Results from Step I of MICE and the Physics Plan for Step IV

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Motivation

**Neutrino Factory**

- $10^{21}$ usable $\mu$ decays per year.
- Cooling may double $\mu$ flux.

**Muon Collider**

- 40k Higgs per year
- 6D cooling required for high luminosity ($> 10^{34}$ cm$^{-2}$s$^{-1}$).

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Step I Results

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Conclusions
Motivation

A comparative study of $\delta$ measurements at different facilities. “Fraction of $\delta$” refers to the fraction of possible $\delta$ values for which a given precision ($\Delta \delta$) is obtainable.
Ionization Cooling

$\tau_\mu \approx 2.2 \, \mu s$ means stochastic, electron beam cooling approaches are not viable. Instead, we employ *ionization cooling*:

$$\frac{d\epsilon_N}{dX} \approx -\frac{\epsilon_N}{\beta^2 E_\mu} \left\langle \frac{dE}{dX} \right\rangle + \frac{\beta_t (0.014 \, \text{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$

... a *cooling term* and a *heating term* from multiple scattering.
MICE, the Muon Ionization Cooling Experiment

1. ~150 collaborators from 9 countries.
2. Hosted at Rutherford Appleton Laboratory in the UK.
3. 4D ionization cooling of 140-240 MeV/c muon beams.
4. Expected to demonstrate a 10% reduction in transverse emittance. We therefore require $\Delta \epsilon_N / \epsilon_N = 1\%$. 

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MICE and the ISIS Beamline

- 800 MeV protons → Ti target → pion “spill” → μ beam.
- $\epsilon_N = 3, 6, 10\pi$ mm-rad.
- $p_z = 140, 200, 240$ MeV/c.
- D2 strength gives $> 95\%$ pure μ beam or “calibration beam”.

Momentum spectra at D2. Select backwards-decaying μ’s in π rest frame for best separation.
800 MeV protons $\rightarrow$ Ti target $\rightarrow$ pion “spill” $\rightarrow$ $\mu$ beam.

$\epsilon_N = 3, 6, 10\pi$ mm-rad.

$p_z = 140, 200, 240$ MeV/c.

D2 strength gives $> 95\%$ pure $\mu$ beam or “calibration beam”. $> 95\%$ muons
MICE is a *systems integration* study.
MICE is an international effort.
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MICE Staging
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Step IV

Step V*

Step VI

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Goals of Step I

- Integrate various time-of-flight (TOF), particle ID systems.
- Large momentum spread → no single transfer matrix for MICE. Demonstrate single-particle beam reconstruction method.
- Characterize $\mu$ beams for next MICE steps.
Step I Components: TOF

X/Y scintillator hodoscope.

- Required for $\pi$ rejection efficiency $> 99\%$.
- Determine RF phase to within $5^\circ$.

- $\sigma_{t}^{\text{TOF0}} = 55 \text{ ps}$
- $\sigma_{t}^{\text{TOF1}} = 53 \text{ ps}$
- $\sigma_{x} \approx 1 \text{ cm}$
Step I Components: Calorimeter

- “KLOE Light (KL)”: KLOE-type sampling calorimeter
- 2:1 fiber/Pb ratio
- \( e^+ / e^- \) tests at INFN-LNF:
  \[ \Delta t \approx 70 \text{ ps}/\sqrt{E}, \text{ and} \]
  \[ \Delta E/E \approx 7\%/\sqrt{E}. \]
Single-particle tracking

Estimate $p_z$ assuming a straight path from TOF0 to TOF1.

Calculate transfer matrices $M_x(p_z)$, $M_y(p_z)$ between TOF0, TOF1.

Get trace space vectors. E.g.:

$$
\begin{pmatrix}
  x'_0 \\
  x'_1
\end{pmatrix}
= \frac{1}{M_{12}}
\begin{pmatrix}
  -M_{11} & 1 \\
  -1 & M_{22}
\end{pmatrix}
\begin{pmatrix}
  x_0 \\
  x_1
\end{pmatrix}
$$

Use new values of $(x_0, x'_0), (y_0, y'_0), p_z$ to get approx. trajectory between TOF0 and TOF1.

Recalculate $p_z$.

Subtract $\sim 1.5$ MeV/$c$ for $dE/dx$.

End.
Step I Results: Trace space distributions

Reconstructed simulation & data for a 200 MeV/c, $6\pi$ mm-rad beam. Trace space distributions known to $\sim 5\%$ at entrance to cooling channel.
Step I Results: $\epsilon_{x,y}$ MC vs. Data

- Error bars include systematic and statistical error.
- Largest contribution to error is effective $c$ in TOF scintillators.
**π contamination studies**

π contamination in 140 MeV/c, 6π mm-rad μ beam.

KL response for μ beam vs. calibration beam. Useful for statistical estimate of contamination.

Preliminary results indicate π contamination is $O(\%)$.
MICE Step IV: Physics Plans
Step IV Physics Goals

1. No absorber: Alignment / optical studies.
2. LH$_2$ absorber: **Cooling**, scattering studies. Test empty & full.
4. LiH wedge for emittance exchange studies (6D cooling).
Step IV status: Spectrometer solenoids

- First solenoid is ready, will be shipped to RAL in September.
- Magnet training, field mapping underway for second solenoid.
Step IV status: Focus coils

- LH$_2$, LiH absorbers fabricated. LH$_2$ system has been tested.
- First coil qualified in solenoid mode. Flip mode qualification is problematic.
- Second focus coil to be delivered this month.
Step IV status: Electron-muon ranger (EMR)

- Prototype already tested in MICE.
- Fabrication nearly complete.
- Delivery in September.
- Commissioning with beam in October.

First cosmic seen with EMR!
Conclusions

- MICE beamline commissioned, $1.3 \times 10^7$ triggers collected.
- Particle ID systems (TOF, KL, Ckov) are working well.
- 2013 will be an exciting year for MICE – lots of systems being completed, delivered, qualified!
- Step IV will start taking data in 2015.