MUON IONIZATION COOLING EXPERIMENT: CONTROLS AND MONITORING

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Abstract

The Muon Ionization Cooling Experiment 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 will produce a 10% reduction in beam emittance which will be measured with a 1% resolution, and this level of precision requires strict controls and monitoring of all experimental parameters to minimize systematic errors. The MICE Controls and Monitoring system is based on EPICS and integrates with the DAQ, data monitoring systems, a conf guration database, and state machines for device operations. Run Control has been developed to ensure proper sequencing of equipment operations and use of system resources to protect data quality. State machines are used in test operations of cooling channel superconducting solenoids to set parameters for monitoring, alarms, and data archiving. A description of this system, its implementation and performance during both muon beam data collection and magnet training 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 1% resolution, making it a precision experiment with an absolute resolution of 0.1%. 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.

Beam 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).

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 momentum 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:

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

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 (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.

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 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 quadrupole triplet (Q1-3) and dipole (D1) magnets. These pions decay into muons within the superconducting Decay Solenoid (DS) and 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 Identif cation (PID) is performed with two threshold Cherenkov counters and two time-of-f ight scintillator hodoscopes (ToF0 & ToF1) surrounding 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 preparing to take f rst data with the EMR. The ToF detectors were calibrated to have time resolutions of 51 ps/58 ps/52 ps for ToF0/ToF1/ToF2, respectively[6].

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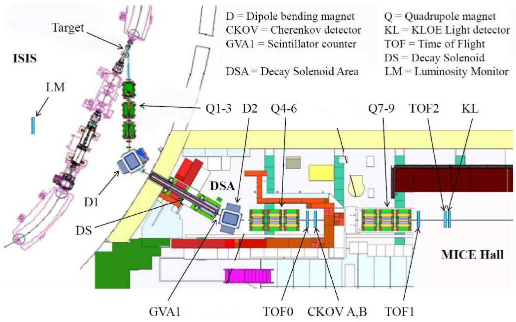

Figure 1: MICE beamline schematic.

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). A tracker–consisting of 5-planes, 3 stereo-view scintillating fibers with 1400 350 μm fibers/plane–is positioned inside the bore of the longest–$\sim 1.3\ m$–coil which provides a uniform $4\ T$ field. The remaining coils server 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" stage. Therefore, following the immanent EMR run, MICE will go into a long construction period.

MICE CONTROLS & MONITORING

Since MICE is a precision experiment, it is imperative that we tightly control systematic errors, which in part is accomplished by carefully monitoring experimental parameters. MICE also has a wide variety of hardware components. These considerations require a mature Controls

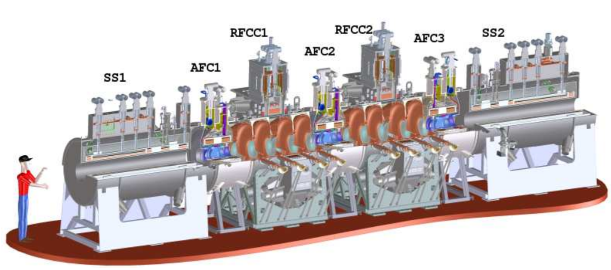

Figure 2: MICE Cooling Channel: 2 tracking spectrometers sandwiching cooling channel of 3 AFC modules and 2 RFCC modules.

and Monitoring (C&M) framework. 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 accessable 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). The IOCs generate "process variables" (PVs) which carry the values of hardware parameters (e.g. pressure, temperature, etc.). Other 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, feedback loops can be implemented, and tasks can be correctly sequenced.

Controls and Monitoring systems are generally developed together. For the purposes of MICE, Controls are to:

- safely control experimental equipment
- share information between systems for interdependent operations and sequencing
- provide user interfaces to hardware
- properly sequence equipment operations
- ensure subsystems share resources appropriately
- interface with a configuration database (CDB) to systematically set operating parameters
- interface with a CDB to systematically record run conditions
- interface with the Data Acquisition (DAQ) system to ensure equipment readiness for a run
- provide single user interface to start/stop data collection runs

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

- provide feedback for control sequencing
- give early notification of potential equipment failure
- provide software interlocks to protect equipment operation
- protect data quality
- archive pertinent data for future hardware debugging
- archive pertinent data which may later be used for data analysis corrections

For MICE, the C&M systems do *not* provide:

- personnel protection
- control of the data acquisition systems other than starting/stopping runs

Subsystems

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

1. *Beamline* – target, conventional beamline magnets, decay solenoid, proton absorber, beamstop, diffuser.
2. *PID* – GVa1, ToF 1/2/3, Ckov A/B, KL, and EMR.
3. *Spectrometers (2)* – SS magnets/fiber trackers.
4. *AFCs (3)* – LH_2 absorber module or solid absorbers, and focusing coils (FC).
5. *RFCCs (2)* – 4 201 MHz RF accelerating cavities and 1 superconducting solenoid coaxially surrounding the RF cavities.
6. *Environment & Services* – temperatures, humidity, radiation, water and air flows, pressures, and leaks.
7. *Data Acquisition and Electronics.*

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 LH_2 system, due to it's 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, 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. As can be seen from Fig. 3, MICE is an international collaboration, with institutions from around the world providing components.

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 both for 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.

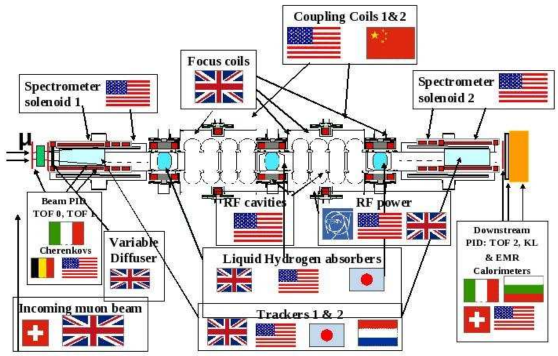

Figure 3: Collaboration contributions to MICE.

Alarms are also made audible by the EPICS alarm handler (ALH). This is also 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 ForcePVs in ALH allows these groups of 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 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.

Higher Level Controls

With the functionality of the controls systems in place for operation of the equipment, higher level functionality is also employed to integrate the systems for use in MICE. Three high level systems have been developed to date, and their functionality continues to be expanded. These are: AutoSMS, Run Control, and State Machines.

AutoSMS is an "auto-dialer" which uses email to SMS gateway functionality to automatically send SMS messages to pertinent experts when a problem arises. Critical PVs serve as flags which initiate the repeated SMS messages to lists of experts when the flag is set. In addition to the SMS messages, a detailed email describes the error condition. The model is to have a list of experts contacted via SMS to warn them to check email and log in to disable the SMS

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f ag. At the time of writing this document, this system is only used on the SS stand-alone C&M system.

The MICE Run Control (RC) brings together several IOCs, the experimental DAQ, the target DAQ, and the CDB. For each run, the operator is queried for preliminary run information: the MICE step and the run type. For each run type, there is is an acceptable list of triggers, beamline settings, and cooling channel settings. Once these are selected, RC queries the beamline IOCs to ascertain the readiness of the equipment and reads from the CDB the proper settings for this run type. If the components are ready, RC will attempt to set these conf gurations and will verify that they are correctly set. If not ready, RC will allow the operator to open the appropriate control panels. Once ready, the operator will do the same for the cooling channel parameters.[1] At the end of the run conf guration gathering step, RC queries the operator to enter a run comment. The different run types for MICE are:

- Reference – f xed parameters
- Calibration – limited parameters
- Physics – limited parameters
- Cosmic – limited parameters
- Pulser – limited parameters
- Special – unspecif ed parameters
- Test – unspecif ed parameters

When the equipment is ready the DAQ can be initialized. After initialization the run can begin. In the future, both of these functions will be initiated from the RC GUI. After the f rst trigger is accepted, all of the components set from RC are queried to verify the conf guration and write it as run-specif c entry in the CDB. This ensures that all of the MICE run conditions are completely documented.

Throughout the run RC monitors the run status. When it identif es the end of a run, it initiates a end run sequence which integrates the triggers, scalars, and target data, and adds an end run comment. These data are also added to the CDB.

The last of the higher level controls are the MICE state machines. Typically, when operating MICE equipment, the needs of the PVs depend on the operational state of the device. For example, when cooling a superconducting magnet, one normally must achieve a certain level of vacuum in the insulating vacuum layer prior to cooling, while other PVs are not of interest. Furthermore, one does not attempt to power the magnet before the coils are superconducting; hence temperatures, liquid He level, and cryostat pressure become important all the while requiring a vacuum level that continues to drop with temperature. These state dependent needs prompted the use of the EPICS State Notation Language (SNL) for the development of equipment state machines.

[1] This feature is not yet implemented, and will precede the beamline settings in the future, since the ramp rate is slower for the superconducting magnets.

The CDB is again employed to insure the correct parameter settings for the state machines. Thus, for each state, the state machine performs the following functions:

1. Enter state and set control panel buttons for new state.
2. Read CDB for this subsystem in this state.
3. Loop over parameters from CDB and f ll: alarm limits, archiver features, and turn on/off AutoSMS PVs.
4. Run Archiver restart script:
   - Create soft link to appropriate conf guration f le.
   - Stop/restart archiver with new conf guration f le.
5. Perform checks on software interlocks for this state and transition to “Error” state if any test is failed.
6. Perform checks on parameter limits for this state and transition to “Error” state if any test is failed.
7. 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 this is automated in the state machine GUI. For each state of each subsystem, the owners provide the following information: Description, Transition into state, PVs of Interest, Alarm Limits, Archiving features, AutoSMS PVs, Hardware Interlocks, and Software Interlocks. Presently the SS state machine is in operation.

CONCLUSIONS

A complete C&M is being developed to ensure that MICE can successfully measure a reduction in μ-beam emittance with a 0.1% absolute resolution. The f rst stage has been successfully completed in summer 2010, and we are presently preparing for the arrival of equipment for the implementation of Step IV.

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