Muon Cooling and Future Muon Facilities

Daniel M. Kaplan
US Spokesperson, MICE Collaboration

ILLINOIS INSTITUTE OF TECHNOLOGY
Transforming Lives.Inventing the Future.www.iit.edu

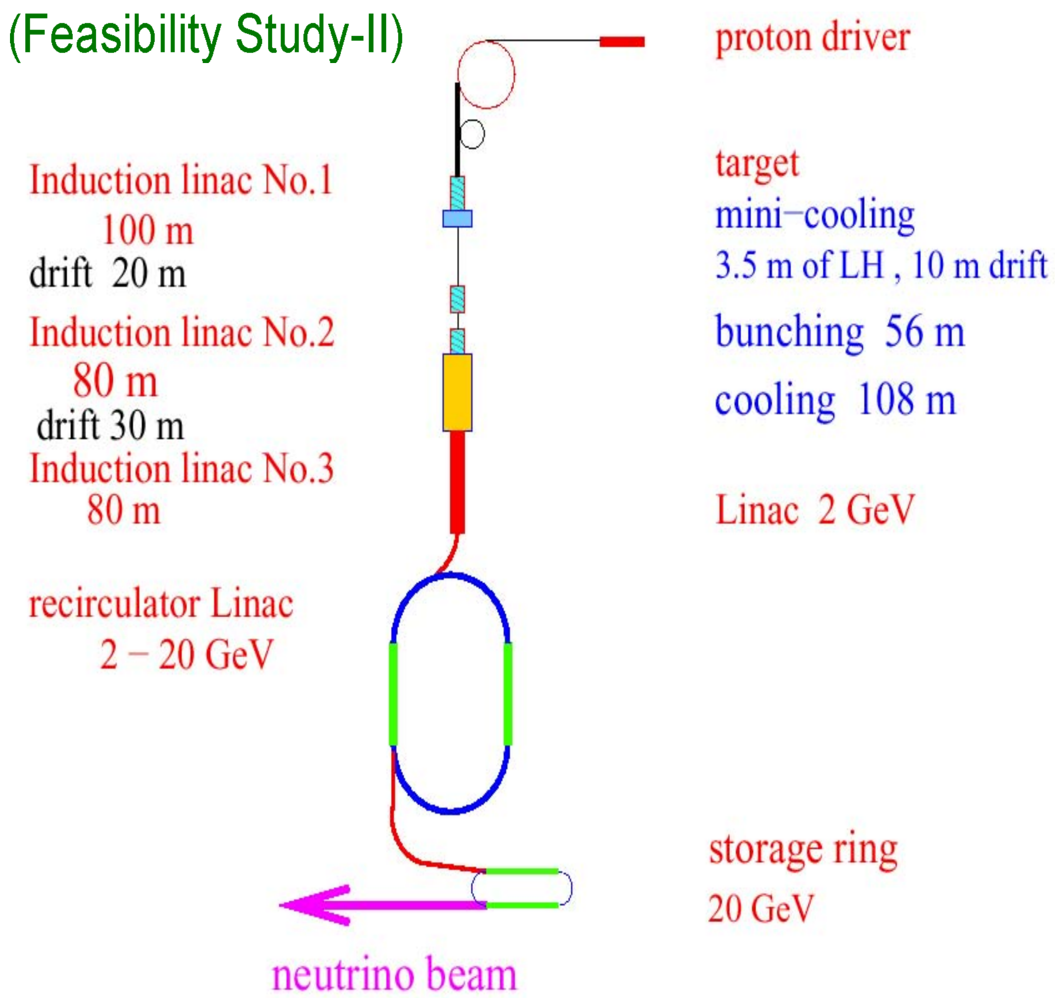
CASA/Beam Physics Seminar
Jefferson Lab
Newport News, VA
19 October, 2006

Outline:

1. Neutrino Factory and Muon Collider: concepts
2. Neutrino Factory and Muon Collider: physics
3. Need for muon cooling
4. Ionization cooling
5. Muon Ionization-Cooling Experiment (MICE) (and other techn. demos)
6. Future
7. Summary

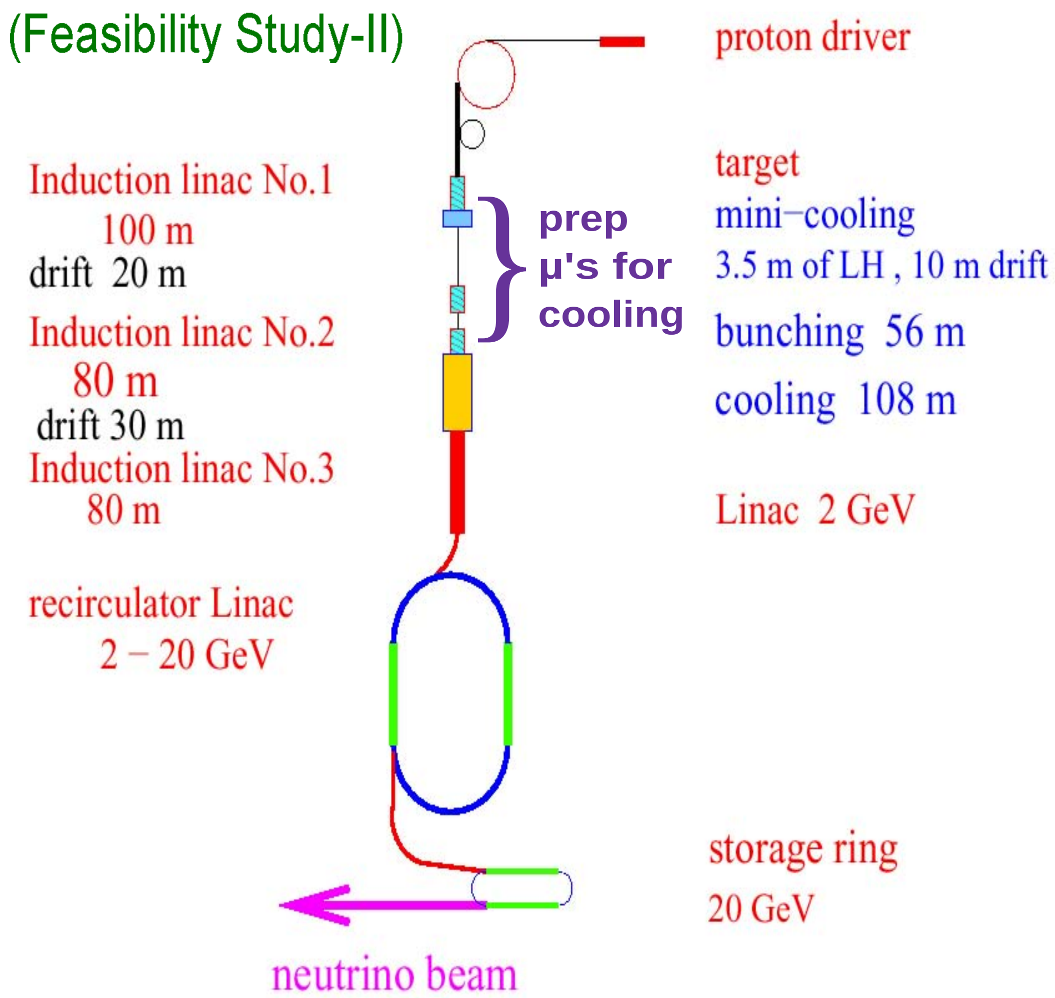
Muon Facility Examples:

- Neutrino Factory:



Muon Facility Examples:

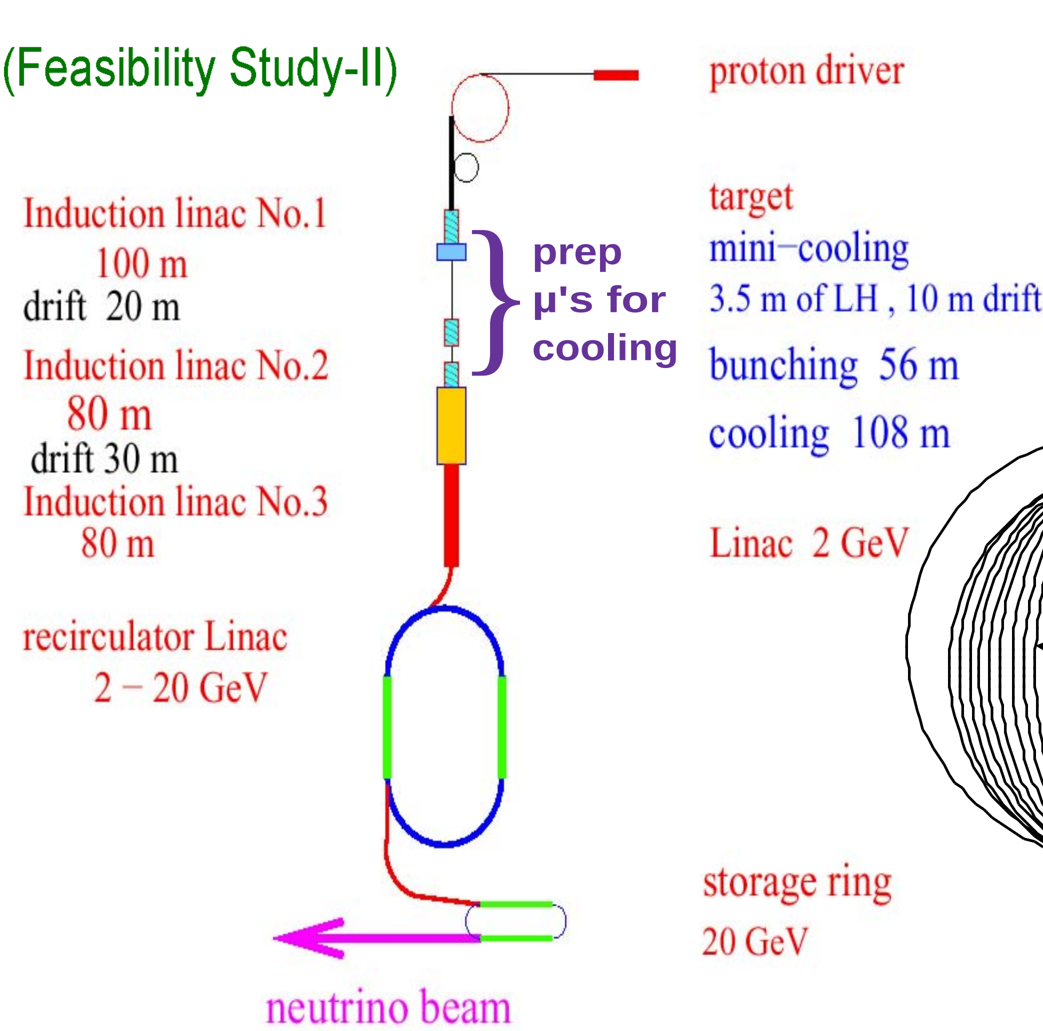
- Neutrino Factory:



Muon Facility Examples:

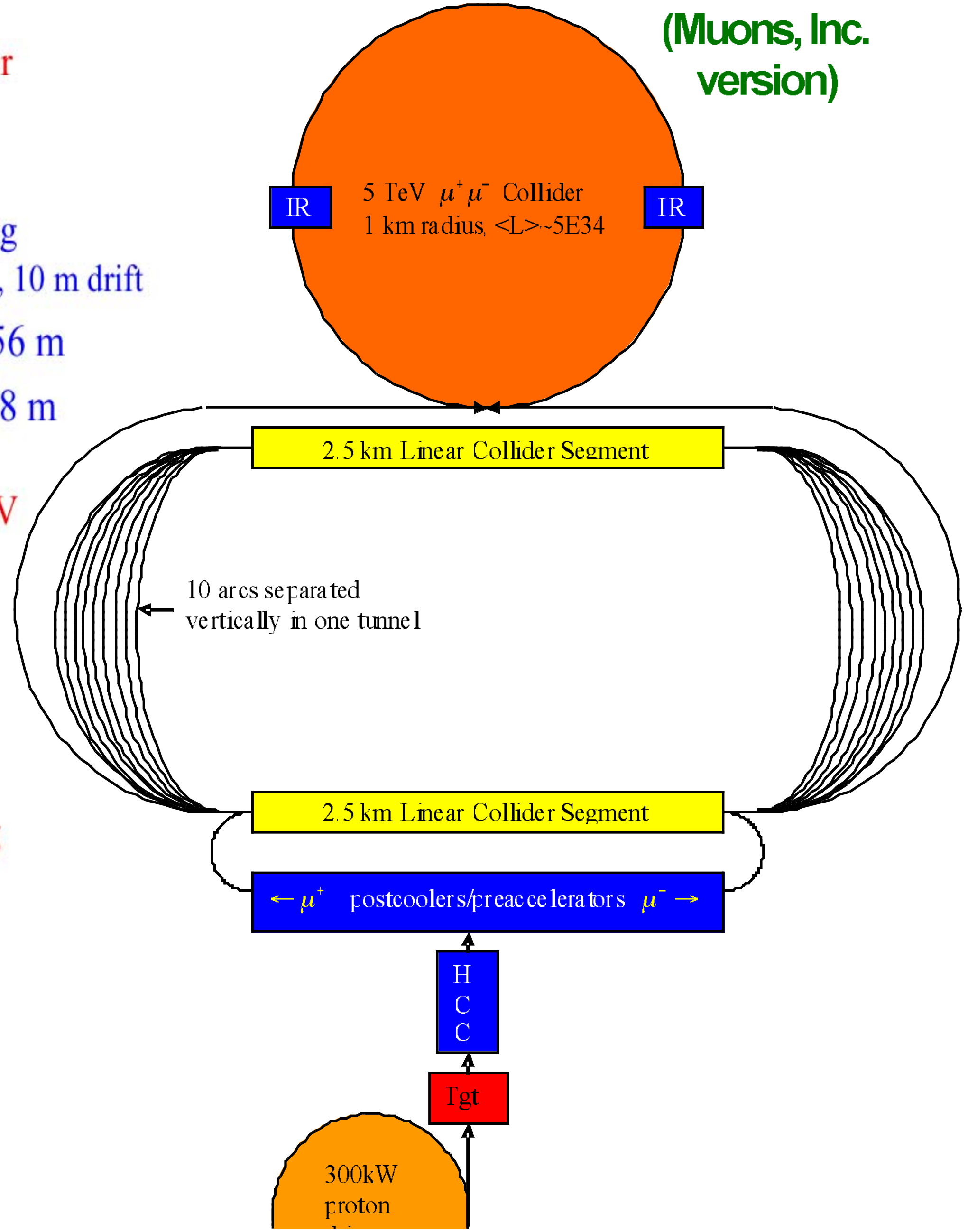
- Neutrino Factory:

(Feasibility Study-II)



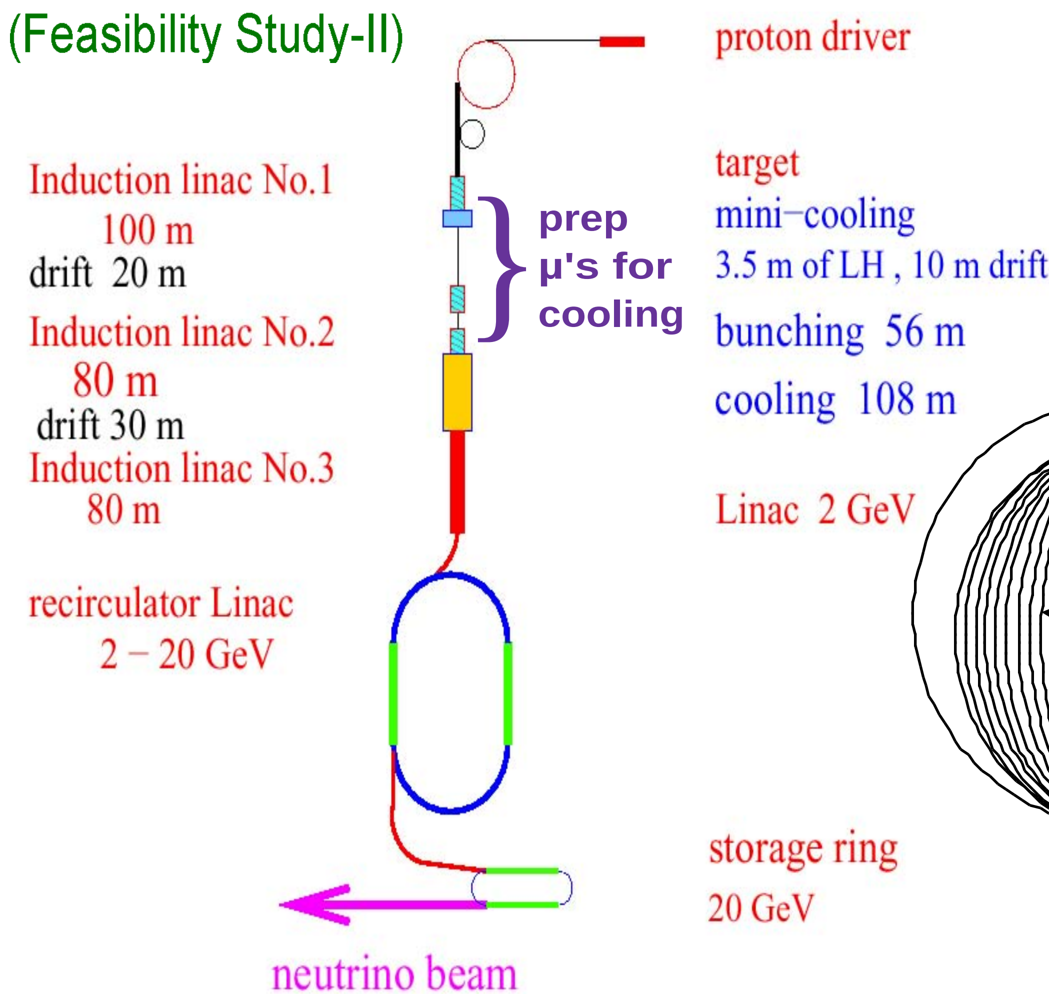
- $\mu^+\mu^-$ collider:

(Muons, Inc. version)

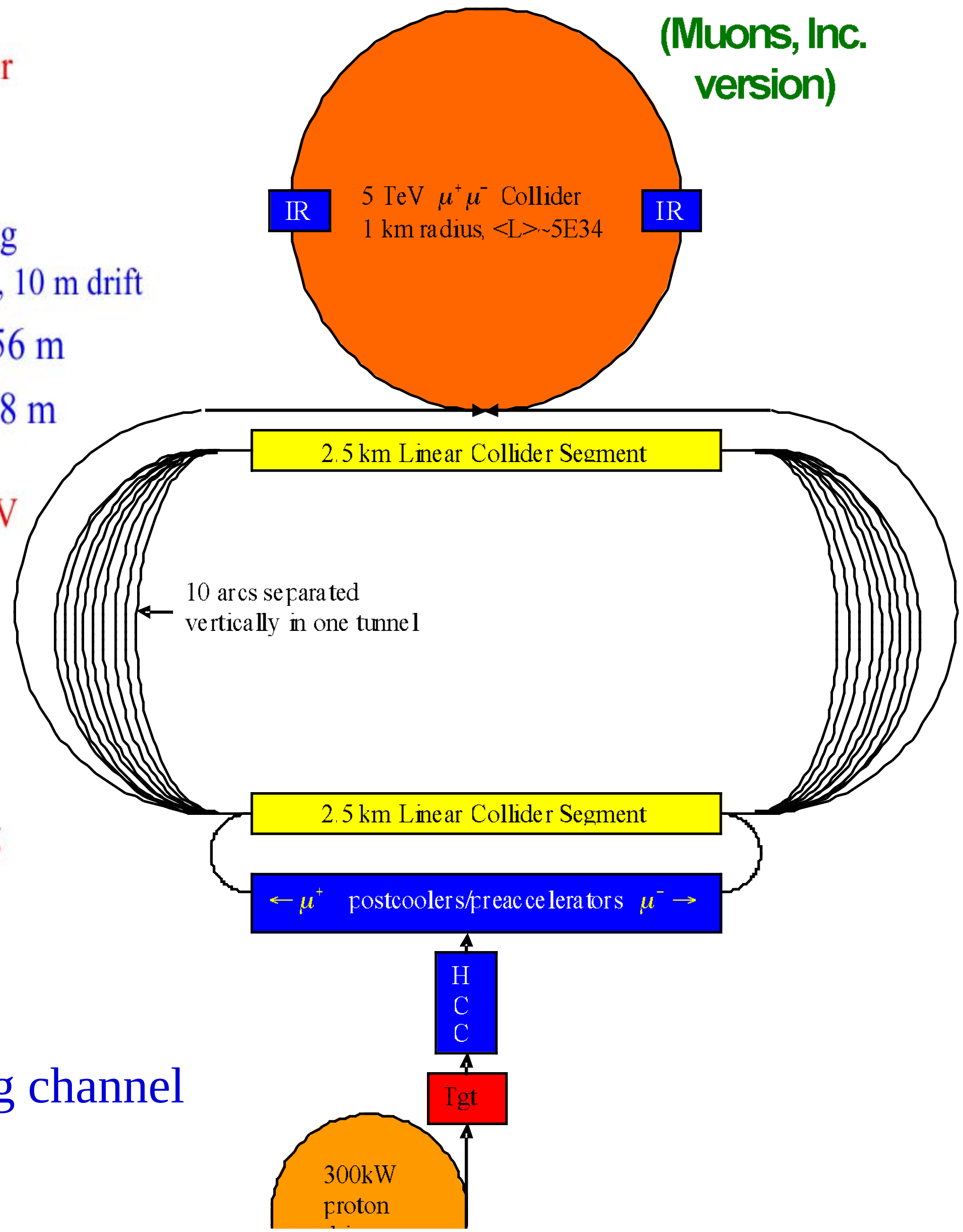


Muon Facility Examples:

- Neutrino Factory:



- $\mu^+\mu^-$ collider:



- Common features:
  1. p on tgt → π → μ, collected in focusing channel
  2. μ cooling, acceleration, & storage

– then:

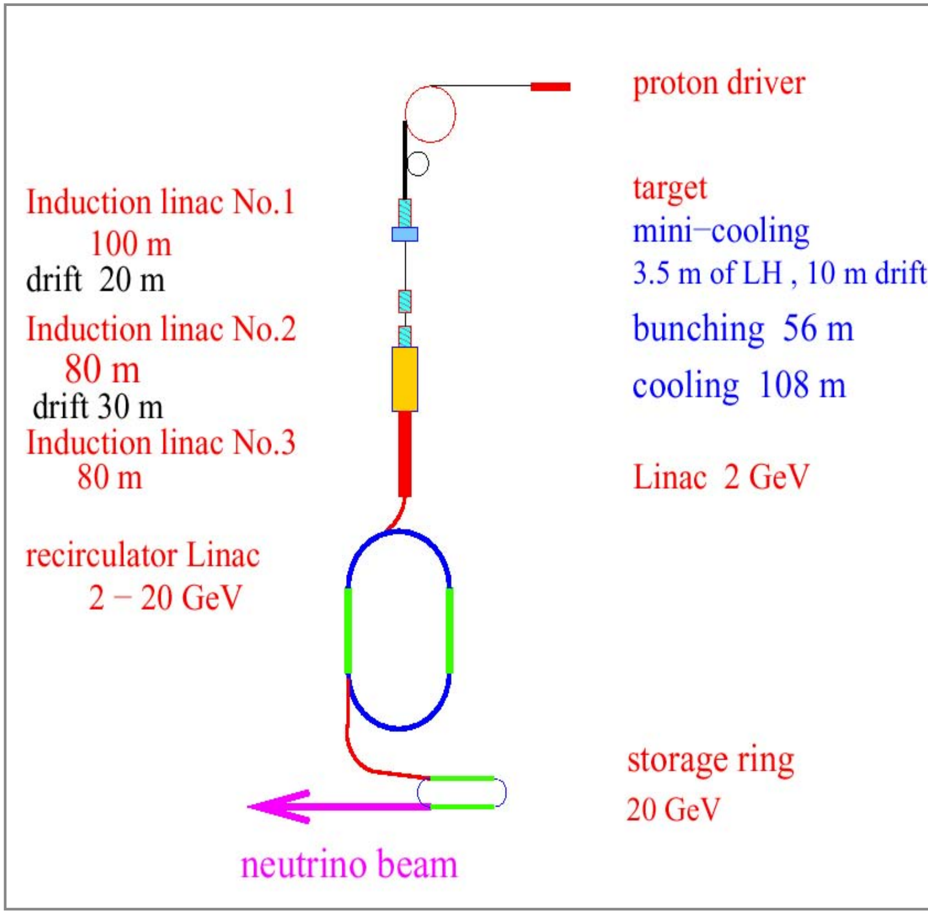
3. neutrino beam via $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$ – or – $\mu^+\mu^-$ collisions

What's a Neutrino Factory?

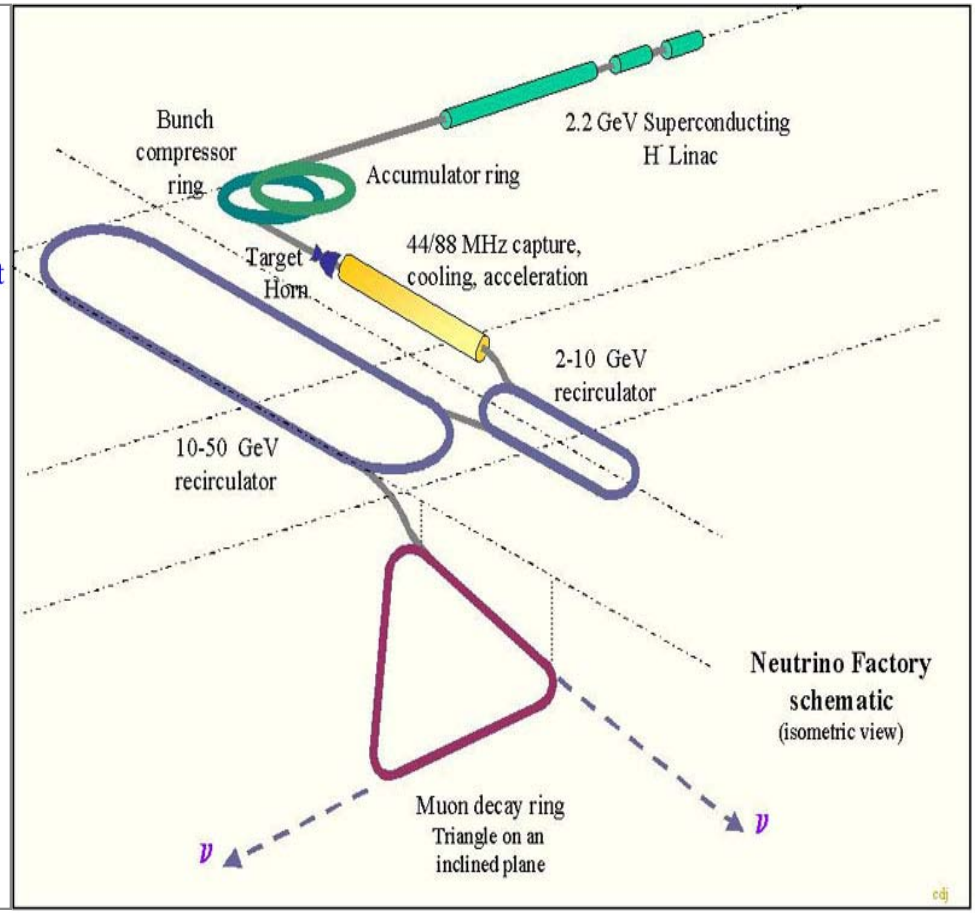
What's a Neutrino Factory?

S. Geer, Phys. Rev. D **57**, 6989 (1998)

A US scheme



CERN 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

Why a Neutrino Factory?

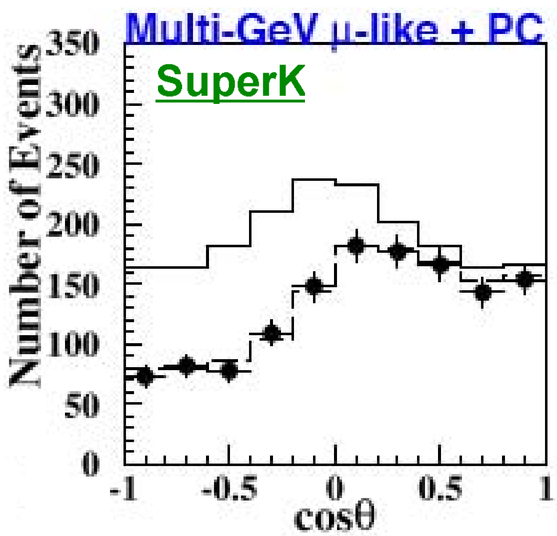
Why a Neutrino Factory?

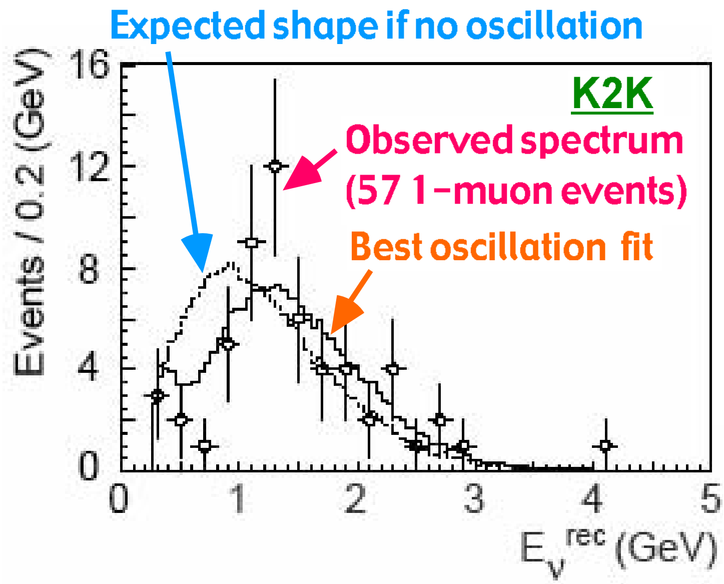
- Most fundamental particle-physics discovery of past decade:

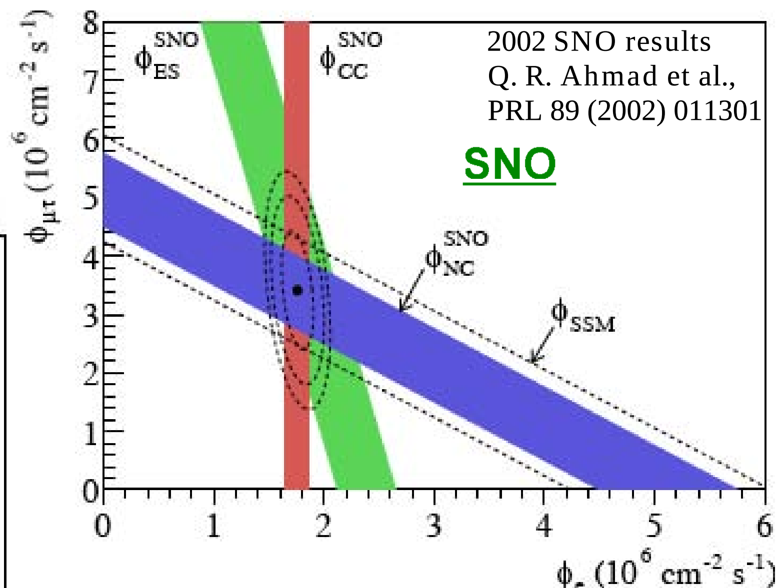
Why a Neutrino Factory?

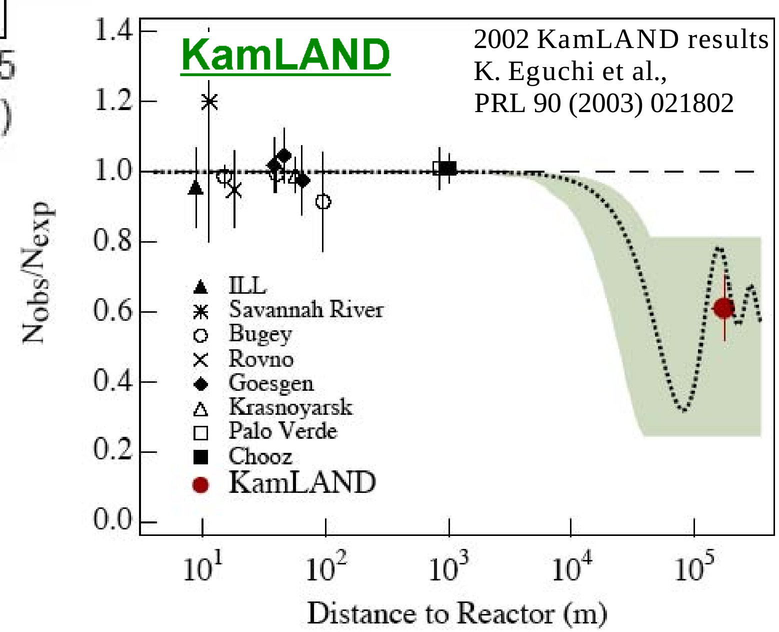
- Most fundamental particle-physics discovery of past decade:

neutrinos mix!





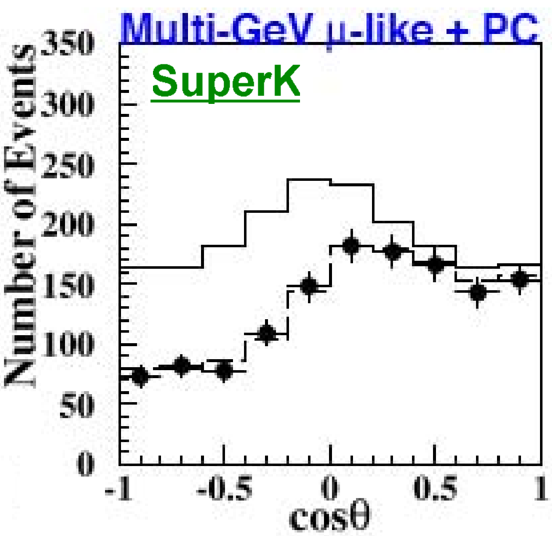


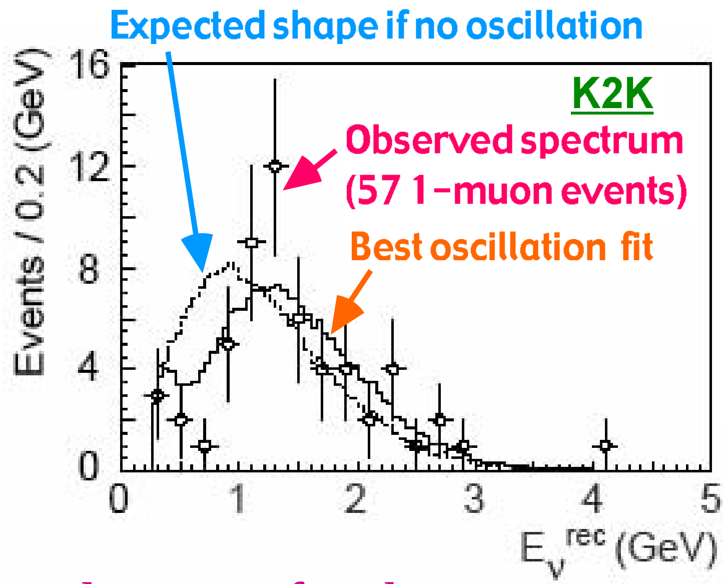


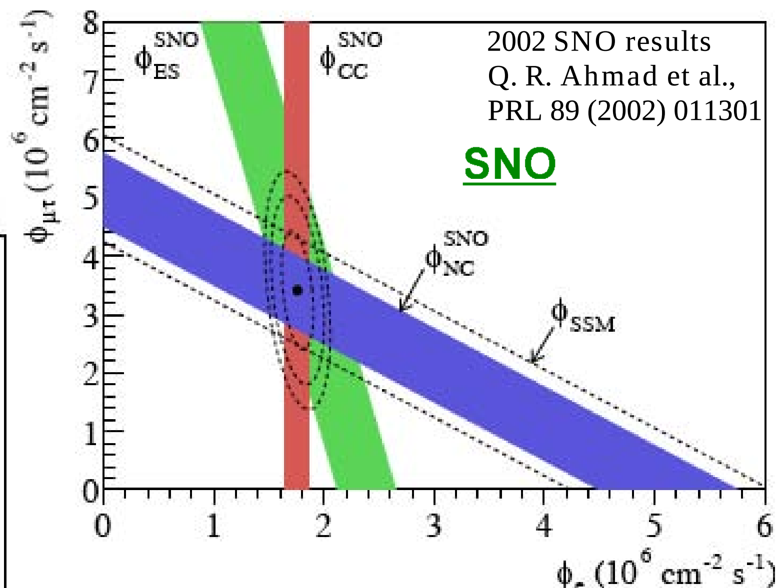
Why a Neutrino Factory?

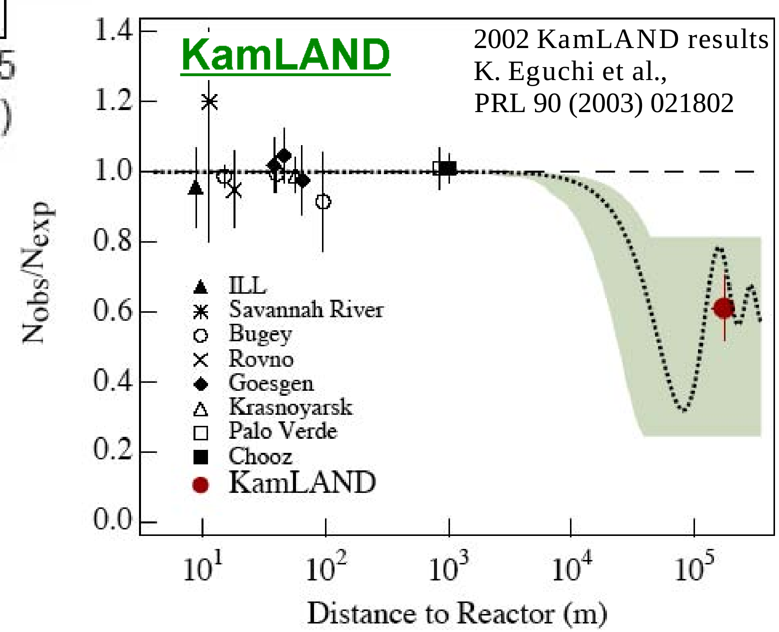
- Most fundamental particle-physics discovery of past decade:

neutrinos mix!









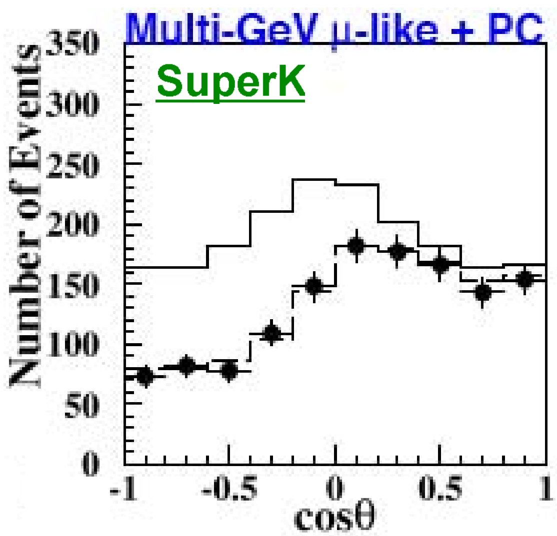
...arguably the leading explanation for the cosmic baryon asymmetry ("Leptogenesis")

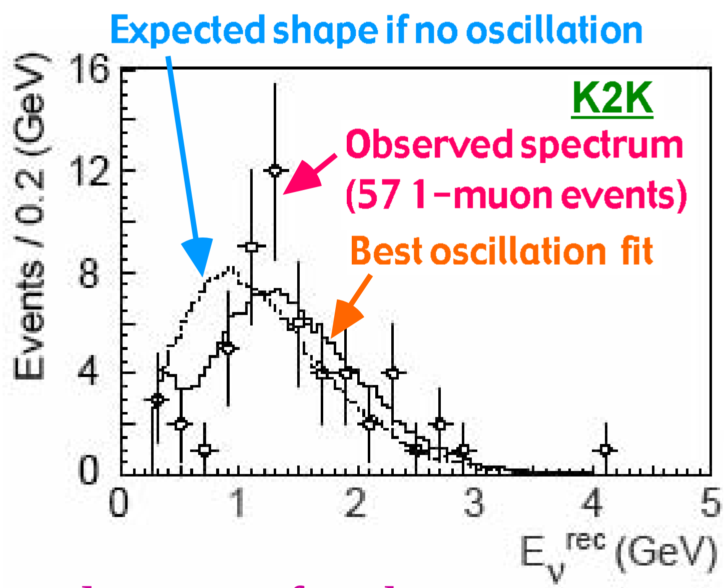
M. Fukugita and T. Yanagida,
Phys. Lett. B174, (1986) 45.

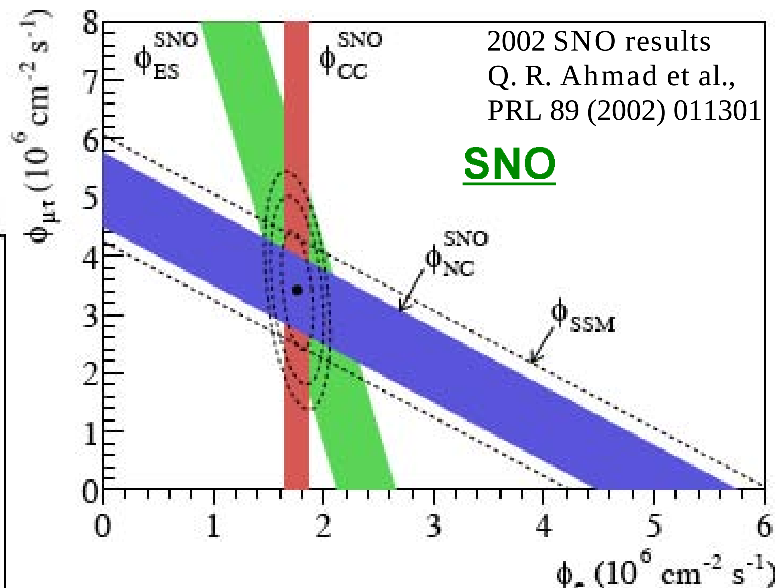
Why a Neutrino Factory?

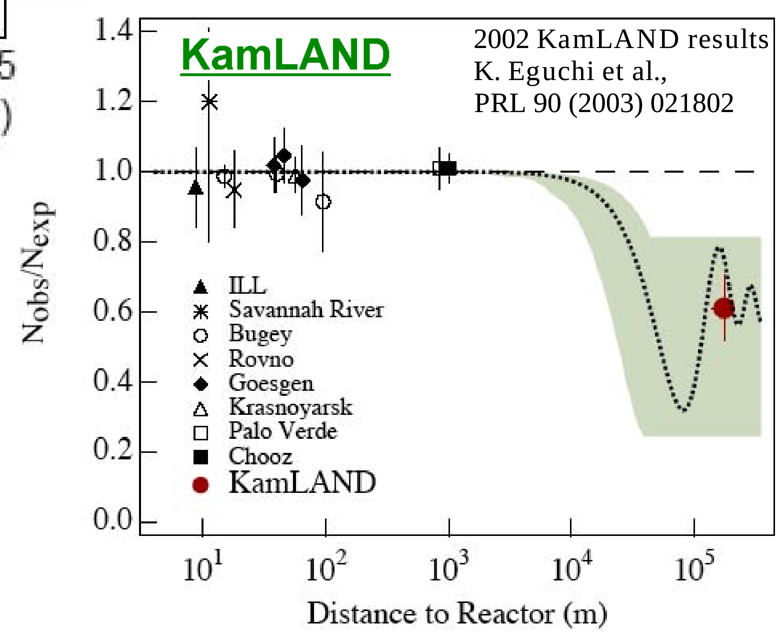
- Most fundamental particle-physics discovery of past decade:

neutrinos mix!









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

M. Fukugita and T. Yanagida,
Phys. Lett. B174, (1986) 45.

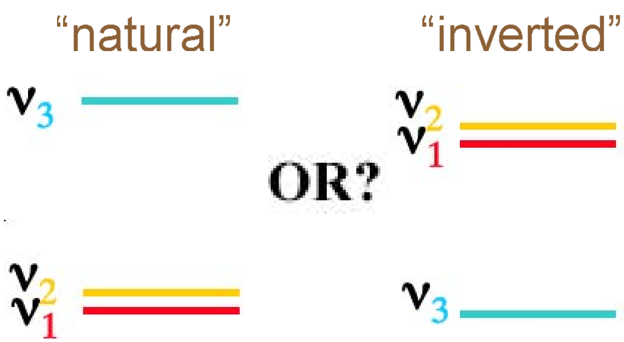
...and possibly relevant to the nature of dark energy ("mass varying neutrinos")

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?



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

CKM matrix:

$\theta_{12} \cong 12.8°$
$\theta_{23} \cong 2.2°$
$\theta_{13} \cong 0.4°$

} hierarchical & nearly diagonal

PMNS matrix:

$\theta_{12} = 30°$ (solar)
$\theta_{23} = 45°$ (atmospheric)
$\theta_{13} < 13°$ (Chooz limit)

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

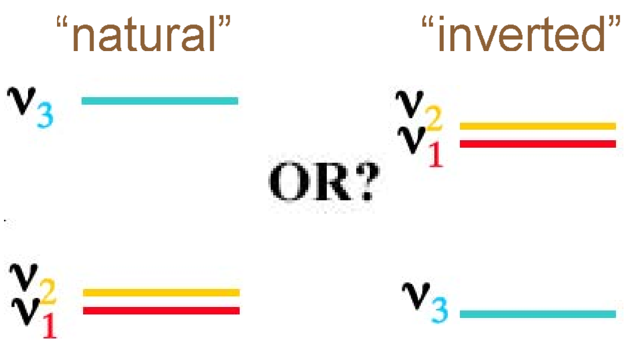
3. How close to zero are the small PMNS parameters θ_{13}, δ ?

$\longrightarrow$ are they suppressed by underlying dynamics? symmetries?

Why a Neutrino Factory?

- Neutrino mixing raises fundamental questions:

1. What is the neutrino mass hierarchy?



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

CKM matrix:

$\theta_{12} \cong 12.8°$

$\theta_{23} \cong 2.2°$

$\theta_{13} \cong 0.4°$

} hierarchical & nearly diagonal

PMNS matrix:

$\theta_{12} = 30°$ (solar)

$\theta_{23} = 45°$ (atmospheric)

$\theta_{13} < 13°$ (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 θ_{13}, δ?

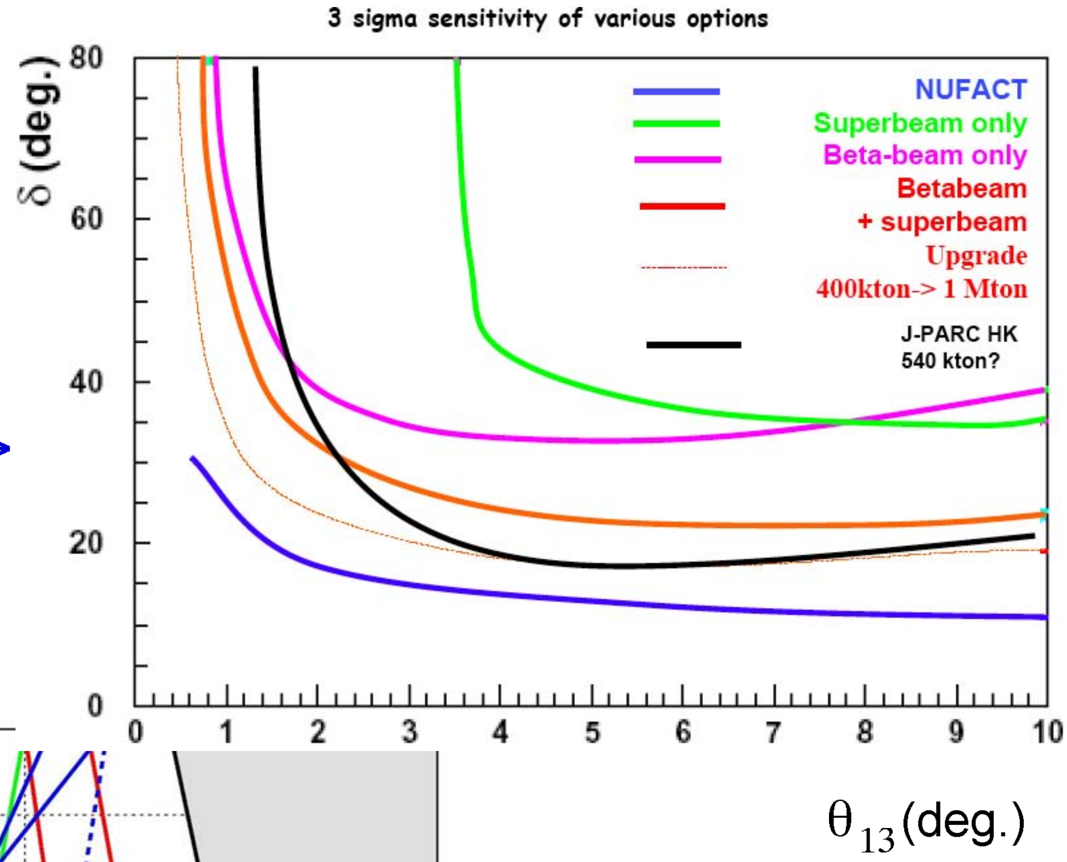
$\rightarrow$ are they suppressed by underlying dynamics? symmetries?

- **These call for a program to measure the PMNS elements as well as possible.**

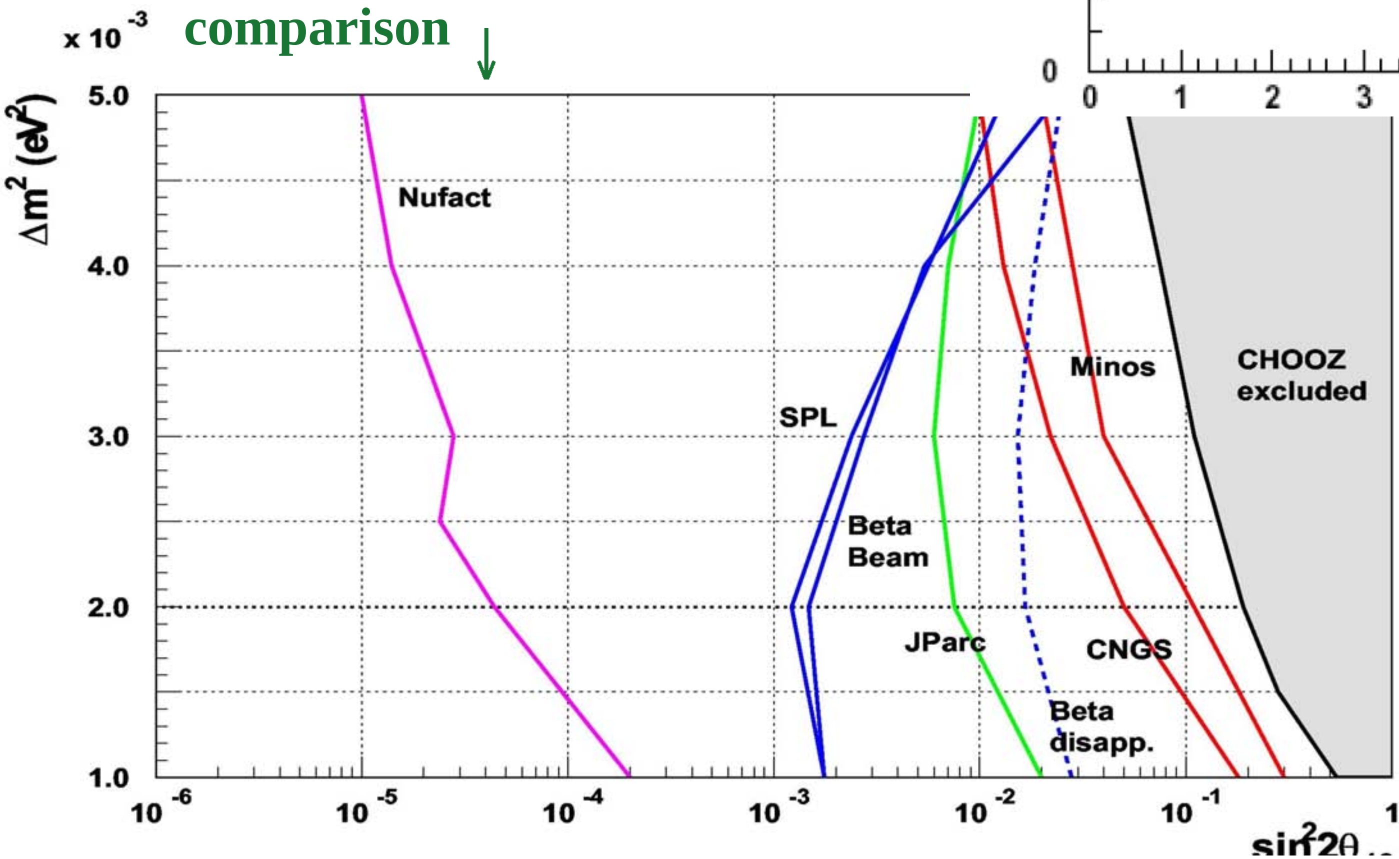
Neutrino Factory Physics Reach

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

CP-sensitivity comparison →



Oscillation-parameter comparison ↓

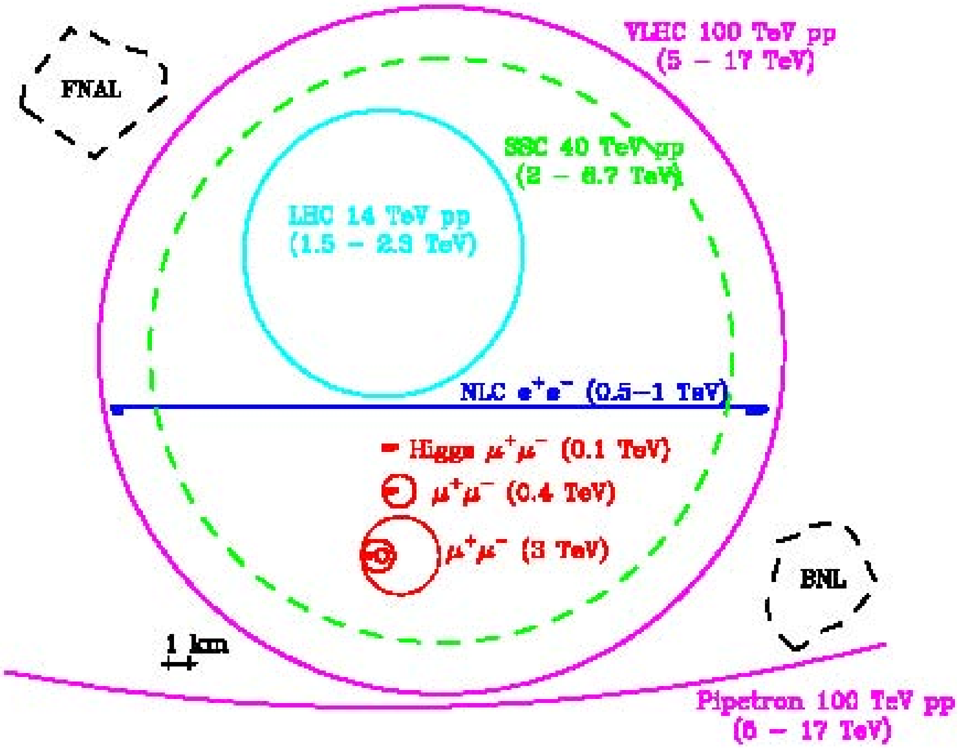


(plots from A. Blondel, NO-VE Workshop, Venice, Dec. 03)

Why Muon Colliders?

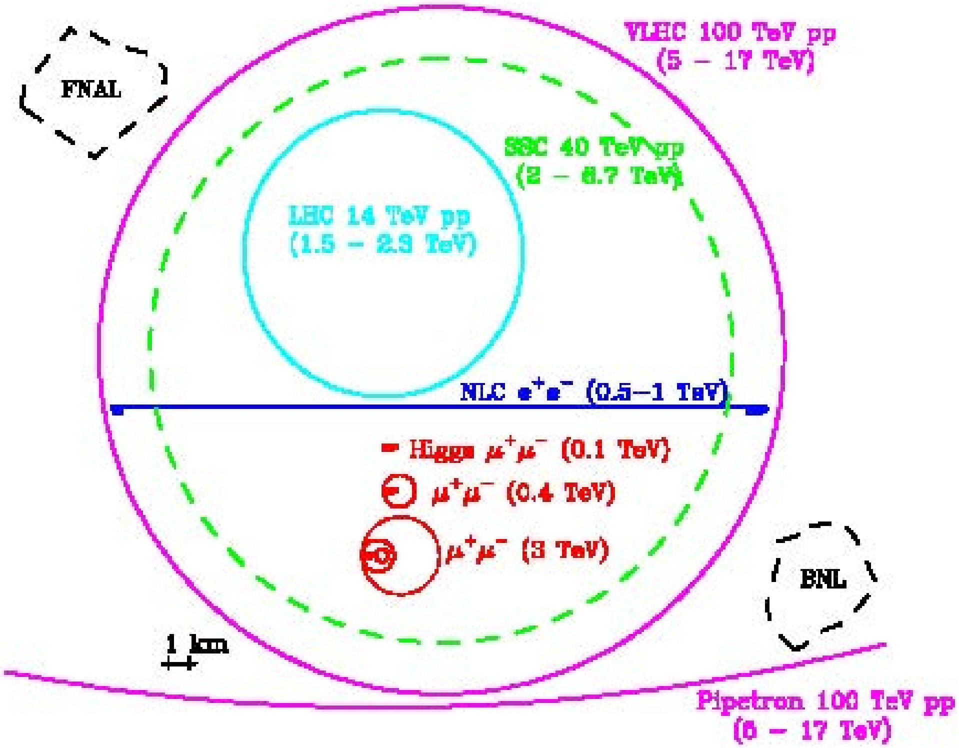
- A pathway to *high-energy* lepton colliders
  - unlike e^+e^-, $\sqrt{s}$ not limited by radiative effects

⇒ a muon collider can fit on existing laboratory sites even for $\sqrt{s}$ > 3 TeV:



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:

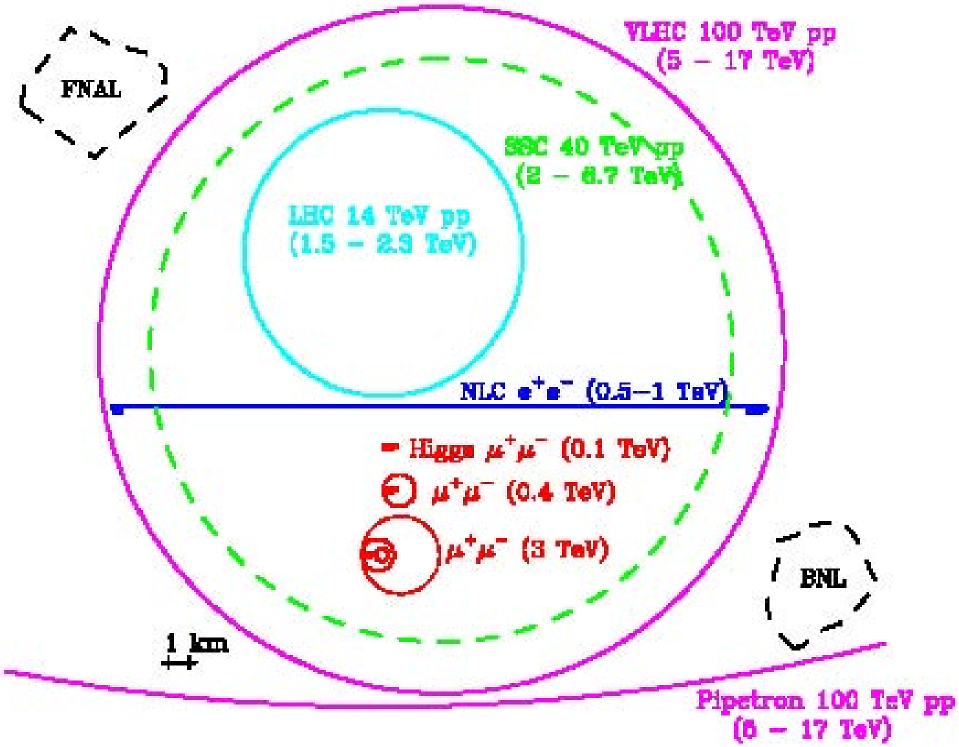


- Also...

Why Muon Colliders?

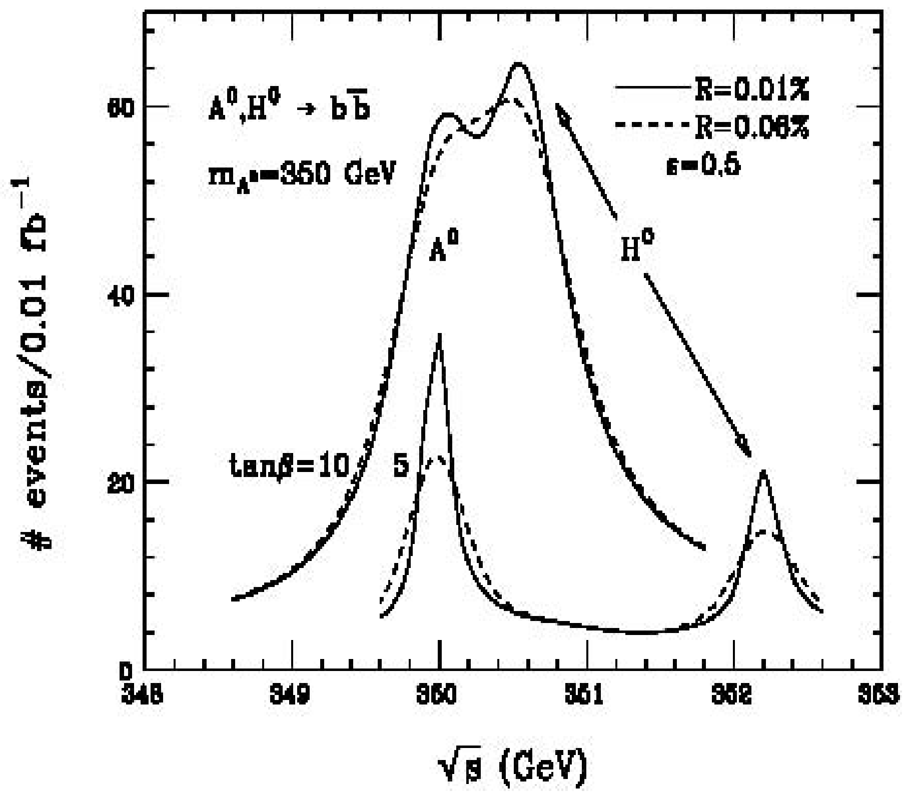
- A pathway to *high-energy* lepton colliders
  - unlike e^+e^-, $\sqrt{s}$ not limited by radiative effects

  ⇒ a muon collider can fit on existing laboratory sites even for $\sqrt{s}$ > 3 TeV:



- Also...

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



- E.g., $\mu\mu$-collider resolution can separate near-degenerate scaler and pseudo-scalar Higgs states of high-tan β 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
  - O'Neill (1956), Lichtenberg *et al.* (1956),

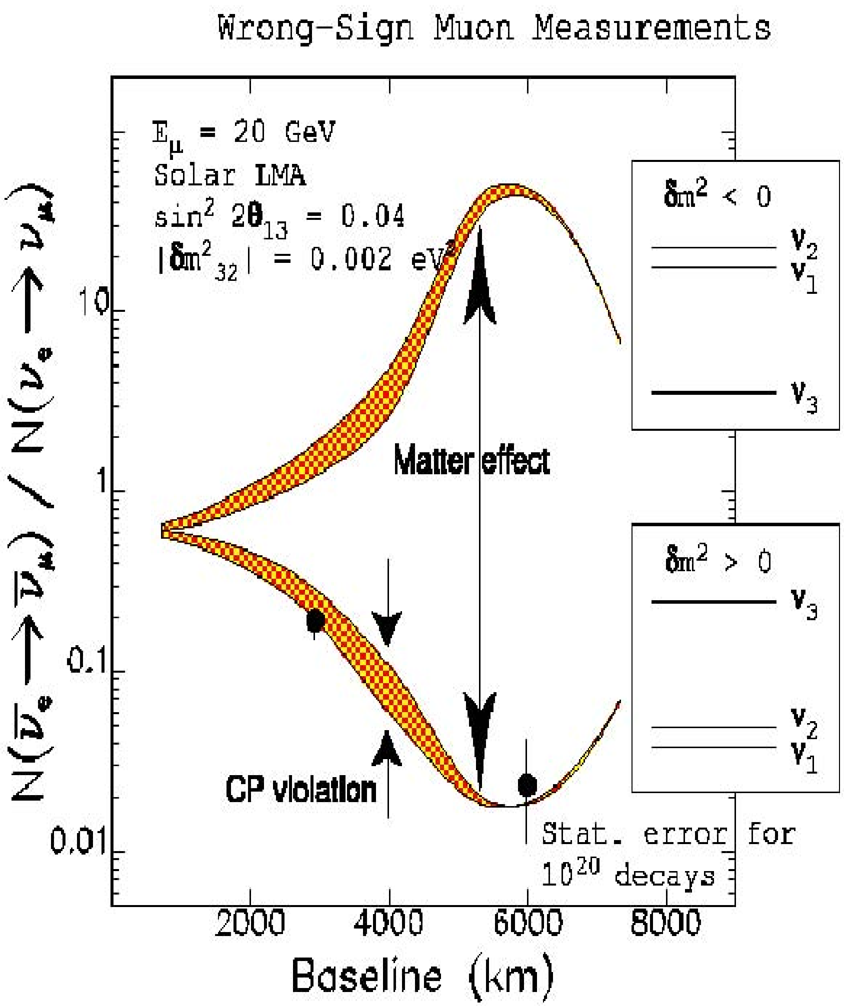
  applied to muon cooling by Skrinsky & Parkhomchuk (1981), Neuffer (1983)
- Realization (Neuffer and Palmer) that a high-luminosity muon collider might be feasible stimulated series of workshops & formation (1995) of Neutrino Factory and Muon Collider Collaboration
  - has since grown to 47 institutions and >100 physicists
- Snowmass Summer Study (1996)
  - study of feasibility of a 2+2 TeV Muon Collider [Fermilab-conf-96/092]
- Neutrino Factory suggested by Geer (1997) at the Workshop on Physics at the First Muon Collider and the Front End of the Muon Collider [AIP Conf. Proc. **435**]; Phys. Rev D **57**, 6989 (1998); also CERN yellow report (1999) [CERN 99-02, ECFA 99-197]
- 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);
  - www.cap.bnl.gov/mumu/; www.fnal.gov/projects/muon_collider

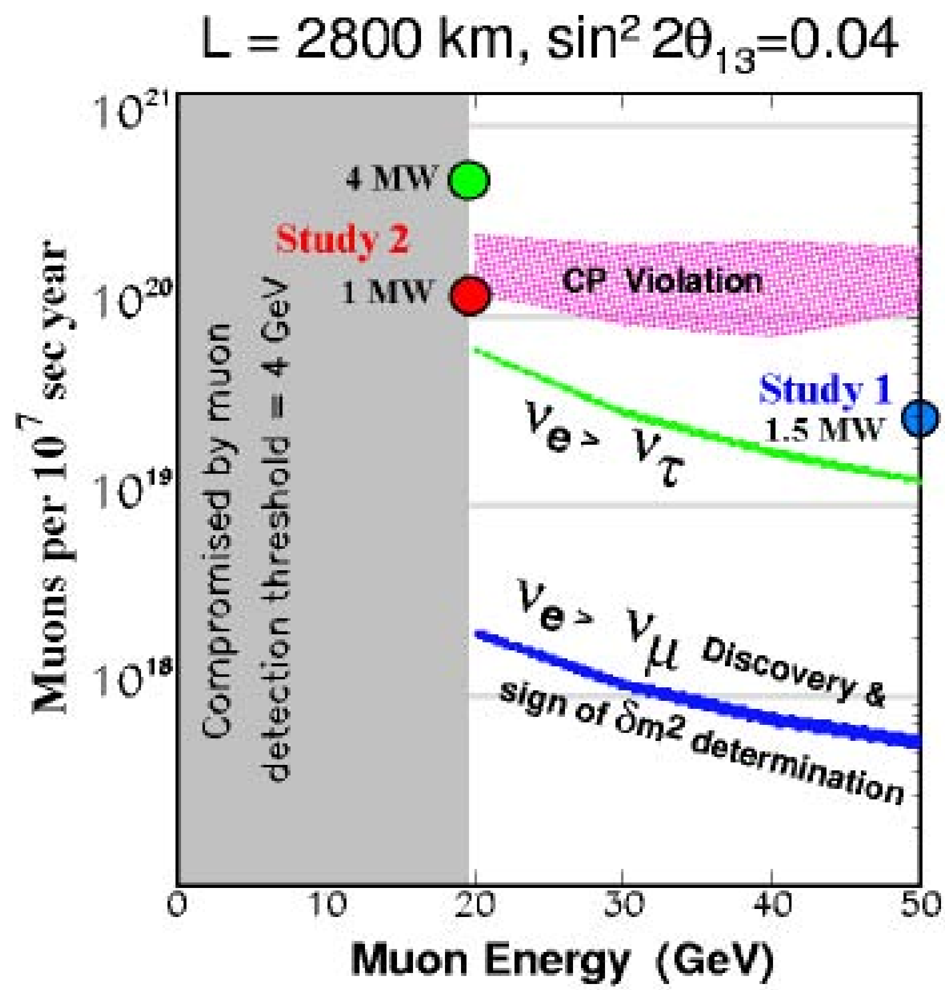
Neutrino Factory Feasibility

- 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 $\nu_e \to \nu_\mu$ & $\bar{\nu}_e \to \bar{\nu}_\mu$ determines mass hierarchy and CP phase δ:

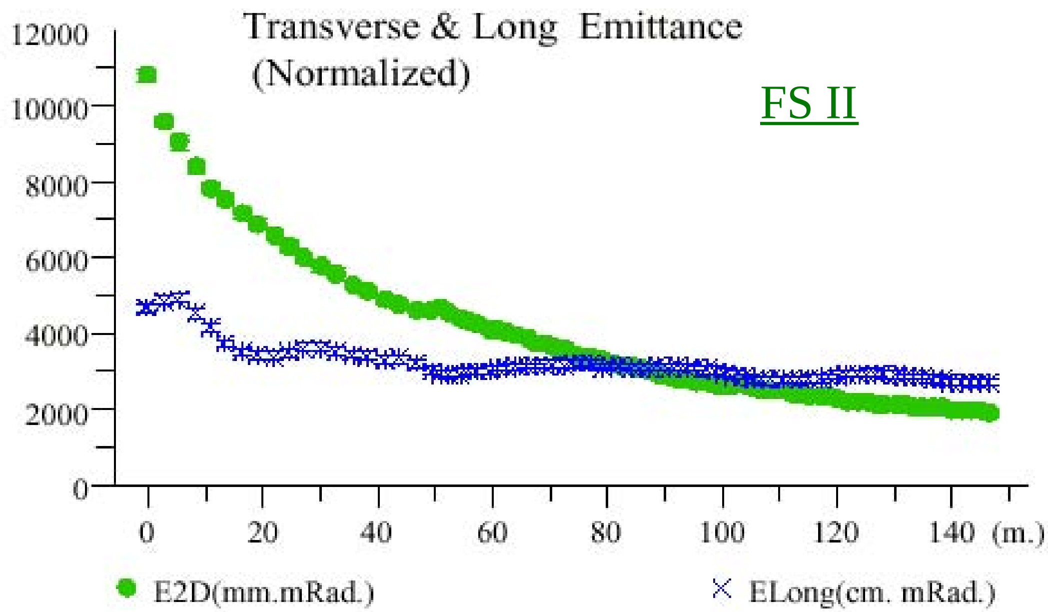


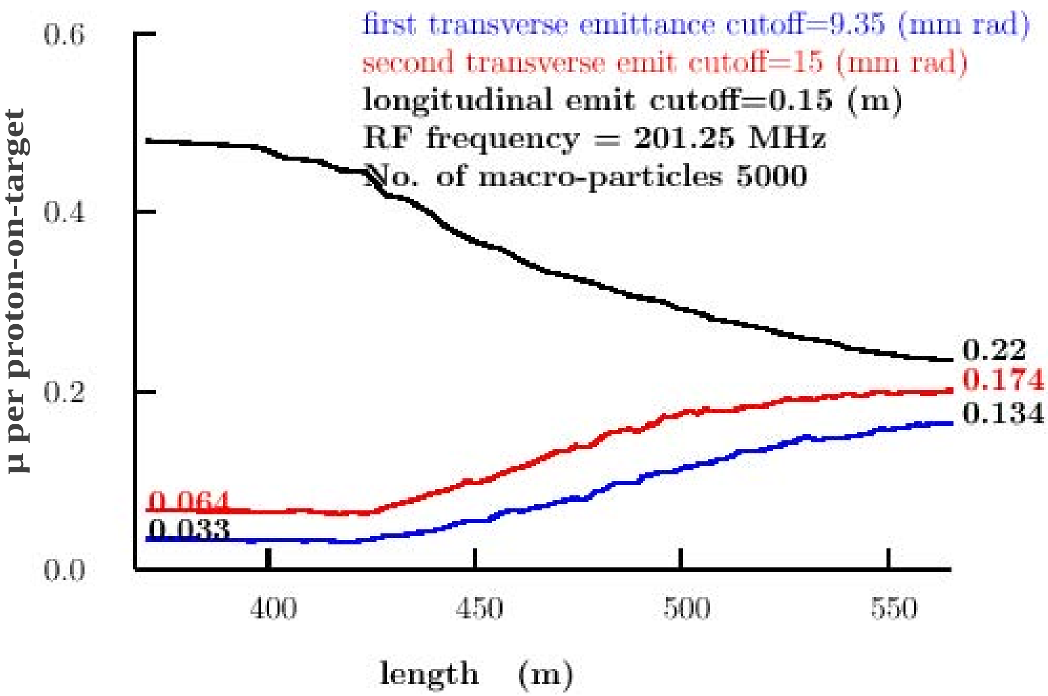


- To set scale, 10^{20} decays with 50-kT detector sees δ down to ≈8°

  ⇒ important to maximize flux!

Neutrino Factory Performance & Cost





Indicative (not definitive!) FS II cost estimate

System	Sum ($M)	Others[a] ($M)	Total ($M)
Proton Driver	167.6	16.8	184.4
Target Systems	91.6	9.2	100.8
Decay Channel	4.6	0.5	5.1
Induction Linacs	319.1	31.9	351.0
Bunching	68.6	6.9	75.5
Cooling Channel	317.0	31.7	348.7
Pre-accel. linac	188.9	18.9	207.8
RLA	355.5	35.5	391.0
Storage Ring	107.4	10.7	118.1
Site Utilities	126.9	12.7	139.6
Totals	**1,747.2**	**174.8**	**1,922.0**

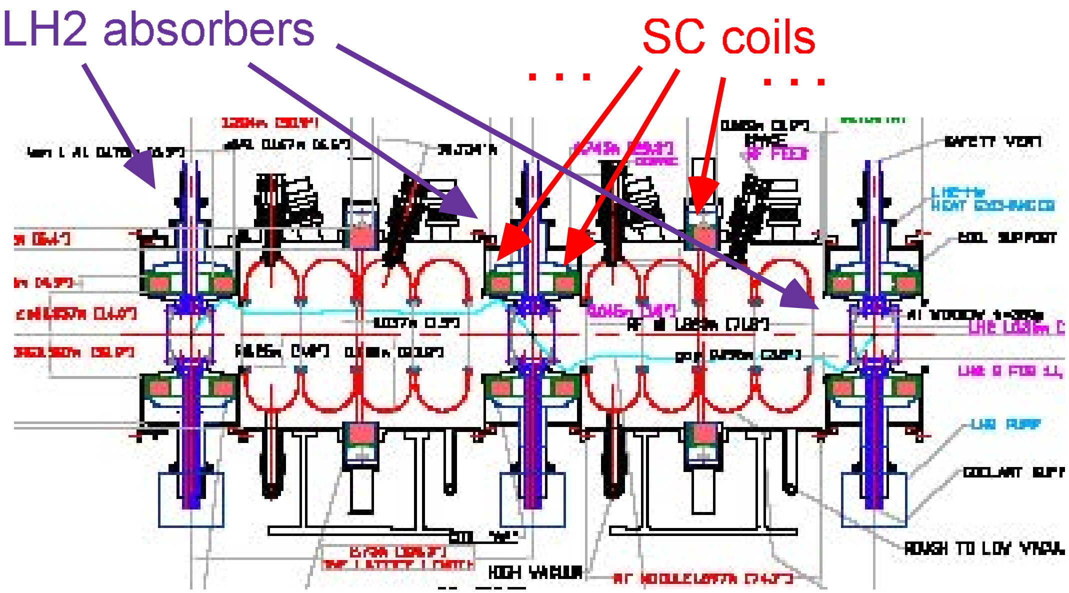
- FS-II cost drivers: phase rotation, cooling, acceleration
- FS-2a features cheaper solutions for all three of these

→ "Bare" cost of Neutrino Factory now estimated at ≈ 1 G$

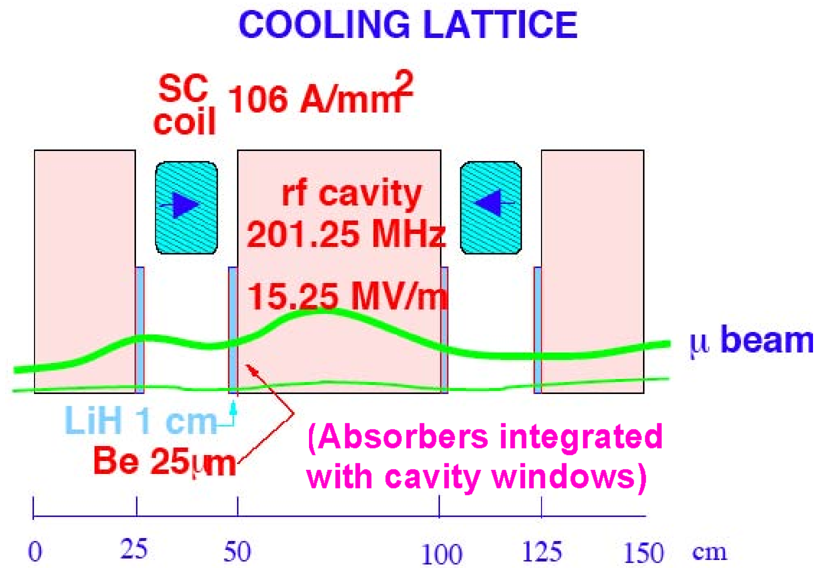
Study 2a Progress

- Simpler, shorter, cheaper cooling channel:

FS-II

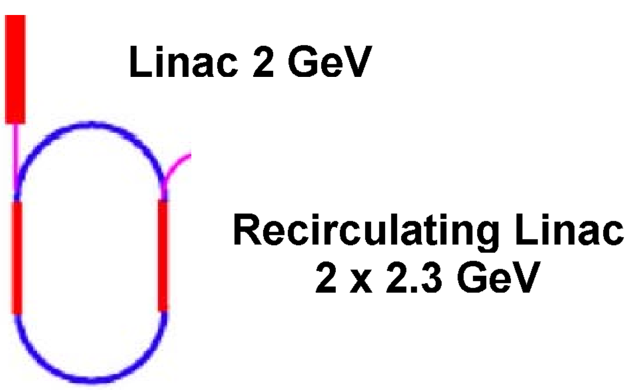


FS-2a

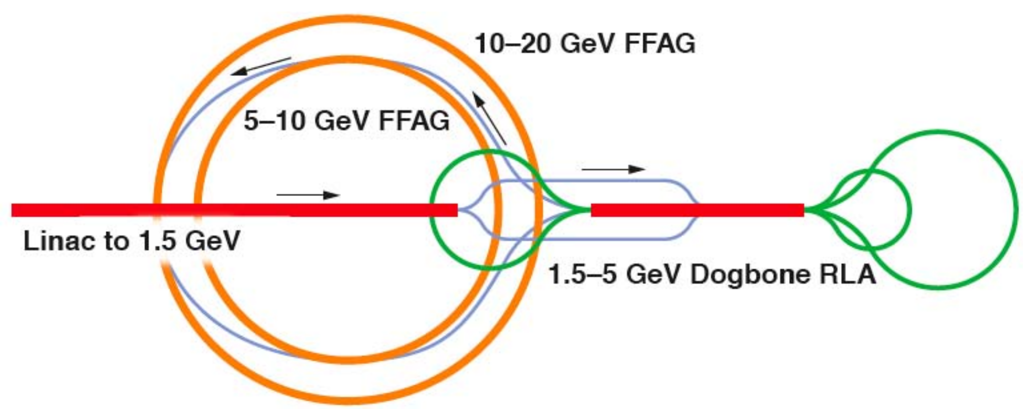


- New, cheaper, "non-scaling FFAG" acceleration:

FS-II



FS-2a



<u>New Physics / New Facilities</u>

(If I may be a bit provocative...)

New Physics / New Facilities

(If I may be a bit provocative...)

- Conventional wisdom:

  – "LEP data demonstrate ∃ SUSY Higgs with m < 500 GeV"

  ⇒ need (12G$?) ILC ASAP

New Physics / New Facilities

(If I may be a bit provocative...)

- Conventional wisdom:
  - “LEP data demonstrate ∃ SUSY Higgs with $m < 500$ GeV”

  $\Rightarrow$ need (12G$?) ILC ASAP

- 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

(If I may be a bit provocative...)

- Conventional wisdom:
  - "LEP data demonstrate ∃ SUSY Higgs with *m* < 500 GeV"

  ⇒ need (12G$?) ILC ASAP

- 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?

- νF physics needs $\gtrsim$ 0.1 μ/*p*-on-target $\Rightarrow$ **very** intense μ beam from π decay

  $\Rightarrow$ must accept large (~10π 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 νF studies, cooling $\rightarrow \times$ 2 – 10 in accelerated muon flux)

- μC: $\mathcal{L} \propto \boldsymbol{I}^2/\sigma_x\sigma_y \Rightarrow$ big gain from smaller beam

  $\Rightarrow$ to achieve useful collider luminosity, *must* cool the muon beam

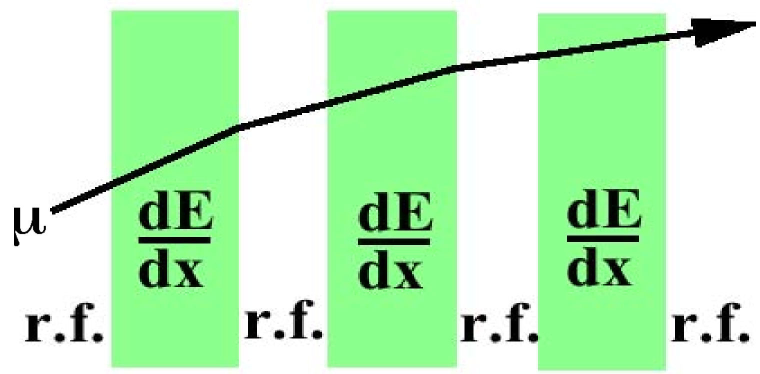
The Challenge:

$$\tau_\mu = 2.2\ \mu s$$

Q: What cooling technique works in microseconds?

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

Ionization Cooling:



G. I. Budker and A. N. Skrinsky, Sov. Phys. Usp. **21**, 277 (1978)
A. N. Skrinsky and V. V. Parkhomchuk, Sov. J. Part. Nucl. **12**, 223 (1981)

A brilliantly simple idea!

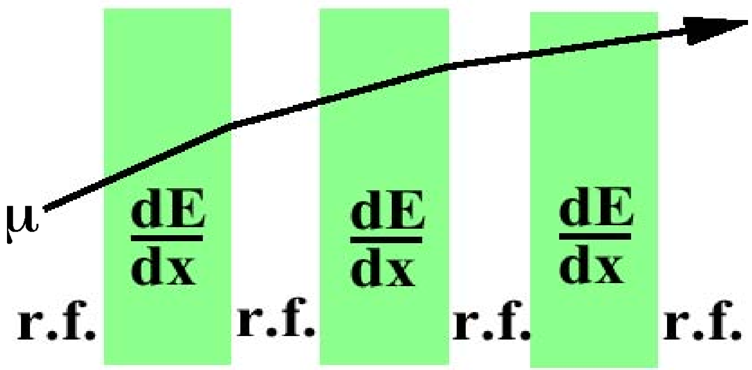
- **BUT:**
  - it has never been observed experimentally
  - studies show it is a delicate design and engineering problem
  - it is a crucial ingredient in the cost and performance optimization of a Neutrino Factory

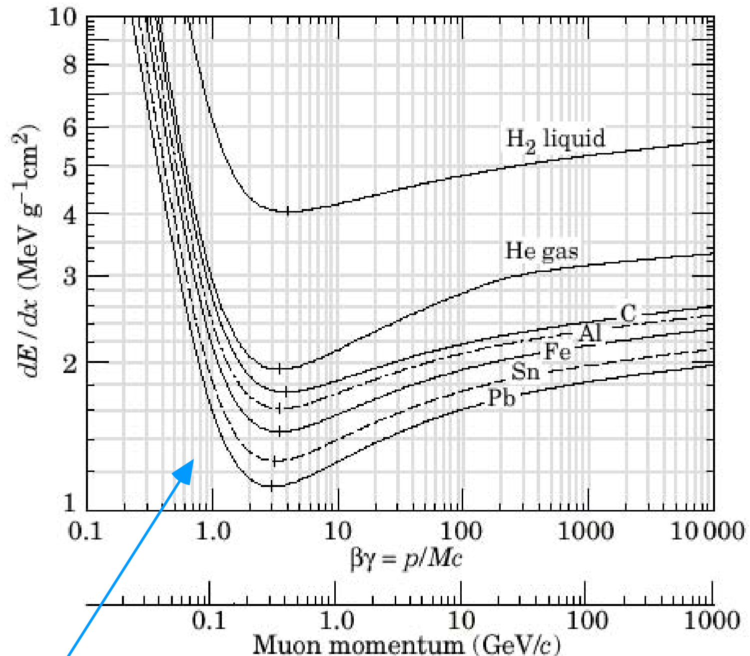
⇒ Need experimental demonstration of muon ionization cooling!

→ **MICE**

Ionization Cooling:

- Two competing effects:





– Absorbers:

$$\begin{cases} E \rightarrow E - \left\langle \dfrac{dE}{dx} \right\rangle \Delta s \\ \theta \rightarrow \theta + \theta^{rms}_{space} \end{cases}$$

ionization energy loss

multiple Coulomb scattering

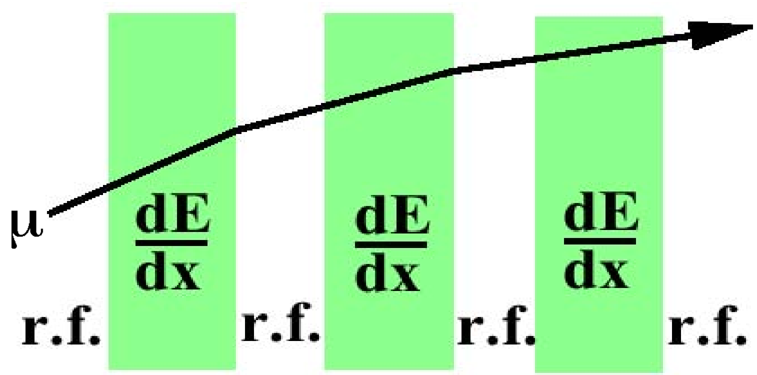
– RF cavities between absorbers replace ΔE

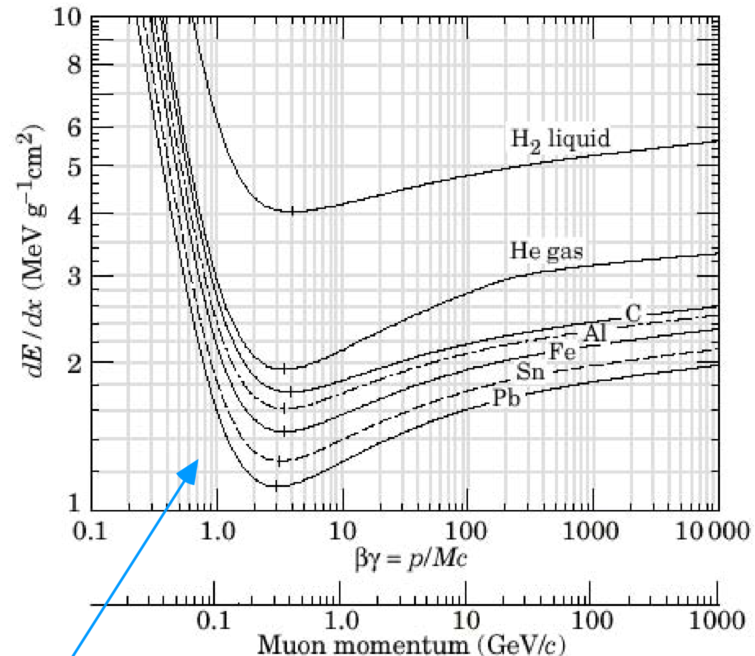
– Net effect: reduction in $p_\perp$ at constant $p_\|$, i.e., transverse cooling

$$\frac{d\epsilon_N}{ds} = -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\ \mathrm{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$ (emittance change per unit length)

Ionization Cooling:

- Two competing effects:





– Absorbers:
$$\begin{cases} E \rightarrow E - \left\langle \frac{dE}{dx} \right\rangle \Delta s \\ \theta \rightarrow \theta + \theta^{rms}_{space} \end{cases}$$

ionization energy loss

multiple Coulomb scattering

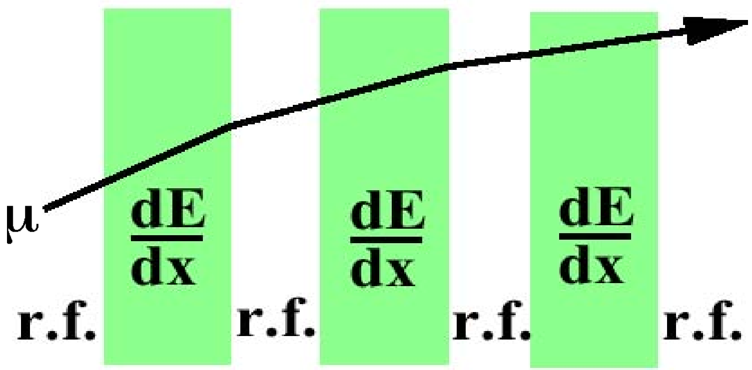
– RF cavities between absorbers replace ΔE

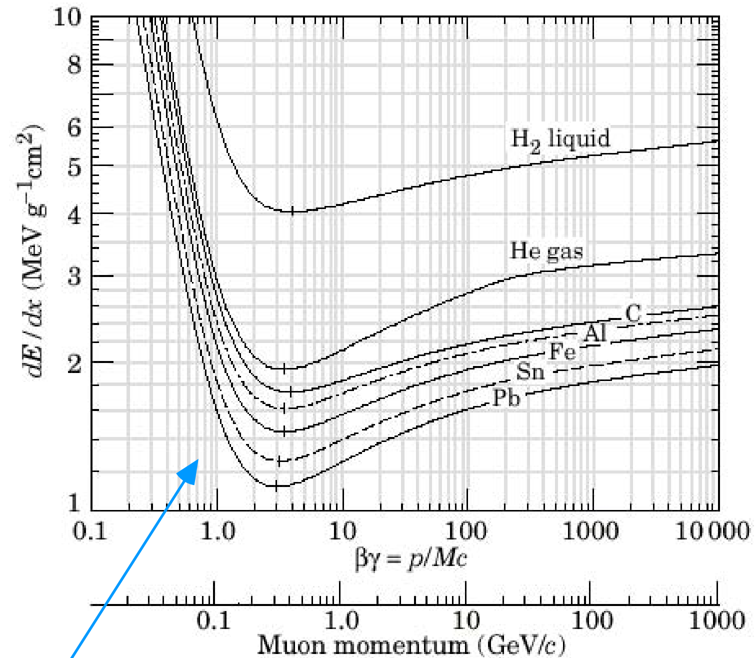
– Net effect: reduction in $p_\perp$ at constant $p_\parallel$, i.e., transverse cooling

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:

- Two competing effects:





- Absorbers:

$$\begin{cases} E \to E - \left\langle \dfrac{dE}{dx} \right\rangle \Delta s \\ \theta \to \theta + \theta^{rms}_{space} \end{cases}$$

ionization energy loss

multiple Coulomb scattering

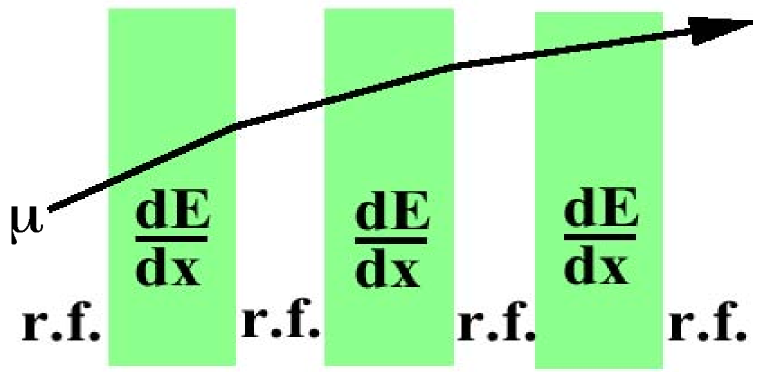
- RF cavities between absorbers replace ΔE
- Net effect: reduction in $p_\perp$ at constant $p_{\|}$, i.e., transverse cooling

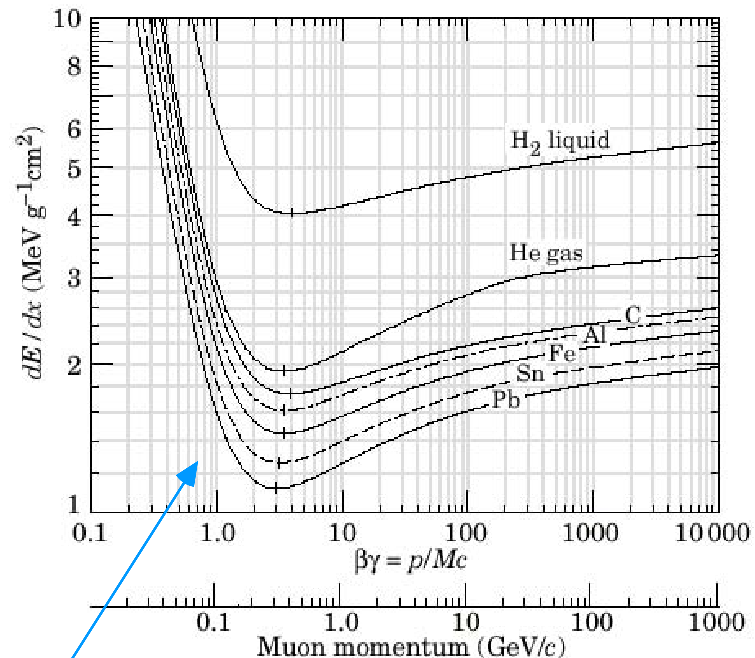
Note: The **physics** is not in doubt – it's just Maxwell's equations!
⇒ in principle, ionization cooling **has** to work!
... but in practice it is subtle and complicated...

...so a test is essential!

Ionization Cooling:

- Two competing effects:





– Absorbers:

$$\begin{cases} E \to E - \left\langle \dfrac{dE}{dx} \right\rangle \Delta s \\ \theta \to \theta + \theta^{rms}_{space} \end{cases}$$

ionization energy loss

multiple Coulomb scattering

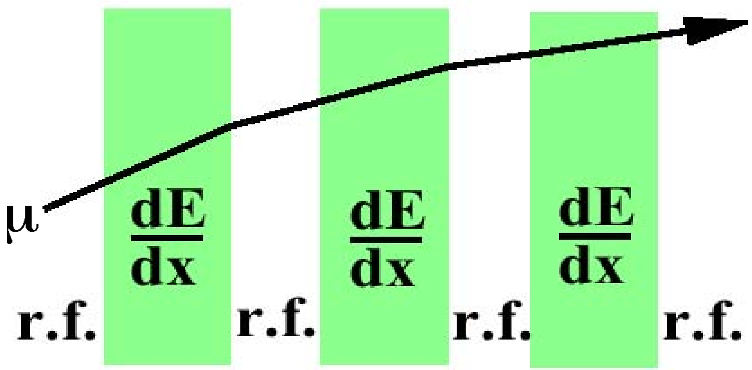
– RF cavities between absorbers replace ΔE

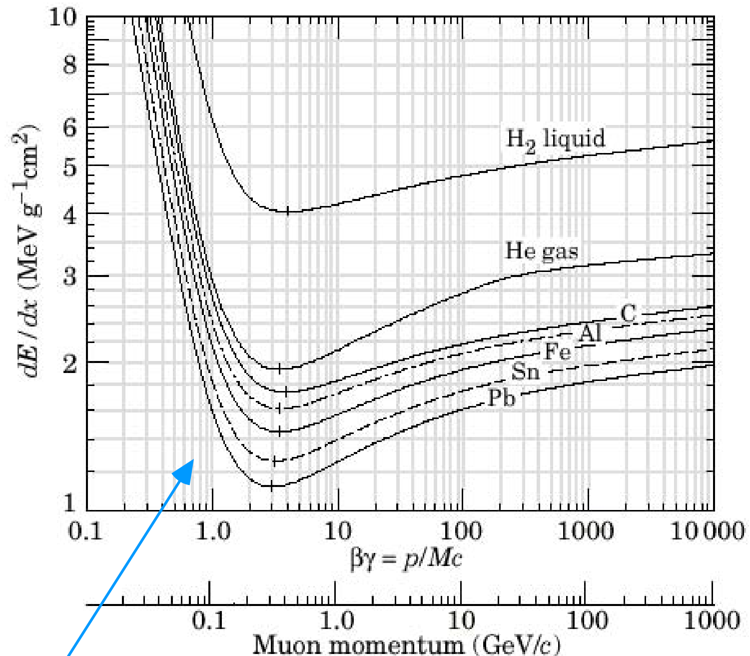
– Net effect: reduction in $p_\perp$ at constant $p_\parallel$, i.e., transverse cooling

$$\frac{d\epsilon_N}{ds} = -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\ \mathrm{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$

Ionization Cooling:

- Two competing effects:





– Absorbers:

$$\begin{cases} E \rightarrow E - \left\langle \dfrac{dE}{dx} \right\rangle \Delta s \\ \theta \rightarrow \theta + \theta_{space}^{rms} \end{cases}$$

ionization energy loss

multiple Coulomb scattering

– RF cavities between absorbers replace ΔE

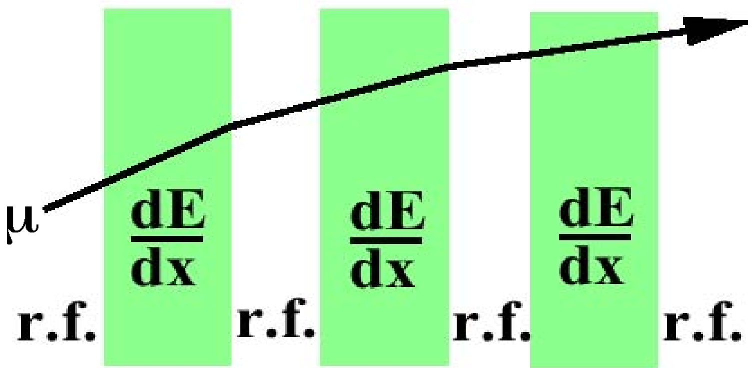
– Net effect: reduction in $p_\perp$ at constant $p_\parallel$, i.e., transverse cooling

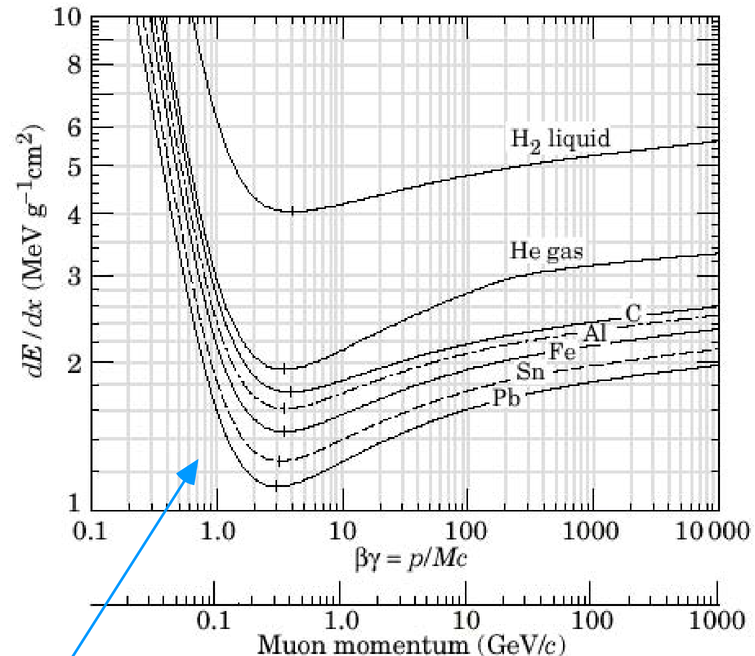
$$\frac{d\epsilon_N}{ds} = -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014 \text{ GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$

$\Rightarrow$ want strong focusing, large X_0, and low E_μ

Ionization Cooling:

- Two competing effects:





  – Absorbers:

$$\begin{cases} E \rightarrow E - \left\langle \dfrac{dE}{dx} \right\rangle \Delta s \\ \theta \rightarrow \theta + \theta^{rms}_{space} \end{cases}$$

ionization energy loss

multiple Coulomb scattering

  – RF cavities between absorbers replace ΔE

  – Net effect: reduction in $p_\perp$ at constant $p_\|$, i.e., transverse cooling

$$\frac{d\epsilon_N}{ds} = -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\ \mathrm{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$

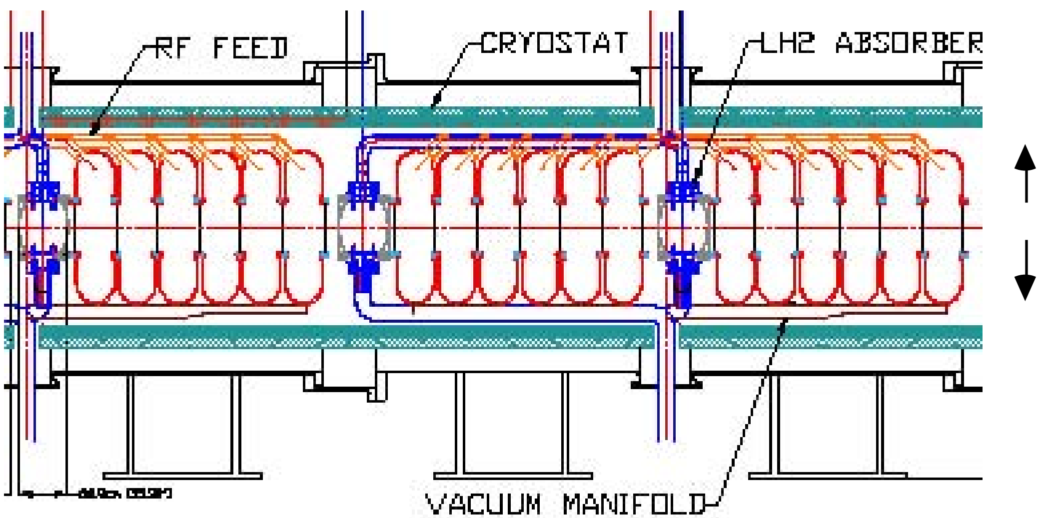
$\Rightarrow$ want strong focusing, large X_0, and low E_μ

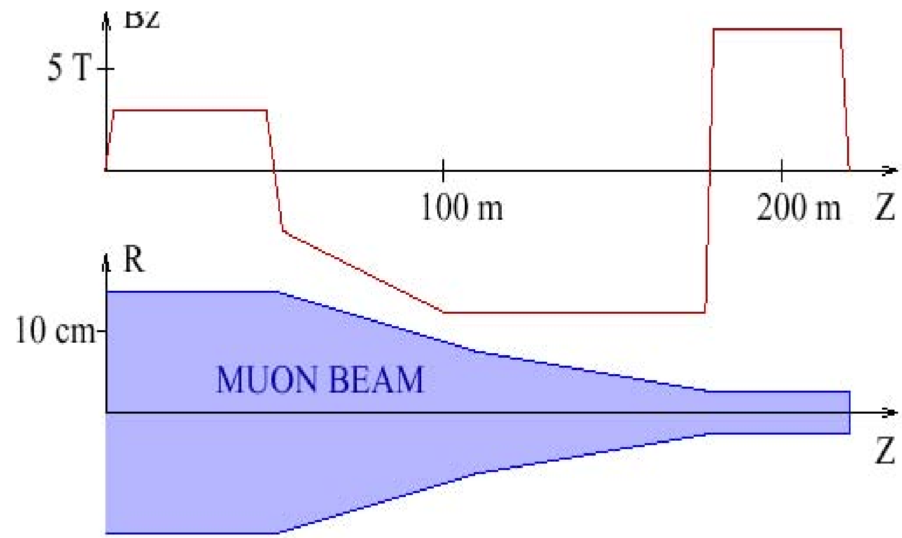
→ How can this be achieved...?

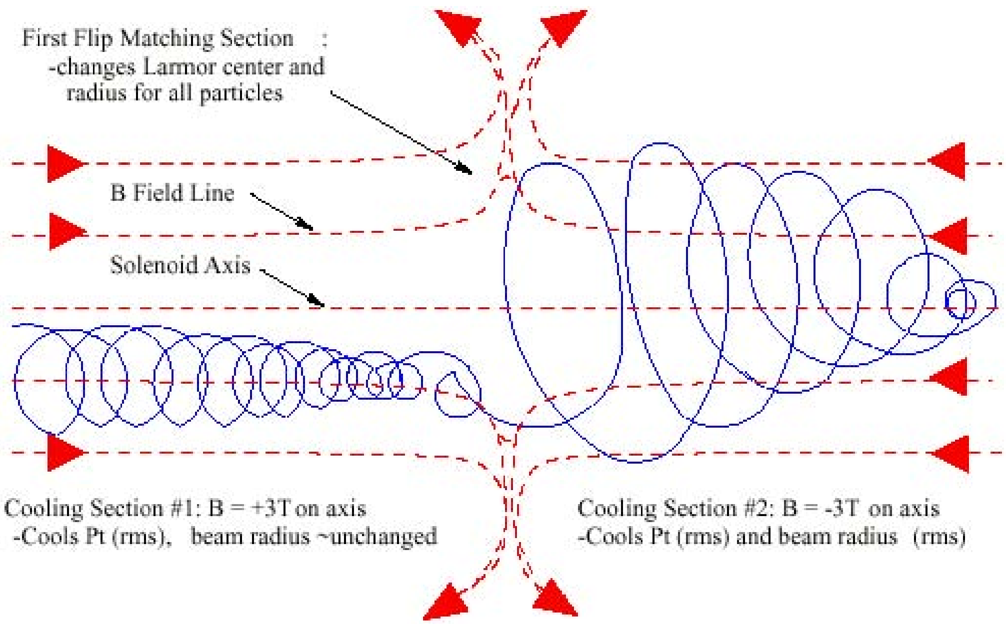
E.g., Double-Flip Cooling Channel

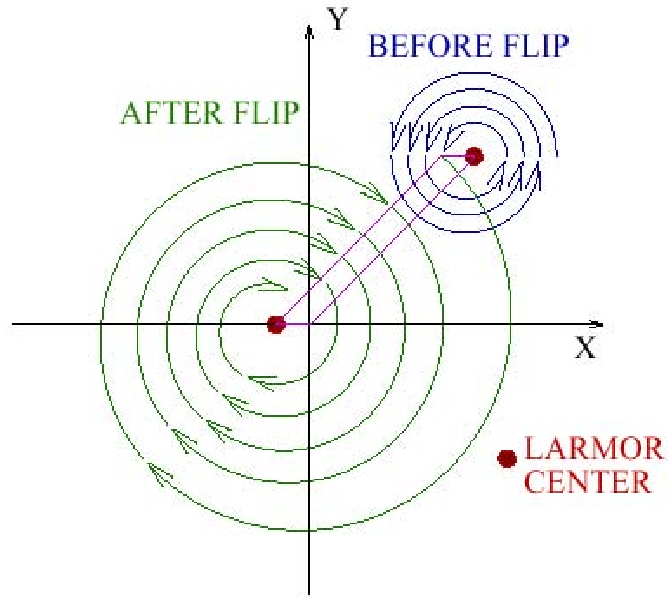
V. Balbekov & D. Elvira (FNAL)

- To get low β $\rightarrow$ big S/C solenoids & high fields!







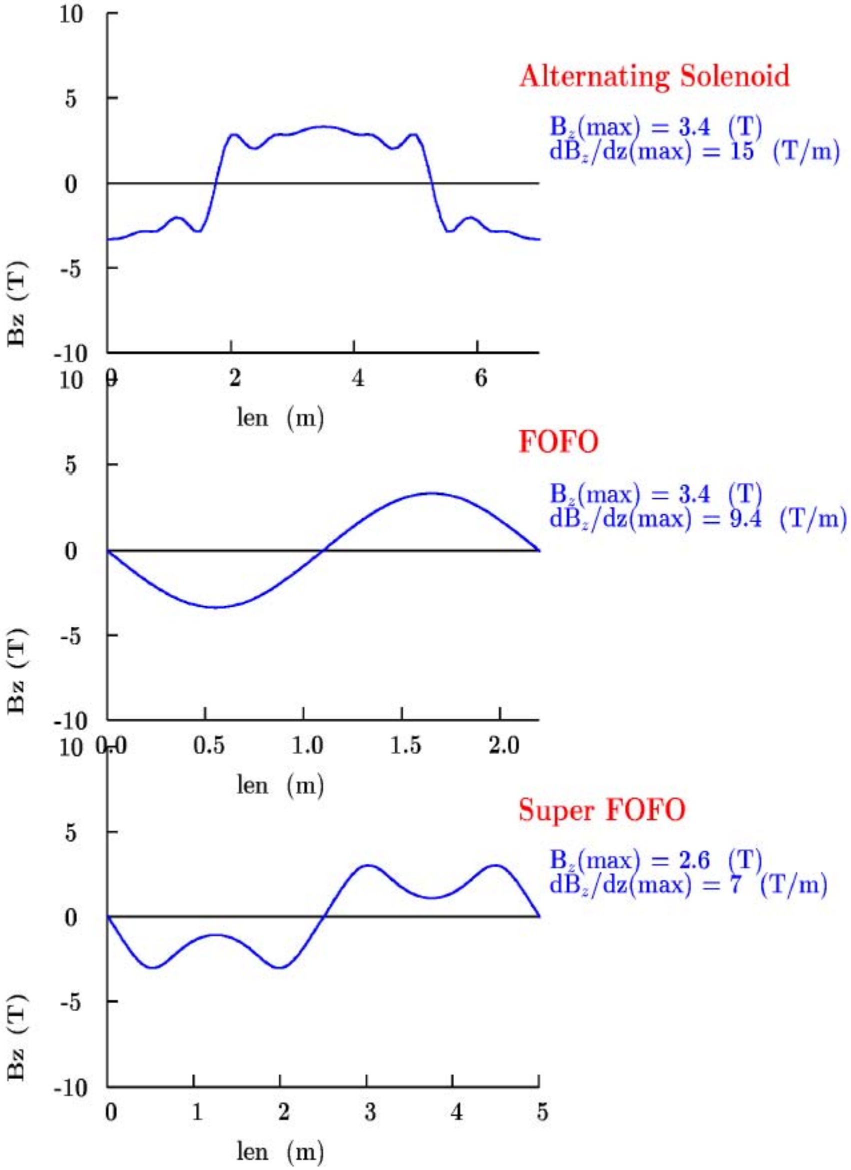


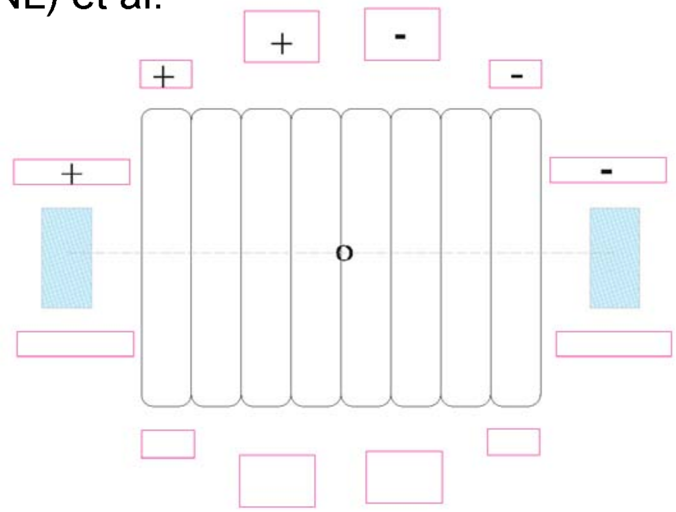
$\Rightarrow$ expensive

Or, Periodic Cooling Lattices

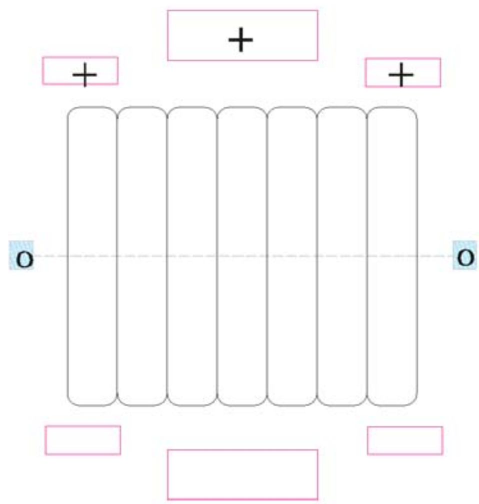
R. Palmer (BNL) et al.

- Various lattice designs have been studied:

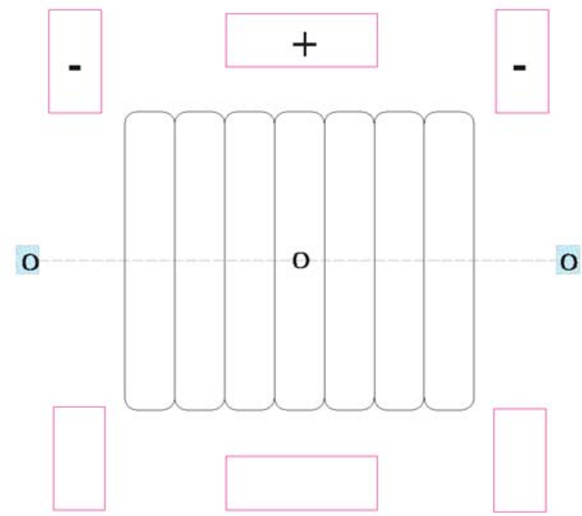




Alternating solenoid



FOFO



Super-FOFO

(+ RFOFO, DFOFO, Single-Flip, Double-Flip)

→ Alternating gradient allows low β with much less superconductor

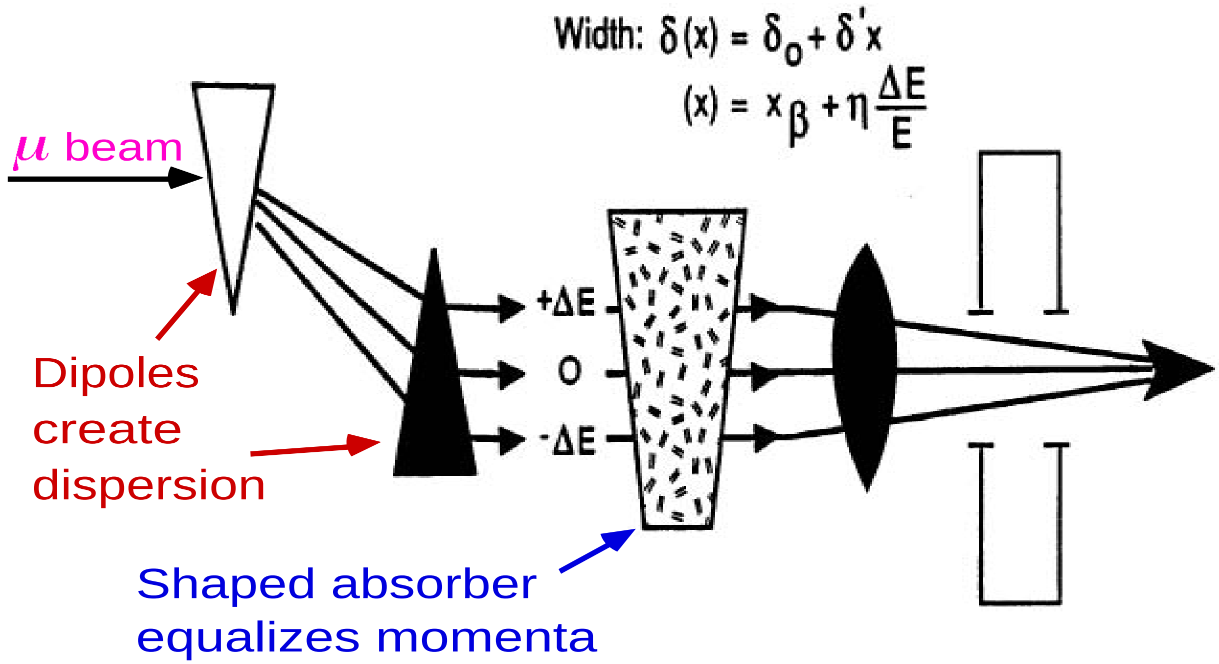
Longitudinal Cooling?

- 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 νF

- 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

$\Rightarrow$ affordable piece of SFOFO channel gives only $\approx$10% emittance reduction

- But standard beam instrumentation can measure emittance to only $\approx$10%

Practical Difficulty:

- Cooling channels are expensive

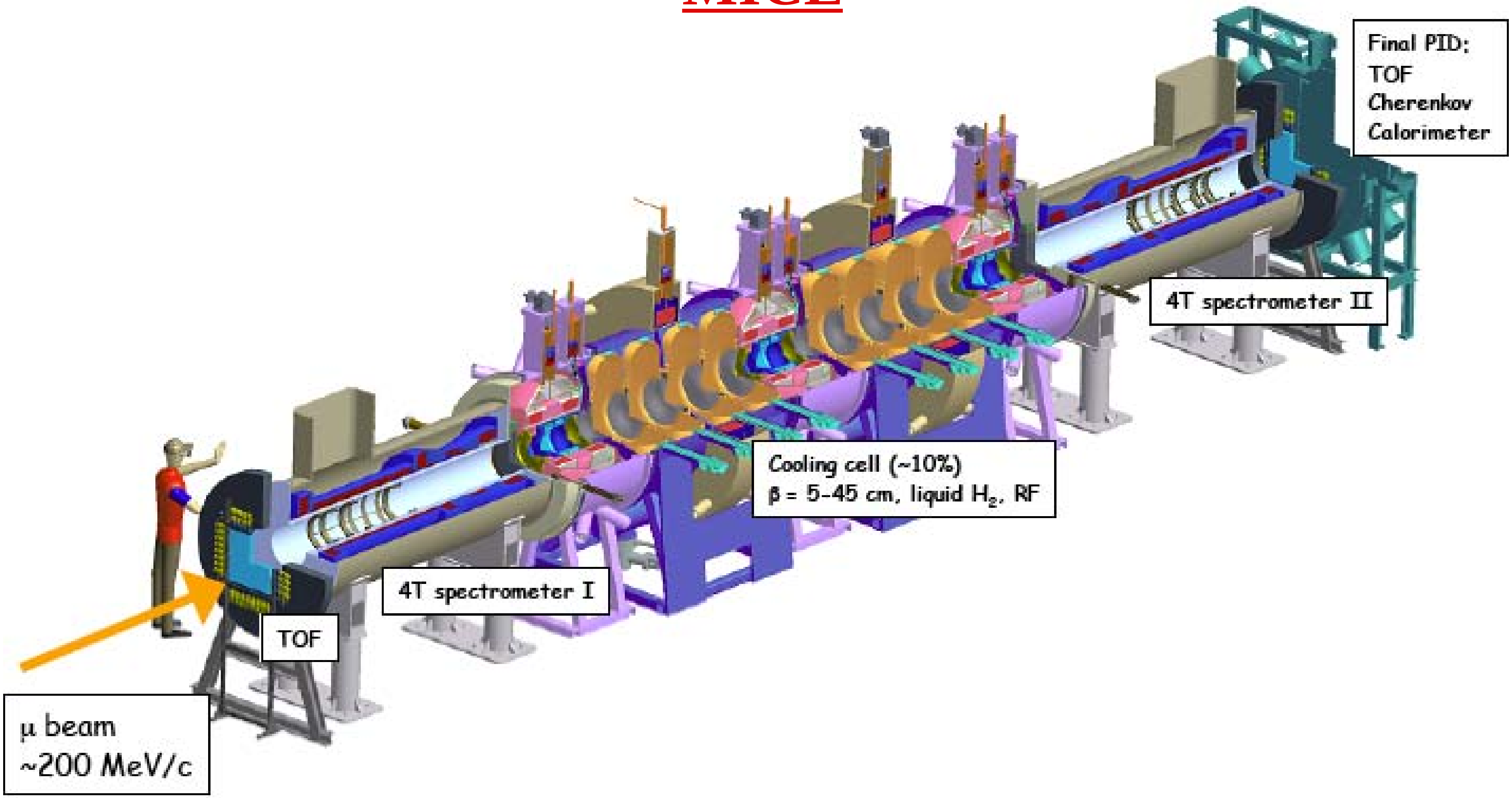
$\Rightarrow$ affordable piece of SFOFO channel gives only ≈10% emittance reduction

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

Solution:

Measure the beam one muon at a time!

MICE



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)
INFN Napoli e Università Federico II (V. Palladino)
INFN 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)
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)
Cockcroft Institute (R. Seviour)
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)
University of Oxford (W. W. M. Allison, G. Barr, U. Bravar, J. Cobb, S. Cooper, S. Holmes, H. Jones, W. Lau, H. Witte, S. Yang)
Daresbury Laboratory (P. Corlett, A. Moss, J. Orrett)
Rutherford Appleton Laboratory (D. E. Baynham, D. Bellenger, T. W. Bradshaw, R. Church, P. Drumm, R. Edgecock, I. Gardner, Y.M. Ivanyushenkov, A. Jones, H. Jones, R. Mannix, A. Morris, W.J. Murray, P.R. Norton, J.H. Rochford, K. Tilley, A. Weber)
University of Sheffield (C. N. Booth, P. Hodgson, L. Howlett, P. Smith)

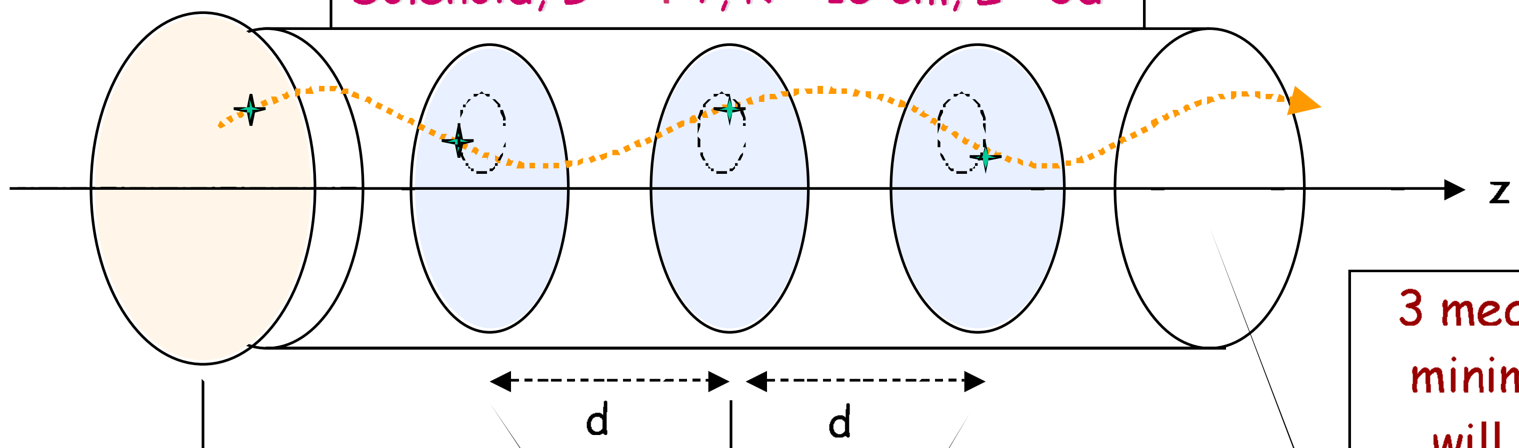
USA: Argonne National Laboratory (J. Norem)
Brookhaven National Laboratory (R. B. Palmer, R. Fernow, J. Gallardo, H. Kirk)
Fairfield University (D. R. Winn)
University of Chicago and Enrico Fermi Institute (M. Oreglia)
Fermilab (A. D. Bross, S. Geer, D. Neuffer, A. Moretti, M. Popovic, R. Raja, R. Stefanski, 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 $\sigma_t \sim 70$ ps

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 0.35mm/√12

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

Extrapolate x, y, t, p_x, p_y, p_z, at entrance of the channel. Make it symmetric at exit.

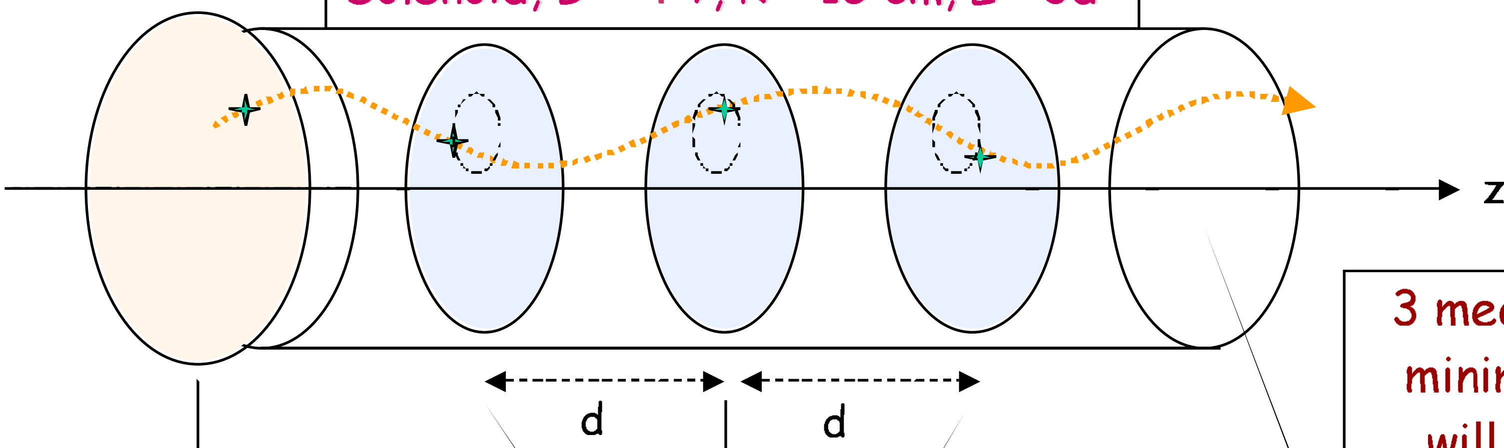
Single-Particle Emittance Measurement

- **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 σ_t ~ 70 ps

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 0.35mm/√12

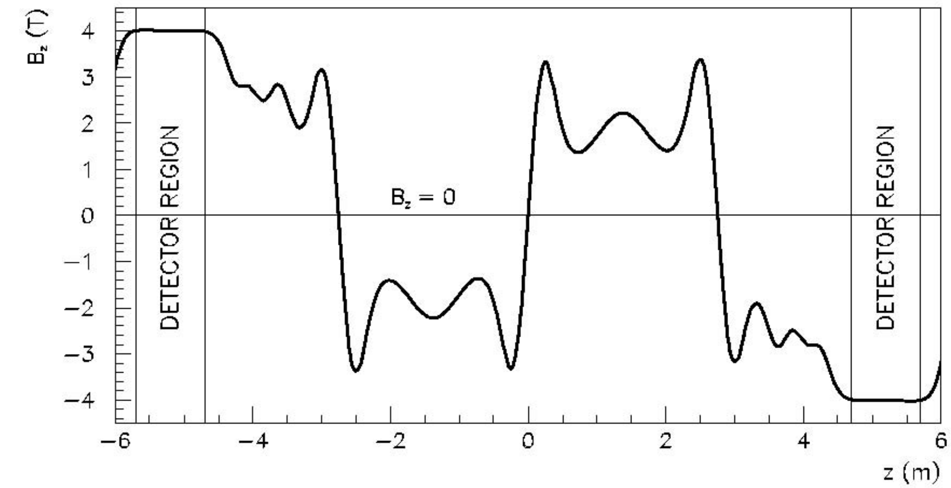
3 measurements is minimal set but 5 will be used for pattern-recognition redundancy

Extrapolate x,y,t,p_x,p_y,p_z,
at entrance of the channel.
Make it symmetric at exit.

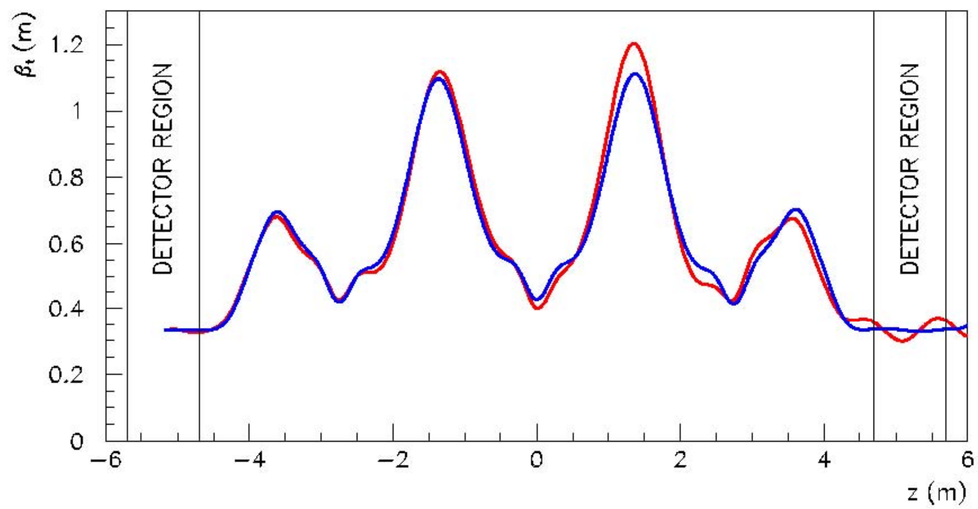
...but mux’ing readout by 7 gives suff. resolution and reduces cost

Nominal ("SFOFO") Lattice (200 MeV/*c*)

- B_z vs. z:



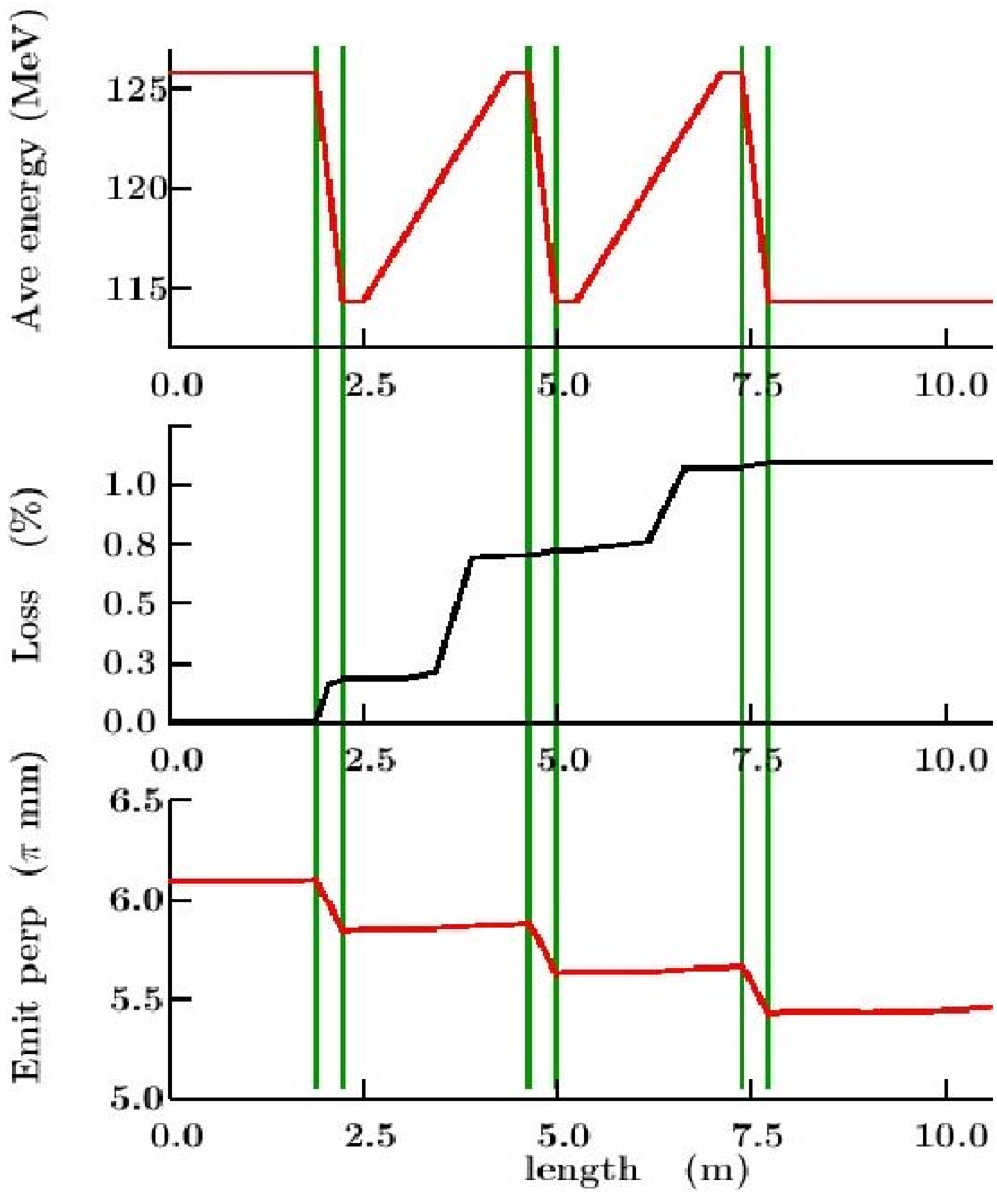
- β_t vs. z:

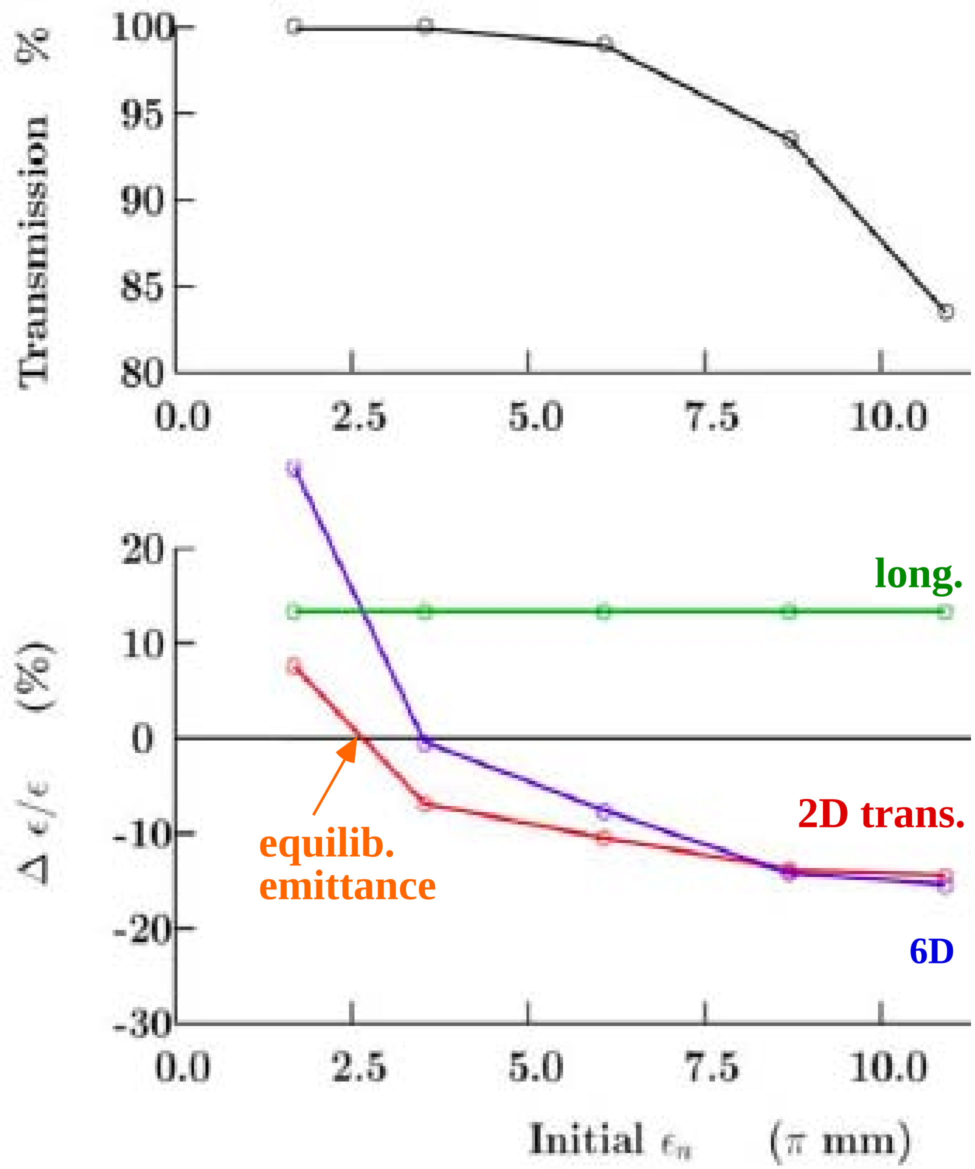


- ∃ flexibility to explore other settings, momenta, absorber mat'ls...

Performance Simulation (nominal SFOFO mode):

(BNL ICOOL simulation)



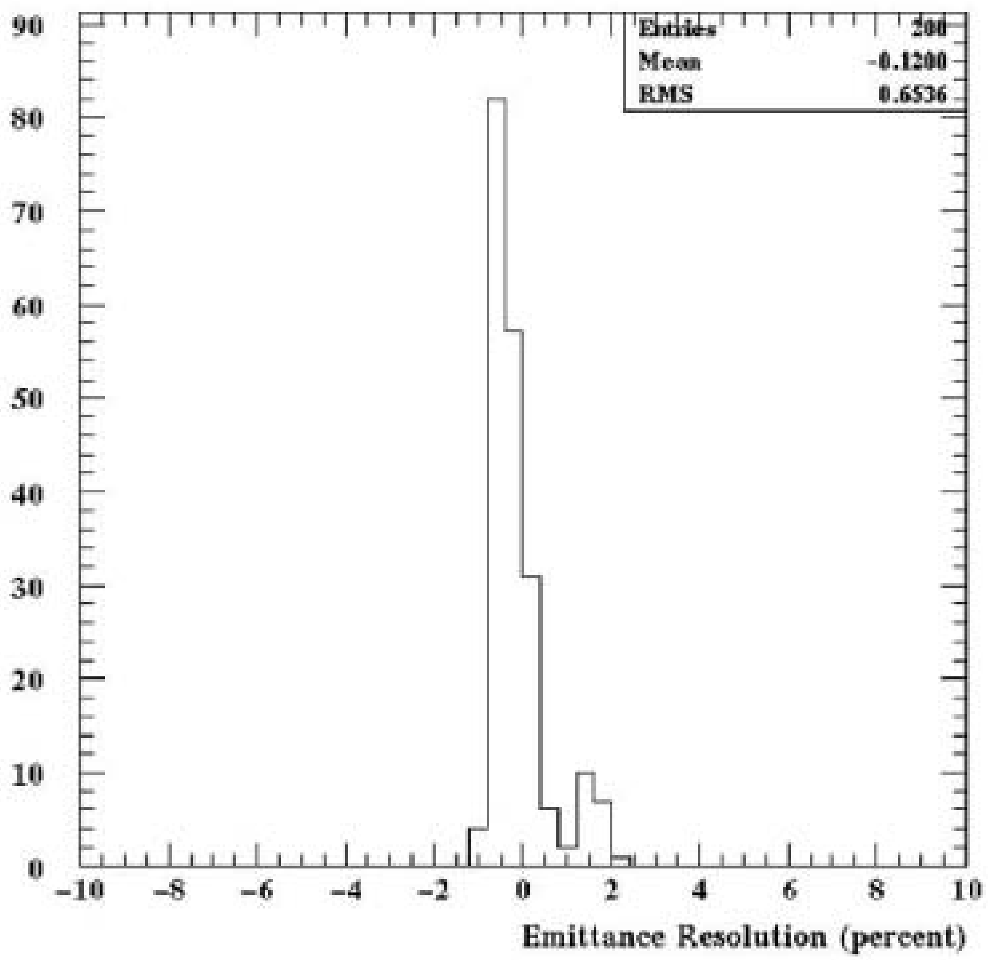


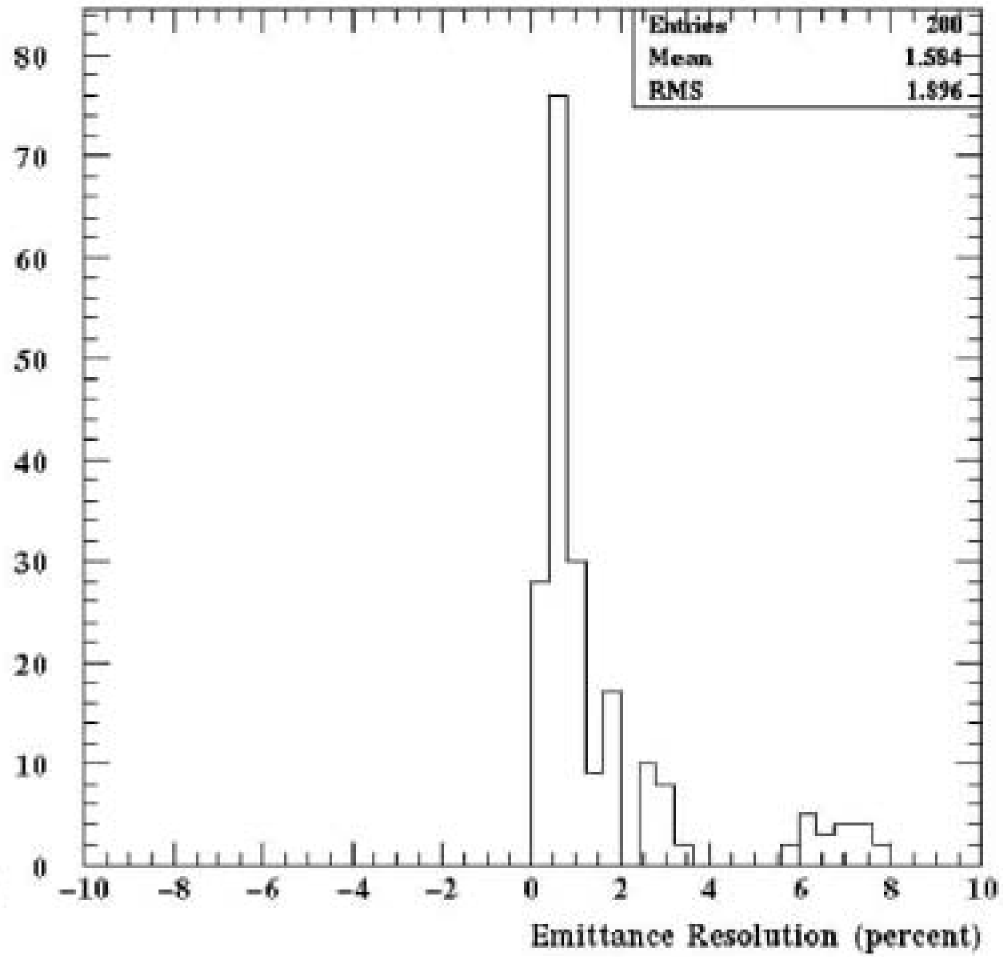
→≈10% transverse emittance reduction, measurable to 0.1% (abs.) given precise spectrometer, clean beam, and efficient, redundant particle ID

Tracker Performance Simulation:

(C. Rogers, ICL G4MICE simulation)

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

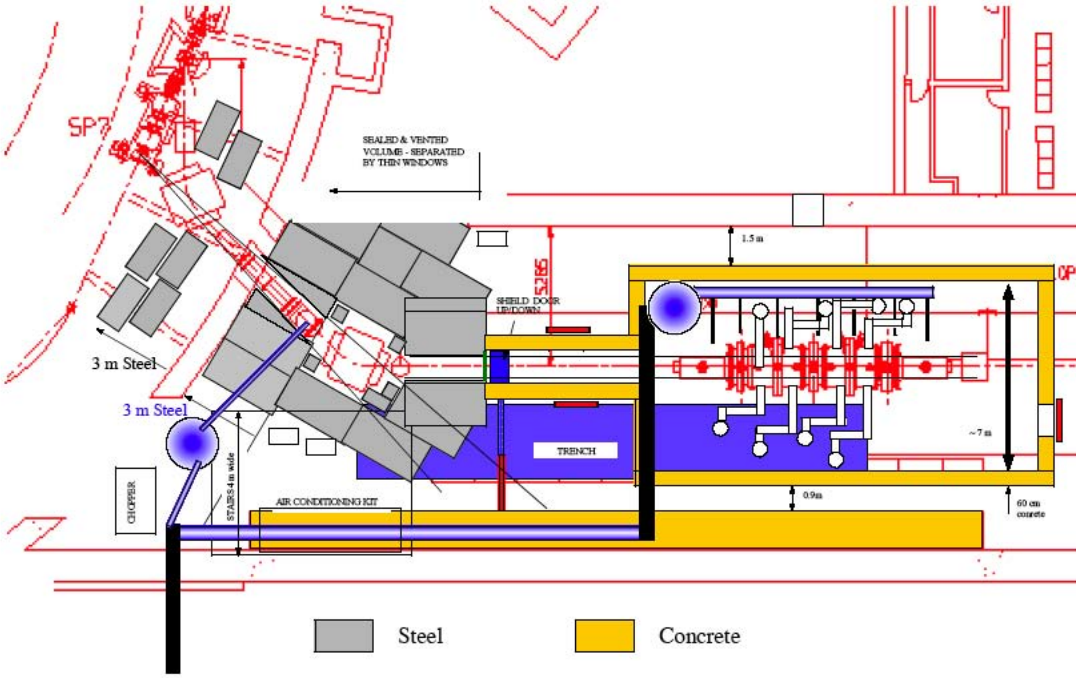




- Key physics goal of “MICE Phase 1”:
  - demonstrate bias correction to <10% of itself as req’d for 0.1% emittance measurement

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:

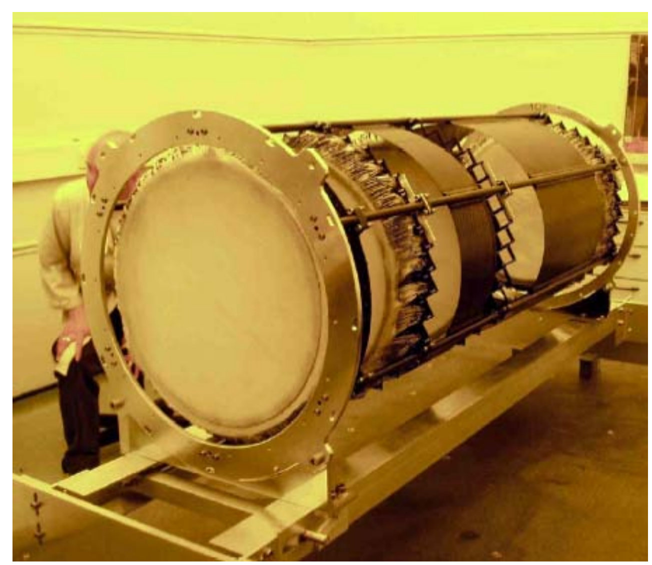


Beamline includes:

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

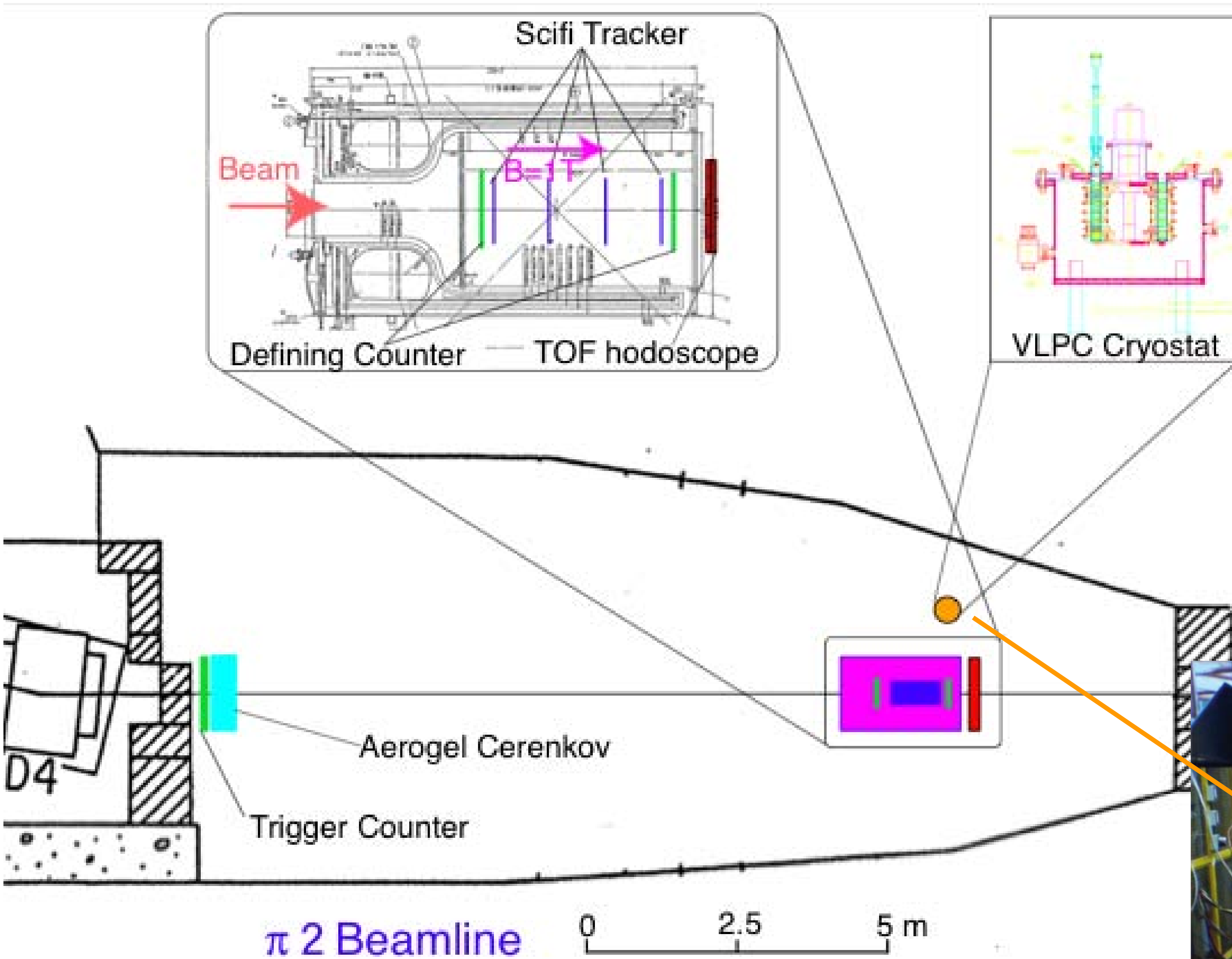


- Plan: 1st MICE beam at RAL 9/07

Some Recent Progress: SciFi Tracker Test at KEK

(KEK / Osaka / UK / FNAL / IIT / UCR / UCLA)

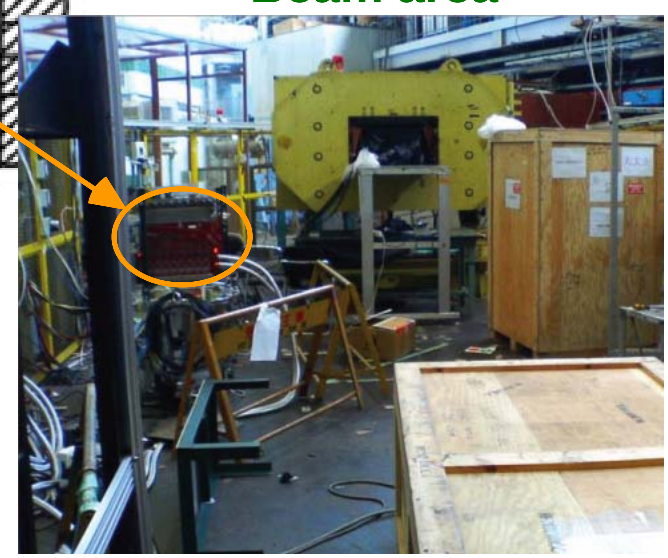
- 4-station prototype tested in 1T SC solenoid:



Tracker prototype

Electronics area

Beam area

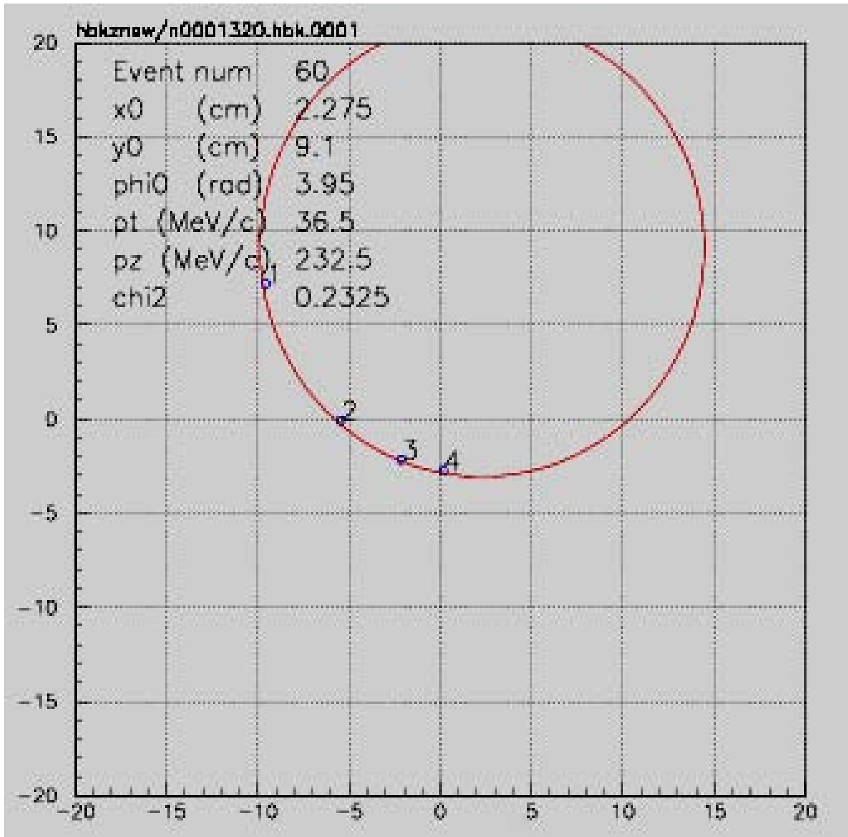


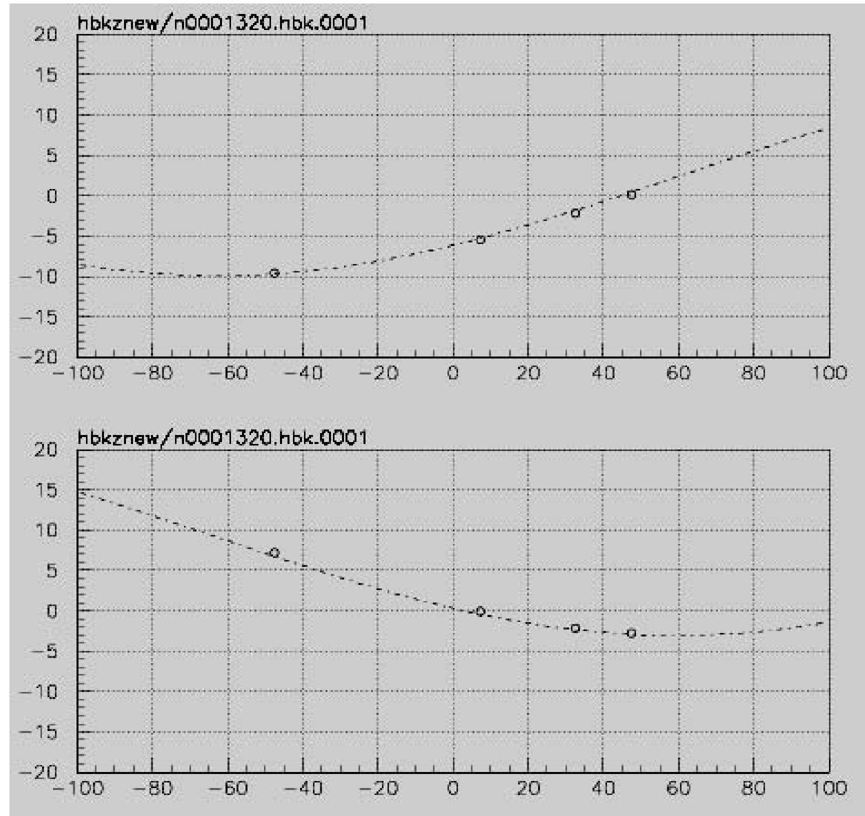
(already passed cosmic-ray test)

- Successful beam test fall 2005

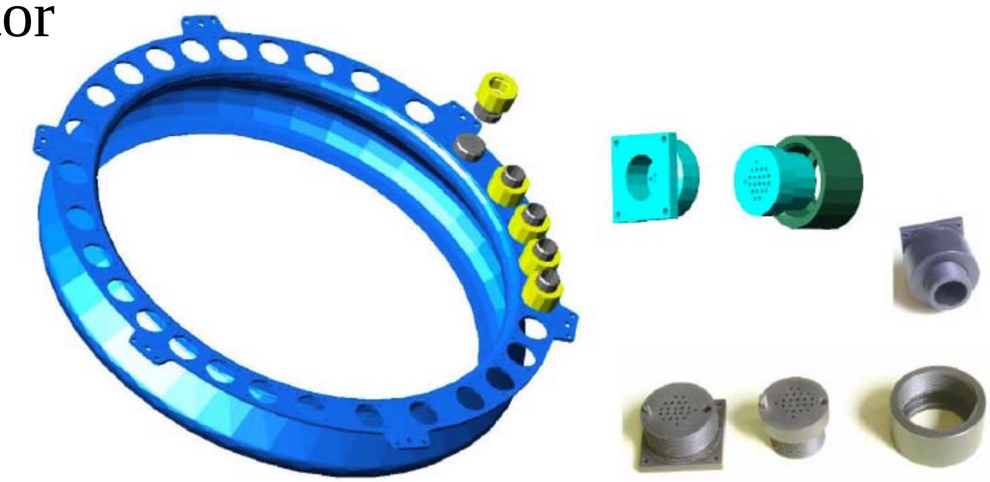
Some Recent Progress: SciFi Tracker Test at KEK

Reconstructed event:





- Prototype plane with latest connector design showed lower light yield
  - study & possible design iteration in progress

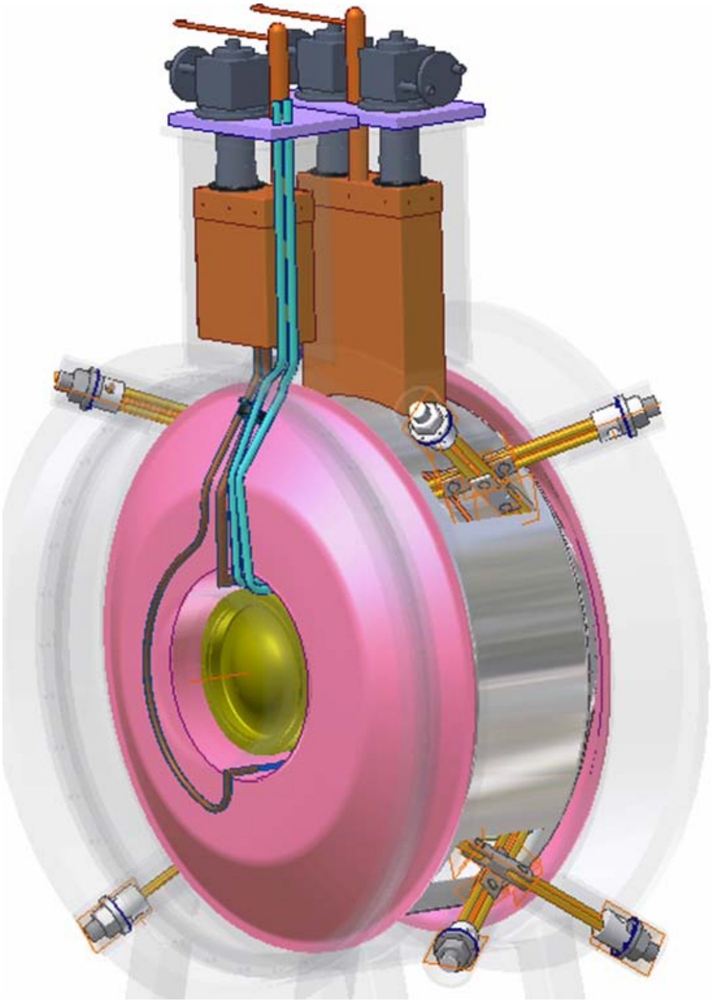


Absorber Design

(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)



MICE low-power design (cryocooler-cooled)

  - also much work on hydrogen safety

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

@ LBNL

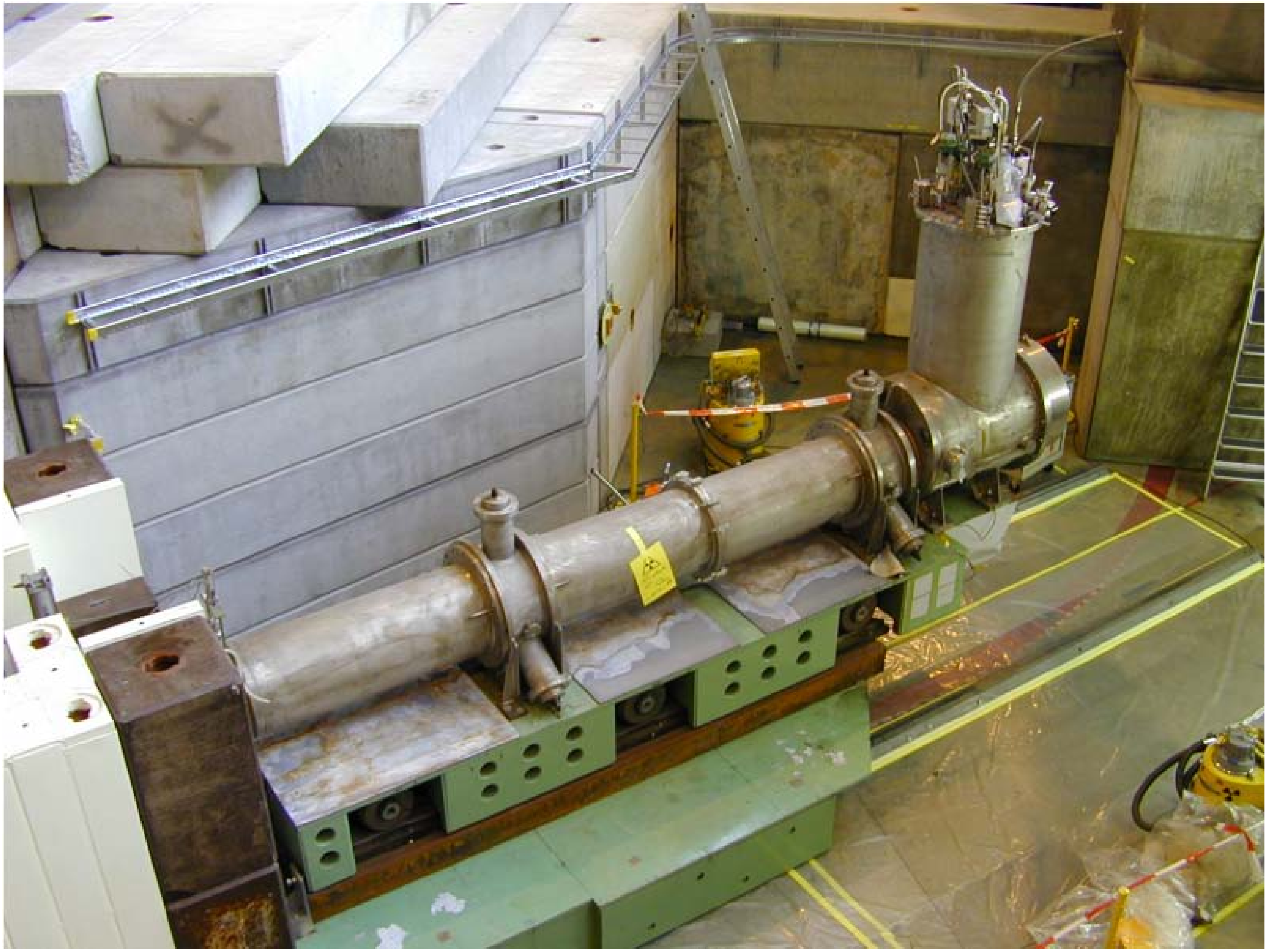
@ DL

- 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 π-decay solenoid from PSI

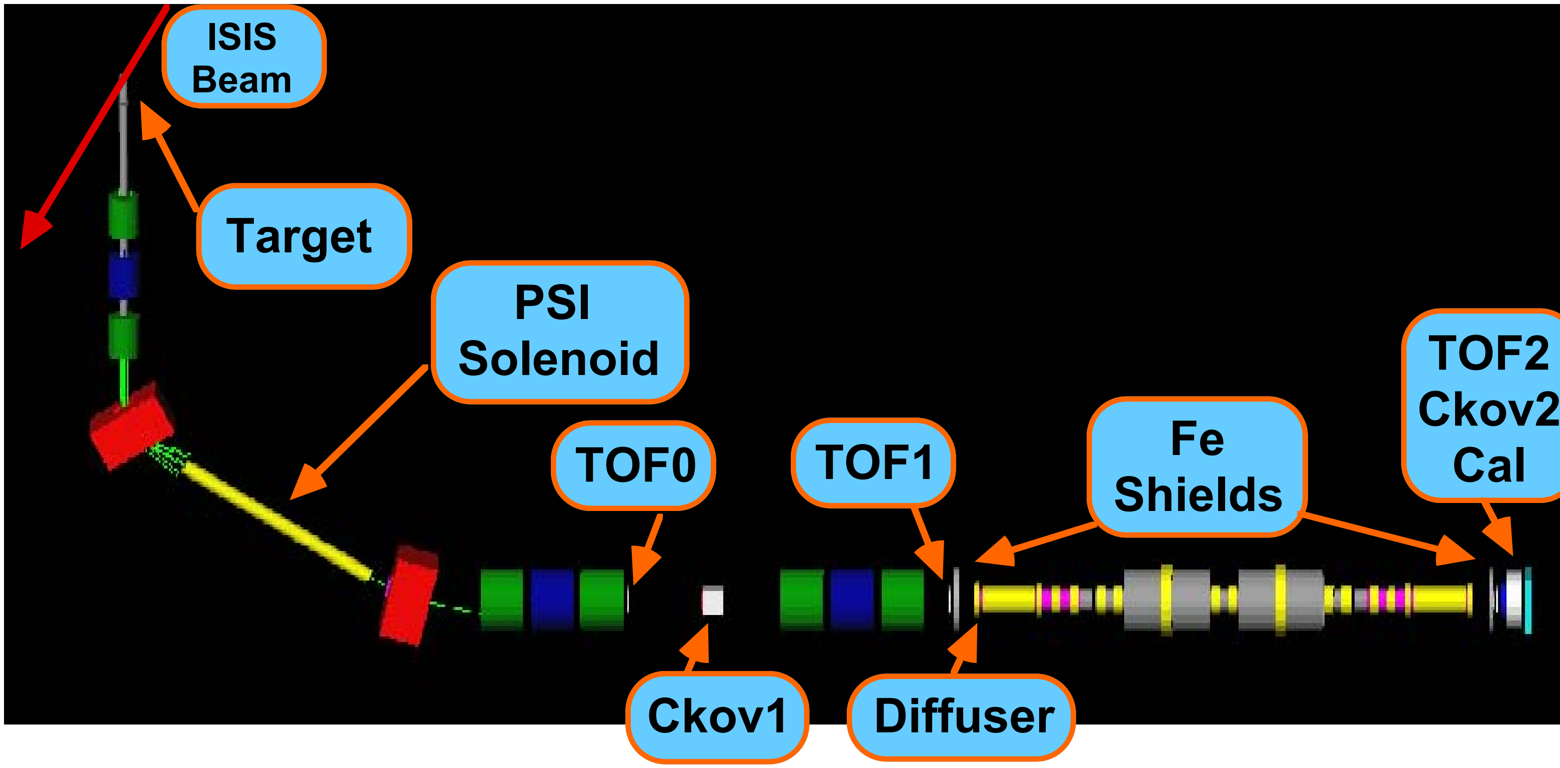


- Gives x10 increase in μ rate comp. to quads
- Delivered to RAL in Dec., 2005

Beamline Simulation

(T. Roberts, Muons, Inc.)

- Using T. Roberts-developed “g4beamline” to simulate MICE beam:



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

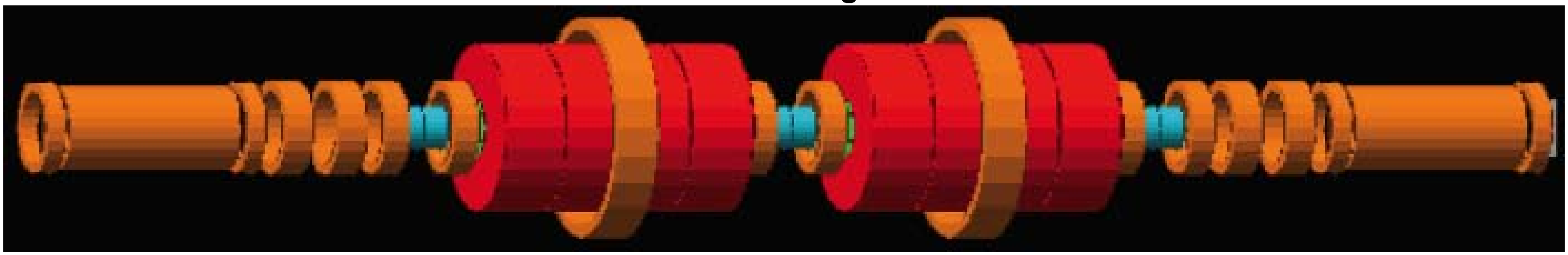
Description	LAHET	Geant4	MARS
1mm x 100mm, 10m from target			33,400
TOF0	2355	2693	2834
TOF1	462	529	557
Tracker1	422	482	507
Tracker2	284	324	342
TOF2	281	321	338
Good μ^+	277	316	333

G4MICE Experiment Simulation

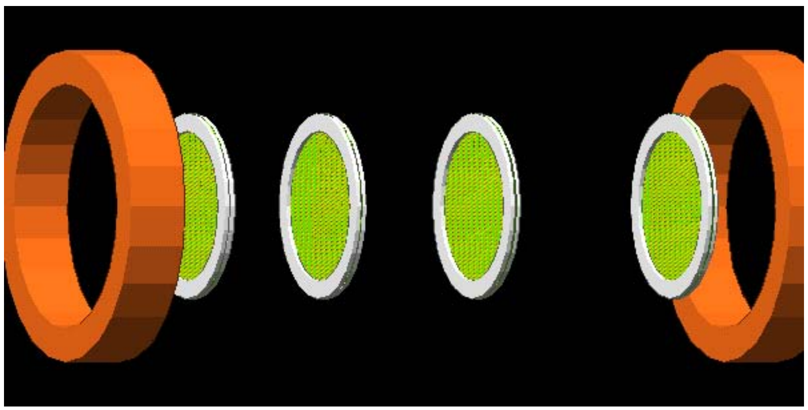
(FNAL / IIT / BNL / Geneva / ICL / UCR et al.)

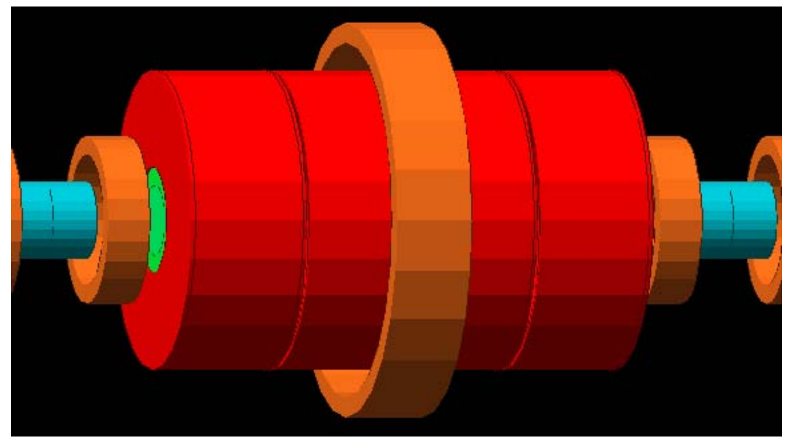
- Under development by int'l team led by Y. Torun, IIT & M. Ellis, FNAL

Screen shot of the magnetic lattice:



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



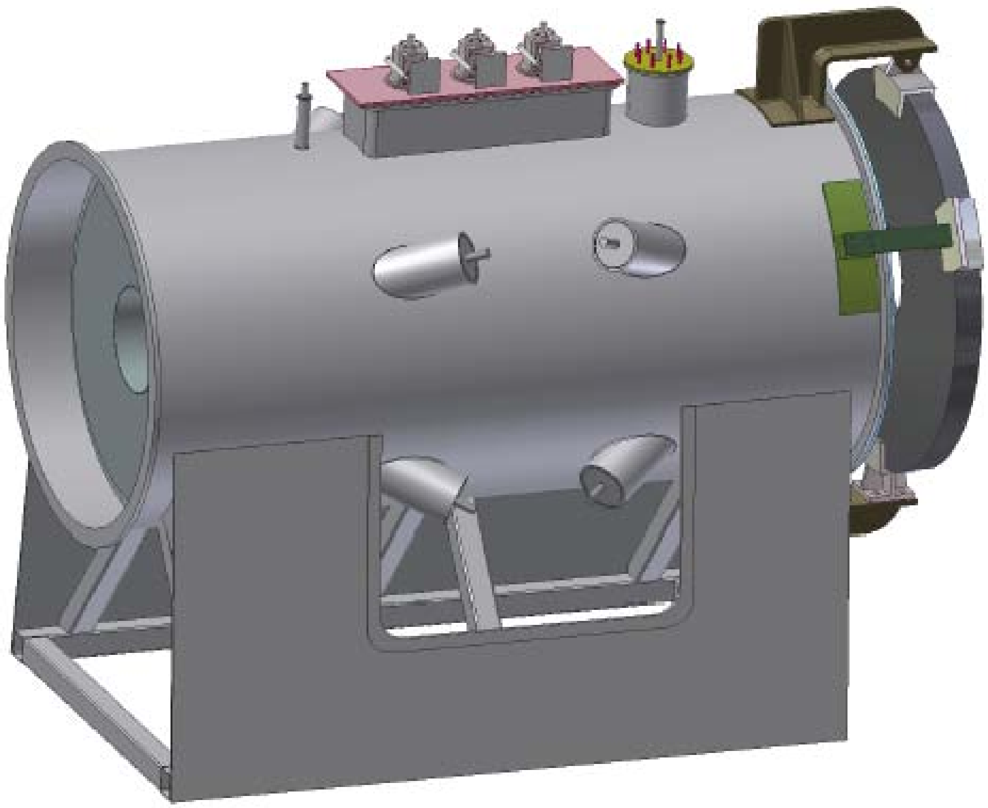


Cooling 1/2-cell: two absorbers (blue), three coils (brown), two focusing and one coupling, and four rf cavities (red)

- 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)

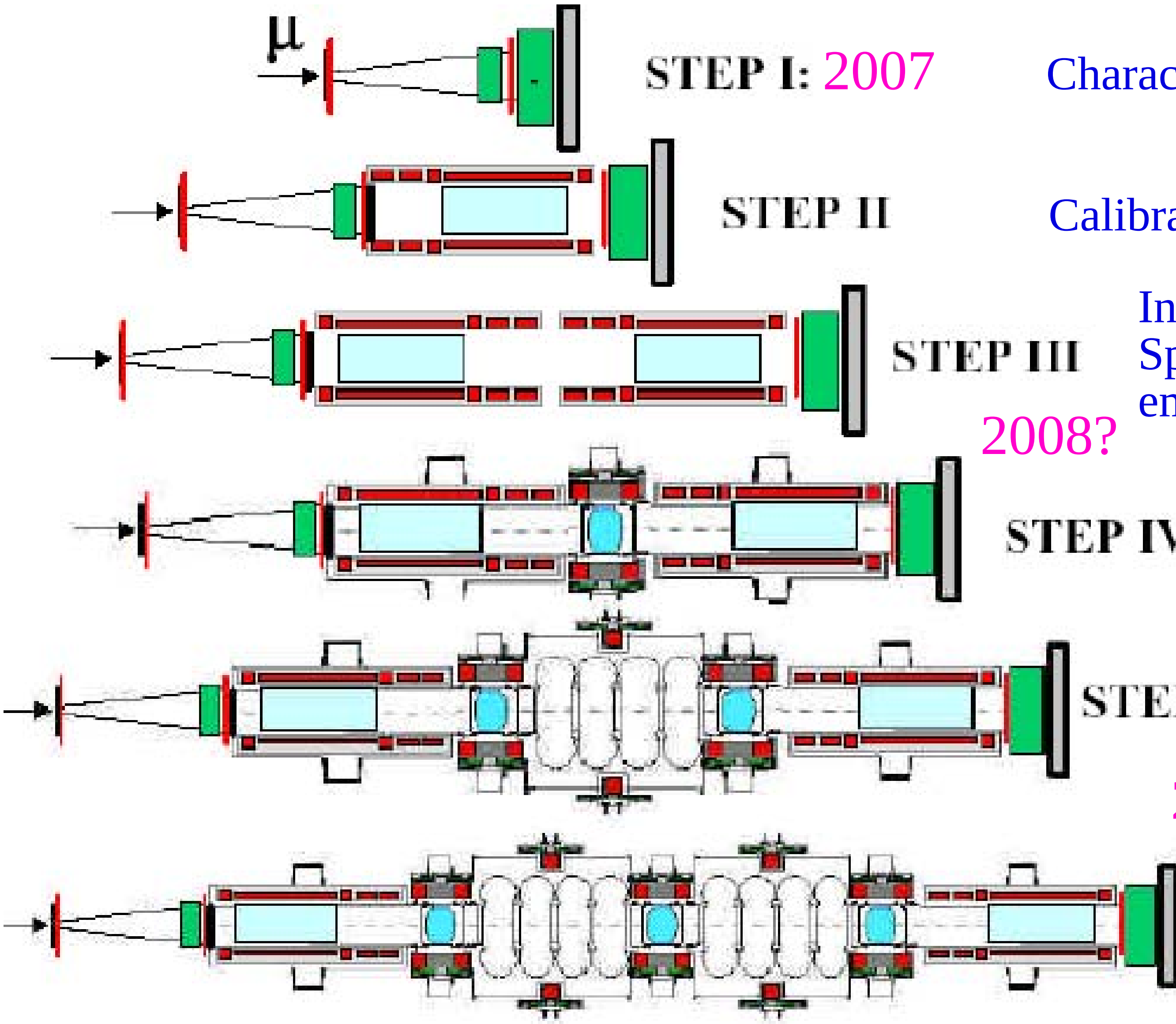
More Progress

- Work also proceding 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

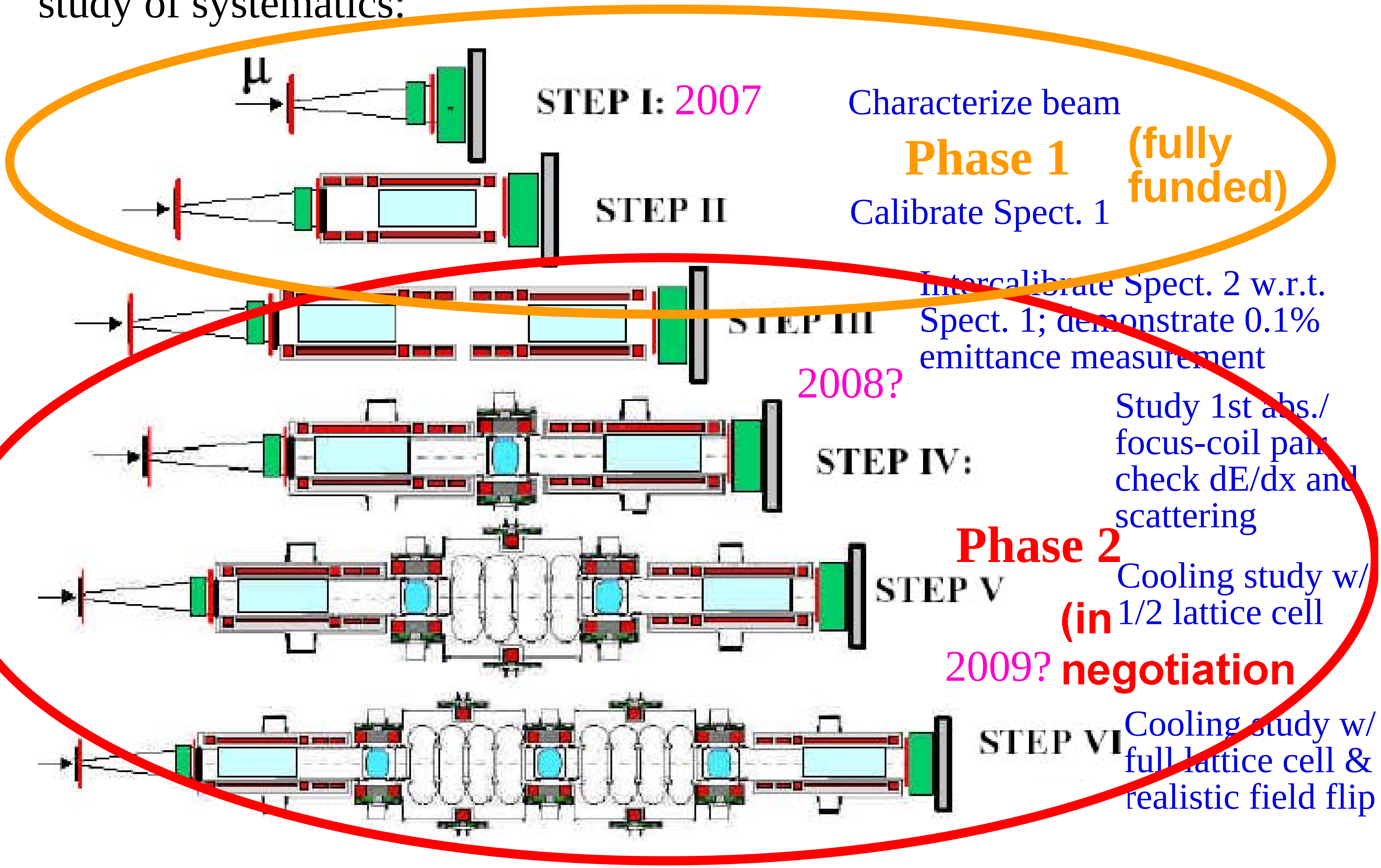
STEP V — Cooling study w/ 1/2 lattice cell

2009?

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:



Muon Facility Feasibility Demonstrations:

1. Transverse ionization cooling: MICE @ RAL ISIS synchrotron

2. Multi-MW targets: MERIT @ CERN *n*TOF facility

3. 6D helical cooling: MANX proposal

4. Non-scaling FFAG acceleration: EMMA @ DL

Muon Facility Feasibility Demonstrations:

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

Muon Facility Feasibility Demonstrations:

1. Transverse ionization cooling: MICE @ RAL ISIS synchrotron √

2. Multi-MW targets: MERIT @ CERN *n*TOF facility

3. 6D helical cooling: MANX proposal ←

4. Non-scaling FFAG acceleration: EMMA @ DL

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

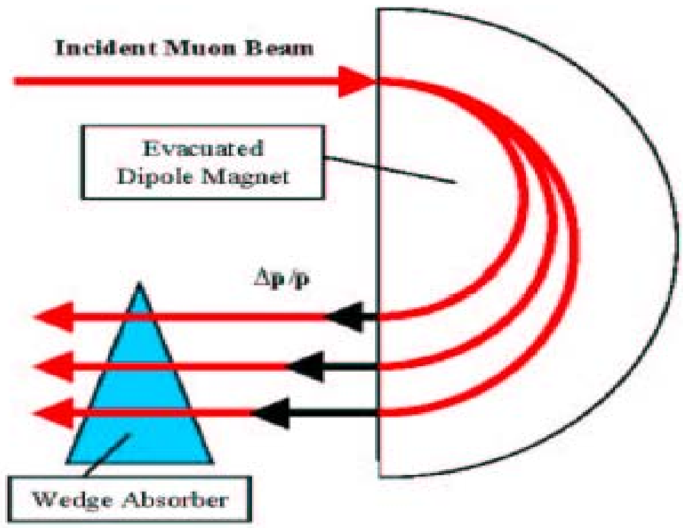


Figure 1. Use of a Wedge Absorber for Emittance Exchange

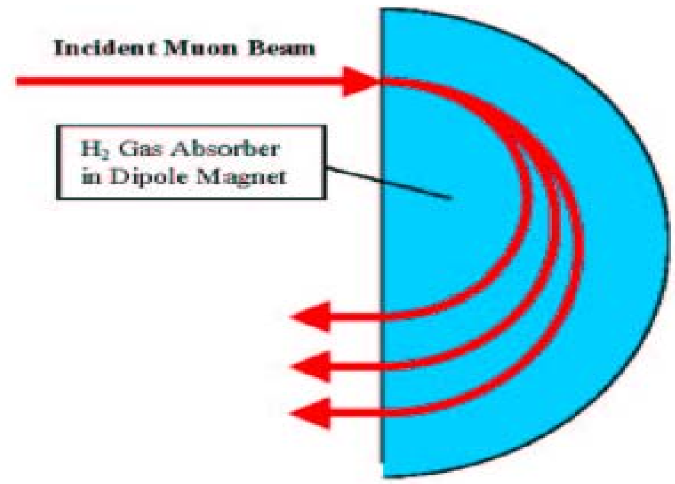
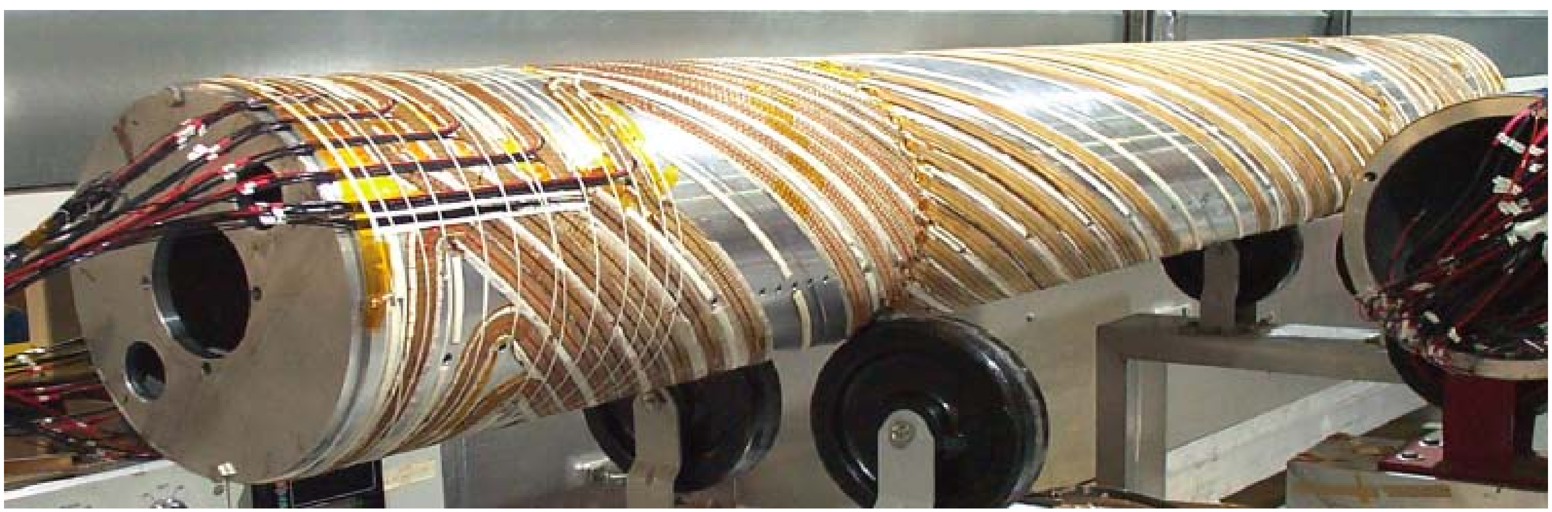


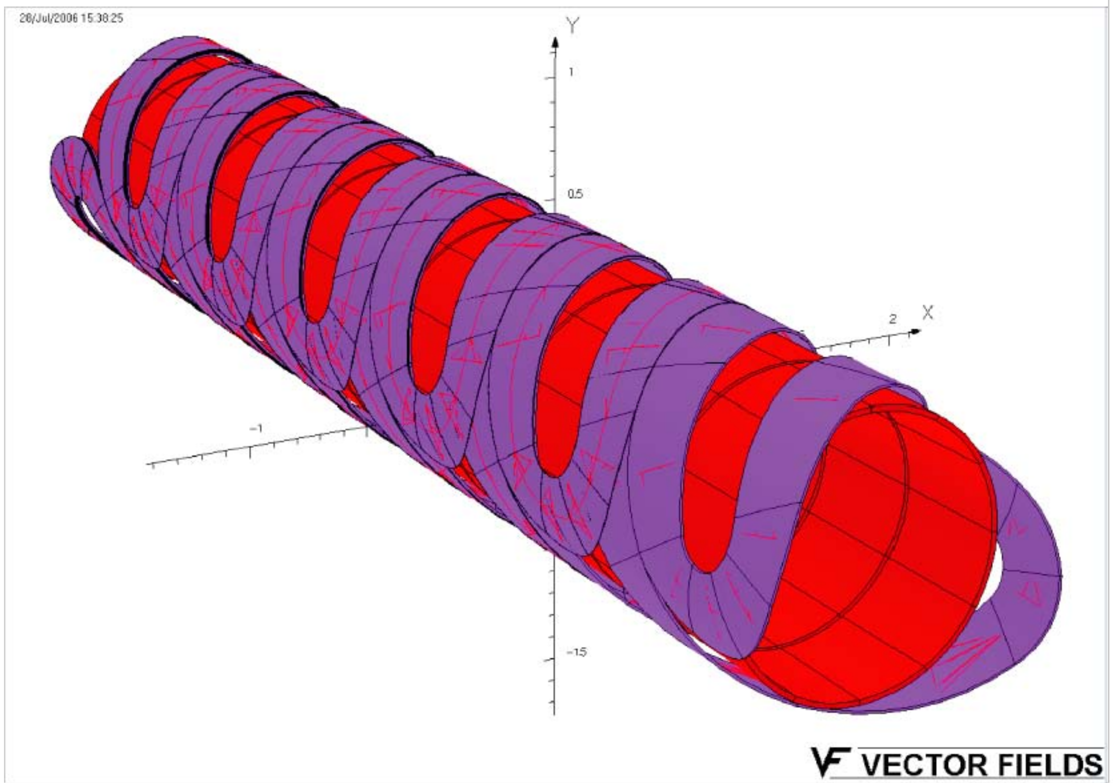
Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

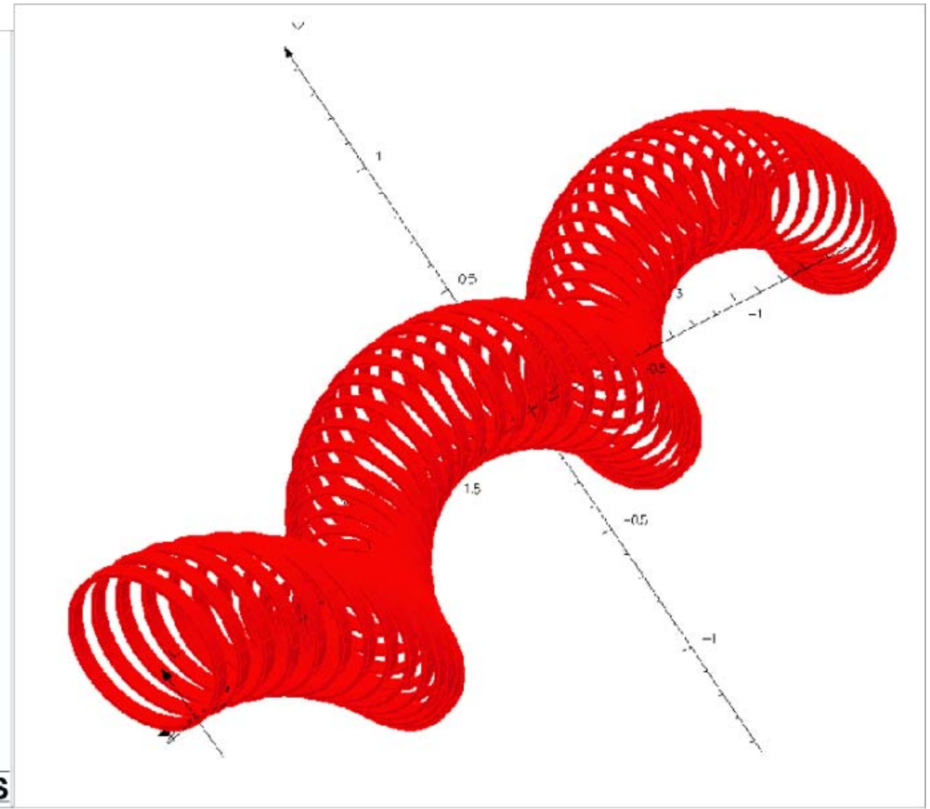


Example helical rotating-dipole magnet from AGS “Siberian Snake”

Helical Cooling Channels

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





→ Small coils could reduce difficulty and cost

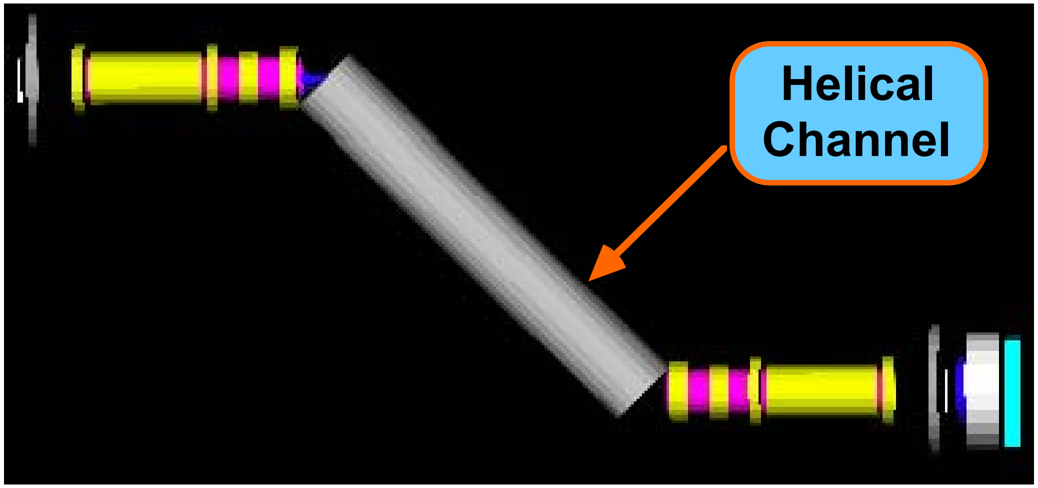
Helical Cooling Channels

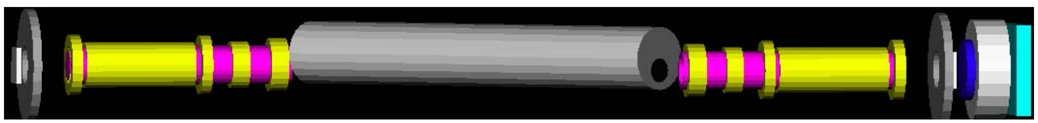
- Possible to test prototype 6D cooler in MICE facility → “MANX”?
  - or with new muon beam at Fermilab?

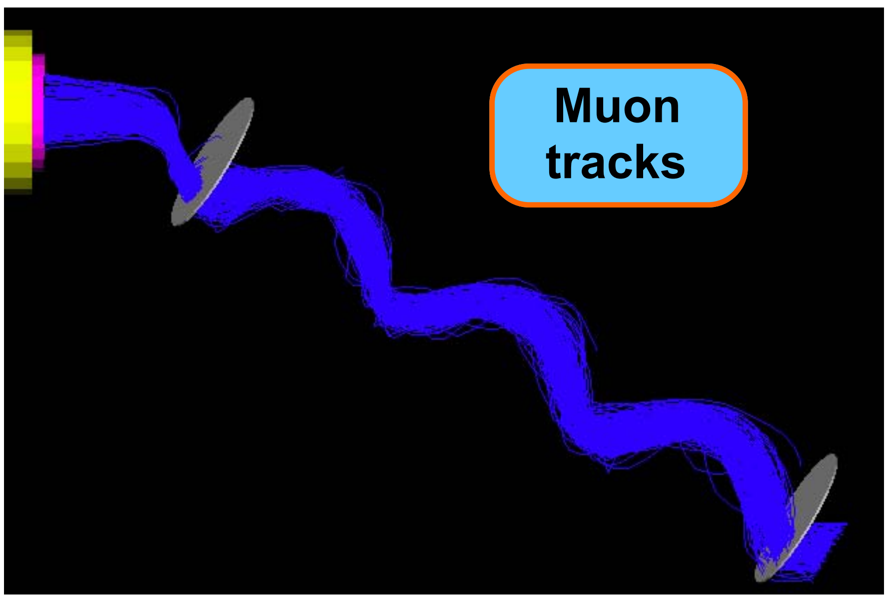
Muon collider And Neutrino factory eXperiment

MANX Letter of Intent

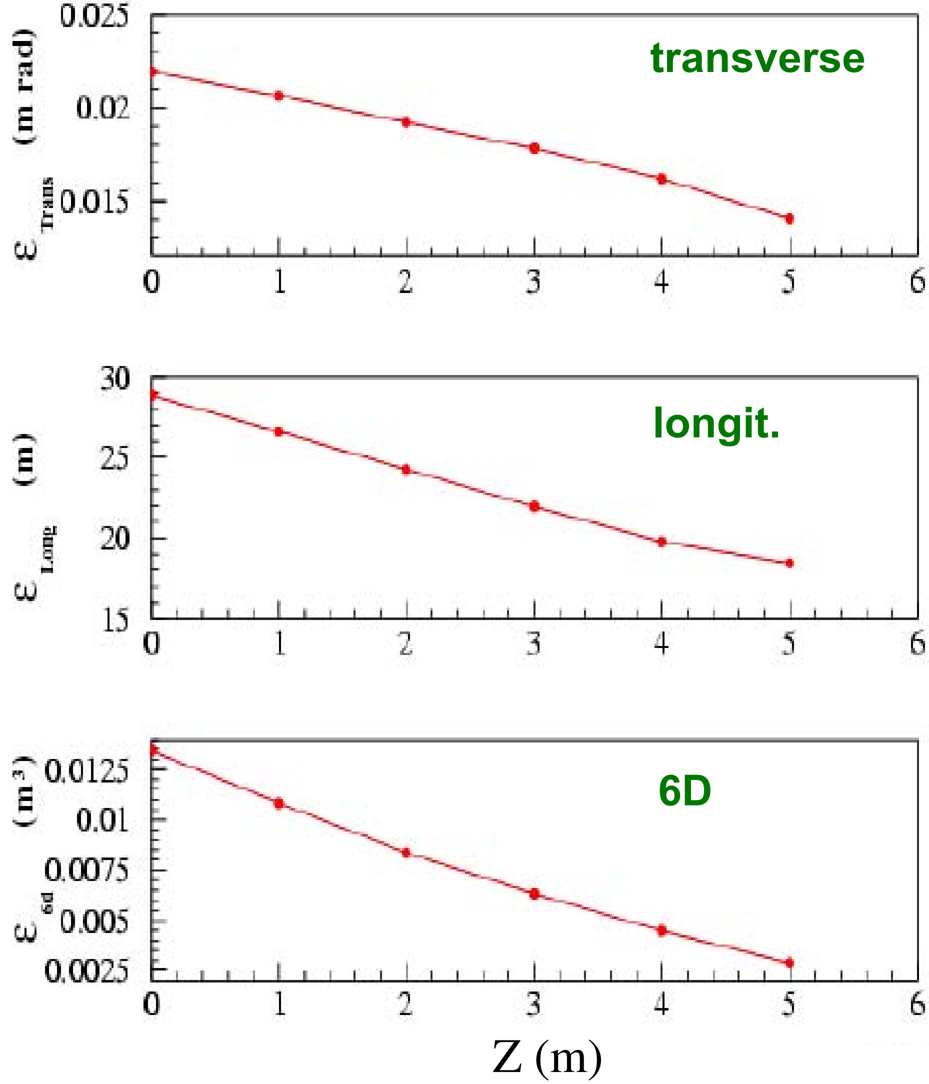
(Muons, Inc.)







Simulated cooling performance



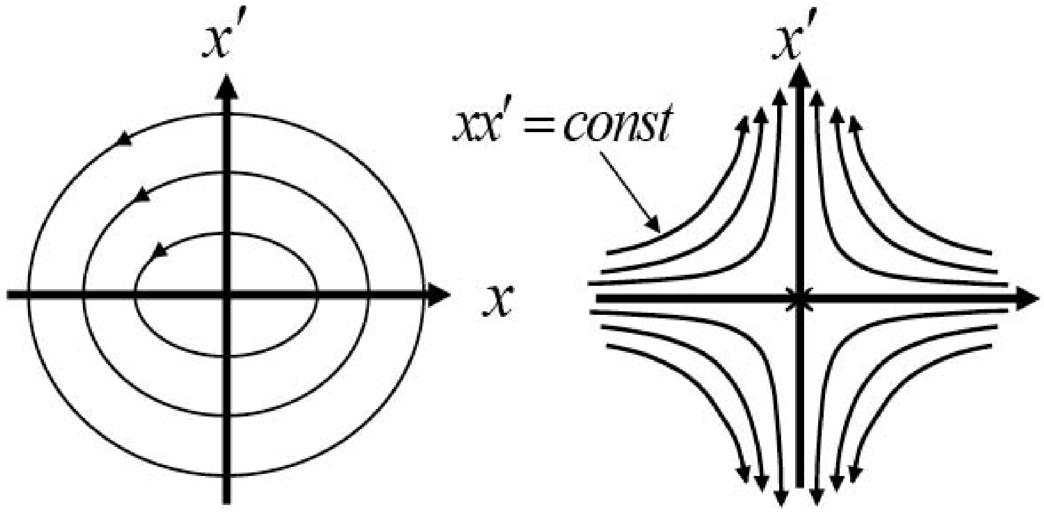
- Factor ≈3–5 in a few m of cooling channel!

- Proposal to Fermilab to design and build helical magnet (May, 2006)

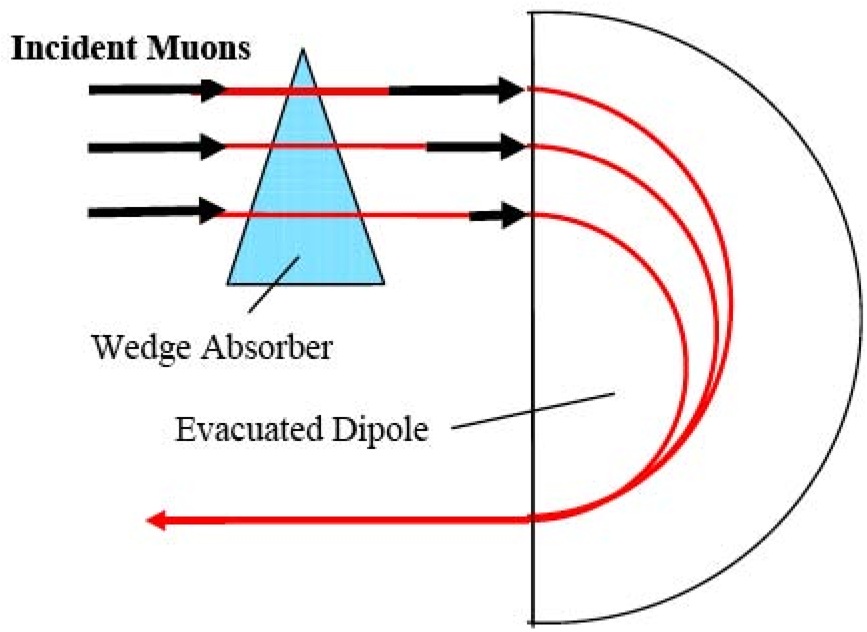
“Extreme Cooling”?

Ya. Derbenev (JLab)

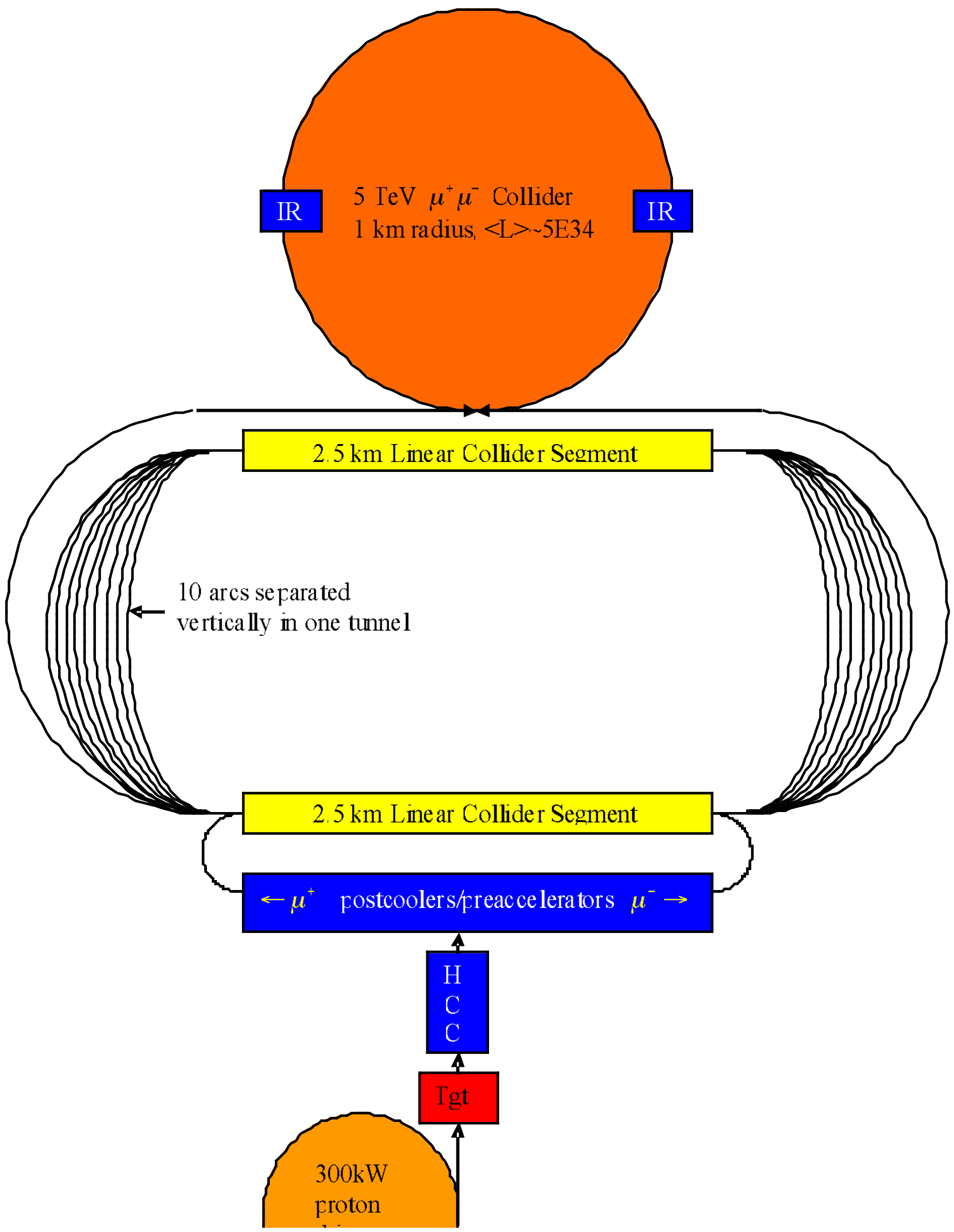
- After cooling × ~10^5 by series of helical channels (~10^2 m), can cool beam further with 2 new approaches:
  - Parametric-resonance Ionization Cooling (PIC)



  - 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, ~10^2 people) funded by DOE at few-M$/year level

  – ~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:

NFMCC home page: `http://www.cap.bnl.gov/mumu/mu_home_page.html`

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

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

Muon Ionization Cooling R&D home page:
`http://www.fnal.gov/projects/muon_collider/cool/cool.html`

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

EMMA home page: `http://hepunx.rl.ac.uk/uknf/wp1/emodel/`

Princeton Muon Collider R&D home page: `http://www.hep.princeton.edu/mumu/`

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:

R. P. Johnson et al., "Recent innovations in muon beam cooling," AIP Conf. Proc. **821**, 405 (2006).

"The Neutrino Matrix," the final report of the APS Multi-Divisional Study, available from `http://www.aps.org/neutrino/`

M. M. Alsharo'a et al., "Recent progress in neutrino factory and muon collider research within the Muon Collaboration," Phys. Rev. ST Accel. Beams 6, 081001 (2003).

A. Blondel et al., ECFA / CERN Studies of a European Neutrino Factory Complex, CERN-2004-002, ECFA-04-230.

Feasibility Study-II of a Muon-Based Neutrino Source, ed. S. Ozaki, R. Palmer, M. Zisman, and J. Gallardo, BNL-52623 (2001); available from `http://www.cap.bnl.gov/mumu/studyii/FS2-report.html`

C. Albright et al., "Physics at a Neutrino Factory," hep-ex/0008064, Fermilab-FN-692 (2000).

S. Geer, "Neutrino beams from muon rings," Phys. Rev. D 57, 6989 (1998).

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

Some recent brief, "approachable" papers:

K. Long, "Neutrino Factory R&D," submitted to Proceedings of the High Intensity Frontier Workshop, La Biodola, Isola d'Elba, Italy, 28th May–1st June 2005; arXiv: physics/0510157

D. M. Kaplan, "Recent Progress Towards a Cost-effective Neutrino Factory Design," submitted to the Lepton-Photon Conference, Uppsala, Sweden, June 30–July 5, 2005; arXiv: physics/0507023

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
- Now gathering necessary resources (collaborators, equipment, funding) from among collaborating world regions, designing & building apparatus
- Good opportunity for students to develop expertise on "cutting-edge" accelerator physics as well as on HEP experimental techniques

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
- Now gathering necessary resources (collaborators, equipment, funding) from among collaborating world regions, designing & building apparatus
- Good opportunity for students to develop expertise on “cutting-edge” accelerator physics as well as on HEP experimental techniques

I believe muon accelerator facilities have a bright future!