SBIR/STTR Beam Cooling Projects

BNL, FNAL, IIT, Jlab, Muons, Inc.

Rolland Johnson, updated April 26, 2005

- GH_2 RF cavities IIT, Kaplan 600k ends 7/05
- 6D HCC Jlab, Derbenev 850k ends 7/06
- REMEX (rev. emit. exch) Jlab, Derbenev 100k new
- GH_2 RF Capture, Ph. Rtn. FNAL, Neuffer 100k new

awaiting grant decisions (~June 1):

- MANX (6D HCC cooling demo) FNAL, Yarba +750k
- H_2 Cryostat (HCC Technology) FNAL, Yarba +750k
- PIC (Parametric-resonance IC) Jlab, Derbenev +750k

Try again next year:

- G4BL (simulation program dev.) IIT, Kaplan 100k
- Helical Cooling Channel Magnets BNL, Gupta 100k

Comparing
Muons, Inc. and MC programs

Muons, Inc.

- >90% Muon Collider
- High brightness (low ε)
- Existence proof
- SBIR/STTR funding
  - Standard reviews

MC

- >90% Neutrino Factory
- High intensity
- Low cost
- Many funding sources
  - MUCOG, MUTAC

Small Business Innovation Research/ Small business Technology TRansfer

- Federally mandated fraction of operating budgets of cabinet level offices goes to private enterprise
- Program administered by Office that is taxed
- Office provides solicitation topics (suggested by Labs)
- Innovation large part of score for grant approval
- Strict timeline

  September: Solicitation provided

  December 13: Phase I proposals due

  June 1: Phase I awards for 9 months/$100k announced (~1/7)

  April 13, next year: Phase II proposals due

  June: Phase II awards for 24 months/$750k announced (~1/3)

More Muons, Inc. Collaborators:

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

<u>Underlined</u> are accelerator physicists in training, supported by grants (1 old +5 new since last MUTAC)

Wonders since last MUTAC:

- The Phase II HCC proposal with JLab was awarded (7/04)
- All 3 Phase I proposals were awarded. (7/04)
- Nine papers submitted to PAC05 on these and HPRF projects
  - e.g. HCC simulations show factor of 5000 cooling with ICOOL & G4BL
- Four new Phase I proposals submitted (12/04)
- All 3 Phase II proposals are strong (4/05)

  New invention of HCC with z-dependent fields

    MANX project is now a precooler prototype and 6D muon cooling demo

  Progress in understanding Parametric-resonance Ionization Cooling (PIC)

    Theory of aberration compensation and first simulations

  Start on HCC technology

    Cryostat, HTS measurements, RF breakdown, Q improvement,…

More than 15 months without RF tests. But thinking was good.
Z-dependent HCC is an alternative to HPRF.
And we came up with four new phase I ideas for proposals.

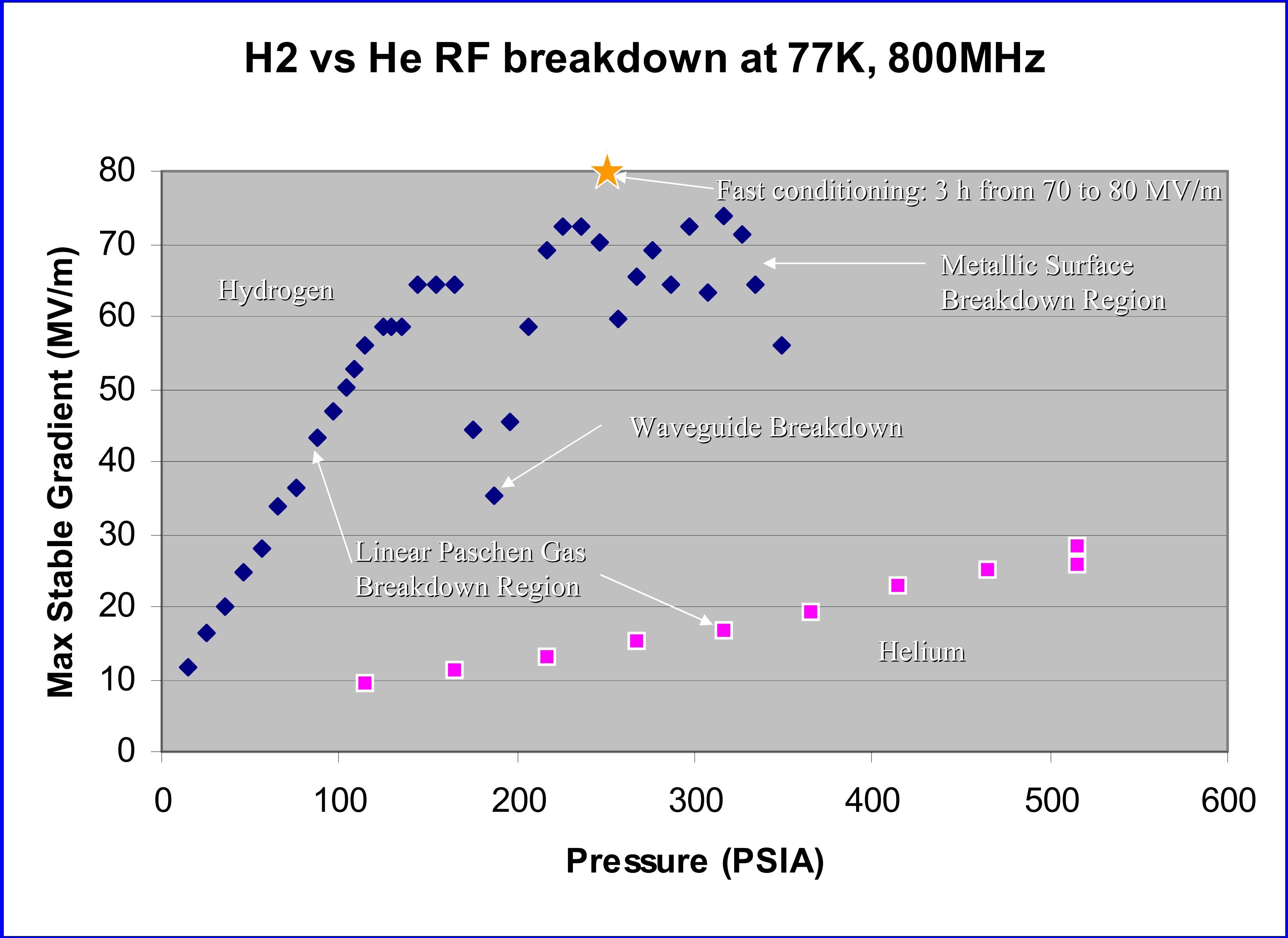
HP HV RF Cavities Ph II, Dan Kaplan, IIT

- 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

2003 STTR Phase II Project

- To develop RF cavities, pressurized with dense hydrogen or helium gas, that are suitable for use in muon cooling and accelerator applications.
- Measurements of RF parameters (e.g. breakdown voltage, dark current, quality factor) for different temperatures and pressures in magnetic and radiation fields will be made in RF cavities to optimize the design of prototypes for ionization cooling demonstration experiments

11/19/03 Lab G Results, Molybdenum Electrode



Hopes for HP GH2 RF

- Higher gradients than with vacuum
- Less dependence on metallic surfaces
  - Dark currents, x-rays diminished
  - Very short conditioning times already seen
- Easier path to closed-cell RF design
  - Hydrogen cooling of Be windows
- Use for 6D cooling and acceleration
  - Homogeneous absorber concept
  - Implies HF for muon acceleration (1.6 GHz)

Present Activities for HP RF Phase II project

- Moving from Lab G to MTA (>1 year delay!)
- Studying RF breakdown with cu, mo, cr, be electrodes 50:85:112:194 (Perry Wilson)
- Planning Test Cell for Operation in the LBL 5 T solenoid at 1600 PSI and 77K
- Working on MTA Beam Line
  – Want radiation test of GH2 RF in 2005

2004 Phase II, w JLab, Derbenev HCC with Emittance Exchange

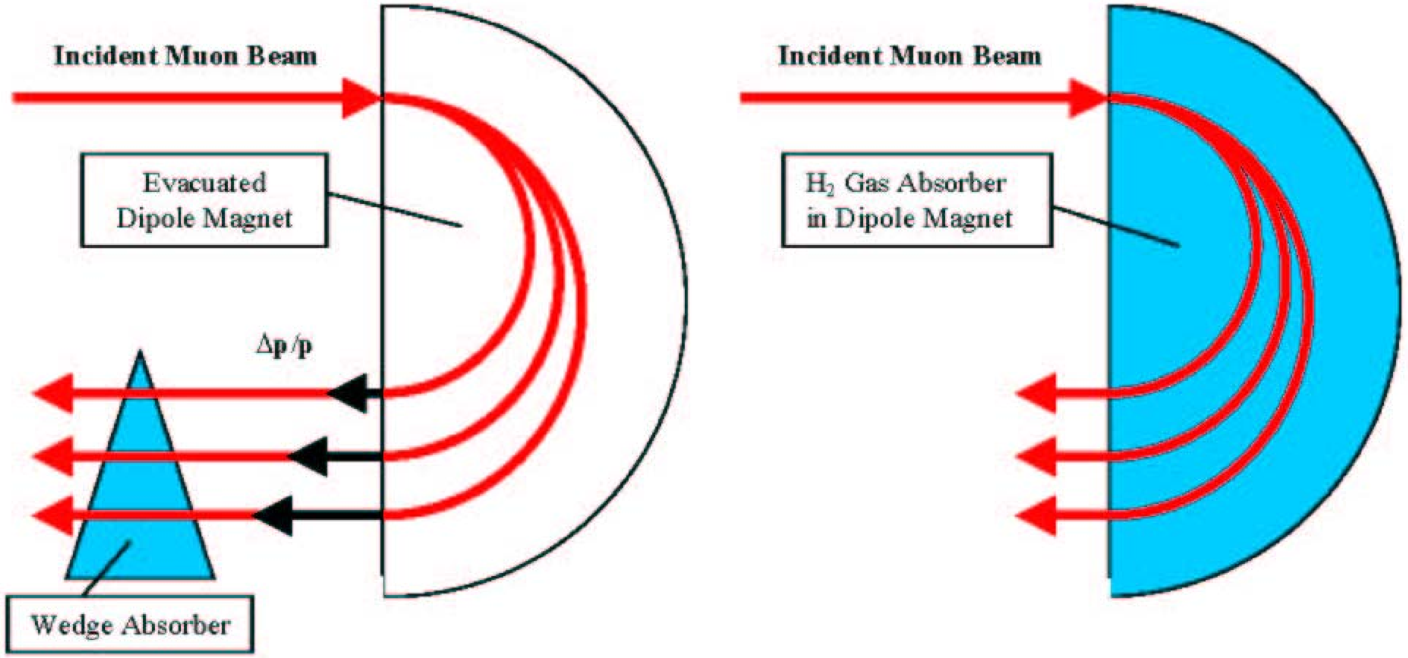


Figure 1. Use of a Wedge Absorber for Emittance Exchange

Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

This concept of emittance exchange with a homogeneous absorber first appeared in our 2003 SBIR proposal!

6D Cooling with HCC

- Helical cooling channel (HCC)
  - Solenoidal plus transverse helical dipole and quadrupole fields (+sextupole for chromaticity)
  - z-independent Hamiltonian
- Avoids ring problems
  - Injection and Extraction
  - Multi-pass Beam loading or Absorber heating
  - Fixed channel parameters as beam cools

Helical Dipole Magnet
(c.f. Erich Willen at BNL)

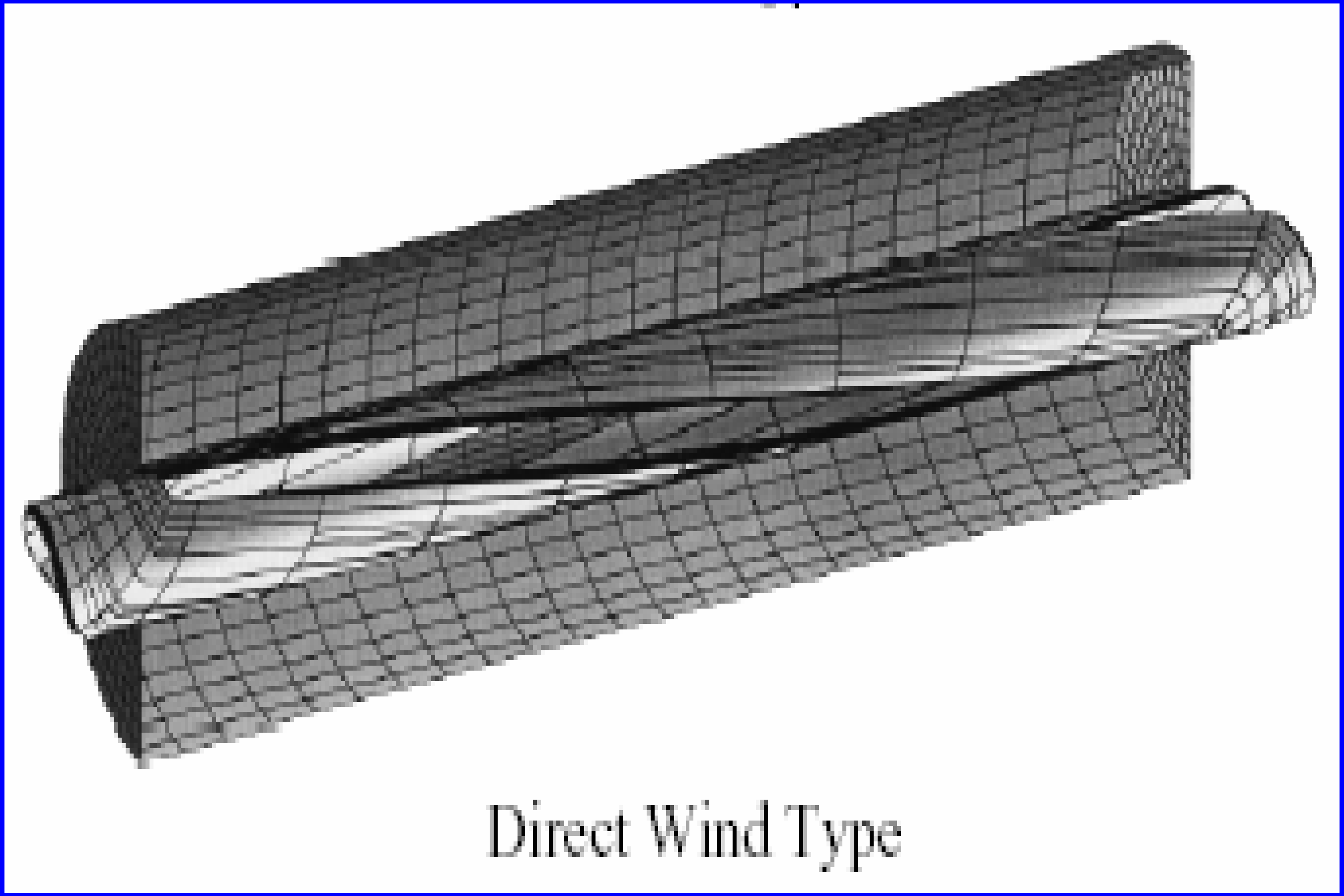
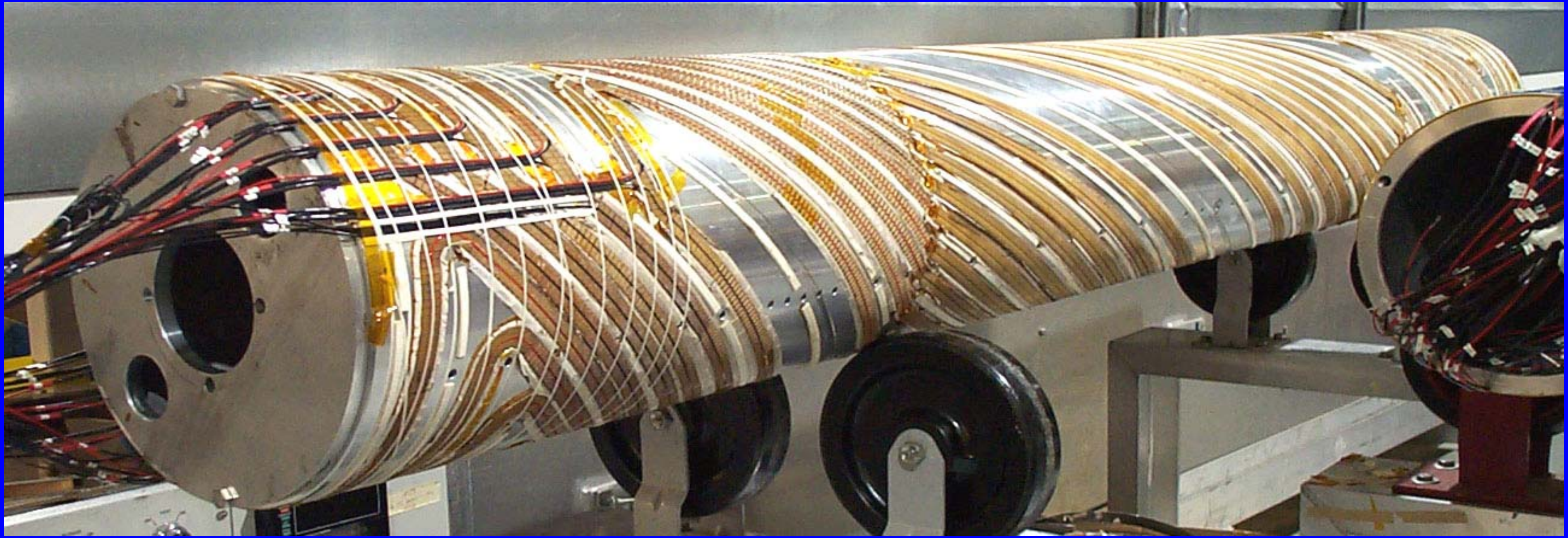


Figure 5. Photograph of a helical coil for the AGS Snake.



oking down the HCC.

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

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

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

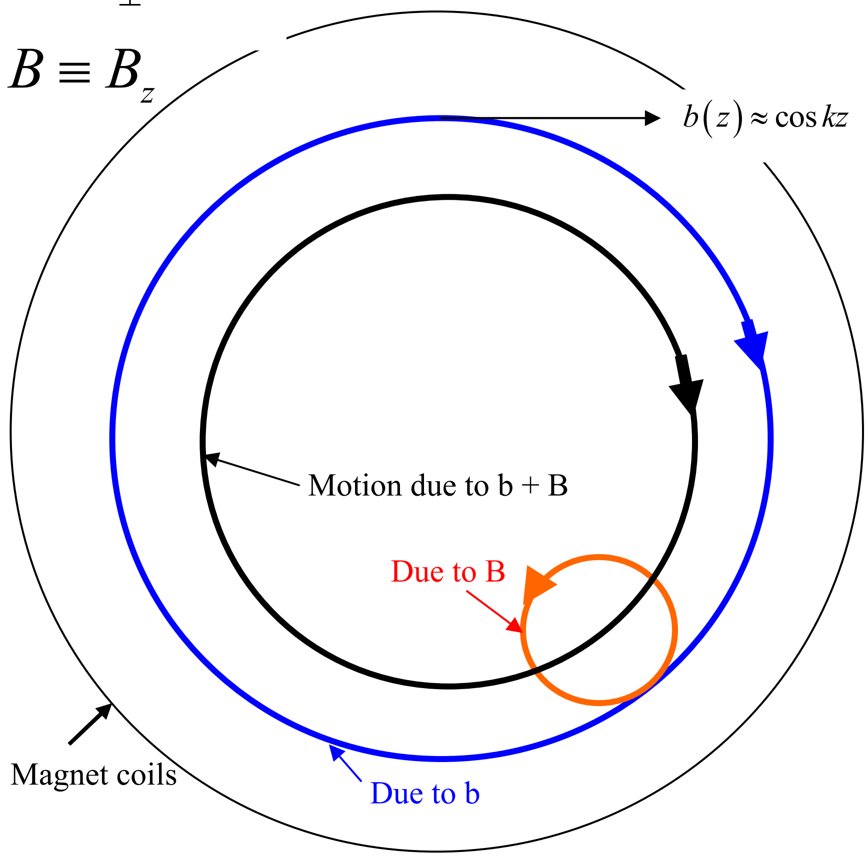
$p = 100 MeV/c$

$p_\perp / p_z = 1.$

$r_{B+b} = 15cm$

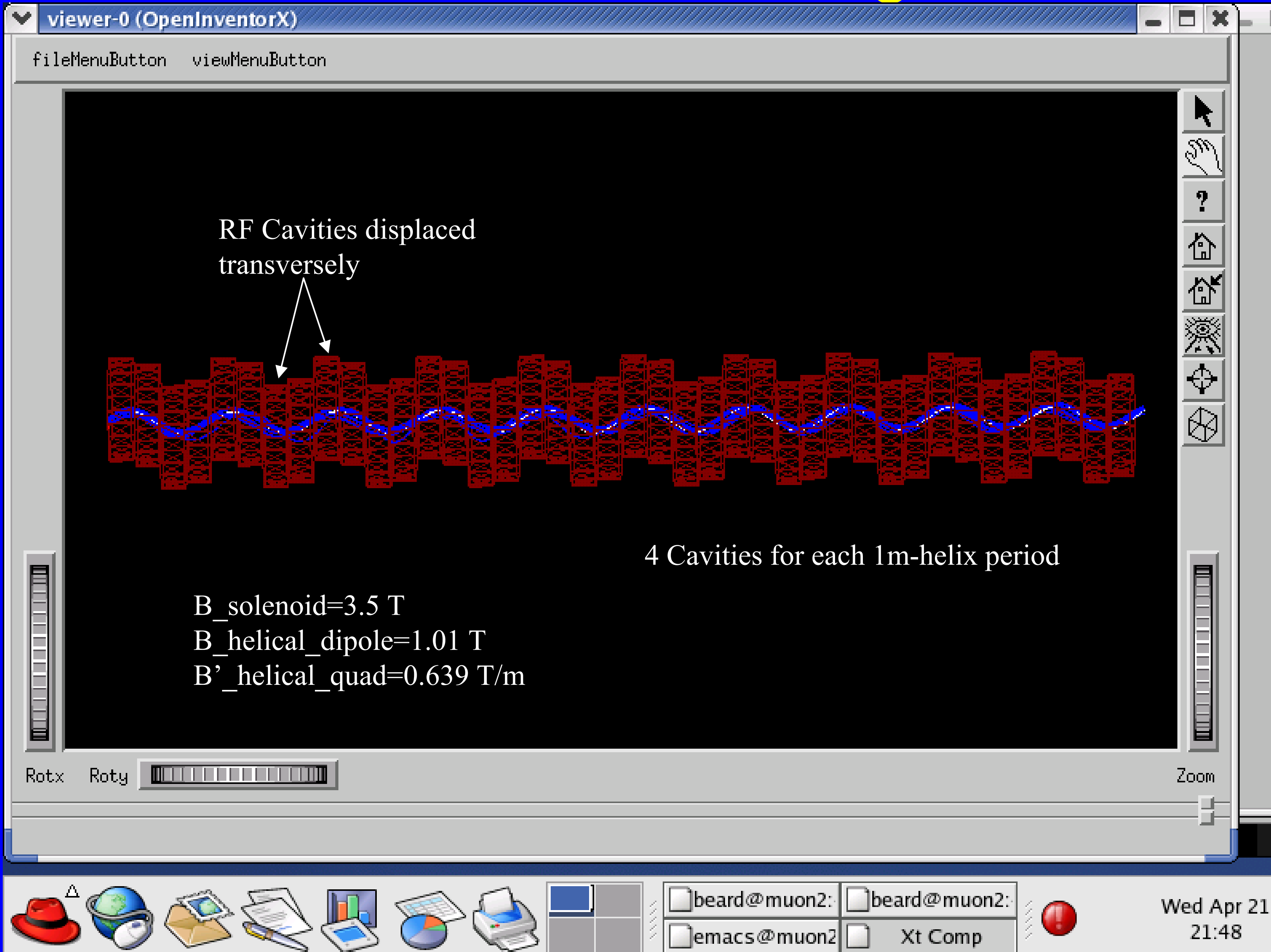
$\lambda = 2\pi / k = 1m$

$r_{coil} = 30cm$

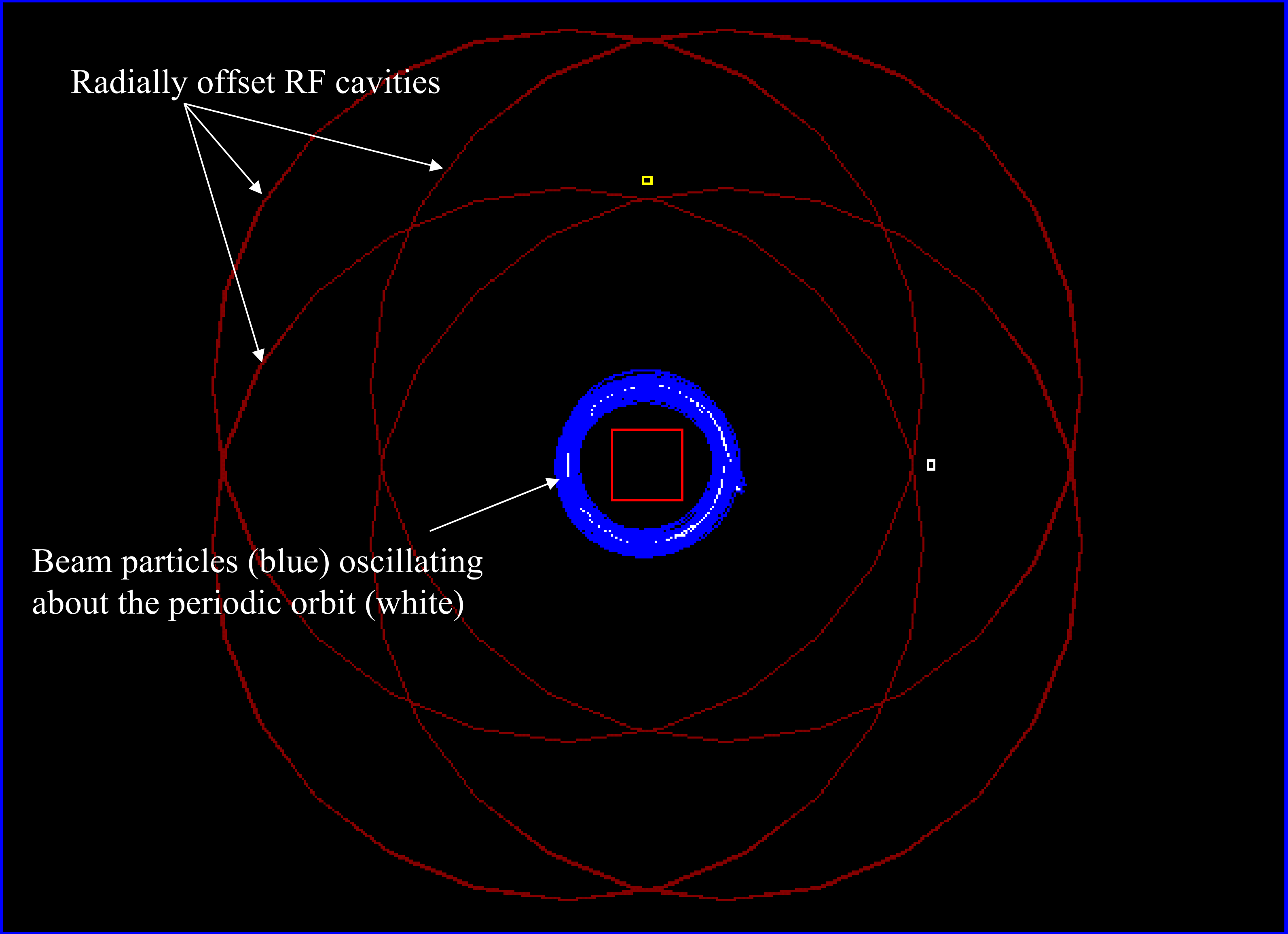


Helical Cooling Channel. Derbenev invention of combination of Solenoidal and helical dipole fields for muon cooling with emittance exchange and large acceptance. Well-suited to continuous absorber. Mucool note 284.

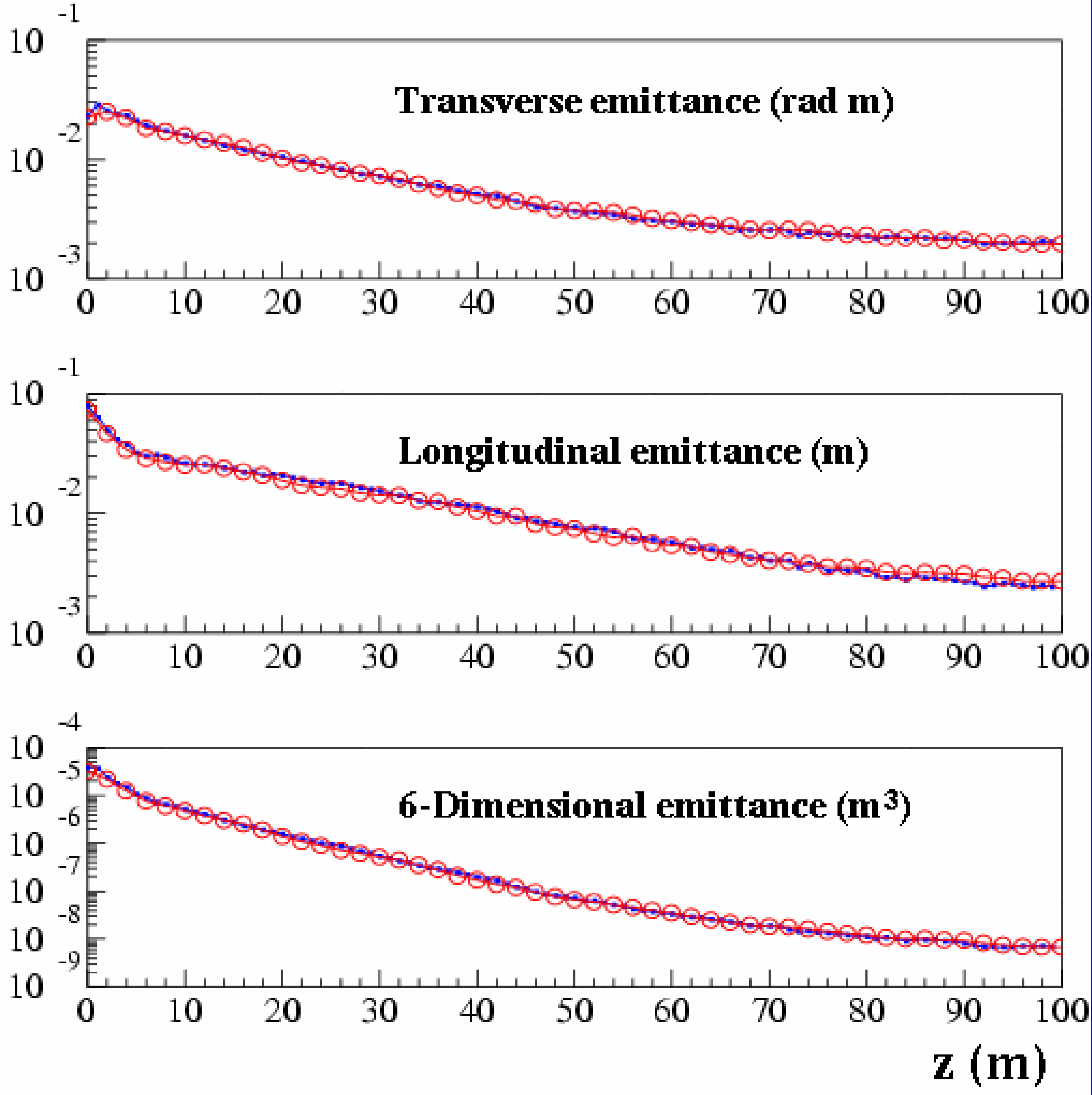
G4BL 10 m helical cooling channel



G4BL End view of 200MeV HCC



Evolution of HCC emittance



Comments on HCC project

- Analytic description essential to guiding simulation effort (see Derbenev et al.)
- Latest simulation results:
  - First of 3 or 4 segments (200 MHz), CF5000
    - Study of other segments and matching between underway
- Addressing RF and SC magnet realism
  - Match to RF capture, precooling sections
    - Can we use higher frequency RF for first HCC section?

MANX

Muon Collider And Neutrino Factory eXperiment

Ph I, w Victor Yarba, Fermilab

- To Demonstrate
  - Longitudinal cooling
  - Helical cooling channel
  - 6D cooling in cont. absorber
  - Prototype precooler
  - New technology (HCC, HTS)
- By using
  - No RF
  - LH2 (or LHe?)
  - MICE detectors

HCC with Z-dependent fields

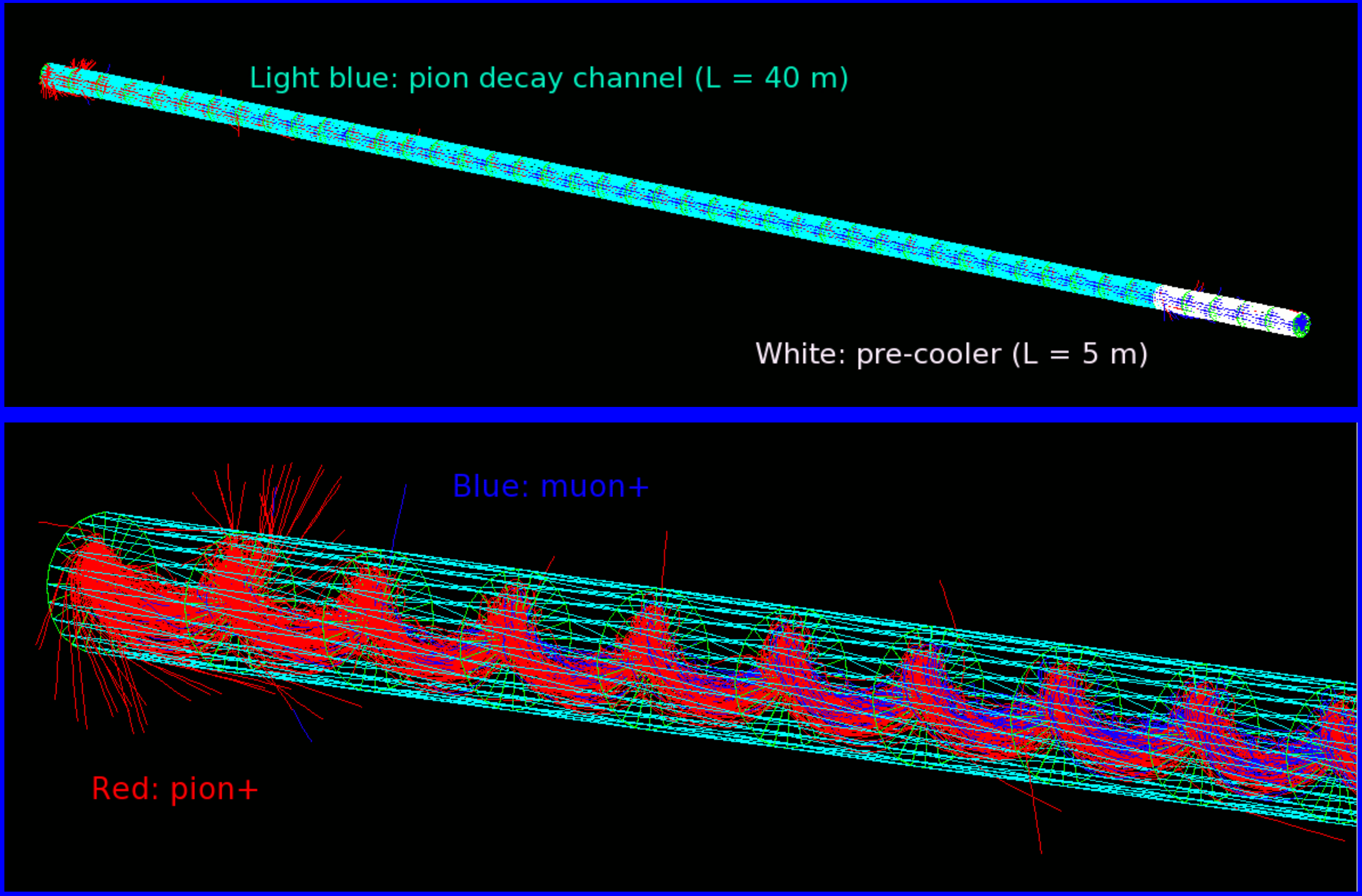
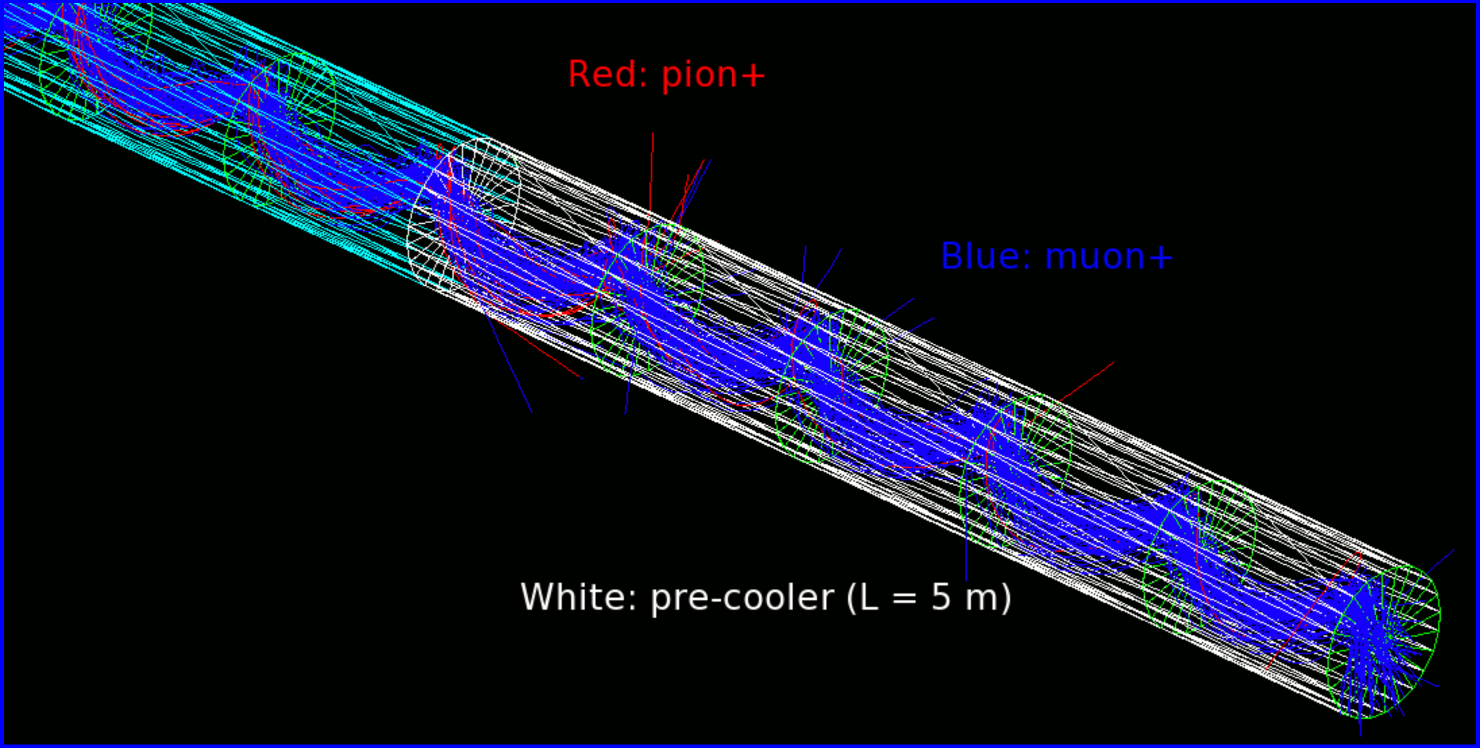


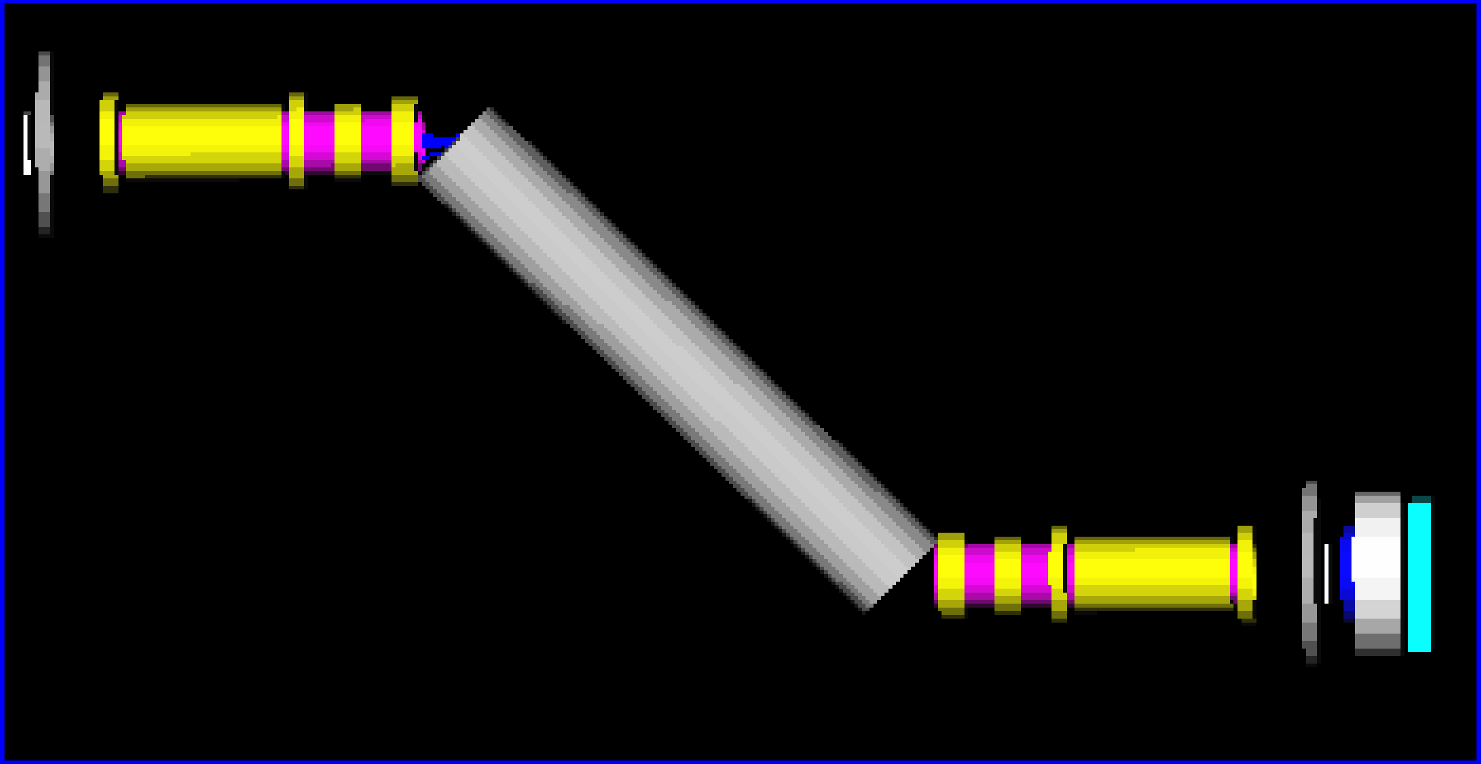
Figure IV.1: Layout of the pion helical decay (light blue) and helical precooling (white) channels. The top picture shows the whole layout, the lower one shows the beginning of the decay channel, and the next slide shows the precooler end. The red and blue lines show the pion and muon tracks, respectively. The helix period is 1 meter.

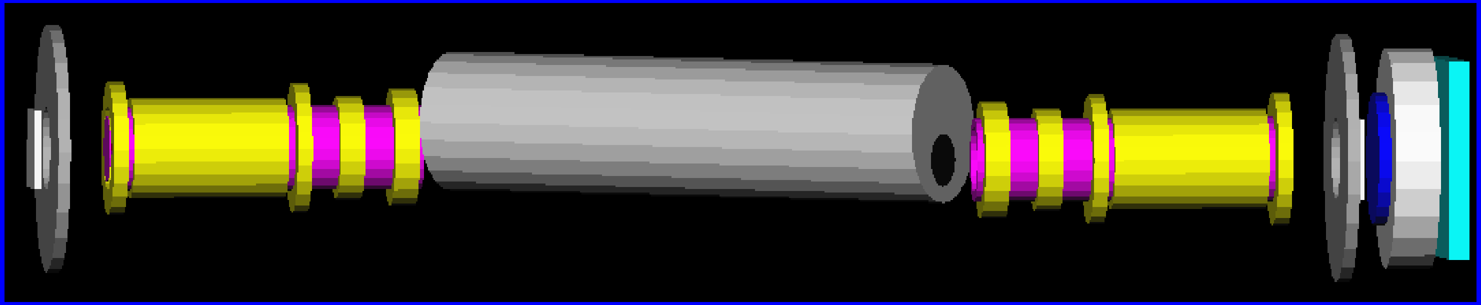
5 m Precooler aka MANX



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

G4BL MANX with MICE spectrometers





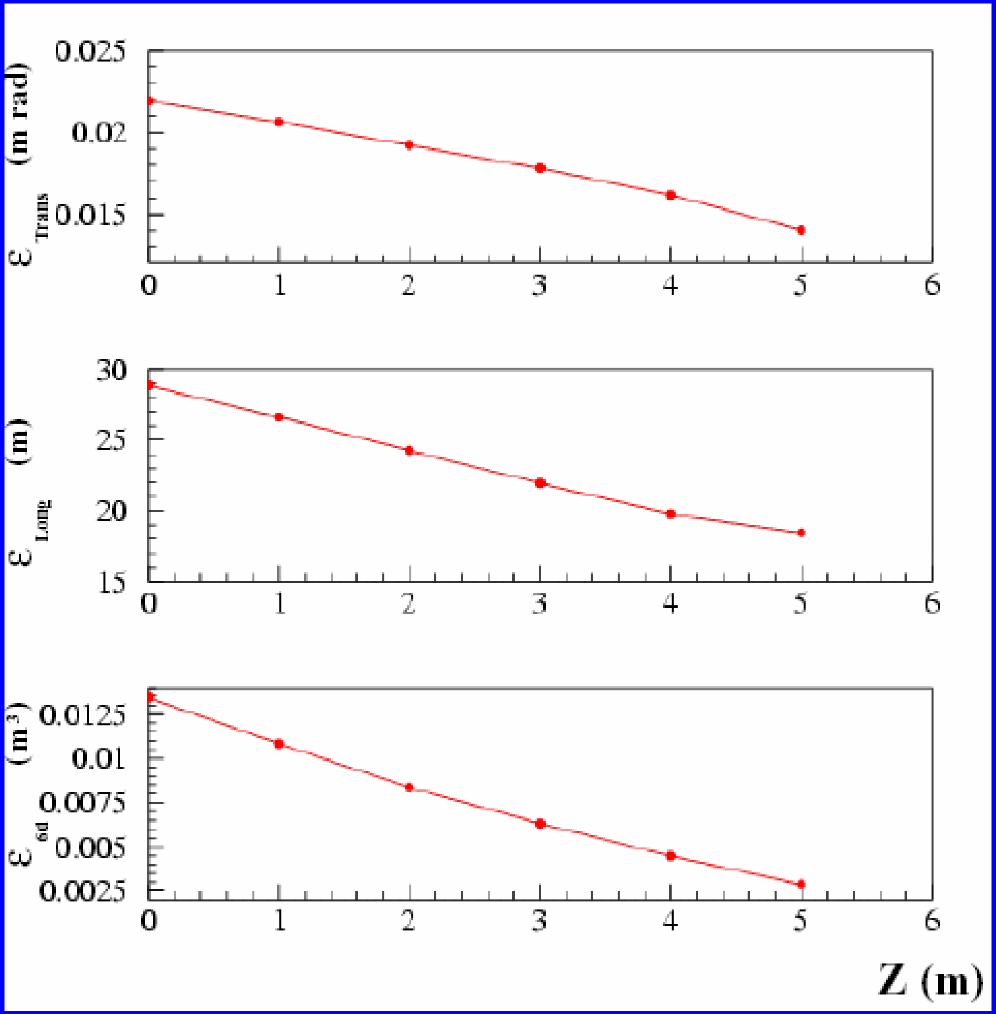
MANX G4BL Simulation

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



Hydrogen Cryostat

w Victor Yarba, Fermilab

- simultaneously refrigerate
  - 1) HTS magnet coils
  - 2) cold copper (or Be?) RF cavities
  - 3) hydrogen gas heated by the muon beam
- extend use of hydrogen to that of refrigerant
  - besides breakdown suppressant and energy absorber
  - large amount of hydrogen for IC anyway
- relevance for hydrogen economy?
- Dr. Moyses Kuchnir

Phase I Fermilab TD Measurements

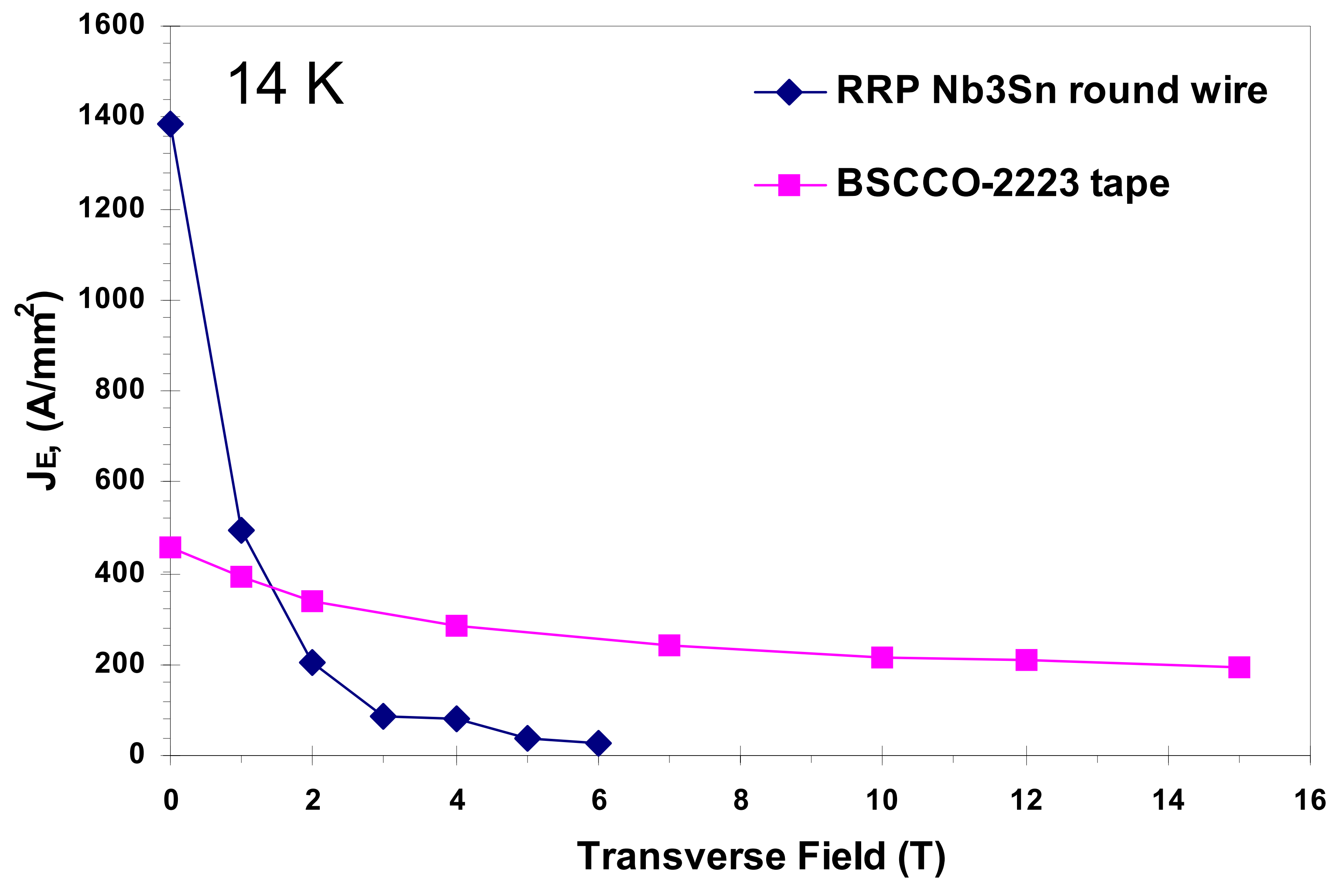


Fig. 9. Comparison of the engineering critical current density, J_E, at 14 K as a function of magnetic field between BSCCO-2223 tape and RRP Nb_3Sn round wire.

MANX/Precooler H2 or He Cryostat

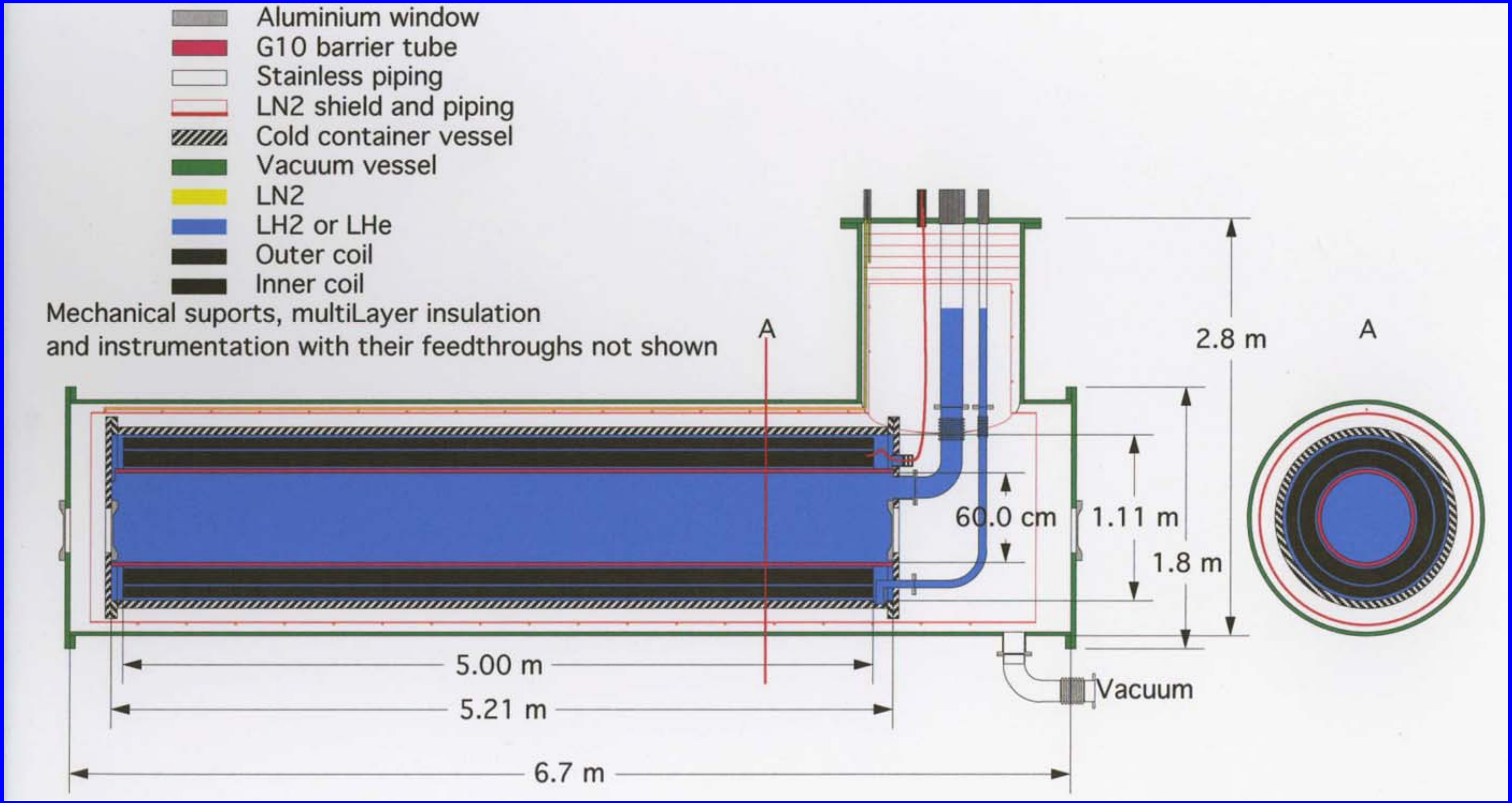


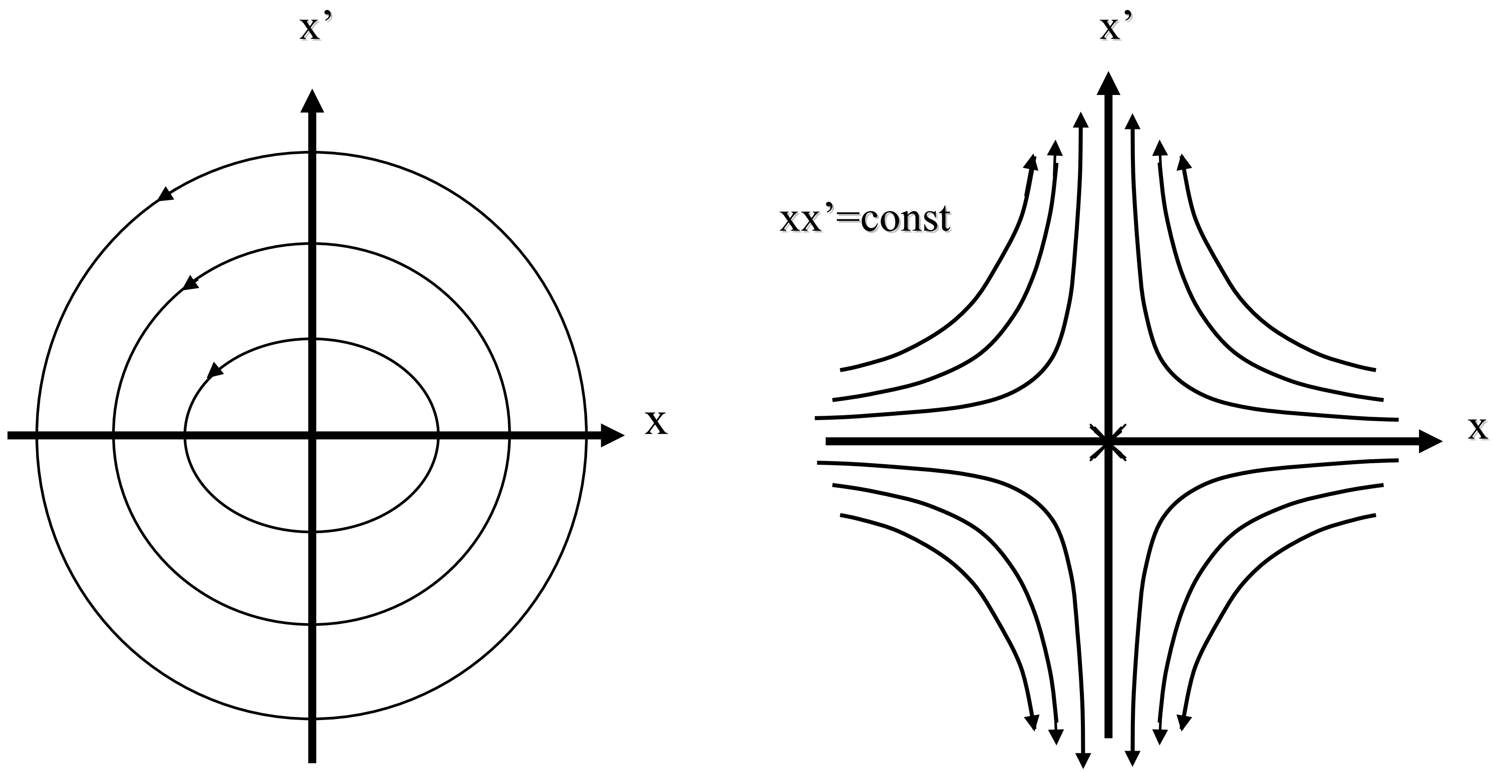
Figure XI.2. Latest iteration of MANX cryostat schematic. Here, liquid H_2 or He is forced through the HTS (16 K) or Nb3Sn (2 K) coils before entering the region where the beam can heat the liquid. A G10 insulating barrier tube keeps the coils at constant temperature, independent of the beam heating in the central volume. The inner coil structure has both helical dipole and quadrupole windings.

Parametric-resonance Ionization Cooling (PIC)

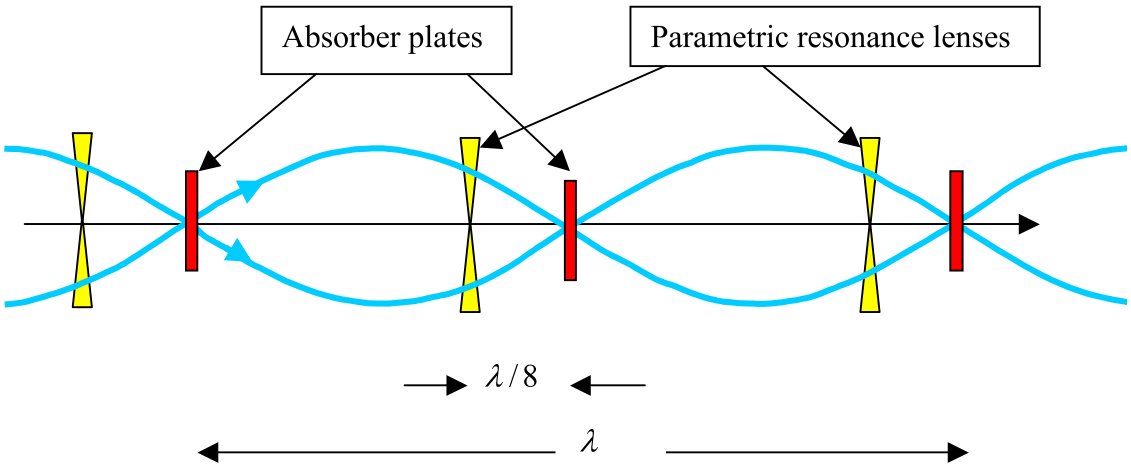
Slava Derbenev, Jlab

- 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'
- 1 to 2 orders smaller emittance than usual IC
  - Fewer muons needed for high luminosity MC
    - Easier proton driver and production target
    - Fewer detector backgrounds from decay electrons
    - Less neutrino-induced radiation

Hyperbolic phase space motion



Transverse PIC schematic



Conceptual diagram of a beam cooling channel in which hyperbolic trajectories are generated in transverse phase space by perturbing the beam at the betatron frequency, a parameter of the beam oscillatory behavior. Neither the focusing magnets that generate the betatron oscillations nor the RF cavities that replace the energy lost in the absorbers are shown in the diagram.

The longitudinal scheme is more complex.

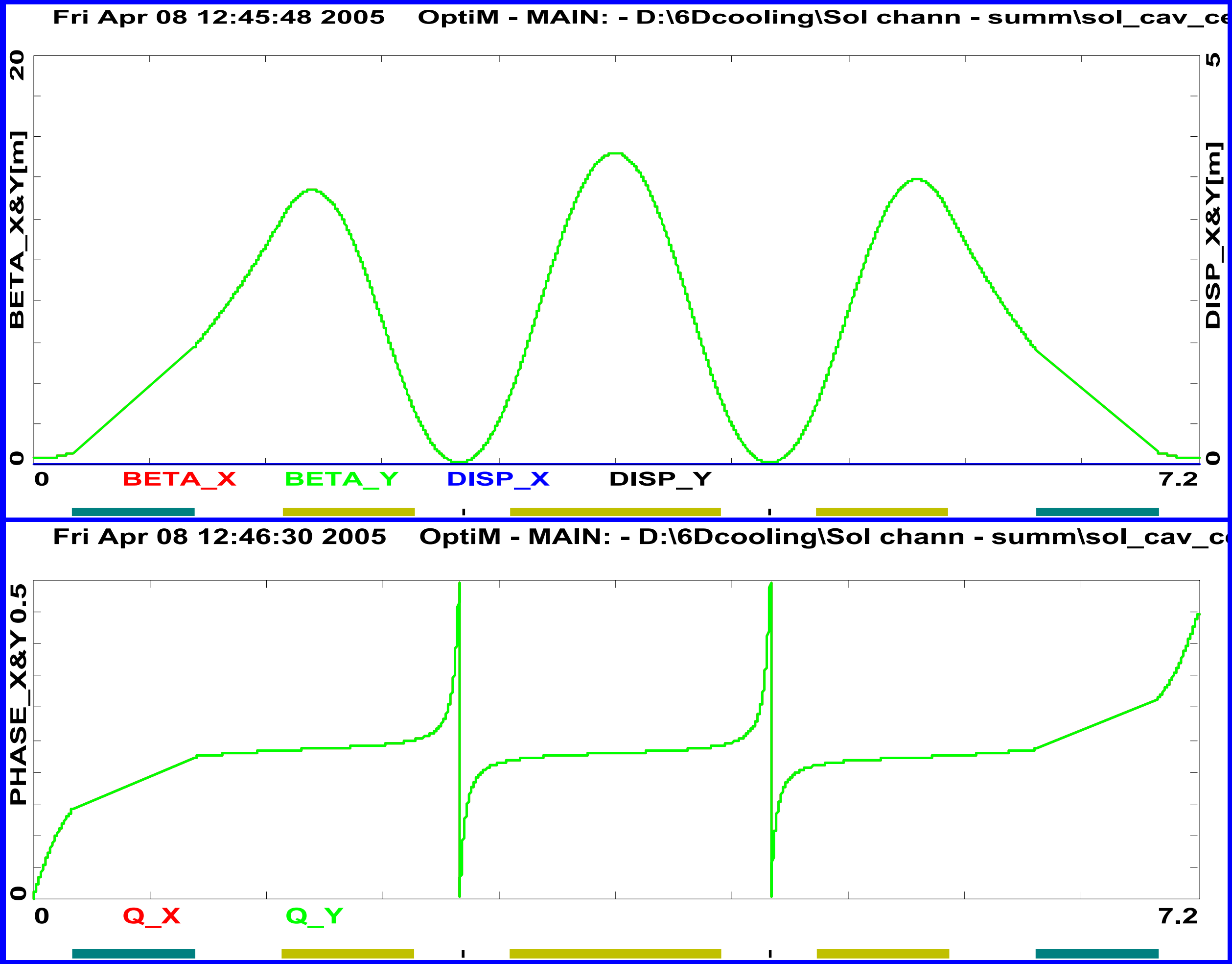


FIG 1. Beta functions and phases for the solenoid triplet cell. Thin absorbers are placed at the two central focal points. In the simulations for FIG 2 the lost energy is simply replaced at the absorbers. For FIG 3, 400 MHz RF cavities shown as blue bars replace the lost energy and provide synchrotron motion.

x'

x

Dp/p

s

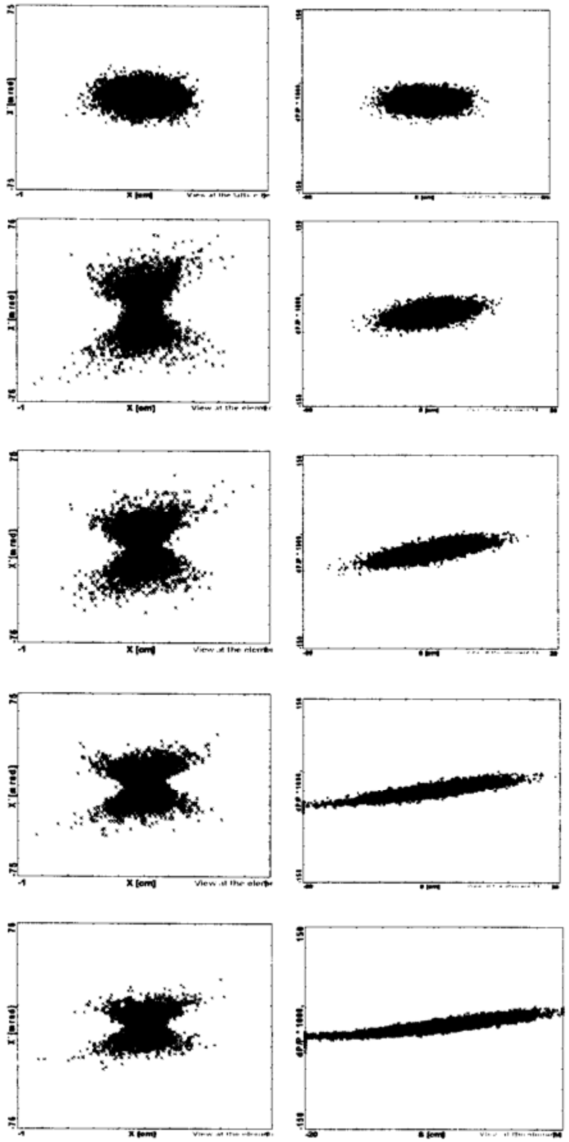


FIG 2. PIC simulation "snapshots" of $x - x'$ (LEFT) and $s - \Delta p / p$ (RIGHT) phase space <u>without</u> synchrotron motion to correct chromatic aberration. Reading from top to bottom, each snapshot corresponds to passage through two of the cells shown in FIG 1.

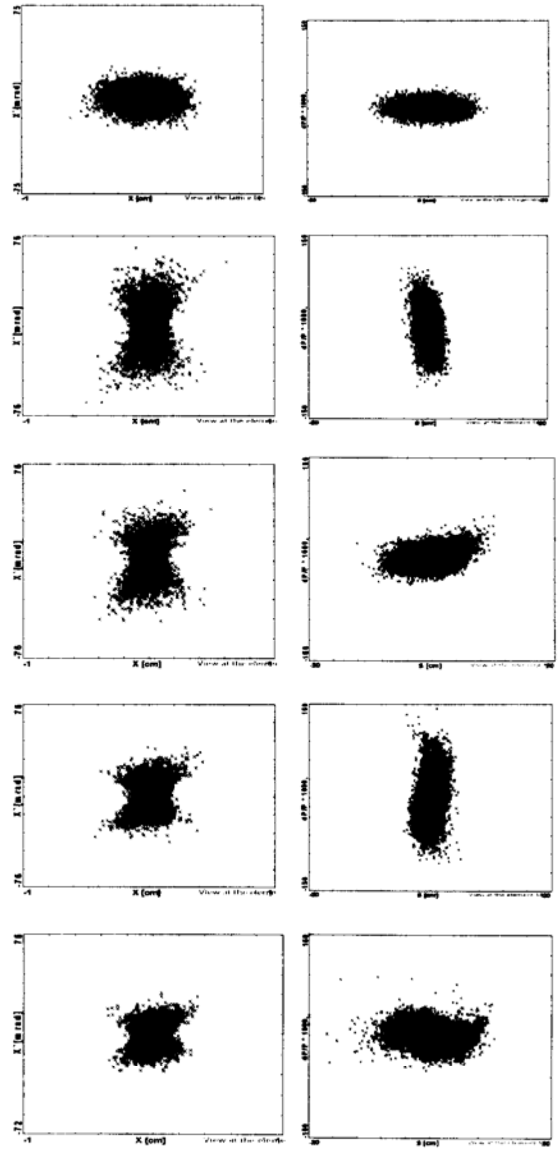


FIG 3. PIC simulation "snapshots" of $x - x'$ (LEFT) and $s - \Delta p / p$ (RIGHT) phase space <u>with</u> synchrotron motion compensation of chromatic aberration. The transverse phase space with synchrotron motion is seen to be smaller than in FIG 2. The RF bunch rotation of

updated

New Proposals Submitted 12/13/04

- Muons, Inc. workshop 10/4-5/04 had 14 ideas for new Phase I proposals.
- The 4 submitted were:
  - Reverse Emittance Exchange with Jlab
  - HCC Magnets with BNL
  - Muon Precooling, bunching with Fermilab
  - G4BL with IIT

Figure 1. Emittance Exchange

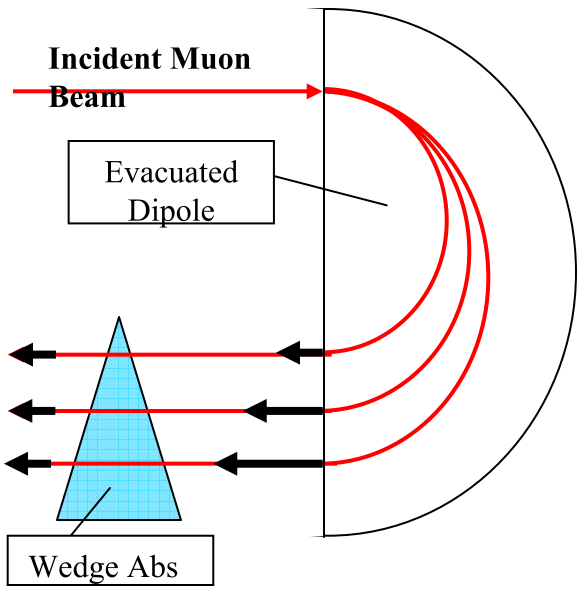


Figure 2. Reverse Emittance Exchange

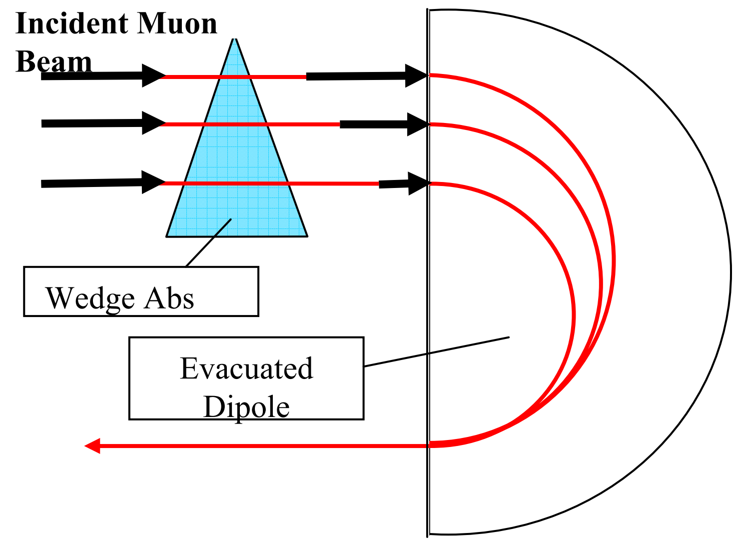
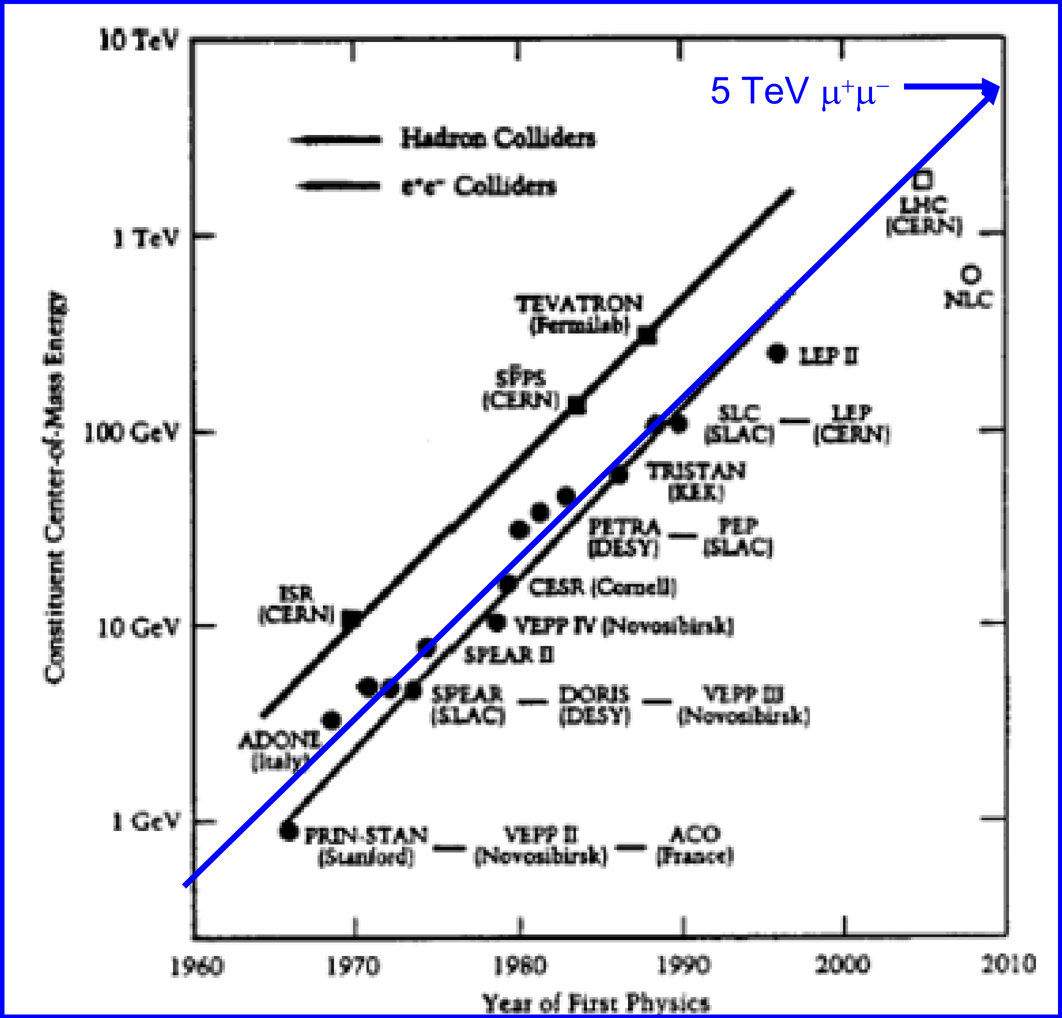


Figure 1. Conceptual diagram of the usual mechanism for reducing the energy spread in a muon beam by emittance exchange. An incident beam with small transverse emittance but large momentum spread (indicated by black arrows) enters a dipole magnetic field. The dispersion of the beam generated by the dipole 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.



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

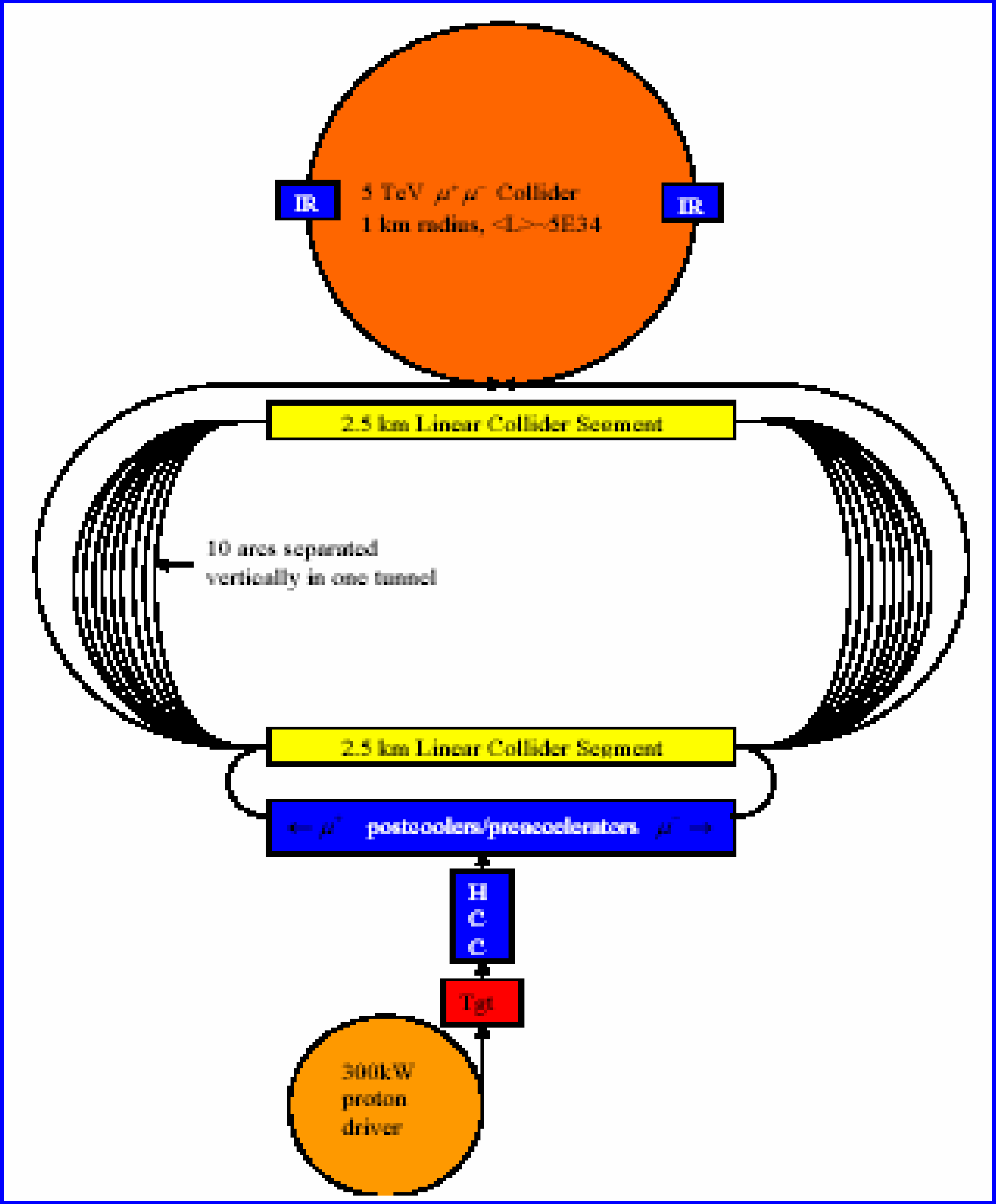
L from small emittance

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

Timing makes recirculating easier than at CEBAF

Can be staged; neutrino factory, Higgs factory, E frontier machine up to limit of R and B

$(m\mu/me)^2$=40,000 s-channel Higgs advantage over e+e-



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

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

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

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

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

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

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

20 Hz Operation:

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

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

$0.3 \mu^\pm / p$

Recap: 9 Muons, Inc. SBIR projects

- GH_2 RF cavities — IIT, Kaplan — 600k ends 7/05
  - New RF option for muons, simultaneous absorber & breakdown suppressor
- 6D HCC — Jlab, Derbenev 850k ends 7/06
  - Basic 6D cooling, simulations and theory, for colliders & factories
- MANX (6D HCC cooling demo) — FNAL, Yarba +750k
  - Essential 6D cooling demonstration experiment, experiment optimization
- H_2 Cryostat (HCC Technology) — FNAL, Yarba +750k
  - Basis for HCC engineering, HTS, RF materials, MANX cryo design
- PIC (Parametric-resonance IC) — Jlab, Derbenev +750k
  - Reduce transverse emittances each a factor >10
- REMEX (rev. emit. exchange) — Jlab, Derbenev 100k
  - Reduce transverse emittances each another factor >10
- Helical Cooling Channel Magnets — BNL, Gupta 100k
  - Develop realistic magnet designs, use field maps to optimize HCC
- GH_2 RF Capture, Phase rotation — FNAL, Neuffer 100k
  - HPRF development, simulations of capture, phase rotation, precooling
- G4BL simulation program development — IIT, Kaplan 100k
  - Needed for our and others' progress