Muon Cooling and Future Muon Facilities

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Muon Facility Examples:

- Neutrino Factory:

  (Feasibility Study-II)
  
  Induction linac No.1
  - 100 m
  - drift 20 m
  Induction linac No.2
  - 80 m
  - drift 30 m
  Induction linac No.3
  - 80 m

  recirculator Linac
  - 2 – 20 GeV

  neutron beam

  proton driver

  target
  - mini–cooling
  - 3.5 m of LH, 10 m drift

  bunching 56 m

  cooling 108 m

  Linac 2 GeV

  storage ring
  - 20 GeV
Muon Facility Examples:

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  - 80 m
  - drift 30 m
- Induction linac No.3
  - 80 m
- Recirculator Linac
  - 2 – 20 GeV

- Prep μ’s for cooling
- Target
  - mini-cooling
  - 3.5 m of LH, 10 m drift
- Bunching
  - 56 m
- Cooling
  - 108 m

- Linac
  - 2 GeV

- Storage ring
  - 20 GeV

- Proton driver

- Neutrino beam
Muon Facility Examples:

- Neutrino Factory:
  (Feasibility Study-II)
  - Induction linac No.1: 100 m, drift 20 m
  - Induction linac No.2: 80 m, drift 30 m
  - Induction linac No.3: 80 m
  - Recirculator Linac: 2 – 20 GeV
  - prep μ's for cooling
  - neutrino beam

- μ⁺μ⁻ collider:
  - proton driver
  - target
  - mini-cooling: 3.5 m of LH, 10 m drift
  - bunching: 56 m
cooling: 108 m
  - Linac: 2 GeV
  - storage ring: 20 GeV
  - 5 TeV μ⁺μ⁻ Collider
  - 1 km radius \(< L > \sim 5 \times 10^{34}
  - 10 arcs separated vertically in one tunnel
  - 2.5 km Linear Collider Segment
  - postcoolers/accelerators μ⁺ → μ⁻
Muon Facility Examples:

- Neutrino Factory:
  
  (Feasibility Study-II)

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    - 100 m
    - drift 20 m
  - Induction linac No.2
    - 80 m
    - drift 30 m
  - Induction linac No.3
    - 80 m
  - recirculator Linac
    - 2 – 20 GeV
  - preparatory cooling
  - proton driver
  - target
  - mini–cooling
  - 3.5 m of LH, 10 m drift
  - bunching 56 m
  - cooling 108 m
  - Linac 2 GeV
  - storage ring
    - 20 GeV
  - neutrino beam

- Common features:
  1. *p* on tgt → *π* → *μ*, collected in focusing channel
  2. *μ* cooling, acceleration, & storage
  - then:
  3. neutrino beam via *μ* → *e*⁻ *ν*ₚ *ν*ₑ — or — *μ*⁺ *μ*⁻ collisions

- *μ*⁺ *μ*⁻ collider:

  (Muons, Inc. version)

  - 5 TeV *μ*⁺ *μ*⁻ Collider
  - 1 km radius <L>~5E34
  - 2.5 km Linear Collider Segment
  - target
  - mini–cooling
  - 3.5 m of LH, 10 m drift
  - bunching 56 m
  - cooling 108 m
  - Linac 2 GeV
  - storage ring
    - 20 GeV
  - neutrino beam

  - 10 arcs separated vertically in one tunnel
  - HCC
  - Tgt
  - 300 kW proton
What’s a Neutrino Factory?
What’s a Neutrino Factory?

A US scheme

- ~MW proton beam on high-power target → pions, collected & decay in focusing channel
- Decay muons undergo longitudinal phase-space manipulation, cooling, acceleration, & storage in decay ring w/ long straight sections
- Makes intense beam of high-energy electron and muon neutrinos via $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$
- Also Japanese design – does not require cooling but could benefit from it
- Recent work shows this is ~ 2G$ facility

CERN scheme

- Induction linac No.1
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- Induction linac No.3
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- Recirculator Linac
  - 2 – 20 GeV
- Neutrino beam
  - 20 GeV
- Proton driver
- Target
  - mini-cooling
  - 3.5 m of LH, 10 m drift
  - Bunching 56 m
  - Cooling 108 m
- Linac 2 GeV
- Storage ring
- 2.2 GeV Superconducting H Linac
- Accumulator ring
- 44/88 MHz capture, cooling, acceleration
- Target Horn
- 2-10 GeV recirculator
- 10-50 GeV recirculator
- Neutrino Factory schematic (isometric view)
- Muon decay ring
  - Triangle on an inclined plane
Why a Neutrino Factory?
Why a Neutrino Factory?

- Most fundamental particle-physics discovery of past decade:
Why a Neutrino Factory?

• Most fundamental particle-physics discovery of past decade: neutrinos mix!

Q. R. Ahmad et al., PRL 89 (2002) 011301

K. Eguchi et al., PRL 90 (2003) 021802
Why a Neutrino Factory?

- Most fundamental particle-physics discovery of past decade: 
  - Neutrinos mix!
  - 2002 SNO results
    - Q. R. Ahmad et al., PRL 89 (2002) 011301
  - 2002 KamLAND results
    - K. Eguchi et al., PRL 90 (2003) 021802

...arguably the leading explanation for the cosmic baryon asymmetry (“Leptogenesis”)

Why a Neutrino Factory?

• Most fundamental particle-physics discovery of past decade: neutrinos mix!


...and possibly relevant to the nature of dark energy (“mass varying neutrinos”) R. Fardon, A. E. Nelson, and N. Weiner, JCAP 0410, 005 (2004).
Why a Neutrino Factory?

- Neutrino mixing raises fundamental questions:

1. What is the neutrino mass hierarchy?

   - "natural"
   - \( \nu_3 \)
   - OR?
   - \( \nu_2 \)
   - \( \nu_1 \)
   - "inverted"
   - \( \nu_2 \)
   - \( \nu_1 \)
   - \( \nu_3 \)

2. Why is pattern of neutrino mixing so different from that of quarks?

   - CKM matrix:
     \( \theta_{12} \approx 12.8^\circ \)
     \( \theta_{23} \approx 2.2^\circ \)
     \( \theta_{13} \approx 0.4^\circ \)
     \[ \text{hierarchical} \quad \& \quad \text{nearly diagonal} \]

   - PMNS matrix:
     \( \theta_{12} = 30^\circ \) (solar)
     \( \theta_{23} = 45^\circ \) (atmospheric)
     \( \theta_{13} < 13^\circ \) (Chooz limit)

   \[ \begin{pmatrix}
   \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin \theta_{13} e^{i\delta} \\
   \sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\
   \sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2}
   \end{pmatrix} \]

3. How close to zero are the small PMNS parameters \( \theta_{13}, \delta \)?

   - are they suppressed by underlying dynamics? symmetries?
Why a Neutrino Factory?

- Neutrino mixing raises fundamental questions:

  1. What is the neutrino mass hierarchy?

     ![Neutrino Mass Hierarchy Diagram]

     - “natural”
     - “inverted”

     OR?

  2. Why is pattern of neutrino mixing so different from that of quarks?

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     \]

  3. How close to zero are the small PMNS parameters \(\theta_{13}, \delta\)?

     \[\rightarrow\text{ are they suppressed by underlying dynamics? symmetries?}\]

- These call for a program to measure the PMNS elements as well as possible.
Neutrino Factory Physics Reach

- Neutrino Factory is most sensitive technique yet devised
  see e.g. M. Lindner, hep-ph/0209083
  & C. Albright et al., Fermilab-FN-692 (2000)

![Diagram: Neutrino Factory Physics Reach]

- CP-sensitivity comparison
- Oscillation-parameter comparison

(plots from A. Blondel, NO-VE Workshop, Venice, Dec. 03)
Why Muon Colliders?

- 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:
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• Also...
Why Muon Colliders?

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

• E.g., $\mu\mu$-collider resolution can separate near-degenerate scaler and pseudo-scalar Higgs states of high-tan $\beta$ 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), Neuffer (1979)

- But no concept for achieving high luminosity until ionization cooling

- Realization (Neuffer and Palmer) that a high-luminosity muon collider might be feasible stimulated series of workshops & formation (1995) of Neutrino Factory and Muon Collider Collaboration
  - has since grown to 47 institutions and >100 physicists

- Snowmass Summer Study (1996)
  - study of feasibility of a 2+2 TeV Muon Collider [Fermilab-conf-96/092]


- See also:
  - Neutrino Factory Feasibility Study I (2000) and II (2001) reports;
  - Recent Progress in Neutrino Factory and Muon Collider Research within the Muon Collaboration, Phys. Rev. ST Accel. Beams 6, 081001 (2003);
  - APS Multidivisional Neutrino Study, www.aps.org/neutrino/ (2004);
  - Recent innovations in muon beam cooling, AIP Conf. Proc. 821, 405 (2006);
Neutrino Factory Feasibility

• Much work on Neutrino Factory design has convinced us that it is feasible

• Feasibility Study I (1999):
  – 6-month study sponsored by Fermilab, led by Norbert Holtkamp
  – many person-years of effort, including detailed simulation studies and engineering of conceptual designs
  – goal: based on assumed technical solutions, estimate relative costs of subsystems to see which ones are “cost drivers” for further R&D
  – main cost drivers were acceleration, cooling, longitudinal phase-space manipulation

• Feasibility Study II (2000–01):
  – 1-year study sponsored by BNL, led by Bob Palmer (BNL) and Mike Zisman (LBNL)
  – again many person-years of effort, including simulation and engineering
  – goal: improve FS-I performance and reduce estimated facility cost

• Feasibility Study 2a (2004):
  – undertaken as part of APS Multi-Divisional Neutrino Study
  – goal: use new ideas to tweak FS-II design to reduce cost while maintaining performance

• International Scoping Study (2005-6)
  – under auspices of CCLRC/RAL, lay groundwork for multi-year Int’l Design Study
Neutrino Factory Performance & Cost

• With suitably chosen baseline(s), comparing $\nu_e \rightarrow \nu_\mu$ & $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ determines mass hierarchy and CP phase $\delta$:

• To set scale, $10^{20}$ decays with 50-kT detector sees $\delta$ down to $\approx 8^\circ$

⇒ important to maximize flux!
Neutrino Factory Performance & Cost

- FS-II cost drivers: phase rotation, cooling, acceleration

- FS-2a features cheaper solutions for all three of these

→ “Bare” cost of Neutrino Factory now estimated at ≈ 1 G$
Study 2a Progress

- Simpler, shorter, cheaper cooling channel:

  - LH2 absorbers
  - SC coils

- New, cheaper, “non-scaling FFAG” acceleration:

  - Linac 2 GeV
  - Recirculating Linac 2 x 2.3 GeV

  - 10–20 GeV FFAG
  - 5–10 GeV FFAG
  - Linac to 1.5 GeV
  - 1.5–5 GeV Dogbone RLA
New Physics / New Facilities

(If I may be a bit provocative...)
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- **Conventional wisdom:**
  - “LEP data demonstrate $\exists$ SUSY Higgs with $m < 500$ GeV”
  - $\Rightarrow$ need (12G$\?$) ILC ASAP
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- **My opinion:**
  - $\Rightarrow$ The data are not yet definitive $\Rightarrow$ conventional wisdom *could* be wrong!

- **Moreover,**

  🦀 The new physics we *know* is there... is neutrino mixing!
New Physics / New Facilities

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• Conventional wisdom:
  
  – “LEP data demonstrate ∃ SUSY Higgs with \( m < 500 \text{ GeV} \)”
  
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• My opinion:
  
  → The data are not yet definitive ⇒ conventional wisdom could be wrong!

• Moreover,

  🔗 The new physics we know is there... is neutrino mixing!

⇒ It is urgent to figure out the best way to study this new physics.

  – may be our best experimental access to physics at the GUT scale*

* Please don’t get me wrong: ILC work is important – but doesn’t mean we should neglect muon facilities.
Why Muon Cooling?

- $\nu F$ physics needs $\gtrsim 0.1 \mu/p$-on-target $\Rightarrow$ very intense $\mu$ beam from $\pi$ decay
  $\Rightarrow$ must accept large ($\sim10\pi$ mm-rad rms) beam emittance

- No acceleration system yet demonstrated with such large acceptance
  $\Rightarrow$ must *cool* the muon beam or develop new, large-aperture acceleration
  (in recent $\nu F$ studies, cooling $\Rightarrow \times 2 - 10$ in accelerated muon flux)

- $\mu C$: $\mathcal{L} \propto I^2/\sigma_x\sigma_y \Rightarrow$ big gain from smaller beam
  $\Rightarrow$ to achieve useful collider luminosity, *must* cool the muon beam
The Challenge:

\[ \tau_\mu = 2.2 \ \mu s \]

Q: What cooling technique works in microseconds?

A: There is only one, and it works only for muons:
Ionization Cooling:

A brilliantly simple idea!

• BUT:
  – it has never been observed experimentally
  – studies show it is a delicate design and engineering problem
  – it is a crucial ingredient in the cost and performance optimization of a Neutrino Factory

⇒ Need experimental demonstration of muon ionization cooling!

⇒ MICE
Ionization Cooling:

- Two competing effects:

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

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

  - Net effect: reduction in \( p_\perp \) at constant \( p_\parallel \), i.e., transverse cooling

\[
\frac{d\epsilon_N}{ds} = -\frac{1}{\beta^2} \left( \frac{dE_\mu}{ds} \right) \epsilon_N + \frac{\beta_{\perp} (0.014 \text{ GeV})^2}{2 \beta^3 E_\mu m_\mu X_0} \quad \text{(emittance change per unit length)}
\]
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    \[ E \rightarrow E - \left( \frac{dE}{dx} \right) \Delta s \]
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- Net effect: reduction in $p_\perp$ at constant $p_\parallel$, i.e., transverse cooling

Note: The **physics** is not in doubt – it’s just Maxwell’s equations!

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

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

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

...so a test is essential!
Ionization Cooling:

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Ionization Cooling:

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\( \Rightarrow \) want strong focusing, large \( X_0 \), and low \( E_\mu \)
Ionization Cooling:

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

⇒ want strong focusing, large \( X_0 \), and low \( E_\mu \)

→ How can this be achieved...?
E.g., Double-Flip Cooling Channel

V. Balbekov & D. Elvira (FNAL)

• To get low $\beta \rightarrow$ big S/C solenoids & high fields!

⇒ expensive
Or, Periodic Cooling Lattices
R. Palmer (BNL) et al.

• 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
    \[ B_z(\text{max}) = 2.6 \ (T) \]
    \[ \frac{dB_z}{dz}(\text{max}) = 7 \ (T/m) \]

→ Alternating gradient allows low \( \beta \) with much less superconductor
Longitudinal Cooling?

- Transverse ionization cooling self-limiting due to longitudinal-emittance growth, leading to particle losses
  - caused e.g. by energy-loss straggling plus finite $dE$ acceptance of cooling channel
  ⇒ need longitudinal cooling for muon collider; could also help for $\nu$F

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

→ Emittance-exchange concept:

- Several promising paper designs exist (see example below)
Practical Difficulty:

- Cooling channels are expensive

  ➞ affordable piece of SFOFO channel gives only ≈10% emittance reduction

- But standard beam instrumentation can measure emittance to only ≈10%
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- Cooling channels are expensive

  ➔ affordable piece of SFOFO 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 40 institutions in 10 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)
China: ICST Harbin (L. Jia, L. Wang)
Italy: INFN Milano (A. Andreoni, D. Batani, M. Bonesini, G. Lucchini, F. Paleari, P. Sala, F. Strati)
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      Kyoto University (Y. Mori)
      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)
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USA: Argonne National Laboratory (J. Norem)
     Brookhaven National Laboratory (R. B. Palmer, R. Fernow, J. Gallardo, H. Kirk)
     Fairfield University (D. R. Winn)
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     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 \, \text{cm}, L > 3d**

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

**T.O.F.**
Measure $t$ with $\sigma_t \sim 70 \, \text{ps}$

**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.
**Single-Particle Emittance Measurement**

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at entrance and exit of the cooling channel:

- **Solenoid,** \(B = 4\ T, R = 15\ cm, L > 3d\)
- (to keep \(B\) uniform on the plates)

\[
\begin{align*}
\text{T.O.F.} & \quad \text{Measure } t \\
\text{With } \sigma_t & \approx 70\ ps
\end{align*}
\]

- **Three plates of, e.g.,**
  three layers of sc. fibres
  (diameter 0.35 mm)
  Measure \(x_1, y_1, x_2, y_2, x_3, y_3\)
  with precision 0.35 mm/\(\sqrt{12}\)

- **Extrapolate** \(x, y, t, p_x, p_y, p_z,\)
  at entrance of the channel.
  Make it symmetric at exit.

...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. $z$:

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

\[ \rightarrow \approx 10\% \ \text{transverse emittance reduction, measurable to 0.1\% (abs.) given precise spectrometer, clean beam, and efficient, redundant particle ID} \]
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 req’d for 0.1% emittance measurement
Current Status:

- MICE proposal submitted January 2003
- Proposal approved by CCLRC (UK gov’t research org.) 10/24/03
- MICE funding (Phase 1) approved in Italy, Japan, Netherlands, Switzerland, UK, US
  - Includes installation of muon beamline on ISIS at RAL:

  Beamline includes:
  
  2 bends
  3 small-aperture quads
  6 large-aperture quads
  4T decay solenoid (from PSI)

... 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 9/07
Some Recent Progress: SciFi Tracker Test at KEK
(KEK / Osaka / UK / FNAL / IIT / UCR / UCLA)

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

- Successful beam test fall 2005
Some Recent Progress: SciFi Tracker Test at KEK

Reconstructed event:

- Prototype plane with latest connector design showed lower light yield
  - study & possible design iteration in progress
Absorber Design
(KEK, Oxford, RAL)

• Need LH$_2$ absorbers with 0.1–1 kW power-handling capability
  – designs build on hydrogen-target experience

Prototype high-power LH$_2$ absorber (MuCool)

– also much work on hydrogen safety

MICE low-power design (cryocooler-cooled)
RF Cavities
(LBNL / JLab / FNAL / Oxford / UMiss)

• Prototype 201 MHz cavity with thin, curved Be windows

...high-power testing in progress at Fermilab MTA
RF Power

• Two surplus 4 MW, 201 MHz power amplifiers shipped from LBNL to Daresbury Lab for refurbishing

• Plan to get two more refurbished power amps from CERN

→ 2 MW per cavity in Step V,
   1 MW per cavity in Step VI
Beamline includes 5T $\pi$-decay solenoid from PSI

- Gives x10 increase in $\mu$ rate comp. to quads
- Delivered to RAL in Dec., 2005
• Using T. Roberts-developed “g4beamline” to simulate MICE beam:

- Optimized beam rates per “target-in” ms (occurring once per s):

<table>
<thead>
<tr>
<th>Description</th>
<th>LAHET</th>
<th>Geant4</th>
<th>MARS</th>
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<tbody>
<tr>
<td>1mm x 100mm, 10m from target</td>
<td></td>
<td></td>
<td>33,400</td>
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<tr>
<td>TOF0</td>
<td>2355</td>
<td>2693</td>
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<td>TOF1</td>
<td>462</td>
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<td>Tracker2</td>
<td>284</td>
<td>324</td>
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</tr>
<tr>
<td>TOF2</td>
<td>281</td>
<td>321</td>
<td>338</td>
</tr>
<tr>
<td>Good μ⁺</td>
<td>277</td>
<td>316</td>
<td>333</td>
</tr>
</tbody>
</table>
G4MICE Experiment Simulation
(FNAL / IIT / BNL / Geneva / ICL / UCR et al.)

• Under development by int’l team led by Y. Torun, IIT & M. Ellis, FNAL

Screen shot of the magnetic lattice:

View with the solenoid removed showing scintillating-fiber tracking stations:

Cooling 1/2-cell: two absorbers (blue), three coils (brown), two focusing and one coupling, and four rf cavities (red)

• Geant 4 simulation generates hits on detectors taking all relevant physics processes into account
• Used to study effectiveness of PID, systematics of emittance reconstruction, etc.
Spectrometer Solenoids

- Superconductor delivered (LBNL/IIT)

- Module fabrication in progress (LBNL)
More Progress

• Work also proceeding on
  – particle-ID detectors
  – DAQ system
  – software...

...but I lack the time to tell you about it!
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
    - 2008?

  - **STEP IV:**
    - Study 1st abs./focus-coil pair, check dE/dx and scattering
    - 2009?

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

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

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

```
Characterize beam

Phase 1 (fully funded)
Calibrate Spect. 1

Intercalibrate Spect. 2 w.r.t. Spect. 1; demonstrate 0.1% emittance measurement

Phase 2 (in negotiation)
Study 1st abs./focus-coil pair; check dE/dx and scattering
Cooling study w/1/2 lattice cell

Cooling study w/full lattice cell & realistic field flip
```
Muon Facility Feasibility Demonstrations:

1. Transverse ionization cooling: MICE @ RAL ISIS synchrotron
2. Multi-MW targets: MERIT @ CERN nTOF facility
3. 6D helical cooling: MANX proposal
4. Non-scaling FFAG acceleration: EMMA @ DL
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MICE Future?

- MICE muon beam + spectrometers + DAQ constitute general-purpose facility for studying muon cooling

- Not limited to SFOFO design, nor to demonstrating just transverse cooling
Helical Cooling Channels

R. Johnson et al. (Muons, Inc., www.muonsinc.com), Ya. Derbenev (JLab)

- Recent work by R. Johnson, Ya. Derbenev, et al. (Muons, Inc.) points to possibility of 6D cooling via emittance exchange in helical focusing channel (solenoid + rotating dipole and quadrupole) filled with dense low-\(Z\) gas or liquid

![Helical Cooling Channels Diagram](image)

- Example helical rotating-dipole magnet from AGS “Siberian Snake”
Helical Cooling Channels

- Implementation options being explored [V. Kashikhin et al., FNAL MCTF]:

→ Small coils could reduce difficulty and cost
Helical Cooling Channels

• Possible to test prototype 6D cooler in MICE facility → “MANX”? – or with new muon beam at Fermilab?
MANX Letter of Intent
(Muons, Inc.)

- Proposal to Fermilab to design and build helical magnet (May, 2006)
- Factor $\approx 3–5$ in a few m of cooling channel!

Simulated cooling performance

- Transverse
- Longitudinal
- 6D
“Extreme Cooling”?
Ya. Derbenev (JLab)

- After cooling $\times \sim 10^5$ by series of helical channels ($\sim 10^2$ m), can cool beam further with 2 new approaches:
  - Parametric-resonance Ionization Cooling (PIC)
  - Reverse Emittance Exchange (REMEX)
Vision of Future Muon Facility using “Extreme Cooling”

• If these ideas work, could cool muons well enough to accelerate them with ILC cavities

• Muon Collider could be ILC energy upgrade

→ International Lepton Collider!
Funding

• Muon-cooling R&D, Neutrino Factory and Muon Collider R&D, and MICE are international efforts supported modestly but significantly in U.S., Europe, and Japan

• U.S. Neutrino Factory and Muon Collider Collaboration (NFMCC, $\sim 10^2$ people) funded by DOE at few-M$/year level
  – $\sim 10\%$ goes to MICE
  – also supporting high-power target experiment, MERIT (CERN nTOF11; see http://proj-hiptarget.web.cern.ch/proj-hiptarget/default/)

• MICE funded by NSF (1.05 M$)

• Muons, Inc. funded by DOE SBIR/STTR program
Some useful web pages:


MICE home page: http://mice.iit.edu/

Neutrino Factory and Muon Collider Studies at Fermilab home page:
  http://www.fnal.gov/projects/muonCollider/

Muon Ionization Cooling R&D home page:

Targetry R&D home page: http://www.hep.princeton.edu/mumu/target/

EMMA home page: http://hepunx.rl.ac.uk/uknf/wpl/emodel/


Neutrino & Muon Activities at CERN:
  http://muonstoragerings.web.cern.ch/muonstoragerings/

UK Neutrino Factory home page: http://hepunx.rl.ac.uk/uknf/

APS Multi-Divisional Study of the Physics of Neutrinos home page:
  http://www.interactions.org/cms/?pid=1009695
  http://www.aps.org/neutrino/

International Scoping Study home page: http://www.hep.ph.ic.ac.uk/iss/

Muons, Inc. home page: http://www.muonsinc.com/
Some important recent reports and papers:


See also the Proceedings of the NuFact Workshops held annually in rotation among the U.S., Europe, and Japan.

Some recent brief, “approachable” papers:


D. M. Kaplan, “Muon Cooling and Future Muon Facilities,” to appear in Proc. ICHEP06, Moscow, Russia, July 26 – Aug. 2, 2006
**Summary**

- Muon storage rings are a uniquely powerful option for future HEP facilities
- A Neutrino Factory may be the best way to study neutrino mixing and CPV
- νF technical feasibility has been demonstrated “on paper”
- A key prerequisite to νF approval: experimental demonstration of muon ionization cooling
- MICE Proposal approved and Phase 1 funded
- Scope and time-scale comparable to mid-sized HEP experiment
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🌟 I believe muon accelerator facilities have a bright future!