Muon Cooling and Future Muon Facilities

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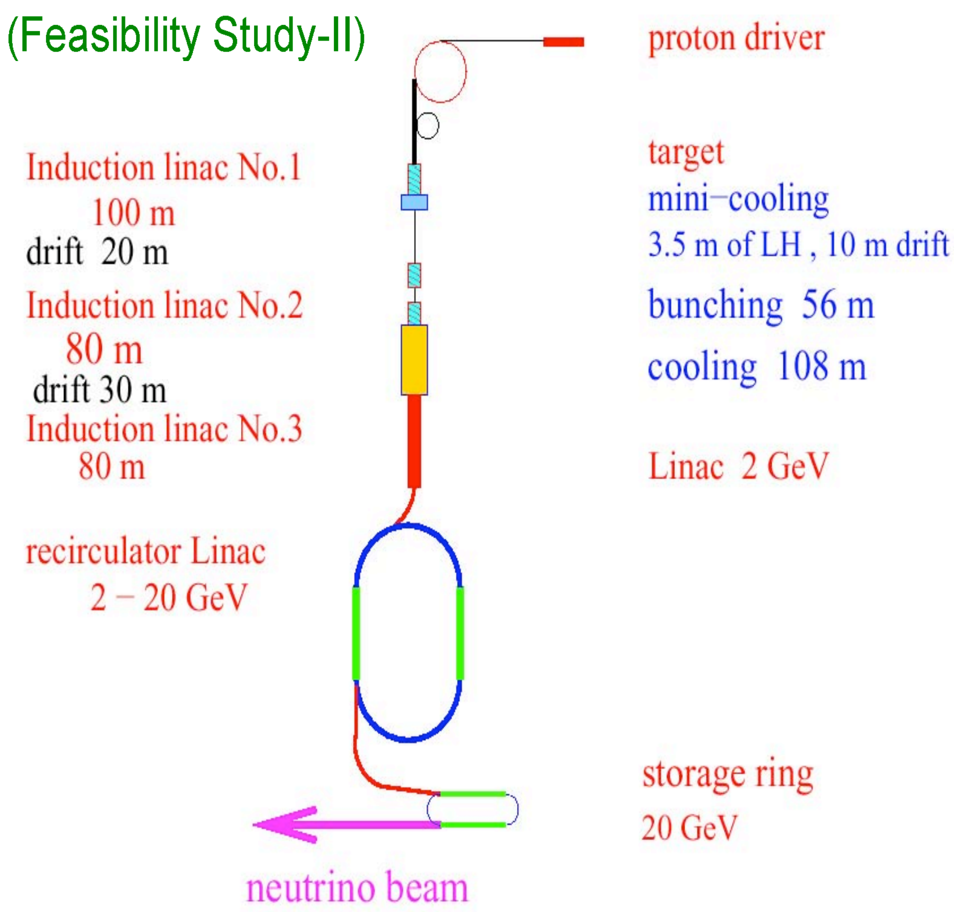
Outline:

- Muon Collider and Neutrino Factory: concepts
- Muon Collider and Neutrino Factory: physics
- Need for muon cooling
- Ionization cooling
- Ongoing R&D program
- Key-technology demonstration experiments
- Future
- Summary

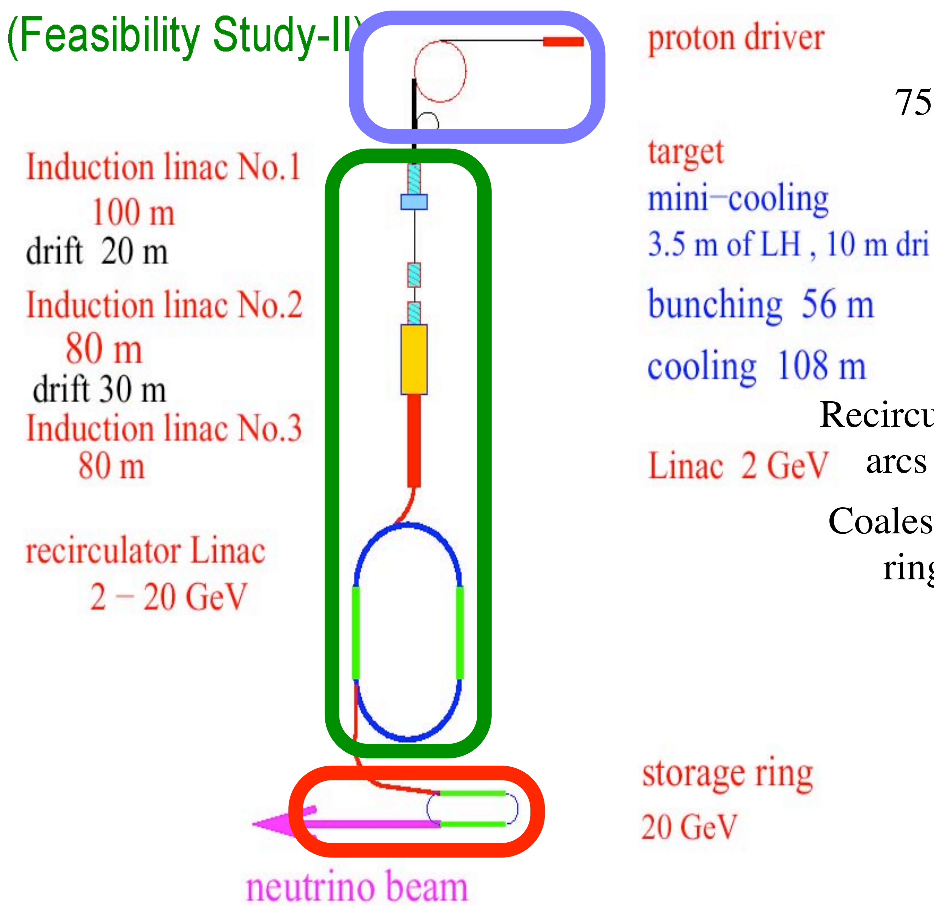
Muon Facility Examples:

- Neutrino Factory:

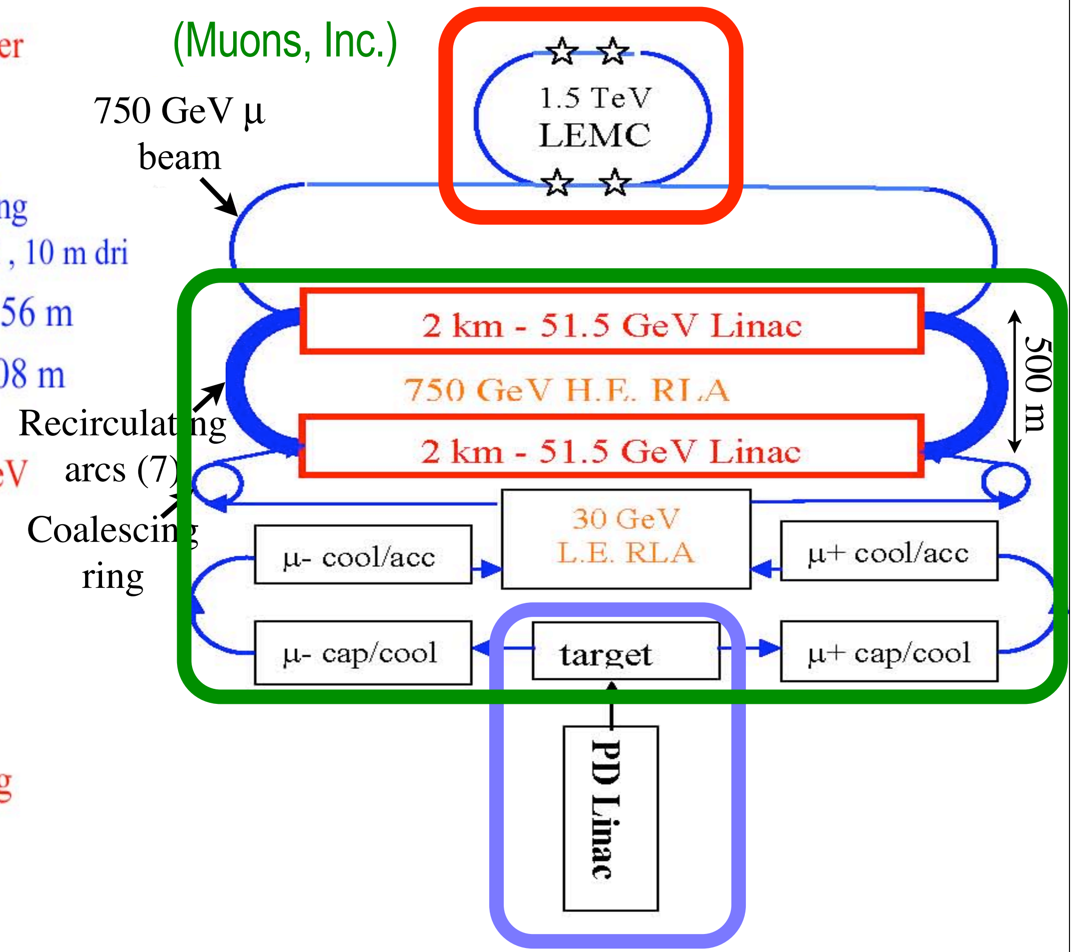


Muon Facility Examples:

- Neutrino Factory:



- $\mu^+\mu^-$ Collider:



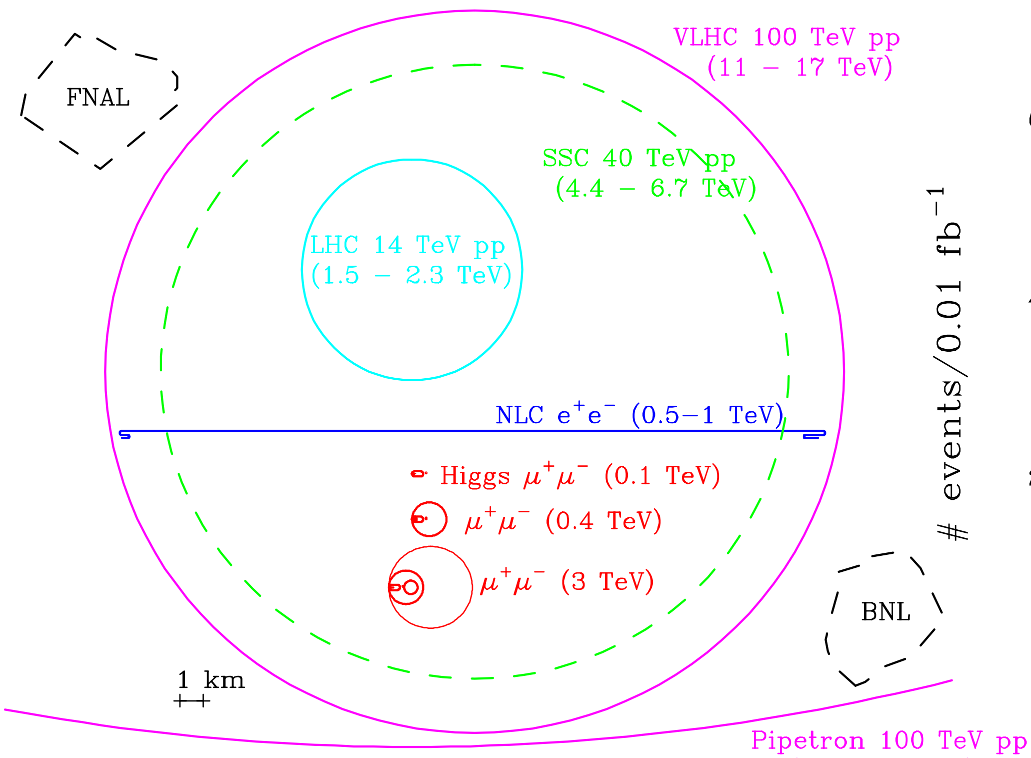
- Common features:
  1. μ production: p on tgt → π → μ, collected in focusing channel
  2. μ cooling & acceleration

– then

  3. μ storage, neutrino beam via $\mu^- \to e^- \nu_\mu \bar{\nu}_e$ – *or* – $\mu^+ \mu^-$ collisions

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:

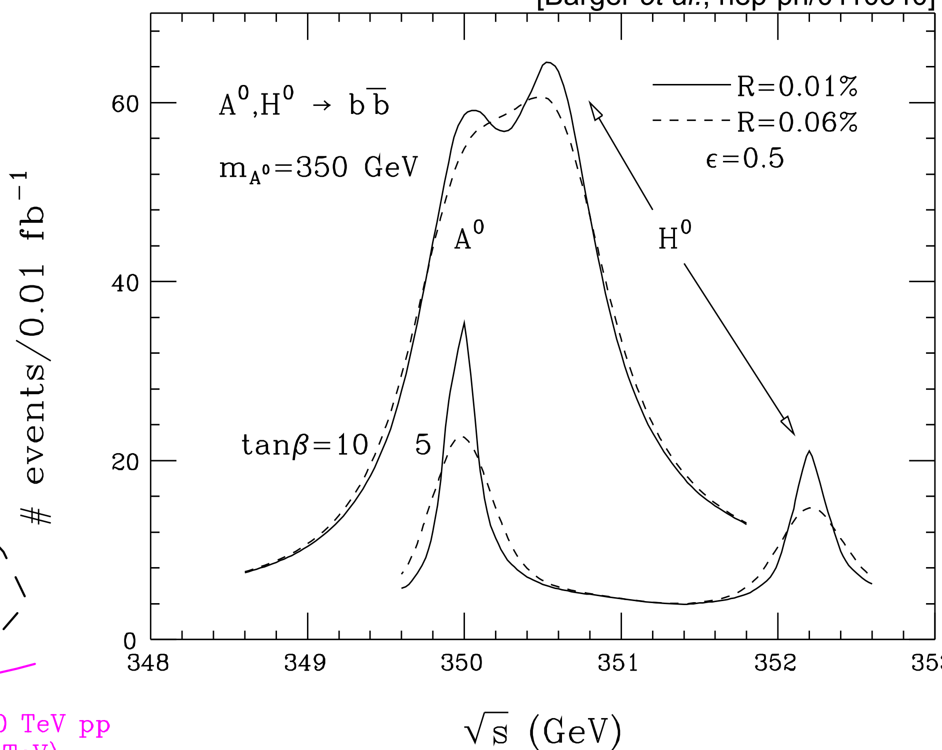


[Ankenbrandt *et al.*, PRST-AB 2, 081001 (1999)]

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

Separation of A^0 & H^0 by Scanning

[Barger *et al.*, hep-ph/0110340]

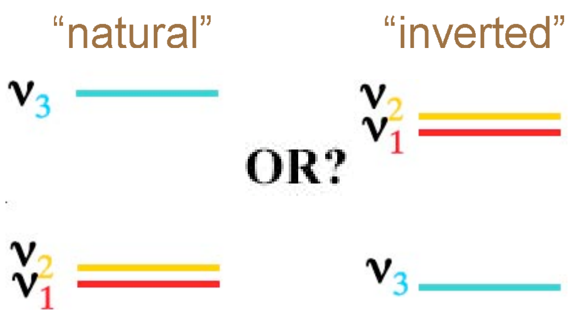


- E.g., μ-collider resolution can separate near-degenerate scaler and pseudo-scalar Higgs states of high-tan β SUSY

Why a Neutrino Factory?

- Neutrino mixing raises fundamental questions:

1. What is the neutrino mass hierarchy? [sgn(Δm^2_{31})]



2. Why is the 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)

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

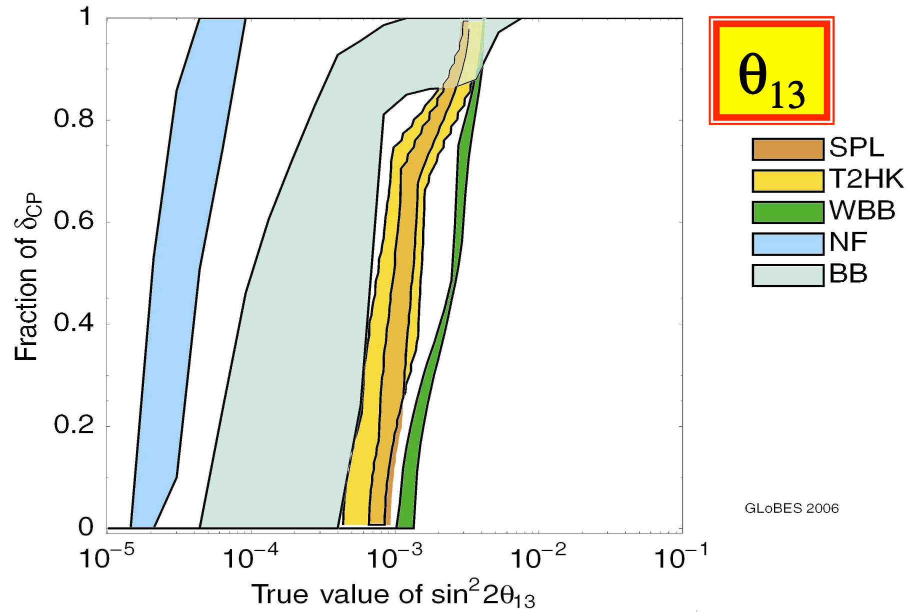
3. How close to zero are the small PMNS parameters θ_{13}, δ?

➡ are they suppressed by underlying dynamics or symmetries?

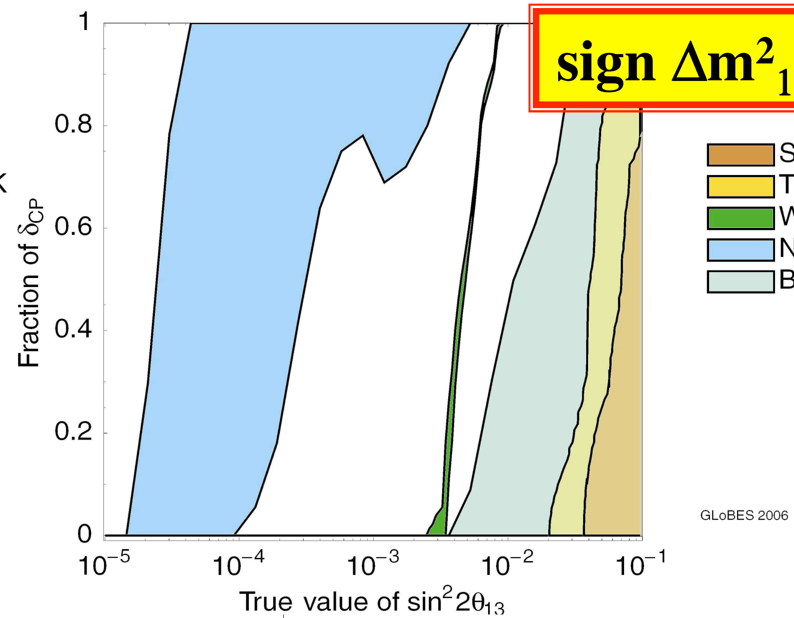
- **These call for a program to measure the PMNS elements as well as possible**
- **Goal**: *overdetermine* the matrix! Is this ***all*** the physics?

Neutrino Factory Physics Reach

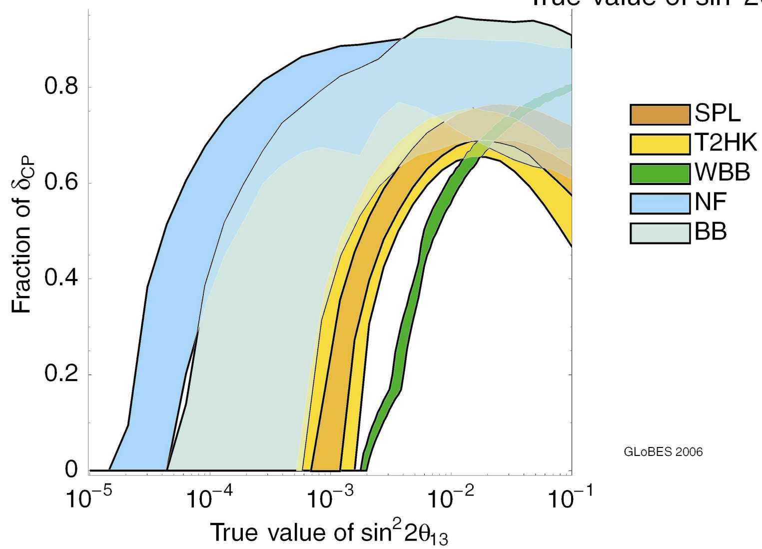
- 3σ contours [ISS Physics Group Report, arXiv:0710.4947v2]:



θ_{13}



sign Δm^2_{13}



CP phase δ

- No other technique is as sensitive!

Why Muon Cooling?

- νF physics calls for ~ 0.1 μ/*p*-on-target

  ⇒ *very* intense μ beam from π decay

  ⇒ must accelerate large (~10π mm·rad rms) beam emittance

- But large-aperture acceleration systems are expensive!

➡ ***cost-effective*** to ***cool*** the muon beam

- μC: $\mathcal{L} \propto I^2/\sigma_x\sigma_y$

  ⇒ big gain from smaller beam

➡ to achieve useful collider luminosity, ***necessary*** to ***cool*** the muon beam

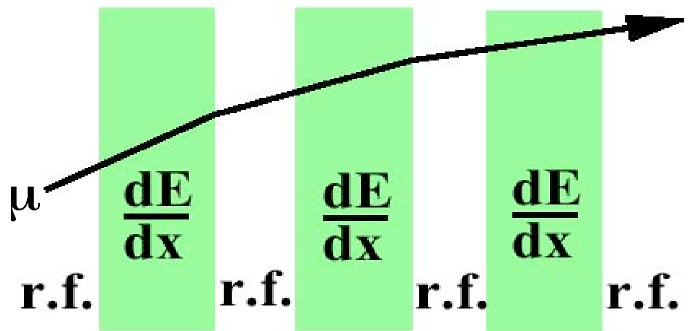
The Challenge:

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

Q: What cooling technique works in microseconds?

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

Ionization Cooling

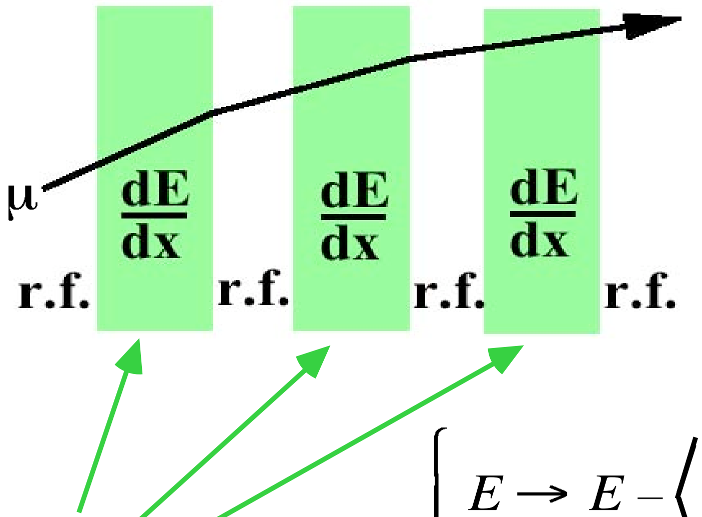


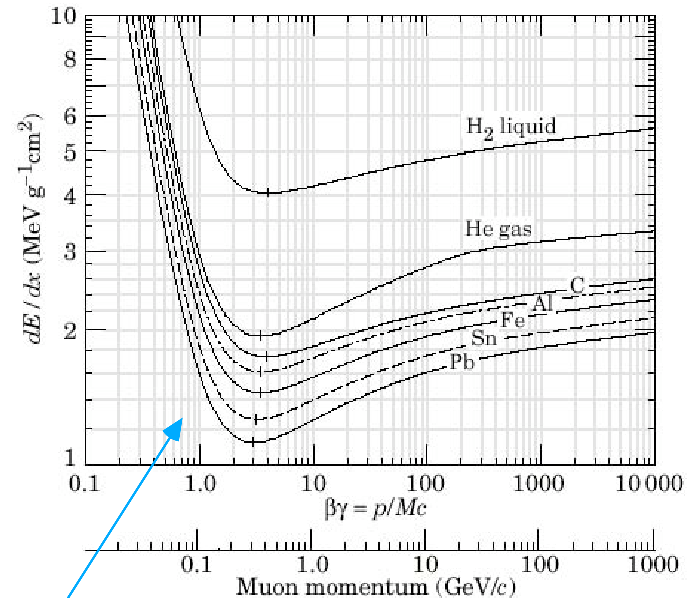
G. I. Budker and A. N. Skrinsky, Sov. Phys. Usp. **21**, 277 (1978)
A. N. Skrinsky and V. V. Parkhomchuk, Sov. J. Part. Nucl. **12**, 223 (1981)

A brilliantly simple idea!

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 muon $\Delta p_\perp$ at constant $p_{\|}$, i.e., transverse cooling

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

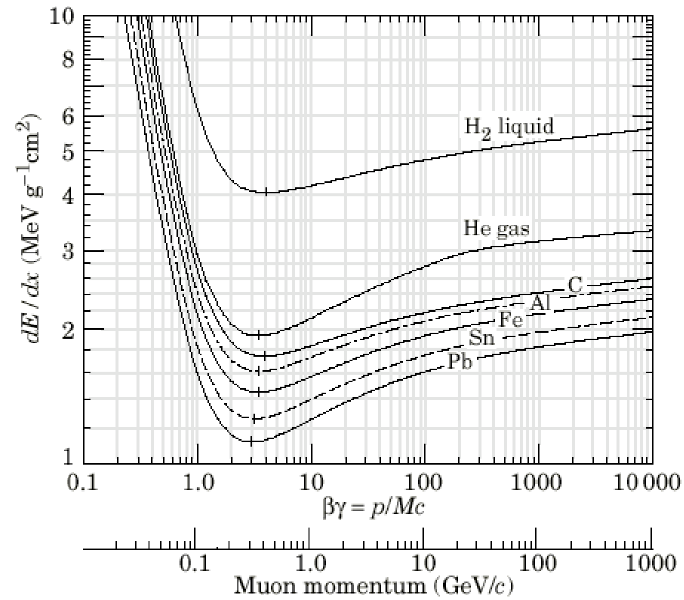
(emittance change per unit length)

Note: It's just Maxwell's equations, so in principle it *has* to work!

But in practice it's subtle and complicated...*so a test is essential!*

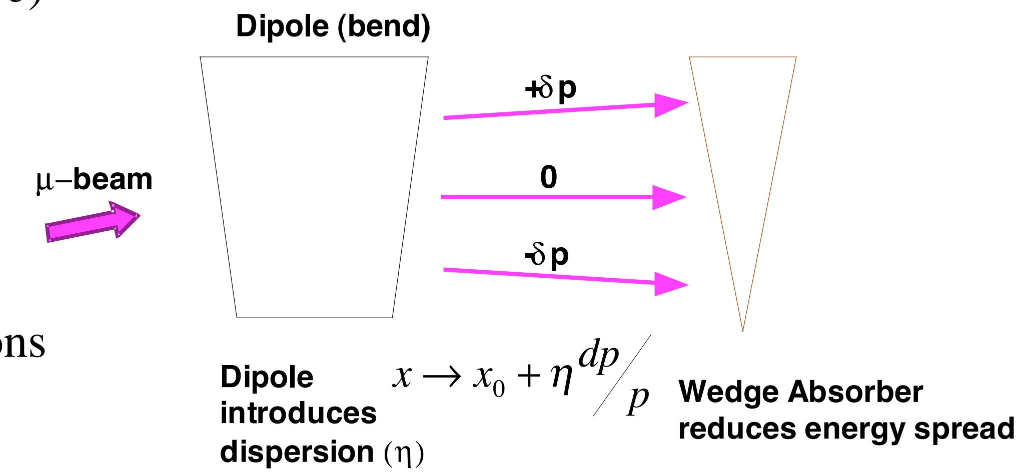
Some Ionization Cooling Details

1. Effect is transverse only
   - might hope to cool longitudinally via *dE*/*dx* curve's slight positive slope above ionization minimum
   - but *dE*/*dx* "straggling" tail leads to heating



2. To optimize cooling requires:
   - low $\beta_\perp$ (strong focusing)
   - large X_0 (low Z)
   - low E_μ (typ. $150 < p_\mu < 400$ MeV/c)

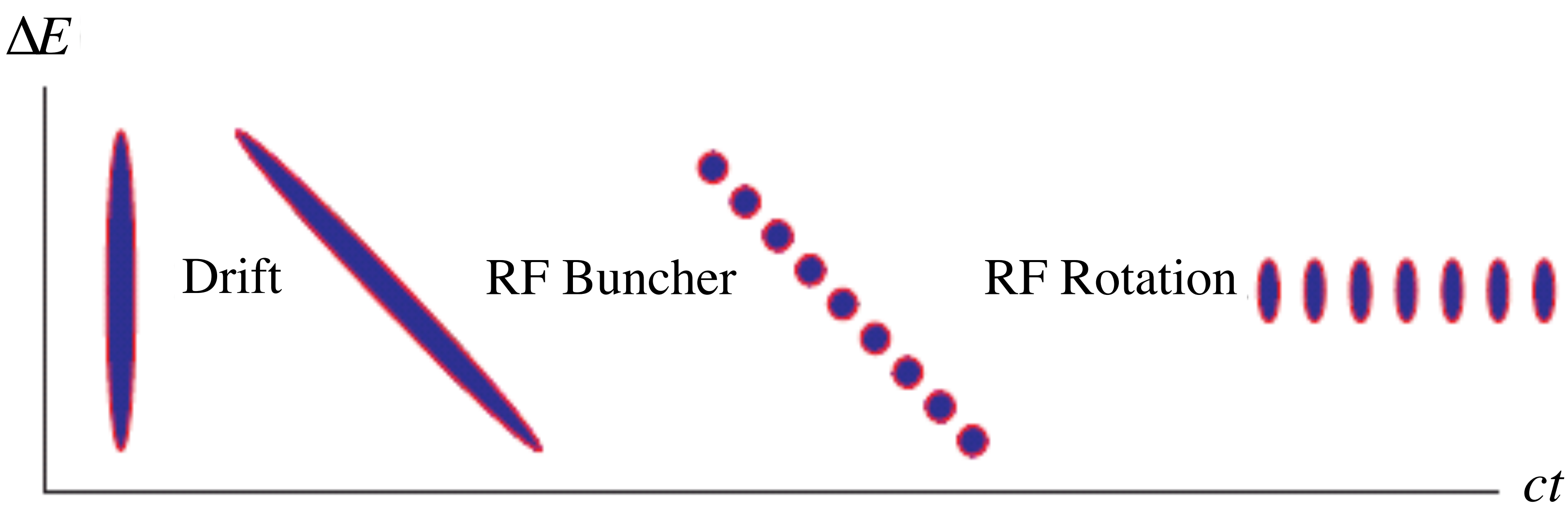
3. Can "rotate" portion of effect into longitudinal phase plane via "emittance exchange"
   - allows all 6 phase-space dimensions to be cooled



Preparing for Ionization Cooling

Example: International Scoping Study (ISS) νF design [JINST **4**, P07001, (2009)]

- Muons born with small Δt but large ΔE
- 1st bunch, then phase-rotate:

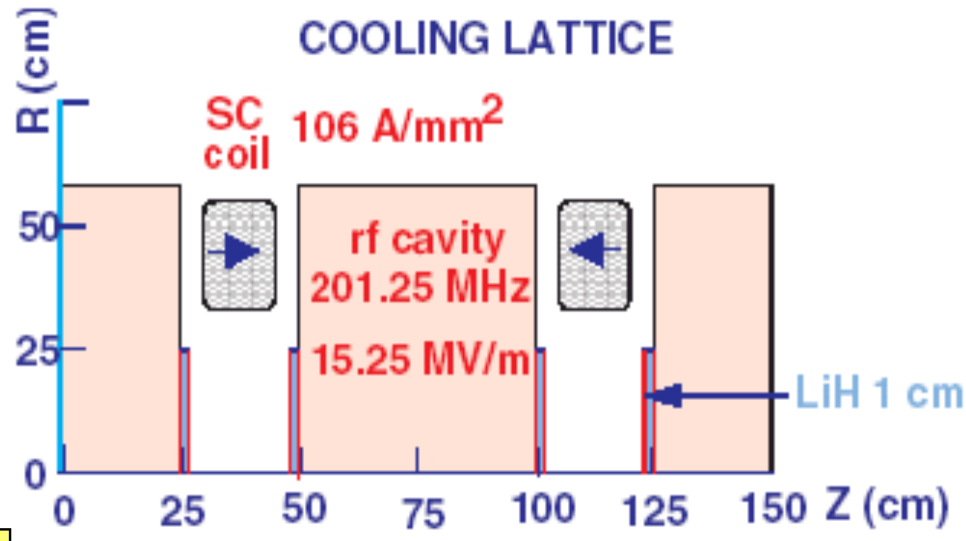


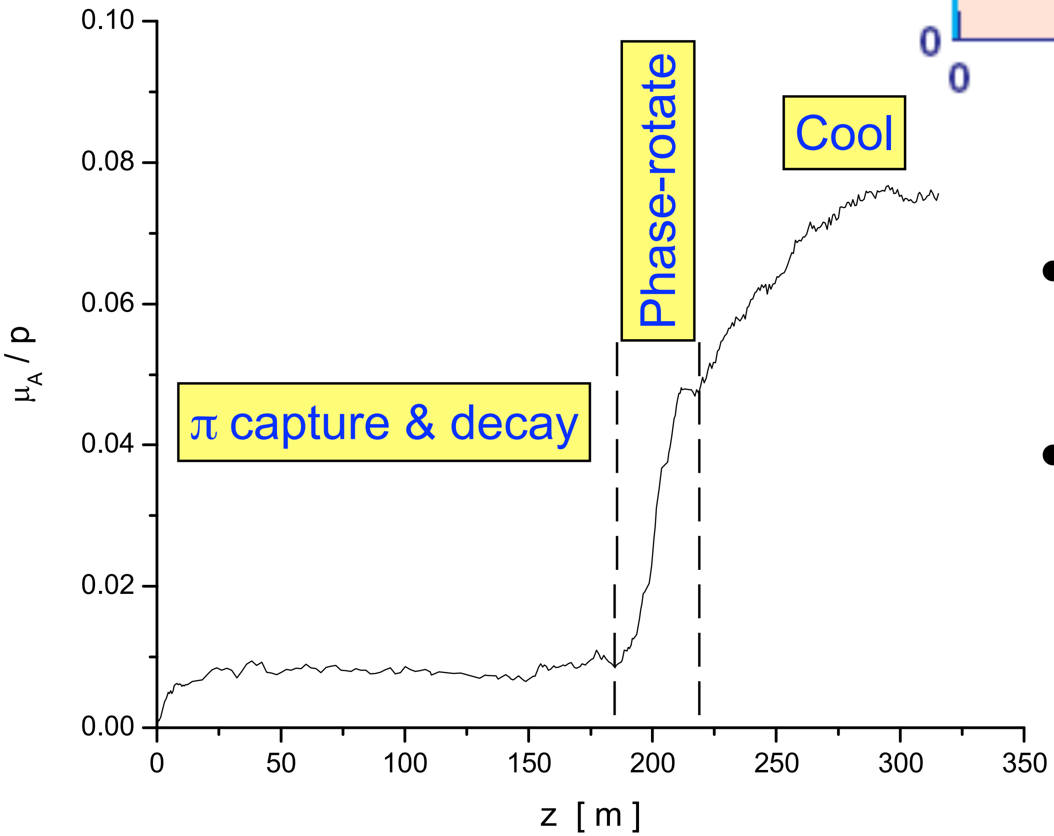
- Bunching via RF “vernier” [D. Neuffer]
  – several RF frequencies starting at ≈ 300 MHz, decreasing to 200

Ionization Cooling

ISS scheme: [JINST **4**, P07001 (2009)]

- Alternating-solenoid focusing
- Thin, Be-coated LiH absorbers double as RF-cavity windows





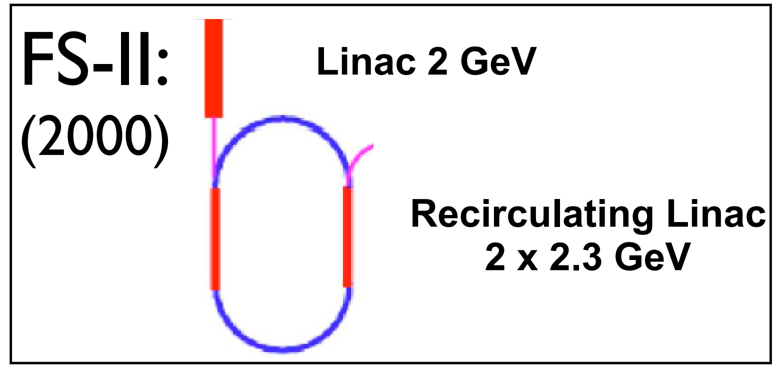
- 80m-long cooling channel increases muon intensity × 1.6
- Accepts and cools μ^+ and μ^- simultaneously

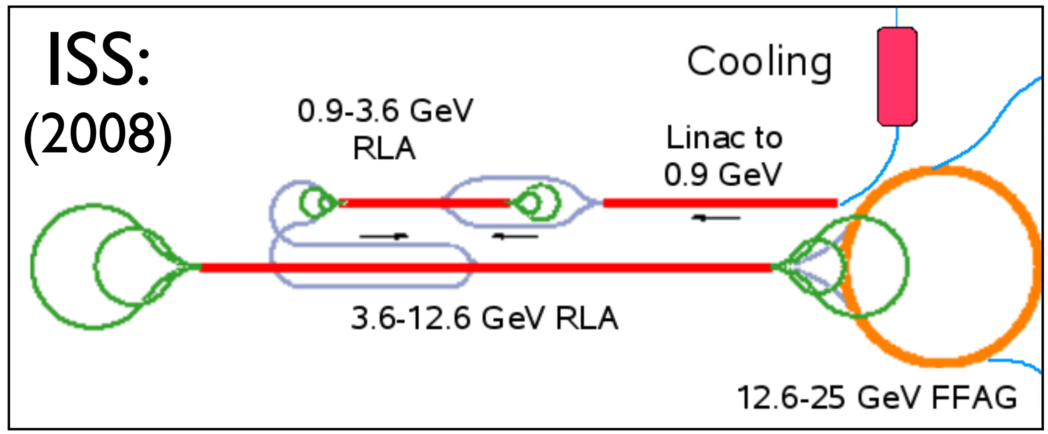
Rapid Muon Acceleration

NFMCC

- Conventional synchrotrons too slow
- Following cooling, muons at ≈ 200 MeV/c

  ⇒ must start with linac
- Subsequent stages:
  - previously (FS-I and -II) racetrack RLAs
  - now favor dogbone RLAs and novel, non-scaling FFAGs
  - also very-RCS considered:





Modify the 400 GeV Main Ring

- 70 → 750 GeV in 68 orbits (1.4 ms). 10 GeV of 1.3 GHz, 30 MV/m SRF. Muon Survival = 79%. r = 1000 m.
- FODO Lattice 30.45 m Long Half Cell. 3.3 m, 160 Hz, 30 T/m Quadrupoles. 3.2 m, 8 Tesla Superconducting Dipoles. 5.7 m, 360 Hz, ∓1.8 Tesla Dipoles. Dipoles oppose, then act in unison. Eddy Currents: Thin copper wire and .28mm grain oriented Si steel laminations.

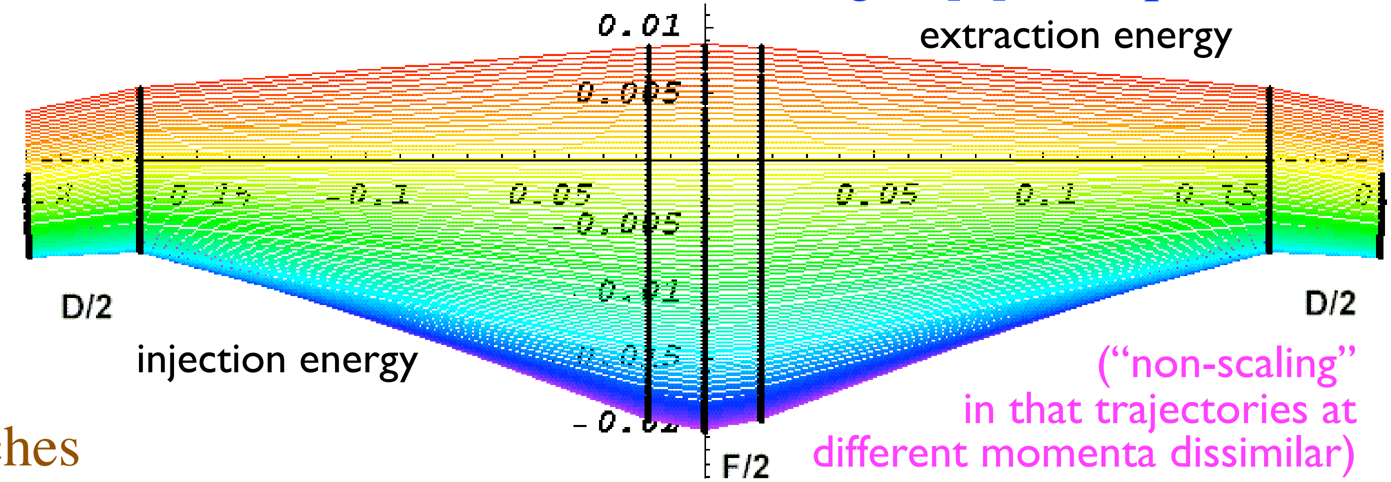
Q F	∓1.8T Dipole	+8T Dip.	∓1.8T Dipole	+8T Dip.	∓1.8T Dipole	Q D

(from D. Summers, "Muon Acceleration to 750 GeV in the Fermilab Tevatron Tunnel," NFMCC mtg, UCLA, 2/1/07)

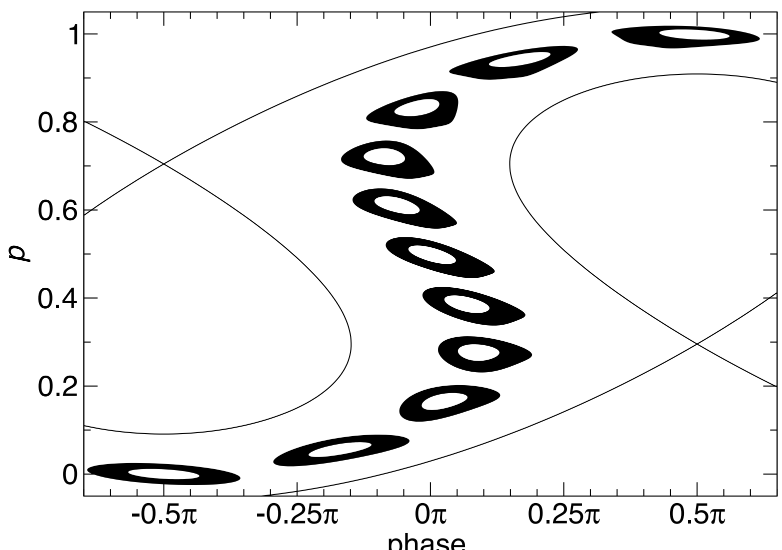
Non-Scaling FFAG Acceleration

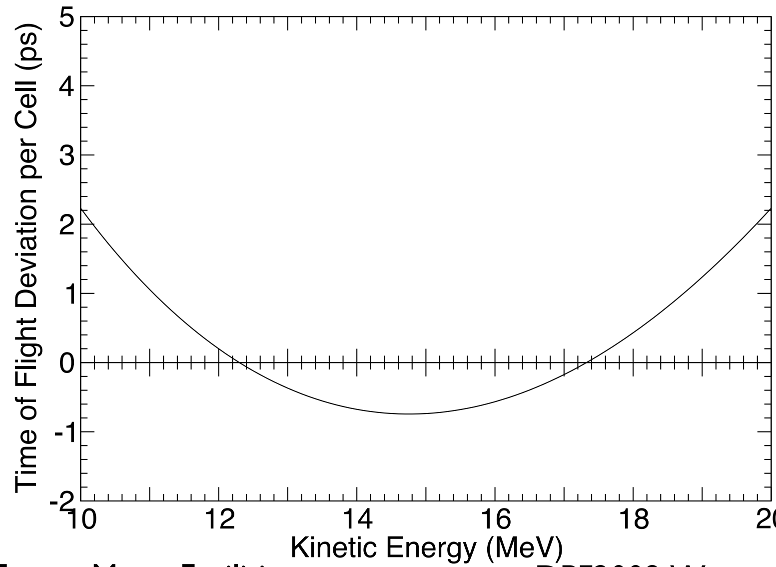
J. S. Berg (BNL), C. Johnstone (FNAL)

- Fixed-field lattice includes both in- & out-bends for large $\Delta p/p$ acceptance
- Beam trajectories move from inside ring at injection to outside at extraction
- Seems lower-cost than other approaches



- Beam timing s.t. synchronization with RF buckets impractical
  $\Rightarrow$ use "serpentine" acceleration, between buckets

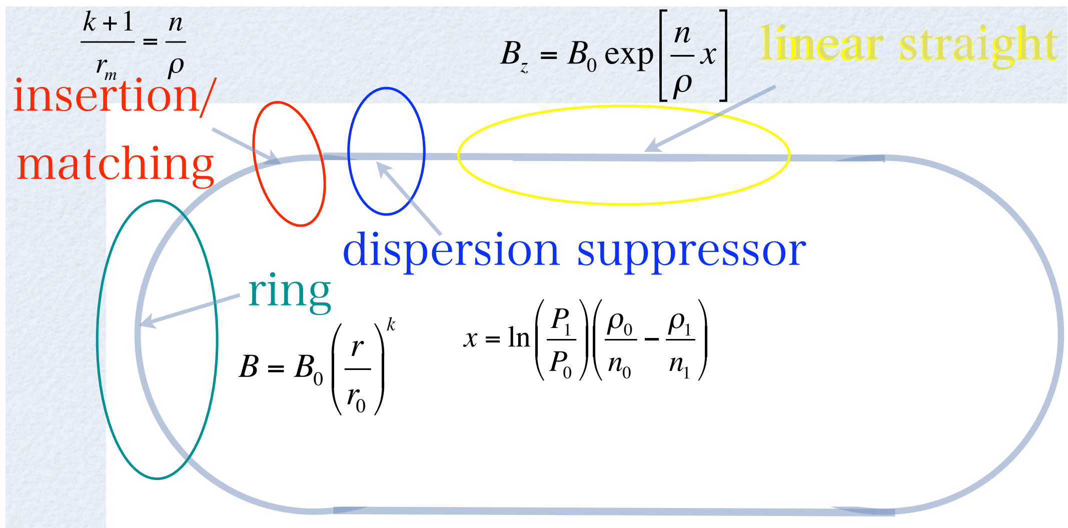




New FFAG Idea (NuFact09)

Y. Mori, T. Planche, et al. (Kyoto)

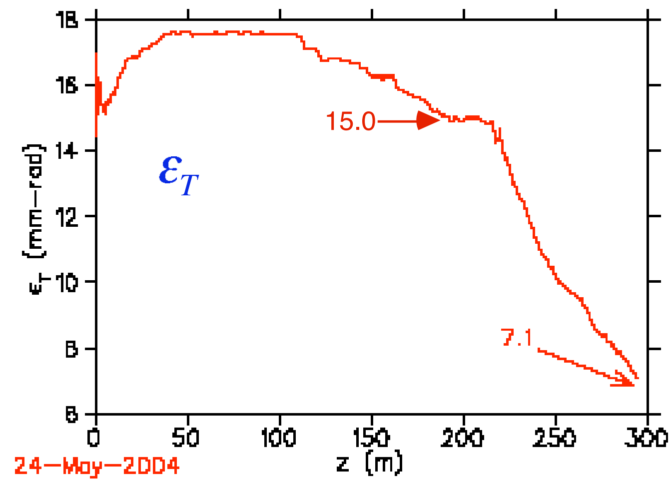
- Scaling FFAGs have attractive features
  - fixed field ⇒ no ramping, allows rapid acceleration
  - zero chromaticity ⇒ constant tunes
- But also drawbacks: large dispersion ⇒ large orbit excursion
  - large-aperture magnets & RF cavities ⇒ low frequency
  - short straight section ⇒ injection/extraction difficult
  - limited space for cavities
- "Advanced" scaling FFAGs:
  - sol'n for straight insertion with dispersion suppression
  - eases above problems
  - allows harmonic-number-jump acceleration



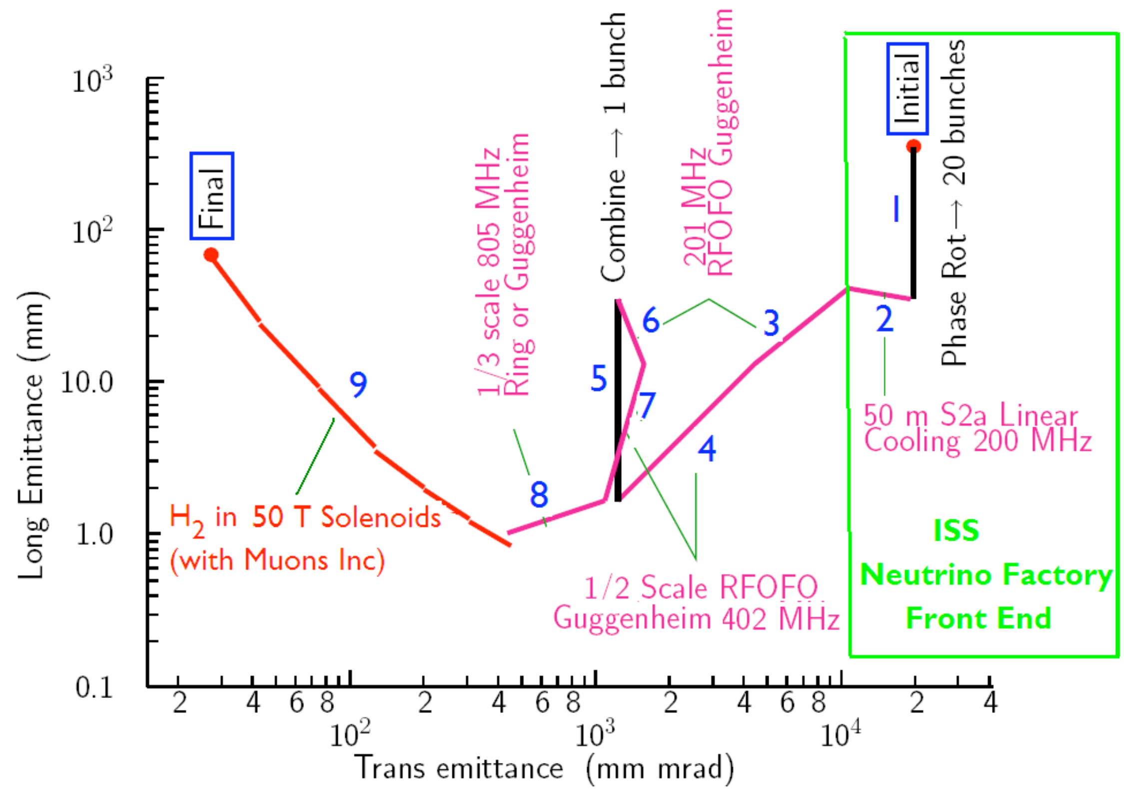
Towards Muon Colliders

Towards Muon Colliders

- $\lesssim \times 10$ transverse cooling sufficient for νF



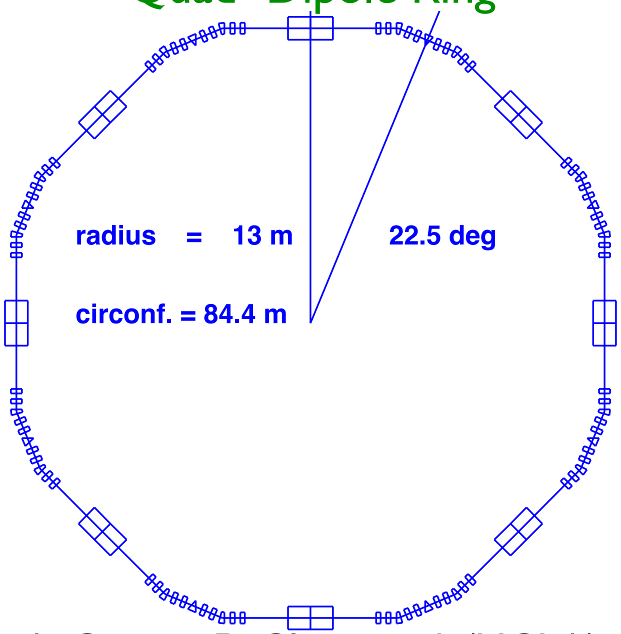
- But μC requires ~ 10^6 emittance reduction
  - both transverse and longitudinal



6D Cooling Approaches

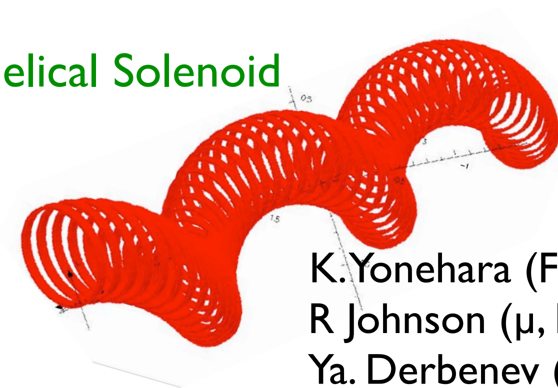
- Transverse ionization cooling self-limiting due to longitudinal-emittance growth, leading to particle losses
  - caused e.g. by energy-loss straggling plus finite *dE* acceptance of cooling channel
  - ⇒ need longitudinal cooling for muon collider (could also help for NF)
- Variety of wedge-absorber, 6D-cooling ring, & spiral lattices explored:

Quad+Dipole Ring



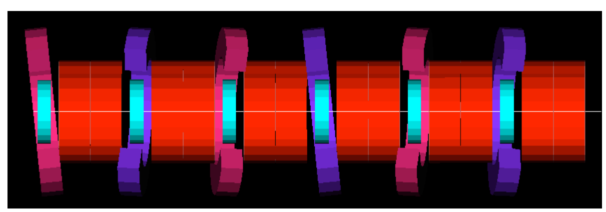
A. Garren, D Cline, *et al.* (UCLA)

Helical Solenoid



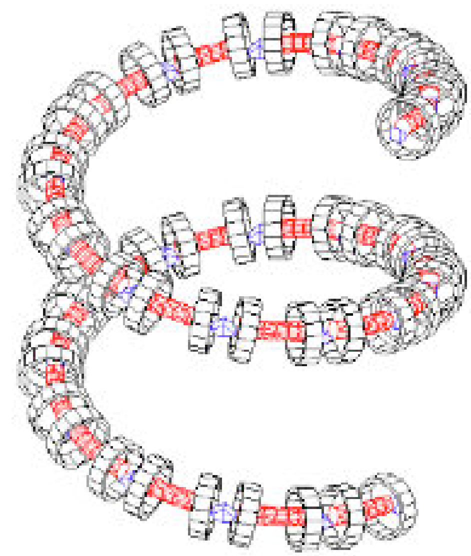
K. Yonehara (FNAL), R Johnson (μ, Inc.), Ya. Derbenev (JLab)

Helical FOFO "Snake"



Y. Alexahin (FNAL)

RFOFO "Guggenheim"



. . .

R. Palmer (BNL), P. Snopok (UCR)

⟶ Helices avoid injection/extraction kickers & allow matching β to $\varepsilon(s)$

Muon Collider Parameters

- What performance can then be envisioned for a muon collider?

NFMCC examples:

4 TeV Collider Ring Parameters from 98 Study, 8 TeV pushed

	Phase 1	Phase 2	
C of m Energy	4	8	TeV
Luminosity	4	8	10^{34} cm^{2}sec^{-1}
Tune Shift	0.1	.1	
Muons/bunch	2	2	10^{12}
Ring <bending field>	5.18	10.36	T
Ring circumference	8.1	8.1	km
Beta at intersection	3	3	mm
rms momentum spread	0.12	0.06	%
Muon Beam Power	9	9	MW
Required depth for ν rad	135 (ILC)	540	m
Repetition Rate	6	3	Hz
Proton Driver power	$\approx$ 1.8	$\approx$ 0.8	MW
Trans Emittance	25	25	pi mm mrad
Long Emittance	72,000	72,000	pi mm mrad

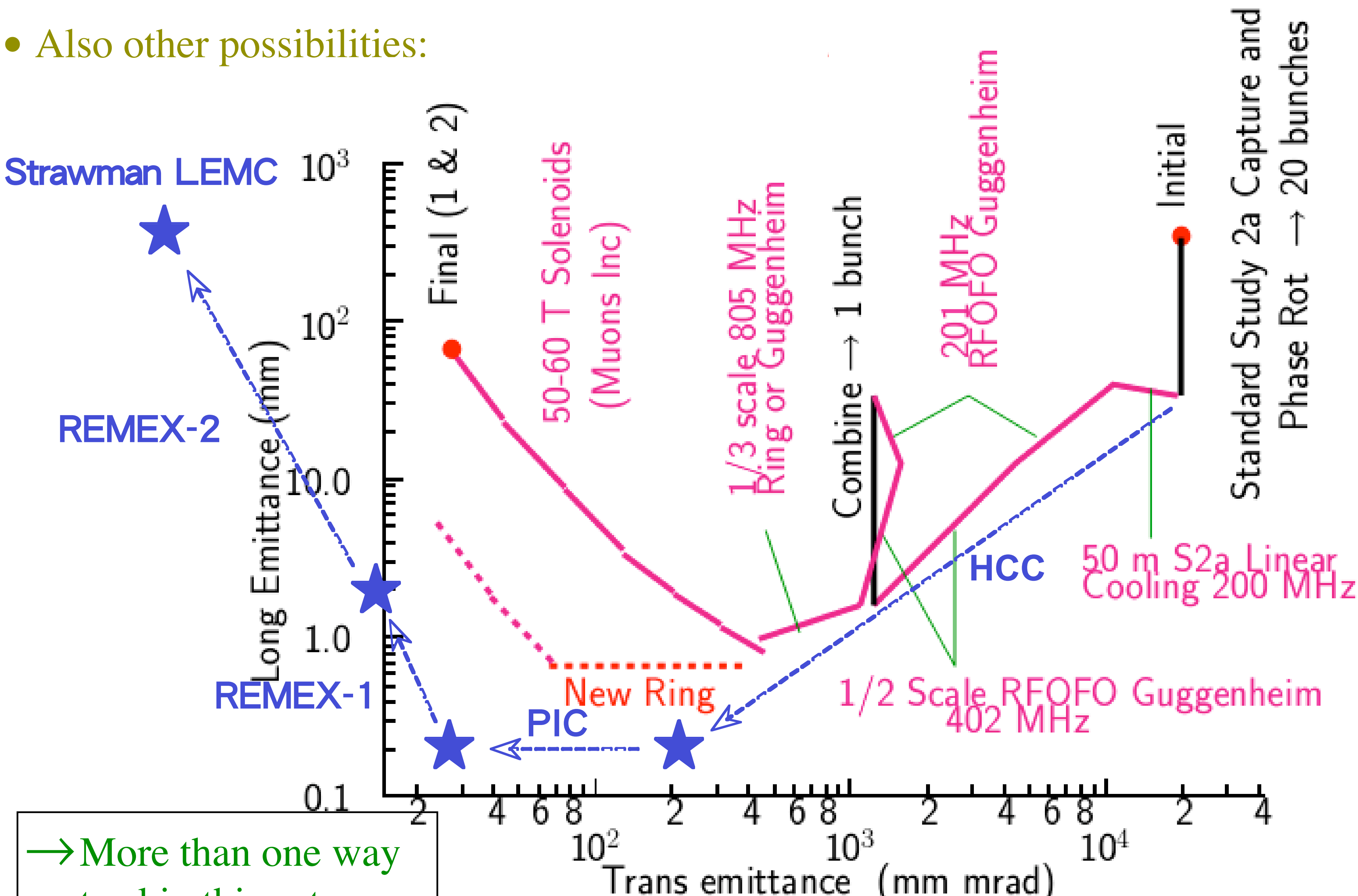
- Assumes ~10^6 in 6D cooling

Muons, Inc. (LEMC strawman):

E (TeV COM)	3
Average dipole field (T)	10
Radius of Arcs (m)	500
Length of Straight Sections (m)	350
Circumference (m)	3842
Revolution frequency (Hz)	78093
Revolution period (s)	1.28053E-05
Number of IPs	4
Number of μ+ bunches	10
bunch intensity	1.00E+11
tune-shift parameter	6.00E-02
β* (cm)	5.00E-01
Peak Luminosity/IP (1/(s cm^2))	8.21E+34
Average Luminosity	3.53E+34
μ lifetime (s)	3.08E-02
rep rate (Hz)	32
Required Norm trans emittance (μm)	2.1
Δ*p*/*p* (%)	1
Bunch length (cm)	0.5
Bunch emittance width in arcs (cm)	0.1
Bunch Δ*p*/*p* width in arcs (cm)	1

Cooling for a Muon Collider

- Also other possibilities:

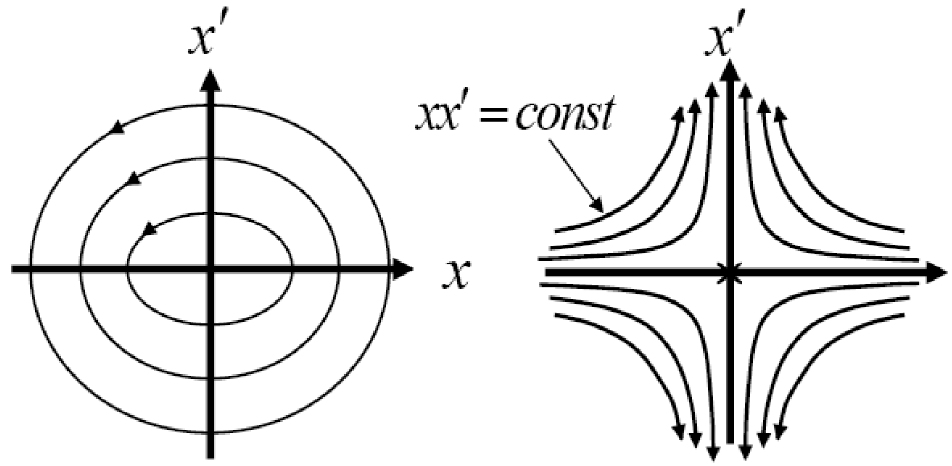


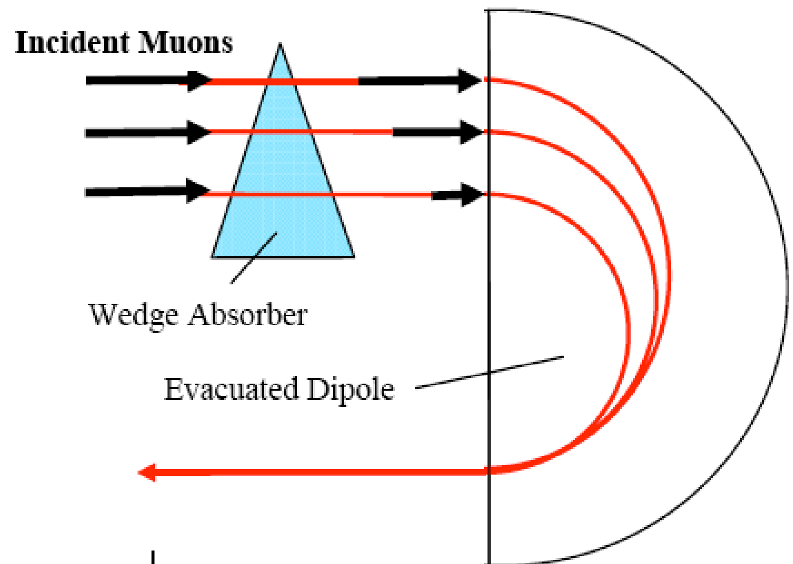
→ More than one way to skin this cat...

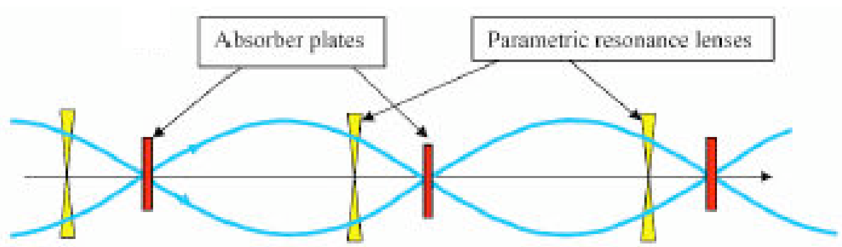
"Extreme Cooling"

Ya. Derbenev (JLab), R. Johnson (Muons), R. Palmer (BNL)

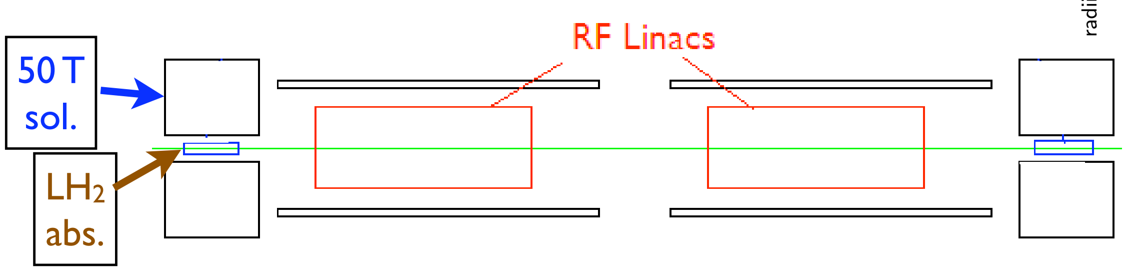
- Can cool beam yet further with new approaches:
  - Parametric-resonance Ionization Cooling (PIC)... ... & Reverse Emittance Exchange (REMEX):

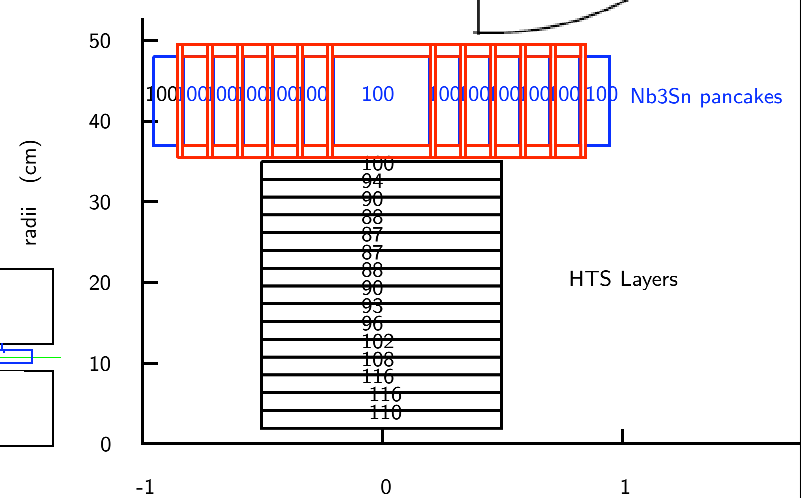






  - or with HTS 50 T solenoids:

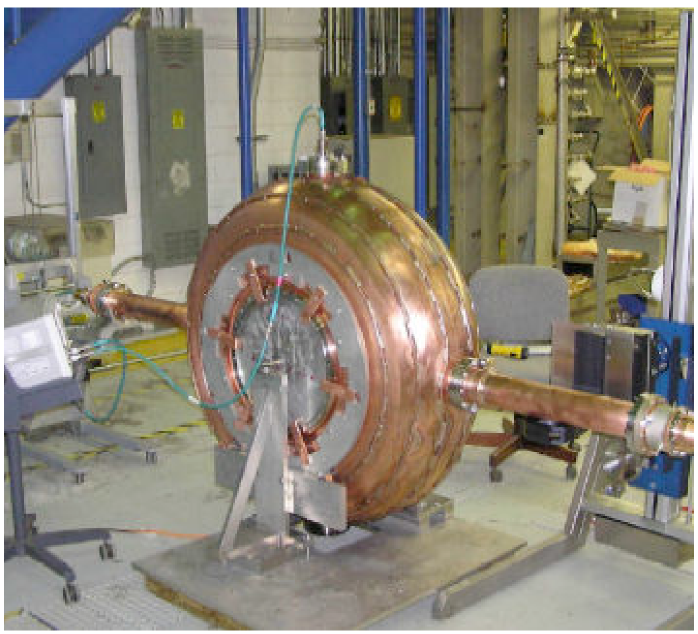




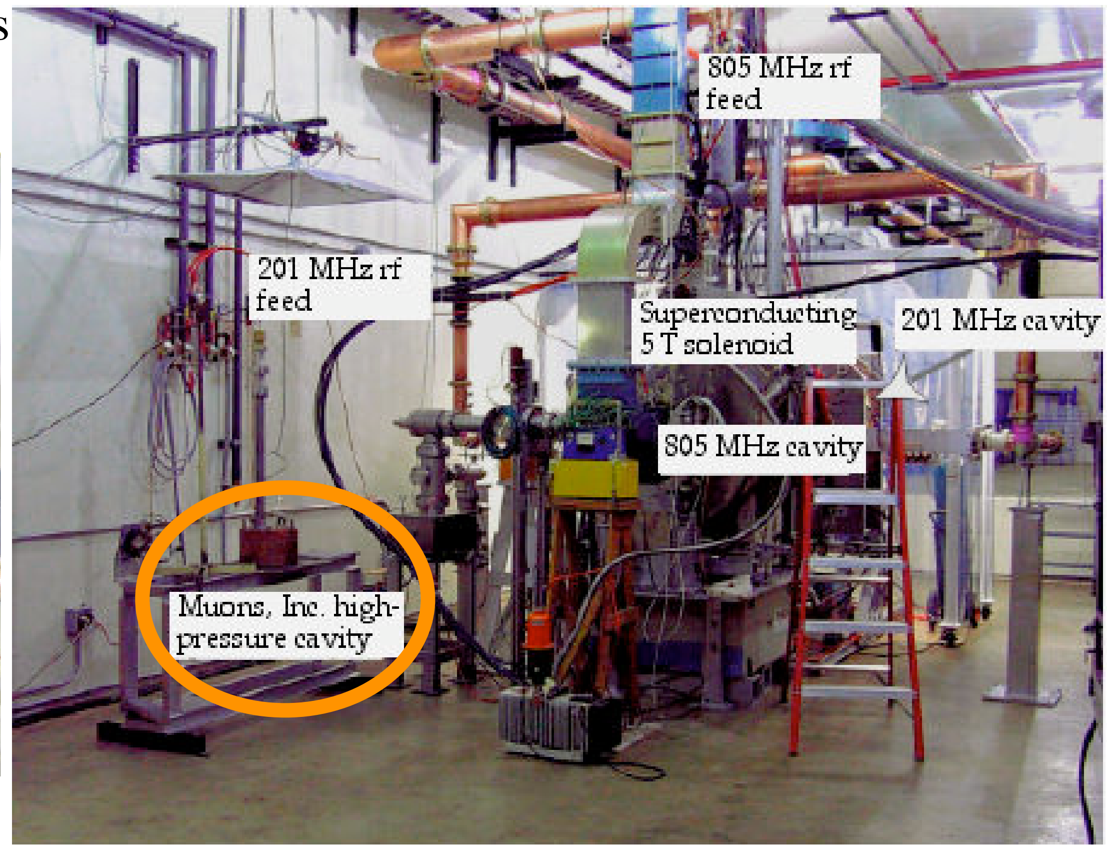
Muon Collider/Neutrino Factory R&D

NFMCC & Muons, Inc.

- Operation of high-gradient RF cavities in strong solenoidal fields
  - to cool large initial muon beam, want high-gradient, moderate-frequency, normal-conducting RF cavities operable in high focusing magnetic fields
  - tests in progress at Fermilab MuCool Test Area (MTA) near Linac, with full-scale (201 MHz) and 1/4-scale closed-cell (pillbox) cavities
  - RF cells closed with Be windows (for higher on-axis field)

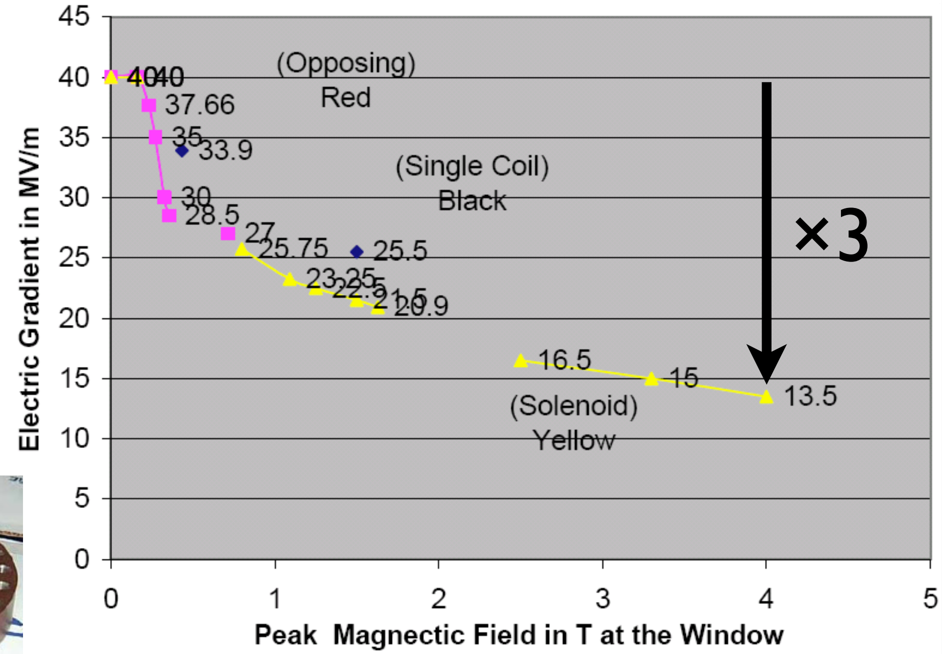


Prototype 201-MHz cavity



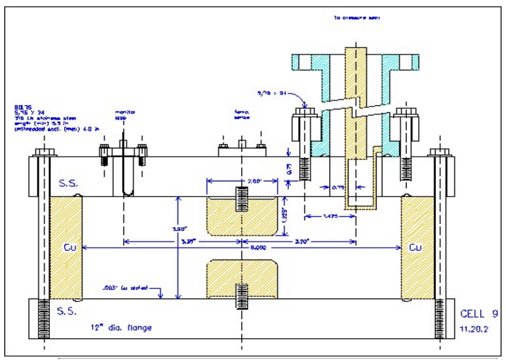
RF Cavity R&D

- Tests at 805 MHz show diminished cavity performance in few-tesla field:

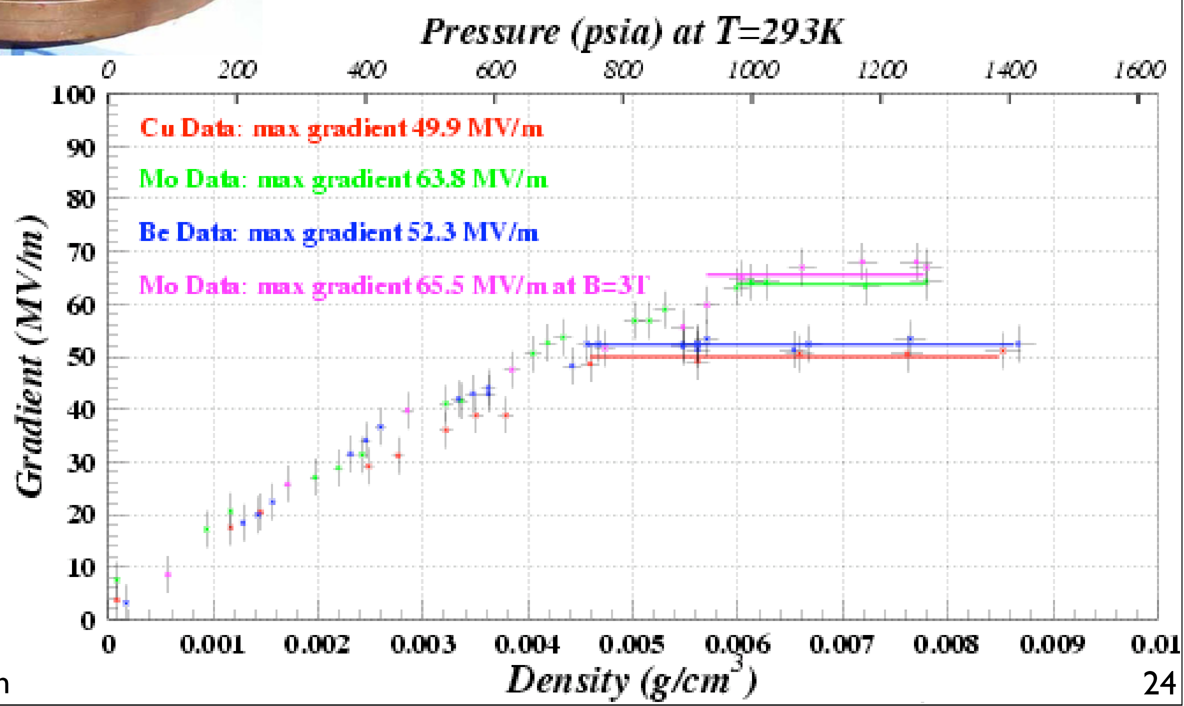


- Muons, Inc.: pressurizing the cavity helps! (Paschen effect)

805 MHz Test Cell



High-P Electrode Structure



- Plan further investigation of materials, coatings, & surface preparations...

- Also work on lattices w/ low field at cavities

Muon Facility Feasibility Demonstrations

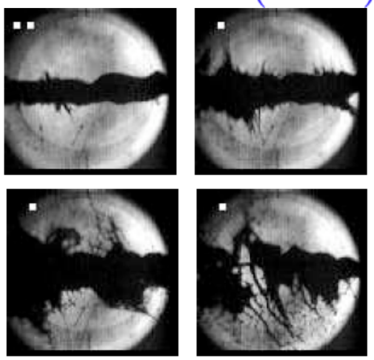
- Multi-MW targets: MERIT @ CERN nTOF facility
- Transverse ionization cooling: MICE @ RAL ISIS synchrotron
- Non-scaling FFAG acceleration: EMMA @ DL
- 6D helical cooling: MANX proposal

MERIT (MERcury Intense Target):

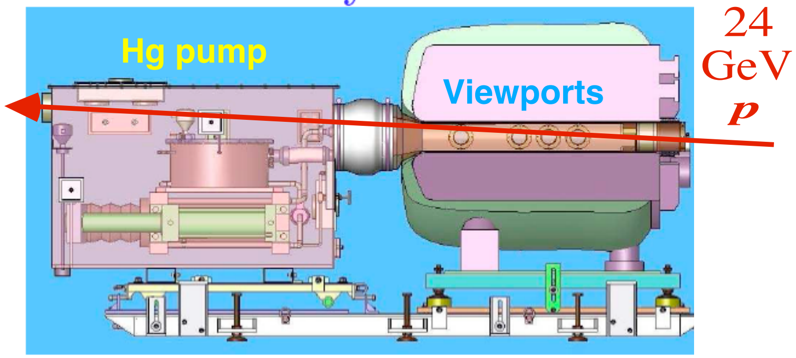
H. Kirk (BNL), K. McDonald (Princeton), et al.

- Proof-of-principle demonstration of Hg-jet target for 4-MW proton beam, contained in a 15-T solenoid for maximal collection of soft secondary pions

BNL E-951 (2001)



MERIT cutaway view:



15-T NC pulsed solenoid:

- Key parameters:
  - 14 & 24-GeV p beam, up to 3×10^{13} p/2-μs spill in ≤ 8 bunches ("pump/probe")
  - σ_r of proton bunch ≤ 1.5 mm, beam axis at 67 mrad to magnet axis
  - Hg jet of 1 cm diameter, v = 20 m/s, jet axis at 33 mrad to magnet axis
  - Each proton intercepts the Hg jet over 30 cm = 2 interaction lengths
- Ran Oct. 22 – Nov. 12, 2007; conclude:
  - 20 m/s operations allows for 70Hz operations
  - 115kJ pulse containment demonstrated

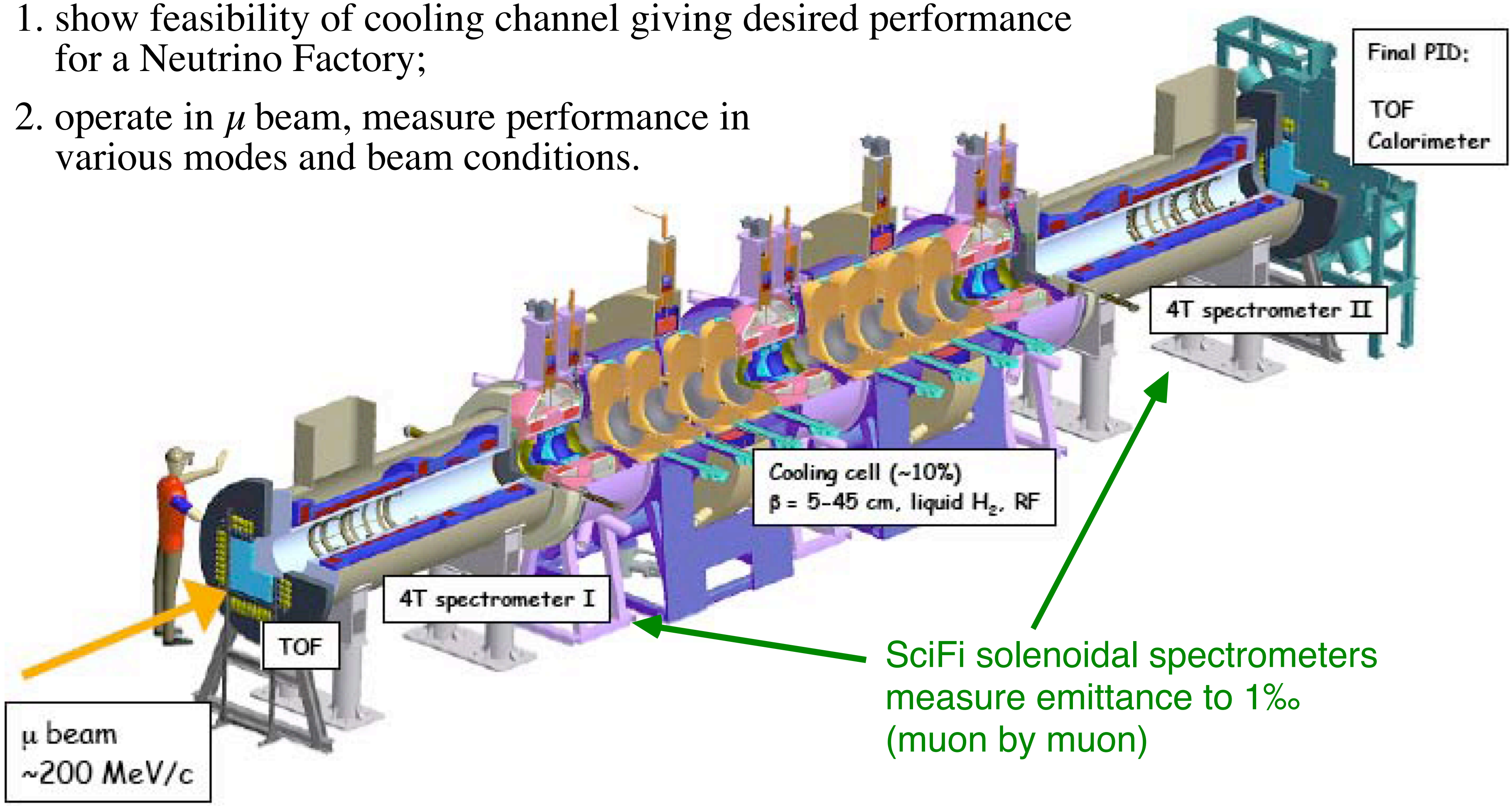
  } ➡ 8 MW operation demonstrated!
  - Hg jet disruption mitigated by magnetic field
  - Hg ejection velocities reduced by magnetic field
  - Pion production remains viable up to 350 μs after previous beam impact
  - 170 kHz operation possible for sub-disruption-threshold beam intensities

Muon Ionization Cooling Experiment (MICE)

A. Blondel (U. Genève), M. S. Zisman (LBNL), et al. (www.mice.iit.edu)

- **Goals:**

  1. show feasibility of cooling channel giving desired performance for a Neutrino Factory;
  2. operate in μ beam, measure performance in various modes and beam conditions.



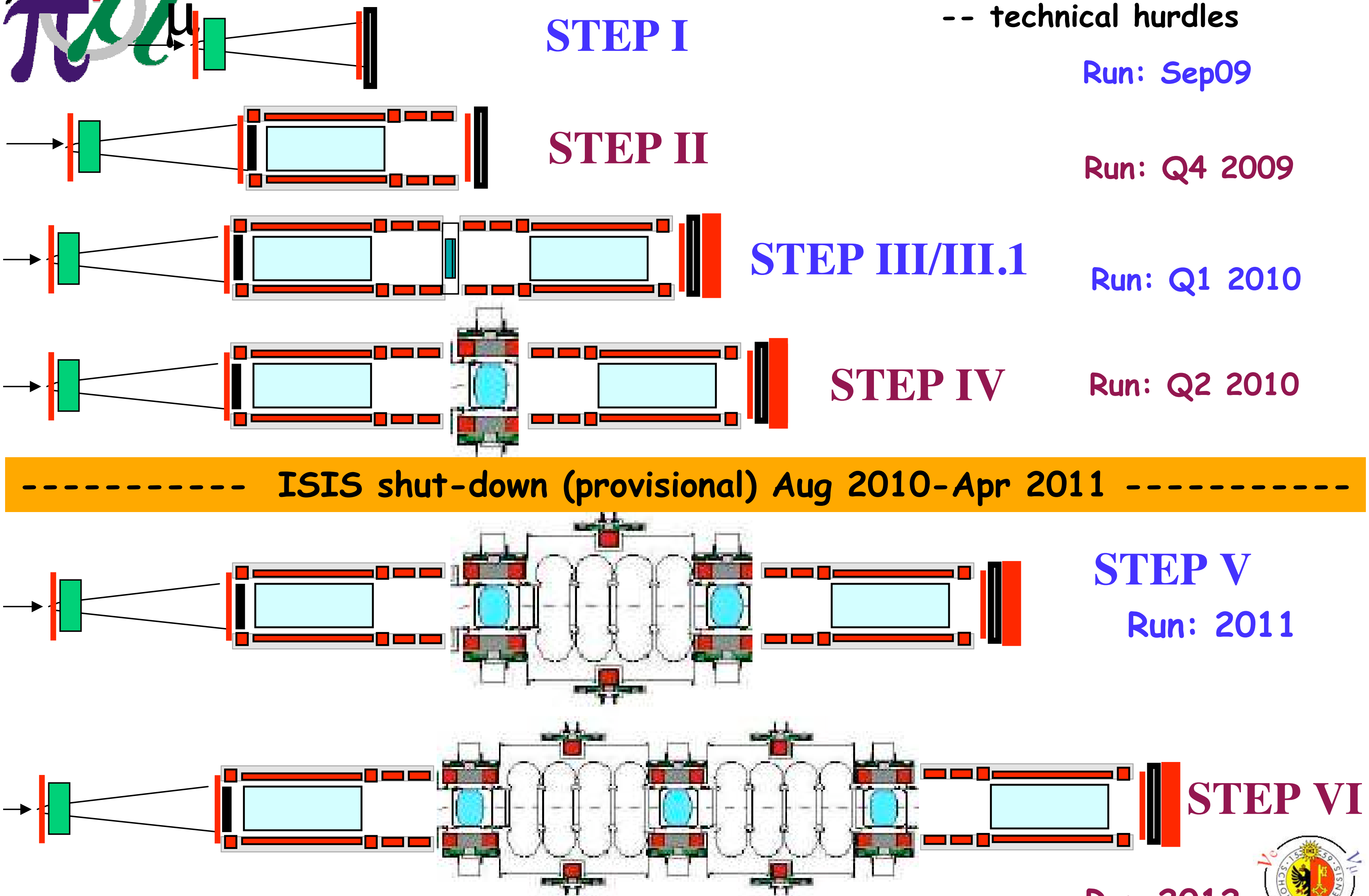
- Large international, interdisciplinary collaboration:

  >100 particle and accelerator physicists and engineers from Belgium, Bulgaria, China, Italy, Japan, Netherlands, Russia, Switzerland, UK, USA

Avatars of MICE

MICE Schedule as of April 2009

Caveats: -- cost and schedule review
-- funding issues in UK
-- technical hurdles

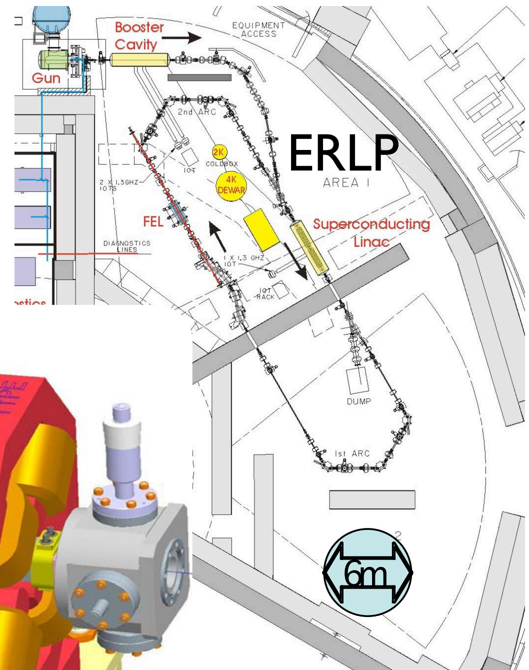


NUFACT09 IIT Chicago 20-07-2009 Alain Blondel

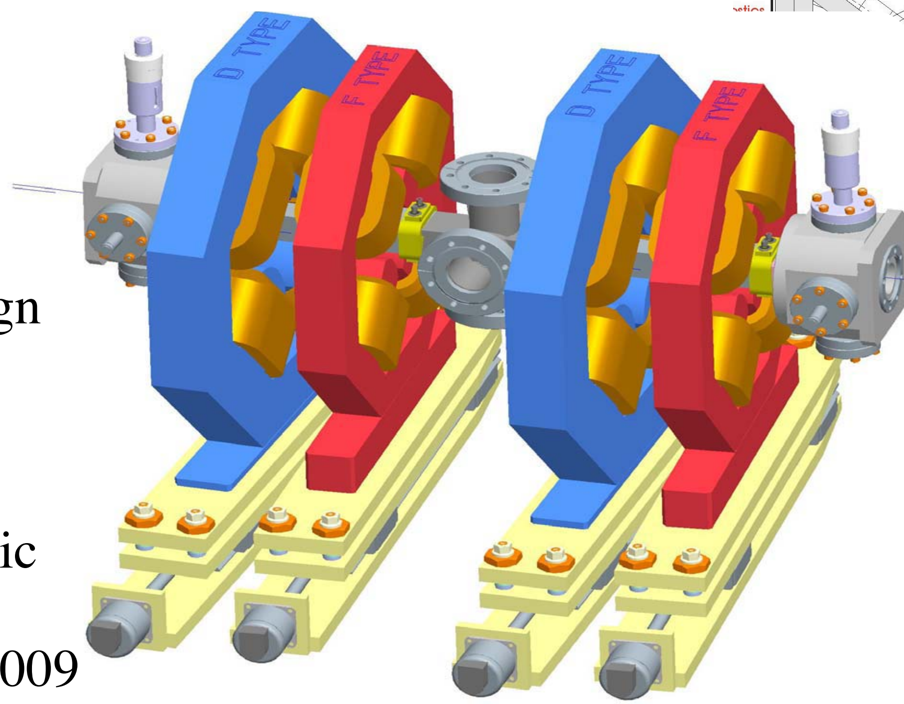
EMMA (Electron Model of Muon Accelerator)

R. Edgecock (RAL) et al.

- Proof of principle demo of non-scaling FFAG using electron beam
- Applications envisioned in muon acceleration, cancer therapy,...
- Needed to verify novel acceleration, including rapid resonance crossing
- Now approved and funded to run at Daresbury Lab:



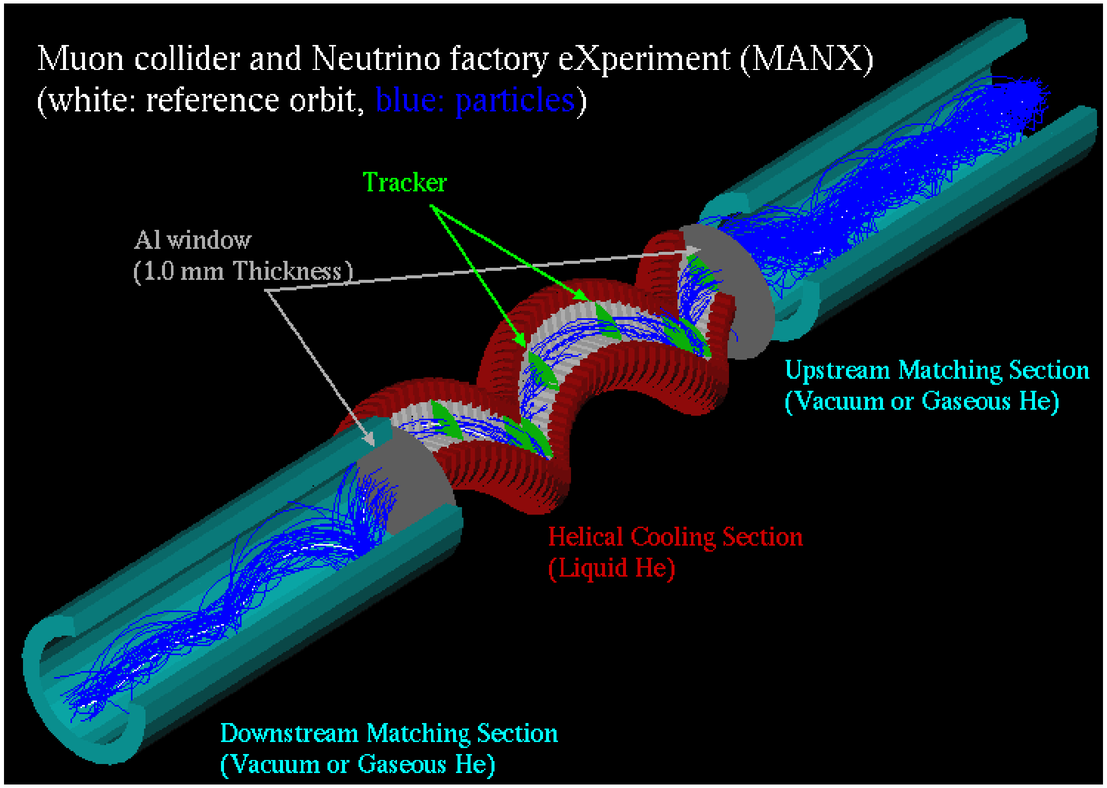
- Int'l collaboration: UK/US/CERN/FR/CA/GE
- Have completed:
  - lattice design
  - tracking studies
  - hardware specs
  - hardware outline design
  - costing
- Status:
  - funding from UK Basic Technology program
  - 1st beam before end 2009



MANX (Muon collider And Neutrino factory eXperiment)

R. Johnson (Muons, Inc.) et al.

- Short HCC designed as "precooler" can also be adapted as 6D cooling demonstration experiment
- Requires short, practical input & output matching
- Current specs:
  - Liquid He absorber
  - No RF cavities
  - Length of cooling channel: 3.2 m
  - Length of matching section: 2.4 m
  - Helical pitch κ: 1.0
  - Helical orbit radius: 25 cm
  - Helical period: 1.6 m
  - Transverse cooling by ~30%
  - Longitudinal cooling by ~10%
  - 6D cooling: ~50 %



- Could be run at RAL using MICE beam & spectrometers
- Also sites at FNAL under consideration

Outlook

Crystal ball slightly hazy, but…

- Around 2012, should know
  - whether ∃ low-mass Higgs &/or SUSY
  - ⇒ whether ILC will proceed
  - cost & feasibility of ν Factory & μ Collider

- Will be ready to proceed with final design & construction of one or both of these muon facilities

- Each appears considerably cheaper than ILC

- Given the will, and the resources, either or both could be operational by 2020

Summary

- Muon storage rings are potentially a uniquely powerful option for future HEP facilities
- Proof of principle accomplished for high-power targetry at > 4 MW!
- After much R&D, muon cooling looks feasible
  - both in transverse and longitudinal phase planes
- MICE should establish feasibility of ionization cooling by ~2012
- New techniques could yield muon emittances comparable to ILC values
- Future looks bright for muon colliders and neutrino factories!

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
  - goals: 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
- International Design Study in progress – next mtg Mumbia, India12–14 October
  - see https://www.ids-nf.org/wiki/FrontPage

“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) [D59:039903,1999(E)]; also CERN yellow report (1999) [CERN 99-02, ECFA 99-197]
- Formation of ICAR (1998), then Muons, Inc. (2002)
- Fermilab Muon Collider Task Force established (2006)
- 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