

Muon Cooling and Future Muon Facilities

Daniel M. Kaplan



Joint Meeting of Pacific Region Particle Physics Communities
(DPF2006 & JPS 2006)

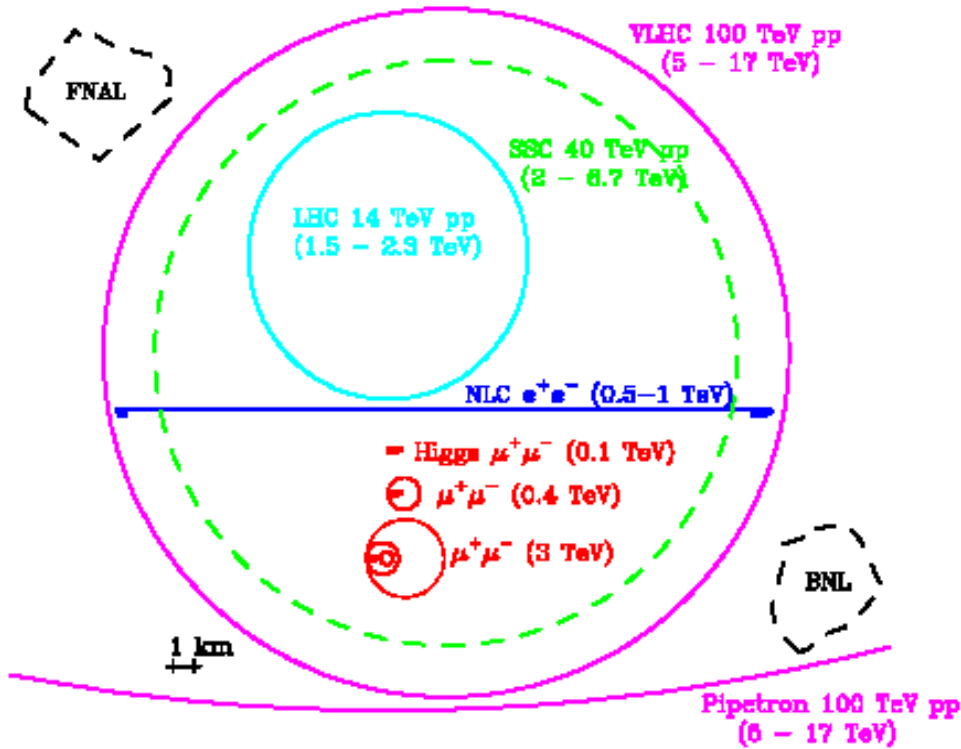
Sheraton Waikiki Hotel, Honolulu, HI
29 October – 3 November, 2006

Outline:

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

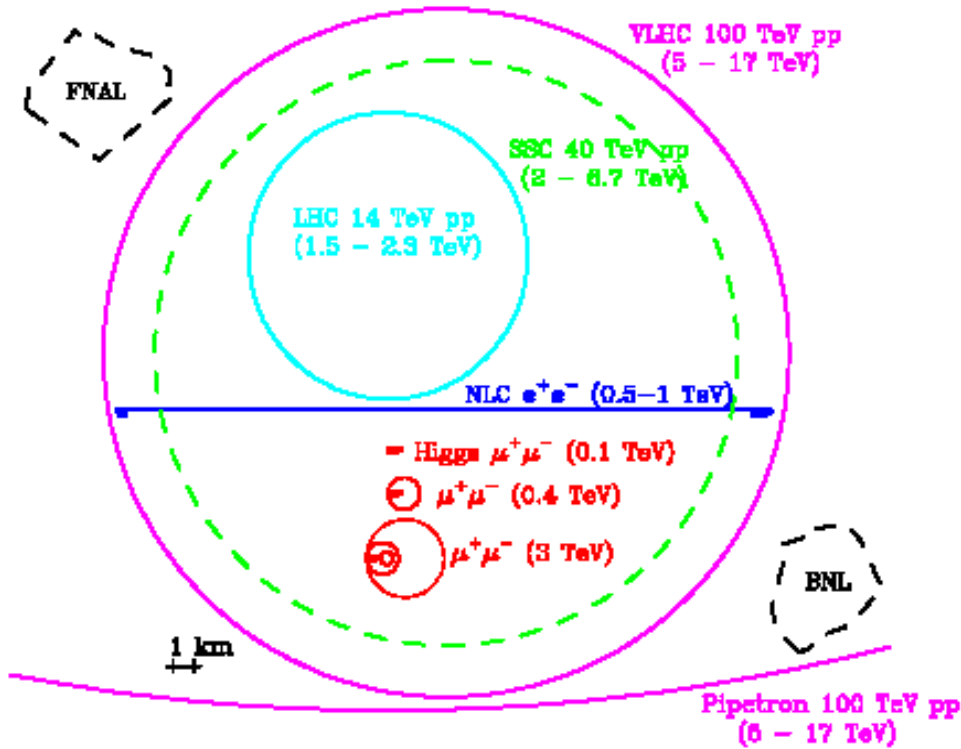
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- A pathway to *high-energy* lepton colliders
 - unlike e^+e^- , \sqrt{s} not limited by radiative effects
- ⇒ a muon collider can fit on existing laboratory sites even for $\sqrt{s} > 3$ TeV:



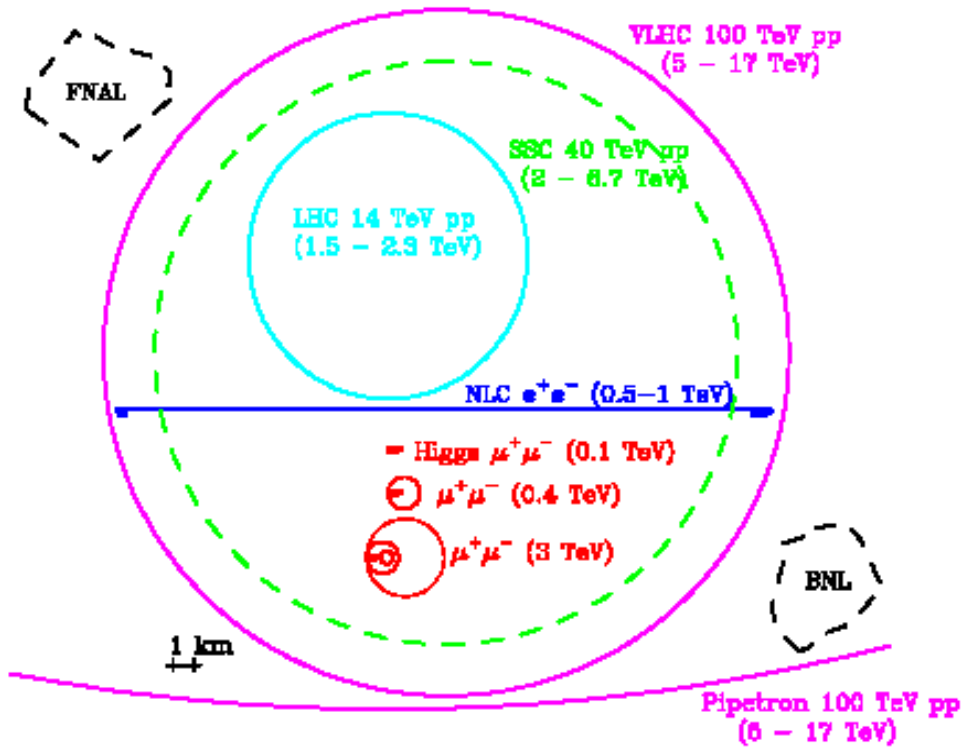
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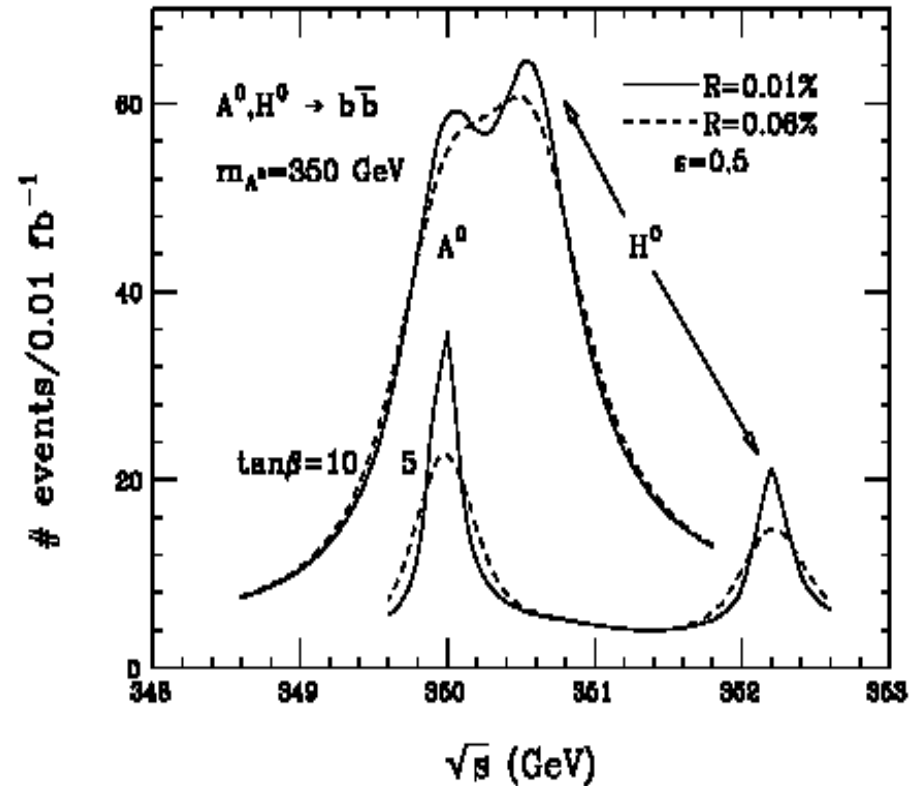
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- Also...

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

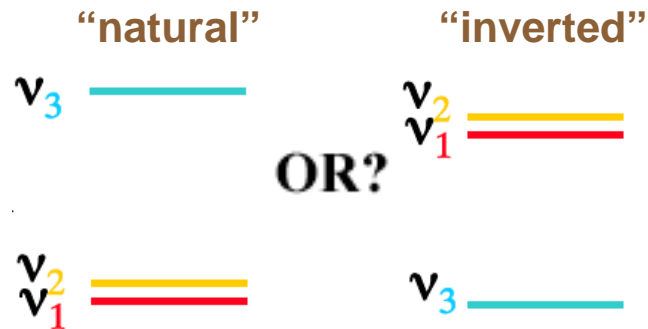


- E.g., $\mu\mu$ -collider resolution can separate near-degenerate scalar and pseudo-scalar Higgs states of high- $\tan\beta$ SUSY

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:

$$\theta_{12} \cong 12.8^\circ$$

$$\theta_{23} \cong 2.2^\circ$$

$$\theta_{13} \cong 0.4^\circ$$

} hierarchical & nearly diagonal

PMNS matrix:

$$\theta_{12} = 30^\circ \text{ (solar)}$$

$$\theta_{23} = 45^\circ \text{ (atmospheric)}$$

$$\theta_{13} < 13^\circ \text{ (Chooz limit)}$$

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

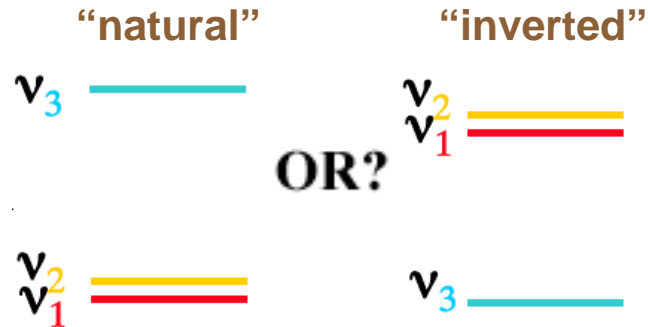
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→ are they suppressed by underlying dynamics? symmetries?

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

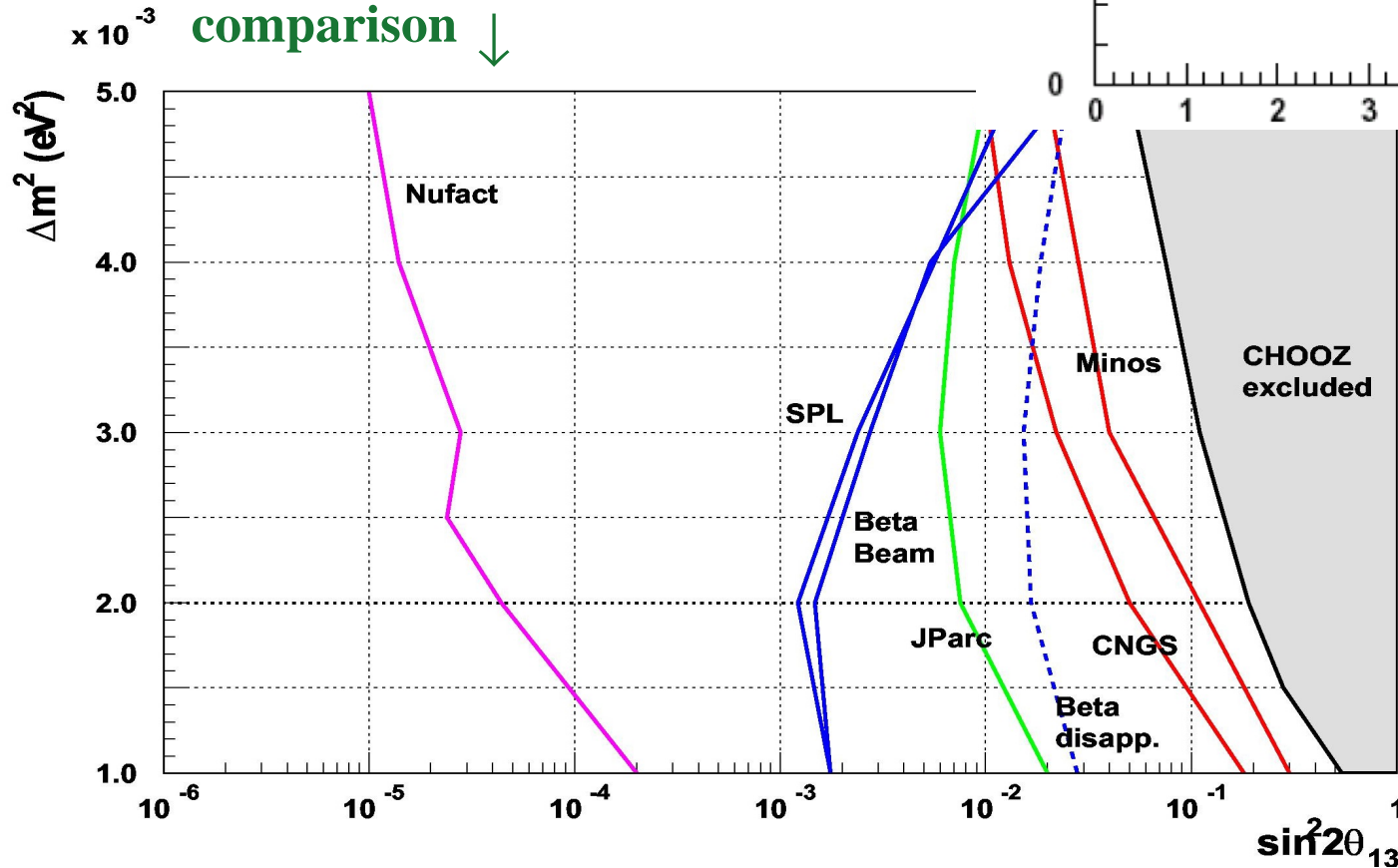
Neutrino Factory Physics Reach

- Neutrino Factory is most sensitive technique yet devised

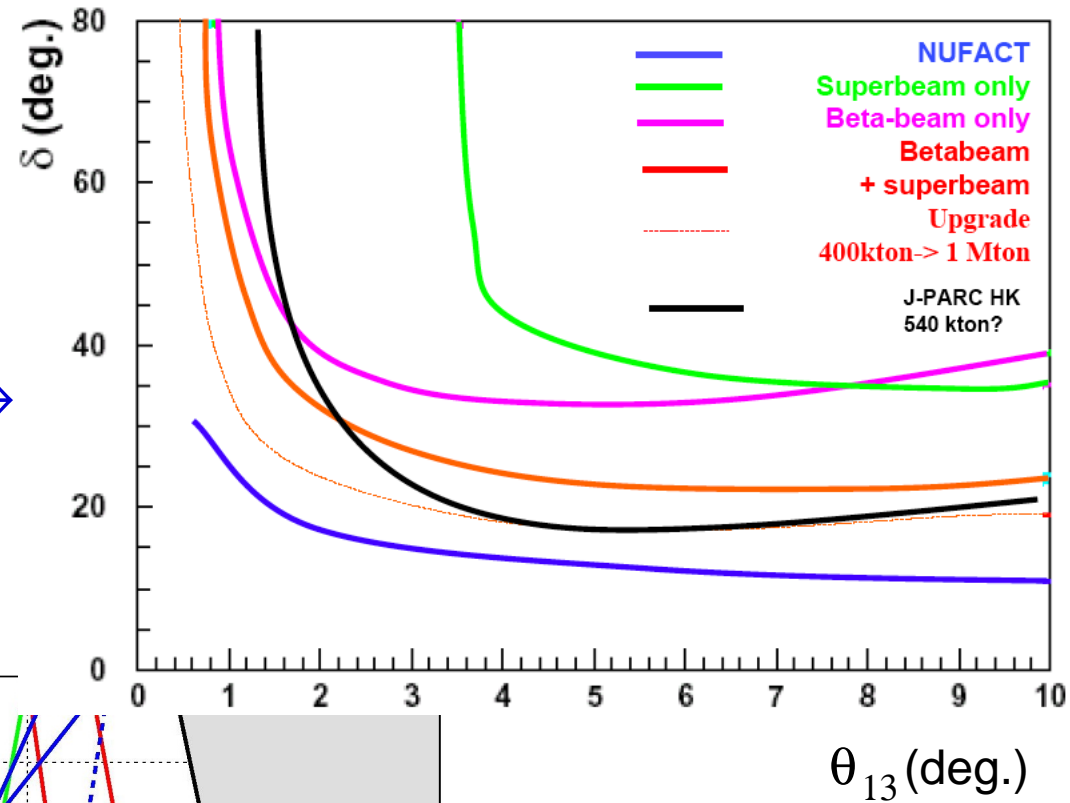
see e.g. M. Lindner, hep-ph/0209083
& C. Albright et al., Fermilab-FN-692 (2000)

CP-sensitivity comparison →

Oscillation-parameter comparison ↓



3 sigma sensitivity of various options



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

Muon Facility Examples:

- Neutrino Factory:

(Feasibility Study-II)

Induction linac No.1

100 m

drift 20 m

Induction linac No.2

80 m

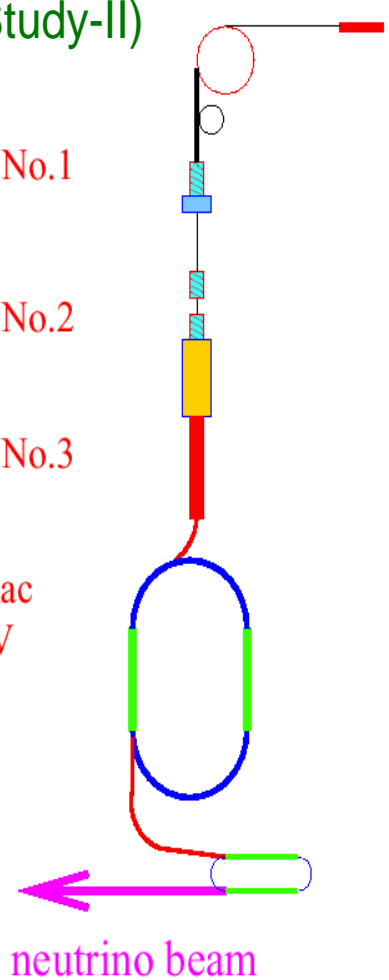
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Induction linac No.3

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recirculator Linac

2 – 20 GeV



proton driver

target

mini-cooling

3.5 m of LH , 10 m drift

bunching 56 m

cooling 108 m

Linac 2 GeV

storage ring

20 GeV

neutrino beam

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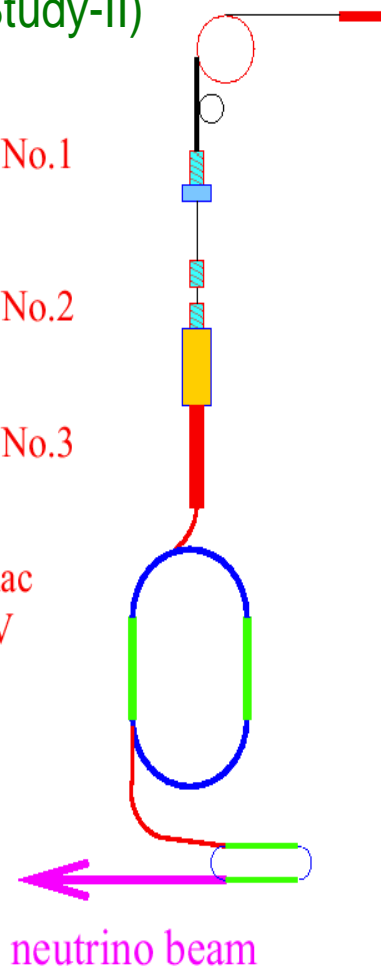
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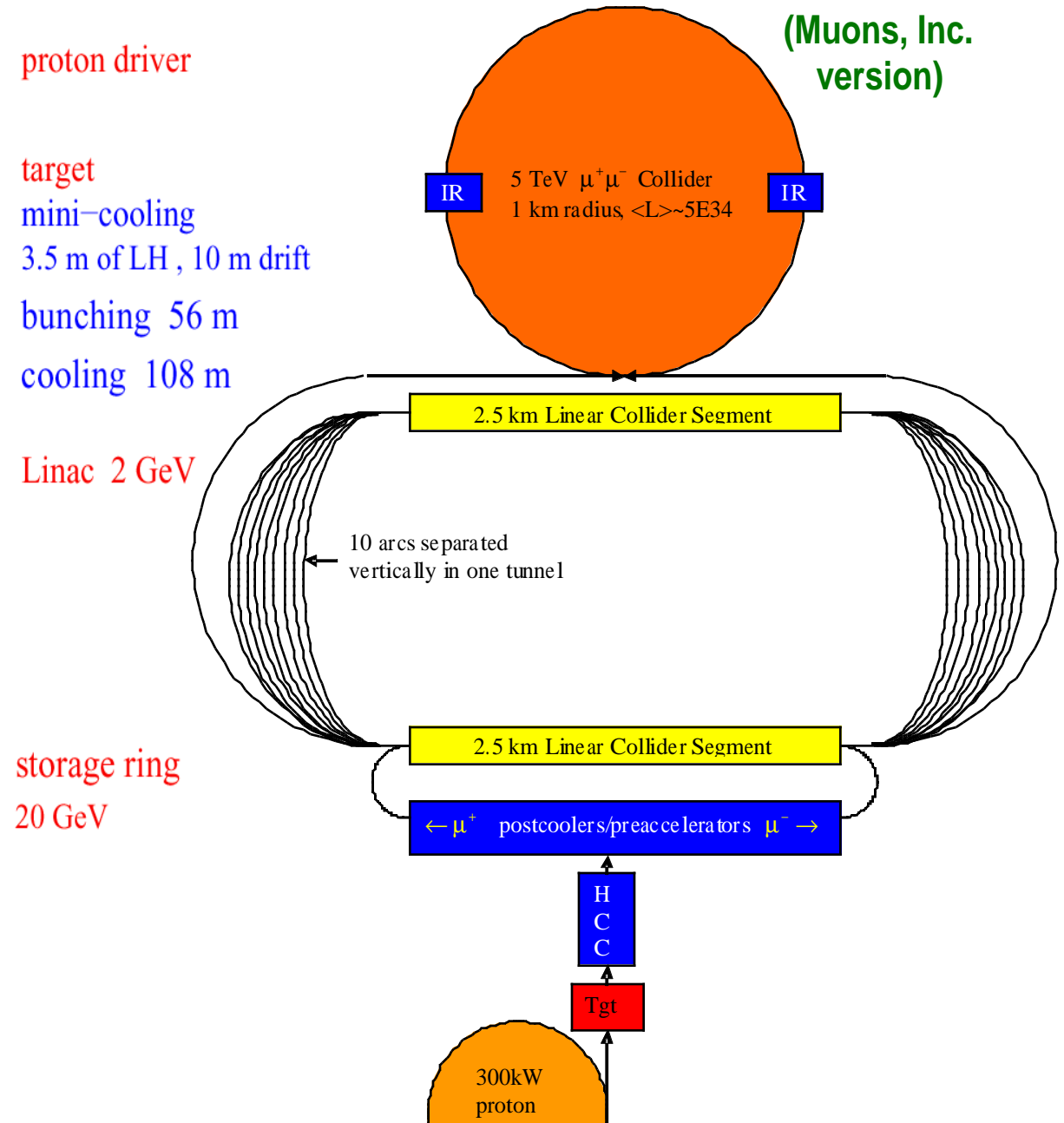
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- $\mu^+\mu^-$ collider:

(Muons, Inc. version)



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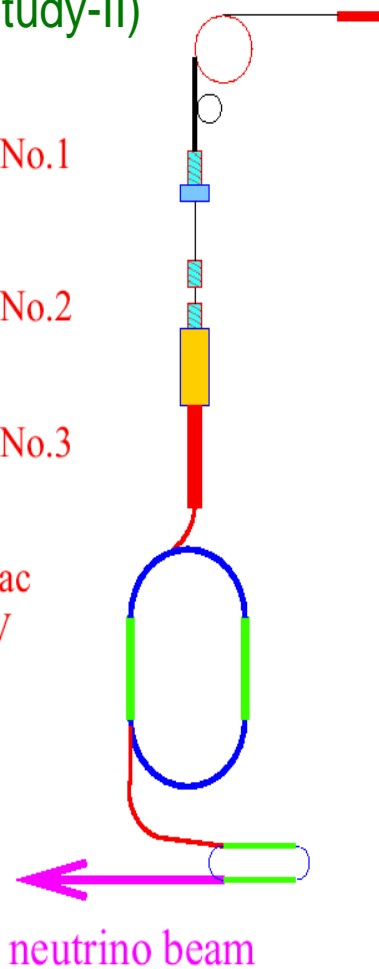
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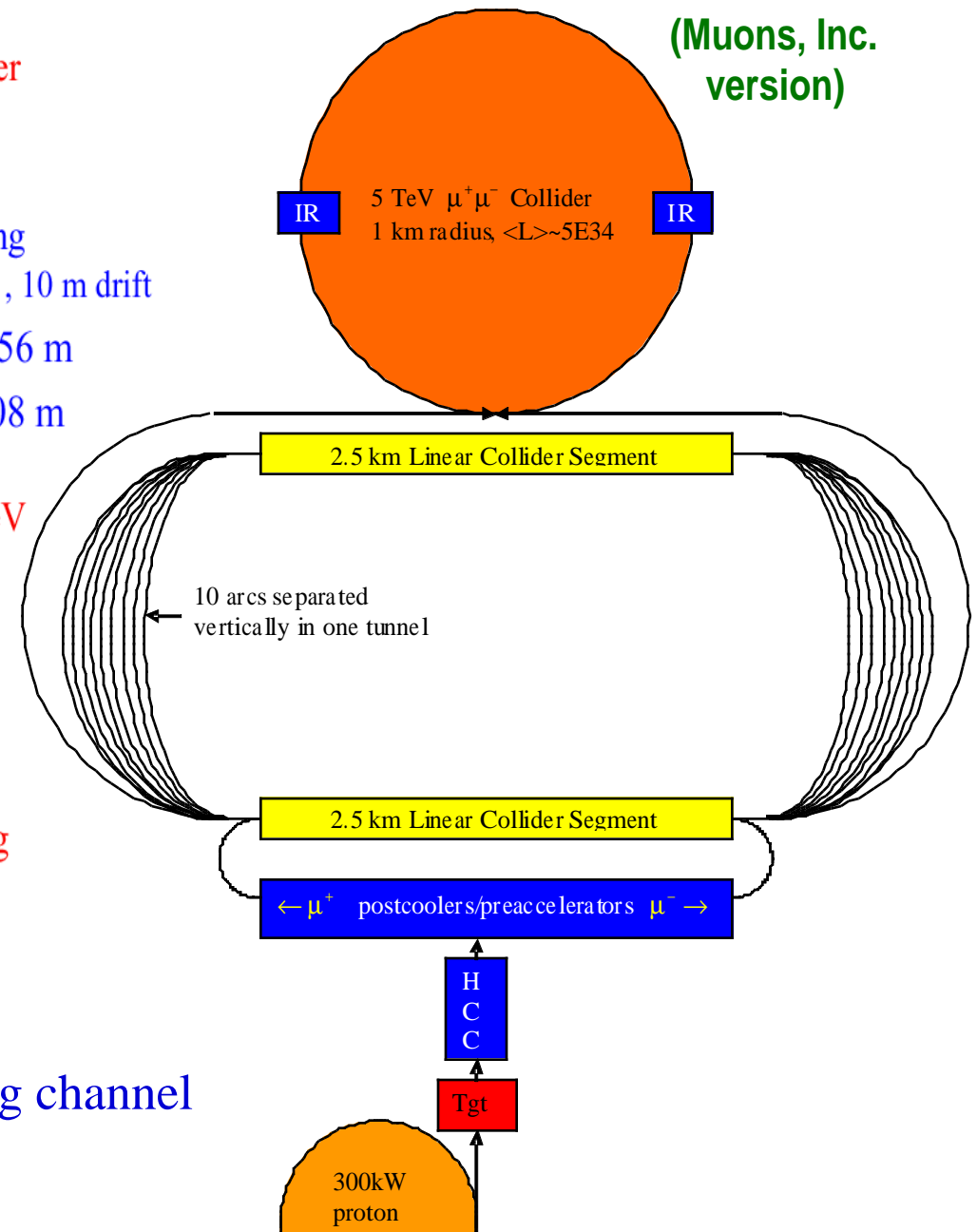
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- Common features:

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:

$$\tau_{\mu} = 2.2 \mu\text{s}$$

Q: What cooling technique works in microseconds?

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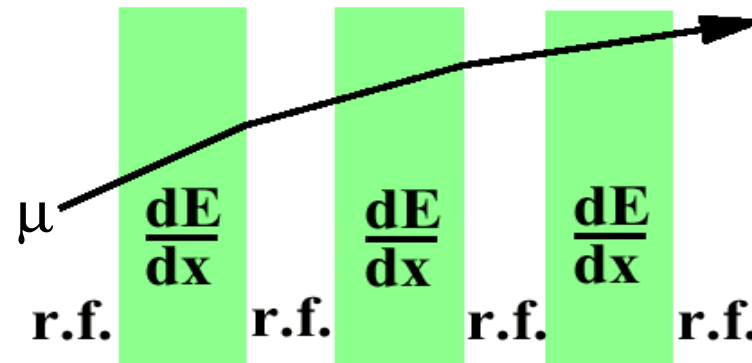
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Ionization Cooling:



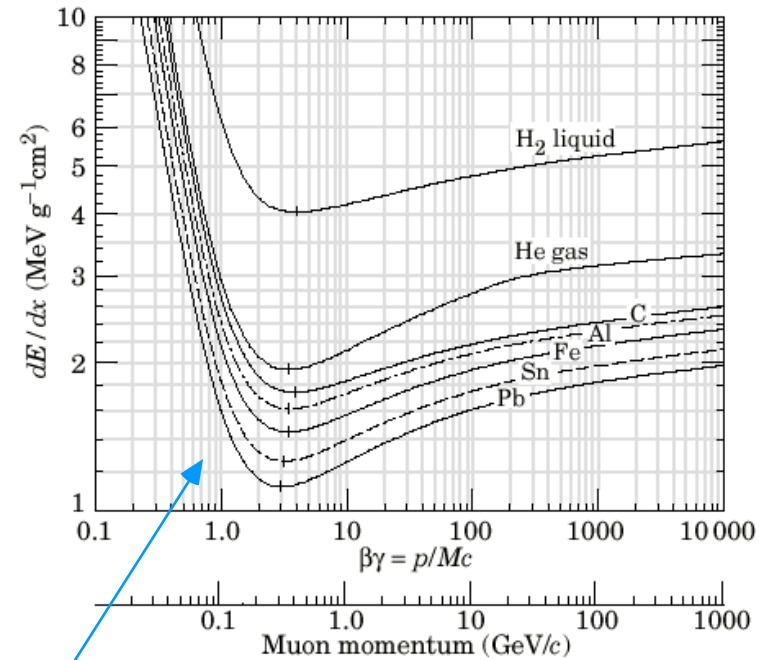
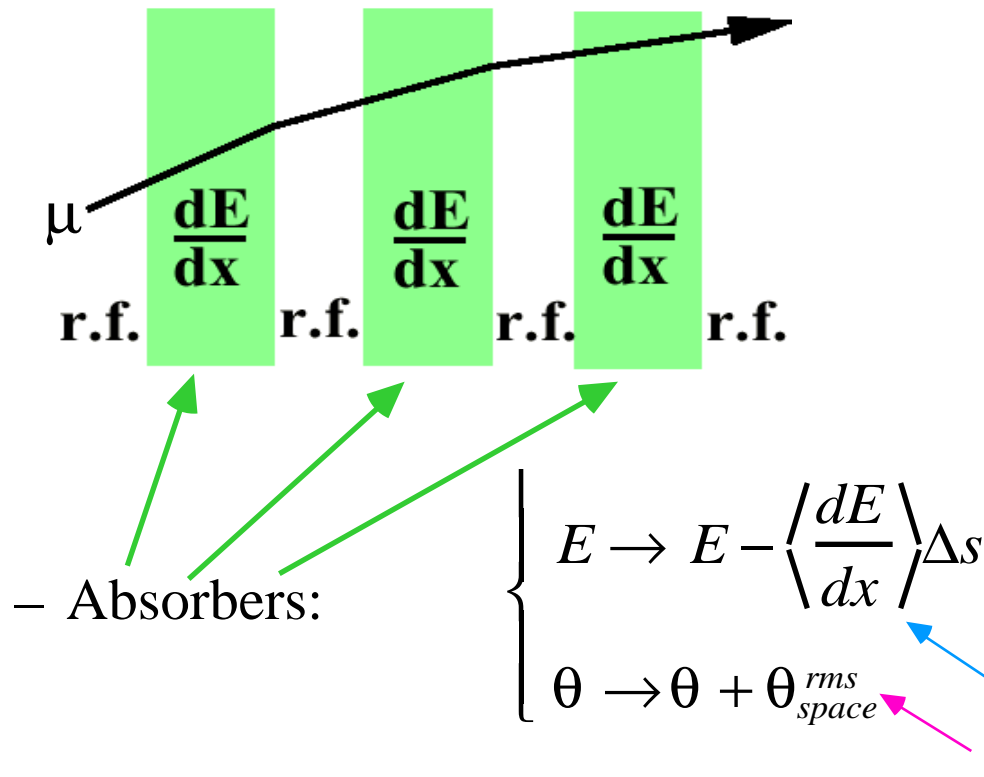
G. I. Budker and A. N. Skrinsky, Sov. Phys. Usp. **21**, 277 (1978)

A. N. Skrinsky and V. V. Parkhomchuk, Sov. J. Part. Nucl. **12**, 223 (1981)

→ **A brilliantly simple idea!**

Ionization Cooling:

- Two competing effects:

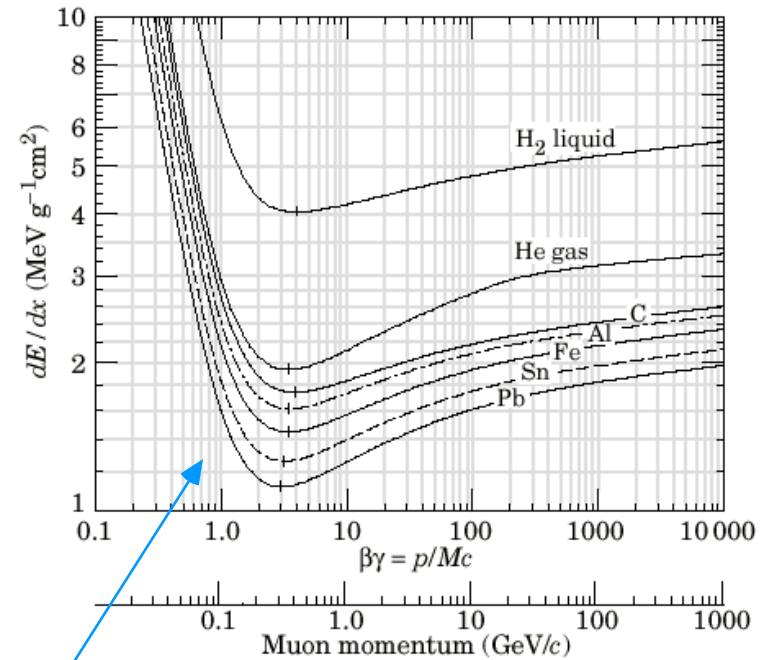
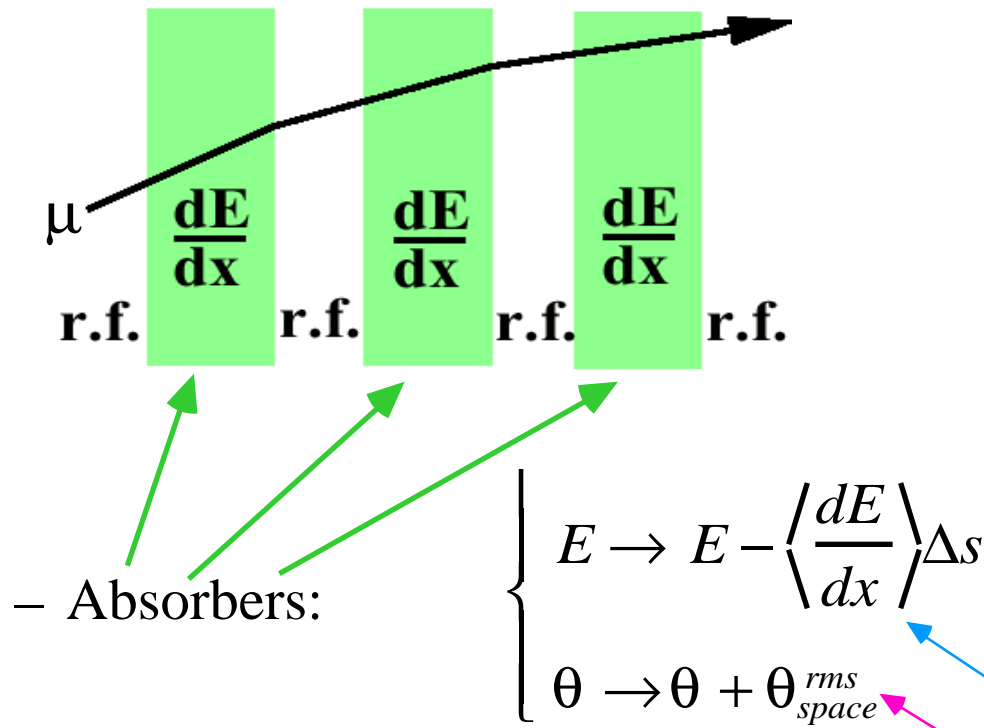


- RF cavities between absorbers replace ΔE
- Net effect: reduction in p_{\perp} at constant p_{\parallel} , i.e., transverse cooling

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

Ionization Cooling:

- Two competing effects:



ionization energy loss

multiple Coulomb scattering

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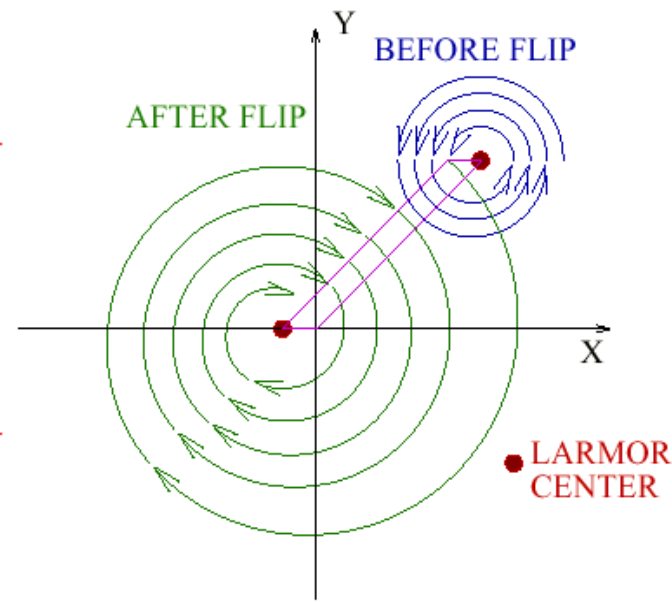
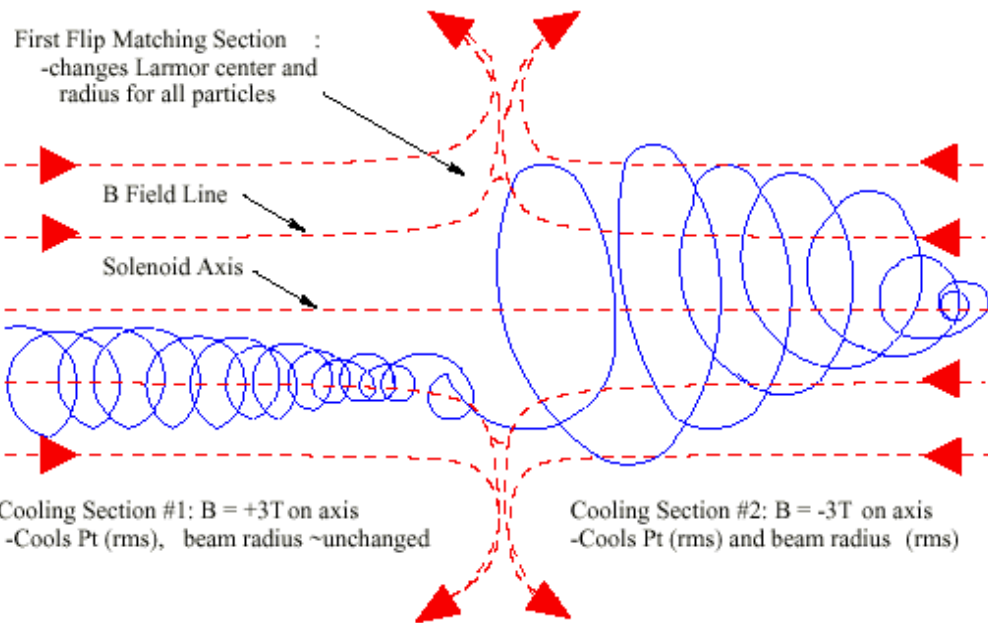
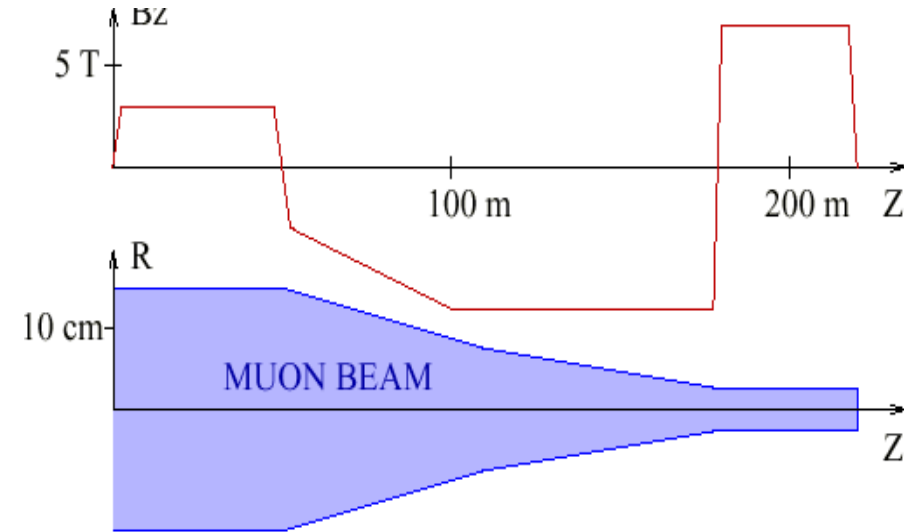
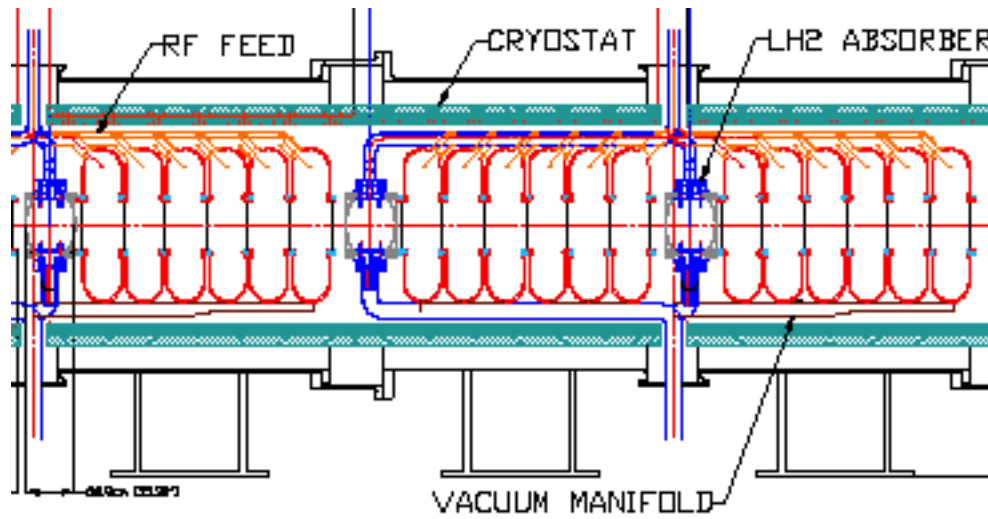
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→ **How can this be achieved...?**

E.g., Double-Flip Cooling Channel

V. Balbekov & D. Elvira (FNAL)

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

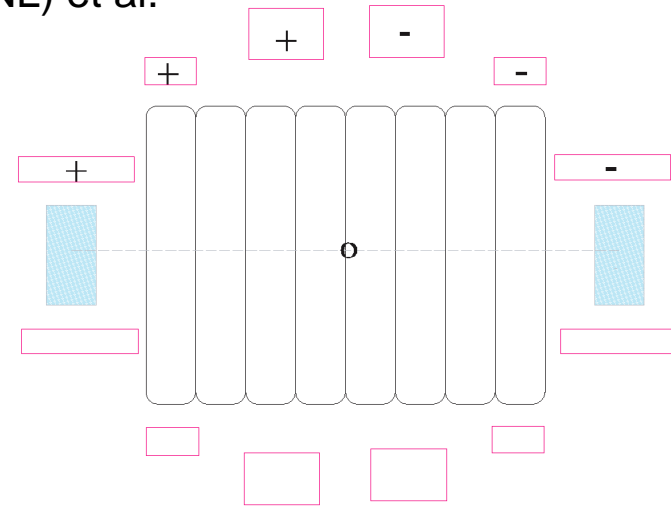
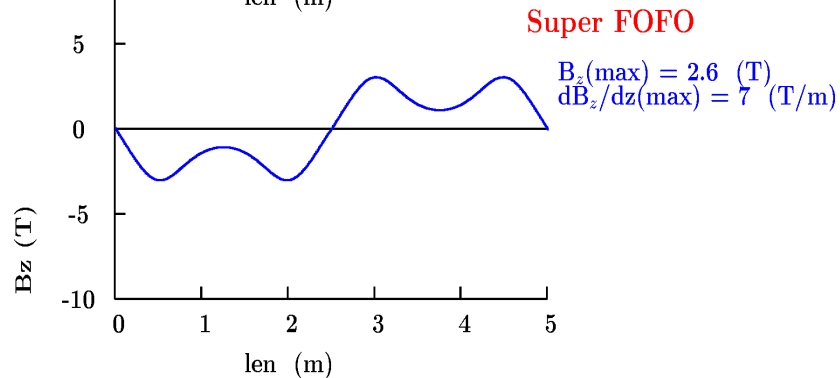
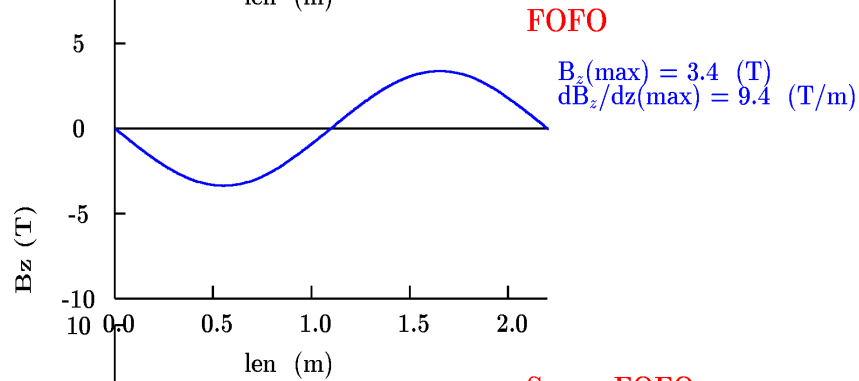
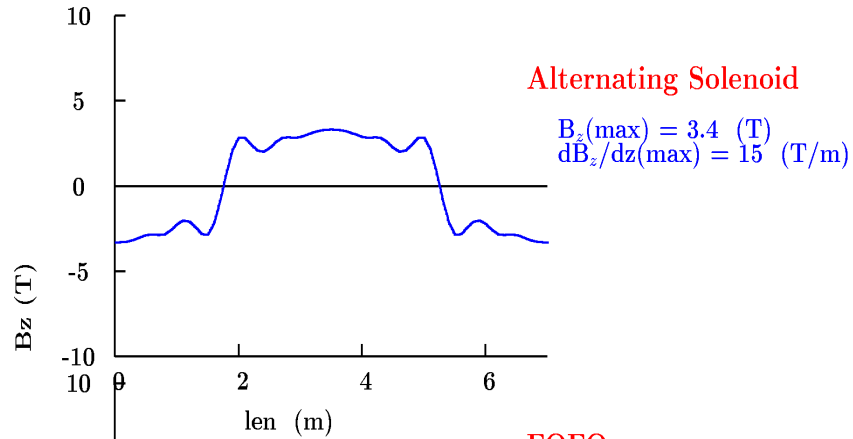


\Rightarrow expensive

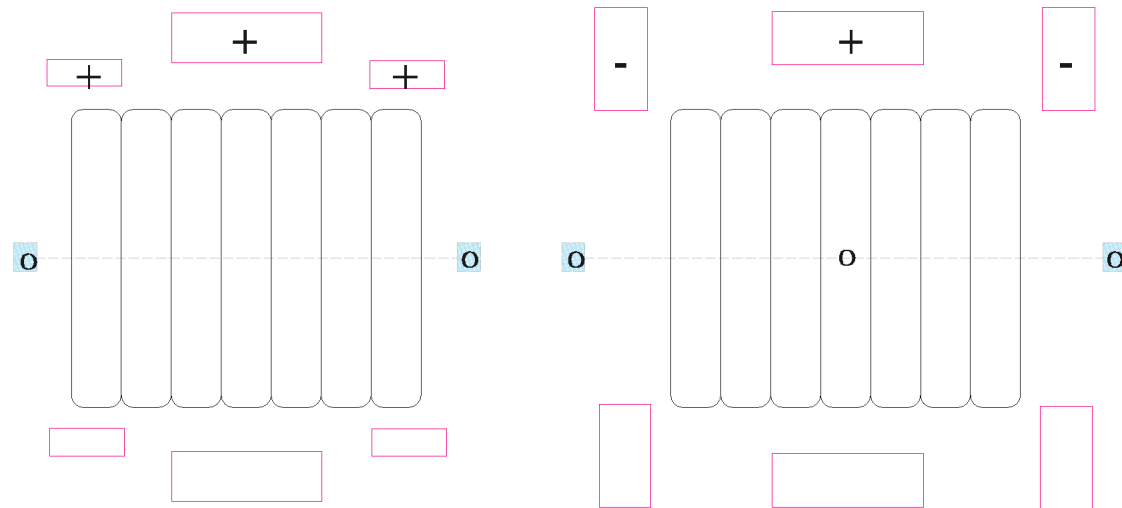
Or, Periodic Cooling Lattices

R. Palmer (BNL) et al.

- Various lattice designs have been studied:



Alternating solenoid



FOFO

Super-FOFO

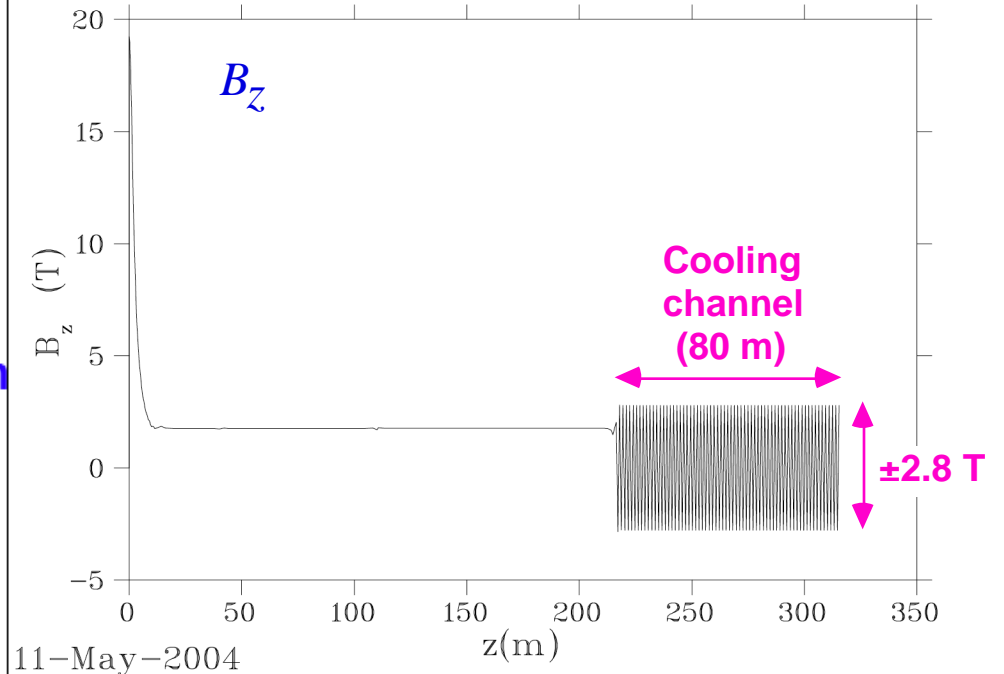
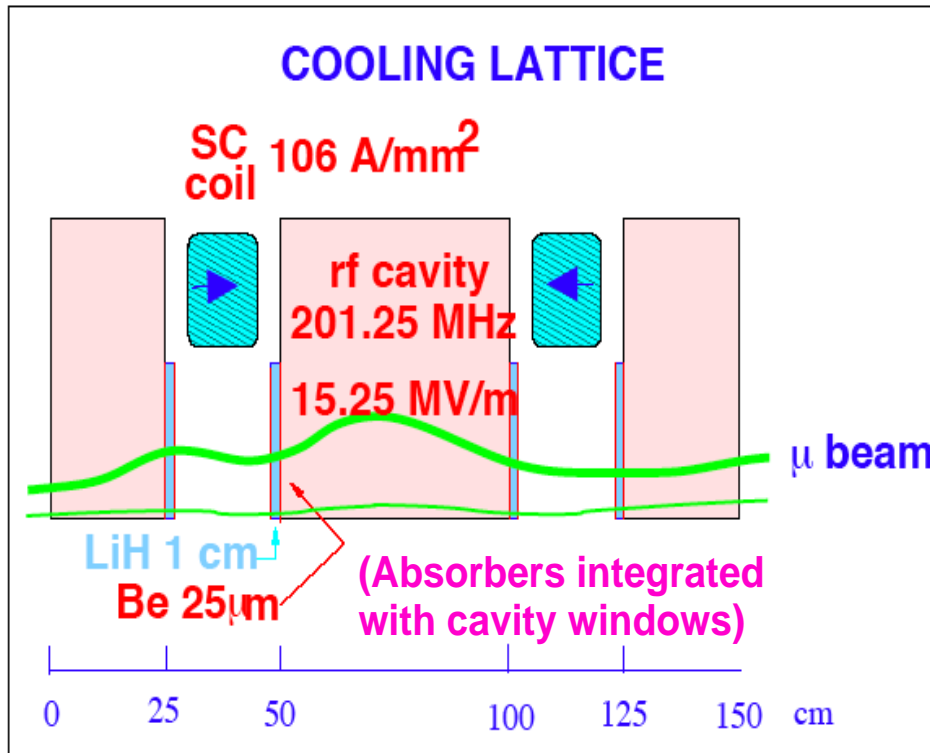
(+ RFOFO, DFOFO, Single-Flip, Double-Flip)

→ Alternating gradient allows low β with much less superconductor

Example: APS 6-Month Neutrino Study Cooling Channel

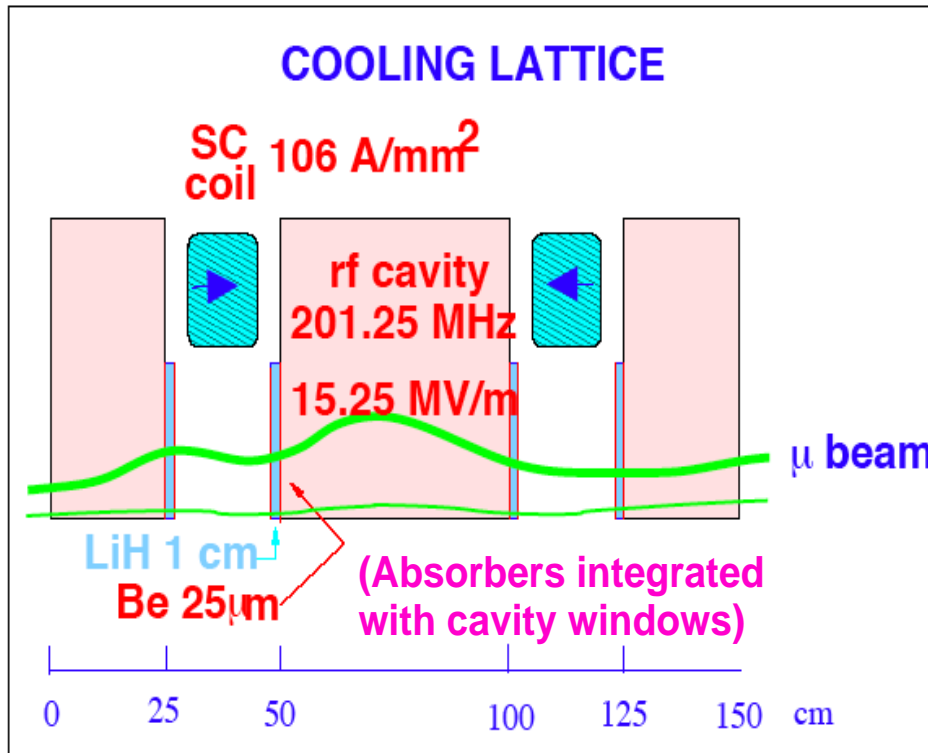
R. Palmer (BNL) et al.

Magnetic Field on axis

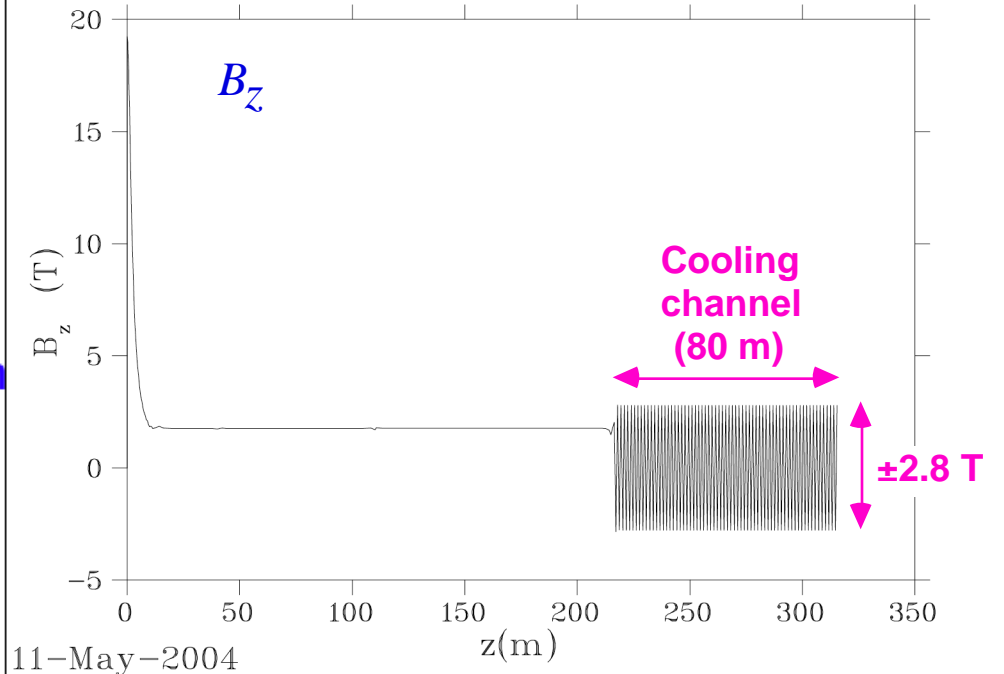


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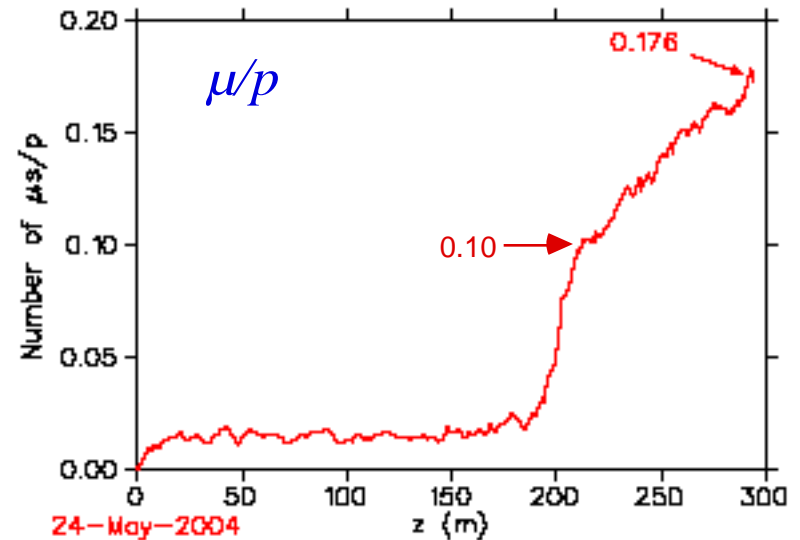
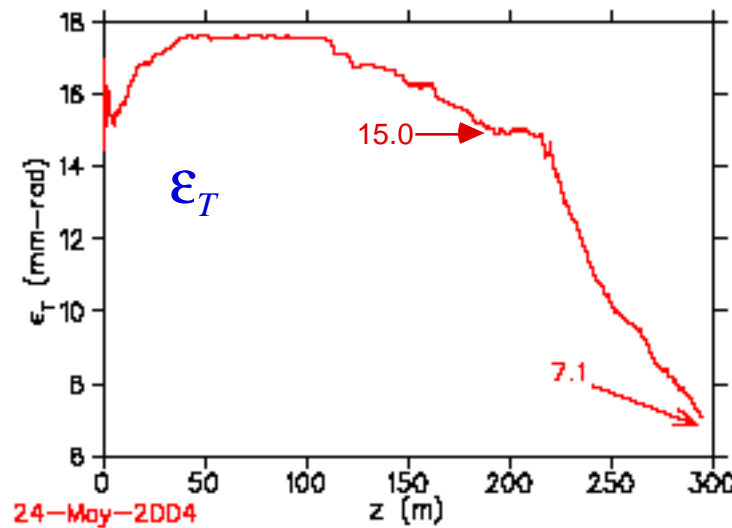
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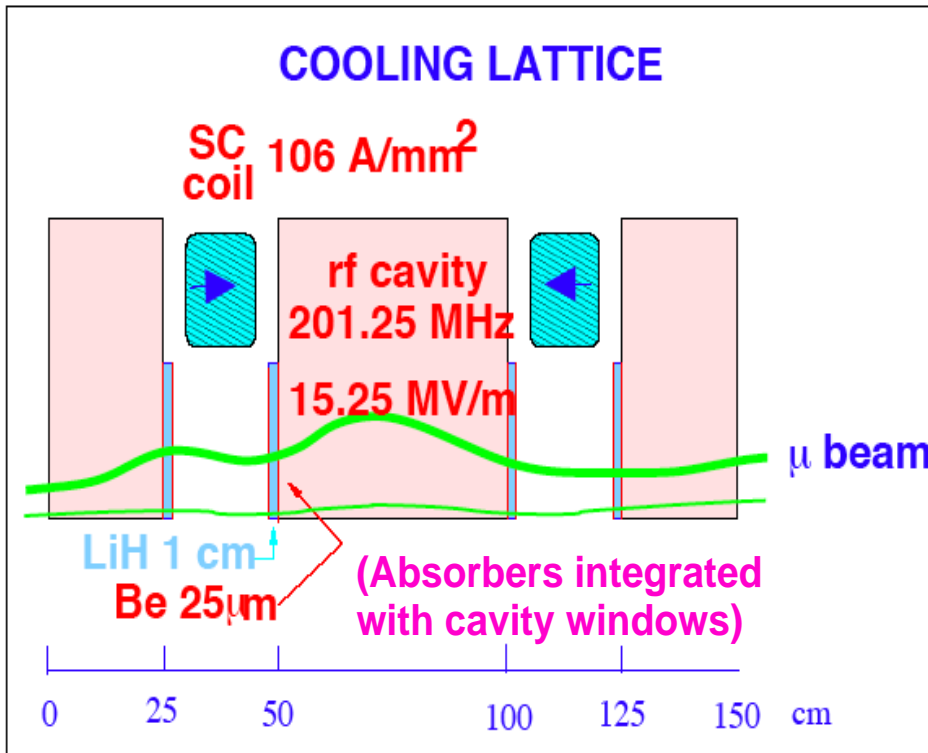
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- Performance:

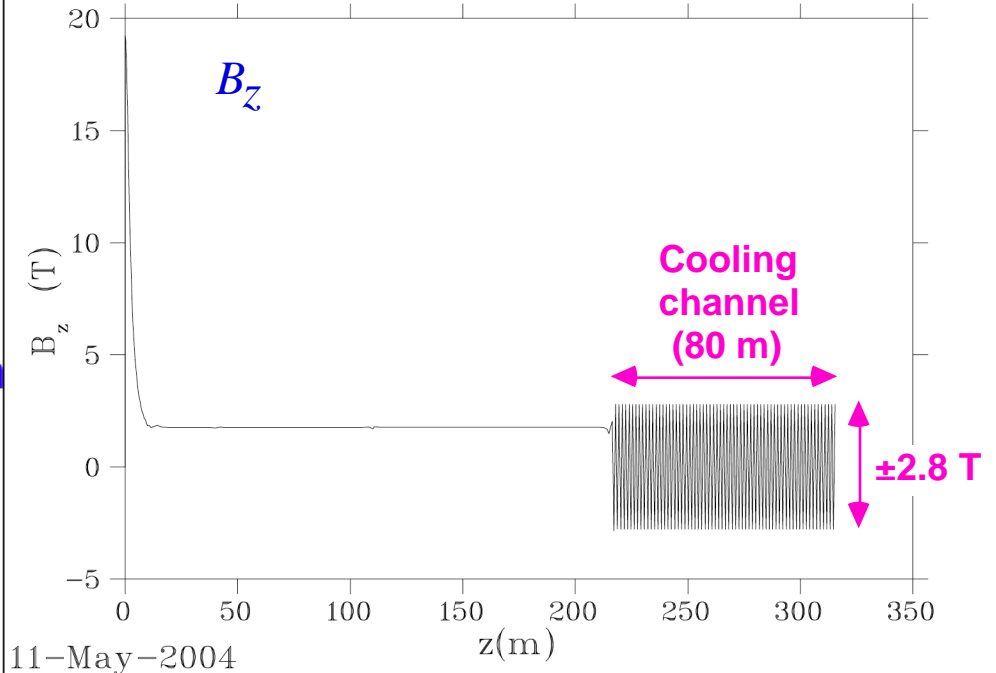


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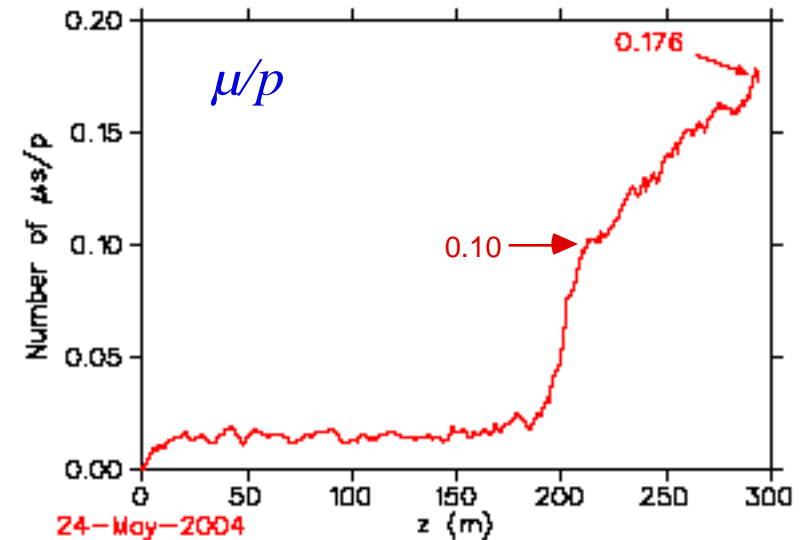
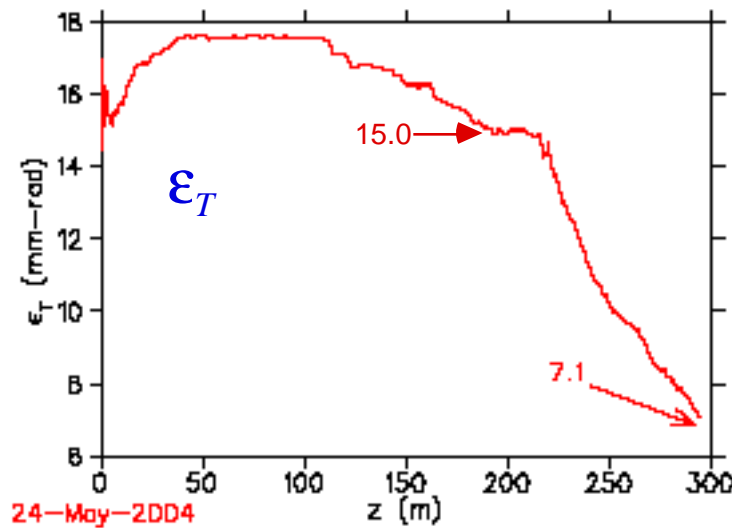


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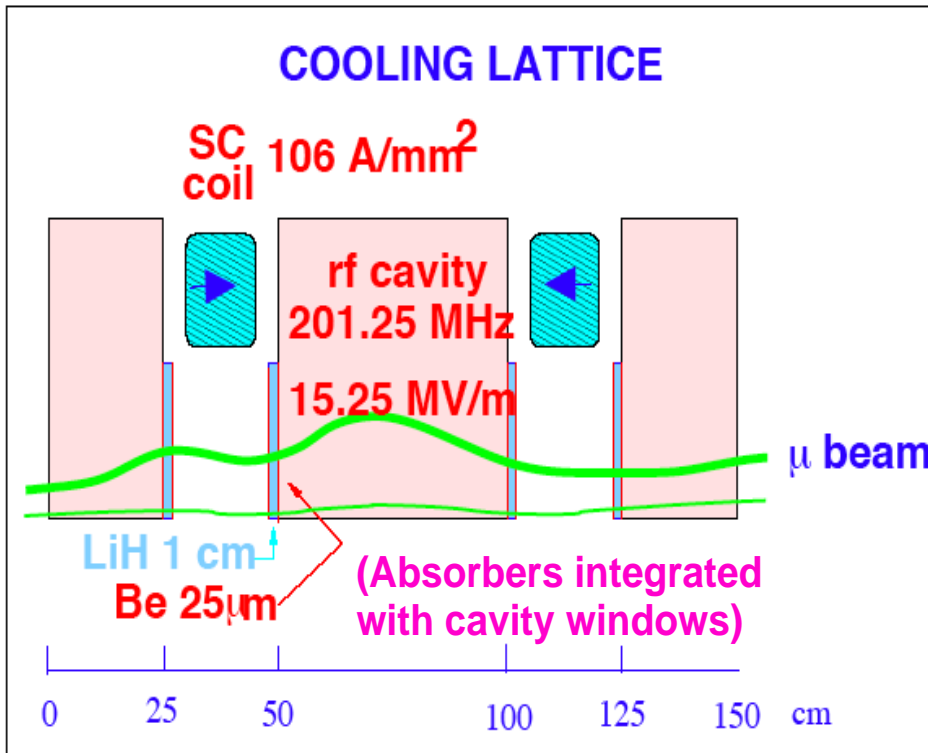


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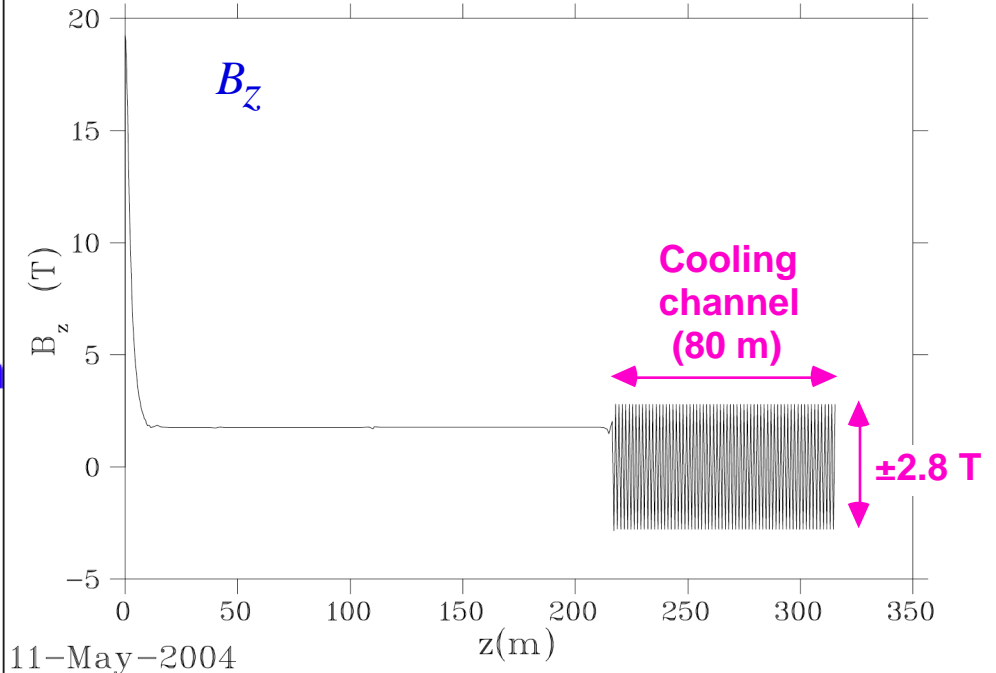
→ 80m “FS2a” cooling channel shrinks $\epsilon_T \times 7.1/15.0 \approx 0.5$,
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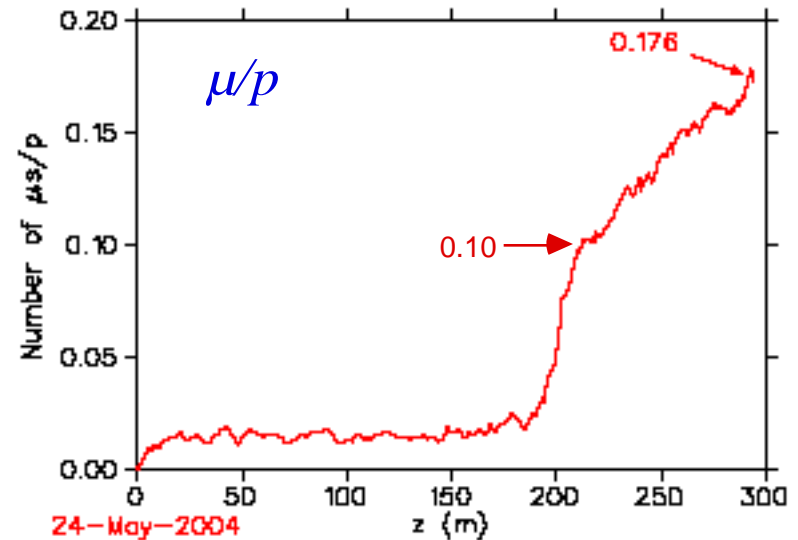
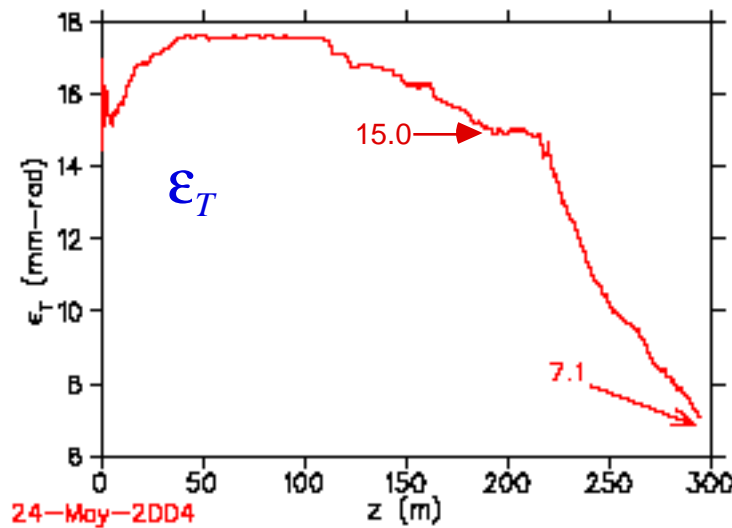


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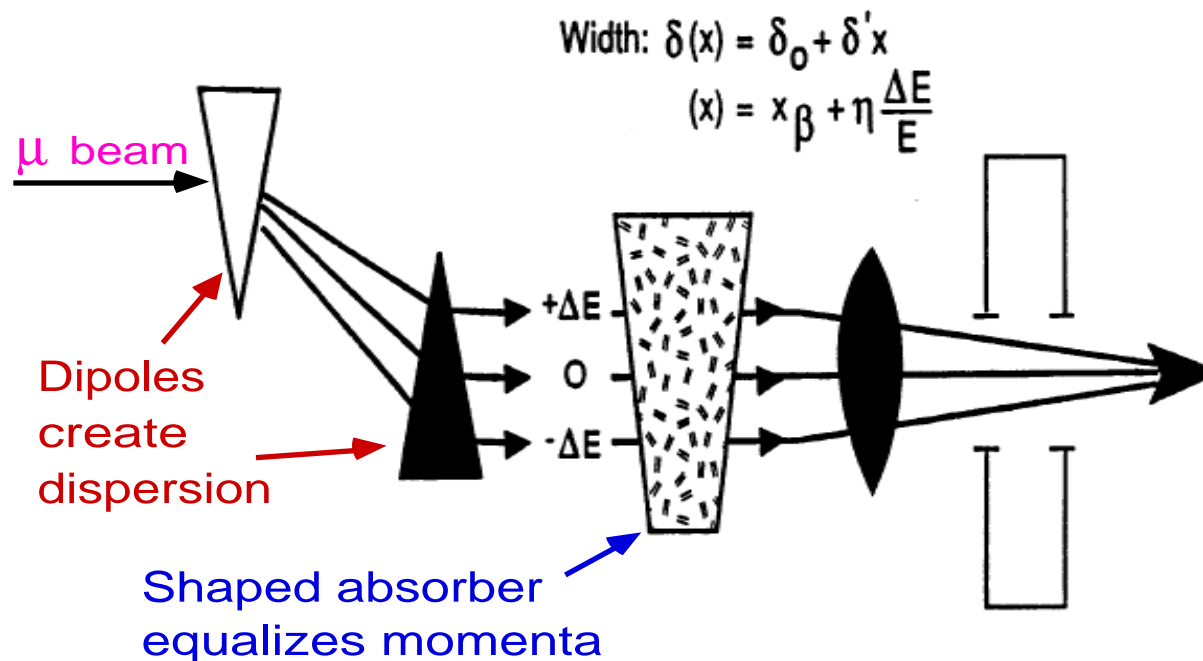
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⇒ **Cost-effective for NF**

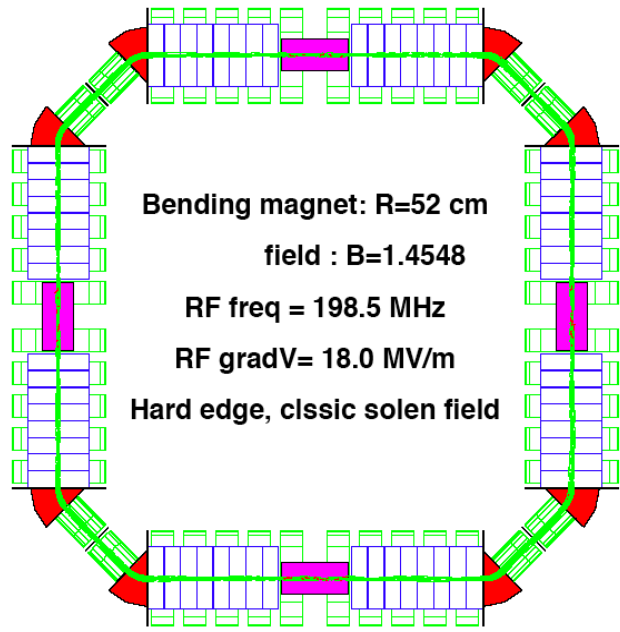
Longitudinal Cooling?

- 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 vF
 - 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:



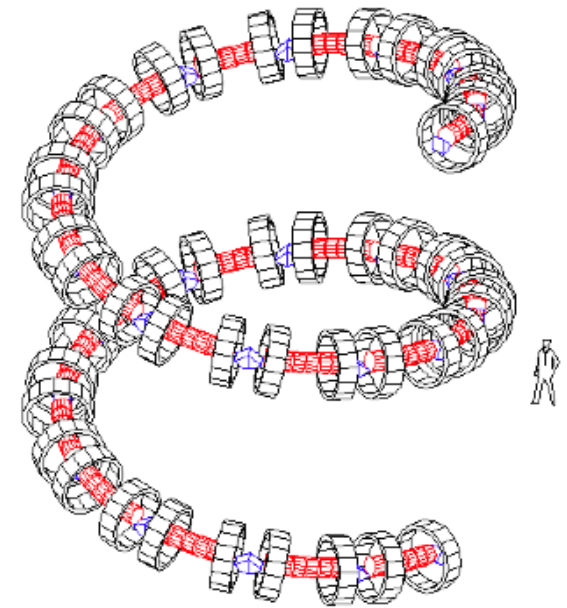
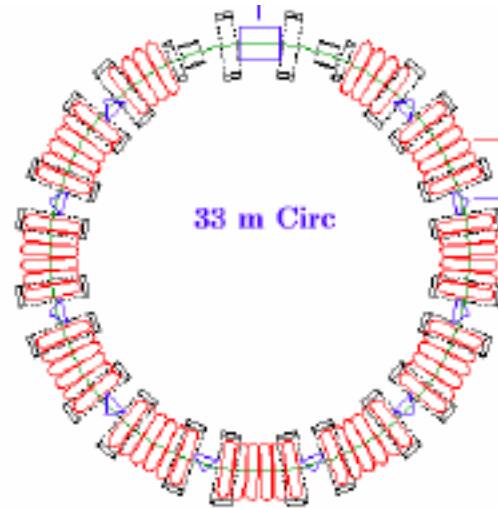
- Promising paper designs exist, e.g.,...

Some 6D Cooling Approaches



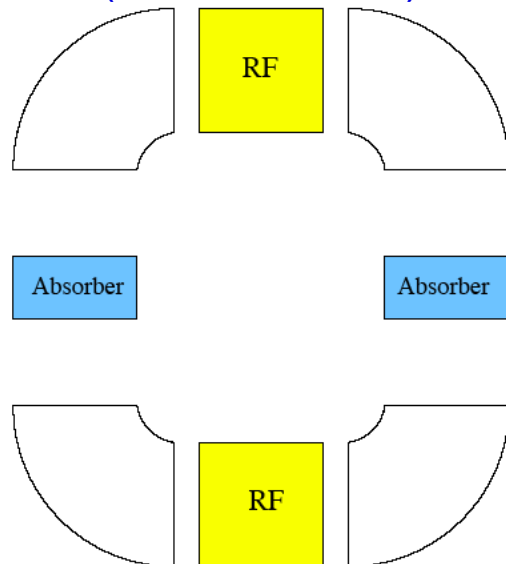
"Tetra" ring (Balbekov)

RFOFO ring (Palmer)

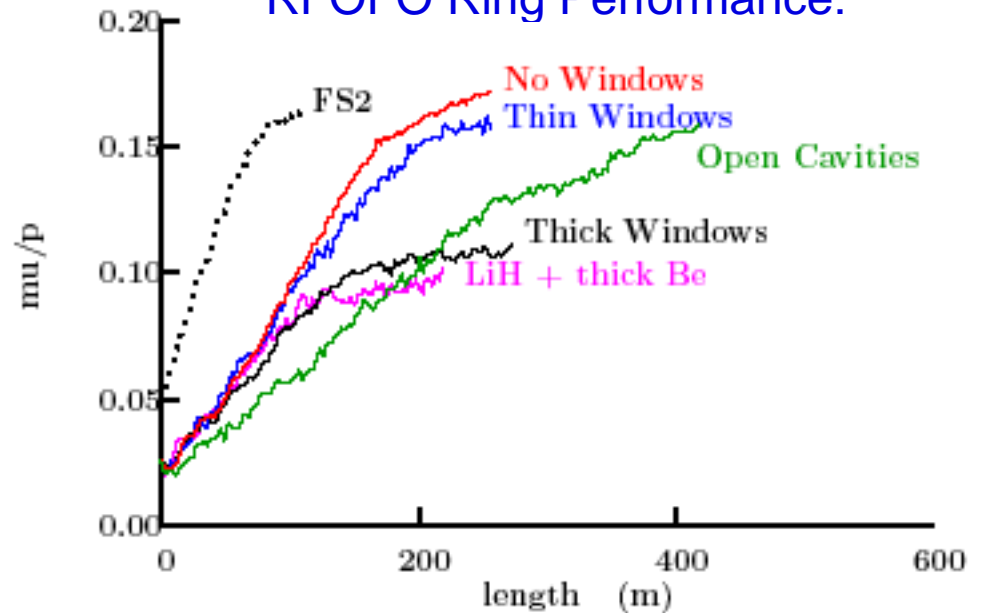


"Guggenheim" version (Klier)

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

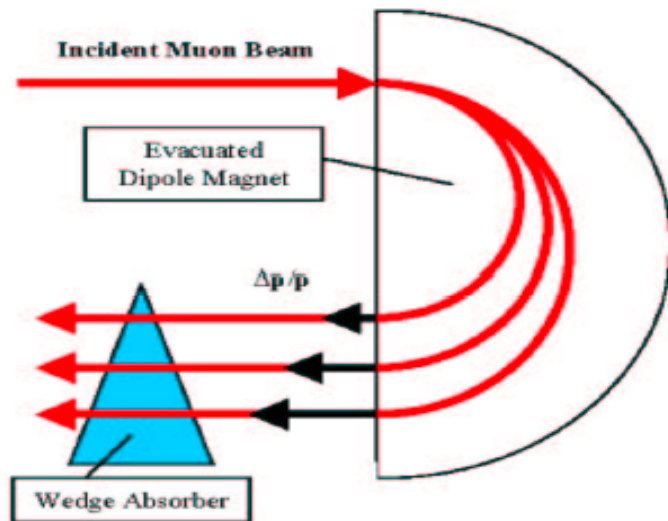


Figure 1. Use of a Wedge Absorber for Emittance Exchange

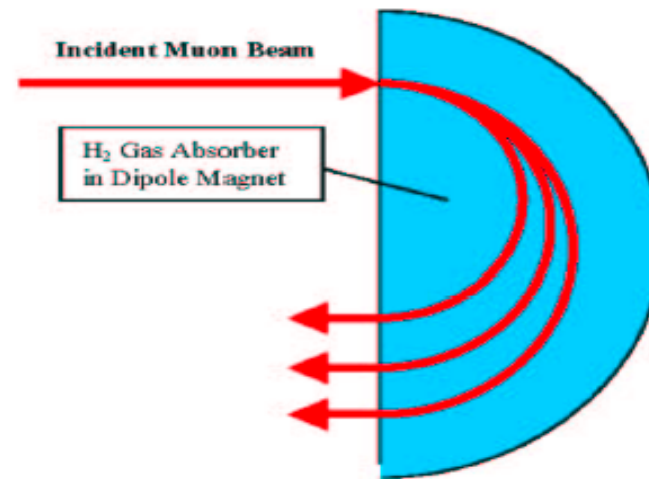
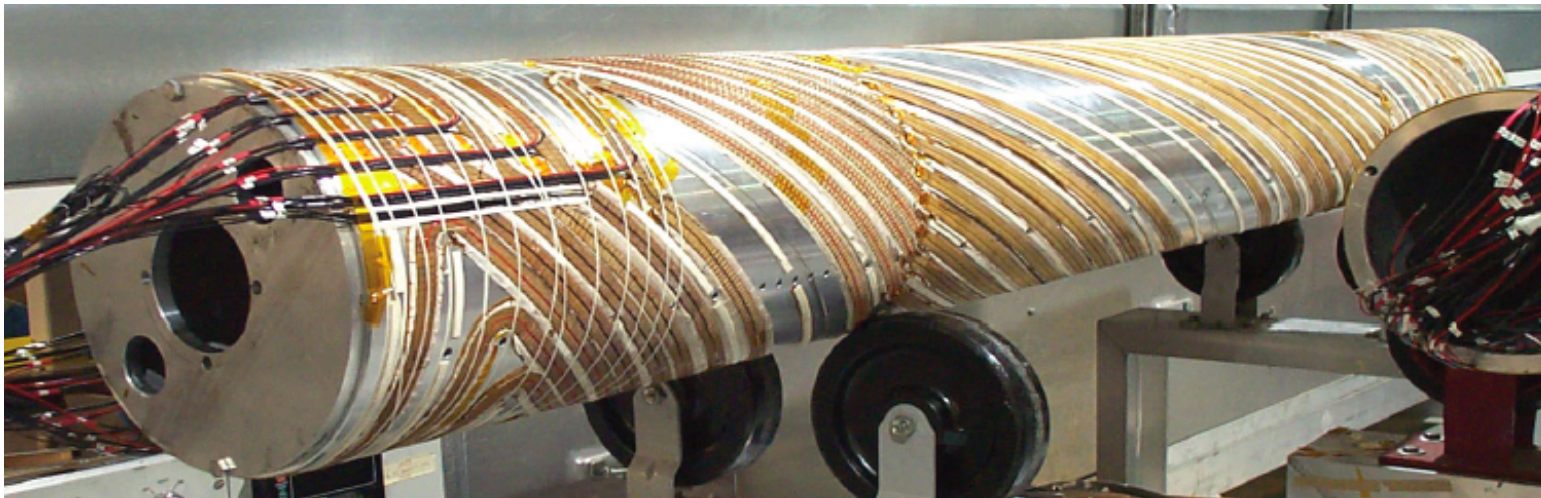


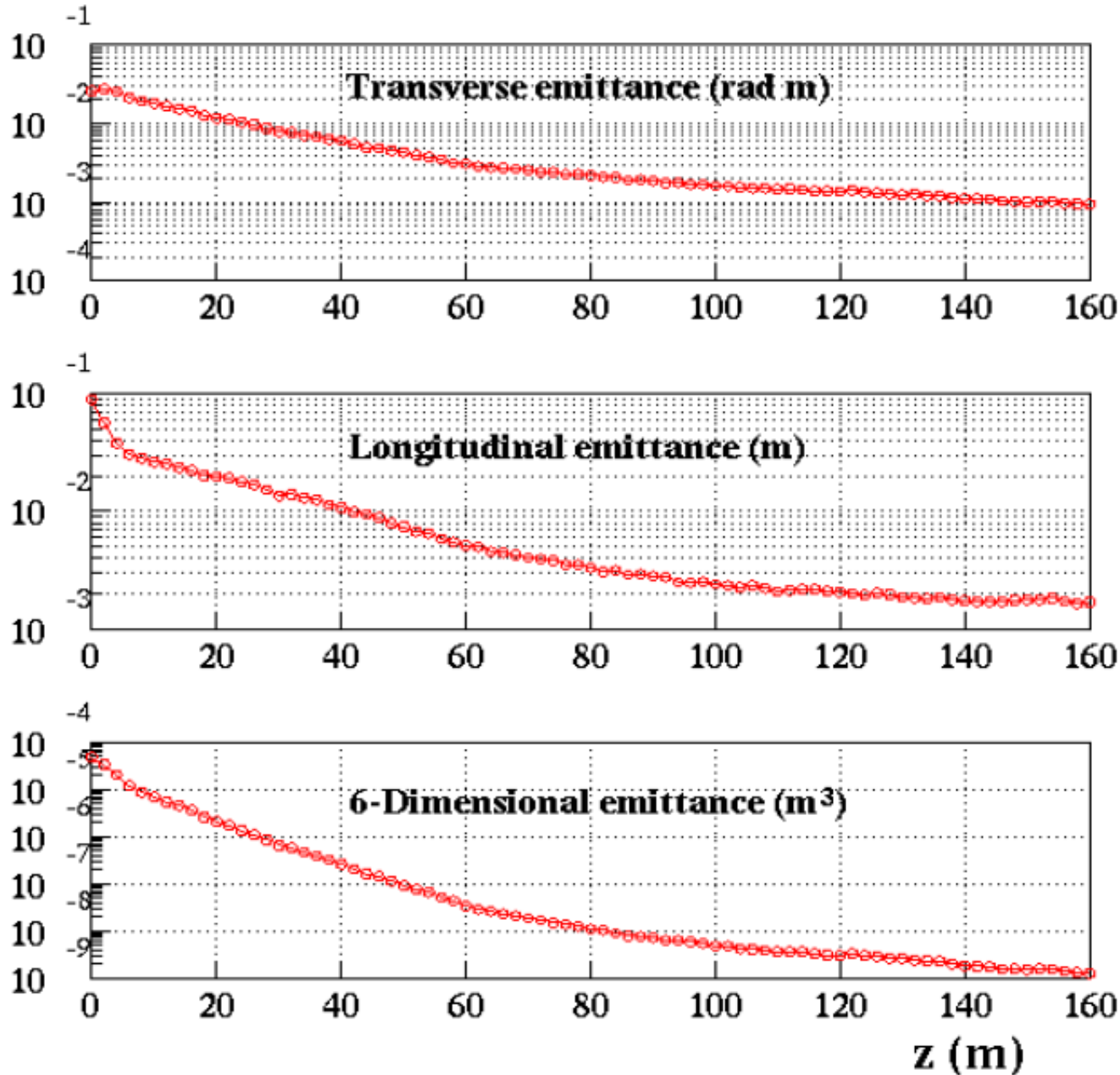
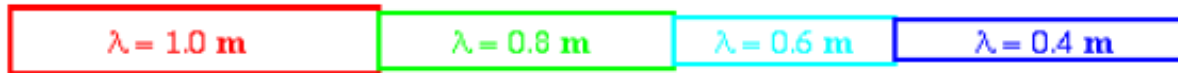
Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange



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

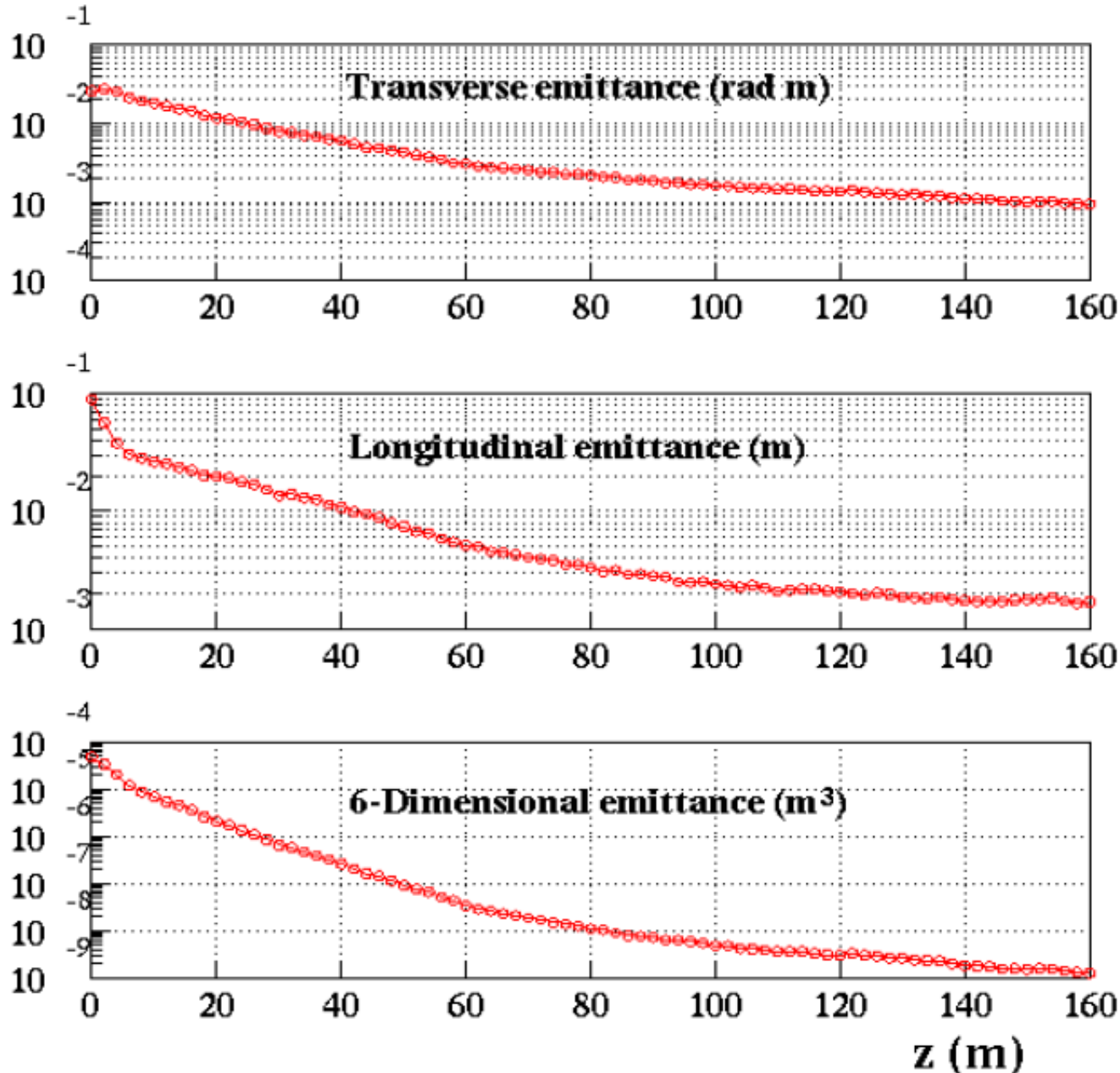
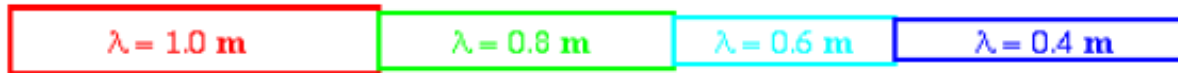
Helical Cooling Channel Performance example:

(Muons, Inc.)



Helical Cooling Channel Performance example:

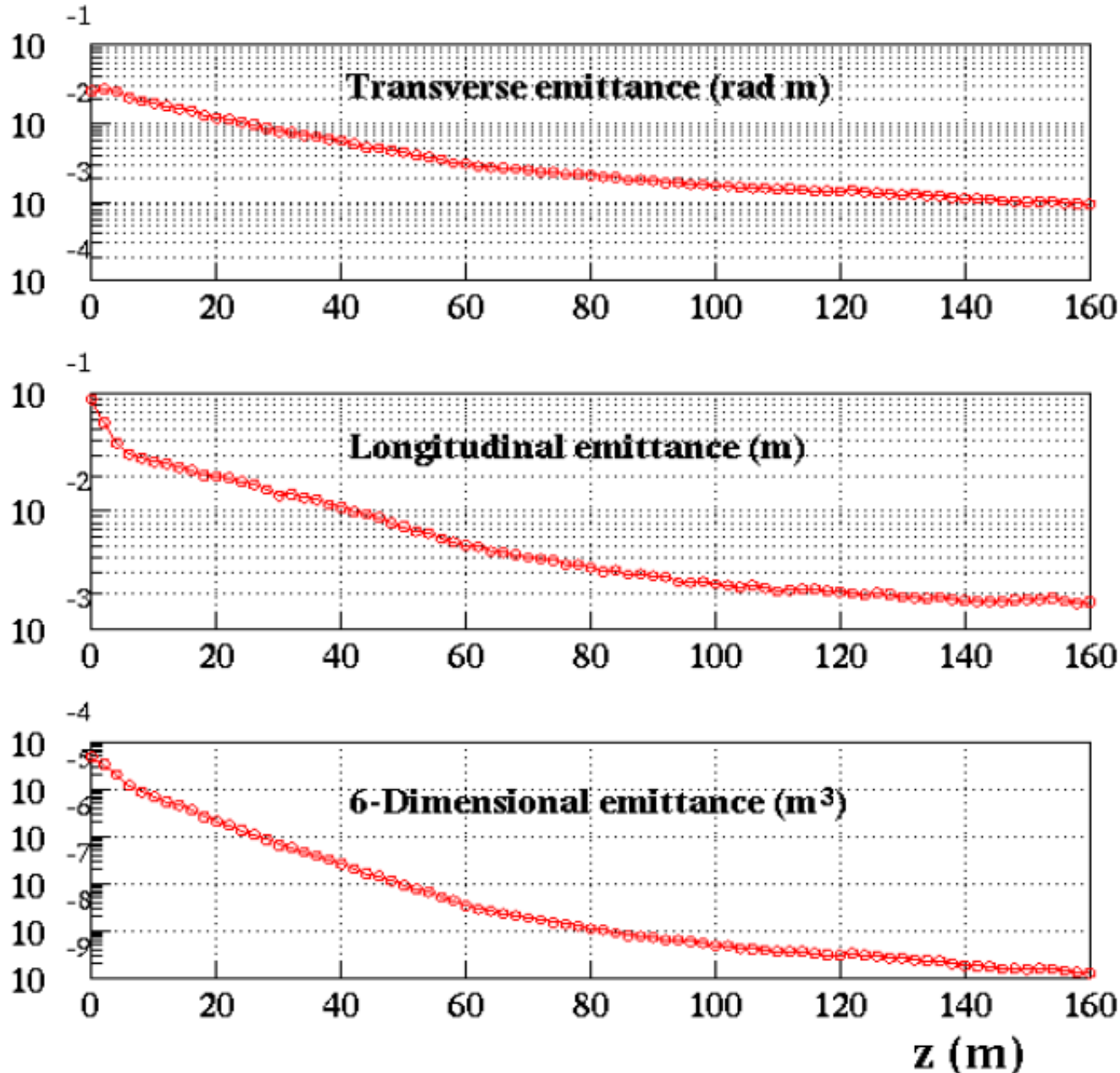
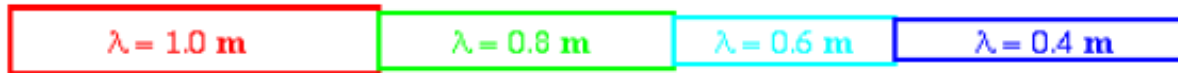
(Muons, Inc.)



- 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

Helical Cooling Channel Performance example:

(Muons, Inc.)



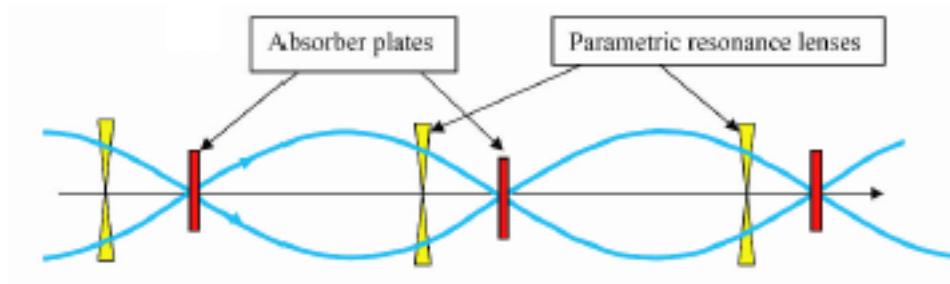
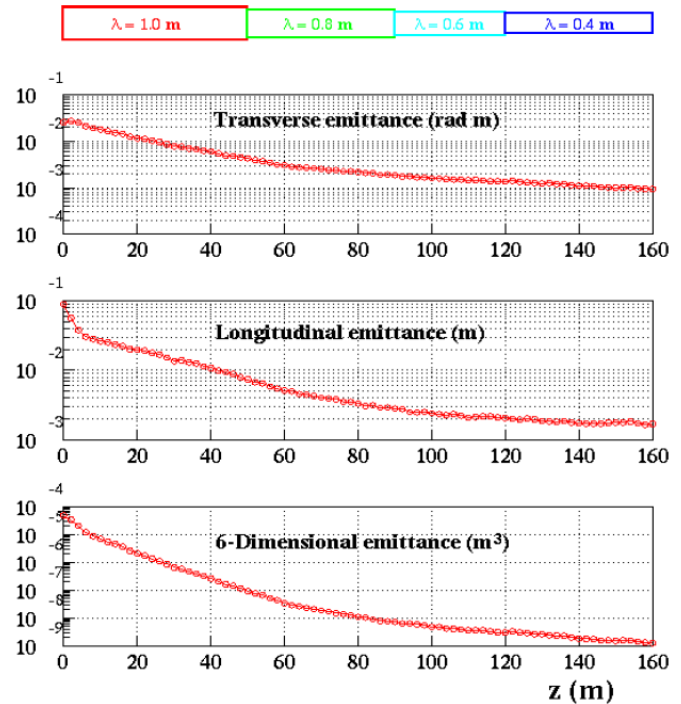
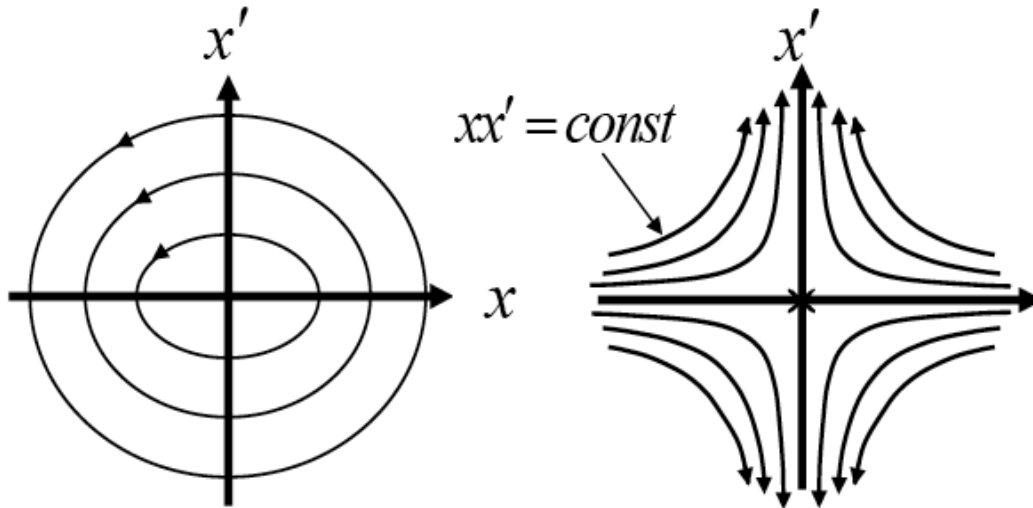
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→ **International Lepton Collider!**

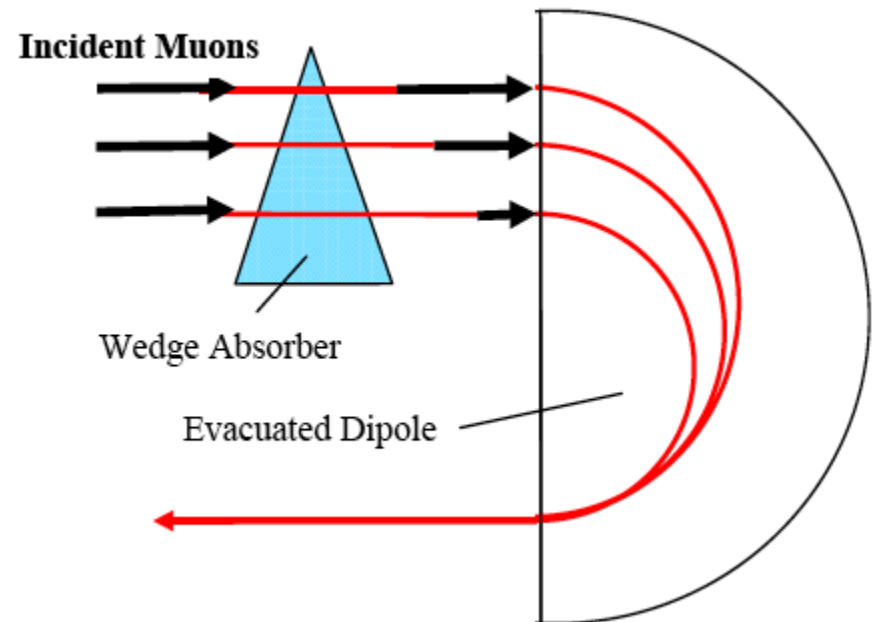
“Extreme Cooling”

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:**

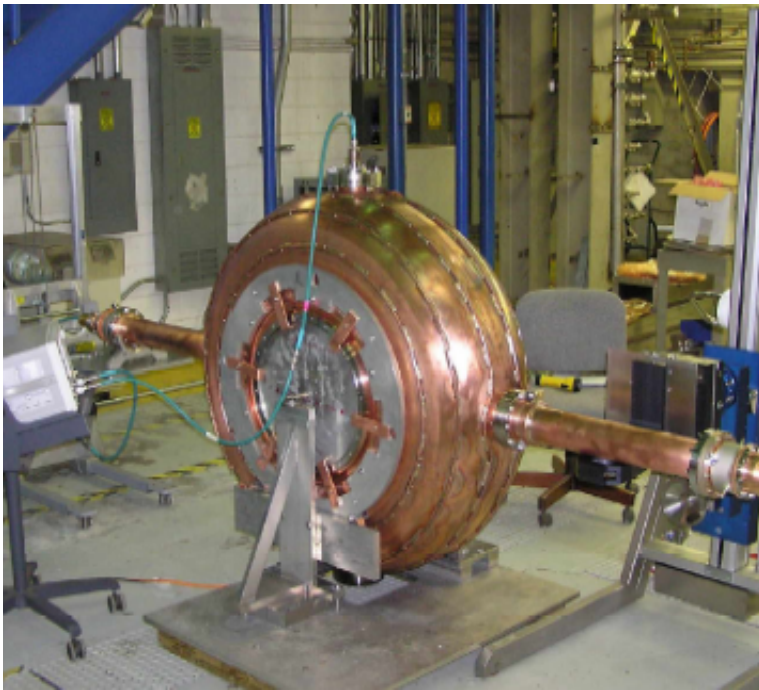
- group based at Fermilab holding regular meetings to explore options for a Muon Collider
- see <http://beamdocs.fnal.gov/AD-public/DocDB/ListBy?topicid=173>

- **Also ongoing program of hardware prototyping and testing by Neutrino Factory and Muon Collider Collaboration, e.g.,...**

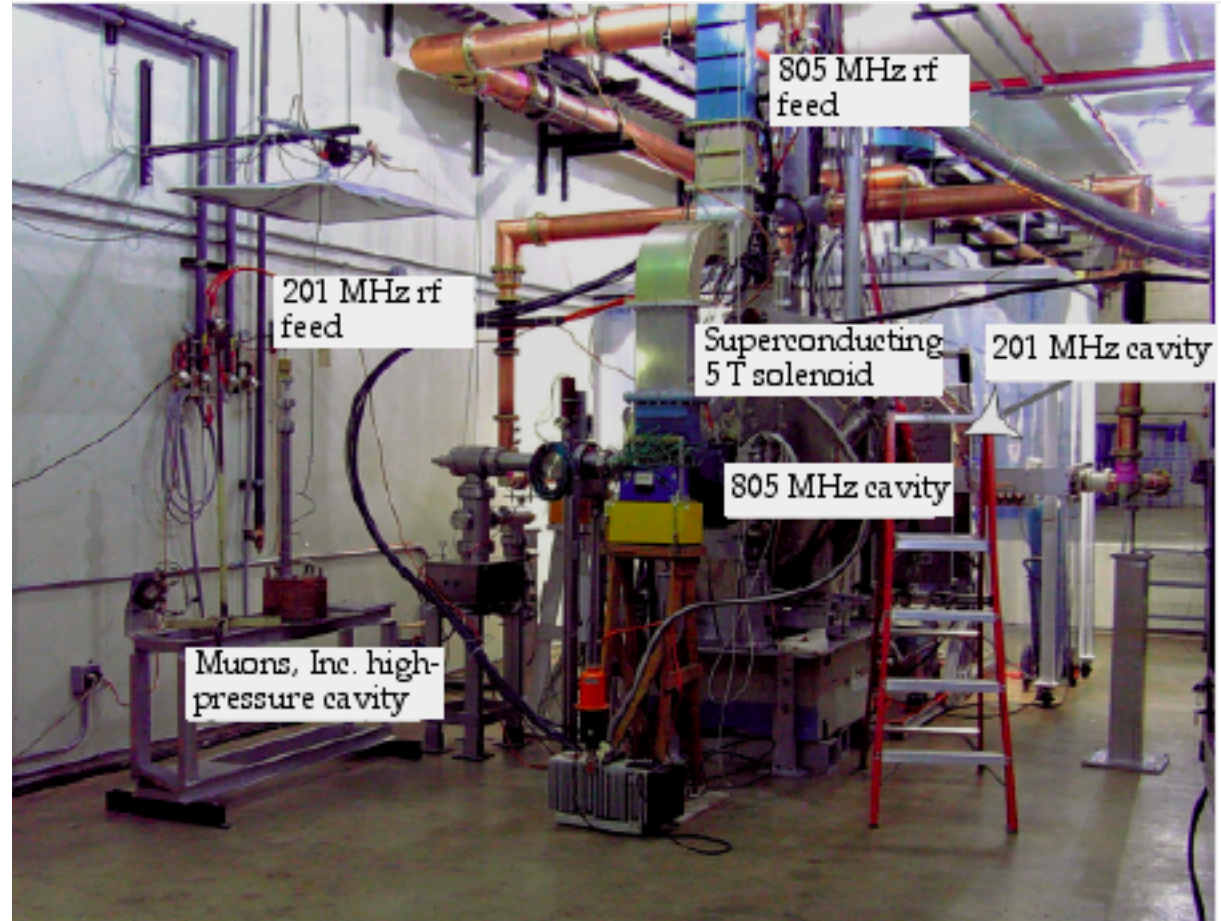
RF Cavity R&D

(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:

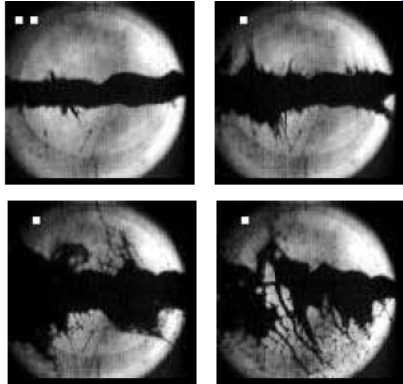
1. Multi-MW targets: **MERIT** @ CERN *n*TOF facility
2. Transverse ionization cooling: **MICE** @ RAL ISIS synchrotron
3. 6D helical cooling: **MANX** proposal
4. Non-scaling FFAG acceleration: **EMMA** @ DL

MERIT (MERcury Intense Target):

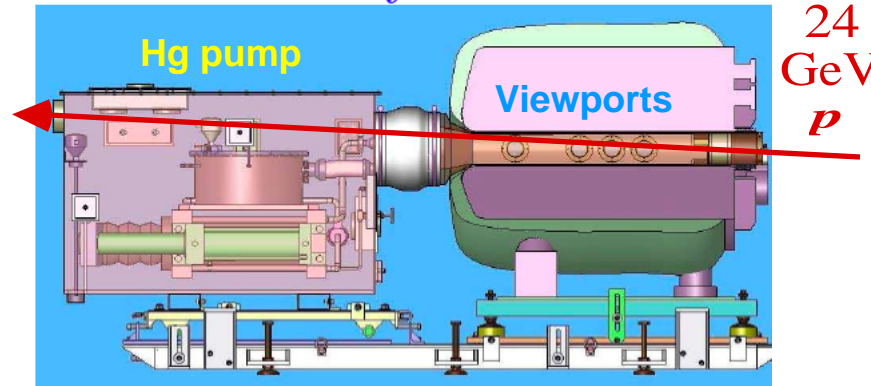
H. Kirk (BNL), K. McDonald (Princeton), et al.

- 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:**

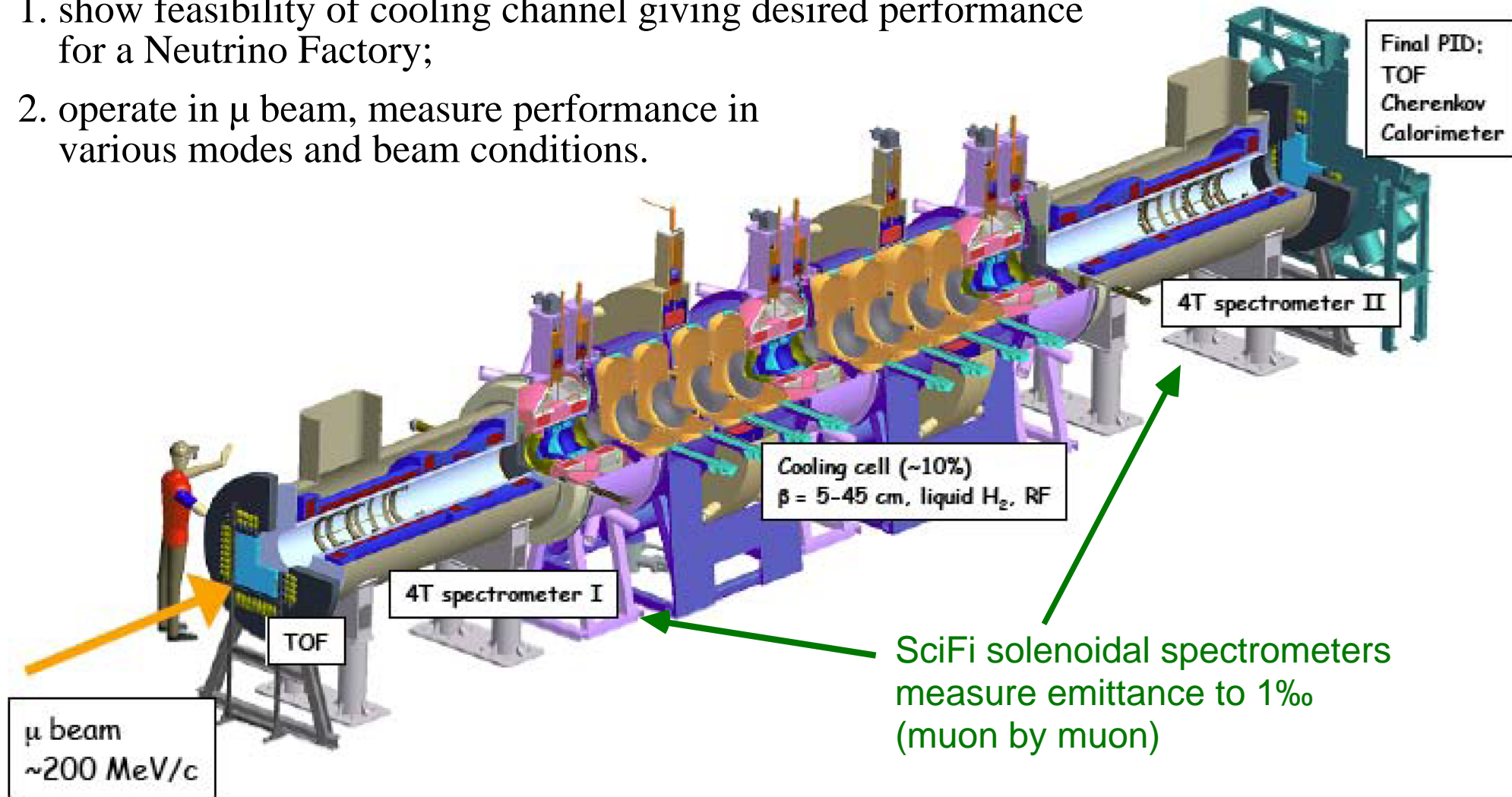
- 2003: LOI's to CERN and JPARC
- 2004: Proposal to CERN; contract let to fabricate 15-T LN₂-cooled NC magnet
- 2005: MERIT approved by CERN
- 2006: Commission magnet at MIT
Fabricate mercury delivery system and test with magnet at MIT
Fabricate cryogenic system
- 2007: Install experiment at CERN (n 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.

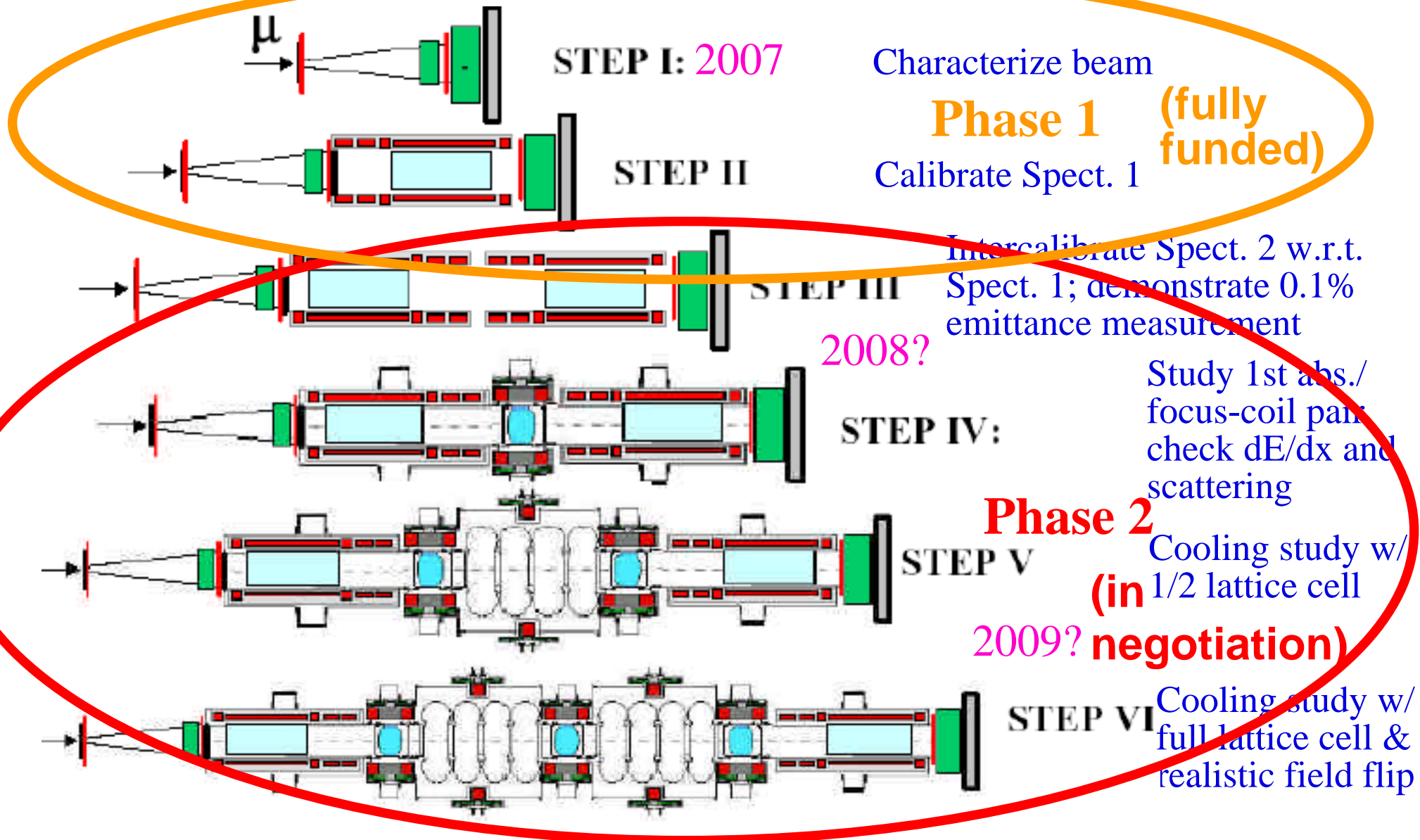


- **Large international, interdisciplinary collaboration:**

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

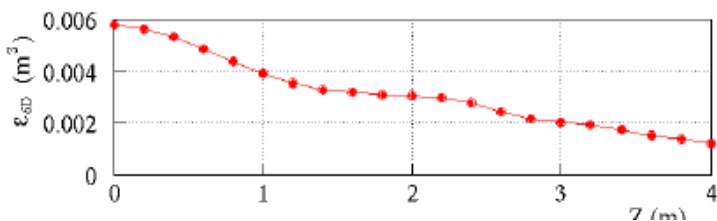
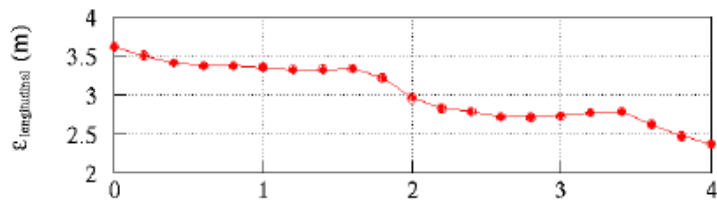
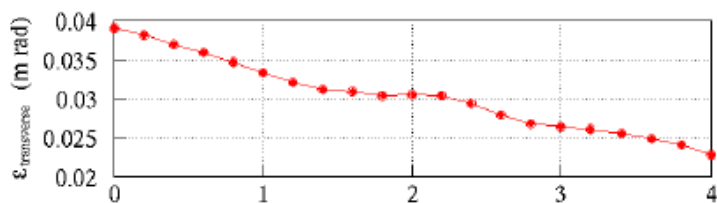
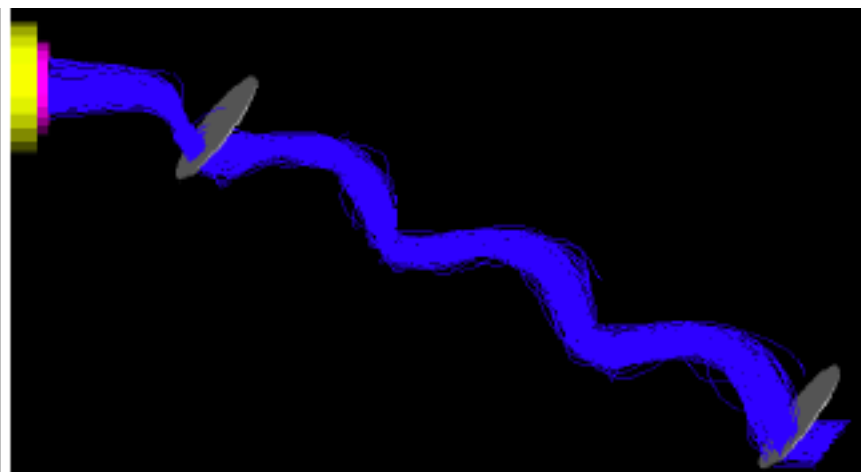
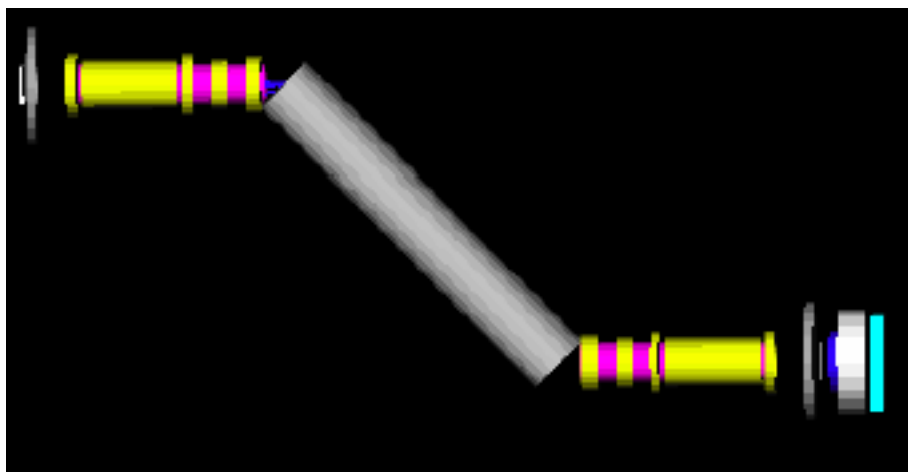
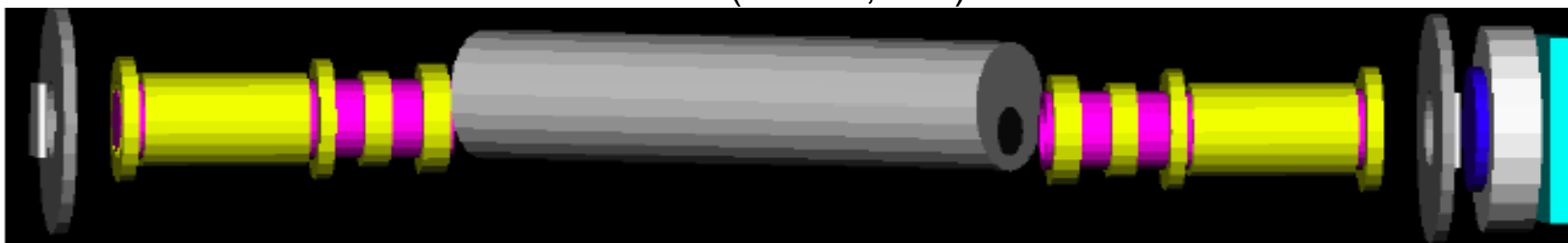
Avatars of MICE

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



MANX (Muon collider And Neutrino factory eXperiment)

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

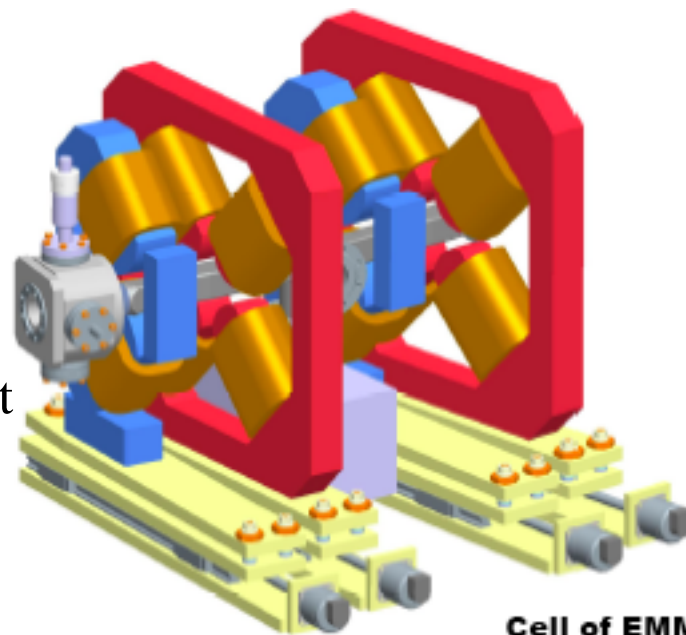
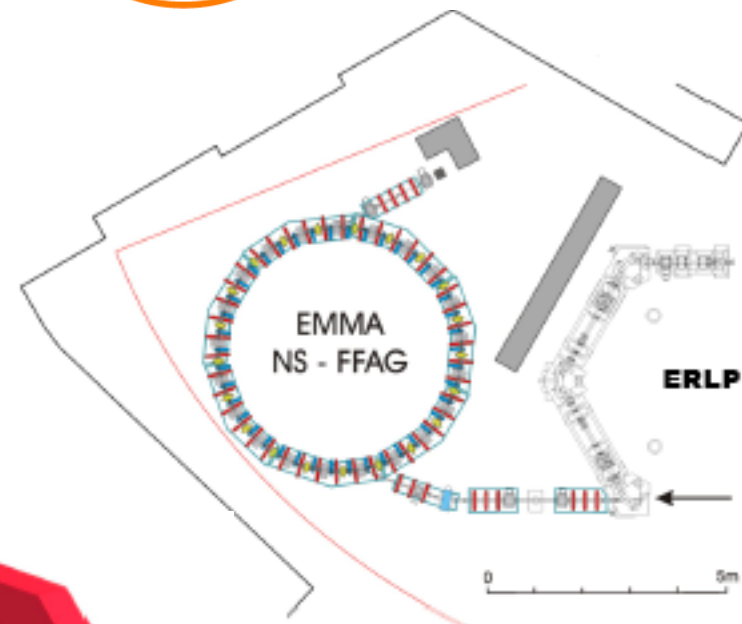
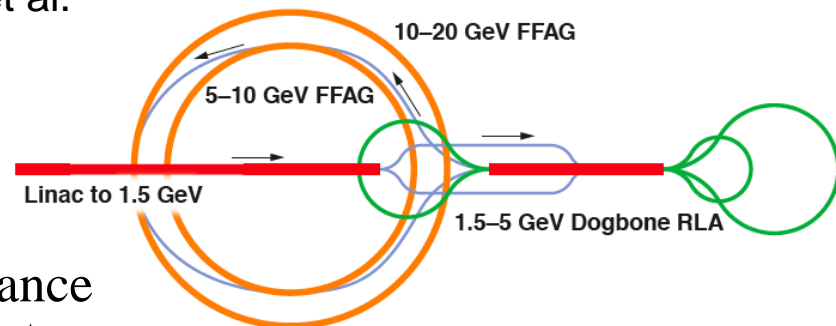


- Proposed follow-on to MICE:
 - insert LHe-filled helical-channel segment between MICE spectrometers
- Obtain large cooling factor (~ 0.5) in few m using graded B fields to match decreasing p_{μ}
- Optimization under study
- Proposal submitted to Fermilab (May 2006) to design and build helical magnet

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...

Outlook

Crystal ball slightly hazy, but...

- Around 2010, should know
 - whether \exists low-mass Higgs &/or SUSY
 \Rightarrow 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

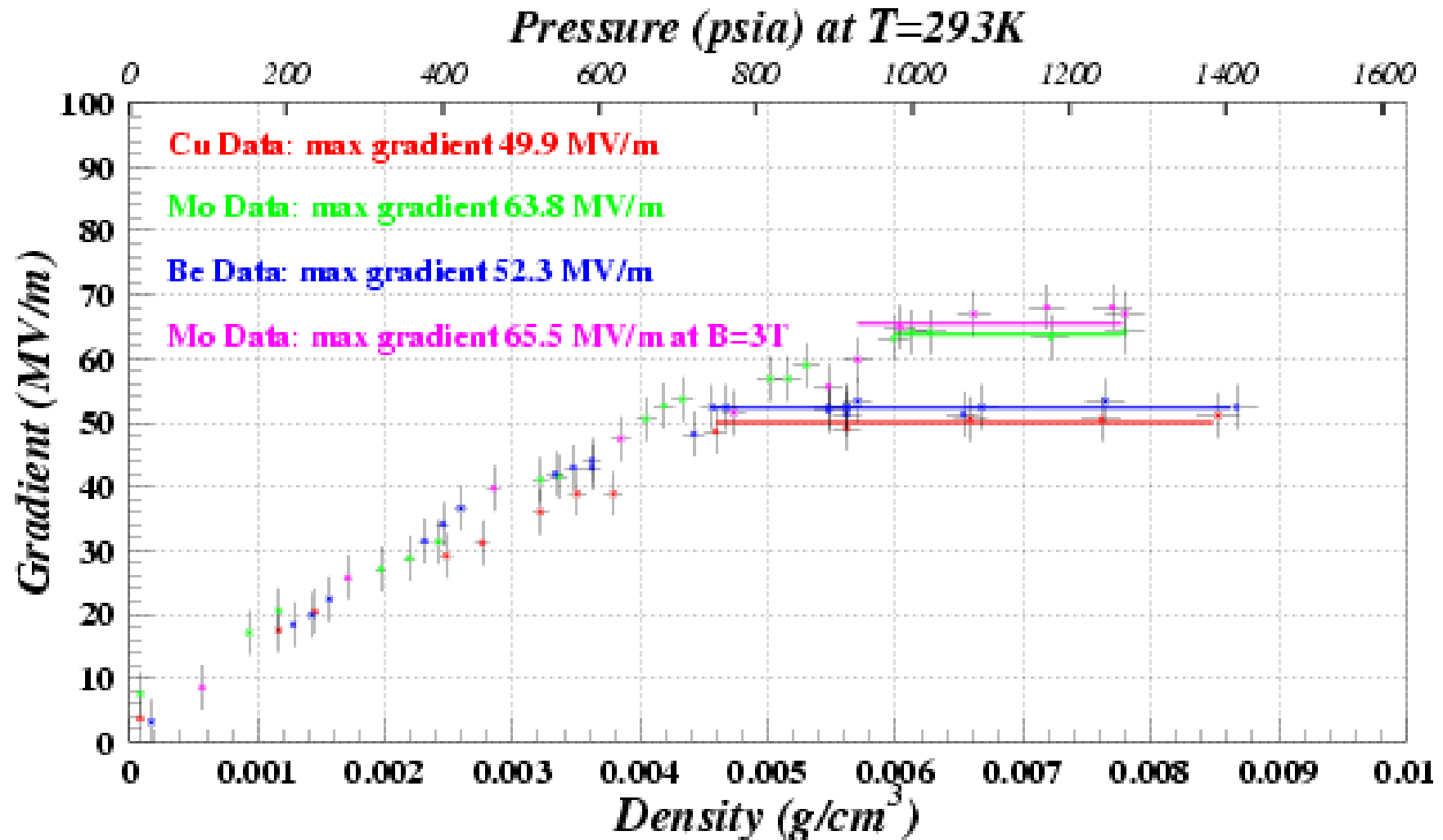
Summary

- 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!

Pressurized vs. Vacuum Cavities

(FNAL, IIT, Muons Inc.)

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



- Pressurizing the cavity helps! (Paschen effect)