developed together. The purposes of MICE Controls are to:

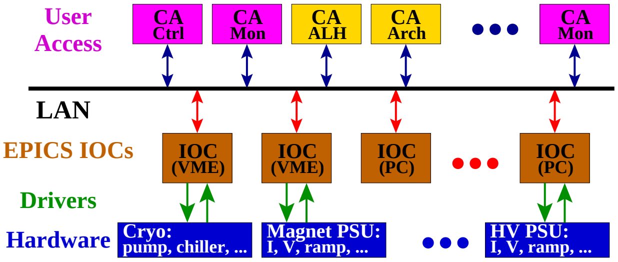


Figure 3: EPICS structure: Hardware connected to LAN via EPICS input/output controllers (IOC); user access through channel access (CA).

- Provide user interface to hardware
- Properly sequence equipment operations
- Ensure subsystems share resources appropriately
- Ensure feedback loops keep system stable

Similarly, the purposes of the MICE Monitoring systems are to:

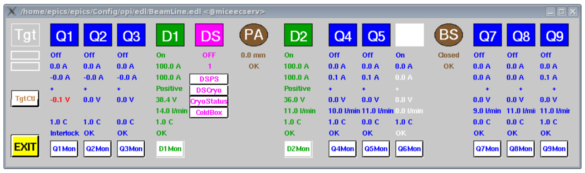
- Provide feedback for control sequencing
- Give early notification of potential equipment failure
- Protect data quality

Completed Systems

Controls and monitoring were required for the first stage of MICE for both the muon beamline and the PID systems, as well as monitoring for the experimental hall infrastructure and environment. Beamline C&M includes target, beamline, Decay Solenoid, and monitoring for the proton absorber and beamstop which are both manually operated. A screen shot of a summary beamline monitoring graphical user interface, "GUI", is shown in Fig. 4. The buttons on this display open control interface GUI's for different devices. Items in white indicate that the device is not connected in EPICS.

MICE also uses the EPICS Archiver to archive selected parameter values with either regular, selectable frequencies or when a change occurs whose magnitude exceeds a dead band. An example is shown for the status of the Tracker electronics cryostats, as shown in Fig. 5. These data may one day be used in corrections for data analyses.

With the exception of the incomplete EMR, all of the PID detectors were controlled and monitored via their high voltage systems, since control of these detectors is through their photomultiplier tubes (PMTs). Here, the on/off status,



```
Off        Off      Off      On          OFF   0.0 mm   On          Off         Off         On          Closed   Off        Off        Off
0.0 A      0.0 A    0.0 A    100.0 A     1     OK       100.0 A     0.0 A       0.0 A       0.0 A       OK       0.0 A      0.0 A      0.0 A
-0.0 A     -0.0 A   -0.0 A   100.0 A                    100.0 A     0.1 A       0.1 A       0.0 A                0.0 A      0.0 A      0.1 A
+          +        +        Positive                   Positive    +           +           +                    +          +          +
-0.1 V     0.0 V    0.0 V    38.4 V                     36.0 V      0.0 V       0.0 V       0.0 V                0.0 V      0.0 V      0.0 V
                             14.0 l/min                 11.0 l/min  10.0 l/min  11.0 l/min  0.0 l/min            9.0 l/min  11.0 l/mi  11.0 l/mir
1.0 C      1.0 C    0.0 C    1.0 C                      1.0 C       1.0 C       0.0 C       1.0 C                0.0 C      0.0 C      1.0 C
Interlock  OK       OK       OK                         OK          OK          OK          OK                   OK         OK         OK
```

Figure 4: Screen shot of beamline summary GUI.

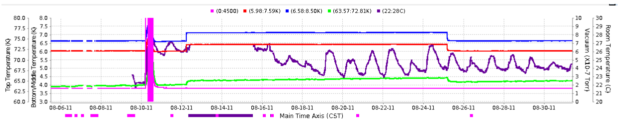


Figure 5: Tracker cryostat4 readout example from archiver. Notable features show a vacuum pump failure, daily temperature fluctuations in the lab, and start and stop of a cosmic data run.

voltage, maximum current, ramp up/down rates, and trip time are controlled and voltage and currents are monitored. Additionally, environment temperatures for the ToF detectors and environment temperature and internal humidity of the CKOV detectors are also monitored.

The MICE experimental hall environment is monitored using temperature and humidity probes, water leak detection, and air flow from the AC units. It is expected that radiation monitors, additional temperature devices, will be added to the hall when tracking and cooling channel devices are introduced.

The parameters previously discussed form an incomplete list of all the parameters in the MICE C&M system. Monitoring of a selected subset of all the parameters is ultimately fed into EPICS Alarm Handlers which compare the readback values to limits which can be set to any combination of lower major, lower minor, upper minor, and upper major alarms. The frequency with which the parameters are scanned is set in EPICS at regular intervals or when they change. The Alarm Handler gives an audible alarm in the MICE control room. An effort is also being made to notify responsible parties via SMS messages; i.e. 24-7 worldwide notification. Note that setting alarm limits is often an iterative process. Limits set too tightly result in frequent alarms which may get ignored; limits set too loosely don't serve their purpose.

A MICE Configuration Database, or CDB, is being developed in parallel to the C&M systems. This will be the ultimate source of running parameter values and alarm limits for the experiment. All subsystems will read their parameter set values and limits from the CDB during initialization. Alarms will occur when parameters values drift from these limits. This reduces human input errors and automatically records any changes. The CDB will allow for alarm limits to change with different operational states.

Future Systems

To date, only the first stage of MICE is complete, and the major components of the tracker and cooling channel are still to be introduced. These new subsystems will each have C&M developed by the individual groups responsible for the hardware. However, an over-arching plan is being developed to ensure that subsystems do not conflict when sharing resources, that a uniform approach is taken for the user interfaces, and that sequences are correctly designed to ensure safe operation of the equipment. An organizational chart of the MICE subsystems which require C&M is shown in Fig. 6.

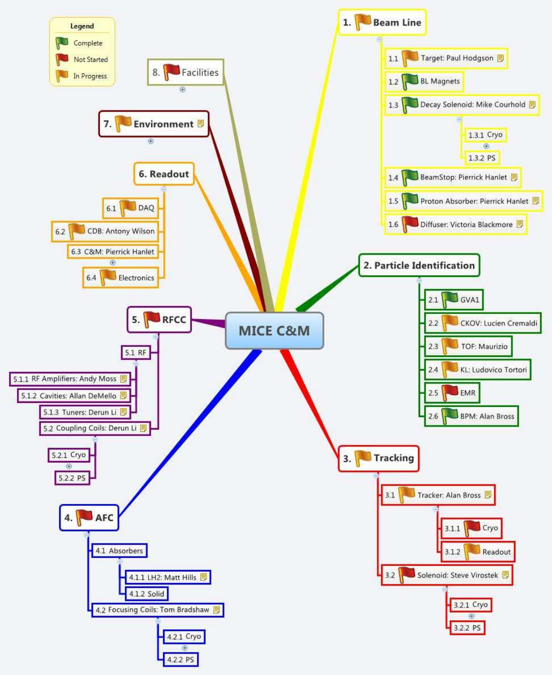


Figure 6: Subsystem organization of MICE C&M.

The EPICS State Notation Language is presently being implemented for this purpose. MICE has operational states: "Off", "Powered", "Standby", "Testing", "Running". Each subsystem also has its own states, which may or may not be allowed depending on the state of MICE. For each combination of states, the monitored parameters and alarm limits are assigned from the CDB, as are the archived parameters and their frequency of recording.

CONCLUSIONS

A complete C&M is being developed to ensure that MICE can successfully measure with 0.1% resolution a reduction in μ beam emittance. The first stage has been successfully completed in summer 2010.

REFERENCES

[1] C. Ankenbrandt *et al.*, Phys. Rev. ST Accel. and Beams **2**, 81001 (1999); M.M. Alsharo'a *et al.*, Phys. Rev. ST Accel. and Beams **6**, 81001 (2003).

[2] "Feasibility Study-II of a Muon-Based Neutrino Souce," ed. S. Ozaki et al., BNL-52623, http://www.cap.bnl.gov/mumustudyii/FS2-report.html

[3] D.M. Kaplan, Nucl. Instrum. Meth. **A453** (2000) 37.

[4] "MICE and International Muon Ionization Cooling Experiment Technical Reference Document," G.Gregoire *et al.*, October 2004., `http://www.isis.rl.ac.uk/archive/accelerator/MICE/TR/MICE_Tech_ref.html`

[5] R. Bertoni *et al.*, Nucl. Instrum. Meth. **A615** (2010) 14.

[6] `http://aps.anl.gov/epics`