A new application for the Grid: muon ionization cooling for a Neutrino Factory

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The muon ionization cooling experiment (MICE) will demonstrate a new technique for reducing the transverse emittance of a beam of muon particles, which are a species of lepton heavier than the electron species, essential for the realization of a future Neutrino Factory research facility. The first use of the Grid within MICE was to run thousands of Monte Carlo simulations to determine the alignment and statistical errors associated with measurements in MICE, which are made at two points in space on a similar sample of particles. The results of this study quantified the effect of correlations between emittance measurements. As a consequence, it has been determined that an order of magnitude less muons are required to achieve the required statistical accuracy than assuming uncorrelated measurements. This first application of the Grid within the MICE experimental domain has yielded results that could significantly impact upon the necessary running time of the experiment.

Keywords: Grid; application; e-Science; particle physics; MICE; Neutrino Factory

1. Introduction

The origin of the matter–antimatter asymmetry of the universe is one of the most important unanswered questions in physics. It is believed that the key to this puzzle is found in a process called leptogenesis (Fukugita & Yanagida 1986), where charge parity (CP) violation in leptons in the early universe led to the asymmetry observed in baryons, the main constituents of matter (Buchmuller 2007). A new generation of neutrino experiments aims to distinguish between neutrino and anti-neutrino oscillations to measure the leptonic CP violating phase responsible for this asymmetry. These experiments will require neutrino beams of unprecedented intensity, so there exists a world-wide effort to design the parameters of a Neutrino Factory facility that will produce these neutrino beams from the decay of muons to meet this challenge (described in §2). A key technology essential for the creation of sufficiently intense muon beams is to demonstrate the idea of ionization cooling of muons. This would allow the transverse size of muon beams to be reduced so they may be injected into an acceleration system, then to be stored in a muon storage ring so they may decay to create intense neutrino beams.

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The muon ionization cooling experiment (MICE; Yoshida 2005), as described in §3 and illustrated in figure 1, is currently under construction at the Rutherford Appleton Laboratory (RAL), and is designed to measure a fractional drop in the transverse emittance (a measure of beam size) of a beam of muons. The expected fractional change in emittance is of the order of 10 per cent, and the accuracy required in this parameter to meet the goals of the experiment is 1 per cent. In order to achieve this, MICE will measure the emittance before and after the cooling channel (consisting of the absorbers and radio frequency (RF) cavities), with two scintillating fibre trackers inside solenoidal magnetic fields and with particle-identification detectors to ensure that the particles contributing to the measurement are muons. The purpose of this paper is to demonstrate that the use of the Particle Physics Computational Grid (Faulkner et al. 2006) has been crucial to determine the systematic and statistical errors of the ionization-cooling measurement, which must be well understood for the experiment to meet its goal.

The four-dimensional emittance $\varepsilon_{4D}$, a measure of the transverse size of a particle beam, is defined as follows:

$$\varepsilon_{4D} = \frac{1}{mc} \sqrt{\text{det}(V)}, \quad (1.1)$$

where the elements of the $4 \times 4$ matrix of covariances $\mathbf{V}$ are $V_{ij} = \text{cov}(x_i, x_j)$, with $x_i$ the four transverse phase-space coordinates $x$, $p_x$, $y$ and $p_y$ for each muon. This covariance matrix is related to the beam parameters inside a solenoidal field through the following relation (Penn 2000):

$$\mathbf{V} = \begin{bmatrix}
  mce_\gamma \beta_\perp p_x & -mce_\gamma \alpha_\perp & 0 & -mce_\gamma (\beta_{\perp K} - \mathcal{L}) \\
  -mce_\gamma \alpha_\perp & mce_\gamma p_x \gamma_\perp & +mce_\gamma (\beta_{\perp K} - \mathcal{L}) & 0 \\
  0 & +mce_\gamma (\beta_{\perp K} - \mathcal{L}) & mce_\gamma \beta_\perp p_x & -mce_\gamma \alpha_\perp \\
  -mce_\gamma (\beta_{\perp K} - \mathcal{L}) & 0 & -mce_\gamma \alpha_\perp & mce_\gamma \frac{p_x}{\gamma_\perp}
\end{bmatrix},$$

Figure 1. MICE is a staged experiment. The full, final Step VI is shown here. Eight radio frequency (RF) cavities inside two coupling coils and three absorbers within focus coil modules form the cooling channel. Particle tracking and identification (PID) detectors, including scintillating fibre trackers, time of flight (TOF) detectors, Cherenkov and calorimeters are positioned at either end, to perform the emittance measurement.
where $\alpha_\perp$, $\beta_\perp$ and $\gamma_\perp$ are the beam Twiss parameters (Wilson 2001), $p_z$ is the momentum along the beam, $\kappa$ the radius of curvature of the muon in the solenoidal field, $\epsilon_N$ the normalized transverse emittance, $\mathcal{L}$ is related to the canonical angular momentum $L_{\text{canon}}$ by $\mathcal{L} = \langle L_{\text{canon}} \rangle / 2mc\epsilon_N$, $m$ is the mass of the muon and $c$ is the speed of light.

The fractional change in emittance is defined as: $f = \delta\epsilon / \epsilon_i$, where $\delta\epsilon$ is the total change in emittance through the course of the MICE cooling channel and $\epsilon_i$ is the input emittance of the beam when it entered the MICE channel. The emittance is measured by the two scintillating fibre trackers positioned at either end of the MICE channel. Crucially, these detectors measure emittance on roughly the same sample of muons, thereby introducing correlations in the two measurements. Verifying the propagation of errors from the elements of the emittance matrices through to the final emittance measurement is therefore non-trivial.

In order to quantify the statistical errors for different input-beam configurations with MICE, a large number of simulations with different pseudo-random conditions was therefore required. This number of simulations could take several years on a desktop computer, but the results are essential to estimate the number of particles needed for each beam configuration, and therefore to determine the amount of time that the experiment needs to run at each configuration. However, with the extra computing power drawn from the Grid, such a study becomes feasible.

This study provides an ideal application for the GANGA job definition and management front end (Egede et al. 2005), described in §5. GANGA provides powerful facilities for job submission, generating job meta data, such as $\text{jdl}$ (job description language) files, collecting output and error messages in a hierarchical manner and handling job-status polling and resubmission from a small number of commands.

2. Neutrino Factory future facility

An International Design Study is currently underway to design and cost a future Neutrino Factory facility (IDS-NF 2009), with one possible configuration illustrated in figure 2 (Berg et al. 2009). The Neutrino Factory includes a high-power proton driver (either a synchrotron or a linear accelerator) that accelerates up to 4 MW protons onto a target. The pions from the target are collected by a solenoidal capture system, bunched and phase rotated in the Neutrino Factory front end, where they decay into muons. The emittance of the muon beam generated is reduced in a muon cooling section, and the beam is injected into a series of nested recirculating linear accelerators. Finally, the accelerated muon beams are injected into two racetrack-shaped decay rings where the muons decay in the long straight sections of the storage rings. The intense beams of muons are fired downwards, through the Earth approximately, 3500 and 7500 km away to underground far detectors of the order of hundred kilotons (Abe et al. 2009).

The Neutrino Factory is the ideal venue for studying the neutrino-oscillation parameters that govern the transformation of neutrinos from one type to another and could be used to discover CP violation in neutrinos, which could be the key to understanding leptogenesis in the early universe. The required number of neutrino interactions necessary requires very intense muon beams ($10^{21}$ muon decays per
Figure 2. A possible design of a future Neutrino Factory facility. Muons are allowed to decay in long decay rings, producing neutrinos that progress through the Earth to hundred kiloton detectors thousands of kilometres away. MICE is a research and development experiment to provide proof of principle for the cooling section of a Neutrino Factory. FFAG, fixed-field alternating gradient; RLA, recirculating linear accelerator.

year). In order for the muon beam to be captured within the acceptance of the acceleration system, we must first reduce its transverse normalized emittance to around 30 mm rad through a cooling channel. MICE is a prototype for this cooling channel and will demonstrate the technique of ionization cooling.

3. The international muon ionization cooling experiment

MICE is a staged experiment, evolving gradually with time to provide a systematic study of ionization cooling, as illustrated in figure 3. The MICE beamline, not pictured, feeds from the ISIS proton source at RAL. Pions are produced from proton collisions with a cylindrical titanium target. These pions are allowed to decay in a superconducting solenoid in the beamline, and their momenta are selected using two dipole-bending magnets.

MICE (figure 1) consists of a cooling channel, flanked on either side by two scintillating fibre trackers for the emittance measurement. Additional detectors, such as time of flight, Cherenkov detectors and calorimeter systems (consisting of a lead/scintillator sandwich for electron identification followed by an electron muon ranger) allow for particle identification and selection of a beam. MICE is a single-particle experiment, and accurate particle identification is crucial in constructing a beam during the offline analyses. The cooling channel itself consists of low-density absorber materials, such as liquid hydrogen or lithium hydride, surrounded by focusing coils, and RF accelerating cavities surrounded by coupling coils.
Figure 3. The staged progression of MICE is illustrated above. At the time of writing, MICE is taking data in a Step I configuration.

Figure 4. These graphs illustrate the principle of ionization cooling, which MICE aims to demonstrate experimentally. Momentum is reduced in the low Z absorber, chosen to minimize multiple scattering. RF cavities restore longitudinal momentum.

The principle of ionization cooling is illustrated in figure 4. Figure 4a shows a loss of total momentum through energy loss as a particle traverses the absorbing material. Figure 4b shows an increase in transverse momentum caused by multiple scattering. The goal of the cooling channel is to reduce transverse momentum, so an absorbing material with low density is chosen to minimize the effect of multiple scattering. Finally, the particle is re-accelerated in figure 4c, where only longitudinal momentum is restored, resulting in a reduction of transverse momentum and consequently a reduction of the transverse-phase-space size of the beam. This technique has yet to be demonstrated experimentally, hence the current interest in MICE. The stated goal of MICE is to measure fractional change of emittance of 10 per cent to an error of 1 per cent.

4. Errors study

In order to meet the goals of the experiment, one must identify and understand the statistical and systematic errors that will combine to form the error on the measurement of fractional change in emittance. One example of systematic
errors discussed here is that of the misalignment of the trackers, which perform
the actual measurement. Misalignments are likely to occur, possibly due to
mechanical tolerances, human error or the effect of magnetic fields, for example,
and a misalignment study is necessary to establish how well the position of the
tracker detectors must be known to meet the experimental goal.

Monte Carlo simulations allow the comparison of simulated measurements
with measured values and enable analyses to quantify the systematic errors
introduced by changing geometry. Statistical and alignment errors together
present a difficult computational challenge, necessitating thousands of simulations
for each experimental configuration. Grid technology therefore found its
first application within MICE in being able to assess the statistical and
alignment errors of the experiment, to determine whether the experimental
goals are achievable and to calculate the number of muons required to
attain them.

(a) Alignment error

The alignment study (Forrest & Soler 2009) involves running a set of
13 geometries, 12 of which are always misaligned, for six different beam
configurations of MICE. Each misalignment represents a translation and/or
rotation to a maximum of 10 mm and 3 mrad, respectively. In each geometry,
only the downstream tracker is misaligned in order to maximize the relative
misalignment between the two trackers.

Although these simulations may be run over a few days on locally available
resources, they provided an excellent template for the larger study into statistical
error. By itself, the alignment study established tolerances of 3 mm and 1 mrad in
tracker position and rotation. Performing both studies using the same simulation
template eases direct comparison and combination of results.

(b) Statistical error

The measurement of fractional change is calculated using emittance
measurements at both scintillating fibre trackers, crucially, upon a similar set
of muons. This introduces correlations in the measurements. Calculating the
statistical error directly is therefore non-trivial, as emittance, defined in §1, is
determined from the fourth root of a $4 \times 4$ covariance matrix. Nevertheless, it
is expected that the error should be inversely proportional to the square root
of the number of events $N$. The main aim of this study was to determine this
constant of proportionality and to verify empirically the scaling law that governs
this error as a function of number of muons, for a number of different beam-
emittance configurations. This was achieved by carrying out a large number
of simulations in which the number of muons and the beam parameters are
changed in the simulation. By quantifying the scale factor, one can determine
the number of particles required to meet the statistical error requirements of the
MICE experiment, as in Forrest & Soler (2010).

A range of beam conditions will be studied during the course of the MICE
experiment. In this study, over 1500 simulations were run for each beam
configuration, with at least 500 each for runs of 1000, 2000 and 10 000 particle
events. There were eight beam configurations that were considered for this study,
with initial emittances between 0.2–10 mm rad. At least 12 000 simulations were required, and retuning and subsequent repeating of the simulations meant that around 40 000 simulations were run and analysed. This study would have taken years, given the computing resources locally available to MICE for this purpose, but instead was able to be carried out in a reasonable time using high-performance Grid computing.

All simulations were performed using the final Step VI configuration of the MICE cooling channel in figures 3 and 1. Analysis of each simulation yielded a calculated value for fractional change in emittance. A distribution of fractional change in emittance was then generated, for each combination of beam configuration and number of events. The standard deviation ($\sigma$) of these distributions was measured, allowing for a comparison between standard deviation and the inverse square root of the number of events, $N$ (figure 5). A linear relationship between $\sigma$ and $1/\sqrt{N}$ was confirmed.

The constant of proportionality, $K$, was found to be different for each beam configuration, but crucially less than 1 for larger beam configurations more pertinent to the goals of MICE. Most $K$ values, shown in figure 6 were around 0.3. For higher emittance beams, this was due to the effect of correlations, previously described, which act to reduce the statistical error. This study quantified that effect for the first time. Since the constant of proportionality is around 0.3, it means that MICE needs to run with 10 times less muons than if the constant was equal to 1 (i.e. with uncorrelated errors).

Since the total error is influenced by systematic errors also, it is desirable for the statistical error to contribute no more than 0.1 per cent to the total error. This requirement allows us to calculate the number of particles required to meet the goals of MICE for a range of beam conditions. The quantification of the effect of correlations upon the measurement means that an order of magnitude less particles are required than if the effect of correlations was not understood. As MICE is a single-particle experiment, this result could have the effect of reducing necessary running time significantly.
Figure 6. The constant of proportionality $K$ between $\sigma$ and $1/\sqrt{N}$ as a function of input beam size.

5. Use of Grid resources

This study was made possible through the processing power of the Grid (§5a) and aided considerably by the archiving and data-management potential of Grid storage resources (§5b). In addition, the use of GANGA (§5c), a Python-based interface for job submission, greatly simplified job management. GANGA provided a level of abstraction for the roughly 40 000 simulations involved in this study, by virtue of composite objects called bulk jobs.

The work represented the first use of the Grid for the MICE experiment, and, as such, was a useful learning experience that can now be drawn upon by the wider collaboration for other uses. However, this study also has considerable direct impact in its own right, as is demonstrated in §6.

(a) Processing

It has already been stated that, in total, roughly 40 000 simulations were generated, of varying size. These simulations each required between 1 and 6 h to complete. The processing overhead on locally available desktop resources would require of the order of 50 000 computing hours or roughly 6 years, which would put completion of the study beyond the lifetime of the MICE experiment. Nevertheless, it was essential that the statistical error in MICE’s final results be quantified.

A fail rate of roughly 10 per cent was observed, attributable to a combination of internal exceptions within the software being run, issues surrounding job submission and rare failure to write a file to storage. In most cases, resubmission overcame these problems.
Through GridPP, there are 4143 processors available to MICE, which have the required G4MICE (version 1.9.5) software installed, although many others presently support the MICE virtual organization. This, in principle, allows the otherwise unfeasible number of simulations to be completed within a matter of weeks. The step change in processing capability allowed the study to be performed incrementally, and iteratively improved with a much greater periodicity than might otherwise be available.

(b) Storage

ScotGrid storage elements were used, both for input and output to and from Grid jobs. Each simulation produces three files as output: the raw simulation results, the log and an analysis file reconstructing physics parameters and histograms from the simulation. Of these, the simulation file is the largest at between 10 and 300 MB, depending on the length of the simulations, with the others less than 200 kB in all cases. In total, 91 GB of files was permanently retained after the study.

MICE, therefore, now has a large body of simulations available for ready access globally, which can be included in future analyses. These simulations are addressed using an agreed logical file catalogue (LFC) directory structure and generated from a version of the G4MICE software uniquely described by a permanent software tag. Additionally, this analysis can now be recreated remotely, a necessary use case in a high-energy-physics collaboration, where reliance on PhD students increases people turnover, and undocumented results risk being obscured or lost.

Grid storage has also been used in the collaboration for remote access of real data from the experiment. Users have been able to quickly and easily include this data in their analyses without being familiar with the details of the implementation of Grid storage.

(c) Job submission using GANGA

This study benefited from the use of version 5 of the GANGA tool, an optional job submission management software tool (Mościcki et al. 2009) for interfacing with Grid resources. It allows one to easily parametrize jobs, in Python, with a level of abstraction from the glite-wms commands and jdl files associated with conventional job submission. This allows the study to be easily understood, repeated and modified by members of the collaboration who presently lack Grid experience.

GANGA provides book-keeping facilities for status polling and persistent archiving of job input, scripting and output, providing a record of running conditions for each simulation that has been run, proving that they are statistically independent from one another. The usefulness of this functionality is particularly apparent when running tens of thousands of simulations.

GANGA also provides ‘splitters’ that facilitate the ready definition of composite jobs. An argument splitter allows composite jobs to be defined based on one job script that produces lists of arguments, each list defining one job. In this study, each job submitted corresponds to one experiment. Thousands of experiments for each configuration were simulated, their Grid jobs differing only with respect to the seed given to the random-number-generating algorithm, rendering each...
experiment statistically independent from every other. A complete job therefore can be described with respect to some starting seed, a parameter describing the total number of particles to be simulated, an experimental geometry and an input beam, as well as some unique identifying tag for organization of output. In no other respect are any of the jobs submitted considered unique.

One may generate all the jobs at once by providing lists of arguments to GANGA’s ARGSPATTER, along with an executable to run. Each list corresponds to one job, for which the jdl file, book keeping and status polling are handled automatically. Handling of these many jobs is simplified by considering them all as subjobs in one composite bulk job, which can be submitted by the user as a single entity, with individual subjob submission handled automatically. The inverse operation, of merging rather than splitting many jobs based on a set of rules, may also be done; however, this functionality was not immediately exploited here since the output was simply written to Grid storage for later analysis.

Where elements of the study had to be repeated, simple modifications were made to the Python scripts, of roughly 15 lines in length, processed by GANGA to produce complex composite Grid jobs. The abstraction of a single bulk job, and resulting short scripts reduced any time that might be required to refamiliarize with a more complicated submission script some weeks or months after the original jobs were submitted.

6. Conclusion: impact of the Grid on the muon ionization cooling experiment project

We have stated that the main goal of MICE is to measure a fractional drop in emittance of the order of 10 per cent to an accuracy of 1 per cent for a range of beams. An understanding of the statistical errors involved in this measurement goal is essential to any assessment of its feasibility. This study has illustrated that the goal of MICE is achievable. Without the use of the Grid or high-performance computing to run tens of thousands of experiments, such a thorough statistical analysis would not have been possible.

MICE is, by design, a single-particle experiment. The results of the statistics study illustrate that an order of magnitude less muons are required than in the case where $K = 1$. This result therefore has a direct effect on the necessary running time for the experiment.

More generally, this study has been the first MICE-related study that has been performed on the Grid, providing useful learning artefacts for the collaboration as a whole (Forrest 2009). It is currently envisaged that, in the future, most MICE analysis using real data will be performed on the Grid.

MICE is currently running and taking data, evolving incrementally towards its final Step VI configuration in 2013. This study will prove useful in the final statement of the measurement of fractional change in emittance necessary for development of the cooling channel in a future Neutrino Factory facility.

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