State Machine Operation of the MICE Cooling Channel

Pierrick Hanlet, for the MICE collaboration
Illinois Institute of Technology, Chicago, IL USA 60616
E-mail: hanlet@fnal.gov

Abstract. The Muon Ionization Cooling Experiment (MICE) is a demonstration experiment to prove the feasibility of cooling a beam of muons for use in a Neutrino Factory and/or 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, MICE will measure the beam emittance before and after the cooling channel at the level of 1%, a relative measurement of 0.001. This renders MICE 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, Data monitoring systems, and a configuration database. The cooling channel for MICE has between 12 and 18 superconducting solenoid coils in 3 to 7 magnets, depending on the staged development of the experiment. The magnets are coaxial and in close proximity which requires coordinated operation of the magnets when ramping, responding to quench conditions, and quench recovery. To reliably manage the operation of the magnets, MICE is implementing state machines for each magnet and an over-arching state machine for the magnets integrated in the cooling channel. The state machine transitions and operating parameters are stored/restored from the configuration database and coupled with MICE Run Control. Proper implementation of the state machines will not only ensure safe operation of the magnets, but will help ensure reliable data quality. A description of MICE, details of the state machines, and lessons learned from use of the state machines in recent magnet training tests will be discussed.

1. Motivation
Muons, for a neutrino factory or muon collider[1, 2], are produced as tertiary particles in the reaction $p + N \rightarrow \pi + X$ 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 Muon Ionization Cooling Experiment (MICE) at the ISIS accelerator at Rutherford Appleton Laboratory (UK), will demonstrate muon ionization cooling with a variety of beam optics, muon momenta (140-240 MeV/c), and emittances. The results of these studies will be used to optimize neutrino factory and muon collider designs, see Figs. 1, 2.

MICE will measure a 10% reduction in beam emittance with a 1% resolution, making it a precision experiment with a 0.1% relative resolution. Thus, it is imperative that the systematic errors be minimized and well understood. For this reason, as well as budget constraints, MICE
Beam emittance is given by $\varepsilon = \sigma_r \sigma_p / (mc)$, where $\sigma_r$ and $\sigma_p$ are, respectively, the RMS spatial and momentum spread and $mc$ is the product of the particle mass and speed of light. The normalized emittance $\varepsilon_n = \varepsilon \gamma \beta$, where $\gamma$ and $\beta$ are the usual relativistic factors, is used to remove the energy dependence (a higher energy beam has smaller transverse emittance due to boosting).

In ionization cooling, the muons lose energy traversing a low-$Z$ absorber and have the longitudinal component of momentum restored in accelerating cavities. Muons are focussed at the absorber to reduce the transverse spread of the beam. In traversing the absorber, muons lose momentum in all directions—“cool”—while Coulomb scattering tends to increase emittance—“heat”. Therefore, the rate of change of $\varepsilon_n$ when traversing a path length $s$ has both a cooling and a heating term, as given in Eq. 1:

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

Here $\beta = v/c$, $\left( dE_\mu / ds \right)$ is the average rate of energy loss, $E_\mu$ and $m_\mu$ are the muon energy and mass, $\beta_\perp$ is the transverse beta function (beam width) 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 $X_0$.

To make the measurement, MICE will: (1) create a beam of muons, (2) identify the muons and reject other particles using particle physics techniques, (3) measure the muon emittance.
in tracking spectrometers, (4) “cool” the beam in low-Z absorbers, (5) restore the longitudinal component of the muon momenta, (6) measure the emittance downstream of the cooling channel, and (7) re-identify muons and reject events with electrons from decayed muons.

2. MICE Description

A more complete description of MICE can be found here[4] and in the MICE technical design report[5].

The muon beam is created using a titanium target which is dipped at $\sim 1$ Hz with acceleration $\sim 90g$ into the ISIS beam halo during the last 3 ms of the acceleration cycle. The pions produced in the collision are transported to the MICE Hall and momentum selected using conventional dipole and quadrupole magnets; here, a quadrupole triplet (Q1-3) and dipole (D1). These pions decay into muons within the superconducting Decay Solenoid (DS) which serves both to increase the path length of the pions as well as focus the pions and muons. The emerging muons are then momentum selected and transported to the cooling channel with a dipole (D2) and quad triplets (Q4-6 & Q7-9), see Fig. 4.

Particle Identification (PID) is performed with two threshold Cherenkov counters and two time-of-flight scintillator hodoscopes (ToF0 & ToF1) up and downstream of the last 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. As of the writing of this paper, data have been collected with all detectors but the EMR, and we are presently taking first data with this detector. The ToF detectors were calibrated to have time resolutions of 51 ps/58 ps/52 ps for ToF0/ToF1/ToF2, respectively[6].

The final MICE cooling channel will consist of 3 “Absorber/Focusing Coil” stations (AFCs) interleaved with 2 “RF/Coupling Coil” stations (RFCCs). This cooling channel is sandwiched between two identical tracking spectrometers (TSs), which are comprised of 5-coil superconducting solenoid magnets, or “Spectrometer Solenoids” (SSs) and trackers. Each tracker consists of 5-stations of 3 stereo-view planes of scintillating fibers with 1400 350 $\mu$m fibers/plane. It is positioned inside the bore of the longest $\sim 1.3\ m$-coil which provides a uniform 4 $T$ field. The remaining SS coils serve to match the magnetic optics to that of the the cooling channel. The trackers will be used to measure muon trajectories, and thus momenta, both 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. The full cooling channel is shown in Fig. 5.

As of the writing of this document, MICE is preparing to introduce tracking spectrometers TS1 and TS2 and the first AFC module into the cooling channel. This is the MICE “Step
IV” configuration. Therefore, following the imminent EMR run, MICE will go into a long construction period with the expectation of running Step IV in 2015.

3. MICE Controls & Monitoring

Since MICE is a precision experiment, it is imperative that we tightly control systematic errors, which is accomplished, in part, by carefully monitoring experimental parameters. MICE also has a wide variety of hardware components to be controlled and monitored. These considerations require a mature Controls and Monitoring (C&M) framework. The EPICS[7] (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 world-wide support network. It is open source software accessible from [7].

EPICS’s backbone is a local area network (LAN) to which hardware components are interfaced, via their drivers, with EPICS Input/Output Controllers (IOCs), see Fig. 6. The IOCs generate “process variables” (PVs) which carry the values of hardware parameters (e.g. pressure, temperature, etc.). Additional PVs can be derived in software. Further description of the PVs is provided by “fields” which serve to increase functionality; e.g. scanning rates, engineering units, high and low alarm limits, operating limits, to name a few. The PVs are then made available on the LAN, such that the IOC is a combination of computer, software, and server. Writing to a PV is the “control” part and reading from a PV is the “monitoring” part of C&M.

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, hardware can be controlled and monitored with graphical user interfaces (GUIs), errors can be identified with alarm handlers, and relevant operating parameters can be archived.

3.1. Subsystems

For the purpose of C&M, MICE is divided into the following systems:

**Beamline** – target, conventional beamline magnets, decay solenoid, proton absorber, moveable beamstop, diffuser, luminosity monitor.

**PID** – GVa1, ToF 1/2/3, Ckov A/B, KL, and EMR.

**Spectrometers (2)** – SS magnets and fiber trackers.

**AFCs (3)** – LH2 absorber module (or solid absorbers) and focus coils (FC).

![Diagram](image-url)  
**Figure 6.** Functional description of EPICS.
**RFCCs (2)** – 4 201 MHz RF accelerating cavities and 1 superconducting solenoid coaxially surrounding the RF cavities.

**Environment & Services** – temperatures, humidity, radiation, water and air flows, pressures, and leak monitoring.

**Data Acquisition and Electronics.**

3.2. Controls Hardware

The larger systems: beamline magnets, decay solenoid, trackers, and target have control systems built by a controls team at Daresbury Laboratory in the UK. Each IOC is a VME based system with a Hytek processor running VxWorks. Sensor controllers are interfaced via RS232. CANbus is employed for interlocks and digital controls, while analog devices are monitored and controlled with VME based ADCs and DACs. The SS and FC magnets are sufficiently complex to require 2 VME crates, and thus IOCs, each. Presently, while testing the SS and FC magnets, stand-alone control systems have been deployed. These will be replaced by integrated racks when the magnets are installed in the experimental hall as early as Fall 2013.

The \( \text{LH}_2 \) system, due to its explosive nature, is controlled by Omron PLCs and is completely self-contained. EPICS is used solely for remote monitoring of this system.

Other IOCs for MICE have been implemented on Linux PCs. These include Ckov, radiation monitoring, high voltage for the PID detectors, proton absorber, beamstop, RF tuners, environment monitoring, air conditioning, \( \text{LH}_2 \) monitoring, and computer/electronics “heart beat” monitoring. These IOCs employ a variety of interfaces: serial RS232 and RS485, SNMP, and TCP/IP.

Though the C&M hardware are built separately, requirements are defined by the subsystem owners. MICE is an international collaboration, with institutions from around the world providing subsystems and components. It is therefore the challenge of the C&M team to provide uniform control and interfaces to all of the apparatus.

3.3. Other EPICS Applications

Most of the MICE graphical user interfaces (GUIs) are based on EPICS edm; though there are some relic GUIs based on QT. These are used for both remote control and monitoring, and employ features such as related displays, hidden buttons, and color coded PVs to indicate alarms when the parameters exceed their limits.

Alarms are also made audible by the EPICS alarm handler (ALH). This is used extensively in the control room and with the stand-alone systems for SS and FC testing. In the alarm handlers, PVs are grouped for convenience. The ALH functionality of configurable flags (which are PVs) allows these groups of “alarmed” PVs to be enabled/disabled on the fly.

The purpose of the MICE ALH is to provide early notification that equipment is approaching a dangerous state as well as to protect MICE data quality. It is important to note that the equipment interlocks serve to protect the equipment from damage; the ALH is meant to prevent the equipment from getting to the point of an interlock trip.

MICE also uses the EPICS Archiver to archive selected parameters with either regular, selectable frequencies or when a change occurs whose magnitude exceeds a dead band. These data may later be used in corrections for data analyses or to help debug equipment.

Due to the international nature of MICE, collaborators around the globe need to be able to remotely monitor their equipment. The EPICS gateway is implemented in MICE to allow for this possibility. The gateway is a secure means of allowing read-only, remote access to the values and fields of the PVs. This allows remote users to display the PVs running EPICS applications locally, without the bandwidth requirements for forwarding the graphics as well.
4. MICE State Machines
Different subsystems have different requirements depending on the operational state of the device. Each subsystem has 10’s to 1000’s of PVs and for each operational state, the list of pertinent PVs changes, the alarm limits (up to 4 per PV) may change, the archive requirements may change, and the list of critical PVs may change. Errors in setting these may lead to costly mistakes in both time and money.

To address this, EPICS State Notation Language (SNL) is invoked to define state machines for each major subsystem. The systems with state machines are: Target, Decay Solenoid, Spectrometer Solenoids, Focus Coils, and Trackers. Note that the principal purpose of the state machines is not to safely protect the equipment, this is assumed to be done by the control systems. Rather, the purpose of the state machines is to operate the subsystems with maximal efficiency. This means that for each state, the pertinent parameters, or PVs, are selected and their alarm limits and archiving features are set. Furthermore, the critical variables are selected for use in AutoSMS, which is the MICE auto-dialer system. The values for these parameters are stored in the MICE Configuration Database, or “CDB”. For each state the state machine performs the following functions–shown graphically in Fig. 7:

(i) Enter state and set control panel buttons on the State Machine GUI
(ii) Read CDB for this subsystem/state: read PVs, their fields, and transitions requirements
(iii) Loop over these PVs to fill alarm limits/archiver features & set AutoSMS enable/disable
(iv) Re-initialize Archiver
(v) Enable/Disable software interlocks
(vi) Perform checks on hardware/software interlocks and transition to “Error” state if necessary
(vii) Perform checks on parameter limits for this state and transition to “Error” state if any test is failed
(viii) Perform check for transition to new state and transition to new state if conditions are met

Note that some of the transitions are manual and others are automatic. Control of the manual transitions is performed in the state machine gui.

![Figure 7. State Machine algorithm: each state of each subsytem follows this sequence.](image-url)
For each state of each subsystem, the following information is generated. Much of this information is stored in the CDB. In order to populate the CDB, subsystem owners are required to generate the following information:

(i) Description
(ii) Transition into state
(iii) Parameters (PVs) of Interest
(iv) Alarm Limits
(v) Archiving
(vi) AutoSMS
(vii) Hardware Interlocks
(viii) Software Interlocks

For each subsystem, with the algorithm, the states, and these values defined by the subsystem owners, the state machines can be defined for all MICE state machines.

5. Conclusion
At the time of writing this document, only the SS state machine is being used for testing an SS magnet at the vendor, and here it is successfully employed. In the future, the state machines will be used for all of the major subsystems and will become a critical part of MICE Run Control[8], in which readiness of these complicated subsystems will be a function of its state rather than a complicated series of tests.

References
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\[^{1}\] Note that the hardware interlocks are implemented in the hardware and not the state machines; however they are more easily identified in the context of state machines, and therefore considered here.