Muon Cooling and Future Muon Facilities

Daniel M. Kaplan

Joint Meeting of Pacific Region Particle Physics Communities
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Sheraton Waikiki Hotel, Honolulu, HI
29 October – 3 November, 2006

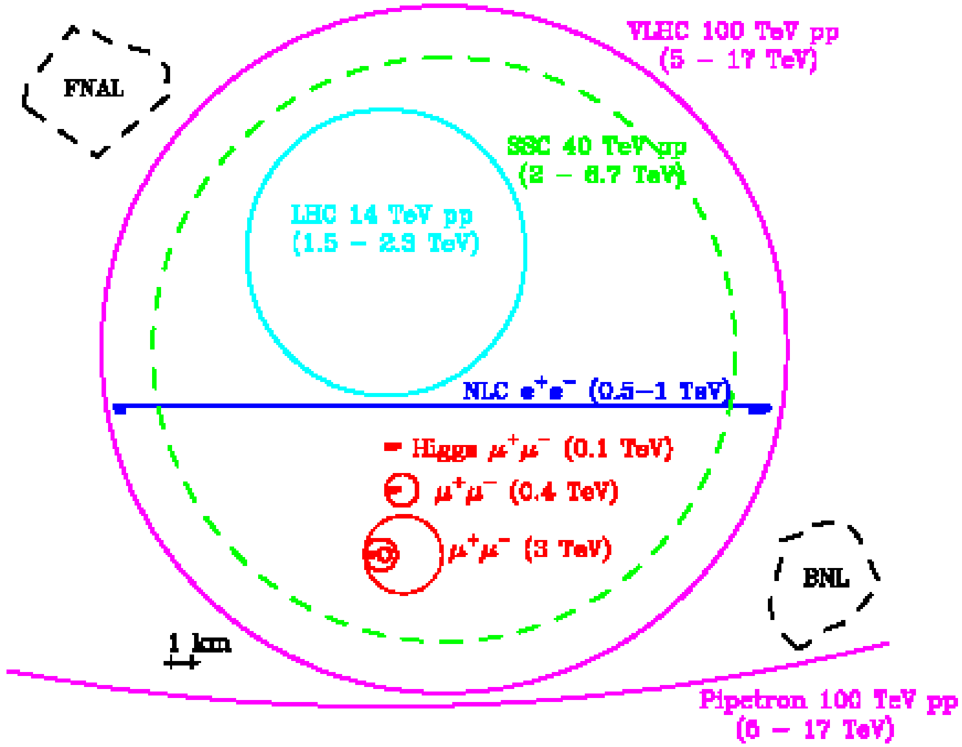
Outline:

1. Muon Colliders
2. Neutrino Factories
3. Muon Cooling
4. MERIT, MICE, MANX, EMMA
5. Summary

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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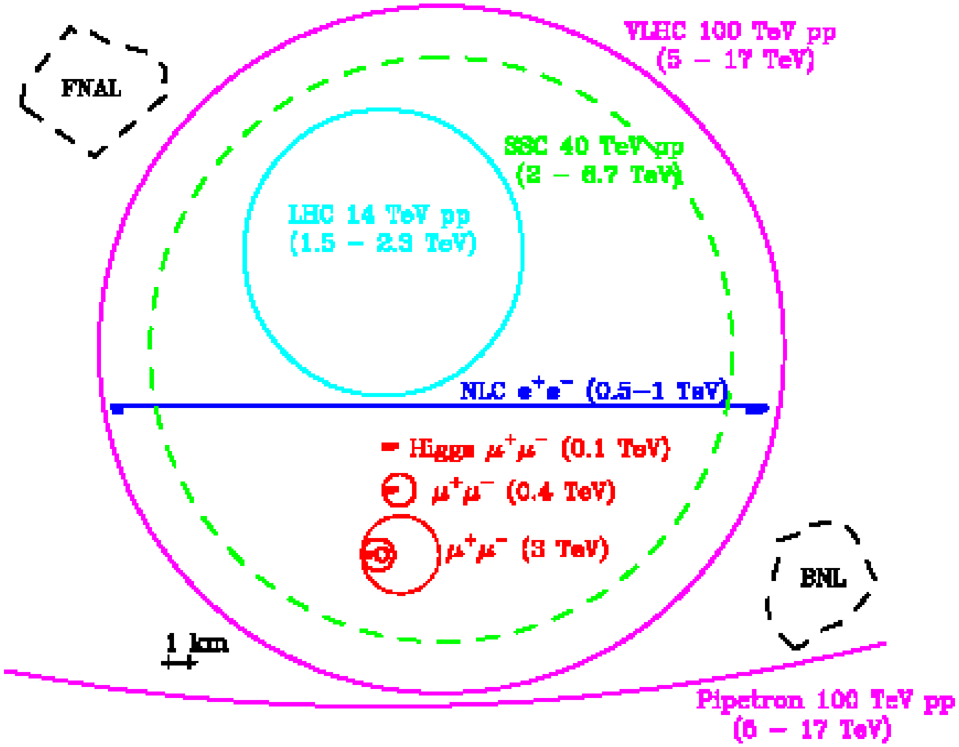

- Also...

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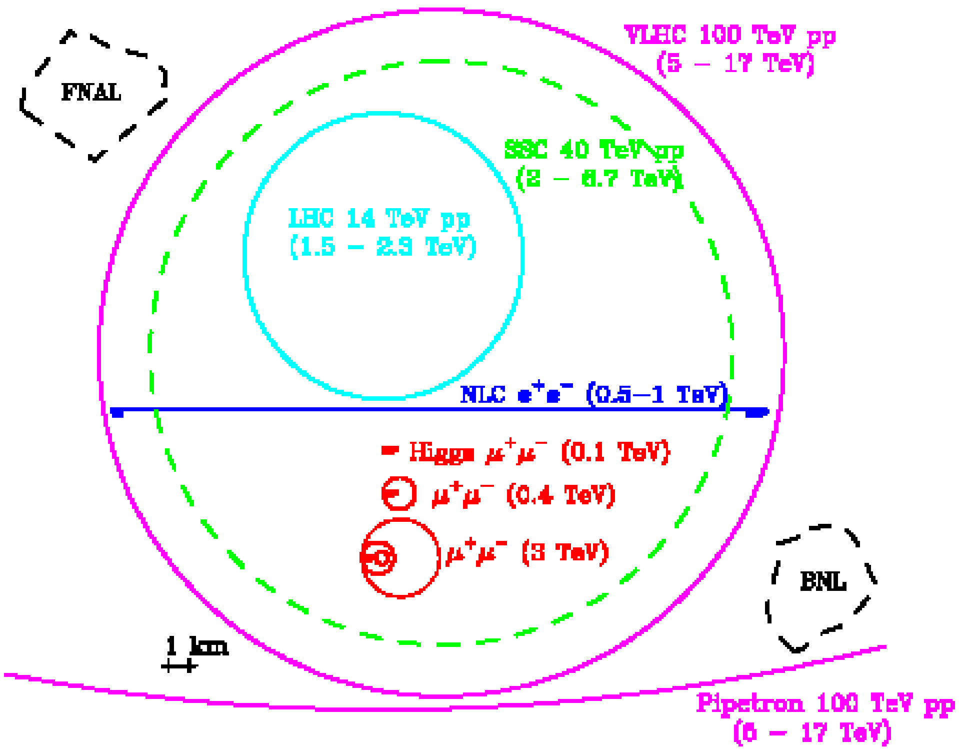
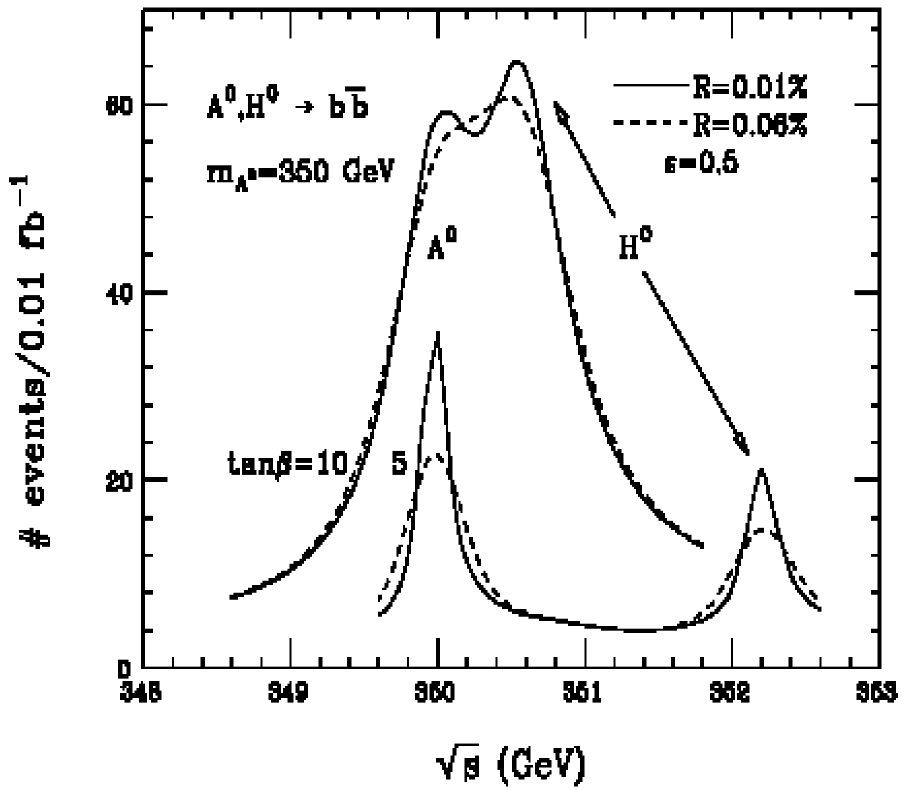


- Also...

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

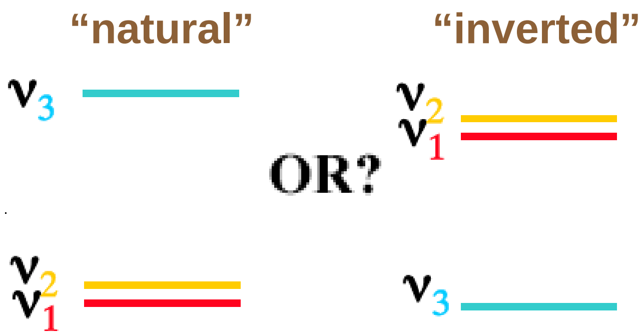


- E.g., μμ-collider resolution can separate near-degenerate scaler and pseudo-scalar Higgs states of high-tan β SUSY

Why a Neutrino Factory?

- Neutrino mixing raises fundamental questions:

1. What is the neutrino mass hierarchy?



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)

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

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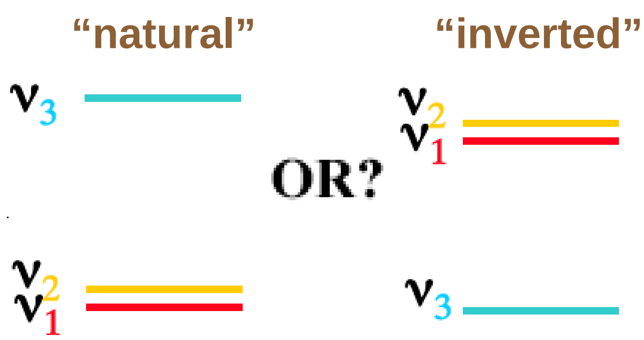

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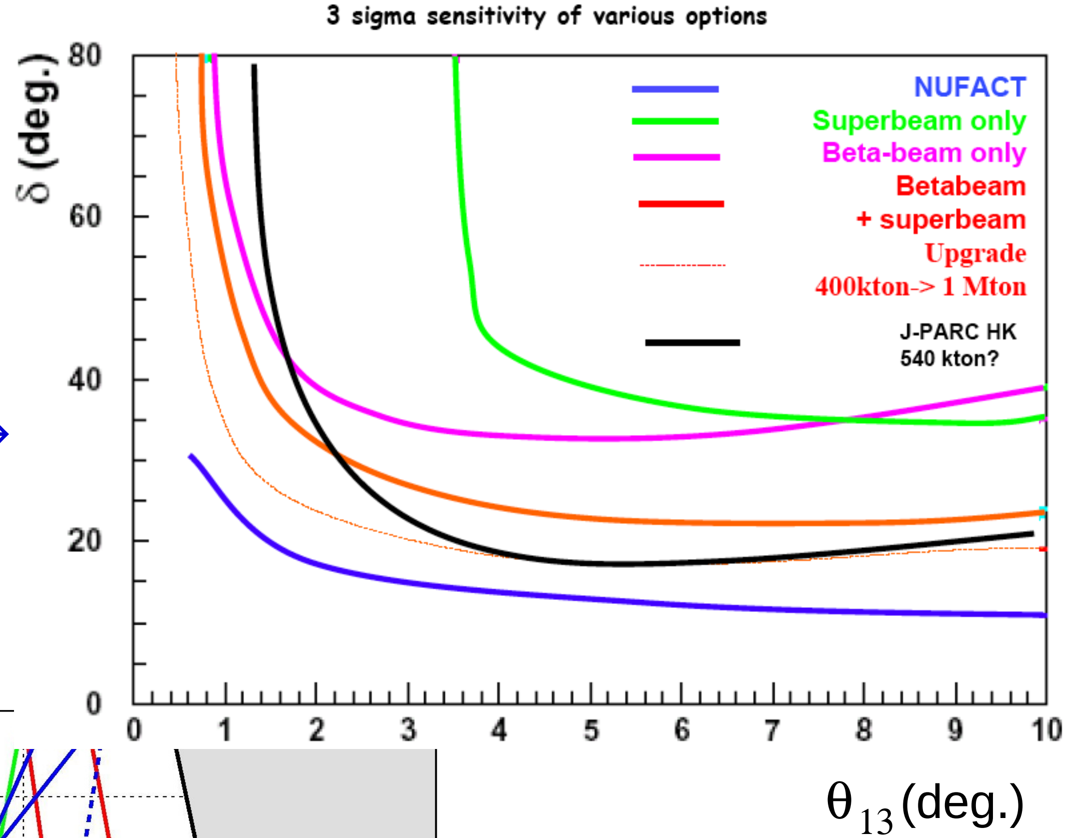
- **These call for a program to measure the PMNS elements as well as possible.**

Neutrino Factory Physics Reach

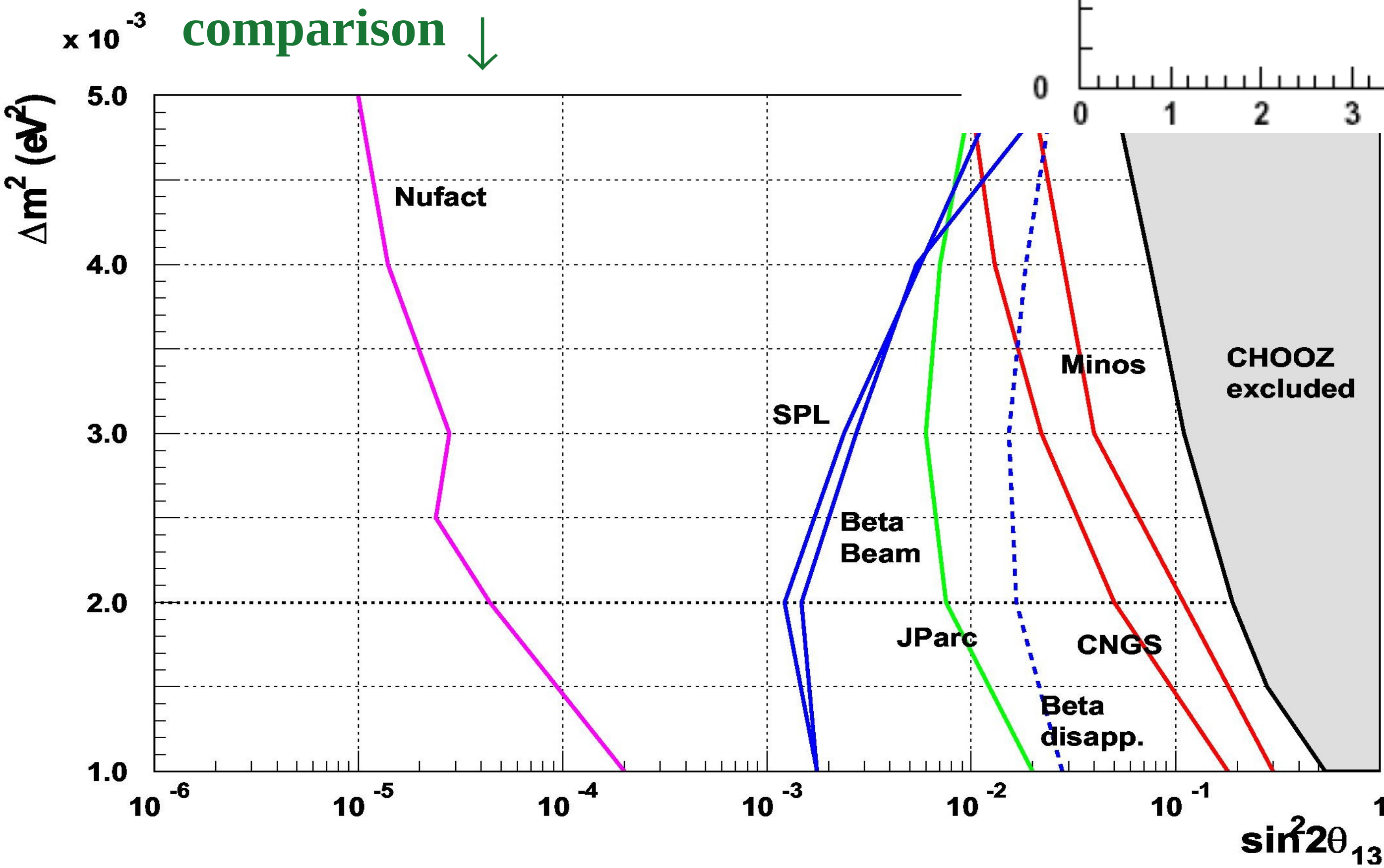
- Neutrino Factory is most sensitive technique yet devised

  see e.g. M. Lindner, hep-ph/0209083
  & C. Albright et al., Fermilab-FN-692 (2000)

CP-sensitivity comparison →



Oscillation-parameter comparison ↓

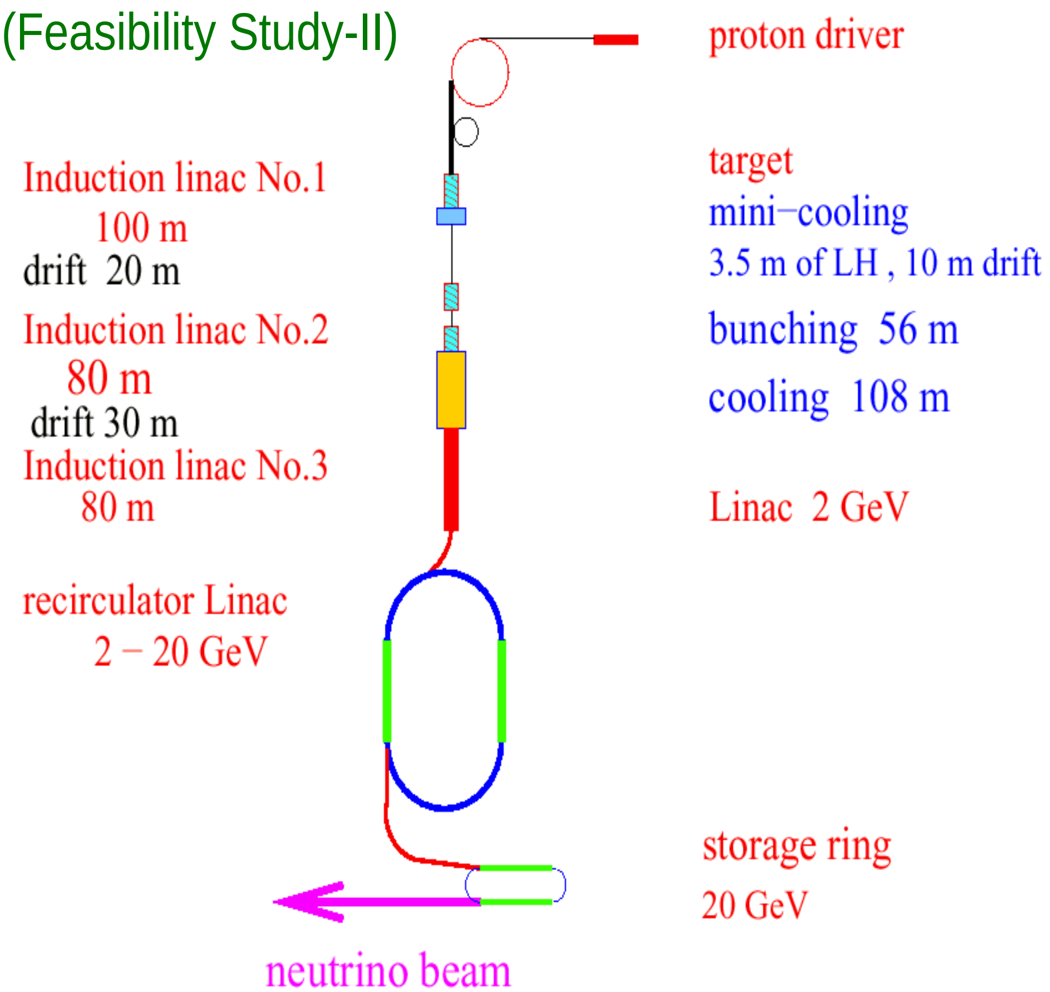


(plots from A. Blondel, NO-VE Workshop, Venice, Dec. 03)

Muon Facility Examples:

- Neutrino Factory:

(Feasibility Study-II)



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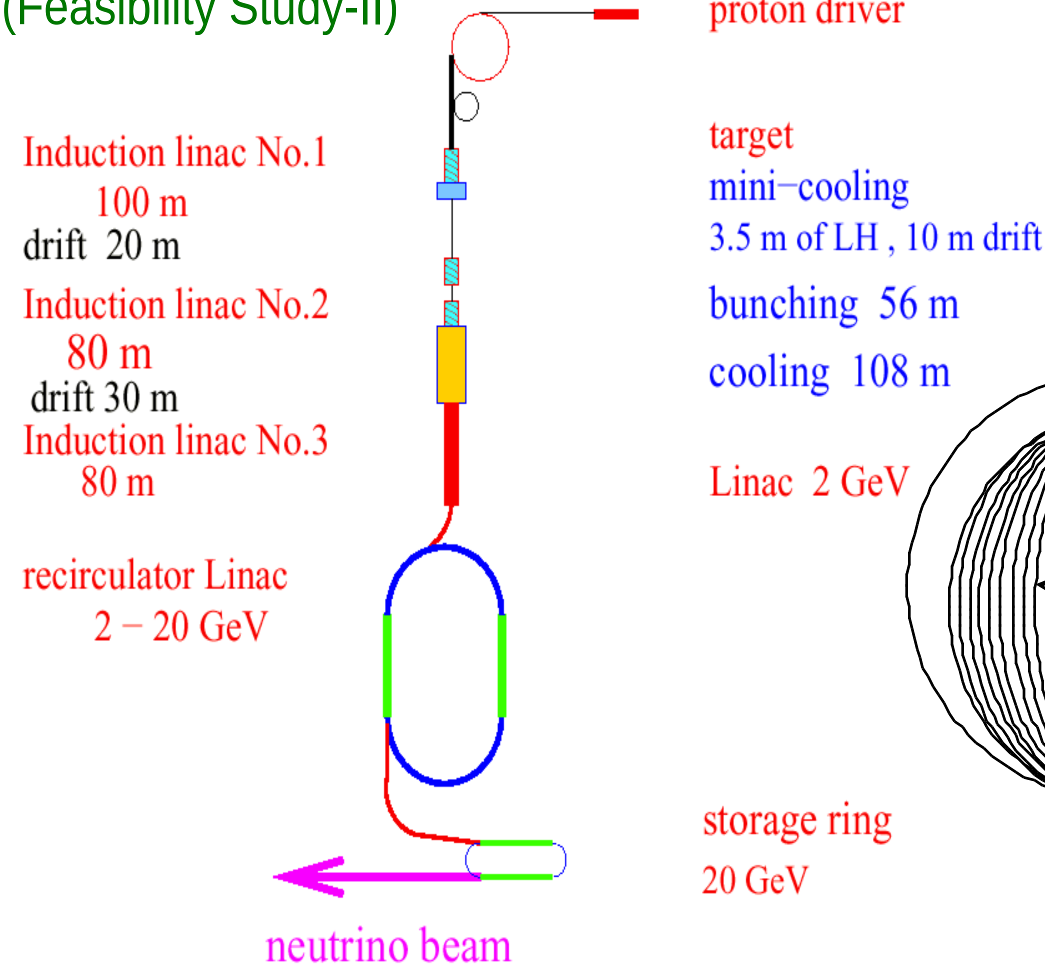
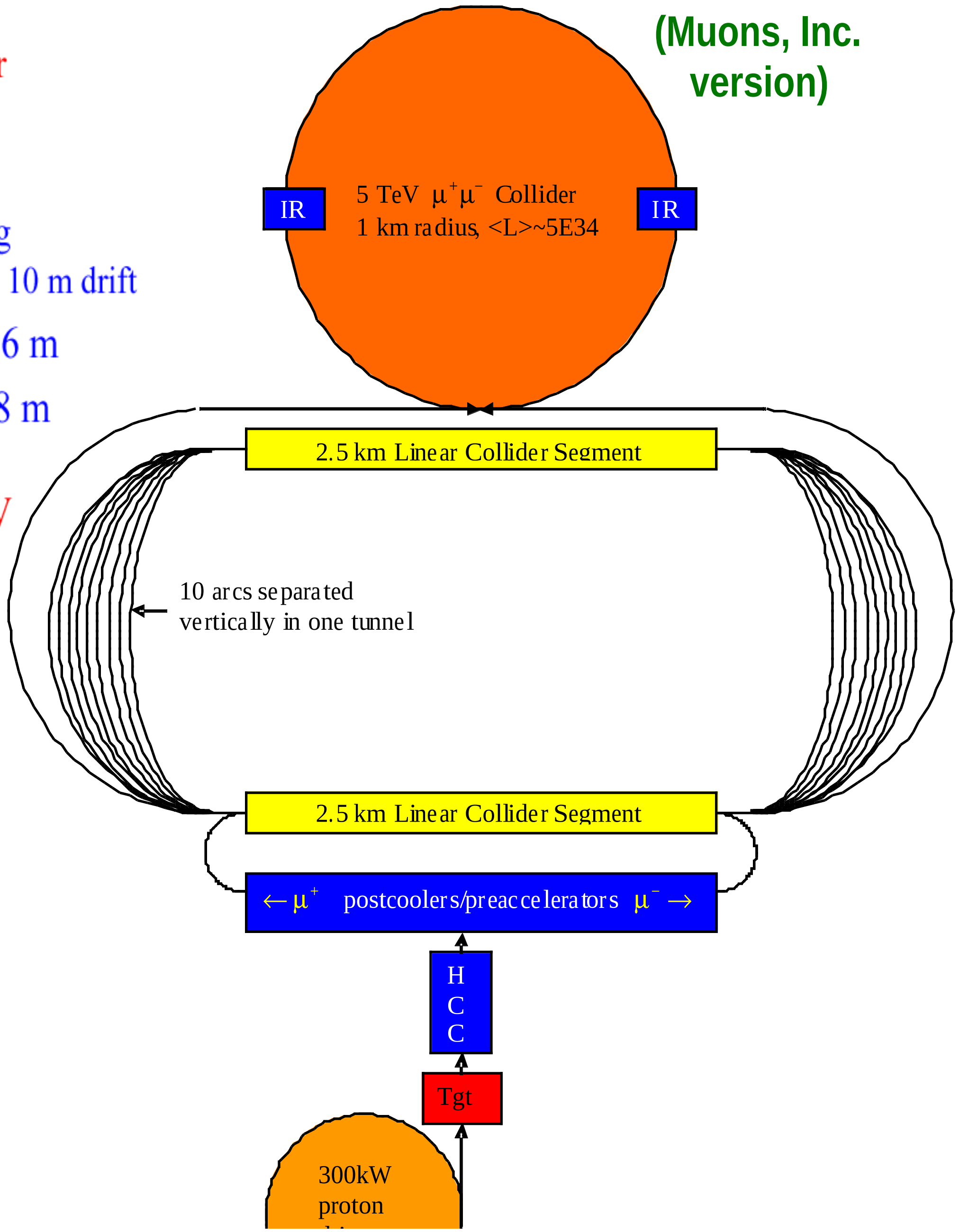


- $\mu^+\mu^-$ collider:

(Muons, Inc. version)



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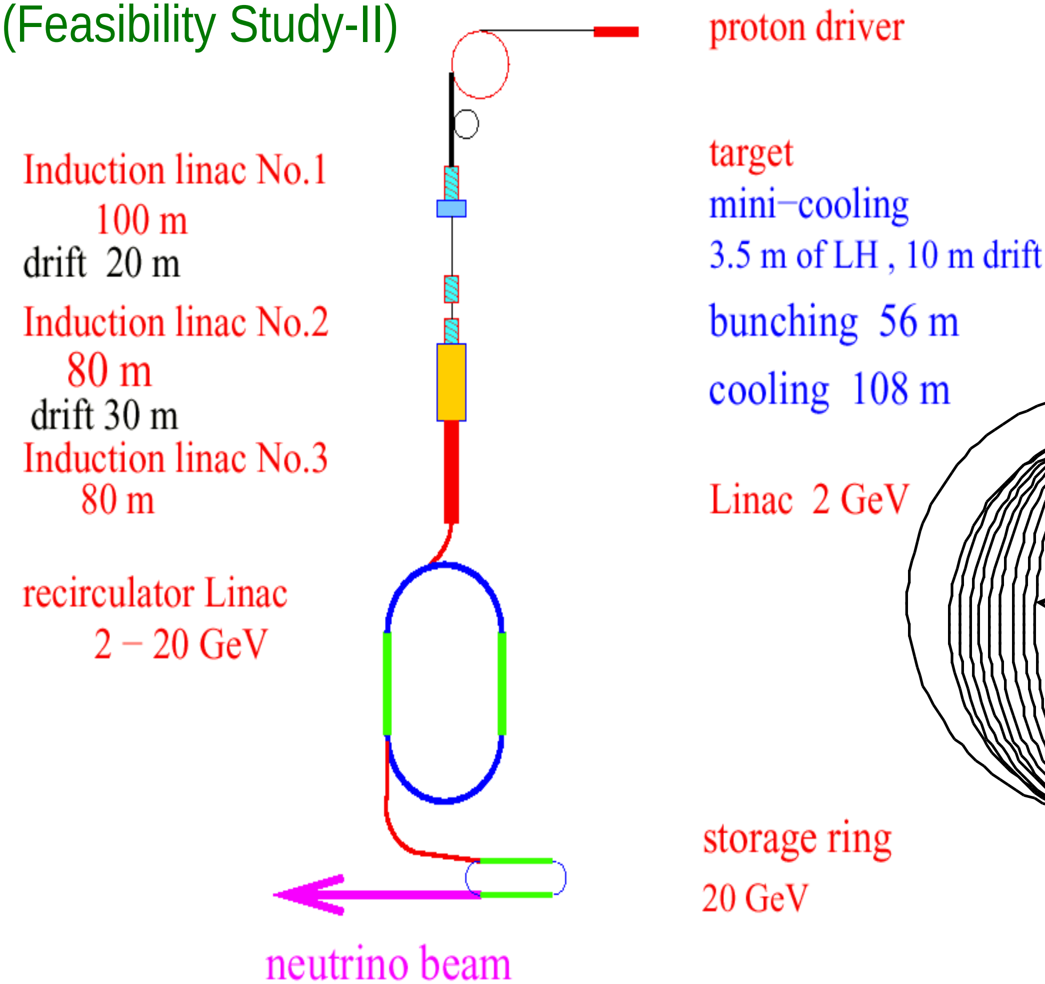

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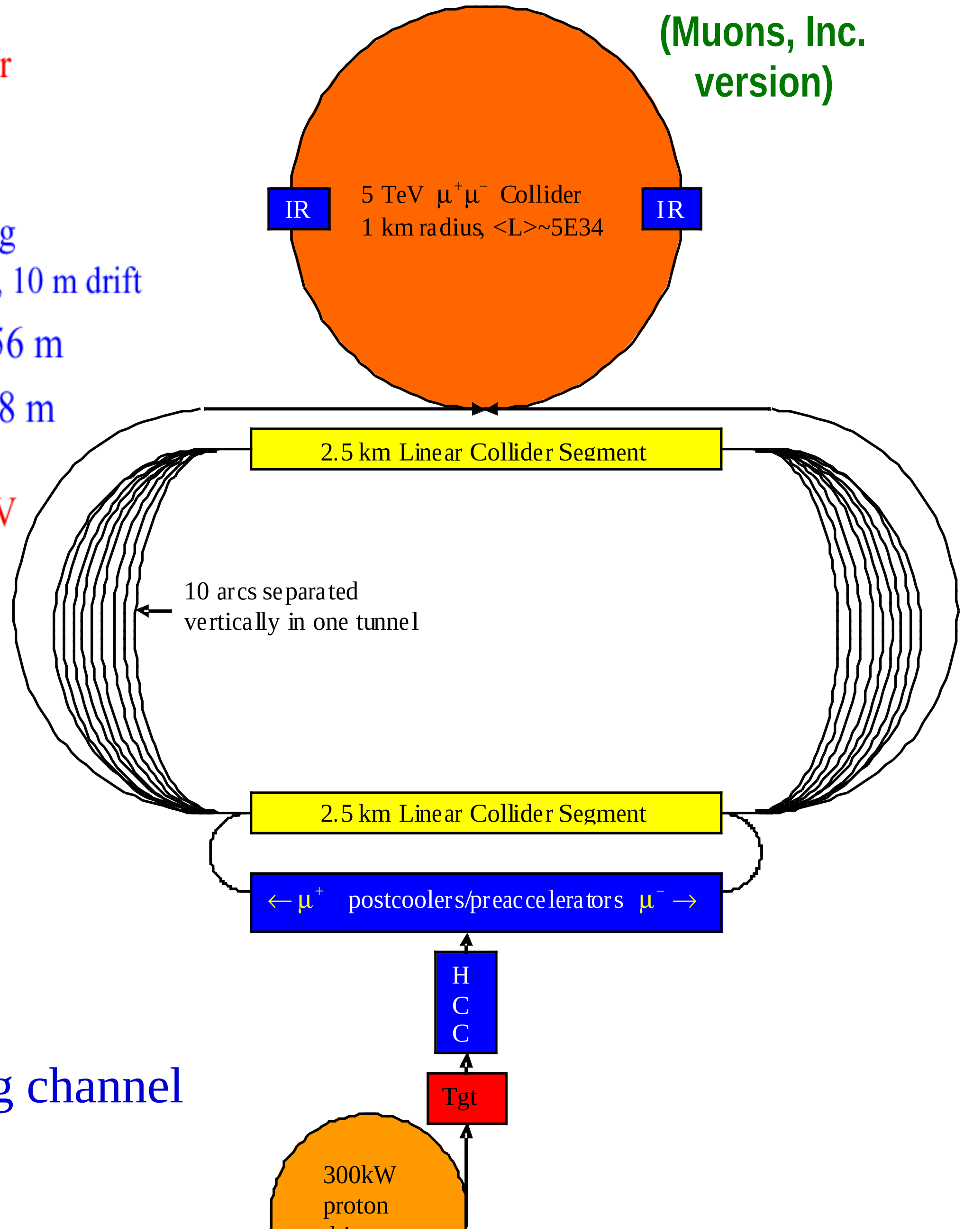

- Common features:
  1. p on tgt $\rightarrow \pi \rightarrow \mu$, collected in focusing channel
  2. μ cooling, acceleration, & storage

– then:

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

“A Brief History of Muons”

- Muon storage rings are an old idea:
  - Charpak *et al.* ($g-2$) (1960), Tinlot & Green (1960), Melissinos (1960)
- Muon colliders suggested by Tikhonin (1968)
- But no concept for achieving high luminosity until ionization cooling
  - 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

Muon Cooling – The Challenge:

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

Q: What cooling technique works in microseconds?

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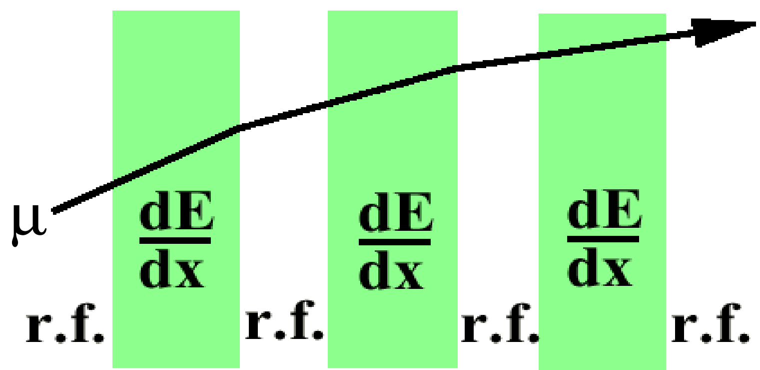
Ionization Cooling:

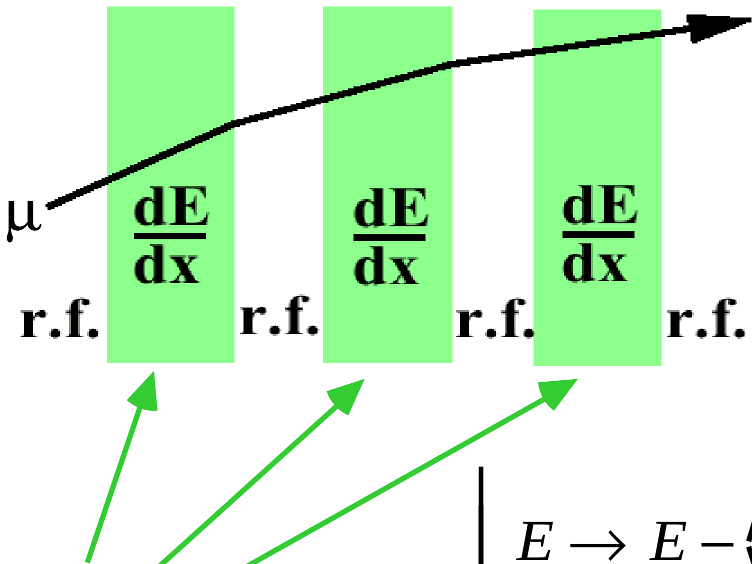


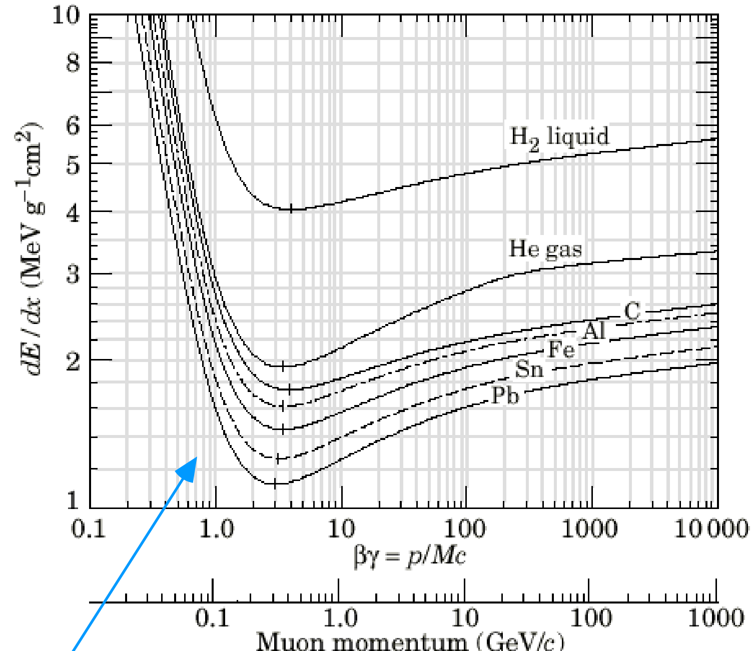
G. I. Budker and A. N. Skrinsky, Sov. Phys. Usp. **21**, 277 (1978)
A. N. Skrinsky and V. V. Parkhomchuk, Sov. J. Part. Nucl. **12**, 223 (1981)

→ **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 $p_\perp$ at constant $p_{\|}$, i.e., transverse cooling

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

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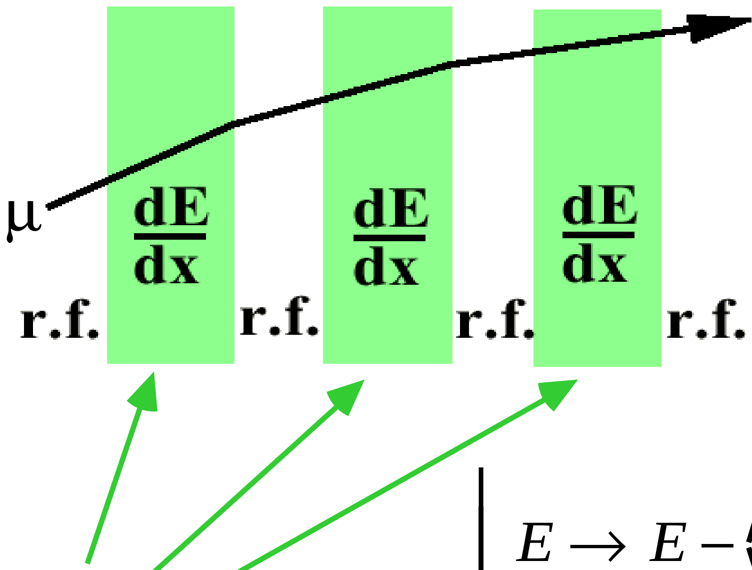

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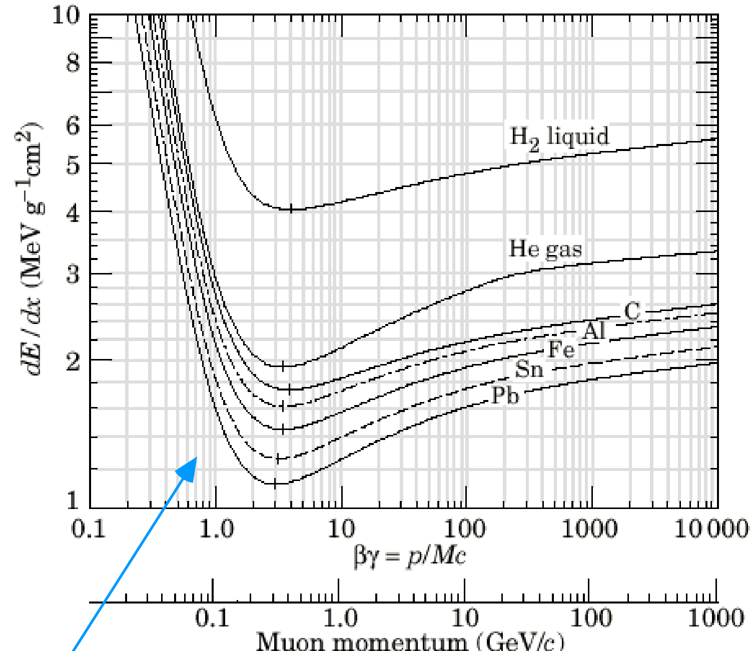

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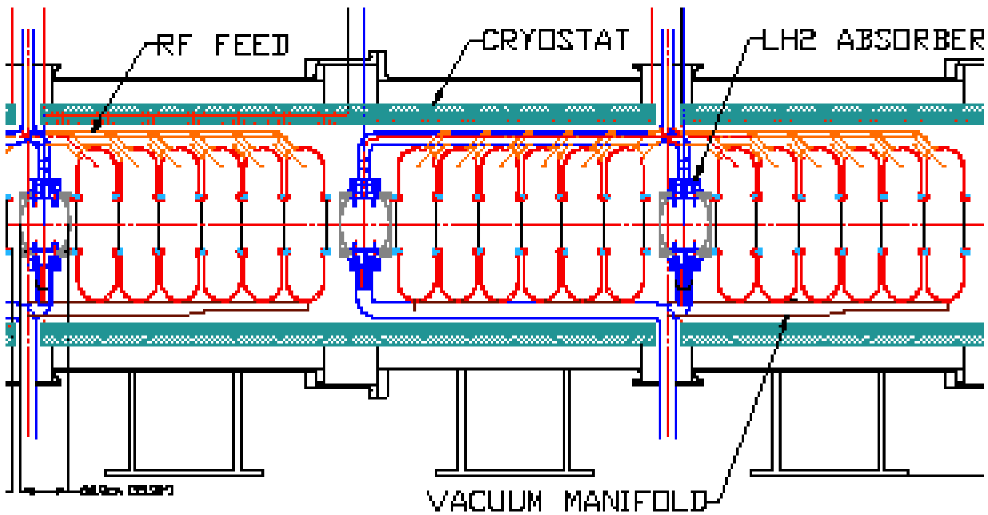
⇒ want strong focusing, large X_0 (low Z), and low E_μ

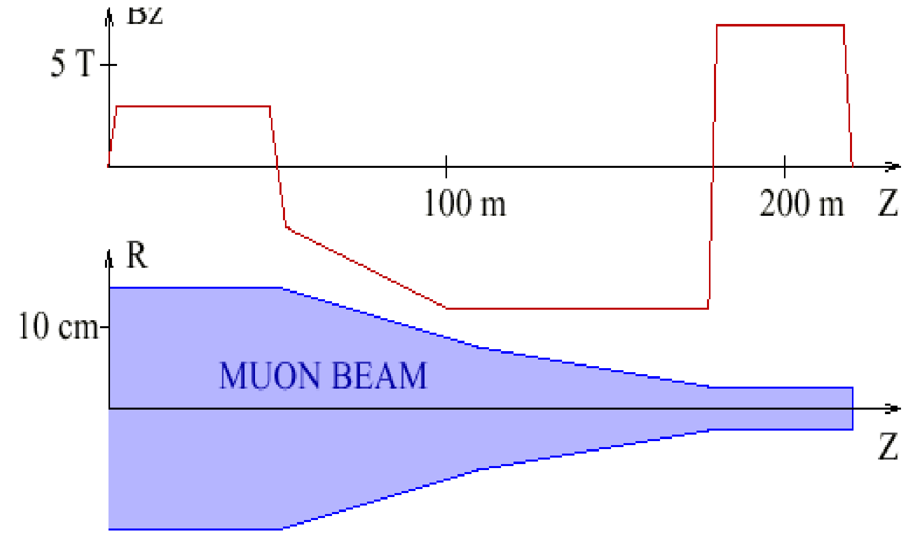
→ **How can this be achieved...?**

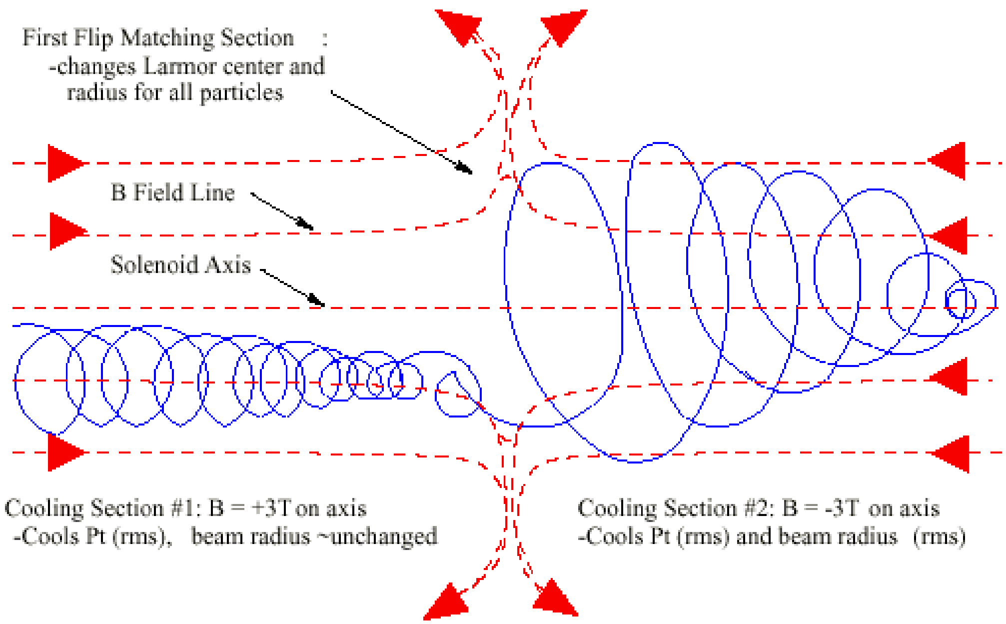
E.g., Double-Flip Cooling Channel

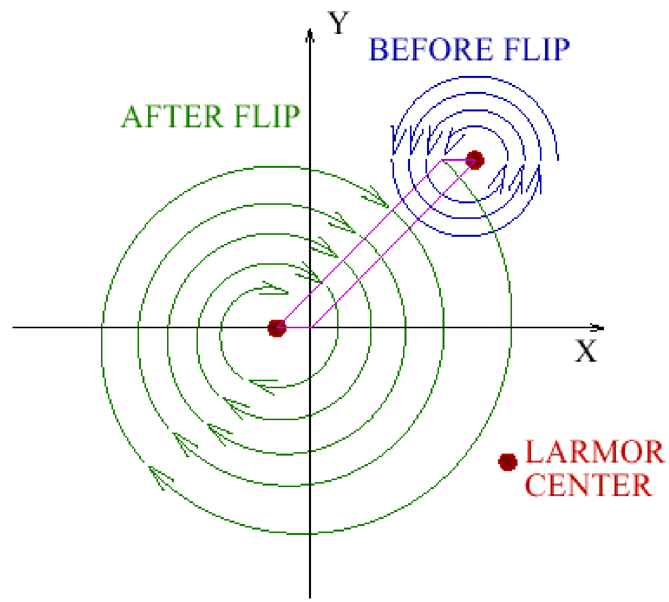
V. Balbekov & D. Elvira (FNAL)

- To get low β → big S/C solenoids & high fields!







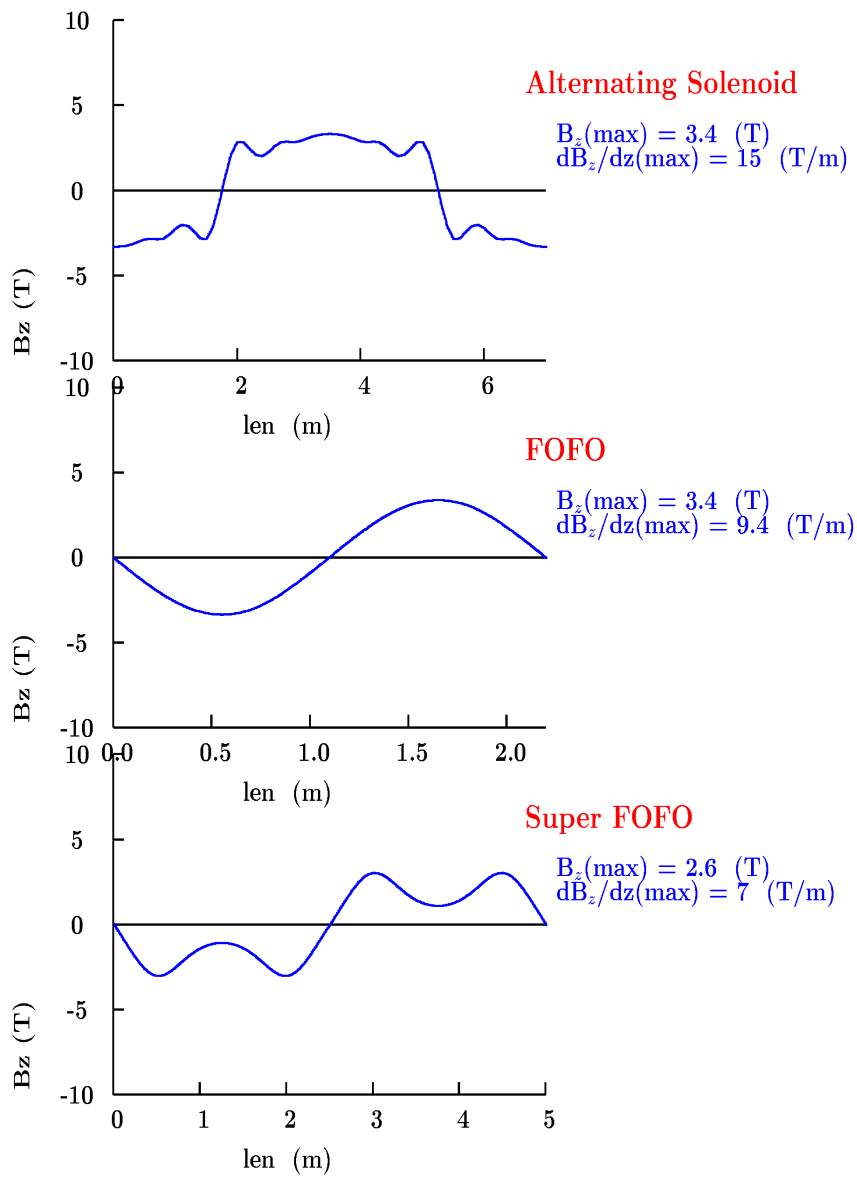


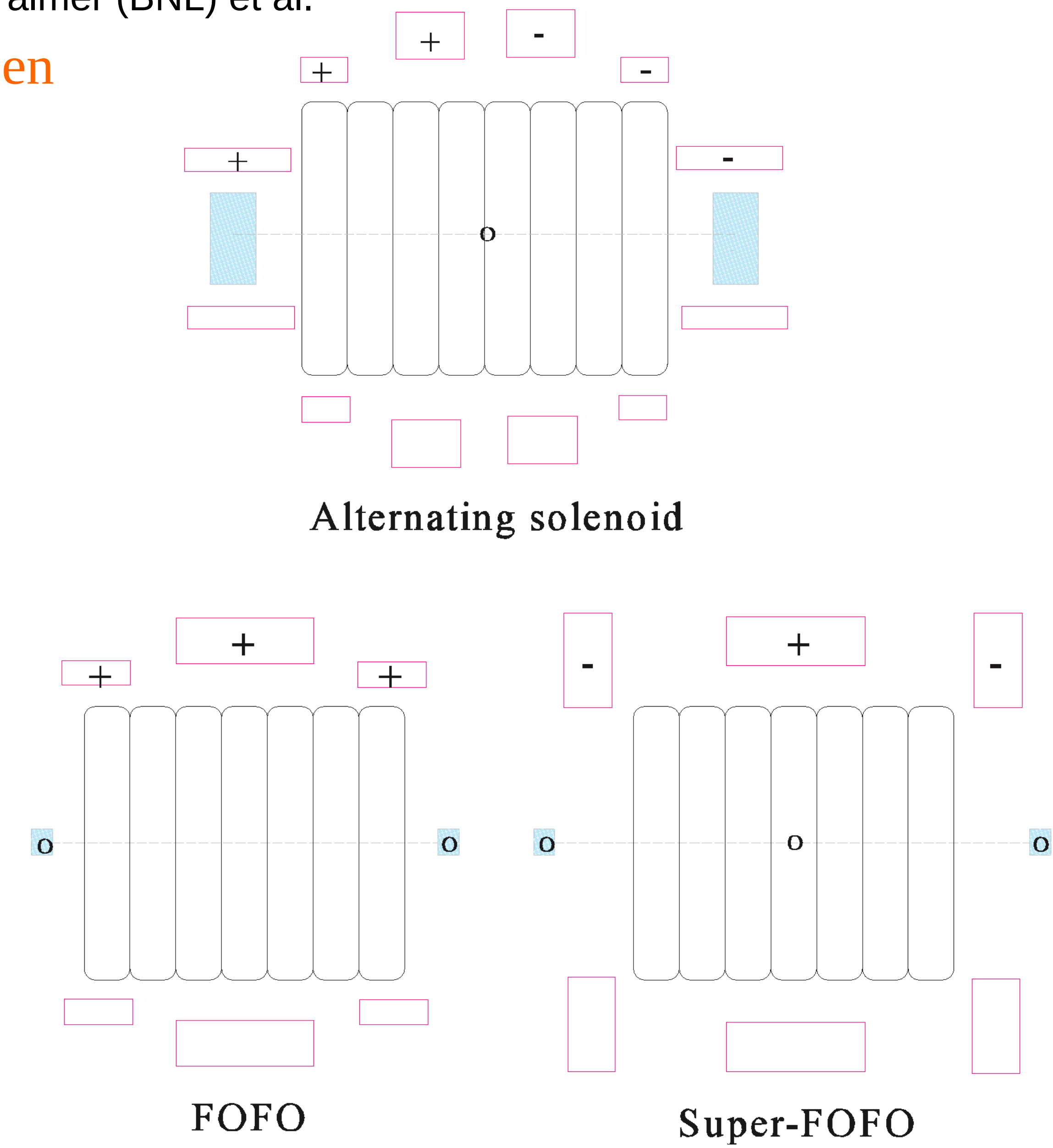
⇒ expensive

Or, Periodic Cooling Lattices

R. Palmer (BNL) et al.

- Various lattice designs have been studied:

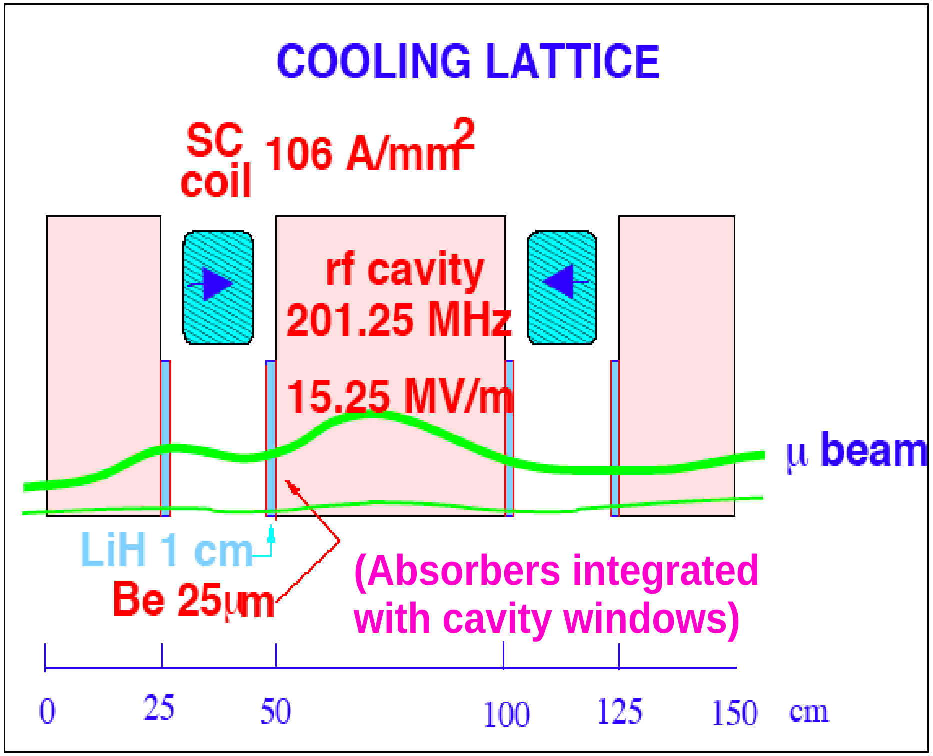




(+ RFOFO, DFOFO, Single-Flip, Double-Flip)

→ Alternating gradient allows low β with much less superconductor

Example: APS 6-Month Neutrino Study Cooling Channel



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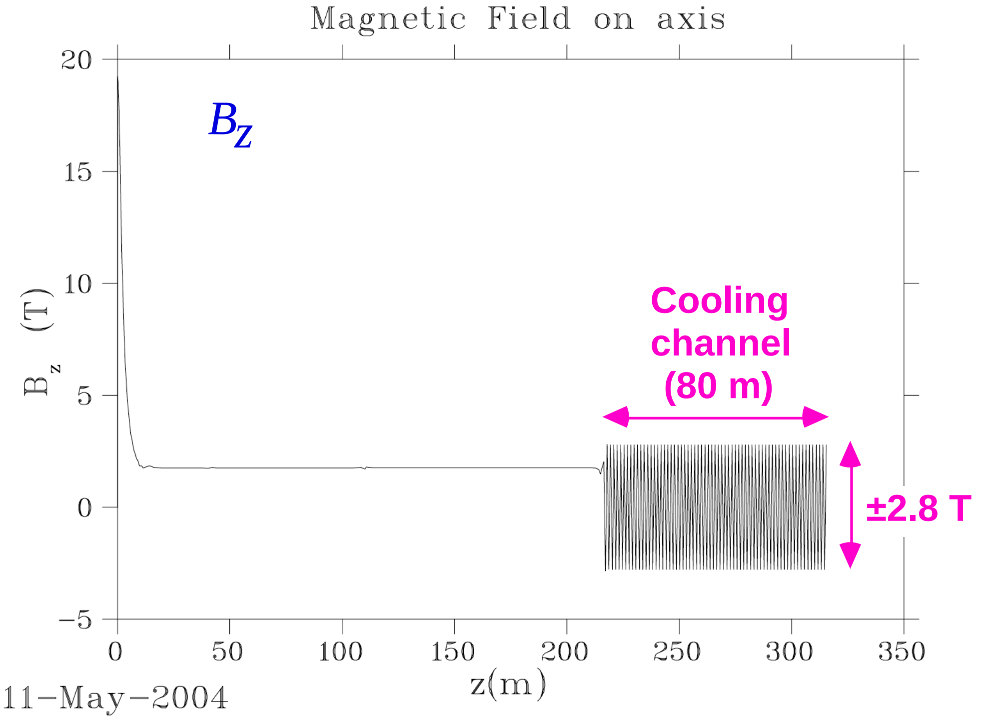

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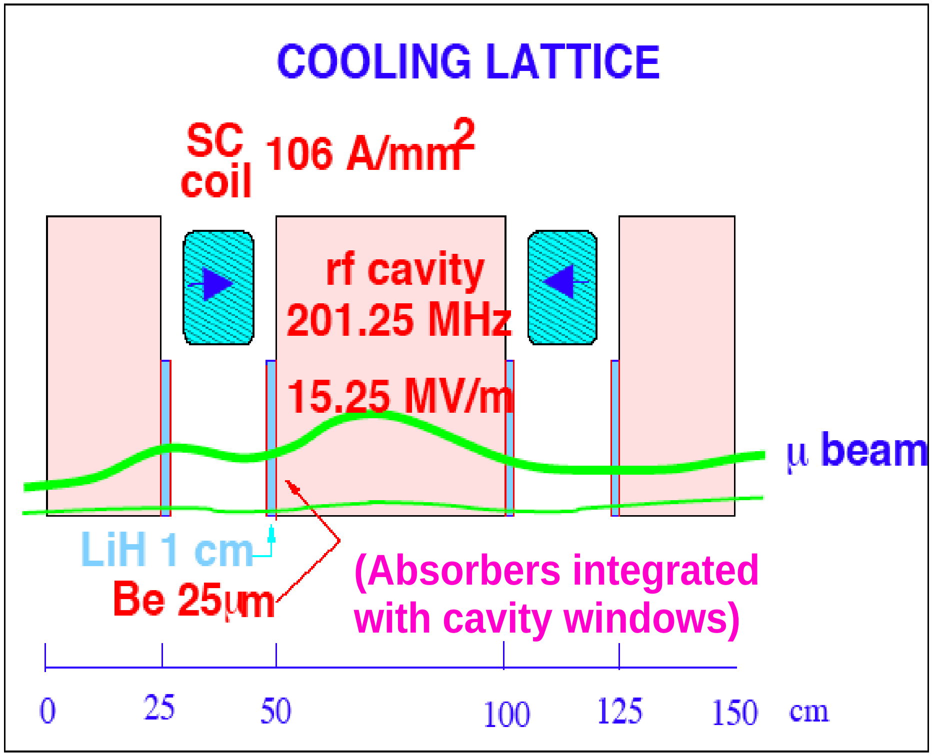

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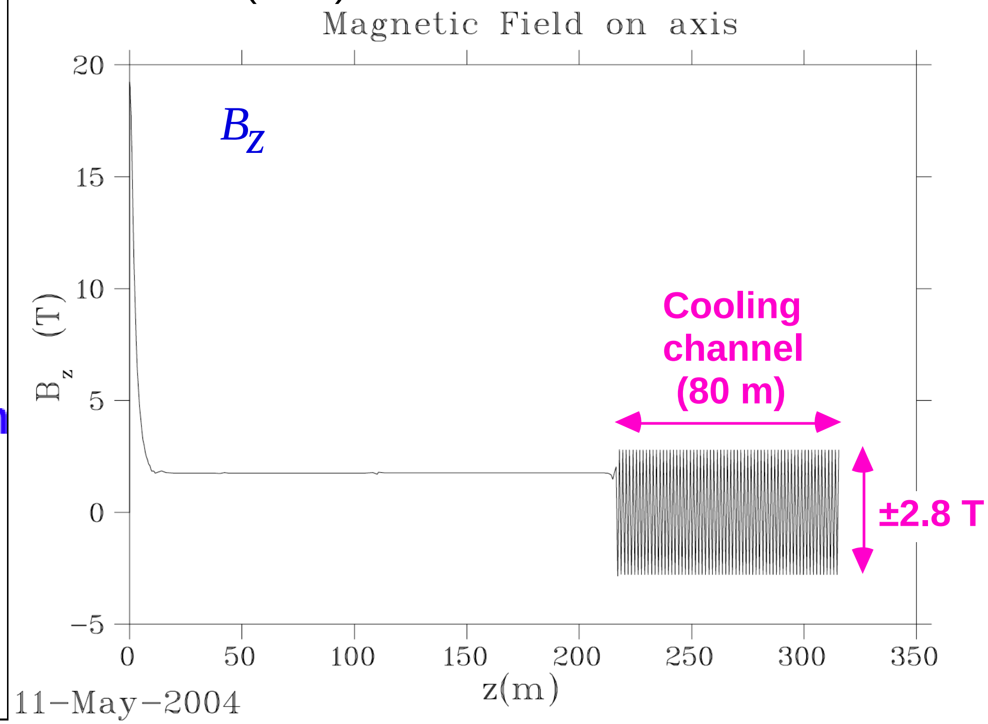
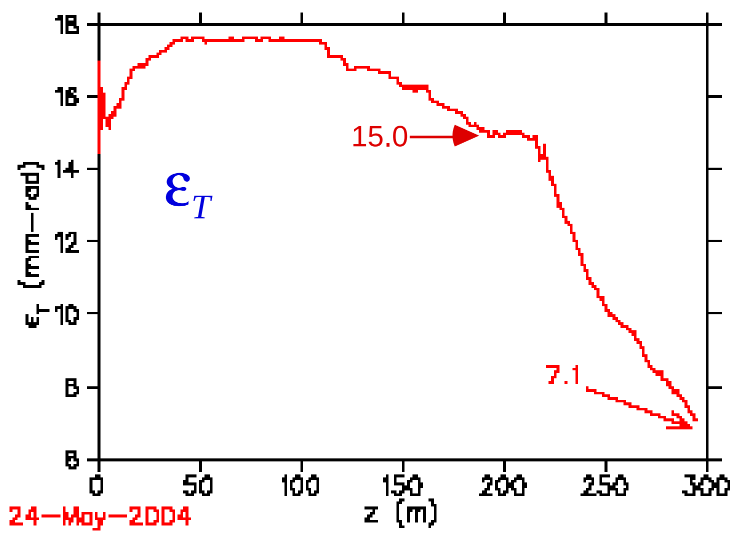
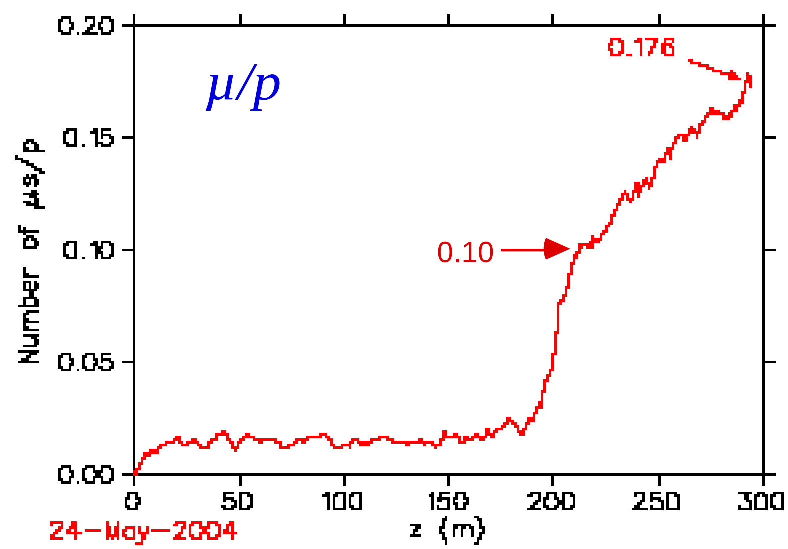


- Performance:





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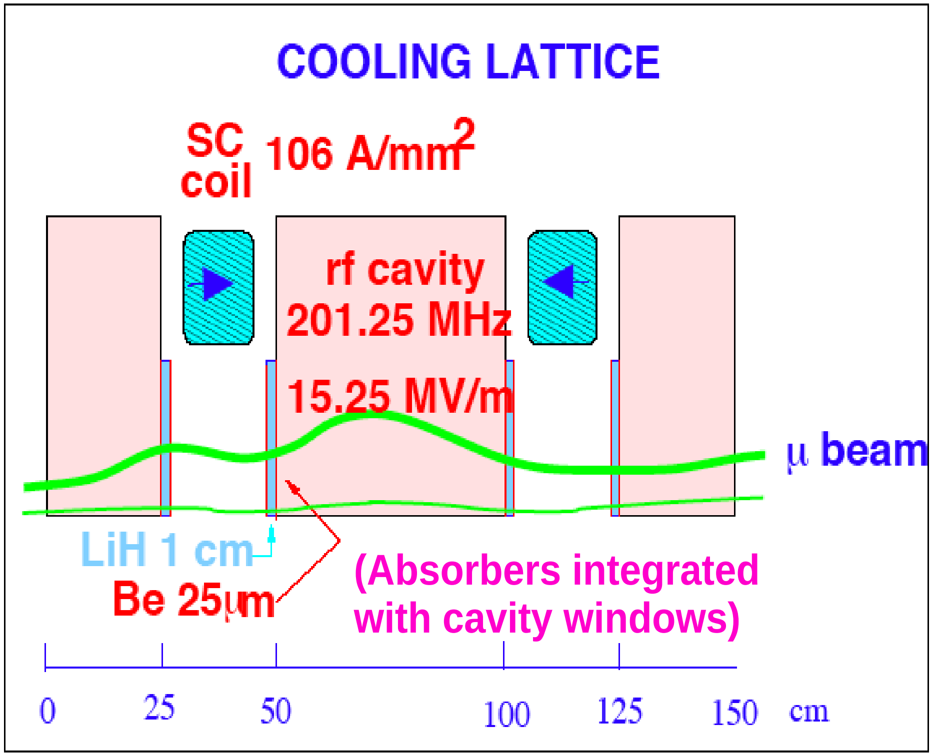

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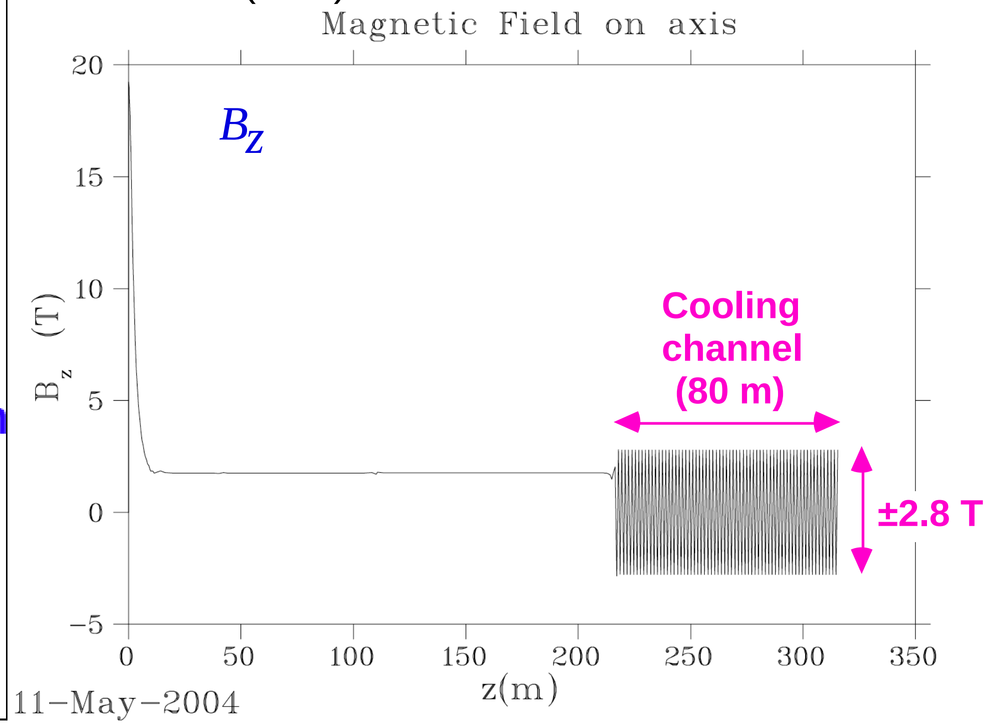

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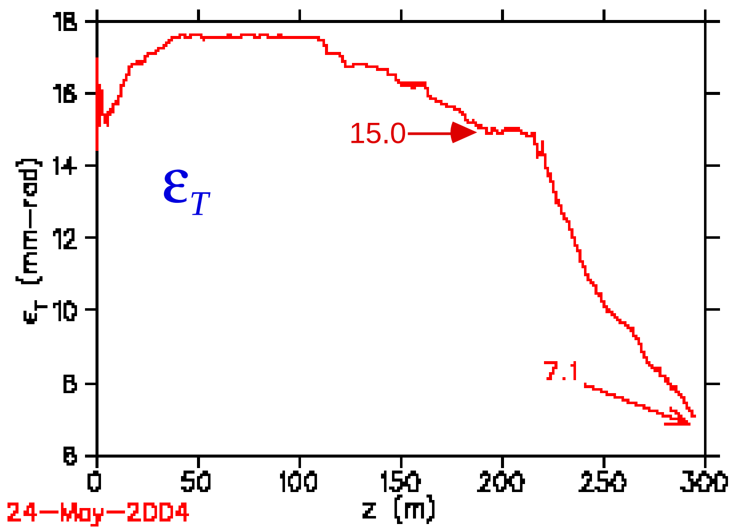

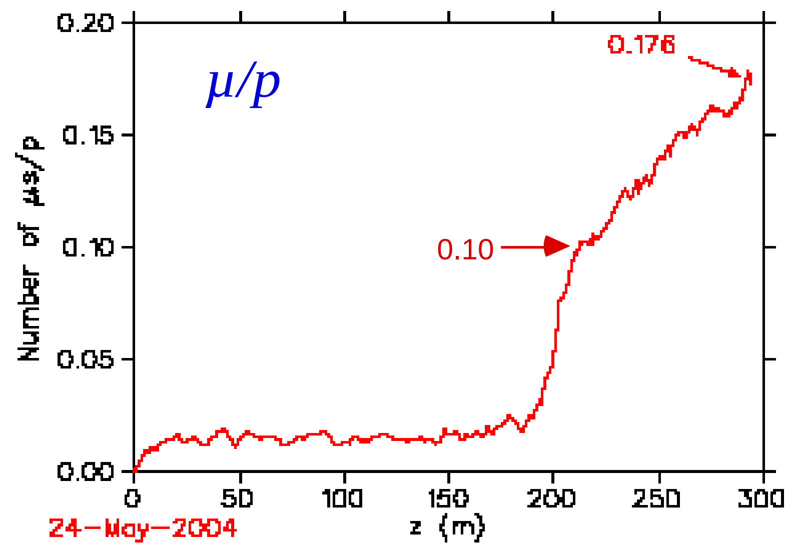

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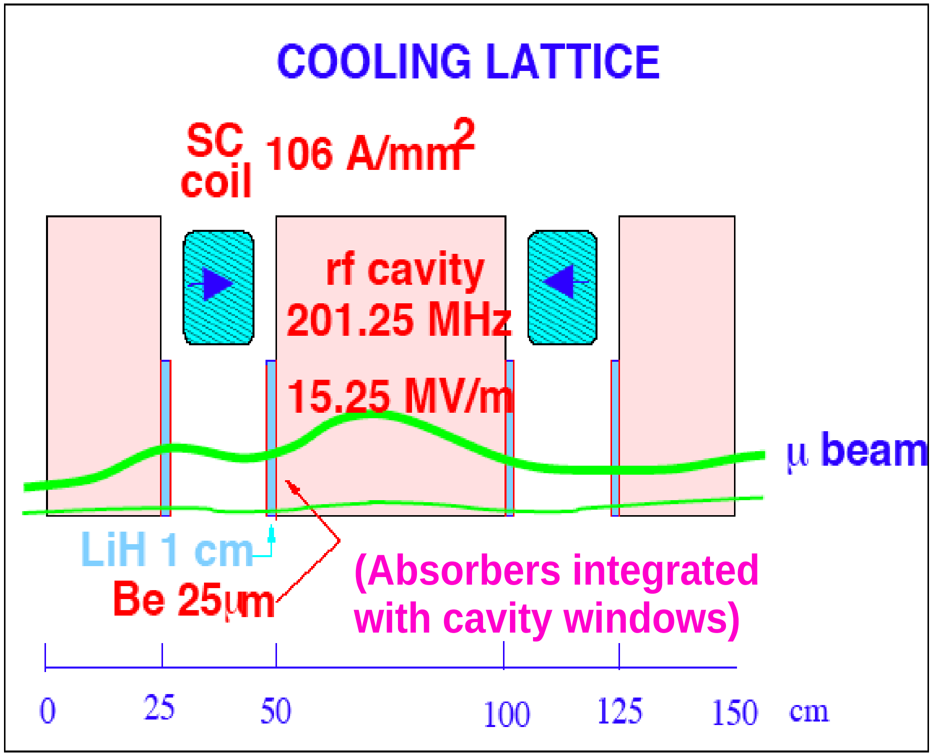

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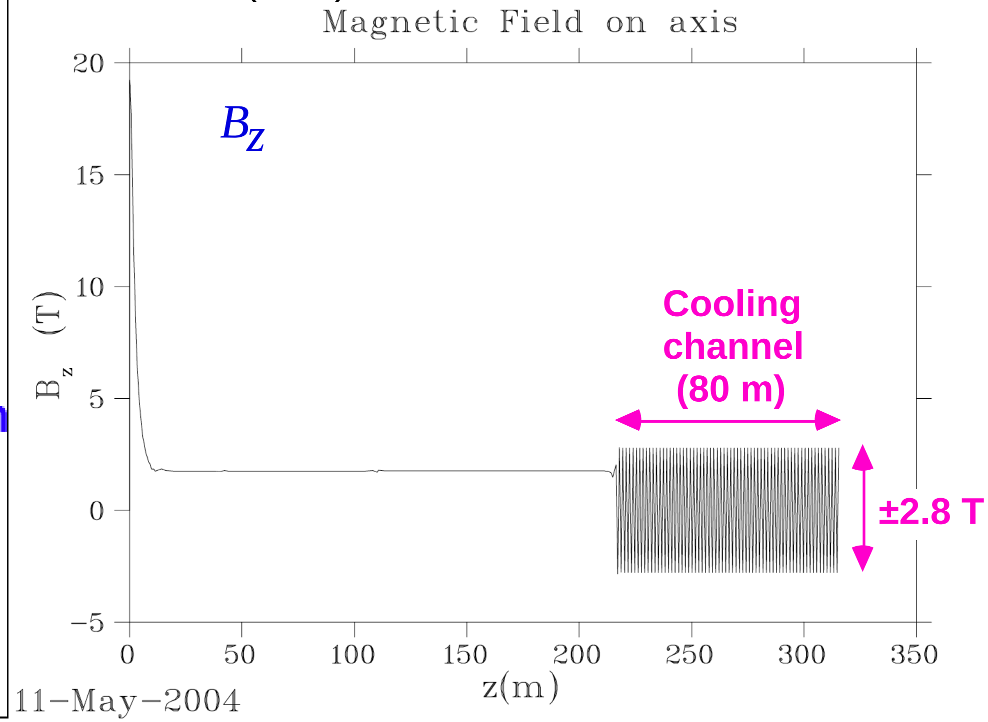

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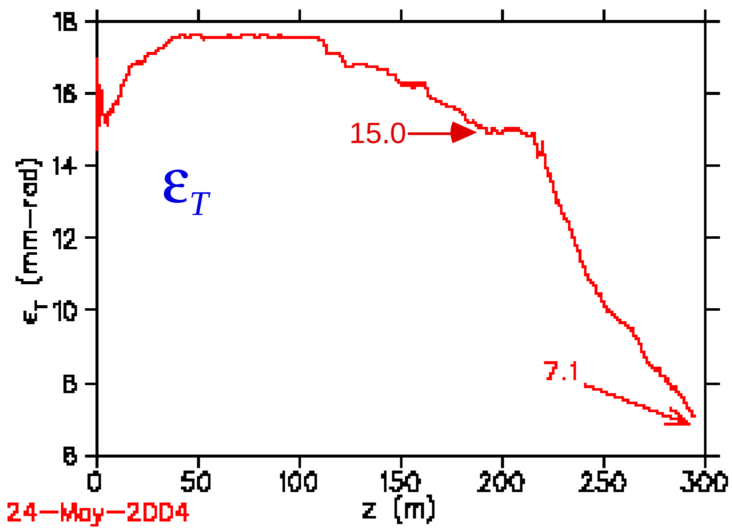

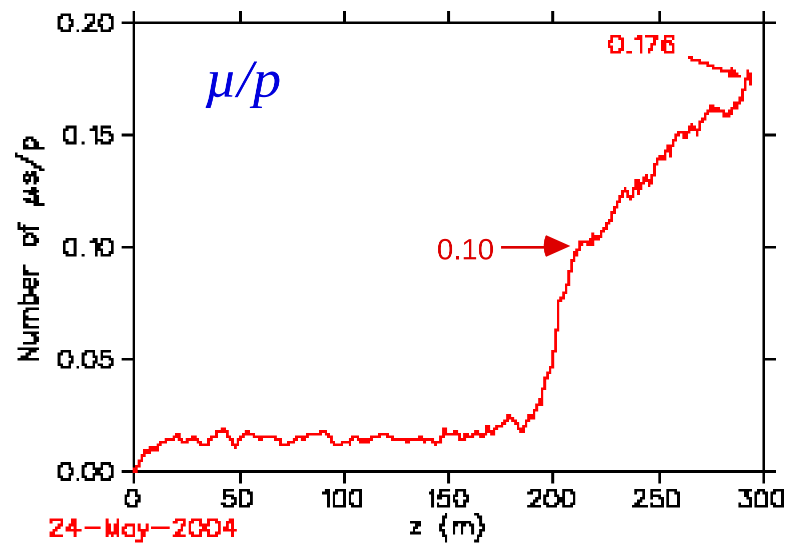

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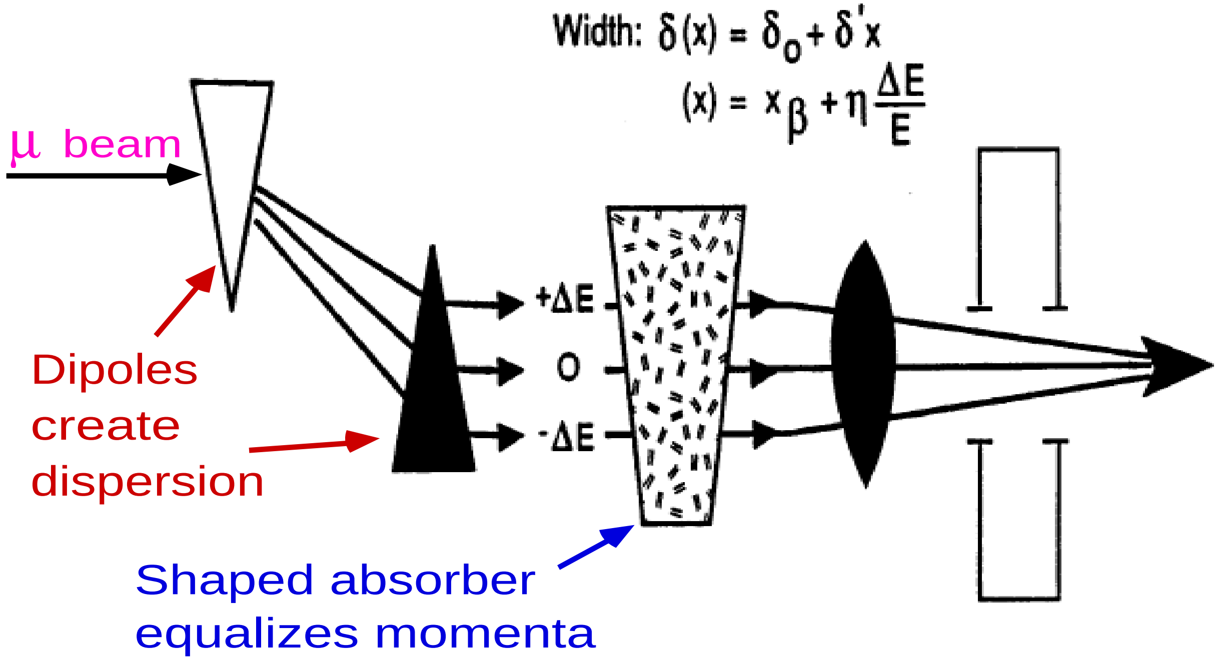
& increases μ/p-on-tgt $\times\, 0.176/0.10 \approx 1.8$ $\Rightarrow$ **Cost-effective for NF**

Longitudinal Cooling?

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

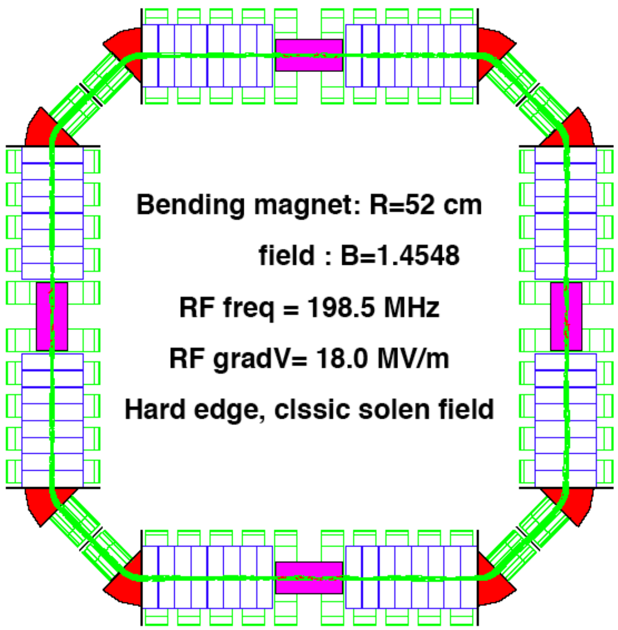
- Possible in principle by ionization (at momenta above ionization minimum), but inefficient due to straggling and small slope *d(dE/dx)/dE*

→ ***Emittance-exchange*** concept:



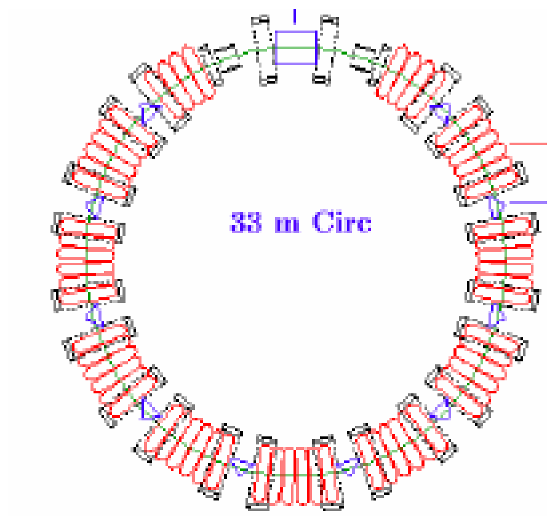
- Promising paper designs exist, e.g.,...

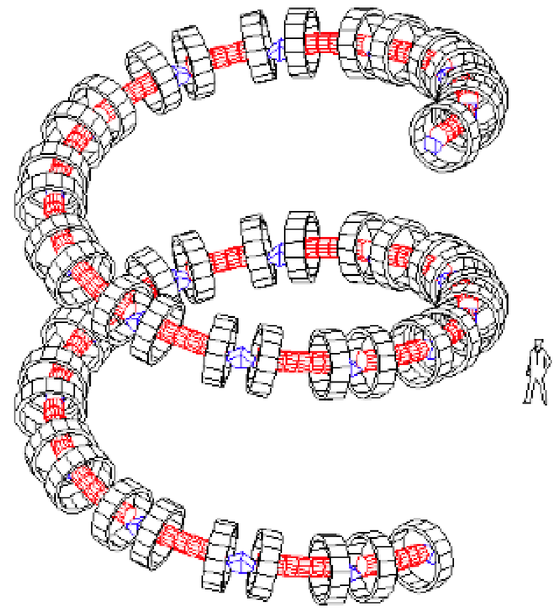
Some 6D Cooling Approaches



"Tetra" ring (Balbekov)

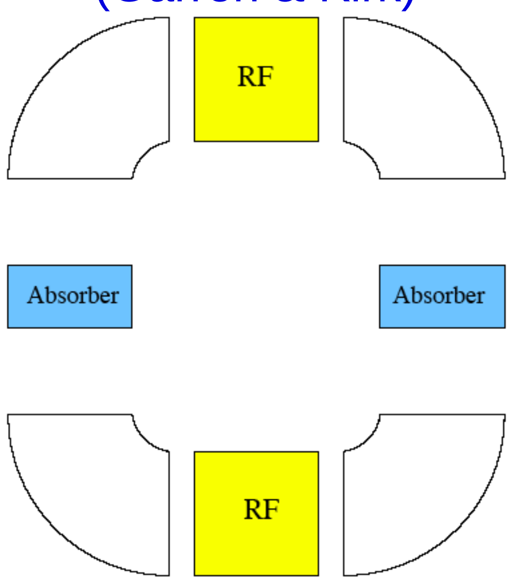
RFOFO ring (Palmer)



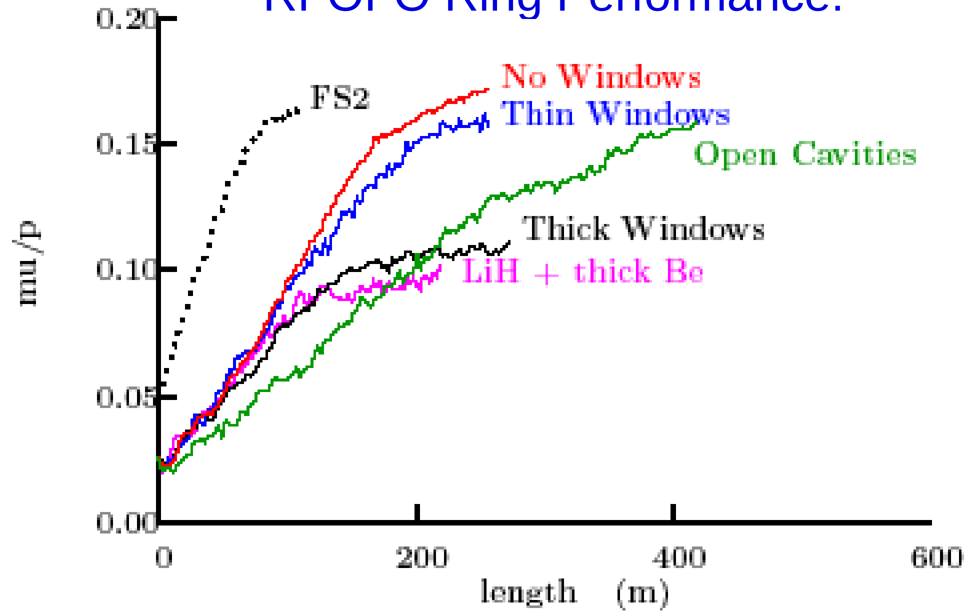


"Guggenheim" version (Klier)

The Two Cell Dipole only Ring
(Garren & Kirk)



RFOFO Ring Performance:



Helical Cooling Channels

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

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

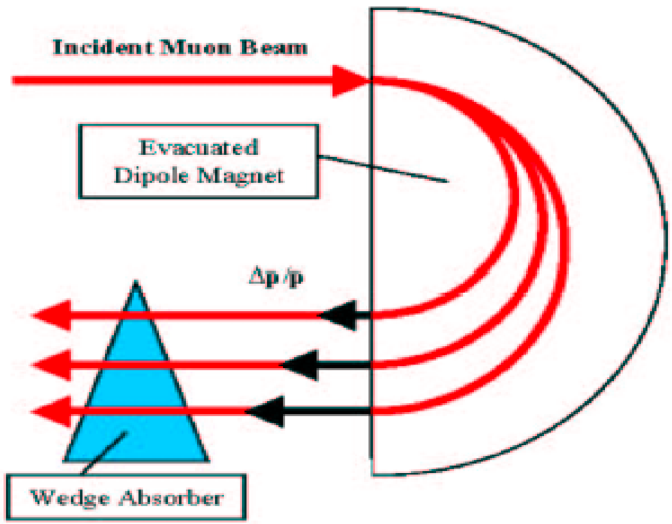


Figure 1. Use of a Wedge Absorber for Emittance Exchange

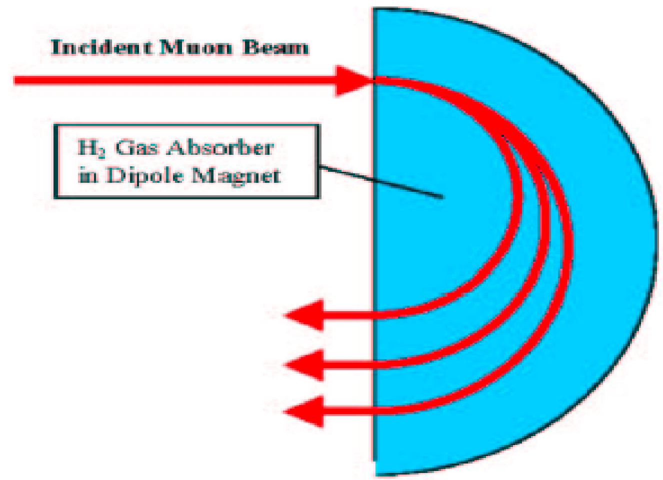
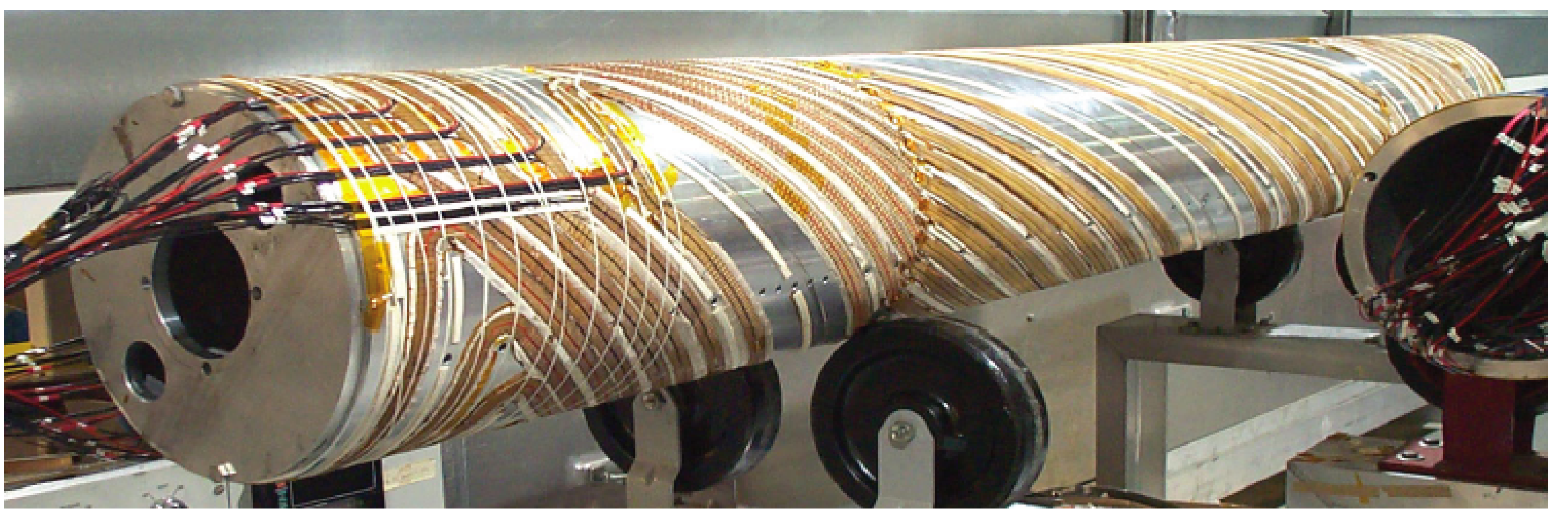


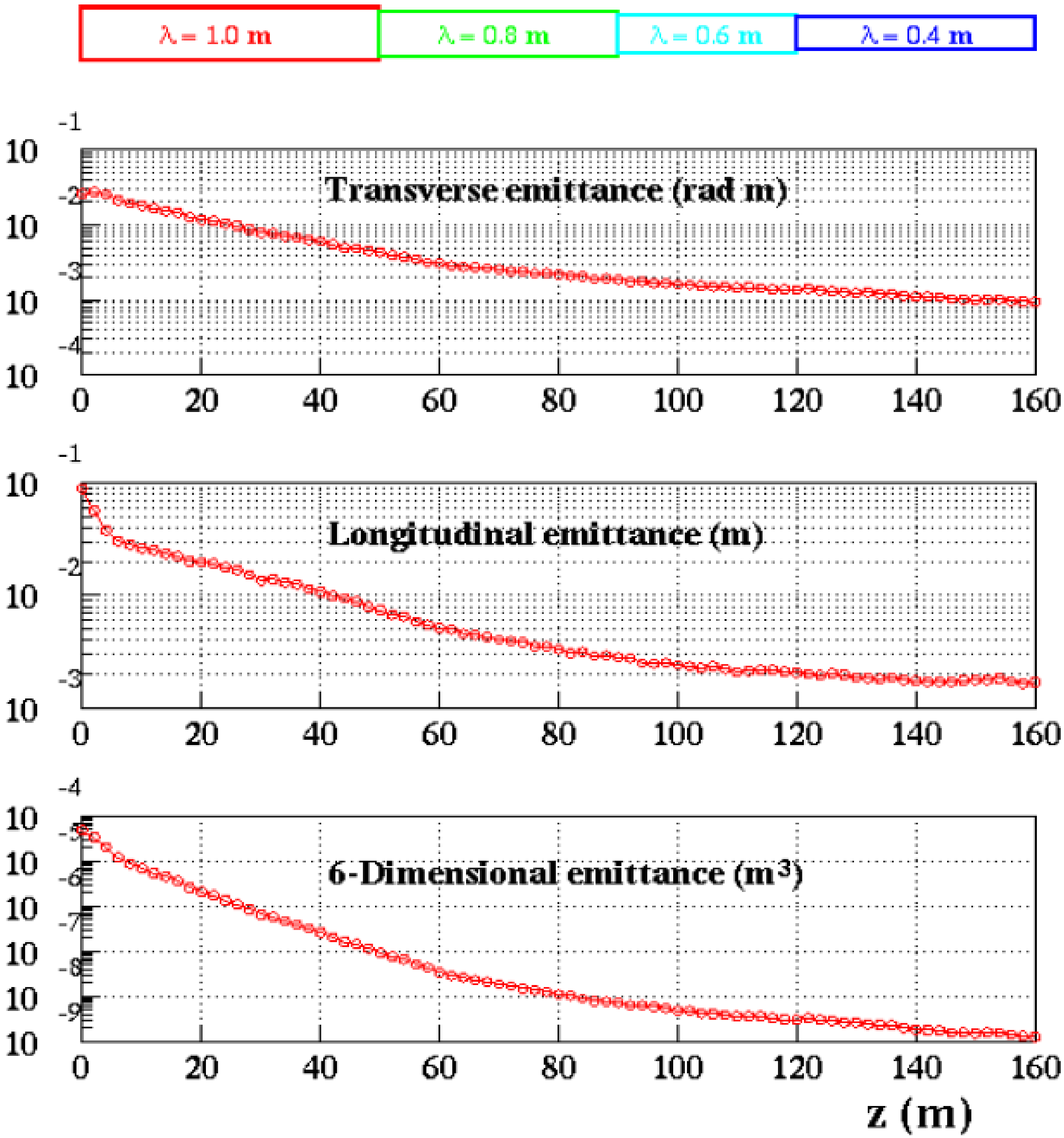
Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange



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

Helical Cooling Channel Performance example:

(Muons, Inc.)



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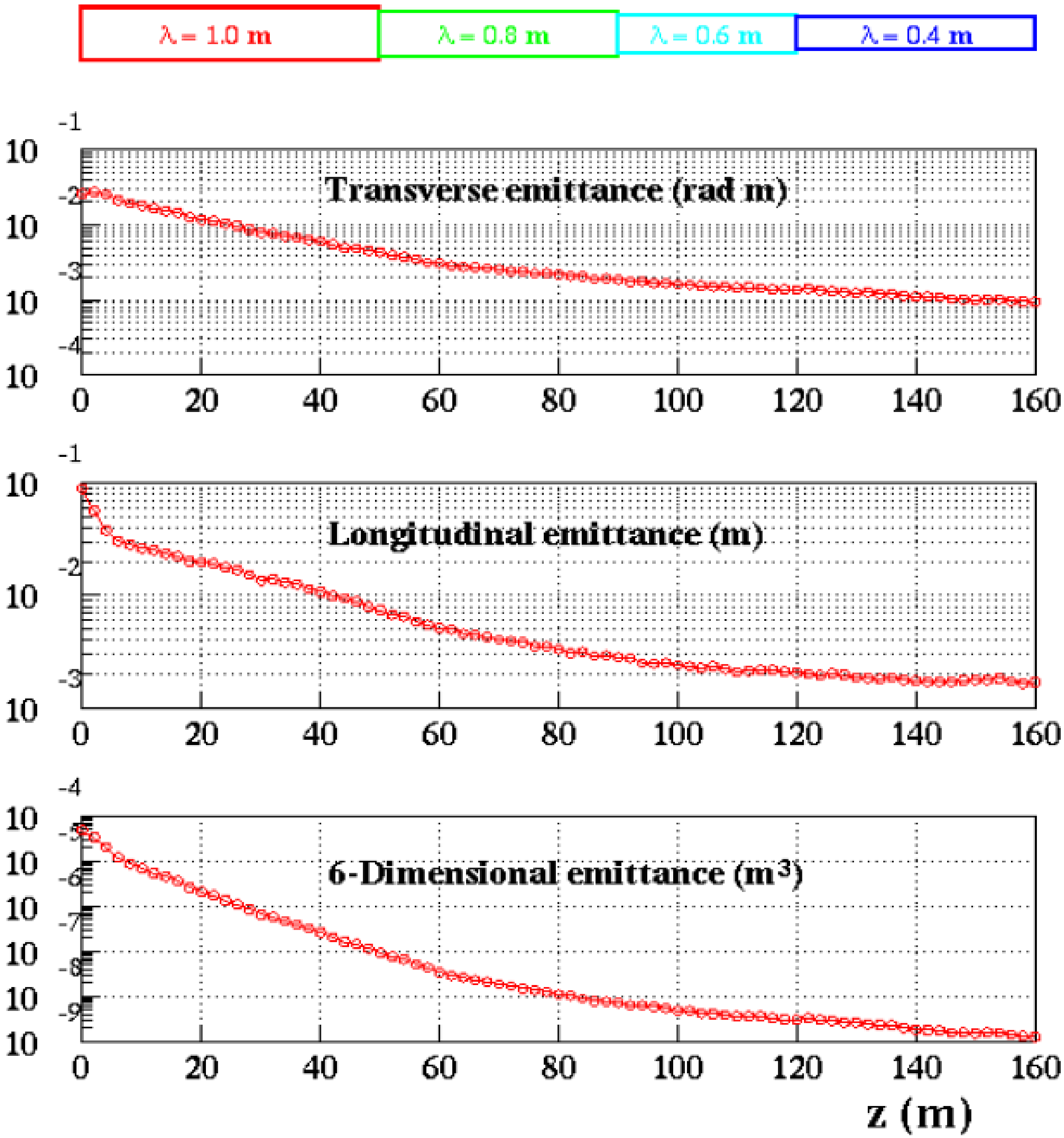

- 10^5 6D-emittance reduction in 160 m
- Ideas for further cooling under investigation
- Suggests feasibility of cooling muons well enough to accelerate them in ILC cavities!
- Muon Collider could be ILC energy upgrade

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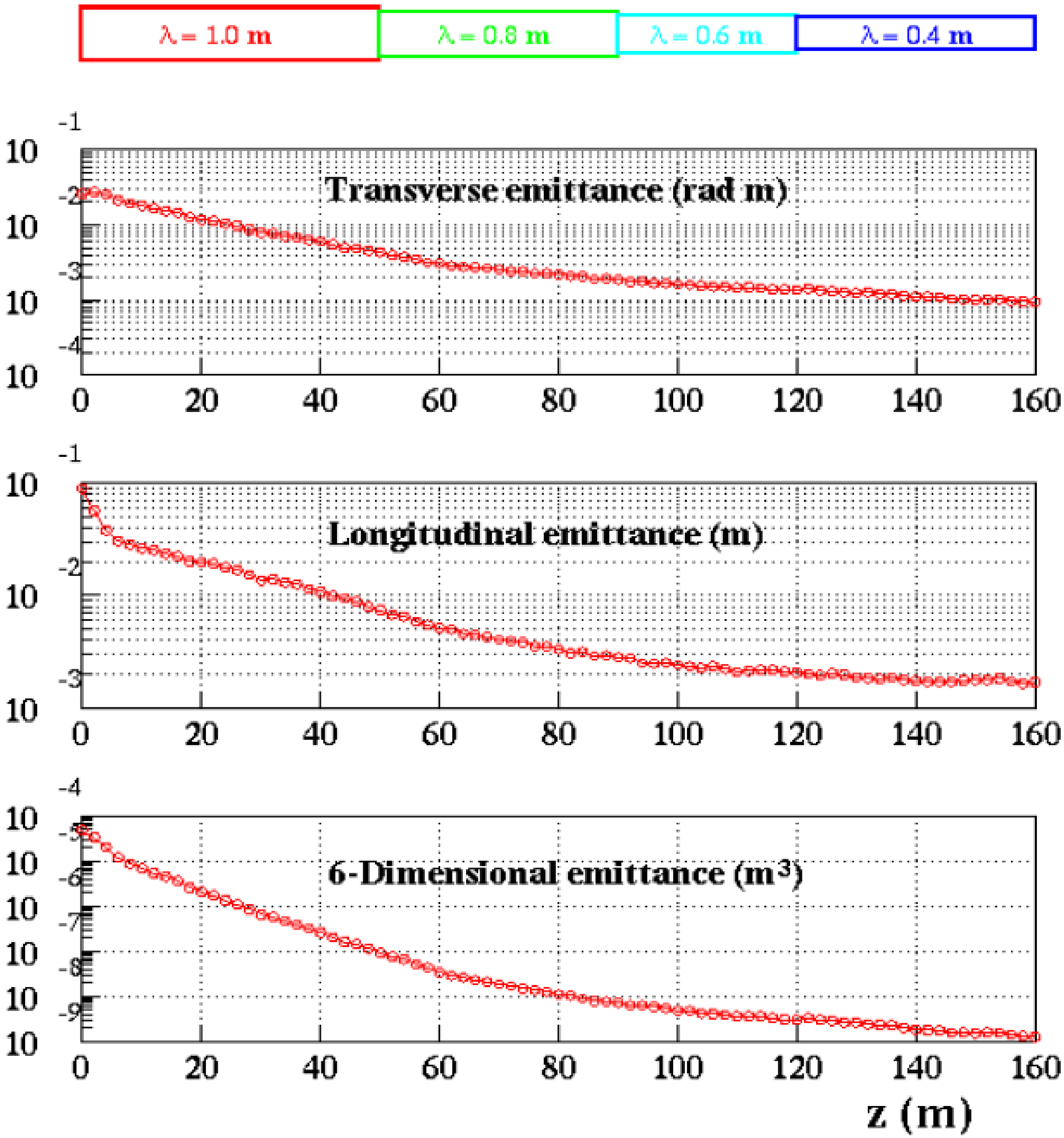

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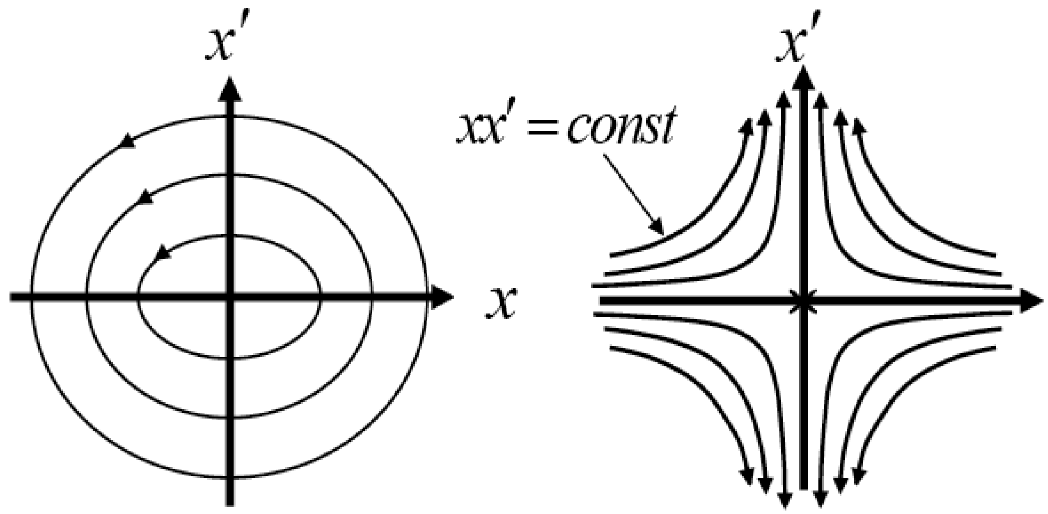
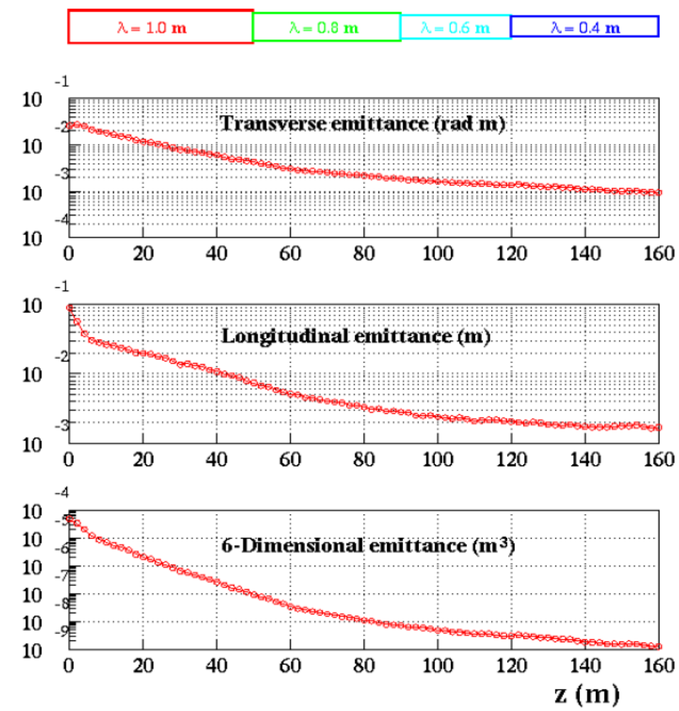
→ **International Lepton Collider!**

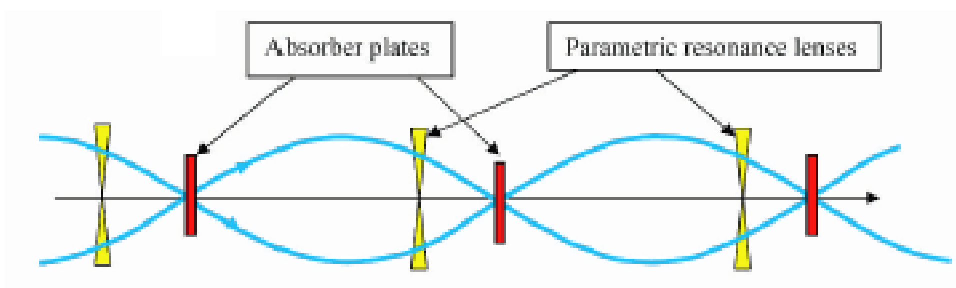
"Extreme Cooling"

Ya. Derbenev (JLab)

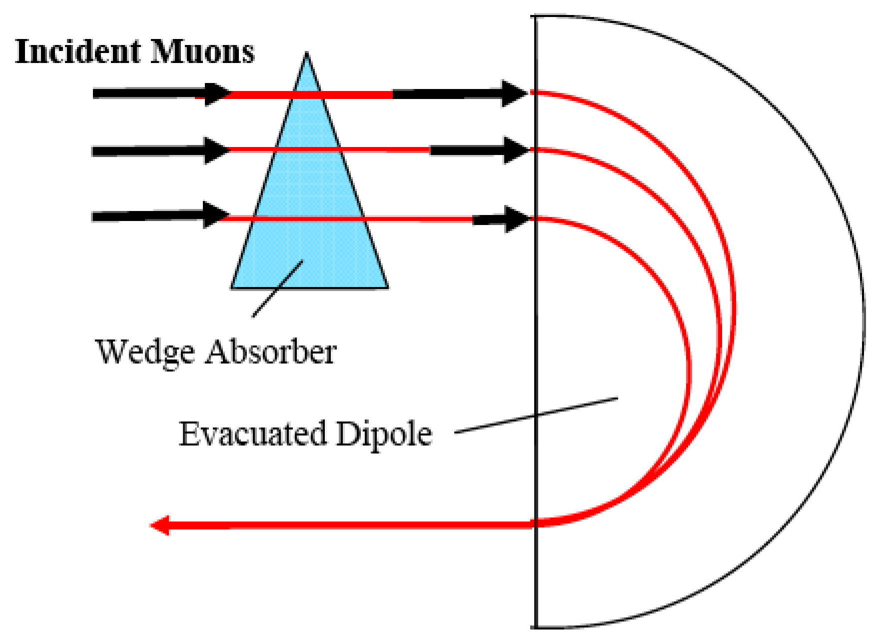
- After cooling $\times \sim 10^5$ by series of helical channels ($\sim 10^2$ m), can cool beam further with 2 new approaches:
  - Parametric-resonance Ionization Cooling (PIC)







  - Reverse Emittance Exchange (REMEX):



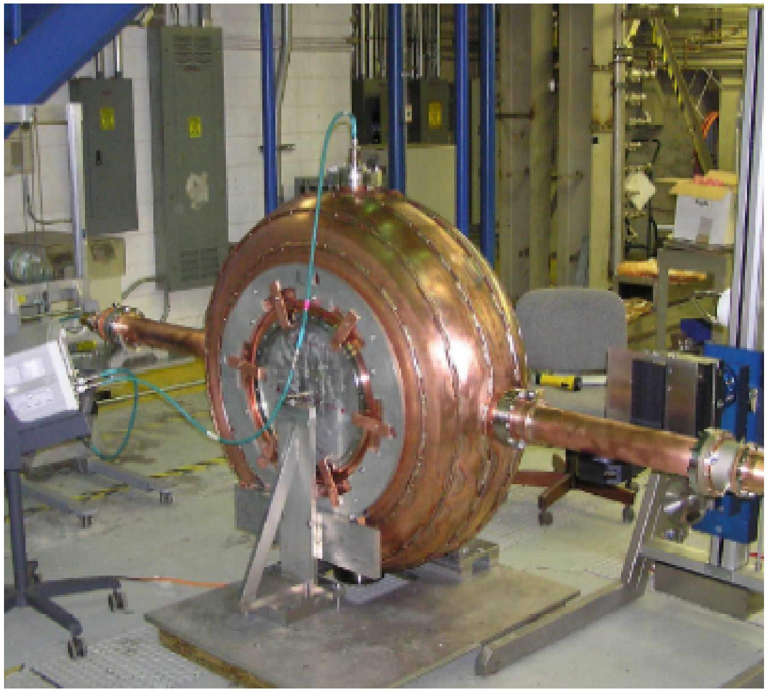
Ongoing Studies

- International Scoping Study:
  - year-long international (Europe, Japan, US) study spearheaded by UK
  - launched at NuFact05 Workshop (Frascati, Italy
  - goals: evaluate the physics case for a future neutrino facility along with options for the accelerator complex and detectors)
  - results shown at NuFact06 Workshop (Irvine, CA, August '06)
  - written report in progress
  - intended to lead to international, multi-year design study
  - website: http://www.hep.ph.ic.ac.uk/iss/
- Muon Collider Task Force:
  - group based at Fermilab holding regular meetings to explore options for a Muon Collider
  - see http://beamdocs.fnal.gov/AD-public/DocDB/ListBy?topicid=173
- Also ongoing program of hardware prototyping and testing by Neutrino Factory and Muon Collider Collaboration, e.g.,...

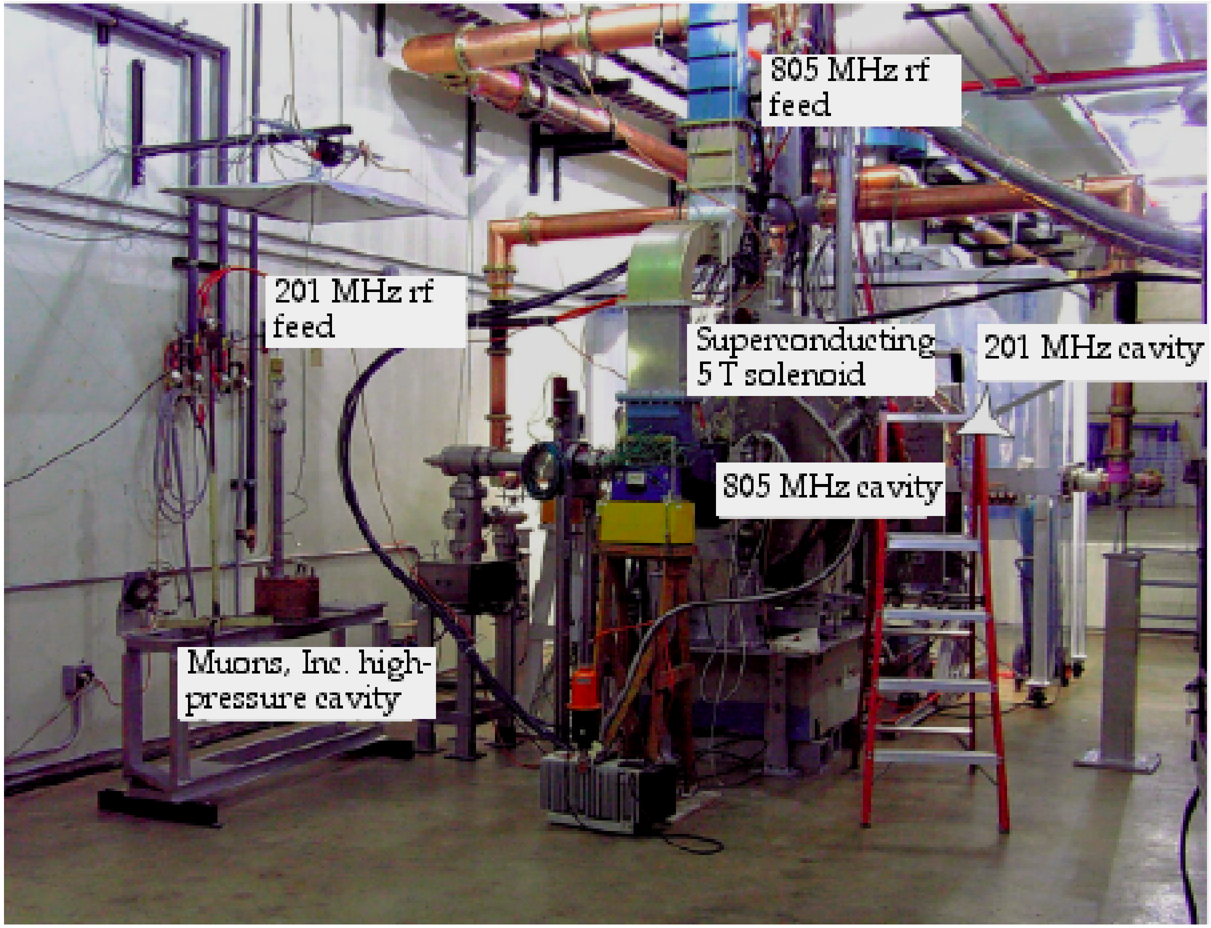
RF Cavity R&D

(ANL, LBNL, FNAL, IIT, JLab, UMiss)

- Muon Cooling calls for high-gradient, moderate-frequency, normal-conducting RF cavities operable in high focusing magnetic fields
- Tests in progress at MuCool Test Area (MTA) near Fermilab Linac with full-scale and 1/4-scale closed-cell (pillbox) cavities (with novel Be windows)



Prototype 201-MHz cavity



See J. Norem et al., “Dark Current, Breakdown, and Magnetic Field Effects in a Multicell, 805 MHz Cavity,” Phys. Rev. ST Accel. Beams **6**, 089901 (2003);

A. Moretti et al., “Effects of High Solenoidal Magnetic Fields on Rf Accelerating Cavities,” Phys. Rev. ST Accel. Beams **8**, 072001 (2005);

A. Hassanein, et al., “Effects of surface damage on rf cavity operation,” Phys. Rev. ST Accel. Beams **9**, 062001 (2006).

Feasibility Demonstrations:

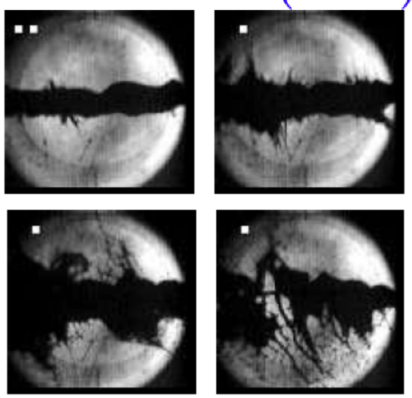
1. Multi-MW targets: MERIT @ CERN *n*TOF facility
2. Transverse ionization cooling: MICE @ RAL ISIS synchrotron
3. 6D helical cooling: MANX proposal
4. Non-scaling FFAG acceleration: EMMA @ DL

MERIT (MERcury Intense Target):

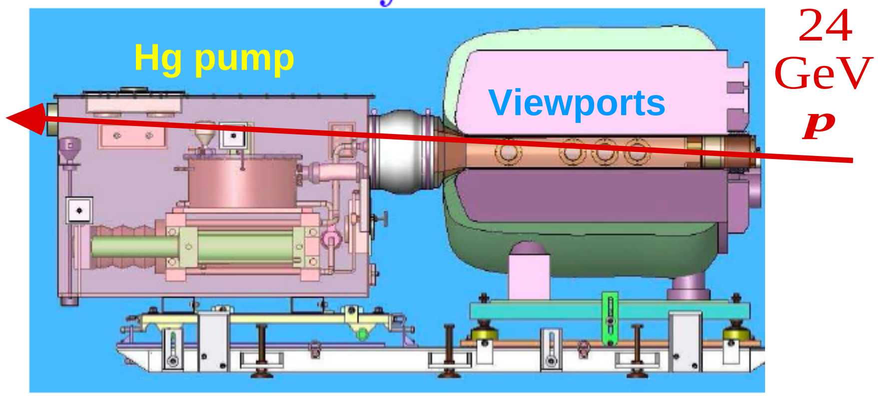
H. Kirk (BNL), K. McDonald (Princeton), et al.

- 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:

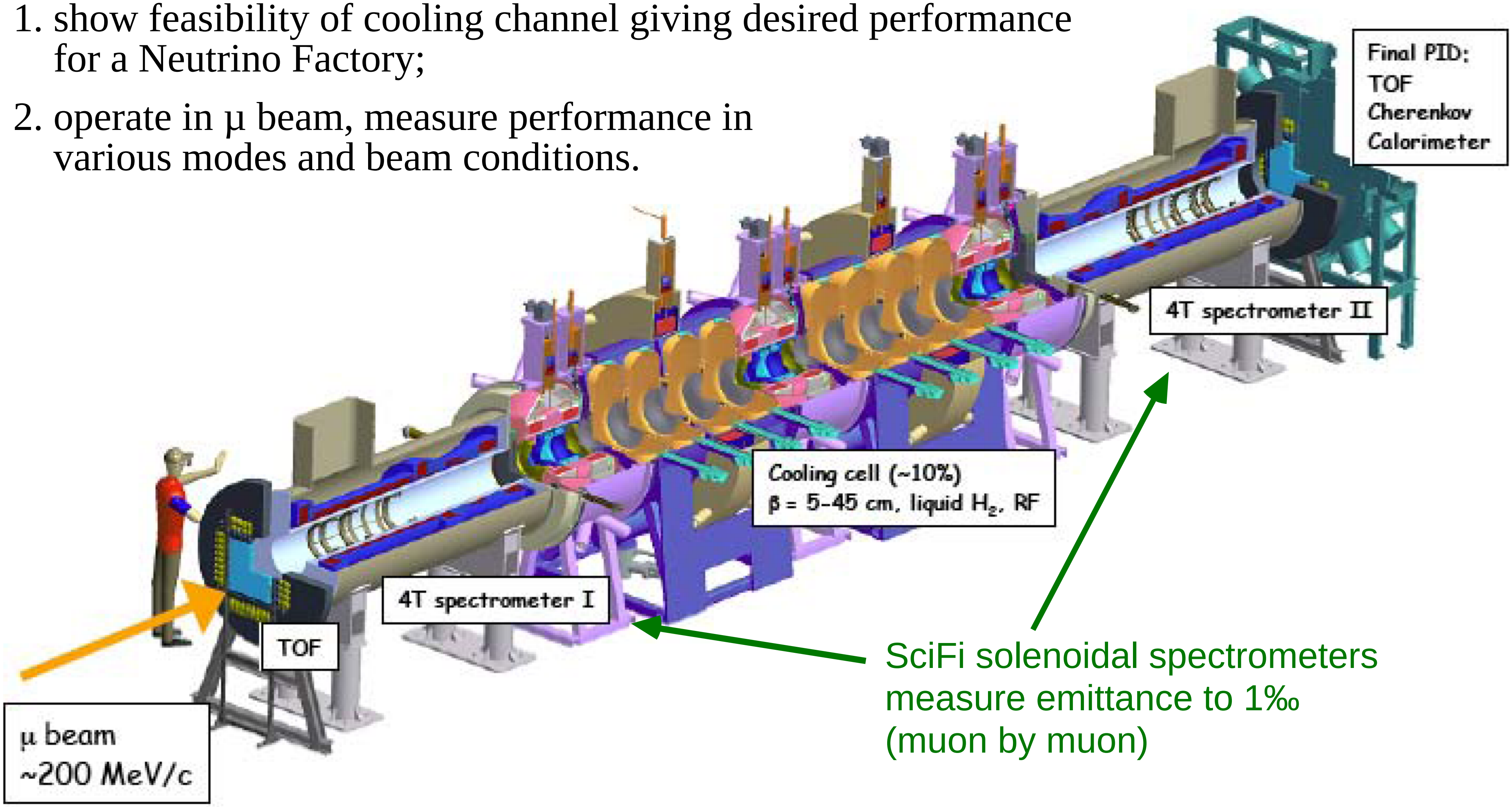
- Key parameters:
  - 24-GeV *p* beam, ≤ 8 bunches/pulse, up to 7×10^{12} *p*/bunch
  - σ_r of proton bunch = 1.2 mm, beam axis at 67 mrad to magnet axis
  - Hg jet of 1 cm diameter, v = 20 m/s, jet axis at 33 mrad to magnet axis
  - Each proton intercepts the Hg jet over 30 cm = 2 interaction lengths
- Timetable:
  - 2003: LOI's to CERN and JPARC
  - 2004: Proposal to CERN; contract let to fabricate 15-T LN_2-cooled NC magnet
  - 2005: MERIT approved by CERN
  - 2006: Commission magnet at MIT
Fabricate mercury delivery system and test with magnet at MIT
Fabricate cryogenic system
  - 2007: Install experiment at CERN (*n*TOF area) and run

MICE (Muon Ionization Cooling Experiment)

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

- **Goals:**

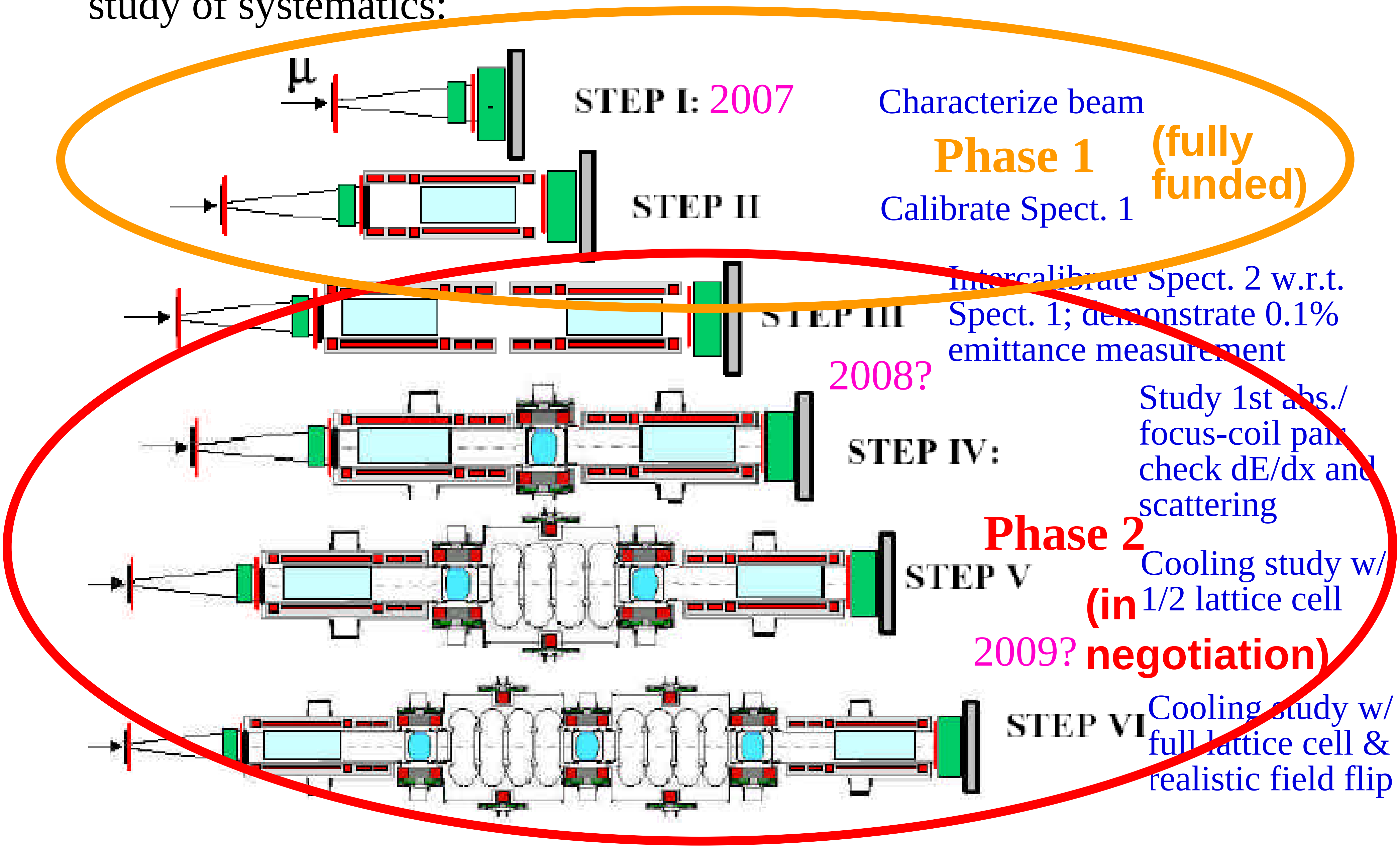
1. show feasibility of cooling channel giving desired performance for a Neutrino Factory;
2. operate in μ beam, measure performance in various modes and beam conditions.



- Large international, interdisciplinary collaboration:
  - >100 particle and accelerator physicists and engineers from Belgium, Bulgaria, China, Italy, Japan, Netherlands, Russia, Switzerland, UK, USA

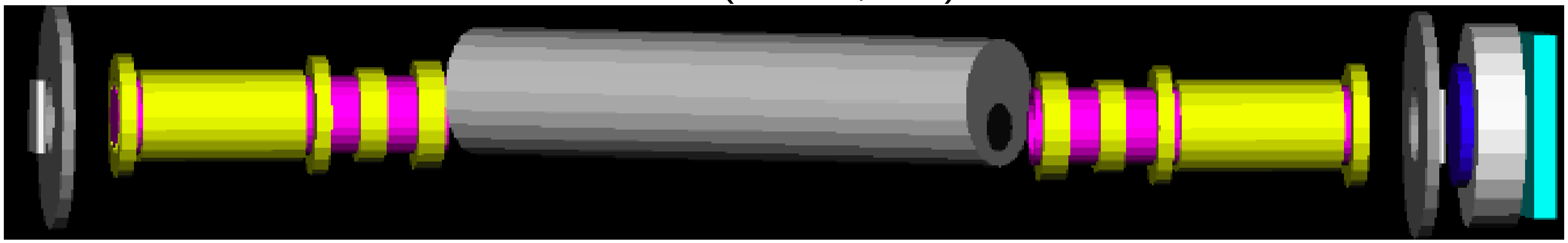
Avatars of MICE

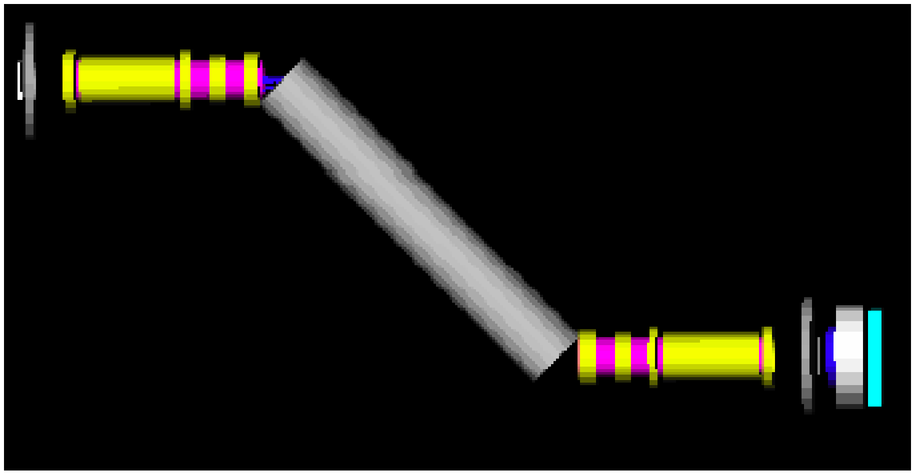
- Measurement precision relies crucially on precise calibration & thorough study of systematics:

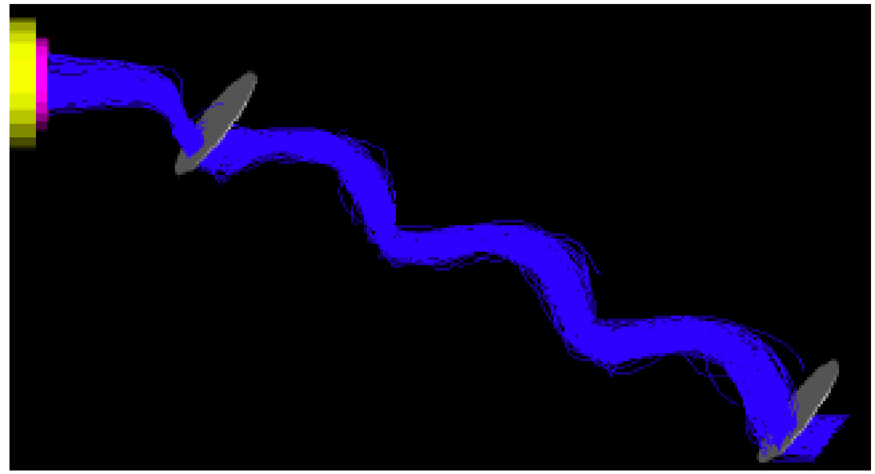


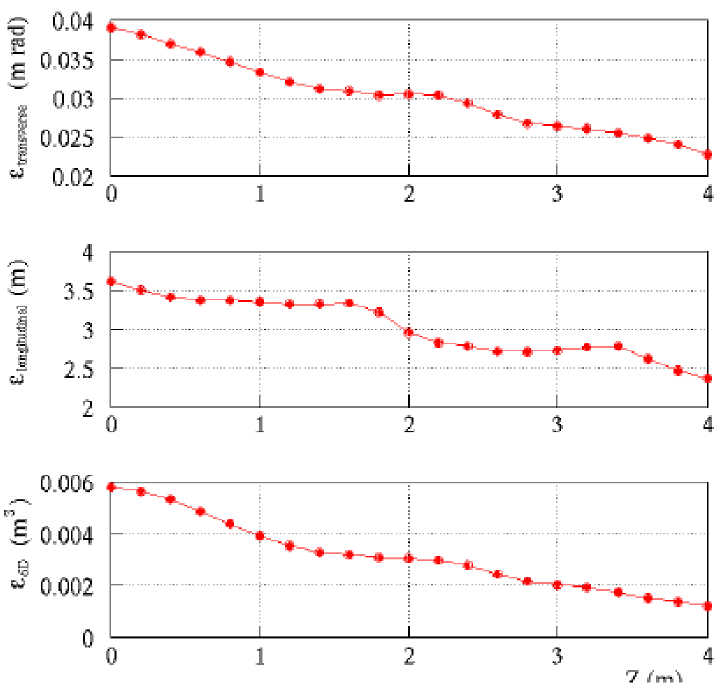
MANX (Muon collider And Neutrino factory eXperiment)

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





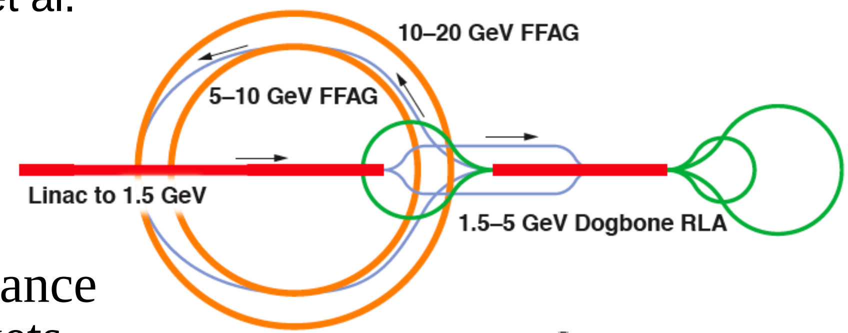




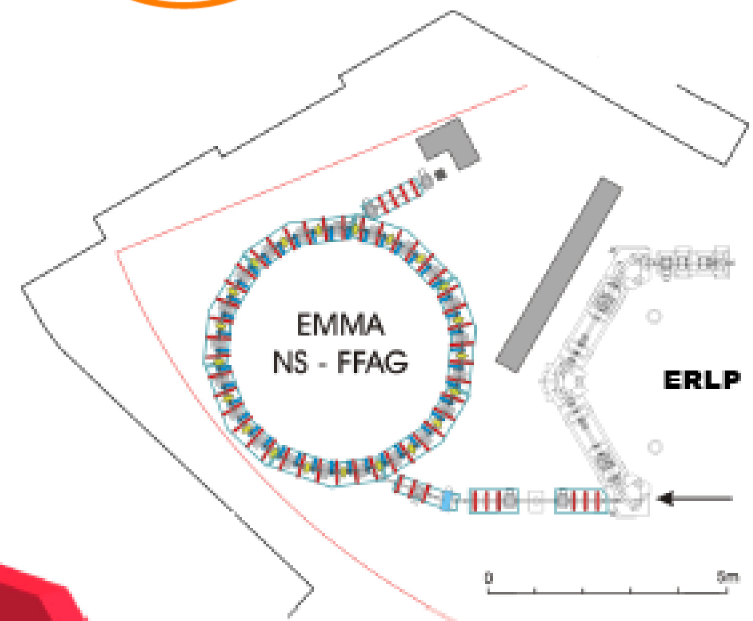
- Proposed follow-on to MICE:
  - insert LHe-filled helical-channel segment between MICE spectrometers
- Obtain large cooling factor (~0.5) in few m using graded *B* fields to match decreasing p_μ
- Optimization under study
- Proposal submitted to Fermilab (May 2006) to design and build helical magnet

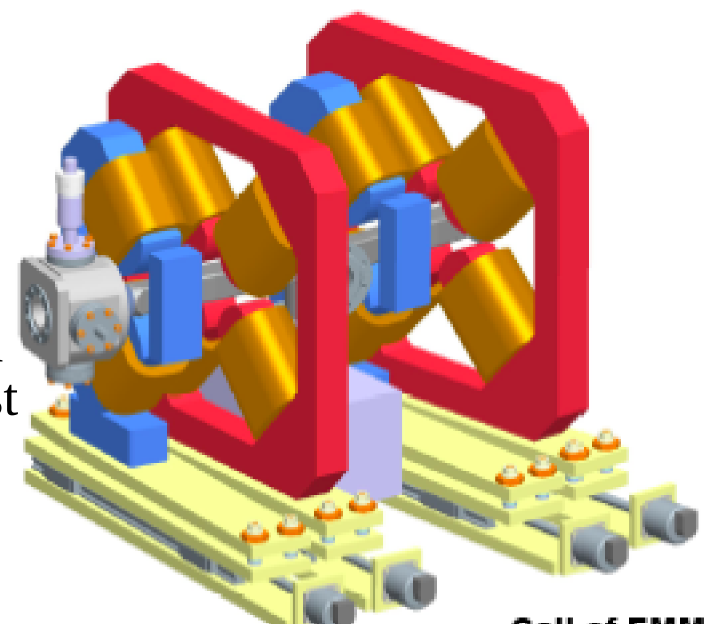
EMMA (Electron Model of Muon Accelerator)

R. Edgecock (RAL) et al.



- APS Neutrino Study FS2a proposed novel, non-scaling FFAG for muon acceleration
  - constant *B* field allows rapid acceleration
  - "out"- + "in"-bends give large momentum acceptance
  - new idea: "stochastic" acceleration between buckets
  - costs seem lower than RLA or scaling FFAG
- Proof of principle demo proposed at Daresbury
- International collaboration
- Have completed:
  - lattice design
  - tracking studies
  - hardware specs
  - hardware outline design
  - costing
- Funding:
  - UK Basic Technology program
  - 2 rounds; "highly ranked" in 1st
  - 2nd round: submitted 27th July
  - funding hoped ~ start 2007
  - 1st beam before end 2009





Cell of EMMA

Outlook

Crystal ball slightly hazy, but...

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Crystal ball slightly hazy, but...

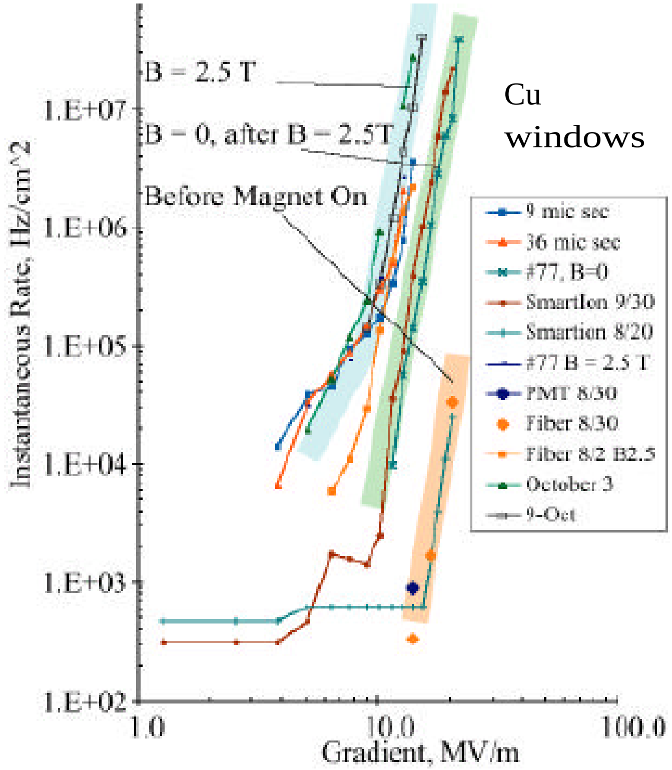
- Around 2010, should know
  - whether ∃ low-mass Higgs &/or SUSY

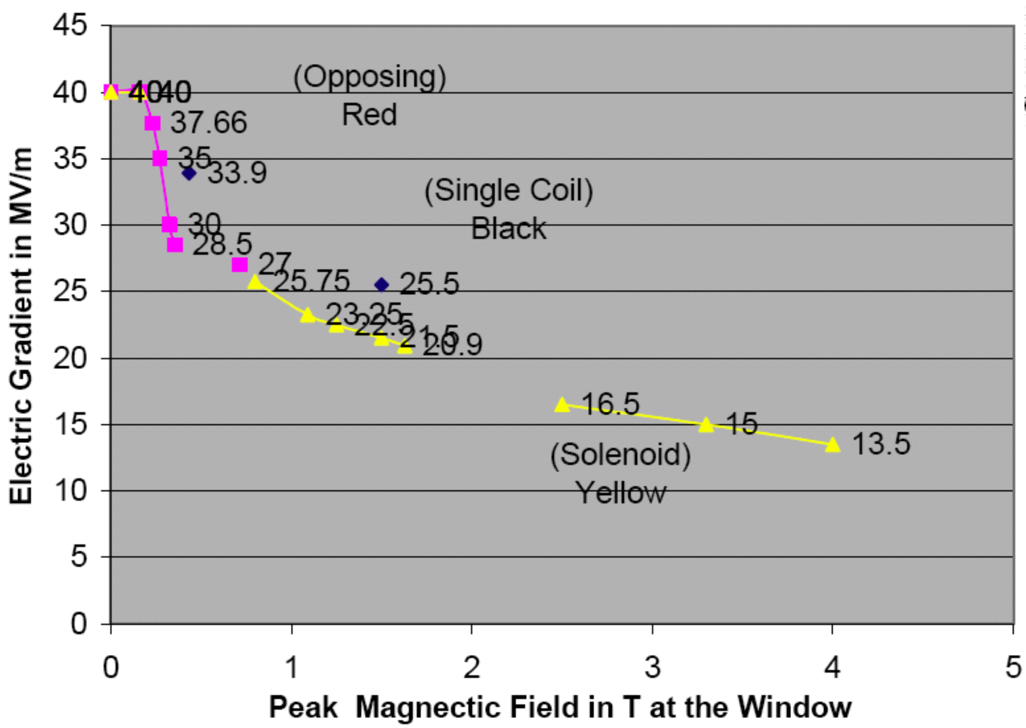
    ⇒ whether ILC will proceed
  - cost & feasibility of ν Factory & μ Collider
- Will be ready to proceed with final design & construction of one or both of these muon facilities
- Each appears to be considerably cheaper than ILC
- Either or both could be operational before 2020

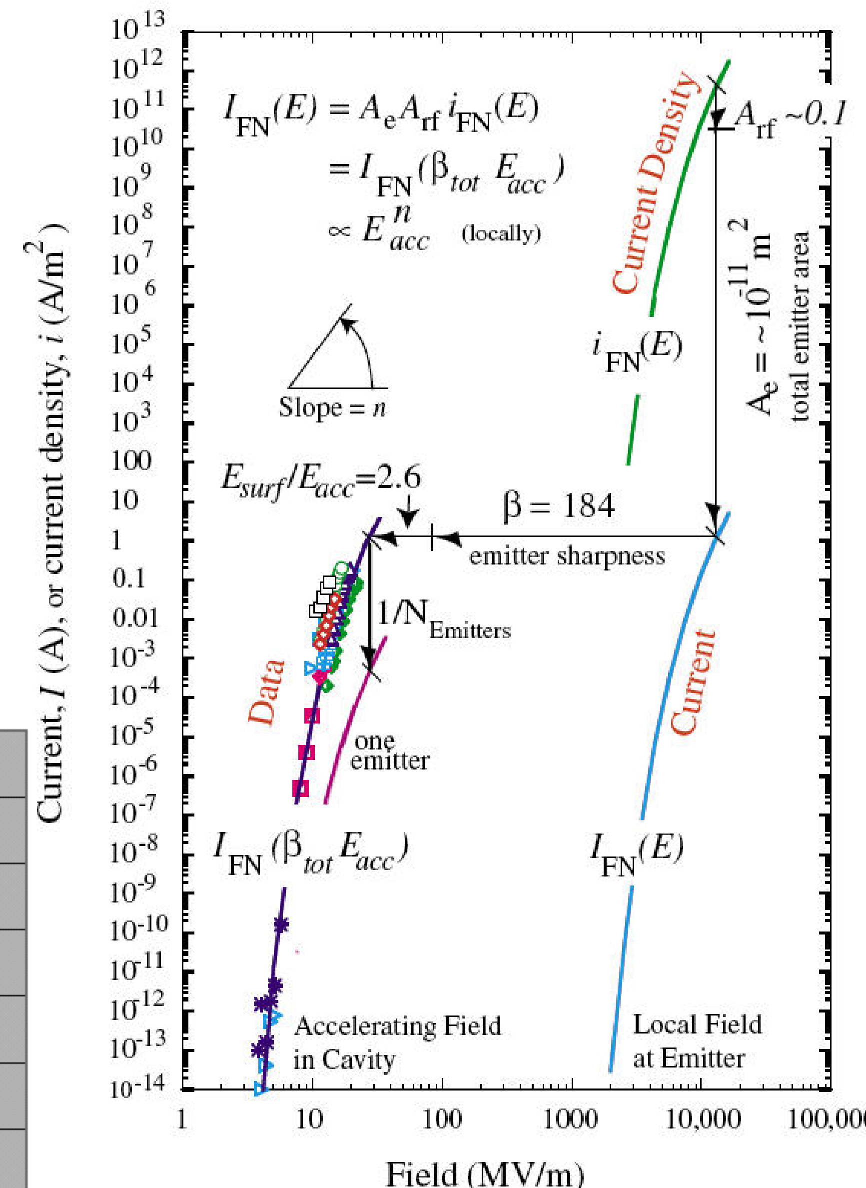
Summary

- Muon storage rings are potentially a uniquely powerful option for future HEP facilities
- After much R&D, muon cooling looks feasible
  - both in transverse and longitudinal phase planes
- Coming demonstration experiments should establish this by ~2010
- New techniques could yield muon emittances comparable to ILC values
- Future looks bright for muon colliders and neutrino factories!

Cavity R&D Results



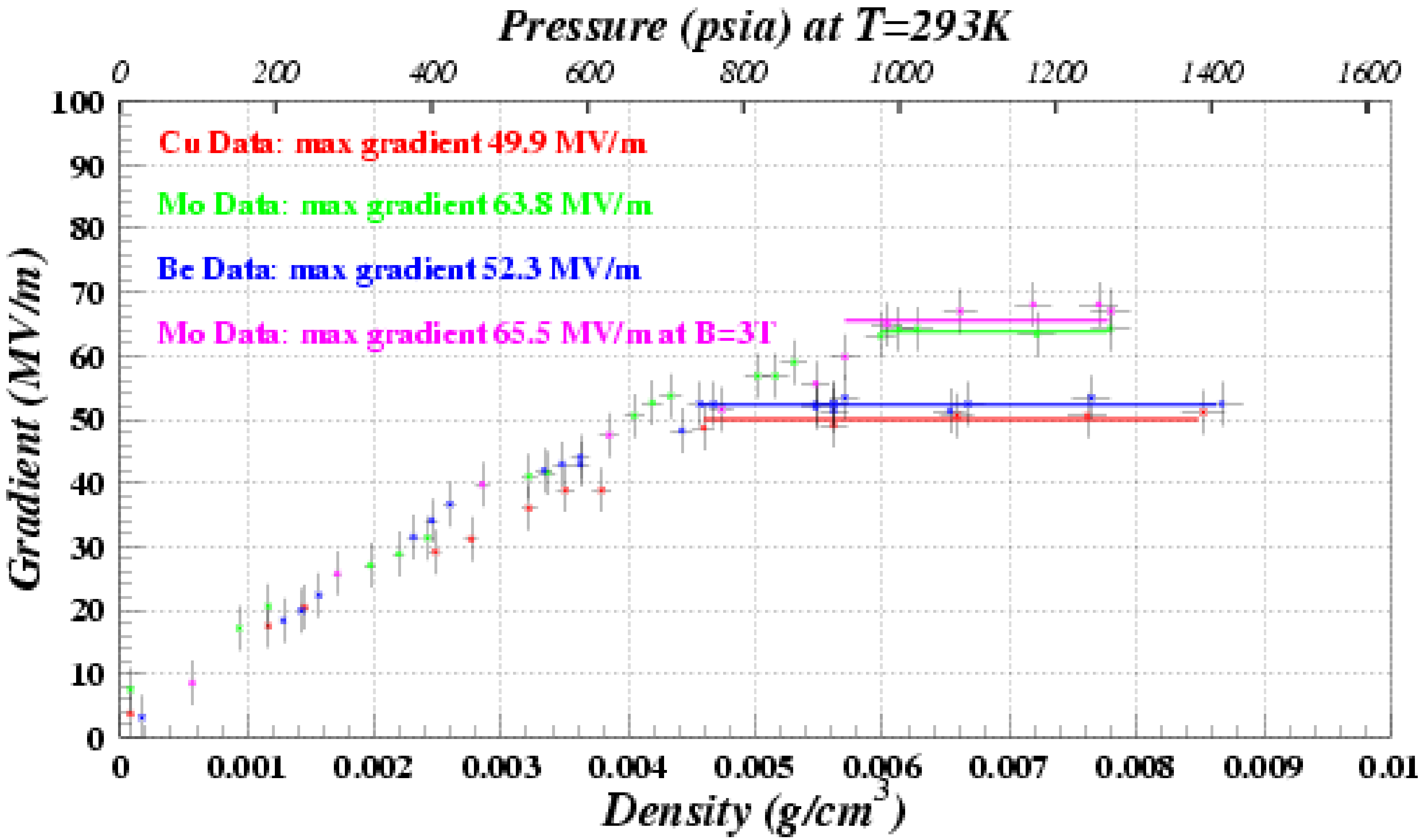




Pressurized vs. Vacuum Cavities

(FNAL, IIT, Muons Inc.)

- Solenoidal *B*-field demonstrated to degrade vacuum-cavity performance



- Pressurizing the cavity helps! (Paschen effect)