Muons, Inc.

Recent Innovations in Muon Beam Cooling and Prospects for Muon Colliders and Neutrino Factories

Rolland P. Johnson

Muon collider And Neutrino factory eXperiment

Muon Beam Cooling Innovations

- Muon Colliders need small muon flux to reduce proton driver demands, detector backgrounds, and site boundary radiation levels. Very effective beam cooling is therefore required to produce high luminosity at the beam-beam tune shift limit and to allow the use of high frequency RF for acceleration to very high energy in recirculating Linacs.
- A Neutrino Factory based on a very cool muon beam which is accelerated in an existing Linac may be very cost-effective.
- Several new ideas have arisen in the last 4 years which are being developed under SBIR grants which have the potential to form muon beams with transverse emittances of a few mm-mr.
- The potential impact of this capability on energy-frontier colliders, Higgs factories, and intense neutrino beams is large. A vigorous R&D program is called for.

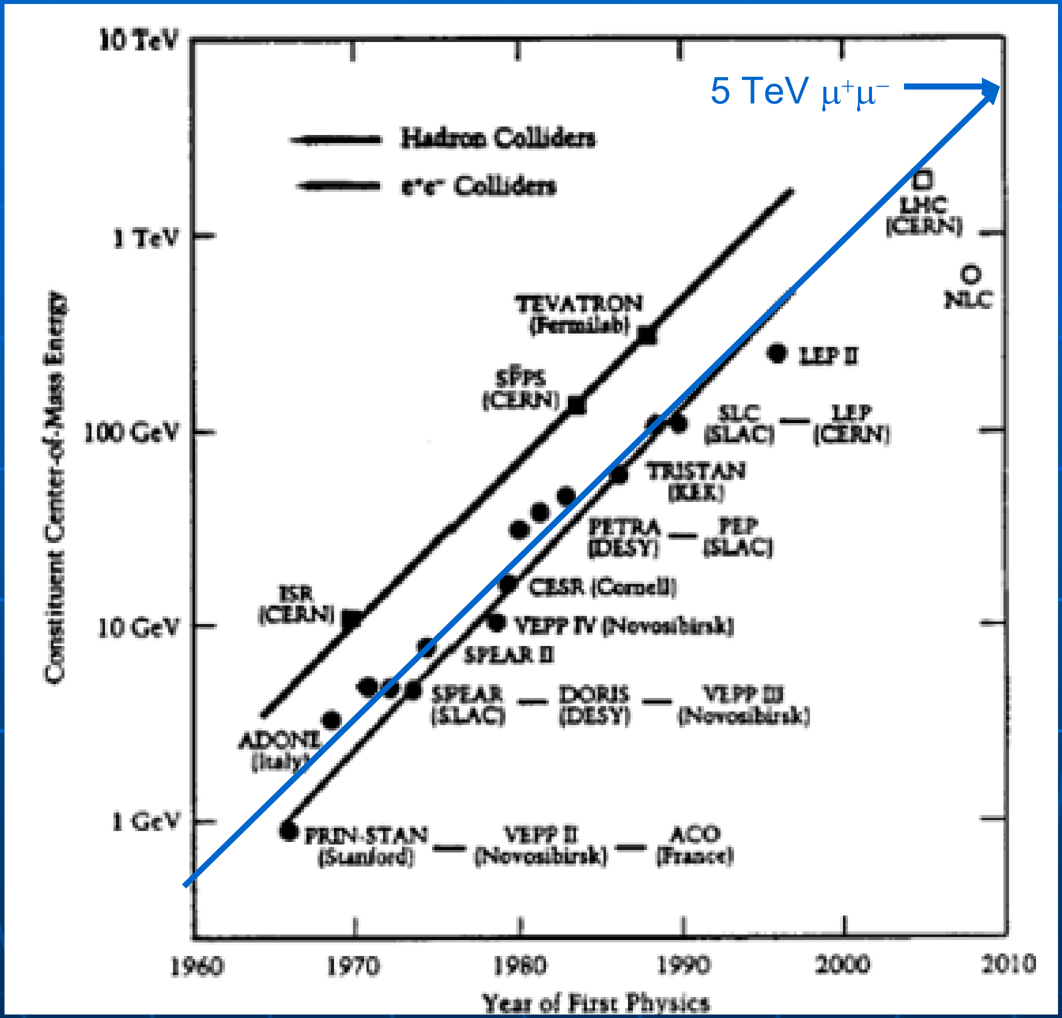
Muons, Inc. SBIR/STTR Collaboration:

(Small Business Innovation Research grants)

- Fermilab;
  - Victor Yarba, Chuck Ankenbrandt, Emanuela Barzi, Licia del Frate, Ivan Gonin, Timer Khabiboulline, Al Moretti, Dave Neuffer, Milorad Popovic, Gennady Romanov, Daniele Turrioni
- IIT;
  - Dan Kaplan, Katsuya Yonehara
- JLab;
  - Slava Derbenev, Alex Bogacz, Kevin Beard, Yu-Chiu Chao
- Muons, Inc.;
  - Rolland Johnson, Mohammad Alsharo'a, Pierrick Hanlet, Bob Hartline, Moyses Kuchnir, Kevin Paul, Tom Roberts

- Underlined are 6 accelerator physicists in training, supported by SBIR/STTR grants

Muon Colliders: Back to the Livingston Plot



Modified Livingston Plot taken from: W. K. H. Panofsky and M. Breidenbach, Rev. Mod. Phys. 71, s121-s132 (1999)

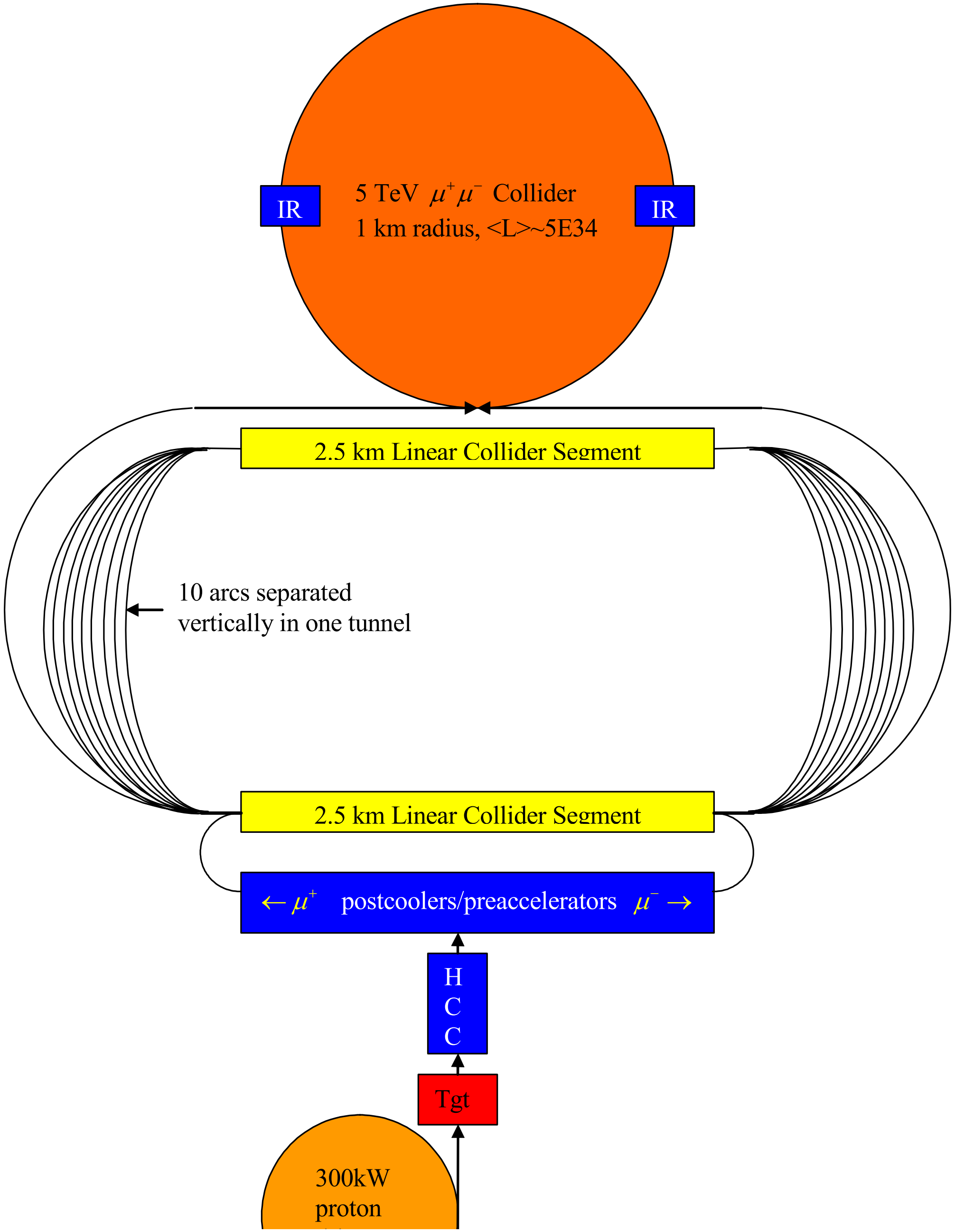
5 TeV ~ SSC energy reach

~5 X 2.5 km footprint

Affordable LC length, includes ILC people, ideas

High L from small emittance!

1/10 fewer muons than originally imagined:
a) easier p driver, targetry
b) less detector background
c) less site boundary radiation



Muon Collider Emittances and Luminosities

After:	ε_N tr	ε_N long.
– Precooling	20,000 μm	10,000 μm
– Basic HCC 6D	200 μm	100 μm
– Parametric-resonance IC	25 μm	100 μm
– Reverse Emittance Exchange	2 μm	2 cm

At 2.5 TeV on 2.5 TeV

$$L_{peak} = \frac{N_1 n \, \Delta\nu}{\beta^* r_\mu} f_0 \gamma = 10^{35} / cm^2 - s$$

$\gamma \approx 2.5\times10^4$ $\quad n = 10$

$f_0 = 50kHz$ $\quad N_1 = 10^{11}\mu^-$

$\Delta\nu = 0.06$ $\quad \beta^* = 0.5\,cm$

$\sigma_z = 3\,mm$ $\quad \Delta\gamma/\gamma = 3\times10^{-4}$

$\tau_\mu \approx 50\,ms \Rightarrow 2500\,turns/\tau_\mu$

20 Hz Operation:

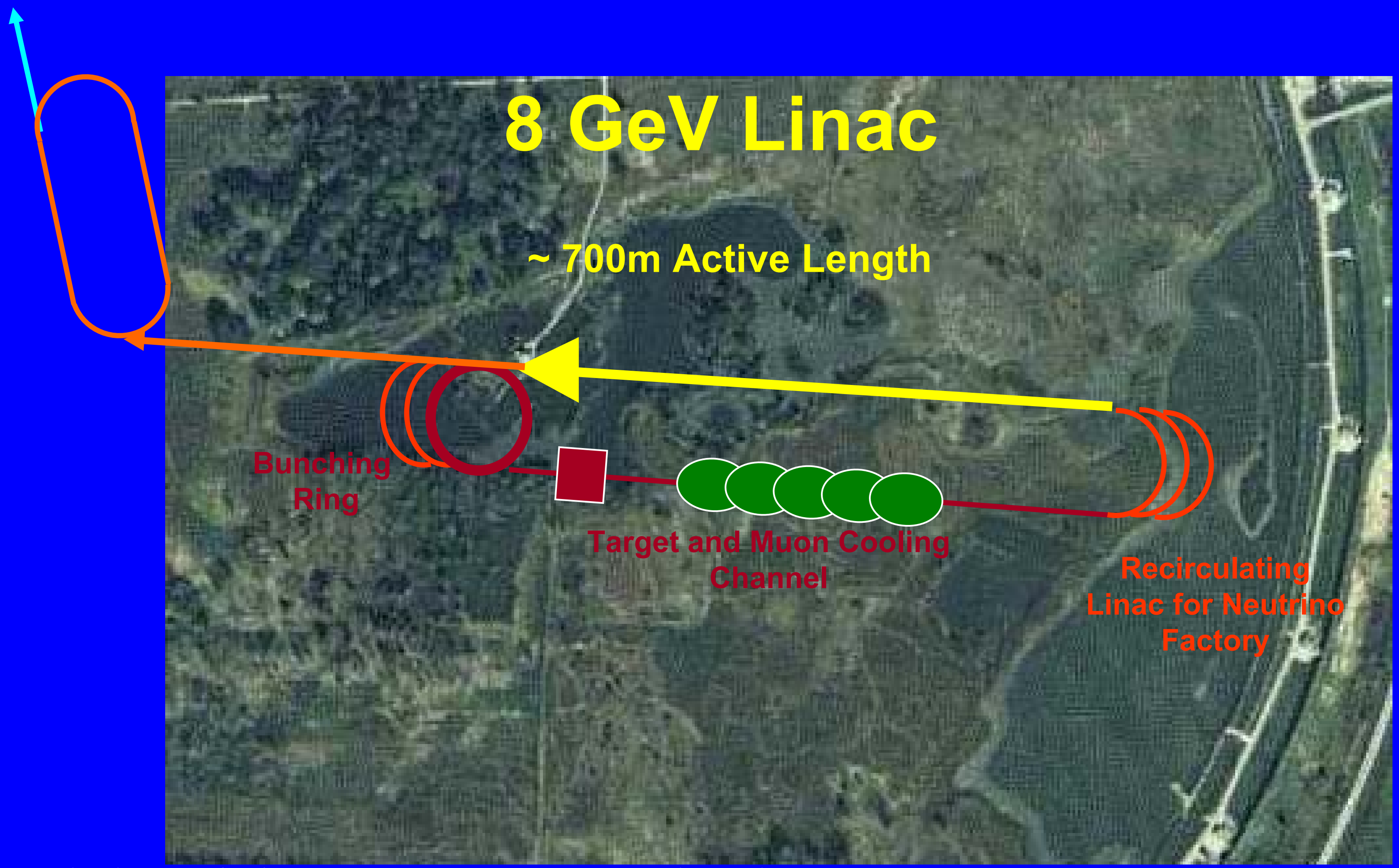
$$\langle L \rangle \approx 4.3\times10^{34} / cm^2 - s$$

$$Power = (26\times10^9)(6.6\times10^{13})(1.6\times10^{-19}) = 0.3MW$$

$0.3\,\mu^\pm / p$

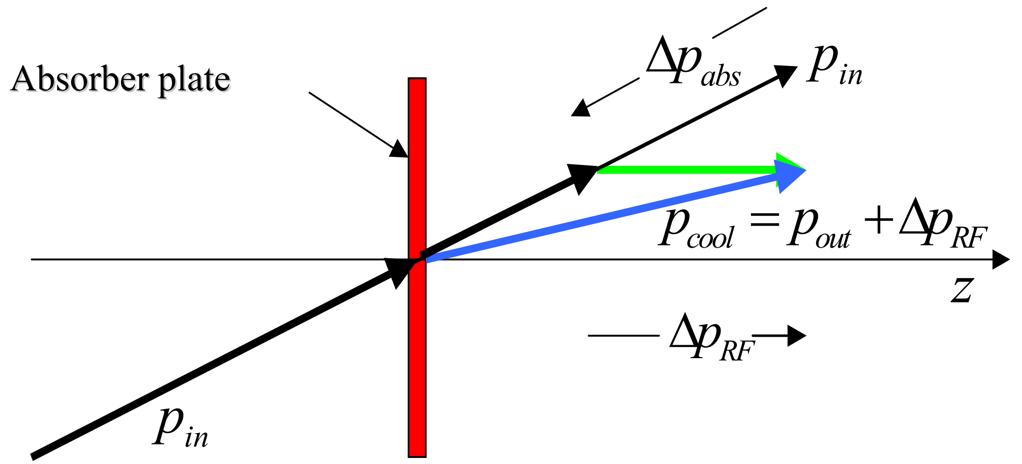
Neutrinos from an 8 GeV SC Linac

Muon cooling to reduce costs of a neutrino factory based on a Storage Ring.
Cooling must be 6D to fit in 1.3 GHz SC RF, where the last 6.8 GeV of 8 GeV are β=1.



Ionization Cooling (IC) Principle

- Schematic of angular divergence cooling



Our cooling ideas use this concept. It is the only method fast enough for muons!

Transverse Emittance IC

- The equation describing the rate of cooling is a balance between cooling (first term) and heating (second term):

$$\frac{d\varepsilon_n}{ds} = -\frac{1}{\beta^2}\frac{dE_\mu}{ds}\frac{\varepsilon_n}{E_\mu} + \frac{1}{\beta^3}\frac{\beta_\perp (0.014)^2}{2E_\mu m_\mu X_0}$$

- Here ε_n is the normalized emittance, E_μ is the muon energy in GeV, dE_μ/ds and X_0 are the energy loss and radiation length of the absorber medium, $\beta_\perp$ is the transverse beta-function of the magnetic channel, and β is the particle velocity.

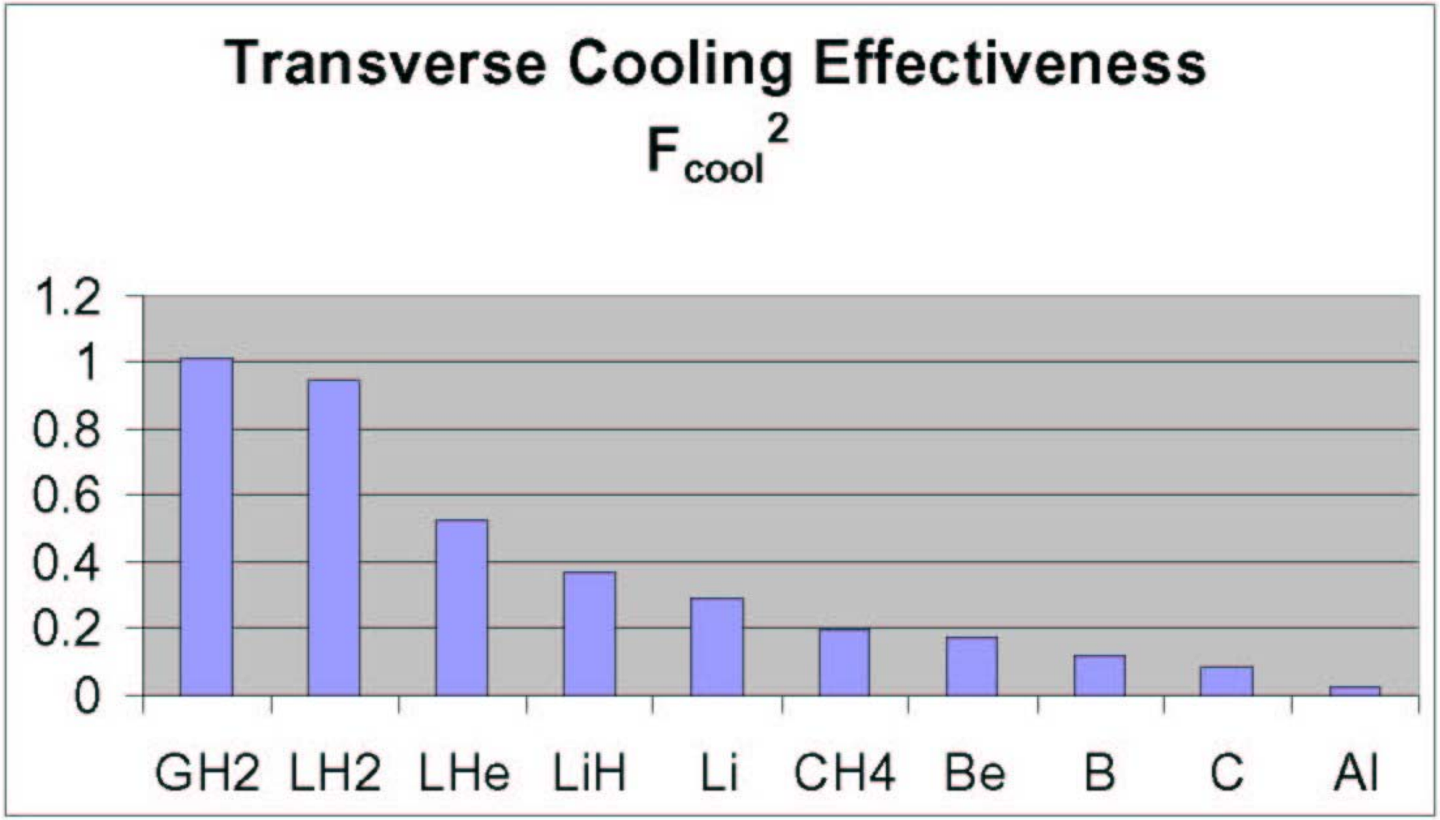
I. C. Figure of Merit

- Setting the heating and cooling terms equal defines the equilibrium emittance:

$$\varepsilon_n^{(equ.)} = \frac{\beta_\perp (0.014)^2}{2\beta m_\mu \frac{dE_\mu}{ds} X_0}$$

A cooling factor ($F_{cool} = X_0 dE_\mu/ds$) can be uniquely defined for each material, and since cooling takes place in each transverse plane, the figure of merit is F_{cool}^2. For a particular material, F_{cool} is independent of density, since energy loss is proportional to density, and radiation length is inversely proportional to density.

Comparison of Absorber Materials



Hydrogen Gas Virtues/Problems

- Best ionization-cooling material
  - $(X_0 * dE/dx)^2$ is figure of merit
- Good breakdown suppression
- High heat capacity
  - Cools Beryllium RF windows
- Scares people
  - But much like CH_4

Idea #1: RF Cavities with Pressurized H_2

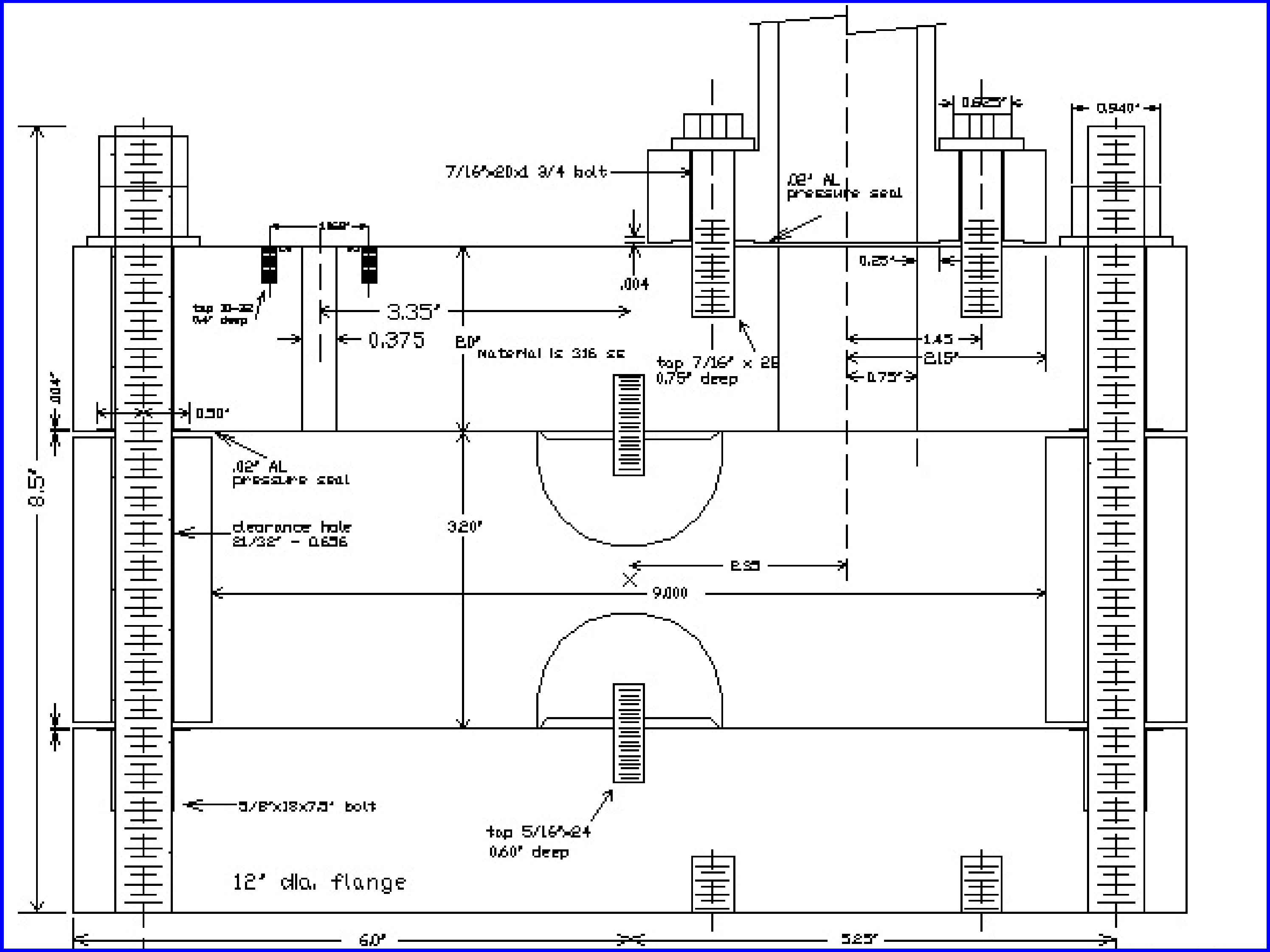
- Dense GH_2 suppresses high-voltage breakdown
  - Small MFP inhibits avalanches (**Paschen's Law**)
- Gas acts as an energy absorber
  - Needed for ionization cooling
- Only works for muons
  - No strong interaction scattering like protons
  - More massive than electrons so no showers

R. P. Johnson et al. invited talk at LINAC2004, http://www.muonsinc.com/TU203.pdf
Pierrick M. Hanlet et al., Studies of RF Breakdown of Metals in Dense Gases, PAC05
Kevin Paul et al., Simultaneous bunching and precooling muon beams with gas-filled RF cavities, PAC05
Mohammad Alsharo'a et al., Beryllium RF Windows for Gaseous Cavities for Muon Acceleration, PAC05
Also see WG3 talks by D. Cline, S. Kahn, and A. Klier on ring coolers for other use of ideas 1 and 2

Hardware Development

- To develop RF cavities, pressurized with dense hydrogen, suitable for use in muon cooling.
- Measurements of RF parameters (e.g. breakdown voltage, dark current, quality factor) for different temperatures and pressures in magnetic and radiation fields to optimize the design of prototypes for ionization cooling demonstration experiments
- *See MuCool Note 285 for paper*

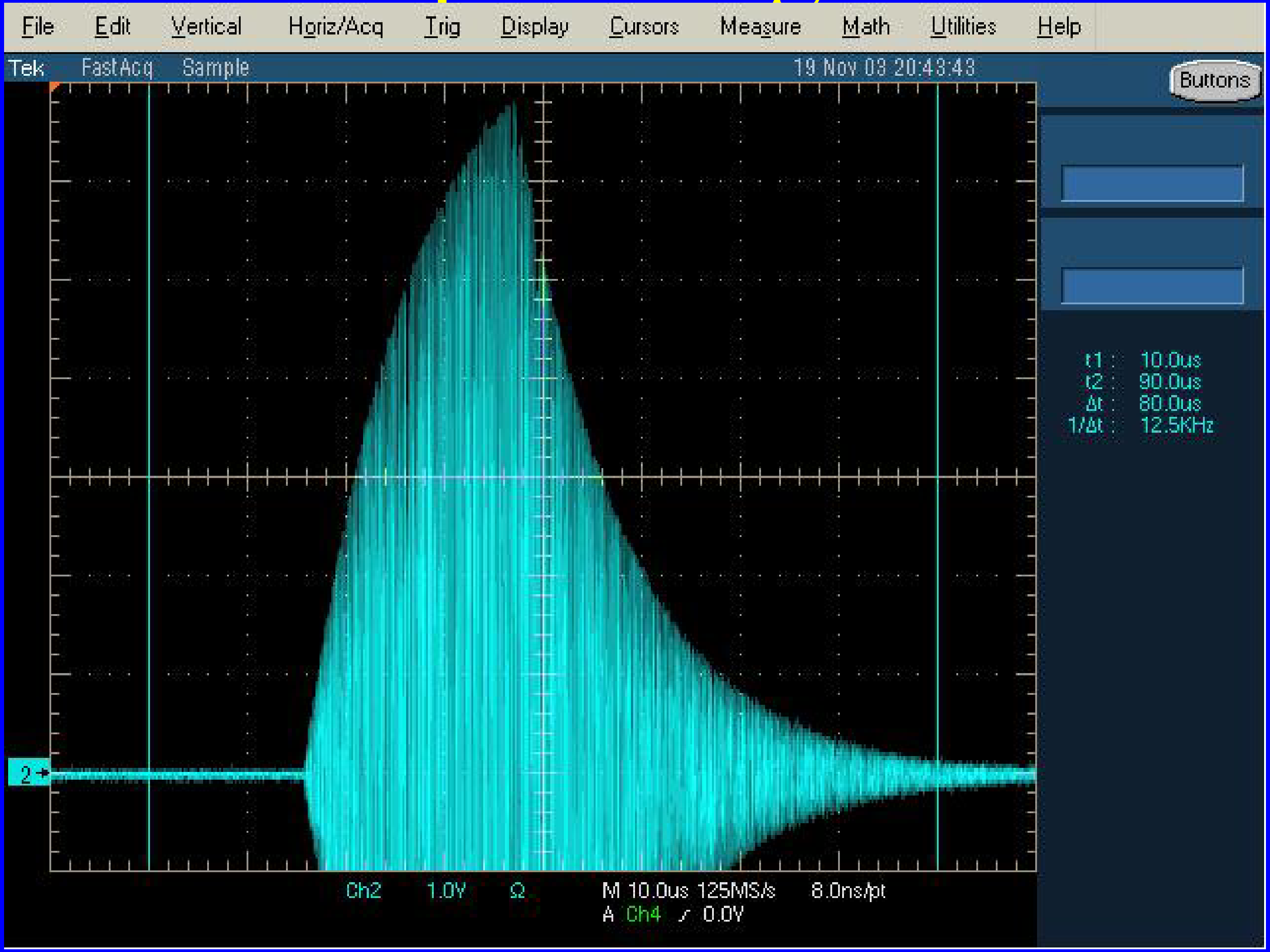
Mark II 805 MHz RF test cell



New TC; 2000PSI @ 77K

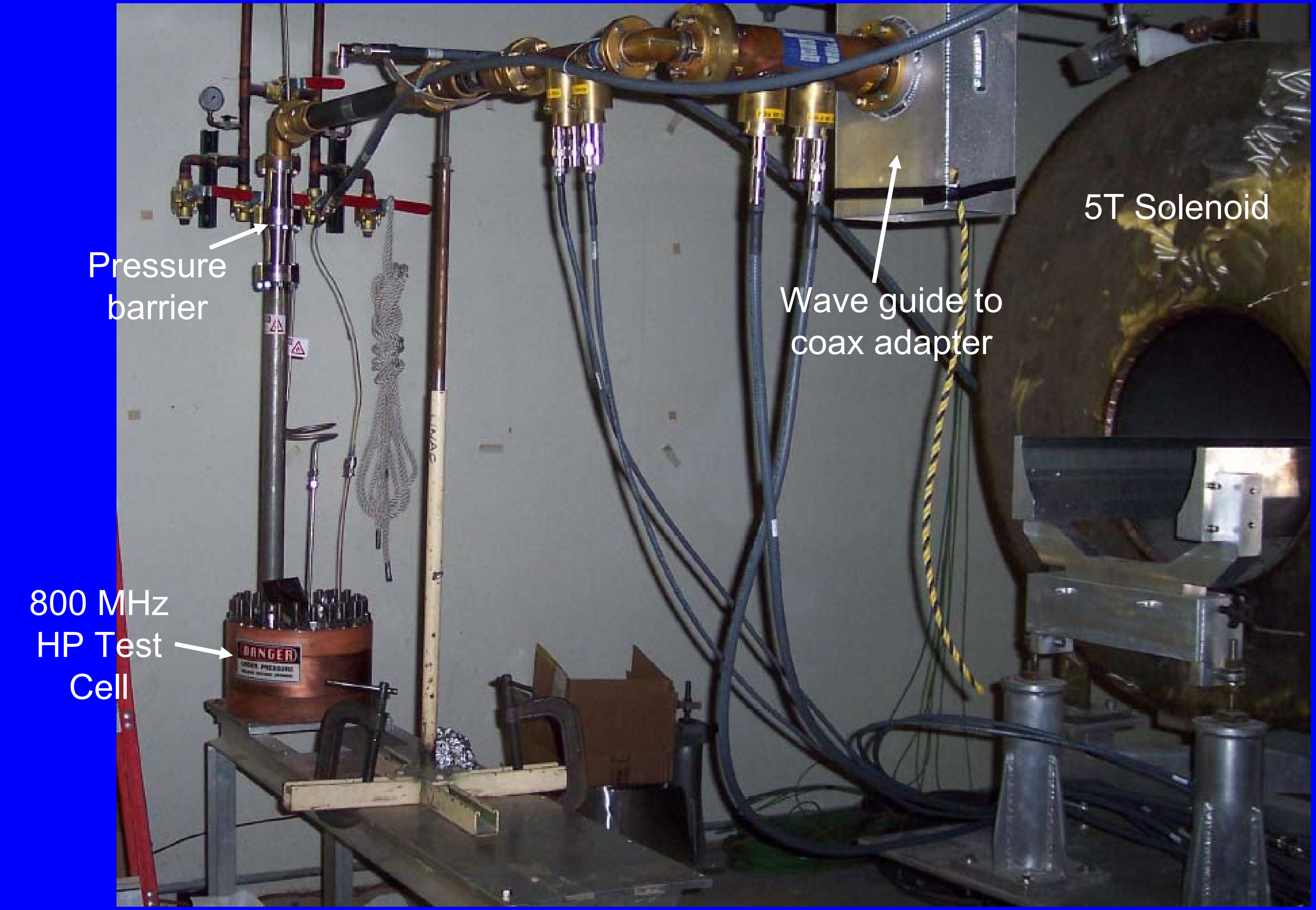

4/9/2003

RF probe signal

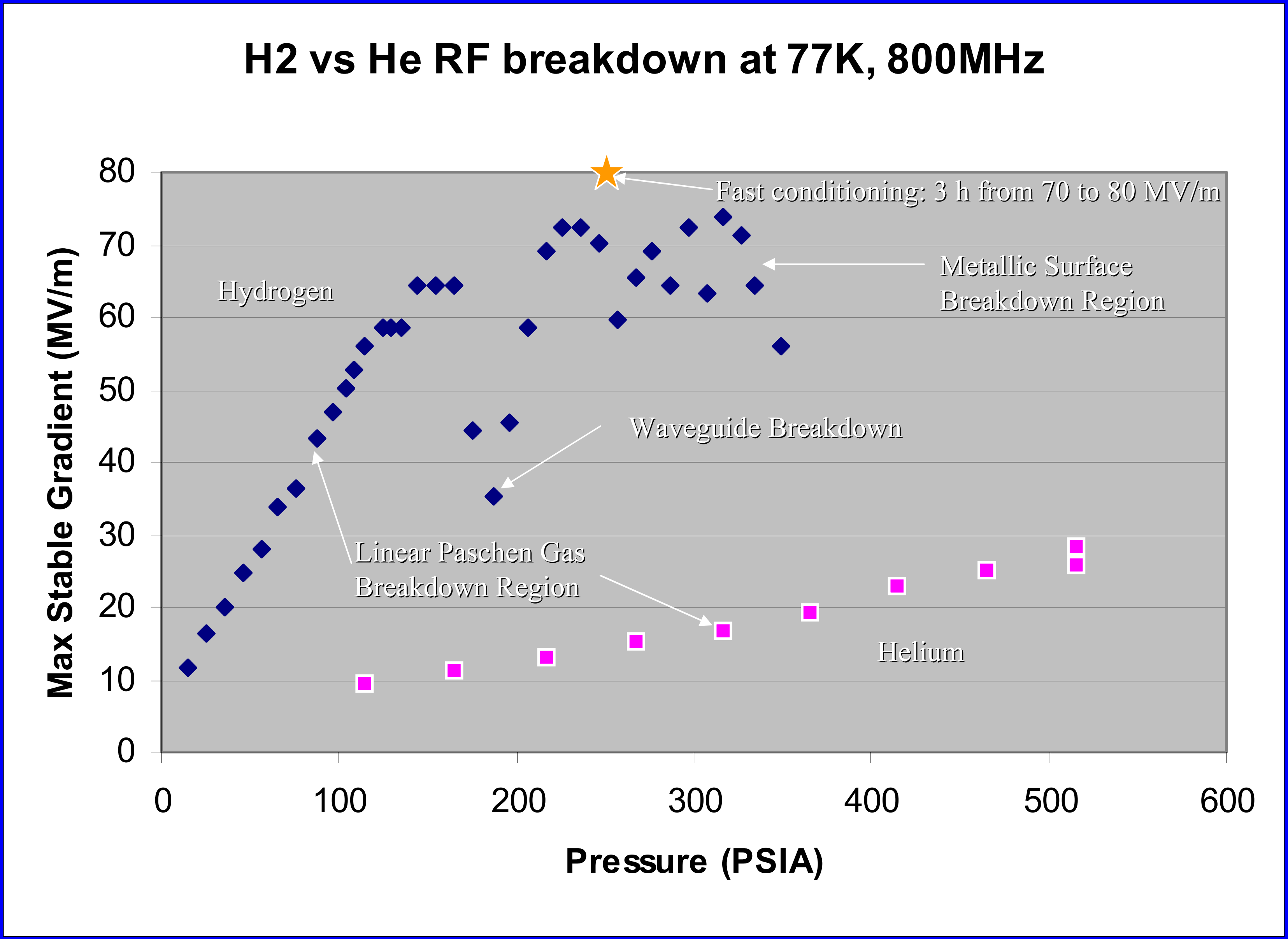


The probe signal taken during the last hours of operation at 250PSI and 77K. The pulse time of 20 μs corresponds to the rising part of the 800MHz envelope. The required pulse length is a few microseconds for a neutrino factory, while a collider may only require a few nanoseconds.

MuCool Test Area (MTA)



Lab G Results, Molybdenum Electrode



Idea #2: Continuous Energy Absorber for Emittance Exchange and 6d Cooling

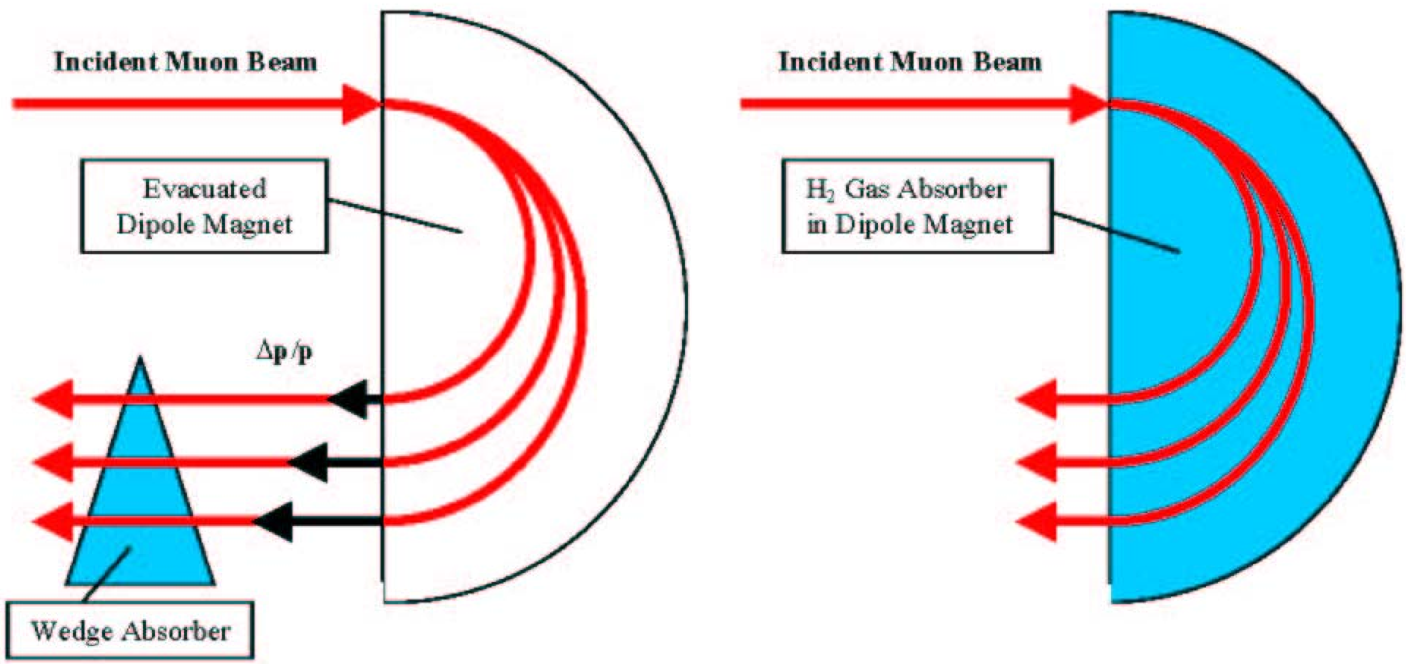


Figure 1. Use of a Wedge Absorber for Emittance Exchange

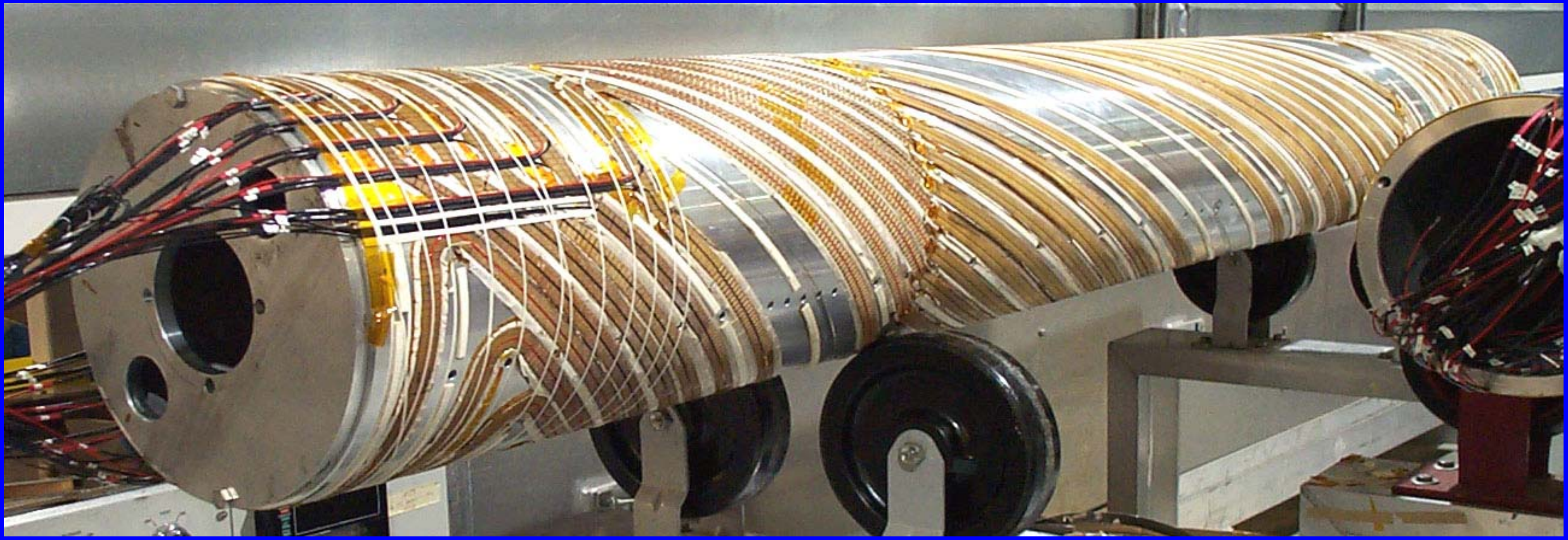
Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

Ionization Cooling is only transverse. To get 6D cooling, emittance exchange between transverse and longitudinal coordinates is needed. In figure 2, positive dispersion gives higher energy muons larger energy loss due to their longer path length in a low-Z absorber.

Idea #3: six dimensional Cooling with HCC and continuous absorber

- Helical cooling channel (HCC)
  - Solenoidal plus transverse helical dipole and quadrupole fields
  - Helical dipoles known from Siberian Snakes
  - z-independent Hamiltonian

Derbenev & Johnson, Theory of HCC, April/05 PRST-AB



Photograph of a helical coil for the AGS Snake

11" diameter helical dipole: we want ~2.5 x larger bore

The centrifugal and centripetal forces that maintain a helical orbit in the Helical Cooling Channel are:

$$F_{h-dipole} = p_z \times B_\perp; \quad b \equiv B_\perp$$

$$F_{solenoid} = -p_\perp \times B_z; \quad B \equiv B_z$$

$b = .7T,\ B = 3.5T$

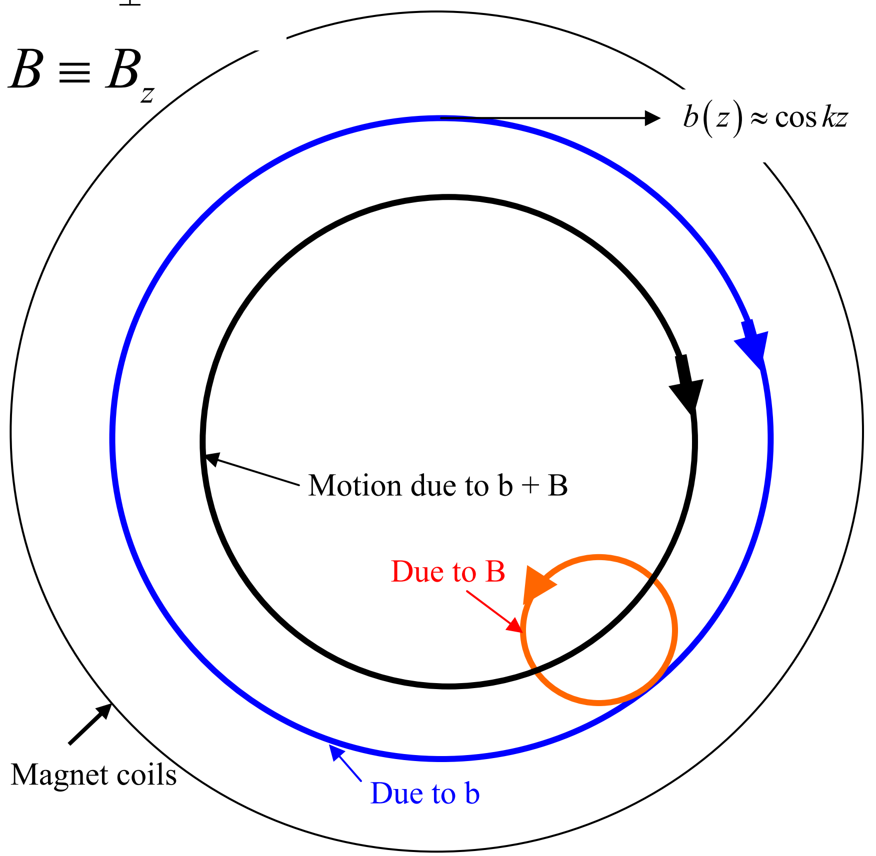
$p = 100 MeV/c$

$p_\perp / p_z = 1.$

$r_{B+b} = 15cm$

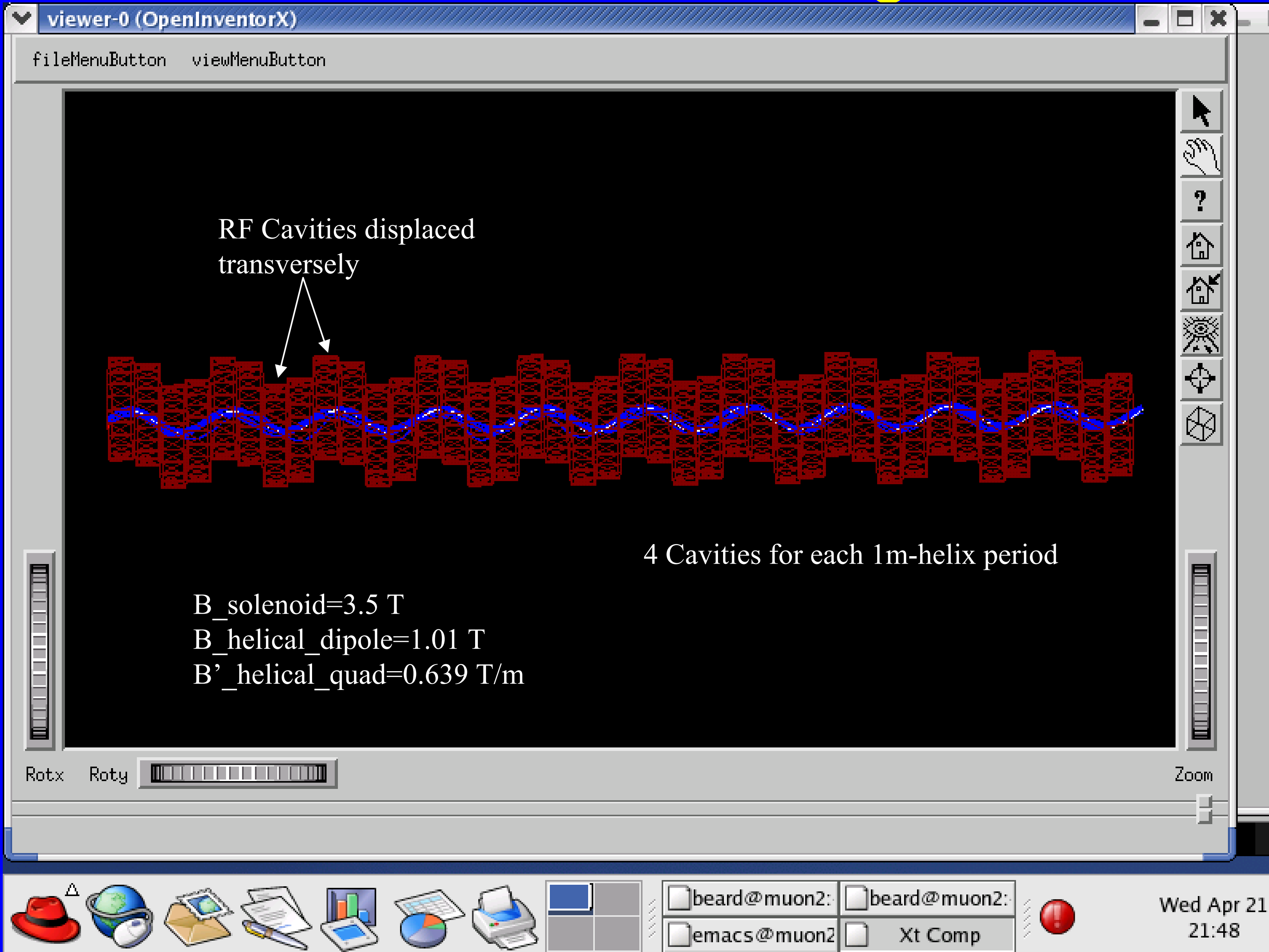
$\lambda = 2\pi / k = 1m$

$r_{coil} = 30cm$

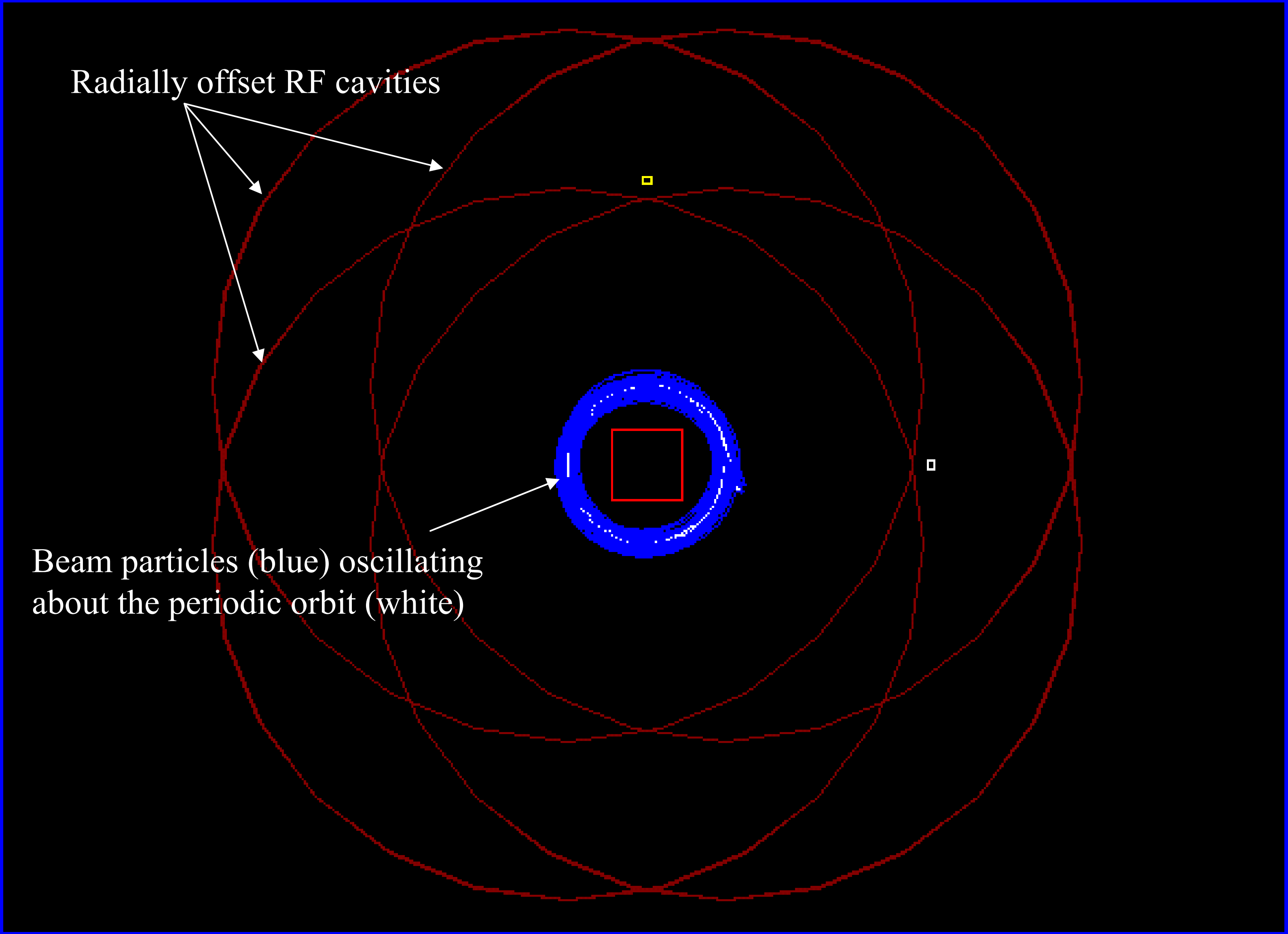


Helical Cooling Channel. Derbenev invention of combination of Solenoidal and helical dipole fields for muon cooling with emittance exchange and large acceptance. In the April PRST-AB, the magnitudes of B and b are constant, only the direction of b changes with z. This leads to a z or time-independent Hamiltonian, which has wonderful properties, well-suited to a continuous absorber. (Note that the helical dipole produces a z component that bucks the Solenoidal field)

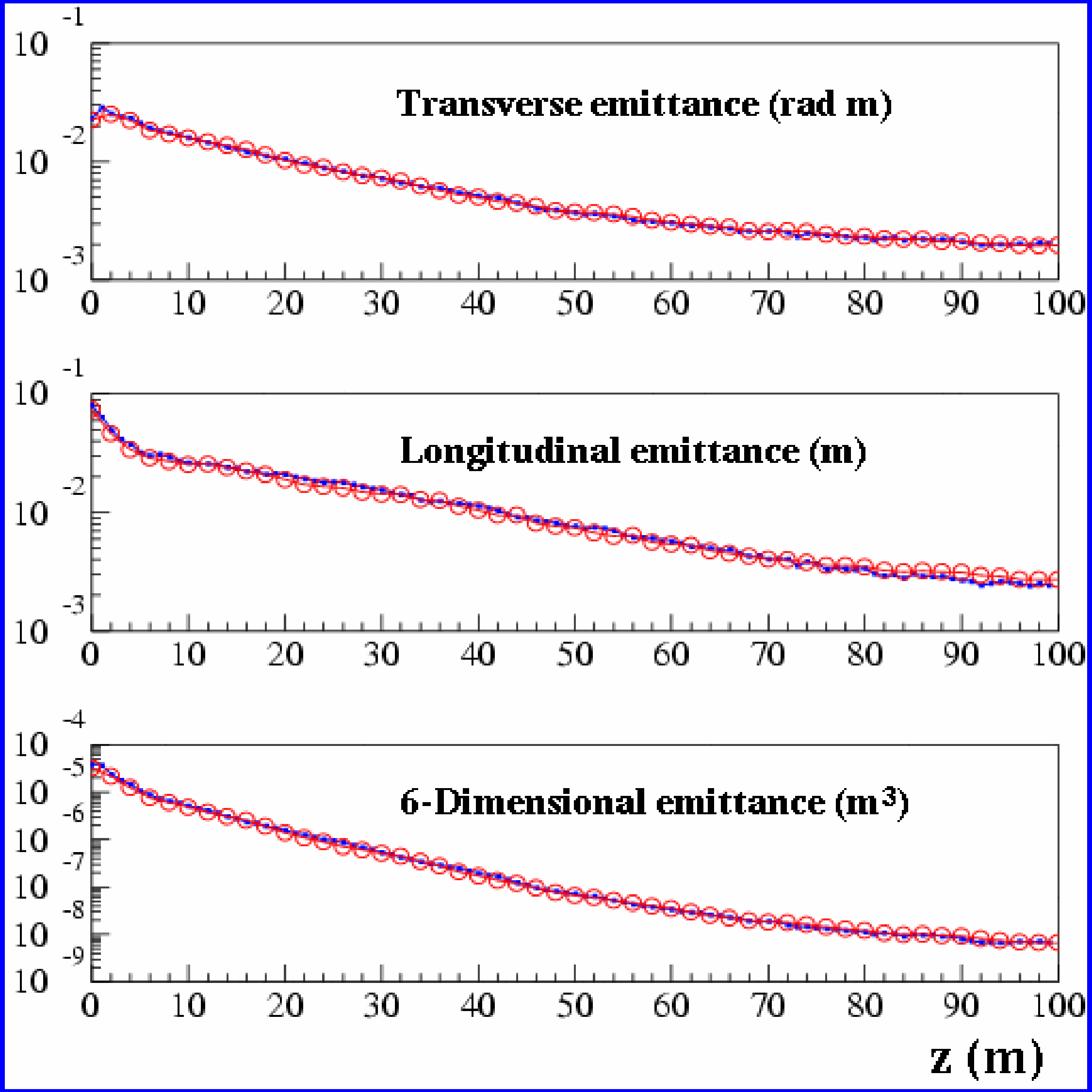
G4BL 10 m helical cooling channel



G4BL End view of 200MeV HCC



HCC simulations w/ GEANT4 (red) and ICOOL (blue)



6D Cooling factor ~5000

Katsuya Yonehara, et al., Simulations of a Gas-Filled Helical Cooling Channel, PAC05

In a Helical Cooling Channel with period $\lambda = 2\pi / k$, the condition for a helical equilibrium orbit for a particle at radius a, momentum p, is:

$$p(a) = \frac{\sqrt{1+\kappa^2}}{k}[B - \frac{1+\kappa^2}{\kappa} b(\kappa)]$$

where $\kappa = ka = p_\perp / p_z$ is the arctan of the helix pitch angle and $b_\rho = 0$ at the periodic orbit.

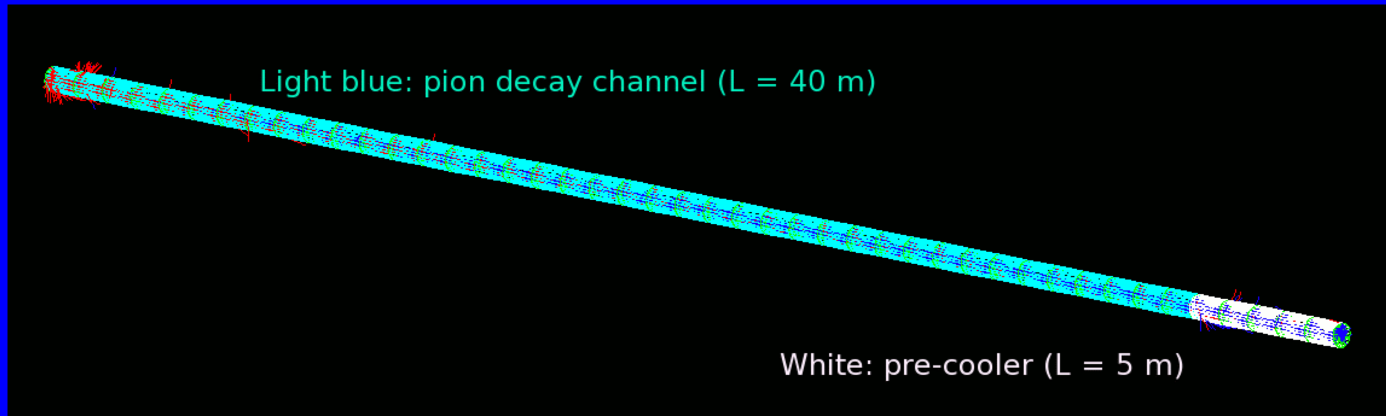
The longitudinal cooling decrement is $\Lambda_\gamma = [-\frac{2}{\gamma^2} + \hat{D}(\frac{\kappa^2}{1+\kappa^2})] \frac{|\gamma'_{abs}|}{\gamma\beta^2}$

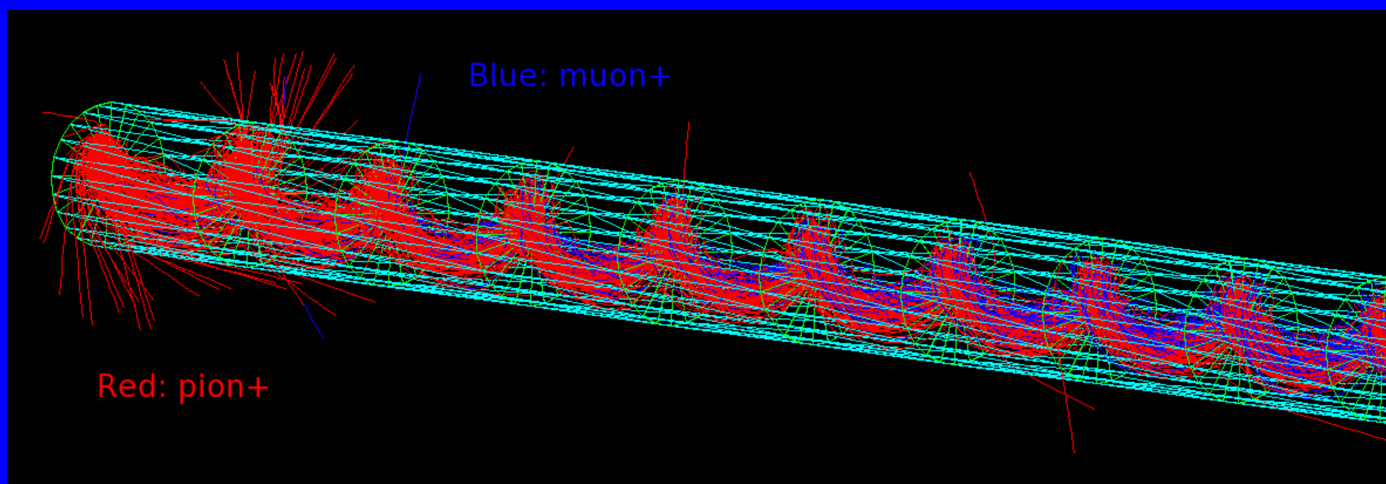
where $\hat{D} = \frac{pda}{adp}$

Up to now, we have only considered constant field magnitudes, where the only the direction of b changes. This gives the z-independent Hamiltonian, etc.

HOWEVER we can use the equation above relating $p,\ a,\ B,\ b,\ and\ \kappa$ to manipulate the fields and helix parameters to maintain the orbit and dispersion properties. The next 2 ideas use this technique to cool when particles lose their energy in an absorber and there is no RF to regenerate the lost energy.

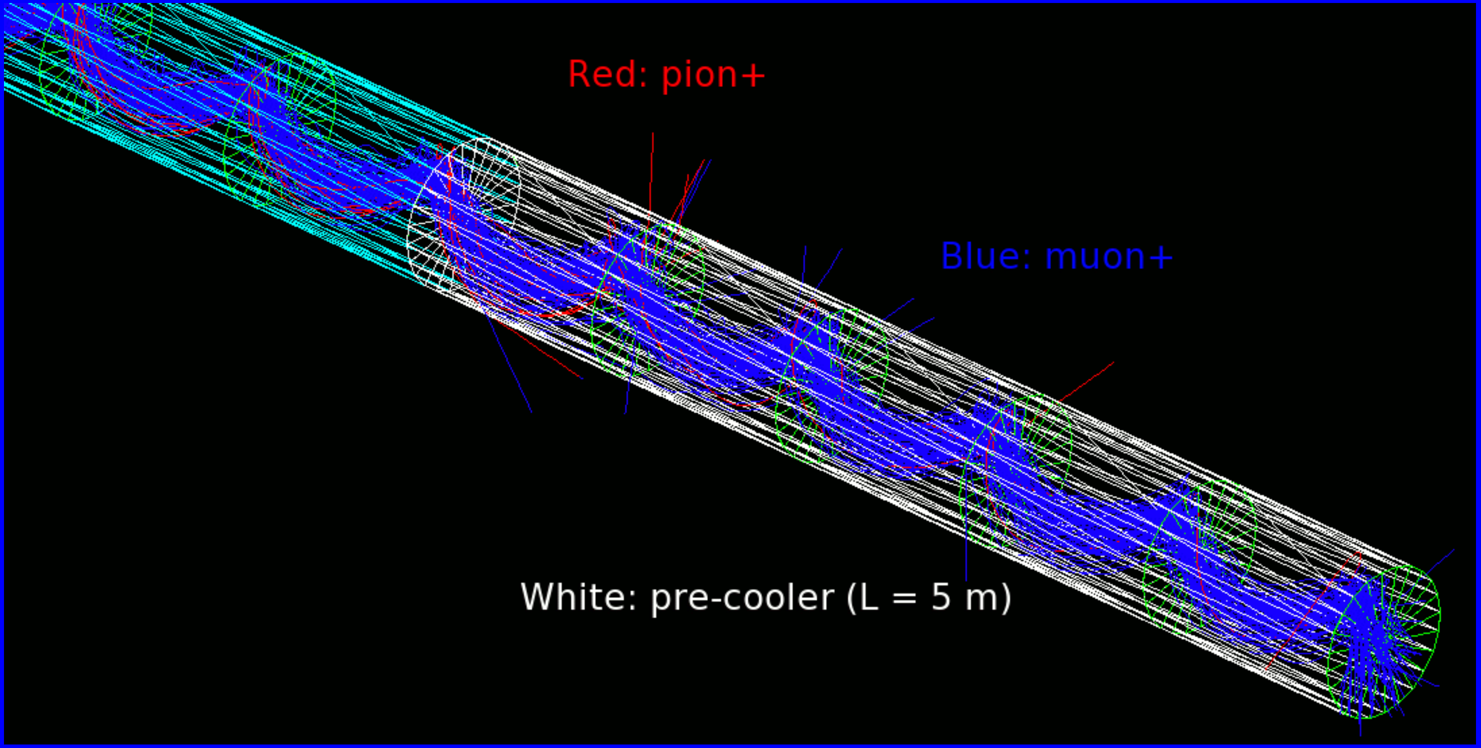
Idea #4: HCC with Z-dependent fields





40 m evacuated helical magnet pion decay channel followed by a 5 m liquid hydrogen HCC (no RF)

5 m Precooler and MANX



New Invention: HCC with fields that decrease with momentum. Here the beam decelerates in liquid hydrogen (white region) while the fields diminish accordingly.

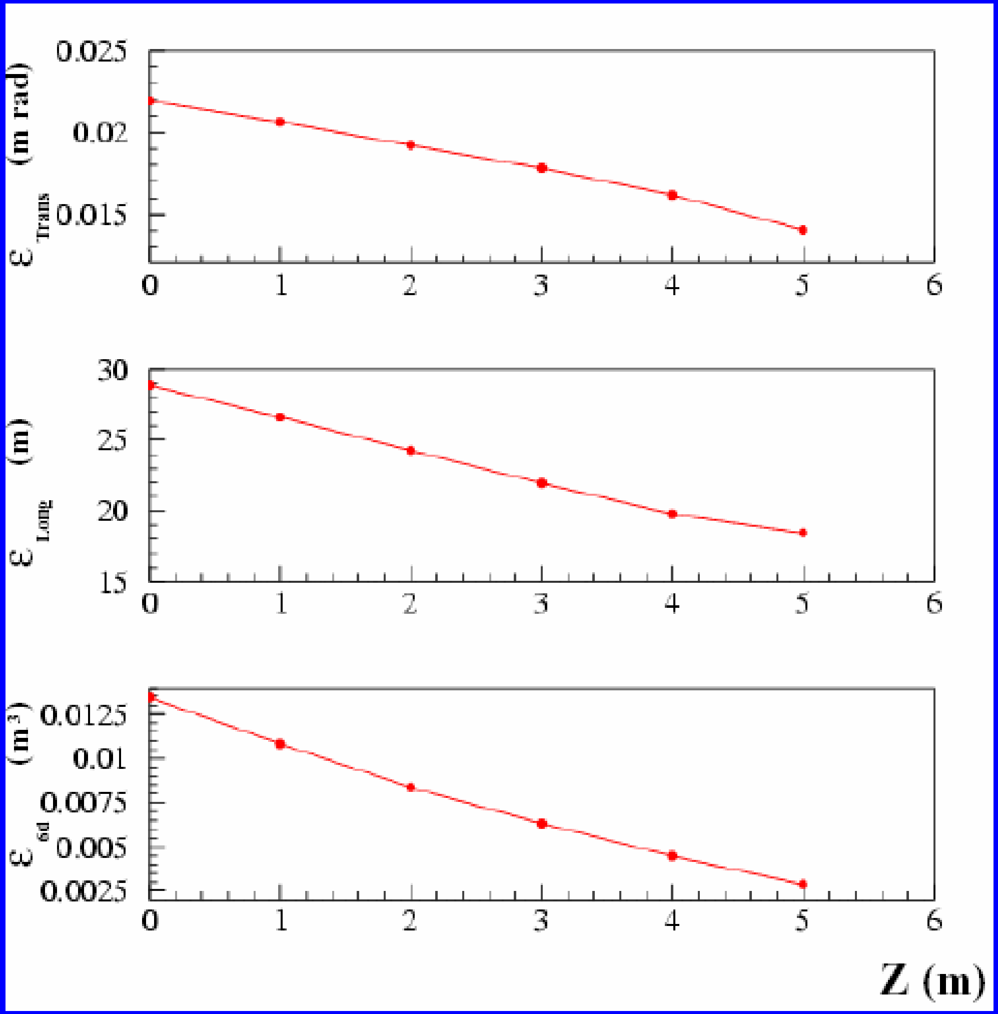
G4BL Precooler Simulation

Equal decrement case.

~x1.7 in each direction.

Total 6D emittance reduction ~factor of 5.5

Note this requires serious magnets: ~10 T at conductor for 300 to 100 MeV/c deceleration



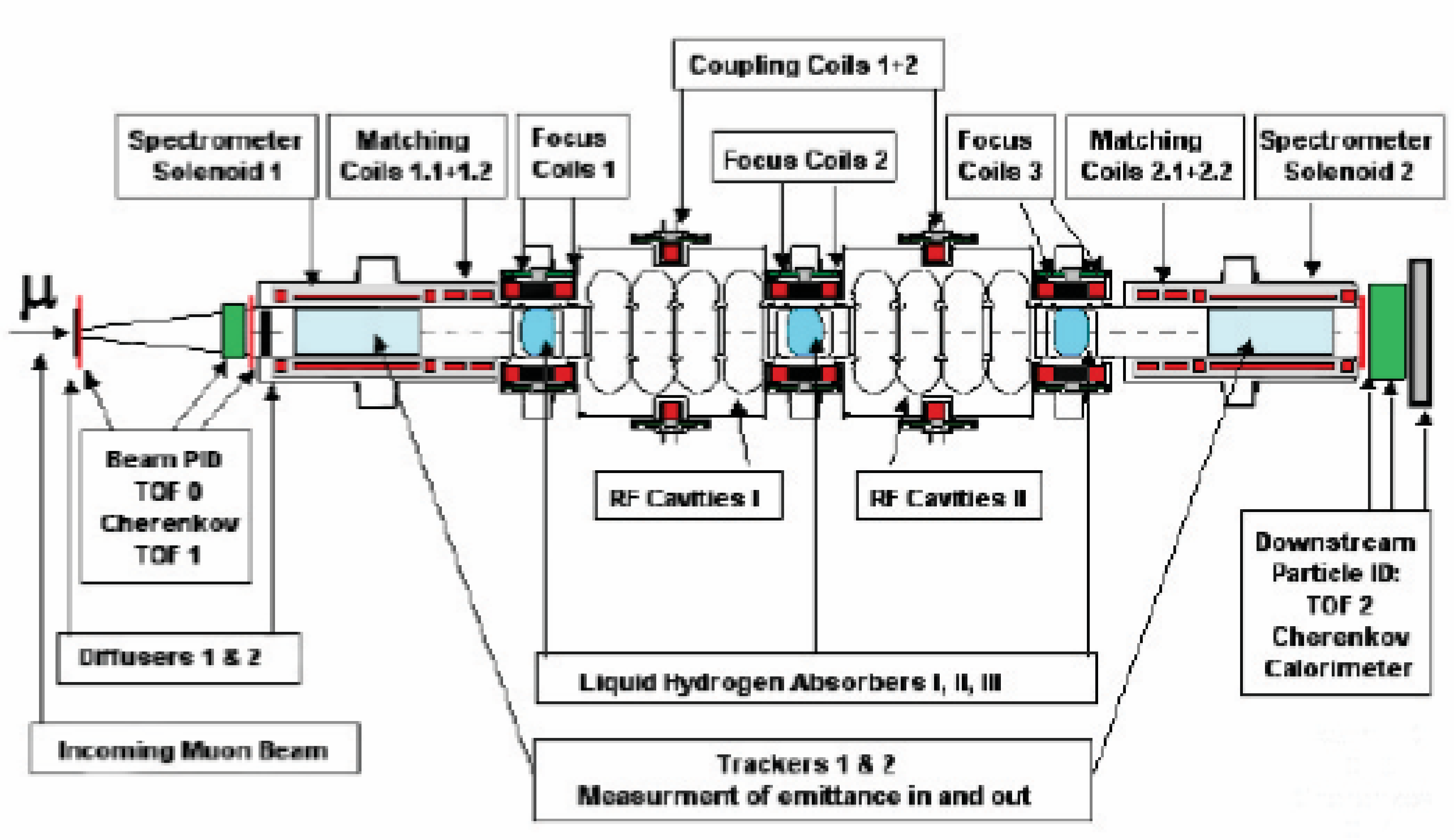
Idea #5: MANX 6-d demonstration experiment

Muon Collider And Neutrino Factory eXperiment

- To Demonstrate
  - Longitudinal cooling
  - 6D cooling in cont. absorber
  - Prototype precooler
  - Helical Cooling Channel
  - Alternate to pressurized RF
  - New technology

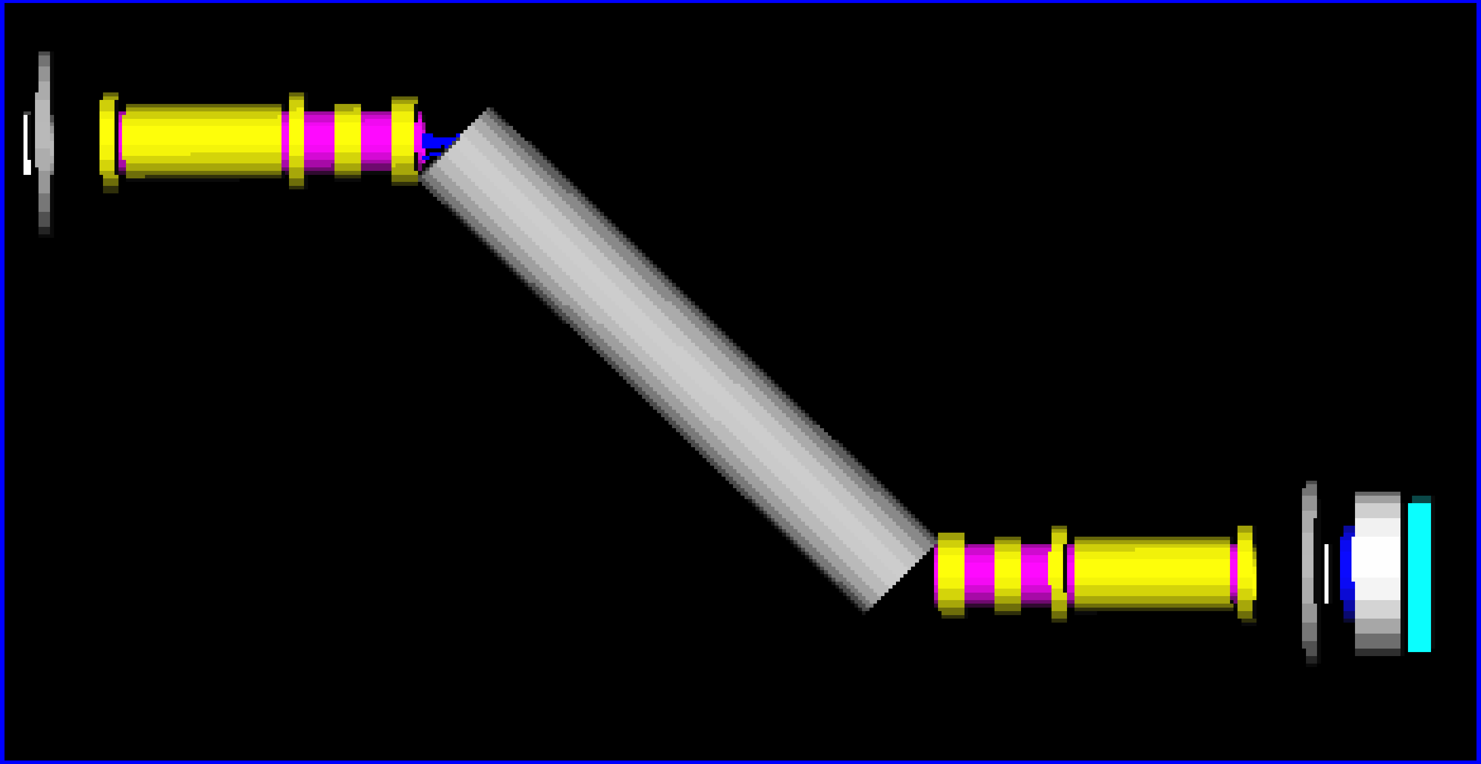
Thomas J. Roberts et al., A Muon Cooling Demonstration Experiment, PAC05

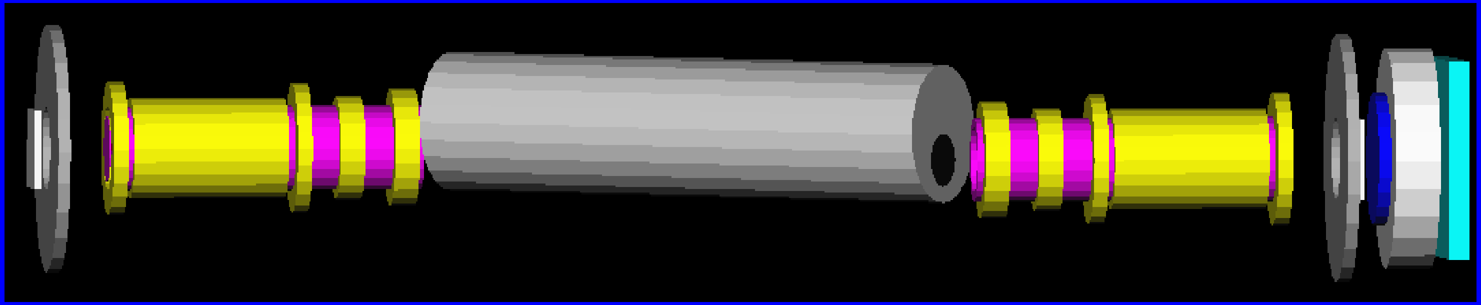
MICE “facility” at RAL



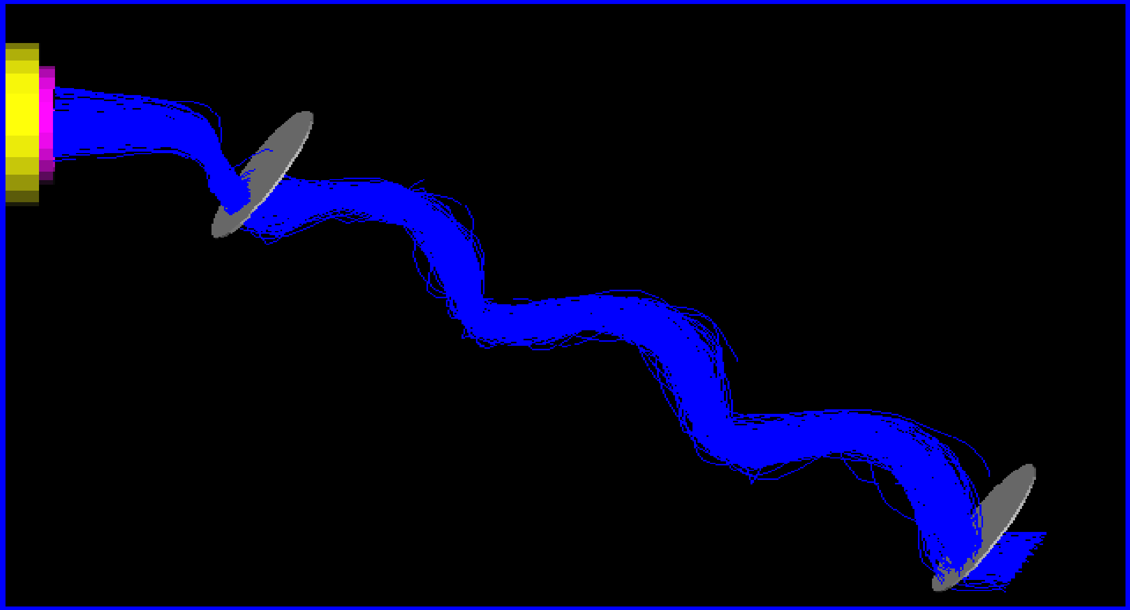
Muons, Inc. has started discussions to use the MICE spectrometers for MANX.

G4BL MANX with MICE spectrometers





Muon Trajectories in 3-m MANX



The design of the coils and cryostat are the next steps for MANX, as seen in the next slides on the technology of the HCC.

Phase I Fermilab TD Measurements

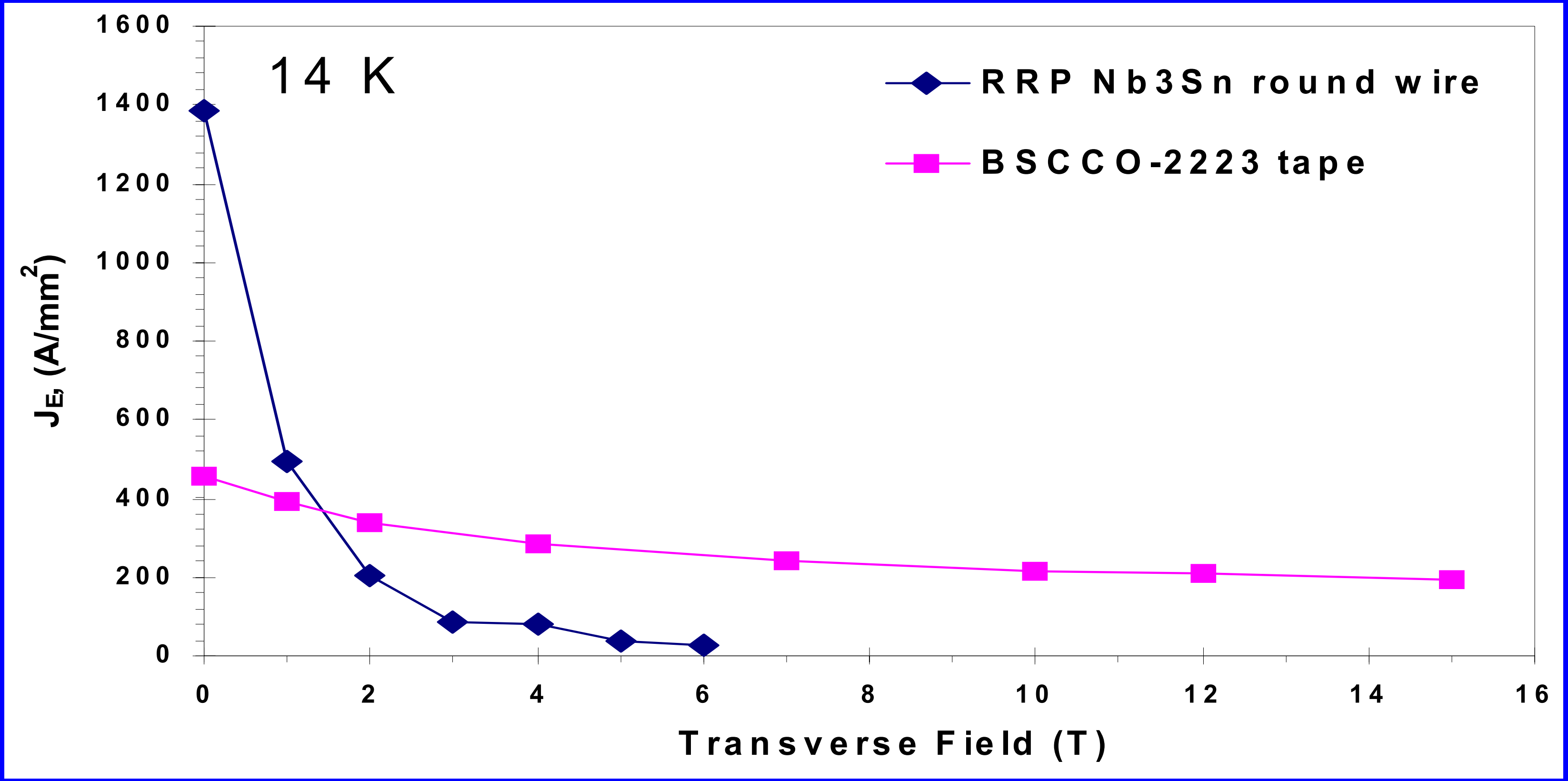
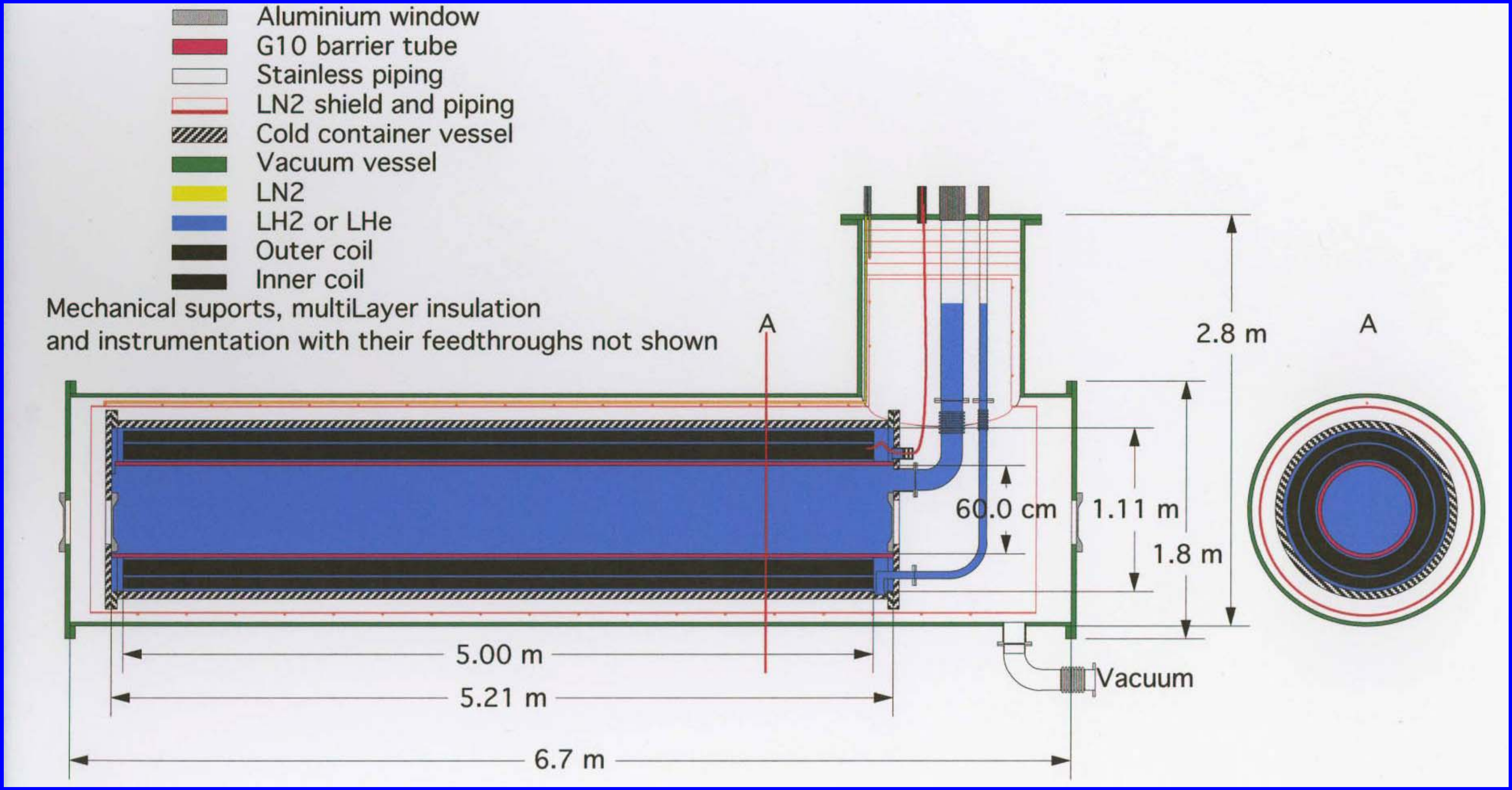


Fig. 9. Comparison of the engineering critical current density, J_E, at 14 K as a function of magnetic field between BSCCO-2223 tape and RRP Nb_3Sn round wire.

Licia Del Frate et al., Novel Muon Cooling Channels Using Hydrogen Refrigeration and HT Superconductor, PAC05

MANX/Precooler H2 or He Cryostat



Five meter long MANX cryostat schematic.

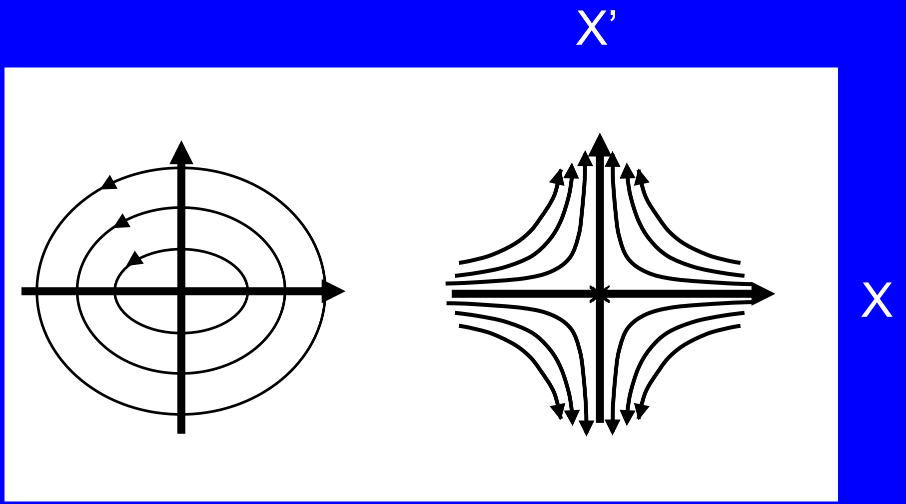
For RAL, the length becomes 3 m. At FNAL perhaps 5 m is possible.

The use of Liquid He at 4 K is possible, with Nb3Sn magnets.

Thin Al windows designed for MICE will be used.

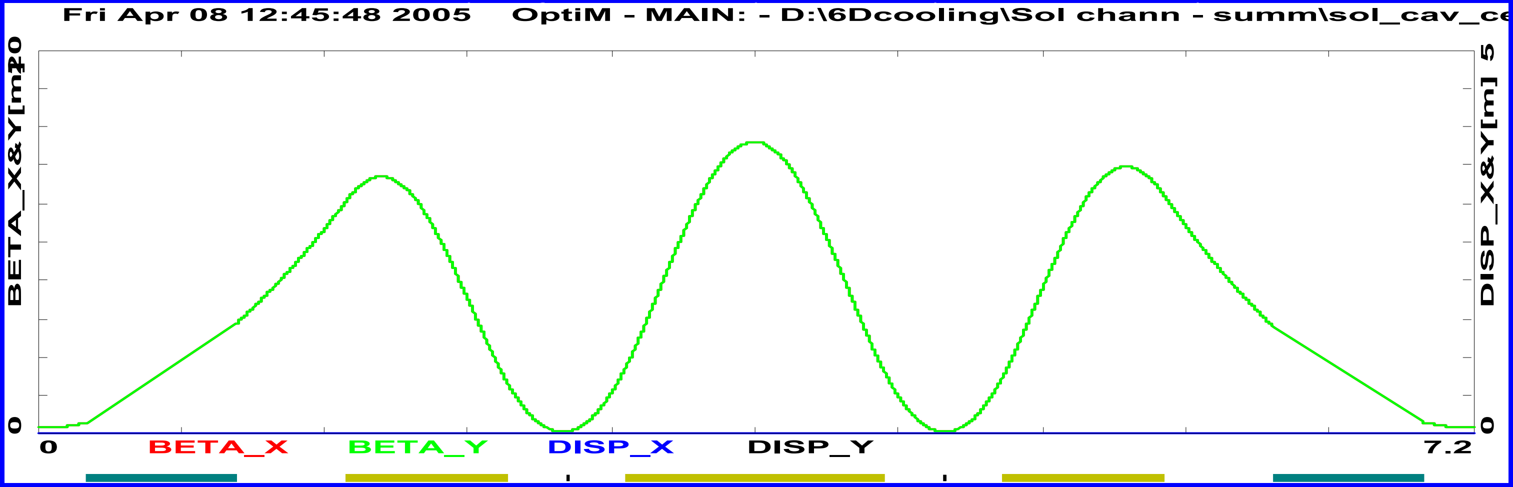
Idea #6: Parametric-resonance Ionization Cooling (PIC)

- Derbenev: 6D cooling allows new IC technique
- PIC Idea:
  - Excite parametric resonance (in linac or ring)
    - Like vertical rigid pendulum or ½-integer extraction
    - Use xx’=const to reduce x, increase x’
  - Use IC to reduce x’
  - Detuning issues being addressed
  - chromatic aberration example

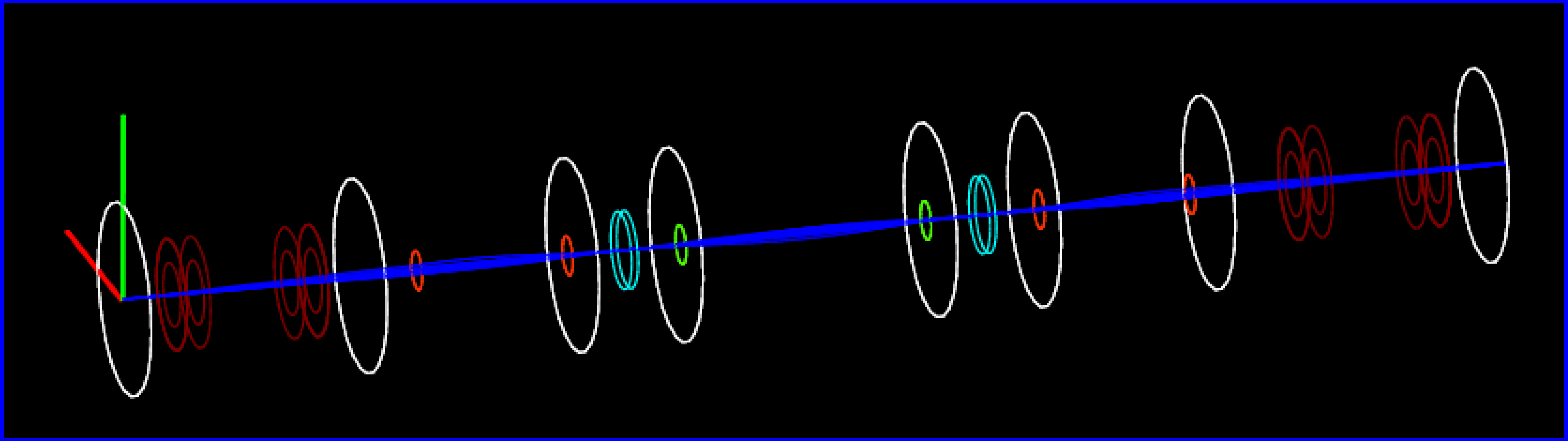


Yaroslav Derbenev et al., Ionization Cooling Using a Parametric Resonance, PAC05
Kevin Beard et al., Simulations of Parametric-resonance IC…, PAC05

Example of triplet solenoid cell on ½ integer resonance with RF cavities to generate

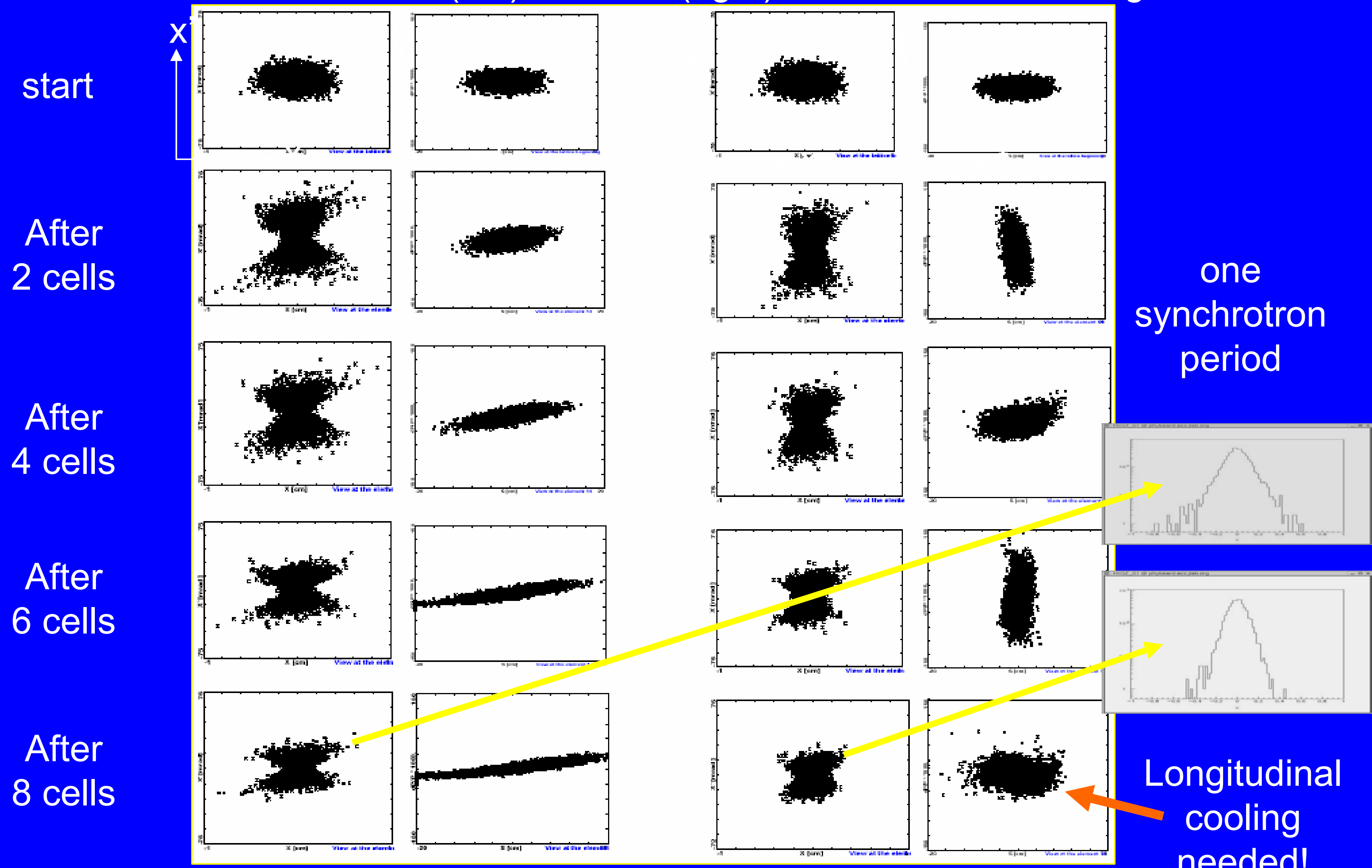


P-dependent focal length is compensated by using rf to modulate p.



OptiM (Valeri Lebedev) above and G4beamline (Tom Roberts) below.

Evolution of transverse and longitudinal phase space through 8 triplet solenoid cells, without (left) and with (right) RF cavities. Alex Bogacz



Idea #7: Reverse Emittance Exchange

- At 2.5 TeV/c, $\Delta p/p$ reduced by >1000.
- Bunch is then much shorter than needed to match IP beta function
- Use wedge absorber to reduce transverse beam dimensions (increasing Luminosity) while increasing $\Delta p/p$ until bunch length matches IP
- Subject of new STTR grant

Figure 1. Emittance Exchange

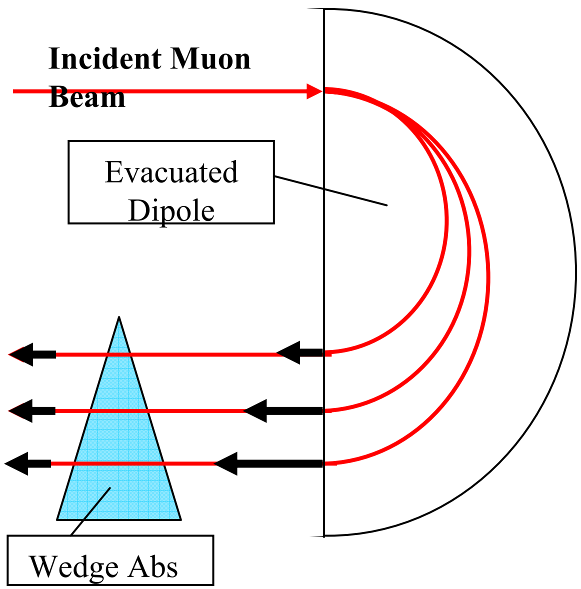


Figure 2. Reverse Emittance Exchange

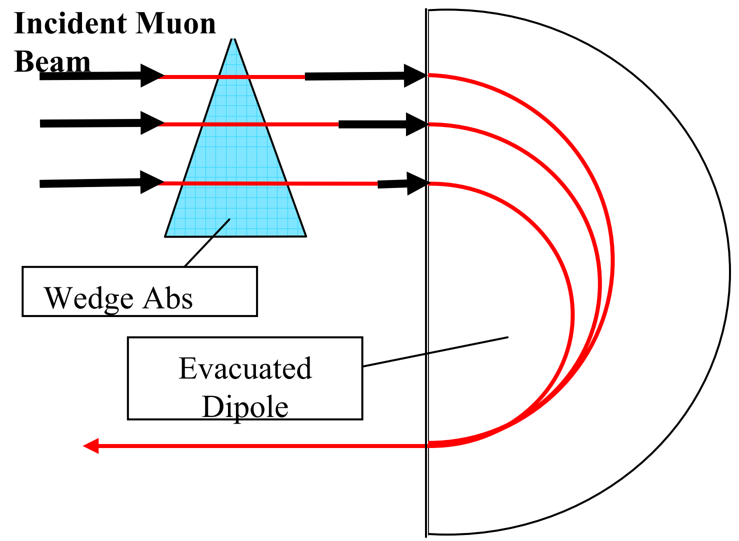
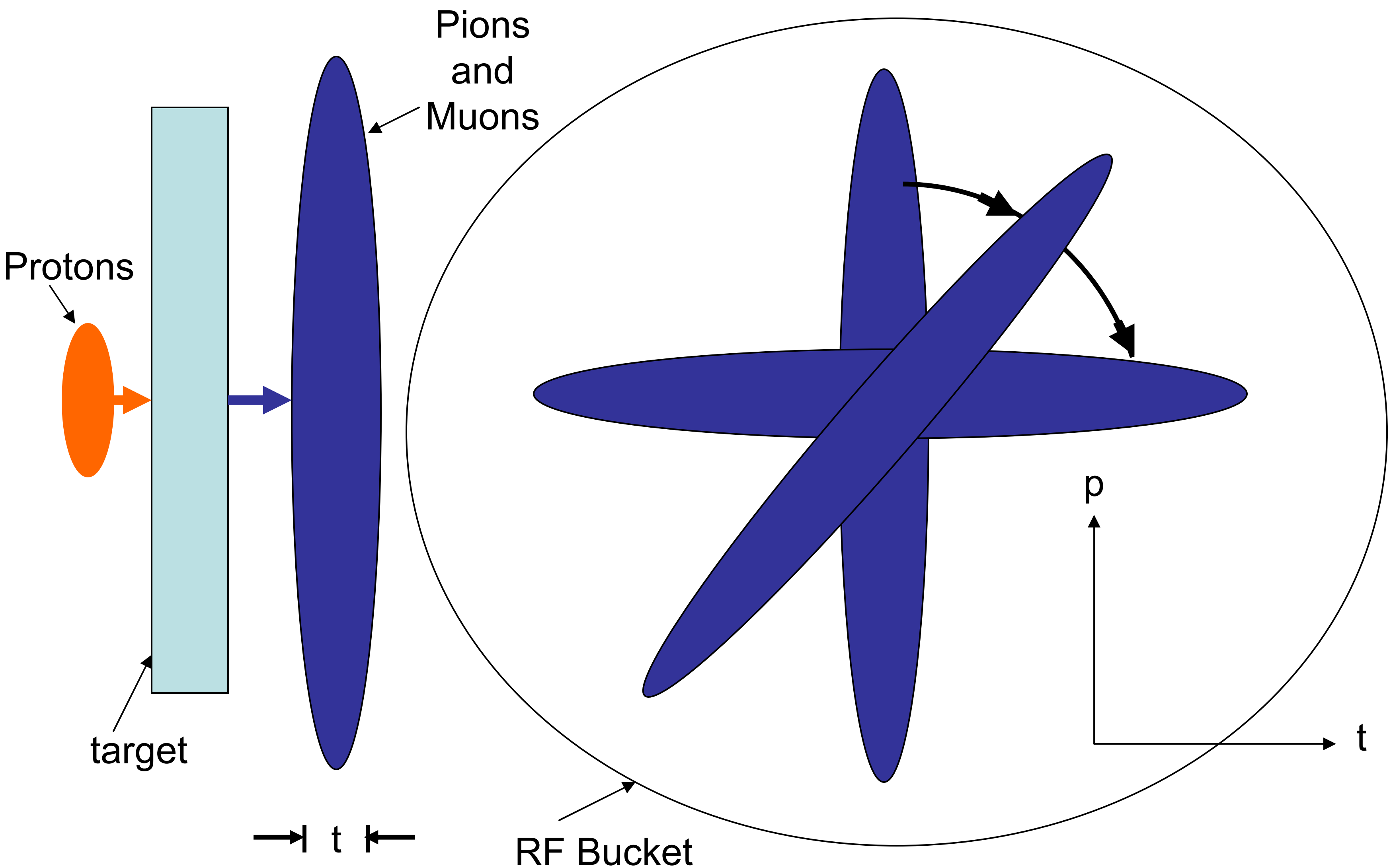


Figure 1. Conceptual diagram of the usual mechanism for reducing the energy spread in a muon beam by emittance exchange. An incident beam with small transverse emittance but large momentum spread (indicated by black arrows) enters a dipole magnetic field. The dispersion of the beam generated by the dipole magnet creates a momentum-position correlation at a wedge-shaped absorber. Higher momentum particles pass through the thicker part of the wedge and suffer greater ionization energy loss. Thus the beam becomes more monoenergetic. The transverse emittance has increased while the longitudinal emittance has diminished.

Figure 2. Conceptual diagram of the new mechanism for reducing the transverse emittance of a muon beam by reverse emittance exchange. An incident beam with large transverse emittance but small momentum spread passes through a wedge absorber creating a momentum-position correlation at the entrance to a dipole field. The trajectories of the particles through the field can then be brought to a parallel focus at the exit of the magnet. Thus the transverse emittance has decreased while the longitudinal emittance has increased.

Idea #8: Simultaneous RF Capture, Bunch Rotation and Cooling in HP RF Cavities

- Proton bunches have $\sigma_t \approx$ 1ns such that produced pion bunches do too.
- Placing RF cavities close to the production target allows 1/4 synchrotron period rotation to get longer pion bunches with smaller momentum spread.
- Subject of new STTR grant


Pions
and
Muons
Protons
target
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RF Bucket
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Simulations of RF phase rotation

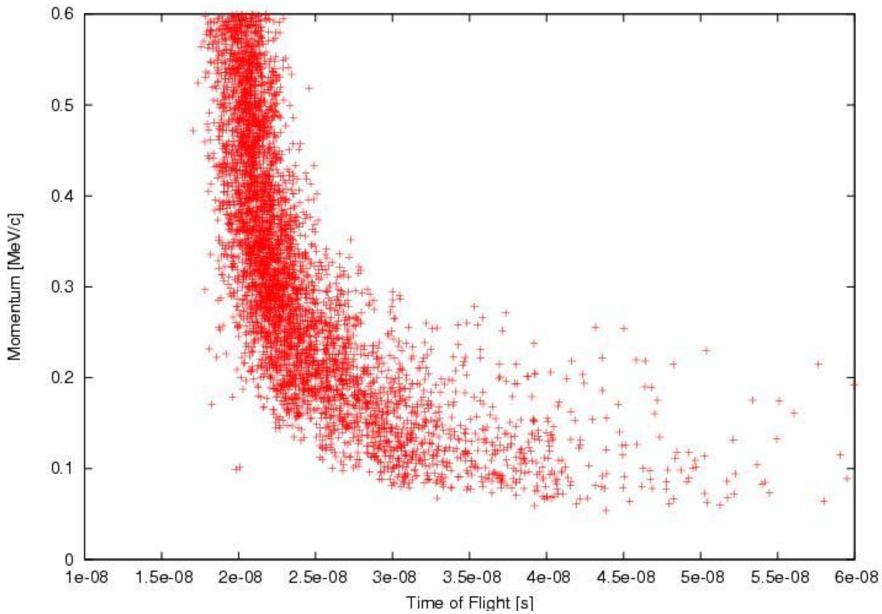

Figure 1. Momentum versus time of flight of muons 5 meters from the production target. Before phase-energy rotation.

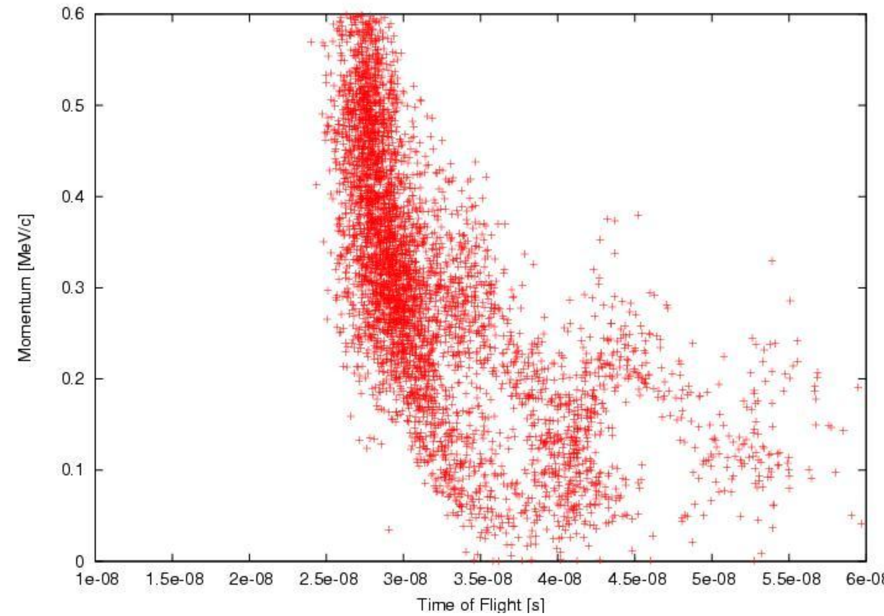

Figure 2. Momentum versus time of flight of muons 7 meters from the production target, after passing through 2 meters of high-gradient phase-energy rotation RF cavities

Simulations of phase rotation to improve muon capture rate

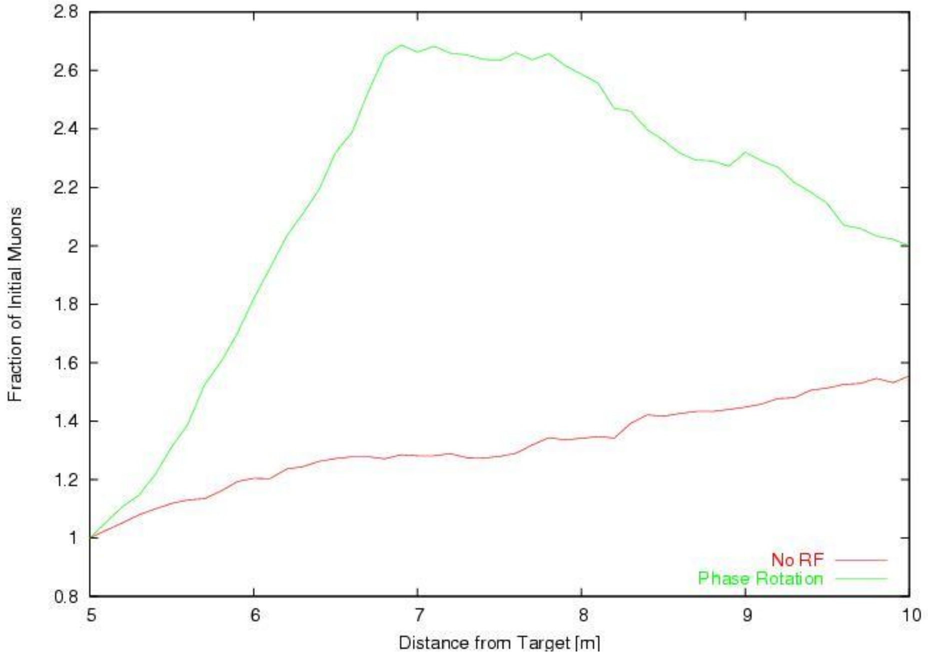

Figure 3. Fraction of muons within the 200 to 300 MeV/c momentum range as a function of distance from the target for the case of the phase rotation RF on or off.

Eight New Ideas for Bright Beams for High Luminosity Muon Colliders

supported by SBIR/STTR grants

- H_2-Pressurized RF Cavities
- Continuous Absorber for Emittance Exchange
- Helical Cooling Channel
- Z-dependent HCC
- MANX 6d Cooling Demo
- Parametric-resonance Ionization Cooling
- Reverse Emittance Exchange
- RF capture, phase rotation, cooling in HP RF Cavities

If we succeed to develop these ideas, an Energy Frontier Muon Collider will become a compelling option for High Energy Physics!

Funding for muon cooling R&D is needed; additional enthusiastic supporters are needed!

- Effective beam cooling for an energy frontier muon collider or Higgs factory is essential
  - Best hope for getting back to the Livingston curve
- Effective muon beam cooling can be used in a SC Linac for a neutrino factory
  - Additional argument for a SC Linac proton driver
  - Could attract super beam and beta beam enthusiasts
- These possibilities use SC RF
  - JLab specialty
  - ILC becomes International Lepton Collider