MUON IONIZATION COOLING EXPERIMENT: CONTROLS AND MONITORING*

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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 (C&M) system is based on EPICS and integrates with the DAQ, Configuration Database, 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 in tertiary reactions: $p+N \rightarrow \pi+X$ with subsequent decay $\pi \rightarrow \mu\nu$. The muons are therefore created with large inherent emittance (beam spread in the 6D position and momentum phase space) which is impractical for use in an 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 cools in 4D transverse phase space. This has been demonstrated in simulations[3]. The international **M**uon **I**onization **C**ooling **E**xperiment, or "MICE", at the ISIS accelerator at Rutherford Appleton Laboratory (UK), will demonstrate the viability of ionization cooling of a real beam of muons using a variety of beam optics, muon momenta (140-240 MeV/c), and emittance (diffuser) settings.

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

The mathematical definition of emittance is $\varepsilon = \sigma_r \sigma_p / m/c$, where σ_r is the RMS spatial beam spread, σ_p is the RMS momentum spread, and mc is the product of the particle's mass and speed of light[1, 5]. One frequently uses the *normalized* emittance $\varepsilon_n = \varepsilon\gamma\beta$, where γ and β are the usual relativistic factors, to remove the energy dependence (a higher energy beam has smaller emittance due to boosting).

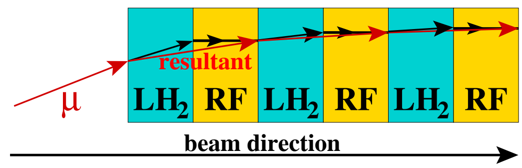

Figure 1: Ionization cooling: Muons traverse the absorber losing energy via dE/dx, and RF replaces longitudinal component of momentum.

Ionization cooling is a procedure in which 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 passing through the absorber, some muons will lose energy in all dimensions, "cool", while others Coulomb scatter such as to increase emittance, or "heat". The rate of change of normalized transverse beam emittance, ε_n , has both a cooling and a heating term when traversing a path s, as shown in Eq. 1:

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

where $\beta = v/c$, the angle brackets denote the average energy loss, E_μ and m_μ are the muon energy and mass, $\beta_\perp$ is the transverse beta function (beam envelope) evaluated at the absorber, and X_0 is radiation length of the absorber. Figure 1.shows a cartoon of the ionization cooling procedure.

MICE DESCRIPTION

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

MICE begins with a muon beamline which consists of a target which dips into the ISIS ring, conventional beamline magnets: two dipoles and three quadrupole triplets, a superconducting solenoid for pion decay, proton absorber, beam stop, and diffuser. Particle identification (PID) consists of fiber beam profile monitors–BPMs, a luminosity monitor–LM, three stations of scintillator hodoscopes (x and y planes) for use in a time-of-flight

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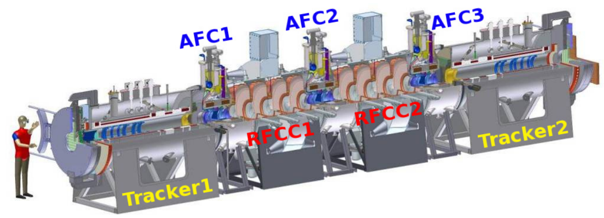

Figure 2: MICE Cooling Channel: 2 trackers sandwiching cooling channel of 3 AFC modules and 2 RFCC modules.

system–TOFx, two aerogel threshold Cerenkov counters–CKOVx, a Kloe-light calorimeter–KL, and an electron-muon ranger–EMR. The upstream PID system consists of TOF0, TOF1, CKOV-A, CKOV-B, and serves to identify the particle species for muon selection upstream of the cooling channel. The downstream PID system is after the cooling channel, (TOF2, KL, EMR) and serves to verify that the muon has not decayed in flight. This first stage of the experiment was successfully completed in summer 2010. It was necessary to commission the target beamline elements, and to calibrate the detectors.

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 stations–AFC interleaved with 2 RF stations–RFCC. This cooling channel is sandwiched between two tracker stations which measure muon trajectories upstream of the cooling channel and again 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, which requires careful monitoring of pertinent experimental parameters. MICE also has a wide variety of hardware components. These considerations required a mature C&M framework.

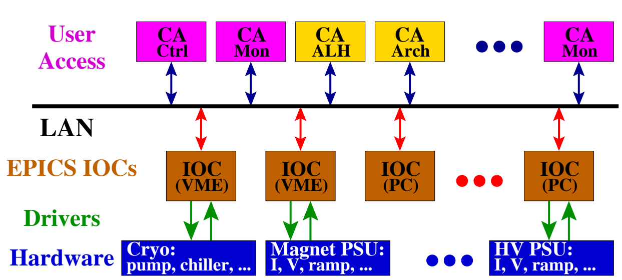

Figure 3: EPICS structure: Hardware connected to LAN via EPICS input/output controllers (IOC); user access through channel access (CA).

EPICS (Experimental Physics and Industrial Control System) platform was chosen for all of MICE Controls and Monitoring because of its reliability, existing support for a wide variety of hardware devices, flexibility to add new hardware devices, wide variety of existing user applications and interfaces, and the world-wide support network. EPICS is open source software and can 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.

Controls and Monitoring systems are generally developed together. The purposes of MICE Controls are:

- User interface to hardware
- Proper sequencing of equipment operations
- Ensure subsystems share resources appropriately
- Ensure feedback loops keep system stable

Similarly, the purposes of the MICE Monitoring systems are:

- Feedback for control sequencing
- Early notification of potential equipment failures
- Protection of data quality

An organizational chart of the MICE subsystems which require Controls and Monitoring is shown in Fig. 6.

Completed Systems

Both the muon beamline and the PID controls and monitoring systems, as well as controls and monitoring of the experimental hall infrastructure and environment, were required for the first stage of MICE.

Beamline controls and monitoring include: 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. The figure shows that for each of the beamline conventional magnets, the monitored parameters are: on/off status, current, voltage, polarity, water temperature, and power supply interlocks. Items in white indicate that the device is not connected in EPICS.

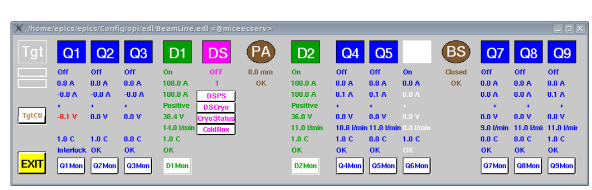

Figure 4: Screen shot of beamline summary GUI.

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 with their photomultiplier tubes (PMTs). Here, the on/off status, 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 is monitored using temperature and humidity probes, water leak detection, air flow from the AC units are also monitored. 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 is an incomplete list. 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.

MICE also uses the EPICS Archiver to archive selected parameter values with either regular selectable frequencies or when a change occurs whose magnitude exceeds an allowable range. These archived parameters are useful to monitor the progress of the decay solenoid cooldown, for example, as shown in Fig. 5. These data may one day be used in corrections for data analyses.

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 parameters' 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.

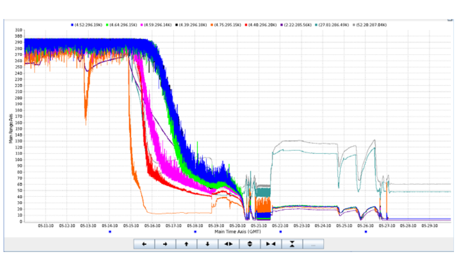

Figure 5: DS cooldown example from archiver.

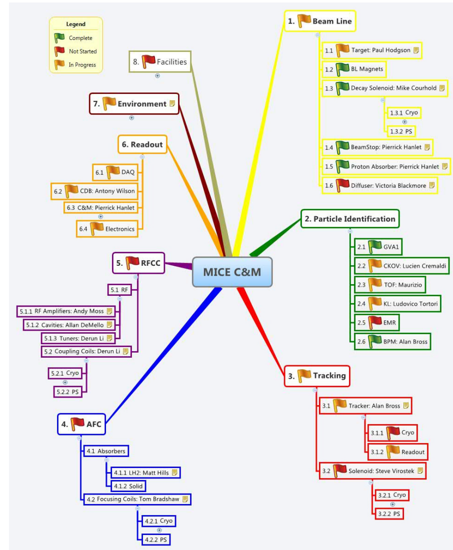

Figure 6: Subsystem organization of MICE C&M.

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 don't conflict when sharing resources, that uniform approach is taken for the user interfaces, and that sequences are correctly designed to ensure safe operation of the equipment.

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. Stay tuned for future results.

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