MICE: First Beam Emittance Results w/Particle Detectors

Pierrick Hanlet
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TIPP'11
Outline

I  Motivation
II  Procedure for cooling muons
III  MICE description
IV  Status and early results
V  Future
Outline

I  **Motivation**

II  **Procedure for cooling muons**

III  **MICE description**

IV  **Status and Early Results**

V  **Future**
Motivation

The goal of MICE is:

- **Design, build, commission and operate a realistic section of cooling channel**
- **Measure its performance in a variety of modes of operation and beam conditions**

Results to be used to optimize Neutrino Factory and Muon Collider designs.
Motivation: Neutrino Factory

Neutrino Factory: accelerate and store muons to produce neutrinos

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

High energy $\nu_e$ are unique among future facilities.

Golden channel: $\nu_e \rightarrow \nu_\mu$

long baseline oscillations manifested by wrong sign muons:

$$\nu_\mu + N \rightarrow \mu^- + X$$
**Motivation**

**Muon Collider**

- “Fallen off” the curve
- $\mu$ accelerator solution
  - fundamental particles
  - cleaner interactions
  - tunable interaction energy
- $m_\mu = 205m_e$ such that less synchrotron radiation

$\mu$ lifetime in rest frame is 2.2 $\mu$s!

**Technological challenge, but not impossible!!!**
**Motivation: Muon Accelerator**

- **High-power target:**
  - 4MW proof of principle
  - MERIT (CERN)

- **Possible targets:**
  - MICE (RAL)
  - EMMA (Daresbury)

- **International R&D efforts to meet the challenges**
MICE is the **Muon Ionization Cooling Experiment**

**MICE** is a proof of principle experiment to demonstrate that we can “cool” a beam of muons.
Why cool muons?

- Muons are created as tertiary particles.
- Created with large inherent emittance – beam spread in 6D phase space:
  - $x$, $y$, $z$
  - $p_x$, $p_y$, $p_z$
- Accelerators require particles in tight bunches.
- Must “cool” muons – reduce emittance of beam:
  - “Smaller beam” reduces cost of accelerator.
  - “Smaller beam” increases luminosity.
I Motivation

II Procedure for cooling muons

III MICE description

IV Status and Early Results

V Future
Procedure: Ionization Cooling

- Muons are created as tertiary particles, and so are created with large inherent emittance:
  \[ p + N \rightarrow \pi + X \rightarrow \mu + X \]

- “Cooling” muons refers to reducing the emittance of the muon beam.

- Due to short muon lifetime, the only viable option is ionization cooling. Must cool **AND** accelerate rapidly:
  - Loose momentum in \( p_T \) and \( p_L \)
  - Restore \( p_L \)
Procedure: Ionization Cooling

- Strong focussing at absorber yields small $\beta_\perp$

$$\frac{d\varepsilon_n}{ds} = -\frac{1}{\beta^2} \left\langle \frac{dE_\mu}{ds} \right\rangle \frac{\varepsilon_n}{E_\mu} + \frac{1}{\beta^3} \frac{\beta_\perp (0.014)^2}{2E_\mu m_\mu X_0}$$

- Low Z absorbers yields large $X_0$

Cooling is:
1) Energy loss in all dimensions via $dE/dx$
2) Replace longitudinal momentum with RF
MICE Procedure

MICE will measure a 10% cooling effect with 1% accuracy => precision measurement

1. create beam of muons
2. identify muons and reject background
3. measure muon emittance
4. “cool” muons in low-Z absorber
5. restore longitudinal momentum
6. re-measure muon emittance
7. identify muons to reject e's from \( \mu \) decay

-with trackers

-here with hodoscopes
Description: The Lab

Rutherford Appleton Laboratory

United Kingdom
Description: Experiment

- **Beamline** – create beam of muons
- **Particle ID** – verify/tag muons (before/after)
- **Trackers** – measure emittance (before/after)
- **Absorber** (LH$_2$ or LiH) – cooling
- **RF** – re-establish longitudinal momentum
Description: Who are MICE?
μ Beam Creation

Selecting a muon beam

~90g acceleration!!!

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## Beam Preparation

### Muon beam preparation for MICE measurements

<table>
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<th>Emittance (mm)</th>
<th>140</th>
<th>200</th>
<th>240</th>
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<td>3</td>
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<td>$p_{tgt}$</td>
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<td>453</td>
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</tr>
<tr>
<td>$p_{dif}$</td>
<td>164</td>
<td>229</td>
<td>267</td>
</tr>
</tbody>
</table>

*momentum (MeV/c)*

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Making a muon beam

- Dipoles select $p$
- Quadrupoles transport

Combinations of D1 & D2:
- $p_1 \sim 2 \times p_2$

used to enhance $\mu$ purity

- $p_1 \sim p_2$

pion/electron beam calibrations

$\mu$ kinematic limits

9 initial settings ($M_0$)

$\mu$ peak

$\pi$ peak

$\mu$ forward peak

$\mu$ backward peak

409 MeV/c

238 MeV/c

$\mu$ Beam Selection
Beam Selection

\[ p_1 \sim p_2 : \text{beamline optimized for calibration studies} \]

\[ p_1 \sim 2p_2 : \text{beamline optimized for } \pi \rightarrow \mu \text{ transmission} \]
MICE PID: Detectors

**Upstream PID:**
- discriminate $p$, $\pi$, $\mu$
- Beam profile monitors
- Time of Flight – ToF0 & ToF1
- Threshold Cerenkov

**Downstream PID:**
- reject decay electrons
- Time of Flight - ToF2
- Kloe-light Calorimeter - KL
- Electron-Muon Ranger - EMR
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Step I Goals

• Calibrate beam line detectors
  – Luminosity Monitor, Beam Profile
  – Monitors\TOF0, TOF1, TOF2, CKOVs, KL

• Understand the beam
  – Composition
  – Rates
  – Momentum scale
  – First phase-space reconstruction

• Take data for each point in (ε-p) matrix
  – MICE beam designed to be tunable
  – Study each configuration's beam parameters

• Compare data to beam line model
• Prepare for Steps with cooling
MICE Progress

Step I complete:

- Record amount of data taken summer 2010
  - Over 335,000 dips of target into ISIS
  - Over 13,000,000 particle triggers

- Beamline studies:
  - Emittance-momentum matrix scan – (in 1k events)
    - dedicated
    - negative beam
    - positive beam

- Daily Reference run and Target test run
- Hardware fully functional and stable
**MICE PID: ToF**

- **ToF** – “Time of Flight”
- scintillator hodoscope
- x-y point determination (single particle)
- fast PMTs for high timing resolution
- used also characterization of BL

1) Used for particle identification
2) Used to determine phase space parameters

**Time resolution after calibration:**
- TOF0 – 51ps
- TOF1 – 62ps
- TOF2 – 52ps

Resolution meets design goals for TOFs
MICE PID: ToF Monitor

- horizontal bars – y position
- vertical bars – x position
- 2 PMTs per ToF bar
- each PMT read out with
  - TDC – time
  - Flash ADC – pulse height
- coincident PMT bars – green bar
- coincident bars – space point
Measuring the effective speed of light in the scintillator, the position measurements are improved (including corrections):

\[ v_{\text{eff}} = 14 \text{ cm/ns} \]

\[ x_{\text{eff}} = \frac{v_{\text{eff}} (t_L - t_R)}{2} \]

\[ \sigma_{\text{eff}} = \frac{v_{\text{eff}} \sigma_{\text{PMT}}}{\sqrt{2}} \]
MICE: Step I Analyses

- Particle Rate vs. Losses in ISIS
  - Study $\mu$ rate – want hundreds/spill
- Beam Composition

*First emittance measurement in MICE*

- Target operation studies
  - Depth, delay, acceleration
- Proton absorber
  - Eliminate protons in $\mu^+$ beam
- Data quality
  - Daily reference runs to verify stability
Making an emittance measurement with particle detectors requires the track parameters: $x$, $x'$, $y$, $y'$

Where:
$x' = \frac{p_x}{p_z}$ & $y' = \frac{p_y}{p_z}$

Use these to form the covariance matrix.

Use the covariance matrix to compute normalized emittance:

Normalized emittance:

$$\varepsilon_n = \frac{1}{m_\mu} \frac{4}{\sqrt{\det|C|}}$$
Emittance Measurement

1) For each particle: know time-of-flight and position \((x,y)\) at each detector – select good muons

2) Momentum-dependent transfer matrices map particle motion from ToF0 to ToF1 through drifts and quad triplet
   - G4MICE (MICE MC) used to simulate beam, determine energy loss along path, and estimate detector effects

3) Estimate initial path length and momentum using transfer map:
   - Iterate to improve calculation of path length and momentum

4) Calculate initial and final momentum at ToF0 and ToF1

5) Determine phase space at ToF planes, \(x,y, p_x, p_y\)

Beam profile at TOF0

Beam profile at TOF1

Q7

Q8

Q9

TOF0

\((x_0, y_0)\)

TOF1

\((x_1, y_1)\)
Emittance Measurement

- Good muon selected & particle positions measured
- Use product of transfer matrices $M(p_z)$ through the drifts and quadrupole magnets to map trace space $(x,x')$ from ToF0 to ToF1 (with $\det M \equiv 1$).

$$
\begin{pmatrix}
  x_1' \\
  x_1
\end{pmatrix} =
\begin{pmatrix}
  M_{11} & M_{12} \\
  M_{21} & M_{22}
\end{pmatrix}
\begin{pmatrix}
  x_0 \\
  x_0'
\end{pmatrix}
$$

- The angles are deduced from the positions

$$
\begin{pmatrix}
  x_0' \\
  x_1'
\end{pmatrix} =
\frac{1}{M_{12}}
\begin{pmatrix}
  -M_{11} & +1 \\
  -1 & M_{22}
\end{pmatrix}
\begin{pmatrix}
  x_0 \\
  x_1
\end{pmatrix}
$$
Emittance Measurement

- Initial path length assumed to be straight line
- Iterate to remove bias in path length
  - Momentum calculated given path length and time-of-flight from TOFs
- Particles tracked using thick edge quadrupole model
- Compared to MC using G4MICE to simulate beam
- Calculate $x'$, $y'$
- Calculate emittance
Emittance Measurement

- Emittance measurement:
  - Good muon selected
  - Muon positions measured
  - Momentum reconstructed
  - $x'$ and $x_1'$ determined
  - Calculate emittance

- G4MICE used to simulate ToF0 to ToF1 beam line

- For baseline (6-200) $\mu^-$ beam

- Promising preliminary agreement observed between data (blue) and MC (red) at ToF1 for momentum and $x,y,x',y'$
Reconstructed transverse phase space of the baseline MICE beam (6-200) at ToF1

- \( y(\text{mm}) \) vs \( x(\text{mm}) \)
- \( x'(\text{mrad}) \) vs \( x(\text{mm}) \)
- \( y'(\text{mrad}) \) vs \( y(\text{mm}) \)

### Data

- Entries: 87843
- Mean \( x \): 15.52
- Mean \( y \): -9.66
- RMS \( x \): 57.19
- RMS \( y \): 61.13

### MC

- Entries: 411023
- Mean \( x \): -1.509
- Mean \( y \): -0.3059
- RMS \( x \): 58.98
- RMS \( y \): 59.62

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Image: Emittance Measurement

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MICE Next Steps

Now that Step I is complete:

Fill up this hall
MICE Next Steps

Tracking

Absorbers

RF

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MICE Cooling Channel

AFC

RFCC

trackers
MICE Schedule

Staged:

- Systematics
- Funding
- Step IV: Q2 2012
Conclusions

• Muons observed in MICE!
• PID detectors in place and being calibrated
• Step I is complete!
• Data are being analyzed
• 1st beam emittance measurement
• Backup slides
MICE Tracking

- Two trackers – before/after
- Measures x, y, x', y'
- 5 stations/tracker
- 3 stereo planes/station – U/V/W
- 1400 350\(\mu\)m fibers/plane
- Double layer, 7 fibers/group
- <0.2% dead channels
- >10.5 photoelectrons/MIP
- 430\(\mu\)m RMS position resolution
MICE Tracking

- 4 T superconducting solenoids
- 20 cm warm bore
- 2 m long

5 coils:
- 1 main tracker coil
- 2 end coils
- 2 matching coils