Neutrino Factories, Muon Colliders, and the International Muon Ionization Cooling Experiment (MICE)

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U.S. Spokesperson, MICE Collaboration

Physics Seminar
Los Alamos National LLab
Los Alamos, NM
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Illinois Consortium for Accelerator Research

- 5-university consortium, founded 1999, led by IIT
- D. M. Kaplan (IIT), PI; T. I. Morrison (IIT), PD
- Includes >10 faculty, >30 researchers
- Close collaboration with Fermilab
- Main research activities: Linear Collider, MU COOL (12 FTE)
- Main funding: 5-year State of Illinois grant at $2.5M/year
- Responds to looming crisis in sustaining progress of accelerator-based particle physics
Outline:

1. Motivation: Neutrino Factory and Muon Collider physics
2. Neutrino Factory Feasibility Studies
3. Need for muon cooling
4. Ionization cooling
5. Neutrino Factory cooling lattices and simulated performance (US, CERN)
6. Cooling experiment
7. Schedule
8. Costs
9. International collaboration
10. Summary
Motivation: Neutrino Factory Physics

1. Most fundamental particle physics discovery of past decade:

→ neutrinos have mass and mix
⇒ 3 Euler angles (and 1 phase):
⇒ neutrino mixing could violate CP
possible mechanism for baryogenesis

2. Pattern of neutrino mixing very different from that of quarks:

CKM matrix: nearly diagonal
\[ \theta_{12} \approx 12.8^\circ \]
\[ \theta_{23} \approx 2.2^\circ \]
\[ \theta_{13} \approx 0.4^\circ \]

MNS matrix (LMA solution):  
\[ \theta_{12} = 20^\circ - 45^\circ \]
\[ \theta_{23} = 35^\circ - 45^\circ \]
\[ \theta_{13} < 10^\circ \]

atmos \[ \Rightarrow \delta m_{32}^2 \sim 3 \times 10^{-3} \text{ eV}^2 \]
solar \[ \Rightarrow |\delta m_{21}^2| \sim 5 \times 10^{-5} \text{ eV}^2 \]

“natural” OR “inverted” hierarchy

Distinction is \( \text{sgn}(\Delta m_{32}^2) \)
3. Leading-order oscillation probabilities (natural hierarchy):

\[
P(\nu_e \rightarrow \nu_\mu) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 (1.267 \delta m^2_{32} L/E_\nu)
\]

\[
P(\nu_e \rightarrow \nu_\tau) = \cos^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 (1.267 \delta m^2_{32} L/E_\nu)
\]

\[
P(\nu_\mu \rightarrow \nu_\tau) = \cos^4 \theta_{13} \sin^2 2\theta_{23} \sin^2 (1.267 \delta m^2_{32} L/E_\nu)
\]

where \( L \) = baseline (km) and \( E_\nu \) = energy (GeV)

⇒ A high-energy \( \nu_e \) beam offers unique possibilities!

→ Gives best sensitivity to \( \theta_{13} \) of any technique:
4. Comparing $\nu_e \rightarrow \nu_\mu$, $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ gives both $\text{sgn}(\Delta m^2_{32})$ and CP phase:

$$A_{CP} = \frac{P(\nu_e \rightarrow \nu_\mu) - P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)}{P(\nu_e \rightarrow \nu_\mu) + P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)} \approx \frac{4 \sin 2\theta_{12} \cdot \sin \delta \cdot \sin(2\Delta m^2_{12} L/4 E)}{\sin \theta_{13}}$$

- For LMA, $10^{20}$ decays with 50-kT detector will see $\delta$ down to $8^\circ \Rightarrow$ flux is crucial!
- Note: SNO now favors LMA at 99% CL (VAC and SMA ruled out @ $>3\sigma$)
Motivation: Muon Collider

• A pathway to high-energy lepton colliders
  – unlike $e^+e^-$, $\sqrt{s}$ not limited by radiative effects
  – a muon collider can fit on existing laboratory sites even for $\sqrt{s} > 3$ TeV

\[ E \propto m_{\text{lepton}}^2 \]

• s-channel coupling of Higgs to lepton pairs $\propto m_{\text{lepton}}^2$

• E.g., $\mu\mu$-collider resolution can separate near-degenerate scalar and pseudo-scalar Higgs states of minimal SUSY
“A Brief History of Muons”

- **Muon storage rings** are an old idea:
  - Charpak *et al.* *(g – 2)* (1960), Tinlot & Green (1960), Melissinos (1960)
- **Muon colliders** suggested by Tikhonin (1968)
- But no concept for achieving high luminosity until **ionization cooling**
- The realization (Neuffer and Palmer) that a **high-luminosity muon collider** might be feasible stimulated a series of workshops & formation (1995) of the **Muon Collaboration**
  - has since grown to 26 institutions and >100 physicists
- **Snowmass Summer Study (1996)**
  - study of feasibility of a 2+2 TeV Muon Collider [Fermilab-conf-96/092]

**νFac Overview**

- Only way to produce intense beam of high-energy electron neutrinos: \( \mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e \)
- 2 schemes with cooling:

  **CERN**

- Both designs feature MW proton beams on high-power target, with pion collection & decay in focusing channel
- Decay muons undergo phase-space manipulations, cooling, acceleration, and storage in decay ring
**νFac Overview (cont’d)**

- 1 scheme without cooling (KEK):
  - Based on large-acceptance FFAGs
  - No phase rotation or cooling
  - Exploring possibility of adding cooling
  - R&D Issues: RF, injection/extraction, magnet design, dynamic aperture

→ 3 world regions cooperatively exploring complementary technical approaches, but all have similar goal:

\[ >10^{20} \text{ useful muon decays per year} \]
**U.S. vFac Feasibility Studies**

Have established (with detailed conceptual engineering)

- that a Neutrino Factory is technically feasible
- likely performance, cost, cost drivers, needed R&D

(partial FS II author list)

<table>
<thead>
<tr>
<th>Study</th>
<th>FS I</th>
<th>FS II</th>
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<tbody>
<tr>
<td>Requestor</td>
<td>Fermilab</td>
<td>Brookhaven</td>
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<tr>
<td>Duration</td>
<td>6 months</td>
<td>12 months</td>
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<tr>
<td>Finished</td>
<td>April, 2000</td>
<td>June, 2001</td>
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<td>Target</td>
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<td>“nondistorting”</td>
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<td># Induction linacs</td>
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<td>3</td>
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<td>Cooling lattices (baseline)</td>
<td>FOFO</td>
<td>SFOFO</td>
</tr>
<tr>
<td>(alternate)</td>
<td>Single-Flip</td>
<td>Double-Flip</td>
</tr>
<tr>
<td>Storage-ring energy</td>
<td>50 GeV</td>
<td>20 GeV</td>
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<tr>
<td># RLA's</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Neutrino flux / 10^23 s / straight / MW</td>
<td>2 x 10^{19}</td>
<td>1.2 x 10^{20}</td>
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</table>

**Indicative (not definitive!) FS II cost estimate**

<table>
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<th>Others (M$)</th>
<th>Total (M$)</th>
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<td>16.8</td>
<td>184.4</td>
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<td>Decay Channel</td>
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<td>Bunching</td>
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<td>Pre-accel. linac</td>
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<td>18.9</td>
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<tr>
<td>RLA</td>
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<td>Storage Ring</td>
<td>107.4</td>
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<td>126.9</td>
<td>12.7</td>
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<td><strong>Totals</strong></td>
<td>1,747.2</td>
<td>174.8</td>
<td>1,922.0</td>
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</table>

R&D now focusing on the “cost drivers”

- Good prospect for substantial cost reduction and/or performance increase via new ideas:
  - bunched-beam phase rotation, ring coolers, cheaper acceleration
FS II νFac Front End

Megawatt beam

target station

matching drift

1st induction linac

mini-cooling

2nd induction linac

3rd induction linac

buncher

cooling

meters

0 .3 36 176 256 286 367 378 433 541
Producing Pions

- BNL E910 pion production results
  - Pion yields peak at few hundred MeV/c
  - Data in fair agreement with predictions of MARS simulation
    (yields may be slightly higher than predicted)

- At constant proton beam power, pion yields vary only slowly with proton energy

>> broad range of proton driver energies can be considered:

CERN 2.2 GeV
FS II 24 GeV
JHF 50 GeV

- More data to come from HARP @ CERN, FNAL E907
Target R&D for MW-Scale Proton Beams

- Carbon Target tested at AGS (24 GeV, 5E12 ppp, 100ns)
  - Probably OK for 1 MW beam

- Target ideas for 4 MW: Water-cooled Ta spheres (P. Sievers), rotating band (B. King), front-runner is Hg jet

- CERN/Grenoble Hg-jet tests in 13 T solenoid
  - Field damps surface tension waves

- BNL E951: Hg jet in AGS beam
  - Jet (2.5 m/s) quickly re-establishes itself
  - Plan future test in 20T solenoid
FS II Proton Driver: AGS×7 (1-MW) Upgrade

- **New SC linacs** bypass booster synchrotron
- 6 bunches of $1.7 \times 10^{13}$ each at 2.5 Hz rep. rate $\rightarrow$ 15 Hz avg. rate, $2.5 \times 10^{14} p/s$
- **20 ms interbunch time** allows Hg jet target to advance to undisturbed material between bunches
- Other 1-MW designs also workable (e.g., JHF, new Fermilab Booster, CERN SPL)
Pion Capture

**US Design:** target in 20-T capture solenoid, with field tapering to 1.25 T

**CERN Design:** magnetic horn (waist radius = 4 cm, peak current = 300 kA)
Radiation Levels/Survivability
(N. Mokhov, FNAL)

- Remote-handling-area layout (Oak Ridge)
**Nondistorting Phase Rotation**

• Nondist. $\phi R$ possible w/ 2 ind. linacs; 3 allow simpler, unipolar pulse design
• 2 “minicooling” absorbers lower $p$ to 200 MeV/c for cooling and $\varepsilon$, by $\approx 30\%$

![Graph showing energy distribution along the linac](image1)

![Graph showing corrected beam energy over time](image2)

- $\sigma_{p/p}$: 4.4%  
- $\sigma_{ct}$: 27.95 m  
- $\epsilon_n$: 12.2 mm  
- $\mu/p$: 0.50

Study I – 1 Ind. Linac

Study II – 2 or 3 Ind. Linacs
Need for Muon Cooling

- Need ~ 0.1 $\mu/p$-on-target ⇒ very intense muon beam from pion decay ⇒ must accept large ($\sim 10\pi$ mm-rad r.m.s.) beam emittance
- No acceleration system yet demonstrated with such large acceptance ⇒ must cool the muon beam

- In current studies, cooling → × ~10 in accelerated muon flux
- Only one technique fast enough to cool muons before appreciable fraction decay:

⇒ Ionization cooling

BUT:
- It has never been observed experimentally
- Studies show it is a delicate design and engineering problem

⇒ Need Muon Ionization Cooling Experimental demonstration!
Ionization Cooling: Background

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

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

- Net effect: reduction in \( p_\perp \) w.r.t. \( p_\parallel \), i.e., transverse cooling:
  \[
  \frac{d\epsilon_N}{ds} = - \frac{1}{\beta^2} \left( \frac{dE_\mu}{ds} \right) \epsilon_N \mu + \frac{\beta_\perp (0.014 \text{ GeV})^2}{2\beta^3 E_\mu m_\mu X_0}
  \]
  \[ \Rightarrow \text{want strong focusing, large } X_0, \text{ and low } E_\mu \]

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

\[ \Rightarrow \text{in principle, ionization cooling has to work!} \]

... but in practice it is subtle and complicated so a test is important
Simplest Conceptual Scheme

- Long SC solenoids containing LH$_2$ absorbers & high-field RF cavities:

- But $\exists$ important subtlety:
  - Need to alternate direction of focusing field to avoid build-up of net angular momentum
Angular Momentum

• Consider particle entering long solenoid off-axis but \( \parallel \) to axis
  – receives \( p_\perp \) kick \( \rightarrow \) helical motion within field
  – At end of solenoid, inverse \( p_\perp \) kick restores straight trajectory
• But if particle loses momentum within solenoid, helix radius decreases
  \( \Rightarrow \) particle receives wrong \( p_\perp \) kick at exit, emerges with net angular momentum
  \( \Rightarrow \) particle entering parallel to axis emerges at angle:

• Would disrupt beam if not handled correctly
**Double-Flip Cooling Channel**

(V. Balbekov & D. Elvira, FNAL)

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**First Flip Matching Section**
- Changes Larmor center and radius for all particles

**B Field Line**

**Solenoid Axis**

**Cooling Section #1:** $B = +3T$ on axis
- Cools Pt (rms), beam radius $\sim$ unchanged

**Cooling Section #2:** $B = -3T$ on axis
- Cools Pt (rms) and beam radius (rms)

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**Diagram:**
- RF FEED
- CRYOSTAT
- LH2 ABSORBER
- VACUUM MANIFOLD
- 5 T
- 100 m
- 200 m
- 10 cm
- MUON BEAM
- AFTER FLIP
- BEFORE FLIP
- LARMOR CENTER
Periodic Cooling Lattices

- Various lattice designs have been studied:
  
  - Alternating Solenoid
    - $B_z(\text{max}) = 3.4$ (T)
    - $\frac{dB_z}{dz}(\text{max}) = 15$ (T/m)

  - FOFO
    - $B_z(\text{max}) = 3.4$ (T)
    - $\frac{dB_z}{dz}(\text{max}) = 9.4$ (T/m)

  - Super FOFO
    - $B_z(\text{max}) = 2.6$ (T)
    - $\frac{dB_z}{dz}(\text{max}) = 7$ (T/m)

(+ RFOFO, DFOFO, Single-Flip, Double-Flip)
Tapered-SFOFO Cooling Lattice:
(R. Palmer, BNL)

Cavities have thin (≈0.5–1-mm) stepped Be windows to reduce surf. fields and RF power.

Absorbers have thin (330-µm) tapered Al windows to minimize muon scattering.
Tapered-SFOFO Cooling Performance

- Transverse emittance damps $\approx$ exponentially

- Longitudinal emittance growth with scraping of tails gives $\approx$ constant longitudinal beam size due to losses

- Two indep. codes used for these sims, GEANT and ICOOL

- Codes agree on emittance decrease & beam transmission within $\approx$10%, as well as with analytic calculations

Assuming 15mm trans. acceptance 9.5mm
CERN Cooling Channel Design
(A. Lombardi, CERN, Neutrino Factory Note NF-34)

- Uses lower-frequency RF (44 & 88 MHz)
- Coils “tucked into” cavities to reduce solenoid cost

High-power test planned for later this year

- Performance simulated using PATH – comparable to that of US design
**Longitudinal Cooling**

- Transverse ionization cooling self-limiting due to longitudinal-emittance growth
  
  ⇒ need longitudinal cooling for muon collider; could also help for νFac

- Possible in principle by ionization above ionization minimum, but inefficient due to small slope $d(dE/dx)/dE$ and straggling

  → Emittance-exchange concept:

  - Several promising designs under exploration
Ring Coolers

- Combine transverse cooling with emittance exchange:
  - Injection/extraction kicker
  - 200 MHz RF 12 MV/m
  - LH2 wedge absorbers
  - Alternating solenoids, tilted for bend $B_y$

- Injection & extraction appear soluble but require very fast kicker
- Could lead to vFac that is both cheaper and higher-performance
Cooling Experiment

The aims of the muon ionization cooling experiment are:

• 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.

As stated in the 2001 review of Muon Collaboration activities by the U.S. Muon Technical Advisory Committee (MUTAC):

⇒ The “cooling demonstration” is the key systems test for the Neutrino Factory.

• Much work over many years has established the components needed for muon cooling: SC solenoids, absorbers, RF cavities

It is time to start assembling a realistic cooling cell and carry out the test
Design Choices & Issues

Which design to test?

- All have common hardware elements: absorbers & cavities in strong solenoidal fields
- Choice constrained by availability of infrastructure (esp. low-frequency RF sources)

⇒ Choose 201-MHz SFOFO cell as baseline:
  - smaller and less expensive installation
  - RF power supply components available
  (But illustrate dynamics today with both 88- and 201-MHz simulations)
  - anticipate future upgrades as more resources available (e.g., adding more cooling cells) or to test new ideas (e.g., emittance exchange)

Multi-particle vs. single-particle emittance measurement:

<table>
<thead>
<tr>
<th>Multi-particle</th>
<th>single-particle emittance measurement:</th>
</tr>
</thead>
<tbody>
<tr>
<td>traditional beam-physics approach</td>
<td>traditional HEP techniques</td>
</tr>
<tr>
<td>• based on multiple beam-profile measurements</td>
<td>• measure trajectory of each muon (x,y,z,x',y',z',t)</td>
</tr>
<tr>
<td>• compute emittance using known transfer matrices</td>
<td>• collect statistics</td>
</tr>
<tr>
<td>detector resolution and knowledge of transfer matrices limits precision to 10%</td>
<td>• form &quot;virtual bunch&quot; off line and compute emittances</td>
</tr>
<tr>
<td></td>
<td>should be capable of 0.1% precision; &quot;software collimation&quot; cut outs e.g. decay</td>
</tr>
</tbody>
</table>

Our choice
**Important further issues**

- **Detectors** must operate in strong solenoidal fields & intense RF-cavity backgrounds & contribute negligible emittance degradation
  
  \[ \Rightarrow e.g., \text{scint. fibers, SiPix detectors, He TPC} \Rightarrow \delta \varepsilon_{\text{out}} / \varepsilon_{\text{in}} \approx 10^{-3} \]

- **FNAL/MUCOOL** tests of 805-MHz prototype cavity up to \( E_{\text{surf}} \approx 53 \text{ MV/m} \) show **high dark current** (>100 mA inst.) and X-ray emission
  
  \[ \Rightarrow \text{LH}_2 \text{ absorbers must shield detectors from cavities} \]

  **R&D to reduce cavity discharge rate starting @ FNAL**
  - will explore surface treatments & coatings
  - closed-cell cavities under development have \( \approx 1/2 \) the surface field for same gradient (rate \( \sim E^{10} \Rightarrow \sim 10^{-3} \) in dark current)

- **\( \mu \)-cooling channel** puts hydrogen flasks with thin windows in close proximity to possible ignition sources!
  
  \[ \Rightarrow \text{working out safe design and operating approaches is a crucial & challenging part of the FNAL/MUCOOL R&D effort} \]
Single-Particle Emittance Measurement
(P. Janot, CERN)

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

\[ \text{Need to determine, for each muon, } x, y, t, \text{ and } x', y', t' \ (= p_x/p_z, p_y/p_z, E/p_z) \]

at entrance and exit of the cooling channel:

\[ \text{Solenoid, } B = 5 \, T, \ R = 15 \, \text{cm, } L > 3d \]

Extrapolate \(x, y, t, p_x, p_y, p_z\),

at entrance of the channel.

Make it symmetric at exit.

\[ \text{Three plates of, e.g.,} \]

\[ \text{three layers of sc. fibres} \]

\[ \text{(diameter 0.5 mm)} \]

\[ \text{Measure } x_1, y_1, x_2, y_2, x_3, y_3 \]

\[ \text{with precision } 0.5\text{mm}/\sqrt{12} \]

\[ \text{T.O.F.} \]

\[ \text{Measure } t \]

\[ \text{With } \sigma_t \sim 70 \text{ ps} \]

3 measurements is minimal set but 4 or 5 will be used for pattern-recognition redundancy

To avoid heating exit of the solenoid due to radial fields, the cooling channel has to either start with the same solenoid, or be matched to it as well as to keep \(B\) uniform on the plates.
Track Reconstruction

In the transverse view, determine a circle from the three measured points:

$\Delta \phi_{12}, \Delta \phi_{23}$

Compute the transverse momentum from the circle radius:

$p_T = 0.3 B R$

$p_x = p_T \sin \phi$

$p_y = -p_T \cos \phi$

Compute the longitudinal momentum from the number of turns

$p_Z = 0.3 B \frac{d}{\Delta \phi_{12}}$

$= 0.3 B \frac{d}{\Delta \phi_{23}}$

$= 0.3 B \frac{2d}{\Delta \phi_{13}}$

(provides constraints for alignment)

Adjust $d$ to make $1/3$ of a turn between two plates (d = 40 cm for B = 5 T and $p_Z = 260$ MeV/c) on average

Determine $E$ from $(p^2 + m^2)^{1/2}$
Baseline 201-MHz Cooling Experiment
(R. Palmer & R. Fernow, BNL)
Experiment Layout

• Based on 2 cells of 2.75m SFOFO (3 absorbers, 2 4-cell 201-MHz cavities):

...with input & output spectrometers & beam preparation section added:

(Need to blow up emittance of input beam for cooling test)
Performance

Various cases considered

<table>
<thead>
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<th>$E_1 = E_2$?</th>
<th>$n_{\text{absorbers}}$</th>
<th>rf grad</th>
<th>rf phase</th>
<th>$\Delta \epsilon_\perp$</th>
<th>rf Power</th>
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<td>1+1+1</td>
<td>0</td>
<td>0</td>
<td>12</td>
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</table>
Cooling Experiment – CERN design
(A. Blondel, K. Hanke, H. Haseroth, et al.)

Field maps:
- RF cavity
  - 84 cm
  - 37 cm

- Solenoids
  - 5T
  - 2T

88 MHz cavities (F. Gerigk)
CERN Simulation Results

(K. Hanke)

- Experiment should verify in detail dynamics of cooling cell:
  - If input beam above equilibrium emittance, cools; if below, heats
  - Scan of input emittance reveals acceptance limits
  - Energy dependence of cooling performance
  - For various cases:
    - Various absorbers full/empty
    - Various input energies
    - Various B-field configs
    - Various RF gradients & phases

...for various cases:
Available Beams/Facilities

Comparison between beams

<table>
<thead>
<tr>
<th>Beam</th>
<th>Momentum (MeV/c)</th>
<th>ΔP (Δ%)</th>
<th>Muon Intensity (during 1 s)</th>
<th>Area (m²)</th>
<th>Exists</th>
</tr>
</thead>
<tbody>
<tr>
<td>BNL D2</td>
<td>100 - 250</td>
<td>10</td>
<td>50,000 / 5 ms</td>
<td>5 x 3</td>
<td>Yes</td>
</tr>
<tr>
<td>CERN – TT1</td>
<td>200 - 450</td>
<td>?</td>
<td>720 / 0.1 ms</td>
<td>&gt; 30 x 4</td>
<td>No</td>
</tr>
<tr>
<td>CERN – East Hall</td>
<td>200 - 450</td>
<td>?</td>
<td>1,000 / 0.5 ms</td>
<td>30 x 5</td>
<td>No</td>
</tr>
<tr>
<td>PSI – μE1</td>
<td>85 - 310</td>
<td>1 (?)</td>
<td>&gt; 50,000 / 5 ms</td>
<td>30 x 5</td>
<td>Yes</td>
</tr>
<tr>
<td>RAL - ISIS</td>
<td>100 - 500</td>
<td>~ 2</td>
<td>20,000 / 5 ms</td>
<td>30 x 5</td>
<td>Yes</td>
</tr>
<tr>
<td>TRIUMF – M20</td>
<td>20 - 180</td>
<td>5</td>
<td>5,000 / 5 ms</td>
<td>12 x 4</td>
<td>Yes</td>
</tr>
</tbody>
</table>

We have submitted LoIs to PSI & RAL – both labs interested

Host lab should provide beamline & infrastructure

Natural opportunity for important European contribution
Schedule Goals & Milestones:

Nov. ’01: Letters of Intent to PSI, RAL
Jan. ’02: Presentation to PSI
Mar. ’02: Presentation to RAL → invitation to present full proposal!
2002: Develop detailed technical proposal; fundraising
2002–4: Spectrometer construction
2004: Spectrometer shakedown in muon beam
2005–6: Assembly and shakedown of first cooling cell
2006–7: Assembly and shakedown of second cooling cell

* This is an aggressive schedule and requires new funding sources to be found
# Preliminary Cost Estimate (M$)

<table>
<thead>
<tr>
<th>Cost Estimate in US$, Fixed cost</th>
<th>1 cavity 4 MW</th>
<th>1 cavity 8 MW</th>
<th>2 cavities 4 MW</th>
<th>2 cavities 8 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>cooling DE (On crest)</td>
<td>11.5MV</td>
<td>16 MV</td>
<td>16 MV</td>
<td>23 MV</td>
</tr>
<tr>
<td>Approx. Δε/ε (%)</td>
<td>5%</td>
<td>7%</td>
<td>7%</td>
<td>10%</td>
</tr>
</tbody>
</table>

## COOLING CELLS

### RF CAVITIES

<table>
<thead>
<tr>
<th></th>
<th>1 cavity 4 MW</th>
<th>1 cavity 8 MW</th>
<th>2 cavities 4 MW</th>
<th>2 cavities 8 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 cell cavity 200 MHz</td>
<td>* 0.3</td>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
</tr>
</tbody>
</table>

### RF Power

<table>
<thead>
<tr>
<th></th>
<th>1 cavity 4 MW</th>
<th>1 cavity 8 MW</th>
<th>2 cavities 4 MW</th>
<th>2 cavities 8 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>CERN-refurbish</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>RAL-refurbish (?)</td>
<td>0.2</td>
<td>0</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

### Magnets

<table>
<thead>
<tr>
<th></th>
<th>1 cavity 4 MW</th>
<th>1 cavity 8 MW</th>
<th>2 cavities 4 MW</th>
<th>2 cavities 8 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focus pair</td>
<td>* 0.55</td>
<td>0.45</td>
<td>0.9</td>
<td>1.35</td>
</tr>
<tr>
<td>Coupling coil</td>
<td>* 0.4</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

### Liquid H2 Absorbers

<table>
<thead>
<tr>
<th></th>
<th>1 cavity 4 MW</th>
<th>1 cavity 8 MW</th>
<th>2 cavities 4 MW</th>
<th>2 cavities 8 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>* 0.5</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3</td>
</tr>
</tbody>
</table>

### LH2 Plant

<table>
<thead>
<tr>
<th></th>
<th>1 cavity 4 MW</th>
<th>1 cavity 8 MW</th>
<th>2 cavities 4 MW</th>
<th>2 cavities 8 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

### Total for Cooling Cell US$

<table>
<thead>
<tr>
<th></th>
<th>1 cavity 4 MW</th>
<th>1 cavity 8 MW</th>
<th>2 cavities 4 MW</th>
<th>2 cavities 8 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.8</td>
<td>5.0</td>
<td>6.85</td>
<td>7.05</td>
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</tbody>
</table>

## SPECTROMETERS

### Solenoids

<table>
<thead>
<tr>
<th></th>
<th>1 cavity 4 MW</th>
<th>1 cavity 8 MW</th>
<th>2 cavities 4 MW</th>
<th>2 cavities 8 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.69</td>
<td>0.5</td>
<td>1.69</td>
<td>1.69</td>
</tr>
</tbody>
</table>

### Detectors

<table>
<thead>
<tr>
<th></th>
<th>1 cavity 4 MW</th>
<th>1 cavity 8 MW</th>
<th>2 cavities 4 MW</th>
<th>2 cavities 8 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

### Total Spectrometers

<table>
<thead>
<tr>
<th></th>
<th>1 cavity 4 MW</th>
<th>1 cavity 8 MW</th>
<th>2 cavities 4 MW</th>
<th>2 cavities 8 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.69</td>
<td>3.69</td>
<td>3.69</td>
<td>3.69</td>
</tr>
</tbody>
</table>

### Subtotal

<table>
<thead>
<tr>
<th></th>
<th>1 cavity 4 MW</th>
<th>1 cavity 8 MW</th>
<th>2 cavities 4 MW</th>
<th>2 cavities 8 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.69</td>
<td>8.49</td>
<td>8.69</td>
<td>10.54</td>
</tr>
</tbody>
</table>

### Infrastr., extras (20%)

<table>
<thead>
<tr>
<th></th>
<th>1 cavity 4 MW</th>
<th>1 cavity 8 MW</th>
<th>2 cavities 4 MW</th>
<th>2 cavities 8 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.23</td>
<td>13.4</td>
<td>13.7</td>
<td>15.9</td>
</tr>
</tbody>
</table>

### TOTAL

<table>
<thead>
<tr>
<th></th>
<th>1 cavity 4 MW</th>
<th>1 cavity 8 MW</th>
<th>2 cavities 4 MW</th>
<th>2 cavities 8 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.23</td>
<td>13.4</td>
<td>13.7</td>
<td>16.1</td>
</tr>
</tbody>
</table>

* development costs borne by MU COOL

cost-effective use of existing RF power sources
Organization of International Collaboration

• Starting at NuFact’01, we have formed the Muon Cooling Demonstration Experiment Steering Committee (MCDESC):
  
  Alain Blondel (Chair and European Spokesperson), U. Geneva  
  Rob Edgecock, Rutherford  
  Steve Geer, Fermilab  
  Helmut Haseroth, CERN  
  Daniel M. Kaplan (US Spokesperson), IIT  
  Yoshitaka Kuno, Osaka U.  
  Michael S. Zisman, LBNL

• We have designated the Technical Team Leaders:

  Particle detectors: A. Bross, V. Palladino  
  RF radiation (dark current and X-Ray) issues: E. McKigney, J. Norem  
  Magnet systems: H. Haseroth (provisional), M. Green  
  RF cavities and power supplies: R. Garoby, R. Rimmer  
  Hydrogen absorbers: M. A. Cummings, S. Ishimoto  
  Concept development and simulations: A. Lombardi, P. Spentzouris  
  Beamlines: R. Edgecock, C. Petitjean

• We have held several video meetings, several workshops (CERN, Chicago, London, CERN), and a workshop is upcoming at Rutherford Lab July 8–10

  (see http://muonstoragerings.cern.ch/October01WS/oct01ws.html,  
  http://www.capp.iit.edu/~capp/workshops/mumice02/mumice02.html, and  
  http://hepunx.rl.ac.uk/neutrino-factory/muons/mice-meeting.html)
**Participating Institutes:**

Louvain La Neuve  
NESTOR Institute  
Hellenic Open University  
INFN LNF Frascati  
INFN Milano  
INFN Napoli  
INFN Roma II  
INFN Trieste  
Osaka University  
Paul Scherrer Institute  
University of Zurich  
Rutherford Appleton Laboratory  
Brookhaven National Laboratory  
Fairfield University  
Illinois Institute of Technology  
Michigan State University  
Princeton University  
University of California, Riverside  
University of Chicago  
University of Iowa  

CERN  
University of Athens  
INFN Bari  
INFN Legnaro  
INFN Padova  
INFN Roma I  
INFN Roma III  
KEK  
ETH Zurich  
University of Geneva  
Imperial College London  
Argonne National Laboratory  
Columbia University  
Fermi National Accelerator Laboratory  
Lawrence Berkeley National Laboratory  
Northern Illinois University  
University of California Los Angeles  
Indiana University  
University of Illinois at Urbana-Champaign  
University of Mississippi
Summary

• Muon storage rings could be a uniquely powerful option for large future facilities

• A Neutrino Factory is the best way to study neutrino mixing

• Technical feasibility has been demonstrated “on paper”

• Prerequisite to Neutrino Factory approval: experimental demonstration of muon ionization cooling

• Scope of the Muon International Cooling Experiment defined; well on the way to specifying the details

• International collaboration formed and leadership structure in place

• Scope and time scale comparable to mid-sized HEP experiment

• Need to line up necessary resources (people, equipment, funding)

• Good opportunity for new collaborators – want to join?