International

Muon Ionization Cooling Experiment

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for the MICE Collaboration

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Introduction

- **Motivation for MICE**
  - muon-based Neutrino Factory is most effective tool to probe neutrino sector and hopefully observe CP violation in lepton sector
    - results will test theories of neutrino masses and oscillation parameters, of importance for particle physics and cosmology
  - a high-performance Neutrino Factory ($\approx 4 \times 10^{20} \nu_e$ aimed at far detector per $10^7$ s year) depends on ionization cooling
    - straightforward physics, but not experimentally demonstrated
  - facility will be expensive ($\mathcal{O}(\text{€1B})$), so prudence dictates a demonstration of the key principle

- **Cooling demonstration aims:**
  - to design, engineer, and build a section of cooling channel capable of giving the desired performance for a Neutrino Factory
  - to place this apparatus in a muon beam and measure its performance in a variety of modes of operation and beam conditions
Introduction

• Another aim
  — show that design tools (simulation codes) agree with experiment
    ◦ gives confidence that we can optimize design of an actual facility
      – we test section of “a” cooling channel, not “the” cooling channel
        ♦ simulations are the means to connect the two
  • Both simulations and apparatus tested must be as realistic as possible
    – incorporate full engineering details of all components into simulation
Neutrino Factory Ingredients

• Neutrino Factory comprises these sections

  — Proton Driver
    (primary beam on production target)

  — Target and Capture
    (create π's; capture into decay channel)

  — Bunching and Phase Rotation
    (create bunches and reduce $\Delta E$)

  — Cooling
    (reduce transverse emittance of beam)
    ⇒ Muon Ionization Cooling Experiment

  — Acceleration
    (130 MeV → 20–50 GeV with RLAs/FFAGs)

  — Storage Ring
    (store muon beam for $\approx$500 turns;
     optimize yield with long straight section aimed in desired direction)

• Not an easy project, but no fundamental problems found to date
Cooling Description

- The need to cool the muons quickly dictates the approach to be used
  - muon lifetime in rest frame is 2.2 µs
    - “standard” stochastic cooling approach is much too slow
    - use novel technique of ionization cooling (tailor-made for muons)
- Analogous to familiar SR damping process in electron storage rings
  - energy loss (SR or dE/dx) reduces $p_x$, $p_y$, $p_z$
  - energy gain (RF cavities) restores only $p_z$
  - repeating this reduces $p_{x,y}/p_z$ and thus transverse emittance
Cooling Description

- There is also a heating term
  - with SR it is quantum excitation
  - with ionization cooling it is multiple scattering

- Balance between heating and cooling gives equilibrium emittance

\[
\frac{d\varepsilon_N}{ds} = -\frac{1}{\beta^2} \left| \frac{dE_\mu}{ds} \right| \varepsilon_N + \frac{\beta_\perp (0.014 \text{ GeV})^2}{2 \beta^3 E_\mu m_\mu X_0}
\]

\[
\varepsilon_{x,N,\text{equil.}} = \frac{\beta_\perp (0.014 \text{ GeV})^2}{2 \beta m_\mu X_0} \left| \frac{dE_\mu}{ds} \right|
\]

- prefer low \( \beta_\perp \) (⇒ strong focusing), large \( X_0 \) and \( dE/ds \) (⇒ \( \text{H}_2 \) is best)
Cooling Description

- Merit factors for candidate MICE absorbers (scaled as equilibrium emittance)

<table>
<thead>
<tr>
<th>Material</th>
<th>$(dE/ds)_{\text{min.}}$ (MeV g$^{-1}$ cm$^2$)</th>
<th>$X_0$ (g cm$^{-2}$)</th>
<th>Relative merit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaseous H$_2$</td>
<td>4.103</td>
<td>61.28</td>
<td>1.03</td>
</tr>
<tr>
<td>Liquid H$_2$</td>
<td>4.034</td>
<td>61.28</td>
<td>1</td>
</tr>
<tr>
<td>He</td>
<td>1.937</td>
<td>94.32</td>
<td>0.55</td>
</tr>
<tr>
<td>LiH</td>
<td>1.94</td>
<td>86.9</td>
<td>0.47</td>
</tr>
<tr>
<td>Li</td>
<td>1.639</td>
<td>82.76</td>
<td>0.30</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>2.417</td>
<td>46.22</td>
<td>0.20</td>
</tr>
<tr>
<td>Be</td>
<td>1.594</td>
<td>65.19</td>
<td>0.18</td>
</tr>
</tbody>
</table>

- requirements for Al windows and extended absorber with H$_2$ and He degrade these merit factors by roughly 30%

- H$_2$ is best, even with windows included.
Cooling Description

- Typical momentum chosen for transverse cooling is $p \approx 200$ MeV/c
  - this is optimal in terms of muon production from thick target

- Running below min. ionization energy increases longitudinal emittance
  - lower $E$ particles have higher $dE/dx$ than do higher $E$ particles

- Running above min. ionization point disadvantageous for several reasons
  - more demanding RF and magnet requirements; more $E$ straggling

Note benefits of LH$_2$ compared with other materials
Benefits of Cooling

- Why does a Neutrino Factory need cooling?
  - large phase space volume ("emittance") of initial muon beam is difficult to transport and accelerate efficiently
    - would require very large magnets and RF cavity apertures (possible in principle, but costly)
  - cooling increases muon density in a given acceptance by 4–10
    - the smaller the downstream acceptance, the larger the gain from cooling...and vice versa

- For many particle physicists, the Holy Grail of muon beam R&D is to build a **Muon Collider**
  - collider gives energy-frontier facility in small footprint
  - for this application, cooling is mandatory!
MICE Implementation

- Layout of MICE components
  - one lattice cell of cooling channel components (based on U.S. Study-II configuration) is indicated
  - note that cooling channel is simply a linac with absorber material added
MICE Implementation

• **Basic ingredients** of a cooling channel are:
  
  — **solenoid magnets** to contain muons as they traverse the channel ($B \approx 3$ T)
  
  — **absorbers** to give energy loss ($LH_2$, capable of handling ~100 W)
  
  — **RF cavities** to restore energy (16 MV/m gradient at 201 MHz)
    
    ○ power limitations (and probably background rates) preclude this gradient for MICE, which will typically operate at 8 MV/m
  
• For **MICE**, we add
  
  — **diffuser** to create large emittance sample
  
  — **upstream diagnostics section** to define initial emittance
  
  — **downstream diagnostics section** to determine final emittance and particle ID
MICE Implementation

- Simulations of MICE performance have been done
  - several tools developed/adapted for cooling simulations (ICOOL, Geant4)
  - simulations of nominal cooling channel performance done with ICOOL
  - full MICE simulations with all details are done with Geant (G4MICE)

- Typical parameters
  - beam
    - momentum: 200 MeV/c (variable)
    - momentum spread: ±20 MeV/c
    - $\sigma_{x,y} \approx 5$ cm; $\sigma_{x',y'} \approx 150$ mrad
  - channel
    - solenoid field: $\approx 3$ T
    - $\beta_1$: 0.42 m
    - cavity phase: 90° (on crest)
MICE Implementation

- ICOOL simulation of the MICE experiment shows transverse emittance reduction of $\approx 10\%$

![Graphical representation of energy variation, particle loss, and 2D $\varepsilon$ reduction.]
MICE Implementation

— virtual “scan” over input emittance locates the equilibrium emittance

\[ \varepsilon_{x,N,\text{equil}} = \frac{\beta_\perp (0.014 \text{ GeV})^2}{2 \beta m_\mu X_0 \frac{dE_\mu}{ds}} \]

— transmission is 100% for input emittance below 6 mm-rad

  • high-emittance behavior reflects “scraping” as well as cooling
MICE Implementation

— important to test alternatives from baseline case to verify scaling

- different absorber materials (LHe, Li, Be,...); different beta functions

— these permit variation of heating and cooling terms, hence $\varepsilon_{\text{equil}}$.

- practical limit on reducing $\beta_\perp$ is current density in focusing coils

- doing low-beta tests at lower momentum avoids this limitation

<table>
<thead>
<tr>
<th>Case</th>
<th>$p$ (MeV/c)</th>
<th>$\beta_\perp$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>200</td>
<td>42</td>
</tr>
<tr>
<td>1b</td>
<td>240</td>
<td>42</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>25.4</td>
</tr>
<tr>
<td>3</td>
<td>175</td>
<td>16.7</td>
</tr>
<tr>
<td>4</td>
<td>150</td>
<td>10.5</td>
</tr>
<tr>
<td>5</td>
<td>140</td>
<td>5.7</td>
</tr>
</tbody>
</table>

— operating with higher RF gradients (fewer cavities) or LN-temperature cavities is also possible
MICE Implementation

• Main challenge of MICE
  — for cost reasons, we use only a single cell of a cooling channel
    ⇒ emittance reduction will be small in absolute terms ($\alpha(10\%)$)
    - wish to measure emittance reduction at level of $10^{-3}$

• Other challenges
  — operating high-gradient RF cavities in solenoidal field and with field terminations (windows or grids)
  — operating LH$_2$ absorbers with very thin windows and consistent with safety regulations
  — integration of cooling channel components while maintaining operational functionality
  — these build upon R&D activities already under way outside of MICE
    ◦ mainly under auspices of U.S. Neutrino Factory and Muon Collider Collaboration ("MC")
Cooling Hardware

- Solenoid magnets
  - two types of coil required
    - focusing coils (integrated with absorber; cooled with cryocoolers)
    - coupling coils (outside of RF cavity module; also uses cryocoolers)

Note “complications” of actual implementation
Cooling Hardware

- Field profile used in the design simulations is based on the indicated coil configuration
  - $z = 0$ is centerline of experiment (middle of central absorber)

- An alternative magnetic configuration with no field flip can also be tested
Cooling Hardware

- Absorbers
  - design based on LH$_2$ system with internal convection cooling
  - requires large diameter (300 mm), very thin (but strong!) Al windows
    - plus a second set of safety windows to form vacuum barrier
  - design tightly integrated with focusing coil package
Cooling Hardware

- 201 MHz RF cavity
  - RF module comprises 4 cavities with individual tuner mechanisms
  - cavities use precurved Be foils to increase shunt impedance

Exploded view of 201 MHz cavity (1.2 m diameter)  
805 MHz version of precurved Be window
MUCCOOL R&D Program

- Ability of MICE collaboration to achieve its goals greatly enhanced by hardware R&D programs under way worldwide

- U.S. MUCCOOL R&D program has substantial effort in place to develop required hardware components for MICE
  - RF cavities, absorbers

- MUCCOOL is building and testing prototypes of the absorber and 201-MHz RF cavity needed for MICE
  - a new area dedicated for component testing, the MUCCOOL Test Area (MTA) is now in use at Fermilab
MUCCOOL R&D Program

- Main RF challenge is to attain high gradient in the presence of a high magnetic field
  - increased breakdown and dark currents observed at 805 MHz
  - tests of different materials and coatings to mitigate effect will begin shortly

![Graph showing magnetic field vs. gradient]

Desired gradient at 805 MHz

Accelerator and Fusion Research Division
MUCOOL R&D Program

- Construction of 201 MHz RF cavity (LBNL, U-Miss., Jlab) is well along
  - Pilot hole for port extrusion
  - Beam iris (42 cm diameter)
  - Fabrication of prototype will be completed this year
MUCCOOL R&D Program

• Absorber work focusing mainly on developing strong, thin windows (IIT, NIU, Oxford, U-Miss.)
  
  — destruction tested windows at NIU (with satisfactory results)
    
    ○ 340 µm windows break at 120 psi (8 atm)
    
    ○ new inflected window shape is stronger and can be even thinner

  — use photogrammetry to characterize window behavior and verify FEA calculations (LH$_2$ safety requirement)
MUCOOL R&D Program

- Convection-cooled absorber prototype fabricated at KEK
  - recently tested at Fermilab with LH$_2$ (with no leaks!)

Prototype LH$_2$ absorber  Test cryostat at MTA
MICE Instrumentation

• Parallel R&D effort on MICE instrumentation is under way

• Upstream PID
  — TOF (70 ps resolution) used for PID, trigger, timing with respect to RF phase; Milan
  — Cerenkov used for $\pi/\mu$ separation; U.-Mississippi

• Downstream PID
  — Electromagnetic calorimeter used for $\mu/e$ separation; Rome III
  — Cerenkov used for $\mu/e$ separation; Louvain

• Tracker (baseline option)
  — scintillating fiber tracker (5 stations, planar) used for 6D emittance measurement; Bari, Brunel, CERN, Edinburgh, FNAL, Geneva, IIT, Imperial College, KEK, Legnaro, Liverpool, Napoli, Osaka, UCLA, UC-Riverside
MICE Status

• **MICE status**
  
  — proposal submitted in January, 2003
    
    o international review held February, 2003 (recommended approval)
    
    o scientific approval from RAL in October, 2003
  
  — absorber system concept passed preliminary safety review by international review panel in December, 2003
  
  — estimated hardware cost is £11M (total cost £25M)
    
    o more than half of this is now in hand (mainly UK)

• In U.S., MUTAC + MCOG have strongly recommended MICE the past two years
  
  — experiment considered “crucially important demonstration”

• U.S. funding request submitted to NSF (under review)
  
  — stagnant funding makes it hard to launch new initiatives
MICE Status

• Collaborating institutions

Europe
Bari
Brunel
CERN
Edinburgh
Genève
Genova
Glasgow
Imperial College
Legnaro
Liverpool
LNF Frascati
Louvain la Neuve
Milano
Napoli
NIKHEF
Novosibirsk
Oxford
Padova
PSI
RAL
Roma III
Sheffield
Trieste

Japan
KEK
Osaka

U.S.
ANL
BNL
Chicago-Enrico Fermi Institute
FNAL
Illinois Institute of Technology
TJNAF
LBNL
Mississippi
Northern Illinois
UCLA
UC-Riverside
Summary

• R&D on required MICE components is already at an advanced stage

• MICE will assemble and test these components in a realistic beam environment
  — as new ideas mature, MICE will likely serve as a test-bed for other components

• MICE is a very challenging “linac R&D” program
  — additional collaborators are still very much welcome!

• Resultant demonstration of muon cooling will validate key concept of Neutrino Factory design
  — and put Muon Collider concept closer to realization

• Measured cooling performance will “calibrate” our design tools
  — permitting cost and performance optimization of future Neutrino Factory

…the beam never lies!
"I guess there'll always be a gap between science and technology."