MICE: the International Muon Ionization Cooling Experiment

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Outline:

1. Introduction: Ionization Cooling
2. MICE
3. Current status
4. Summary
Introduction

• Would like to be able to cool muon beams
  – this would enable

  1. Neutrino Factories – ultimate tool for study of $\nu$ oscillations
  2. Muon Colliders – route to multi-TeV lepton collisions
Introduction

• Muons decay too quickly for stochastic or electron cooling, but can be cooled via. . .
Ionization Cooling

- Absorbers:
  
  \[ E \rightarrow E - \left( \frac{dE}{dx} \right) \Delta s \]
  
  \[ \theta \rightarrow \theta + \theta_{\text{space}}^{\text{rms}} \]

- RF cavities between absorbers replace \( \Delta E \)

- Net effect: reduction in \( p_{\perp} \) w.r.t. \( p_{\parallel} \), i.e., transverse cooling

**Note:** The physics is not in doubt

⇒ in principle, ionization cooling **has** to work!

... but in practice it is subtle and complicated...
Ionization Cooling

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E \rightarrow E - \left( \frac{dE}{dx} \right) \Delta s \\
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• RF cavities between absorbers replace $\Delta E$

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Note: The physics is not in doubt

⇒ in principle, ionization cooling has to work!

... but in practice it is subtle and complicated...

...so a test is essential!
Practical Difficulty:

• Cooling channels are expensive

⇒ affordable channel gives only \( \approx 10\% \) emittance reduction

• But standard beam instrumentation can measure emittance to only \( \approx 10\% \)
Practical Difficulty:

- Cooling channels are expensive

→ affordable channel gives only ≈10% emittance reduction

- But standard beam instrumentation can measure emittance to only ≈10%

Solution:

*Measure the beam one muon at a time!*
Goals of MICE:

- to show that it is possible to design, engineer and build a section of cooling channel capable of giving the desired performance for a Neutrino Factory;
- to place it in a muon beam and measure its performance in a variety of modes of operation and beam conditions.
MICE Collaboration (>100 collaborators from 36 institutions in 9 countries)

Belgium: Universite Catholique de Louvain (G. Gregoire)
Bulgaria: St. Kliment Ohridski University of Sofia (M. Bogomilov, D. Kolev, A. Marinov, I. Russinov, R. Tsenov)
Italy: INFIN Milano (A. Andreoni, D. Batani, M. Bonesini, G. Lucchini, F. Paleari, P. Sala, F. Strati)
      INFIN Napoli e Università Federico II (V. Palladino)
      INFIN Roma III and ROMA TRE University (A. Cassatella, D. Orestano, M. Parisi, F. Pastore, A. Tonazzo, L. Tortora)
      University of Trieste and INFN, Trieste (M. Apollonio, P. Chimenti, G. Giannini, A. Gregorio, A. Romanino, T. Schwetz)
Japan: KEK (S. Ishimoto, S. Suzuki, K. Yoshimura)
      Osaka University (A. Horikoshi, Y. Kuno, H. Sakamoto, A. Sato, M. Yoshida)
Netherlands: NIKHEF, Amsterdam (S. de Jong, F. Filthaut, F. Linde)
Russia: Budker Institute, Novosibirsk (N. Mezentsev, A. N. Skrinsky)
CERN: CERN (H. Haseroth, F. Sauli)
Switzerland: Université de Genève (A. Blondel, A. Cervera, J.-S. Graulich, R. Sandstrom, O. Voloshyn)
      Paul Scherrer Institut (C. Petitjean)
UK: Brunel University (P. Kyberd)
      University of Edinburgh (A. Khan, A. Walker)
      University of Glasgow (F. J. P. Soler, K. Walaron)
      University of Liverpool (P. Cooke, J. B. Dainton, J. R. Fry, R. Gamet, C. Touramanis)
      Imperial College London (G. Barber, P. Dornan, M. Ellis, A. Fish, K. Long, D. R. Price, C. Rogers, J. Sedgbeer)
      Daresbury Laboratory (P. Corlett, A. Moss, J. Orrett)
      University of Sheffield (C. N. Booth, P. Hodgson, L. Howlett, P. Smith)
USA: Argonne National Laboratory (J. Norem)
      Brookhaven National Laboratory (R. B. Palmer, R. Fernow, J. Gallardo, H. Kirk)
      Fairfield University (D. R. Winn)
      University of Chicago and Enrico Fermi Institute (M. Oreglia)
      Fermilab (A. D. Bross, S. Geer, D. Neuffer, A. Moretti, M. Popovic, R. Raja, R. Stefanski, Z. Qian)
      Illinois Institute of Technology (D. M. Kaplan, N. Solomey, Y. Torun, K. Yonehara)
      Jefferson Lab (R. A. Rimmer)
      Lawrence Berkeley National Laboratory (M. A. Green, D. Li, A. M. Sessler, S. Virostek, M. S. Zisman)
      UCLA (D. Cline, K. Lee, Y. Fukui, X. Yang)
      Northern Illinois University (M. A. C. Cummings, D. Kubik)
      University of Iowa (Y. Onel)
      University of Mississippi (S. B. Bracker, L. M. Cremaldi, R. Godang, D. J. Summers)
      University of California, Riverside (G. G. Hanson, A. Klier)
      University of Illinois at Urbana-Champaign (D. Errede)
**Single-Particle Emittance Measurement**

- **Principle:** Measure each muon precisely before and after cooling cell Off-line, form “virtual bunch” and compute emittances in and out

Need to determine, for each muon, x,y,t, and x’,y’,t’ (=p_x/p_z, p_y/p_z, E/p_z) at entrance and exit of the cooling channel:

Solenoid, B = 4 T, R = 15 cm, L > 3d

(to keep B uniform on the plates)

**T.O.F.**

**Measure t**

With \( \sigma_t \sim 70 \text{ ps} \)

**Three plates of, e.g., three layers of sc. fibres**

(diameter \( 0.35 \text{ mm} \))

**Measure** \( x_1, y_1, x_2, y_2, x_3, y_3 \) with precision \( 0.35 \text{mm}/\sqrt{12} \)

Extrapolate \( x,y,t,p_x,p_y,p_z \) at entrance of the channel. Make it symmetric at exit.
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Need to determine, for each muon, $x, y, t,$ and $x', y', t'$ ($= p_x/p_z, p_y/p_z, E/p_z$)

at entrance and exit of the cooling channel:

Solenoid, $B = 4 \text{ T}, R = 15 \text{ cm}, L > 3d$

(to keep $B$ uniform on the plates)

...but mux’ing readout by 7 gives suff. resolution and reduces cost
Nominal ("SFOFO") Lattice (200 MeV/c)

- $B_z$ vs. $z$:

- $\beta_t$ vs. $z$:

- Exist flexibility to explore other settings, momenta, absorber mat’ls...
Performance Simulation (nominal SFOFO mode):
(BNL ICOOL simulation)

\[ \rightarrow \approx 10\% \ \text{transverse emittance reduction, measurable to } 0.1\% \ \text{(abs.) given precise spectrometer, clean beam, and efficient, redundant particle ID} \]
Tracker Performance Simulation:
(C. Rogers, ICL G4MICE simulation)

- Correctable ≈1% bias due to scattering in detectors:

- Key physics goal of “MICE Phase 1”:
  - demonstrate bias correction to <10% of itself, as needed for 0.1% emittance measurement
Current Status:

• MICE proposal submitted January 2003
• Proposal approved by CCLRC 10/24/03
• MICE funding (Phase 1) approved in Italy, Japan, Netherlands, Switzerland, UK, US
  – Includes installation of muon beamline on ISIS at RAL:

... as well as MICE spectrometers, e.g.:

Prototype solenoidal spectrometer:
  4 3-view SciFi stations
designed for insertion in 4T SC solenoid

• Plan: 1st MICE beam at RAL 4/07
Avatars of MICE

• Measurement precision relies crucially on precise calibration & thorough study of systematics:

  - **STEP I:** 2007
    - Characterize beam

  - **STEP II**
    - Calibrate Spect. 1

  - **STEP III**
    - Intercalibrate Spect. 2 w.r.t. Spect. 1; demonstrate 0.1% emittance measurement

  - **STEP IV:** 2008?
    - Study 1st abs./focus-coil pair, check dE/dx and scattering

  - **STEP V**
    - Cooling study w/ 1/2 lattice cell

  - **STEP VI:** 2009?
    - Cooling study w/ full lattice cell & realistic field flip
Avatars of MICE

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Sampler of Recent Progress: SciFi Tracker Test at KEK
(KEK / Osaka / UK / FNAL / IIT / UCR / UCLA)

• Installing 4-station prototype in 1T SC solenoid:
  (already passed cosmic-ray test)

• Test beam scheduled for Sept. 27 – Oct. 7
Absorber Design
(KEK, Oxford, RAL)

• Need LH$_2$ absorbers with 0.1–1 kW power-handling capability

Prototype high-power LH$_2$ absorber
MICE low-power design
(MuCool)  

– also much work on hydrogen safety
RF Cavities (LBNL)

- Prototype 201 MHz cavity with thin, curved Be windows

...about to begin high-power testing at Fermilab MTA
RF Power

- Two surplus 4 MW, 201 MHz power amplifiers shipped from LBNL to DL for refurbishing

- Plan to get two more refurbished from CERN

→ 2 MW per cavity in Step V,
   1 MW per cavity in Step VI
• Work also proceeding on
  – spectrometer solenoids
  – beamline and infrastructure
  – particle-ID detectors
  – DAQ system
  – software...

...but I’m out of time to tell you about it!
Conclusions

• MICE is now approved and Phase 1 is funded
• Progressing well technically
• On track to exploit first beam in 2007
• Complete program requires Phase 2 funding approvals
  – additional collaborators could help
• Aim to finish by 2010