The MICE Run Control System

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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%, or 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 new MICE Run Control has been developed to ensure proper sequencing of equipment and use of system resources to protect data quality. A description of this system, its implementation, and performance during recent muon beam data collection 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.

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 is a staged experiment in which the parameters of the beam, detectors, tracking, and cooling channel components are studied in detail in each step.

2. MICE Description

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. A more complete description of MICE can be found here[3] and in the MICE technical design report[4].

The muon beam is created using a titanium target which is dipped at ~1 Hz with acceleration ~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. 1.

Particle Identification (PID) is performed with two threshold Cherenkov counters and two time-of-flight scintillator hodoscopes (ToF0 & ToF1) up and down stream 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, though 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[5].

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 µm fibers/plane. It is positioned inside the bore of the longest ~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. 2.

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 present 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[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 world-wide support network. It is open source software accessible from [6].

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. 3. The IOCs generate “process variables” (PVs) which carry the values of hardware parameters (e.g. pressure or temperature). 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” and reading from a PV are the “monitoring” parts 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).

**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 LH2 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, LH2 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 notify operators so as to prevent 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 by locally running EPICS applications, therefore reducing the bandwidth required for forwarding the graphical displays.

4. MICE Run Control
MICE Run Control (RC) is a higher level of control which integrates the C&M systems for: Target, Environment, Beamline Magnets, DAQ Monitoring, PID, and cooling channel elements (for Step IV). Its purpose is to ensure: (1) experimental readiness of the apparatus, (2) that subsystems share resources appropriately, (3) that run settings are systematically and reliably set, (4) that run conditions/settings are reliably stored for each run, and (5) that run statistics are properly gathered/stored at the end of each run.
Figure 4. MICE Run Control Algorithm.

The RC start run sequence is to (1) query operator for run type, trigger conditions, (2) retrieve the beamline and cooling channel parameters from the configuration database (CDB), (3) set the beamline and cooling channel parameters, (4) wait for beamline and cooling channel readiness, and finally when these are ready and as the run begins, (5) record the run parameters to the CDB. Once the run is underway, RC continuously monitors the DAQ collecting statistics associated with the run (target, ISIS losses, triggers, scalers, etc.), sums these, and records them to the CDB at the end of a run. This algorithm is shown graphically in Fig. 4. In the figure, the RC responsibilities are shown in blue boxes, interface with the CDB, in violet boxes, and user input in green boxes.

At the beginning of a run, the user selects a menu-driven run configuration: run-type, trigger, beamline settings and RC uses these inputs to query the CDB. C&M uses these parameters to set the beamline, detectors, and cooling channel elements after checking their present status. If after a specified period a system does not achieve the desired configuration, the user is presented with buttons to additional guis to intervene in setting the parameters; e.g. a magnet does not ramp up to current because the water flow was never turned on. Once all systems are ready, RC presents the user with an option to write a comment and then an option to start the DAQ. After the first trigger is accepted, RC reads all of the present run parameters and stores them in the CDB.

Throughout the run, RC continuously checks for an end of run flag. When this is found, RC collects all of the target, DAQ, and scaler data, presents the user with an option to write end of run comment, and stores these data in the CDB.

As seen in Fig. 4, at step (3) above, RC divides its responsibilities between the beamline, the PID detectors, and the cooling channel. Due to the complexity of the C&M systems for the cooling channel elements, checking for their readiness and ensuring appropriate control would require a multitude of checks. To address this challenge, the anticipated next version of RC will employ MICE State Machines[7] to check for readiness of the cooling channel components, thus greatly simplifying its role. In this way, RC simply checks the “states” of the cooling channel elements, rather than their details.

During the early stages of MICE (Step I – in which consisted of only the muon beamline and PID), RC was successfully used to bring up standard run settings and to store configurations for
each run. The standard settings included preset magnet currents for the conventional beamline magnets and the DS as well high voltage settings for the detectors. At the end of each run, the number of target activations, triggers, beam condition averages, and other scaler data were stored in the CDB. Later data analyses used these run conditions and run summary data.

5. Conclusion
The MICE Run Control has been developed as a high level C&M tool to interface major subsystems to ensure systematic and reliable operation of the Target, Beamline Magnets, DAQ Monitoring, PID, and cooling channel elements. In working with the state machines for the cooling channel components, RC will serve to safely operate the equipment and protect data quality for a high precision measurement of the ionization cooling principle.

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