μ

Muons, Inc.

Innovation in Research

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Innovations in Muon Beam Cooling; Prospects for a Muon Collider

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

Rolland Johnson, January 20, 2005

- HP HG GH2 RF
  - Ph II, w IIT, DK
- 6D HCC
  - Ph II, w Jlab, YD
- Pulse Compression
  - Awarded, not funded
- H2 Cryostat due **4/13/2005**
  - w FNAL, VY
- MANX due **4/13/2005**
  - w FNAL, VY
- PIC due **4/13/2005**
  - w Jlab, YD
- 4 New Proposals in Progress
  - HCC Magnets w BNL RG
  - REMEX w Jlab YD
  - G4BL w IIT DK
  - GH2 Phase rotation w FNAL DN

Thanks to Excellent Collaborators

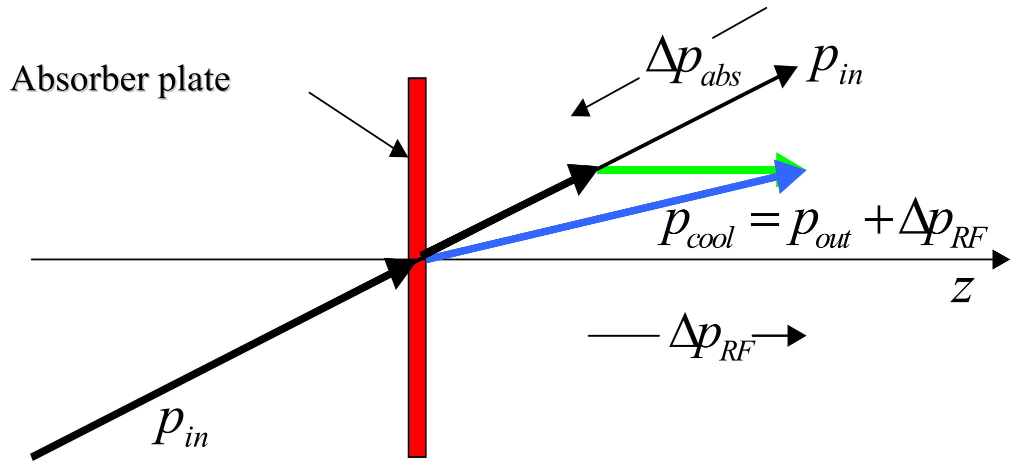
- JLab; Slava Derbenev, Alex Bogacz, Kevin Beard
- BNL; Ramesh Gupta, Erich Willen, Steve Kahn
- IIT; Dan Kaplan, Katsuya Yonehara
- Fermilab; Victor Yarba, Chuck Ankenbrandt, Emanuela Barzi, Timer Khabiboulline, Al Moretti, Dave Neuffer, Milorad Popovic, Gennady Romanov
- Muons, Inc.; Mohammad Alsharo'a, Pierrick Hanlet, Bob Hartline, Moyses Kuchnir, Kevin Paul, Tom Roberts

Project 1: 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

Ionization Cooling (IC) Principle

- Schematic of angular divergence cooling



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.

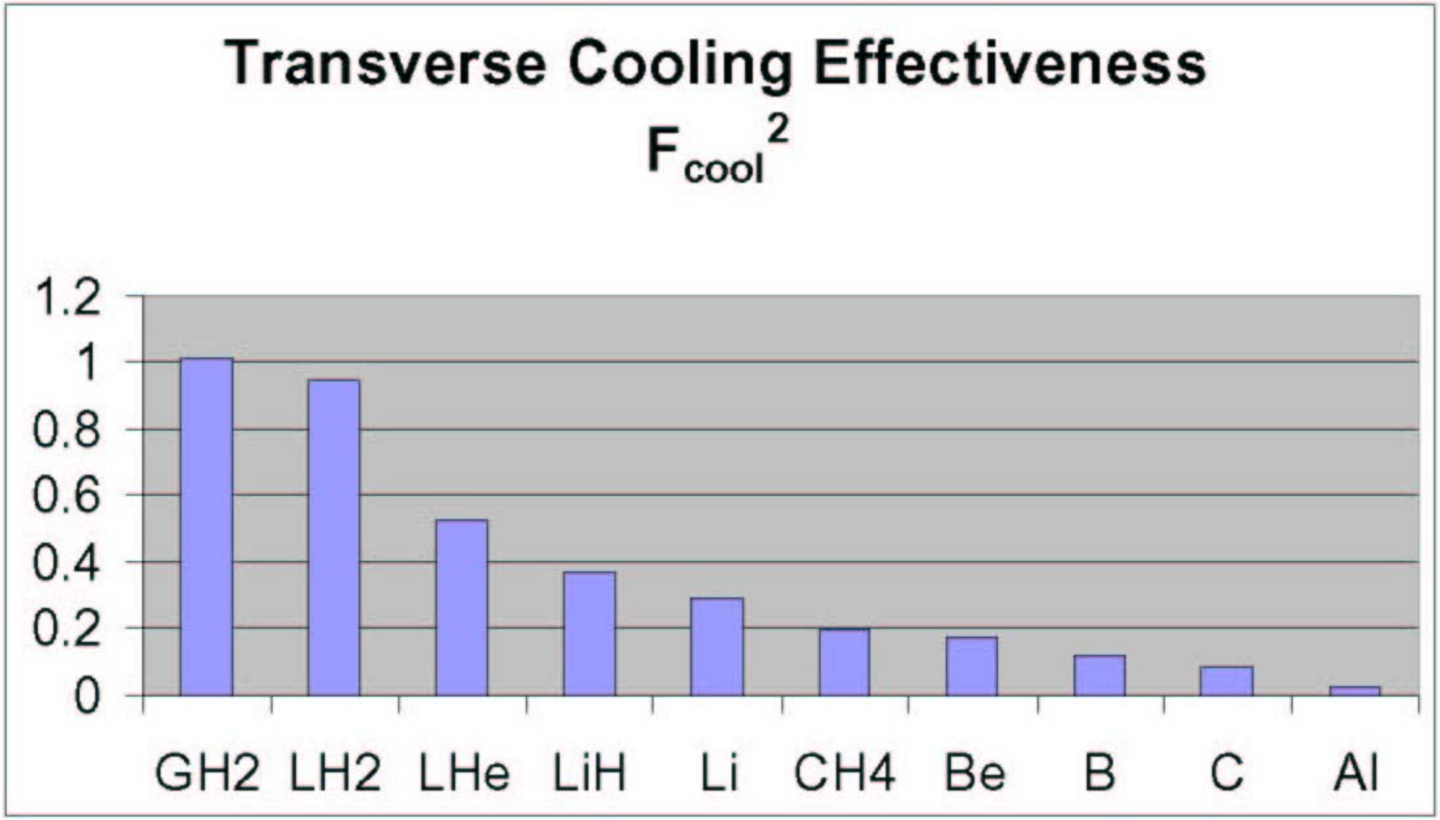
I. C. Figure of Merit

- 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 ($F_{cool} = X_0 dE_m/ds$) 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

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

High-Pressure RF Test Cell w Moly Electrodes at Lab G

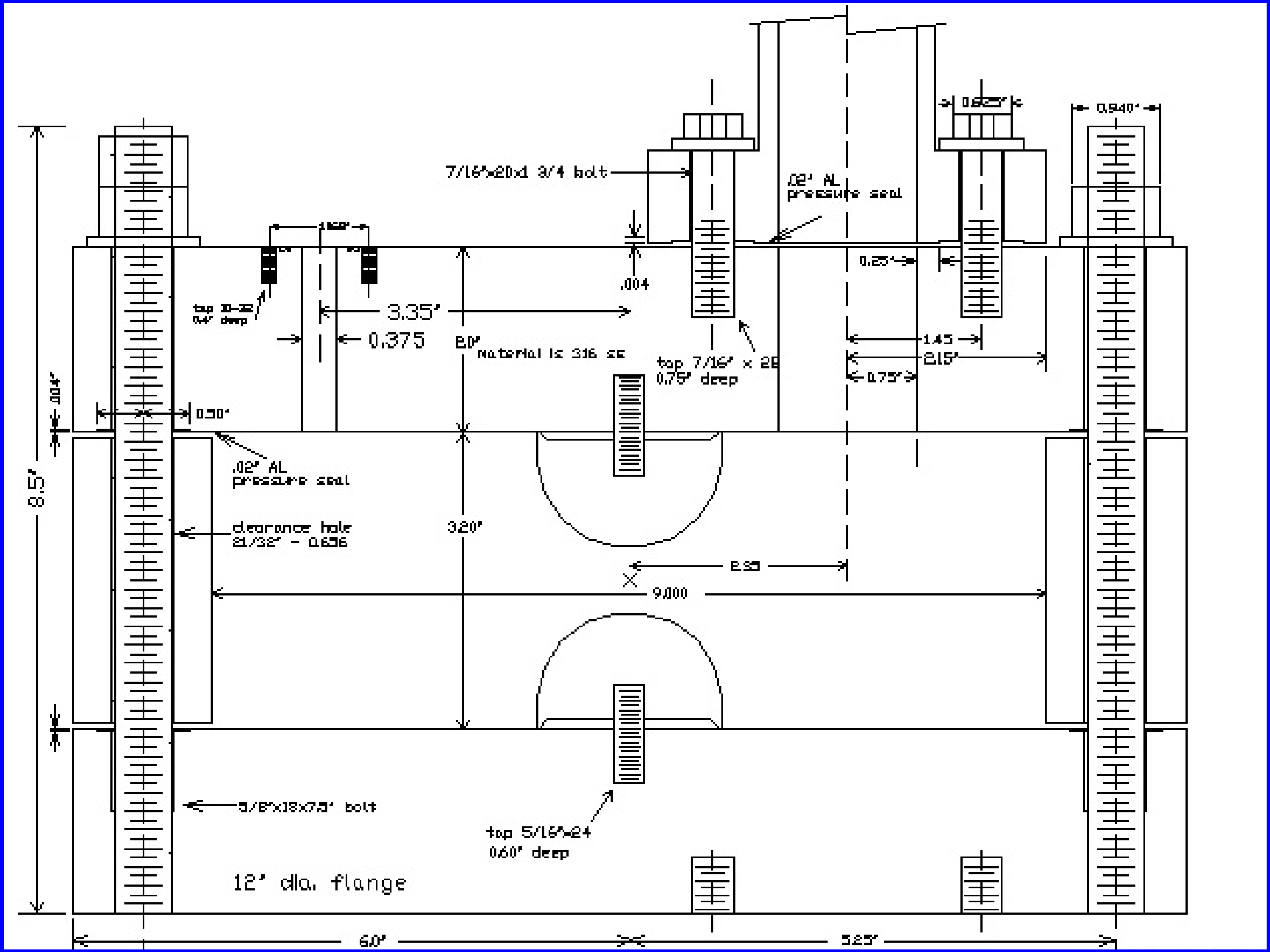
R. E. Hartline, R. P. Johnson, M. Kuchnir
Muons, Inc.

C. M. Ankenbrandt, A. Moretti, M. Popovic
Fermilab

D. M. Kaplan, K. Yonehara
Illinois Institute of Technology

See MuCool Note 285 for paper

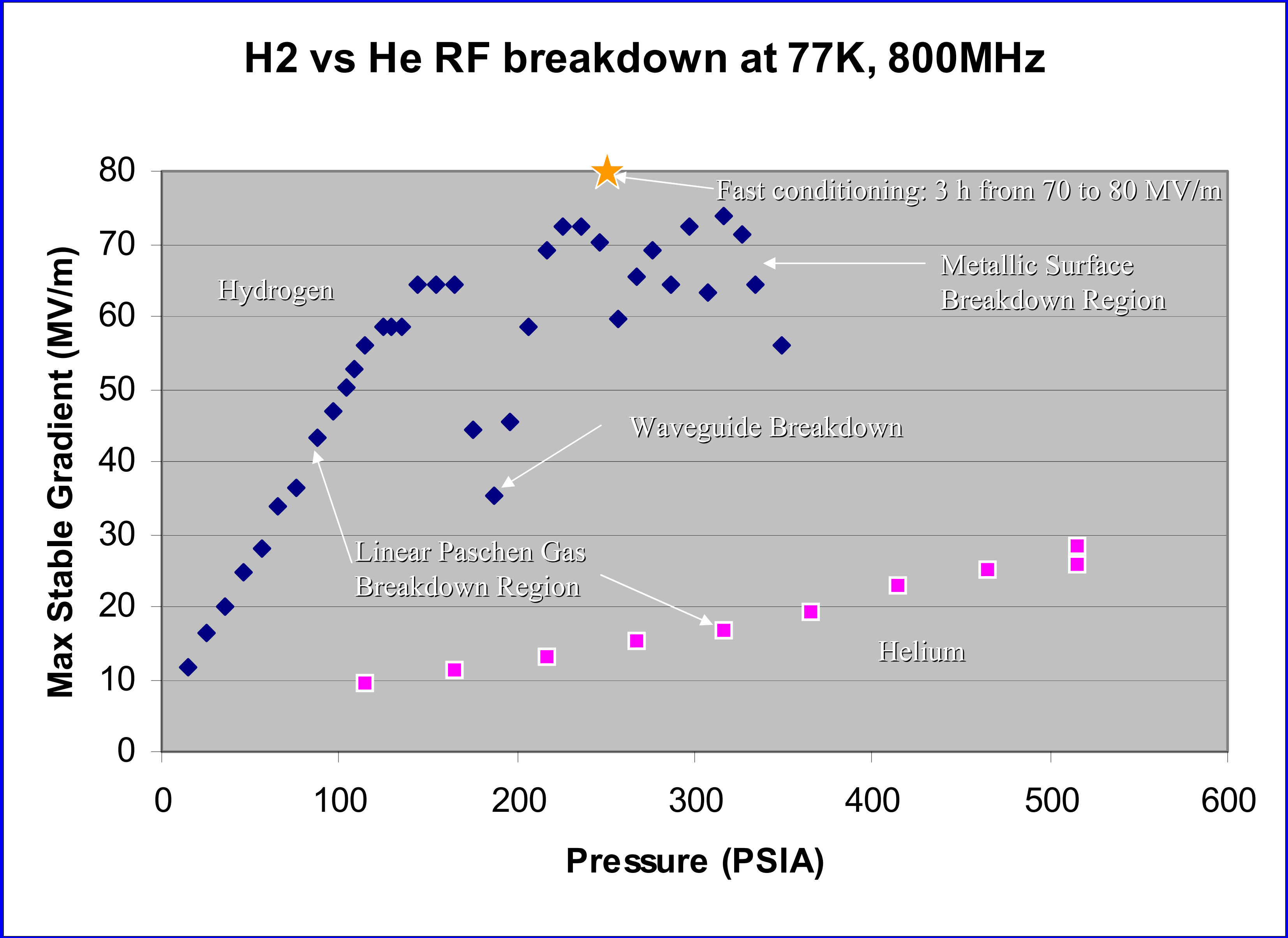
Mark II 805 MHz RF test cell



New TC; 2000PSI @ 77K


4/9/2003

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 GH2 Emittance Exchange

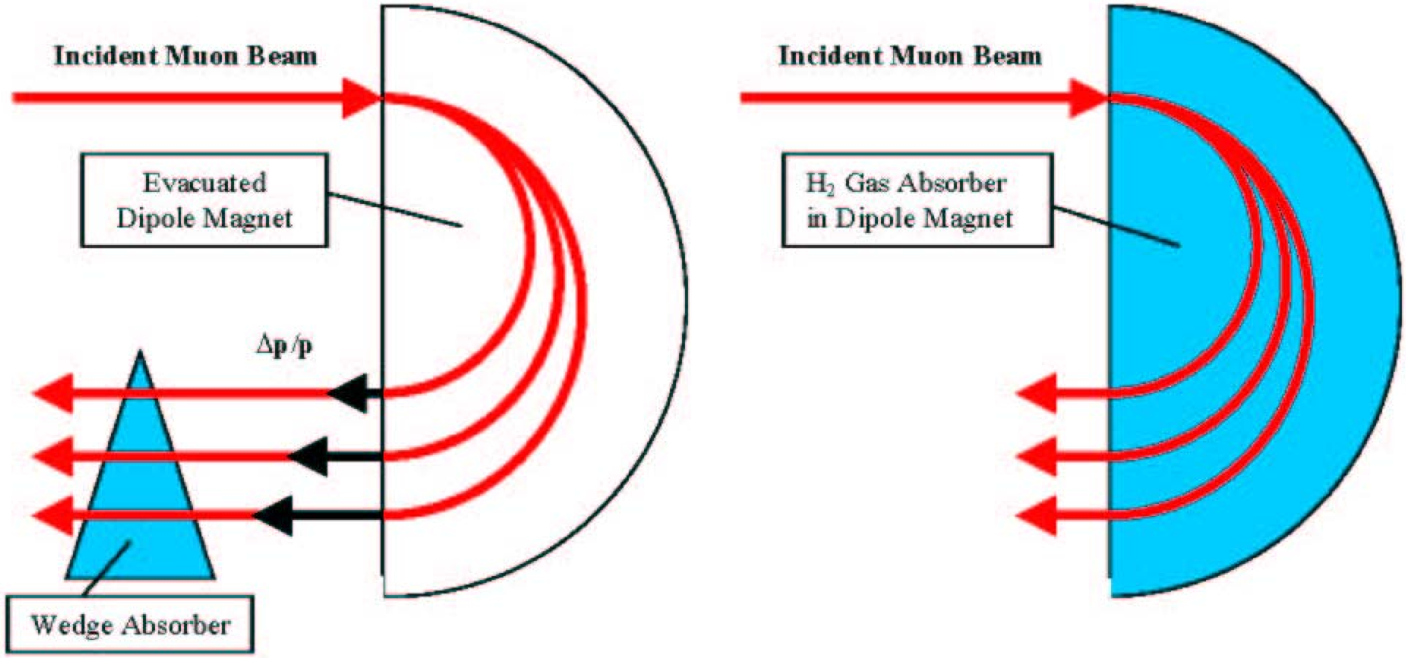


Figure 1. Use of a Wedge Absorber for Emittance Exchange

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 GH2

- Helical cooling channel (HCC)
  - Solenoidal plus transverse helical dipole and quadrupole fields
  - 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)

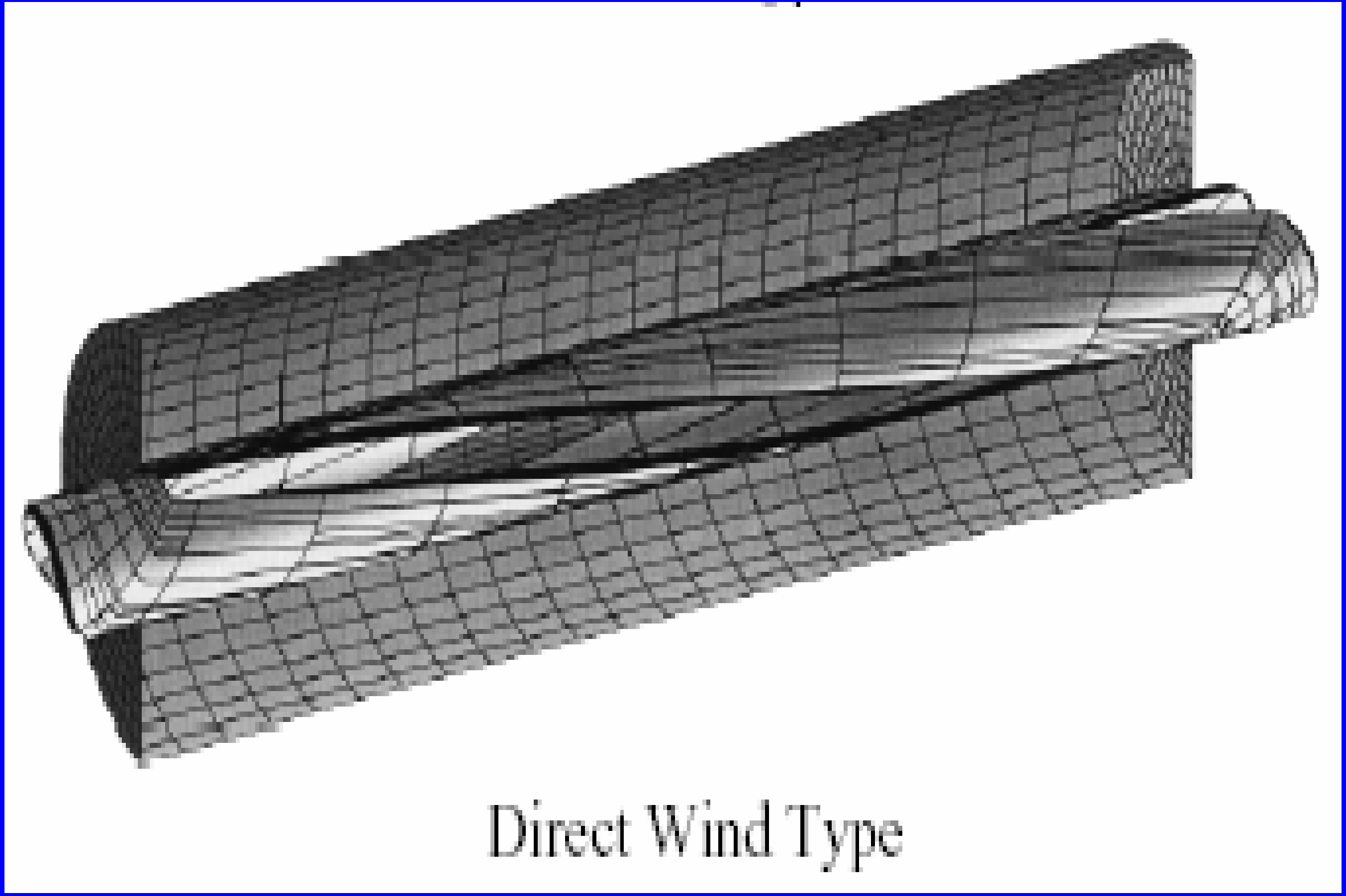
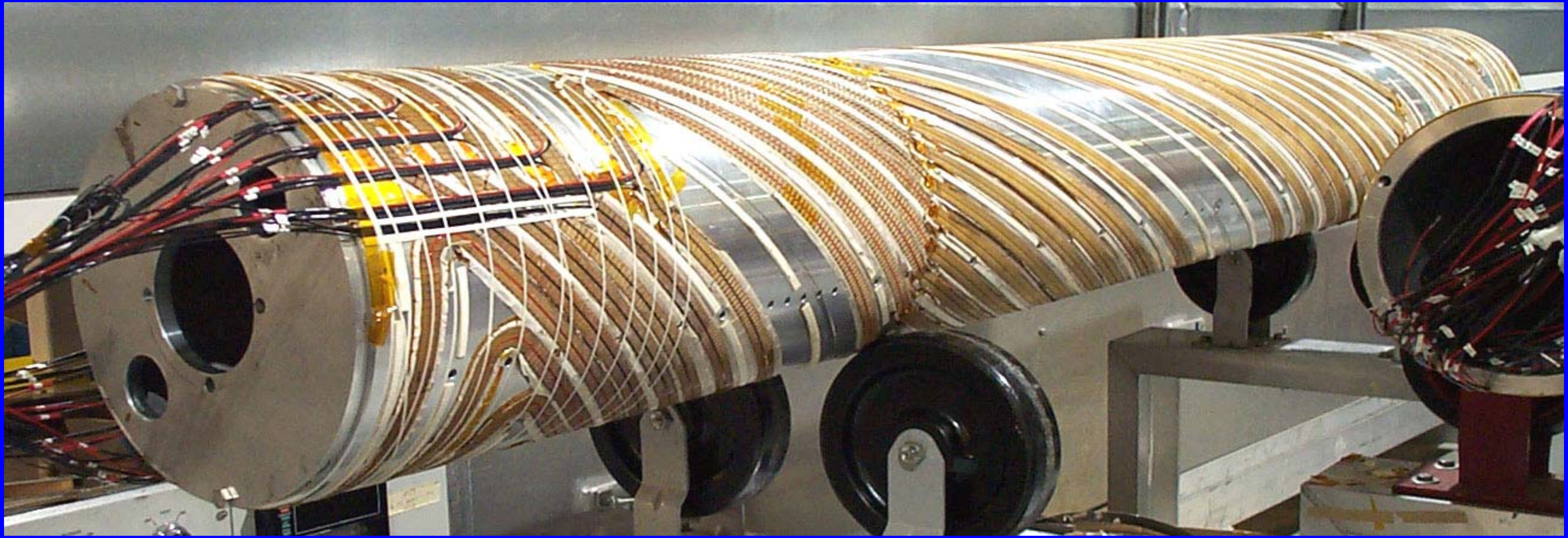


Figure 5. Photograph of a helical coil for the AGS Snake.



oking down the HCC.

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

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

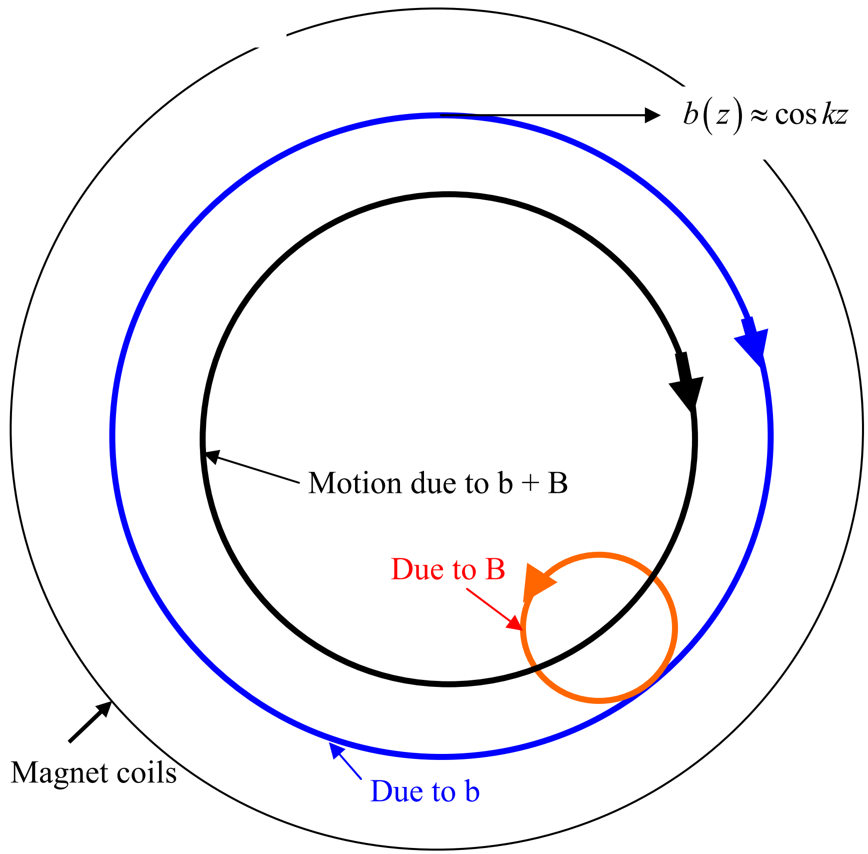
$p = 100 MeV / c$

$p_\perp / p_z = 1.$

$r_{B+b} = 15cm$

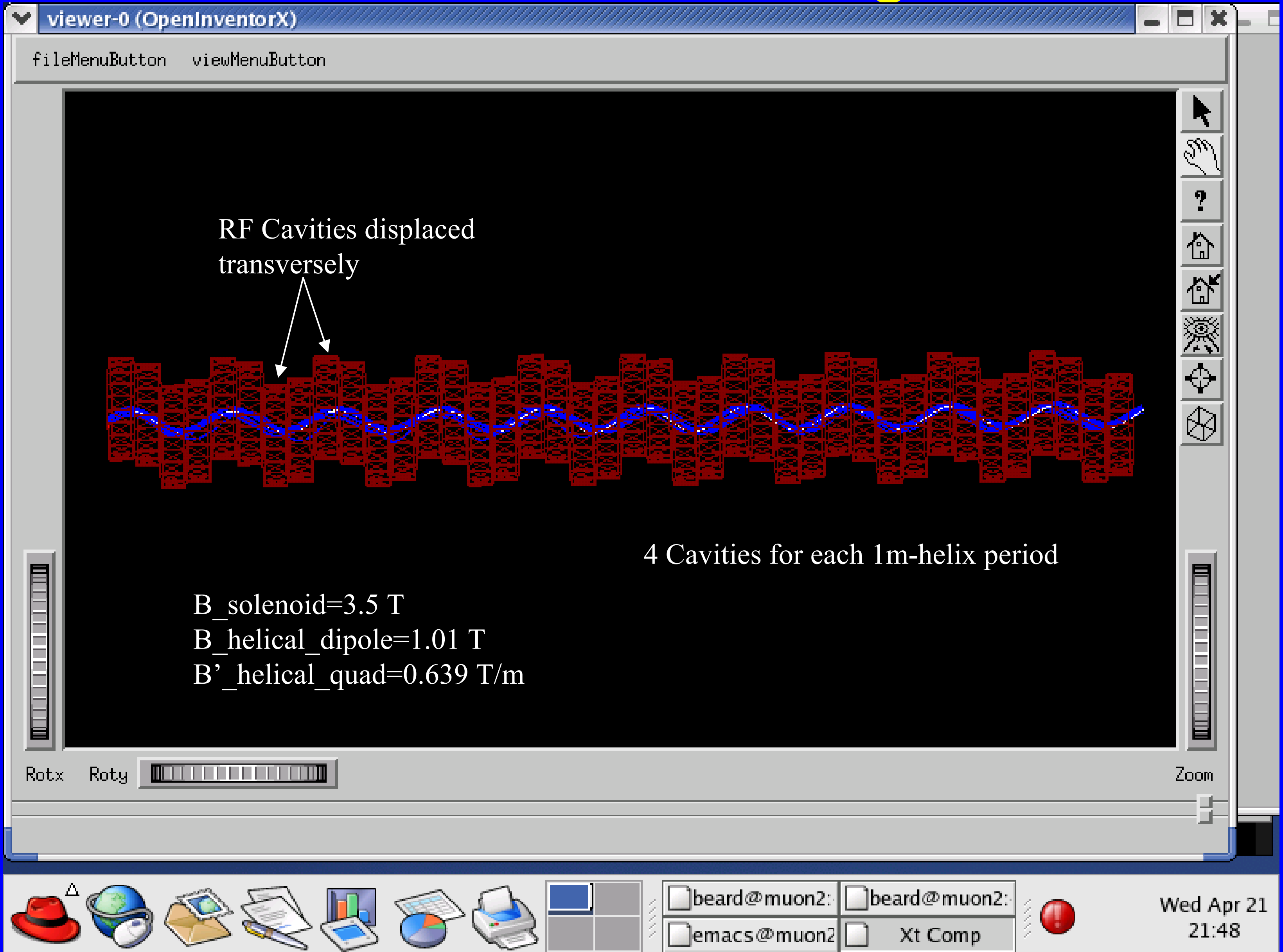
$\lambda = 2\pi / k = 1m$

$r_{coil} = 30cm$

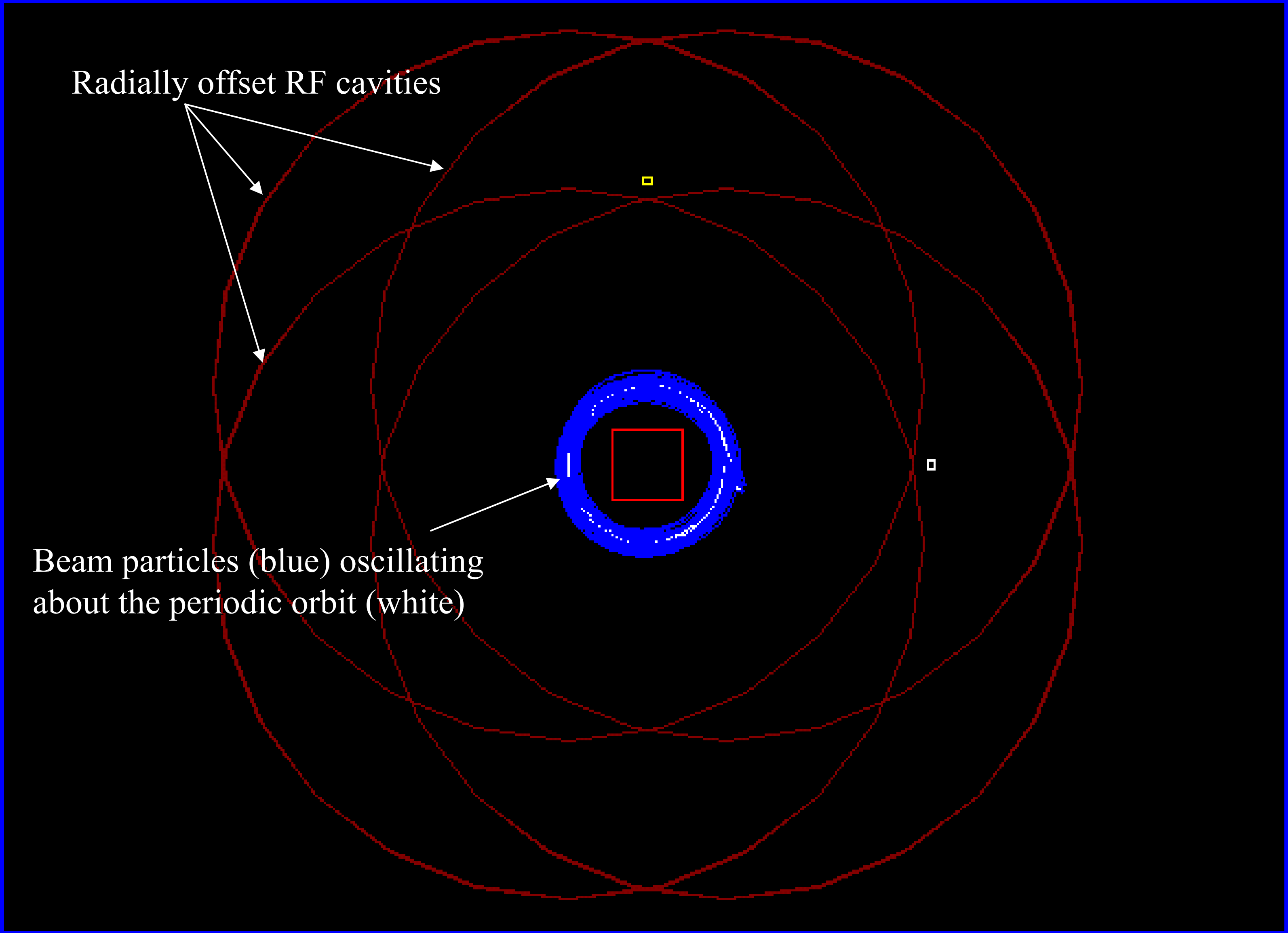


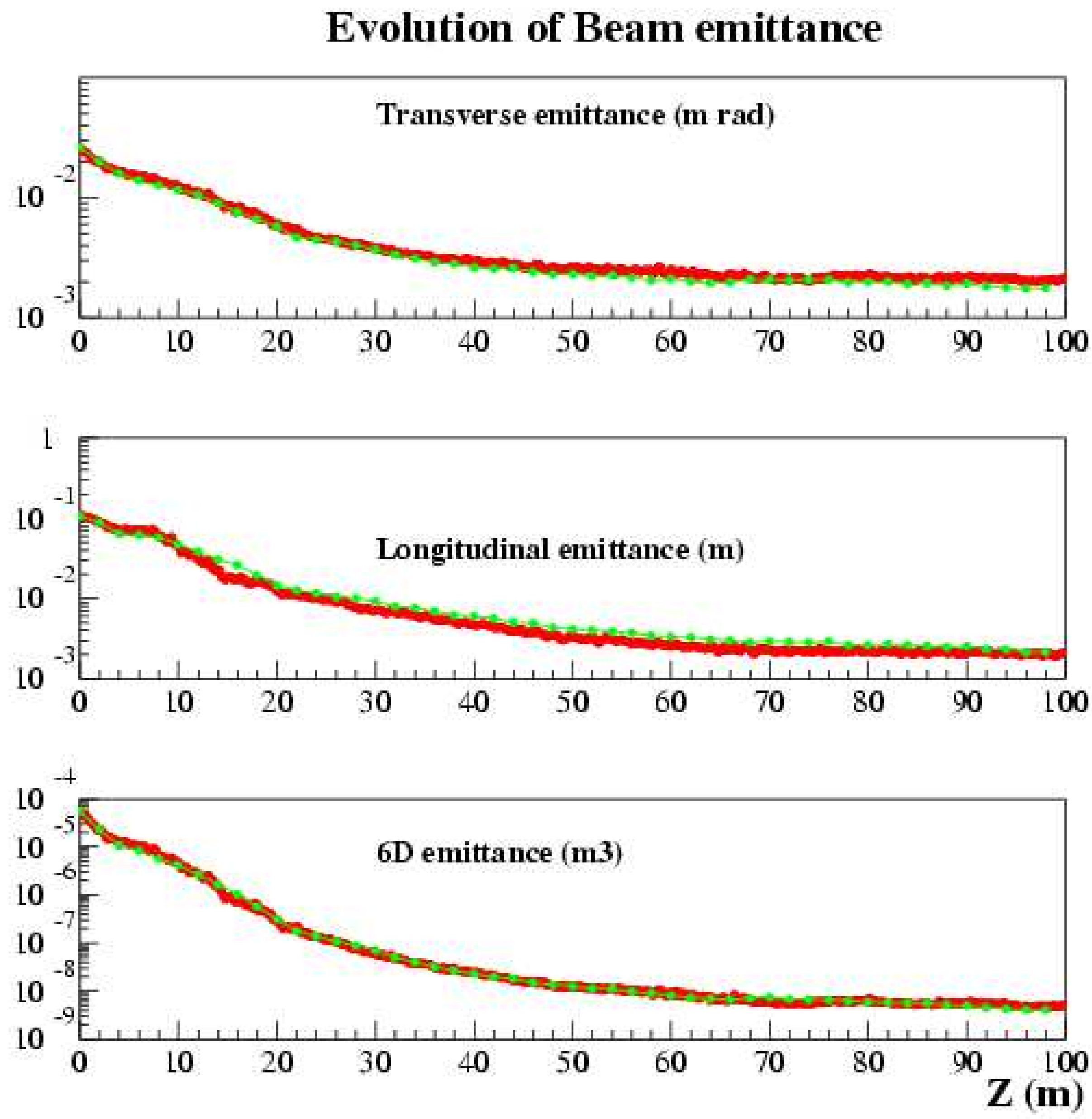
Helical Cooling Channel. Derbenev invention of combination of Solenoidal and helical dipole fields for muon cooling with emittance exchange and large acceptance. Well-suited to continuous absorber. Mucool note 284.

G4BL 10 m helical cooling channel



G4BL End view of 200MeV HCC




Evolution of Beam emittance
Transverse emittance (m rad)
Longitudinal emittance (m)
6D emittance (m3)
Z (m)
0
10
20
30
40
50
60
70
80
90
100
10^-2
10^-3
1
10^-1
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9

Comments on 6D cooling project

- Analytic description essential to guiding simulation effort (see Derbenev et al.)
- Latest simulation results:
- First of 3 or 4 segments (200 MHz), MF5000
    - Study of other segments and matching between them next
  - Addressing RF and SC magnet realism
  - Match to RF capture, precooling sections
    - Can we use higher frequency RF for first HCC section?

Project 3 Cryogenic Pulse Compressors Ph I, Dave Finley, Fermilab

These are seven foot diameter spheres for 200 MHz

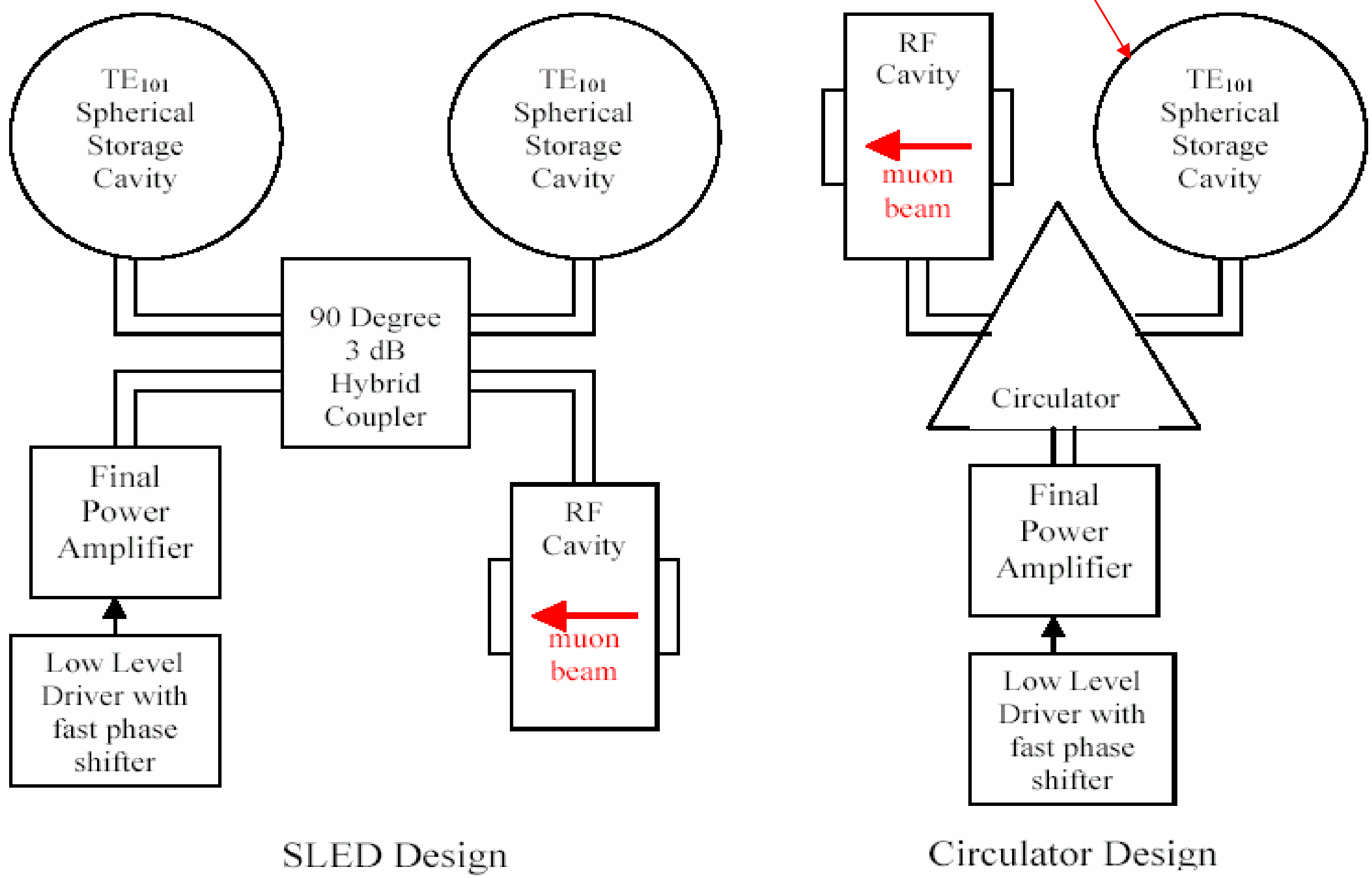


Figure 1. A comparison of the SLED and Circulator designs.

Status of Cryogenic Pulse Compressor Project

- Principles developed for >50 MV/m @200MHz
  - Two compression schemes to get power compression by a factor of 7, or voltage by SQRT(7)=2.65
  - Cold RF increases voltage by (resistivity ratio)$^{1/4}$=1.68
  - Voltage thus increased by (4.45 * 15) = 66.7 MV/m

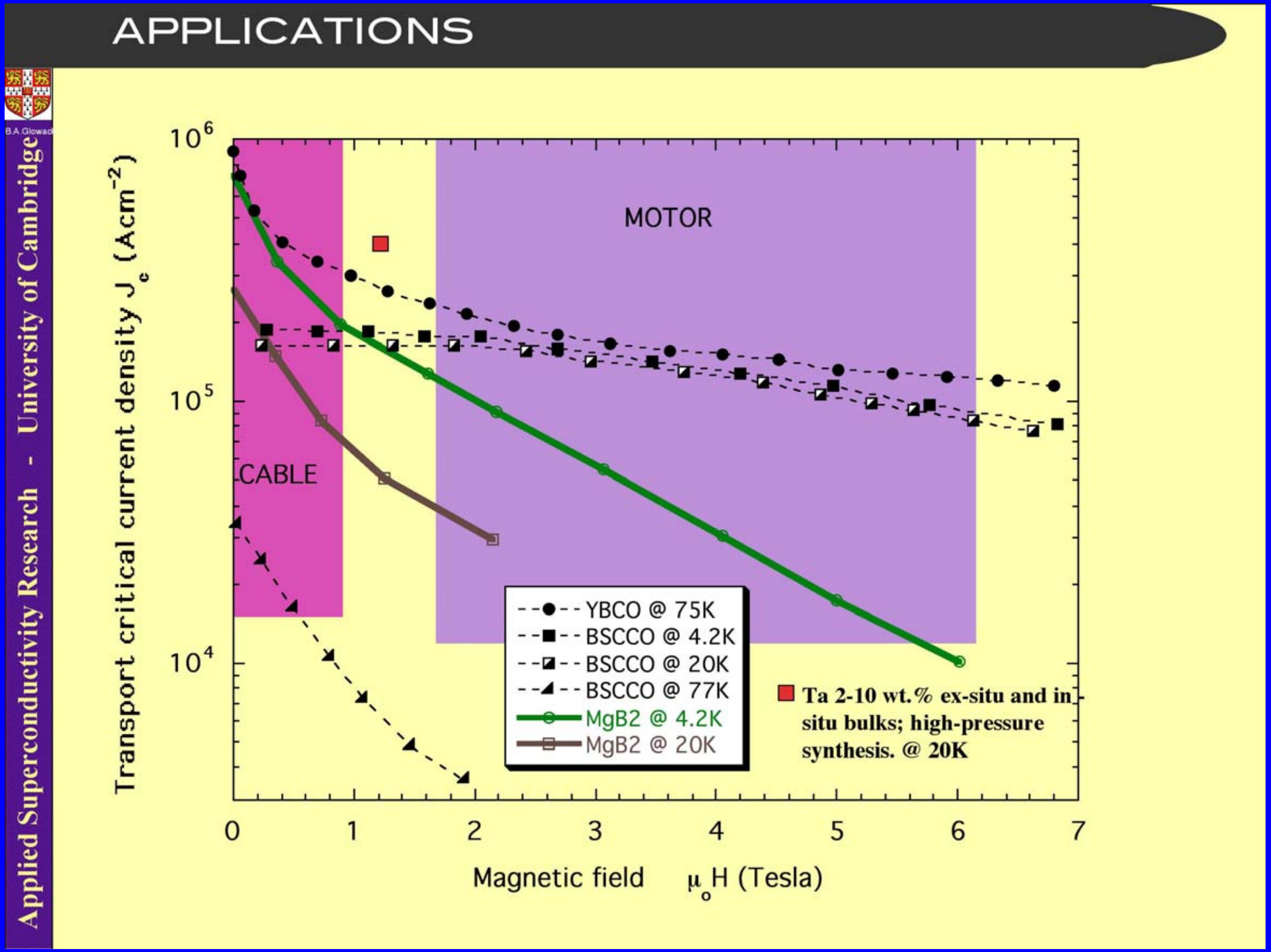
New 2004 Project!!

Hydrogen Cryostat

w Victor Yarba, Fermilab

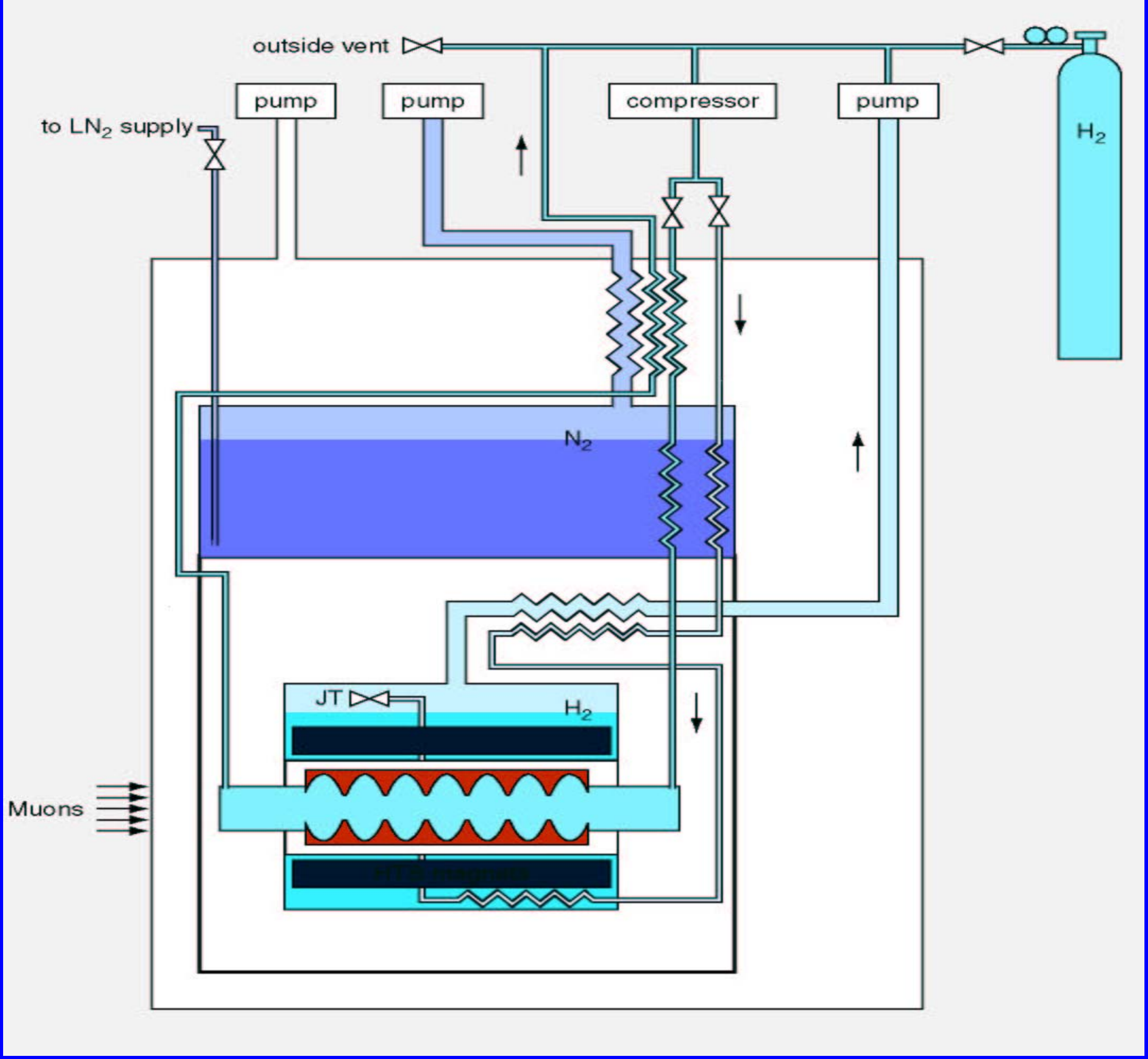
- simultaneously refrigerate
  - 1) HTS magnet coils
  - 2) cold copper RF cavities
  - 3) hydrogen gas heated by the muon beam
- extend use of hydrogen to that of refrigerant
  - besides breakdown suppressant and energy absorber
  - large amount of hydrogen for IC anyway
- relevance for hydrogen economy?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

HTSC I, B, T



APPLICATIONS
B.A.Glowacki
Applied Superconductivity Research - University of Cambridge
Transport critical current density J_c (Acm^{-2})
Magnetic field $\mu_o H$ (Tesla)
CABLE
MOTOR
YBCO @ 75K
BSCCO @ 4.2K
BSCCO @ 20K
BSCCO @ 77K
MgB2 @ 4.2K
MgB2 @ 20K
Ta 2-10 wt.% ex-situ and in-situ bulks; high-pressure synthesis. @ 20K

Hydrogen Cryostat



New 2004 Project!!

MANX

Muon Collider And Neutrino Factory eXperiment

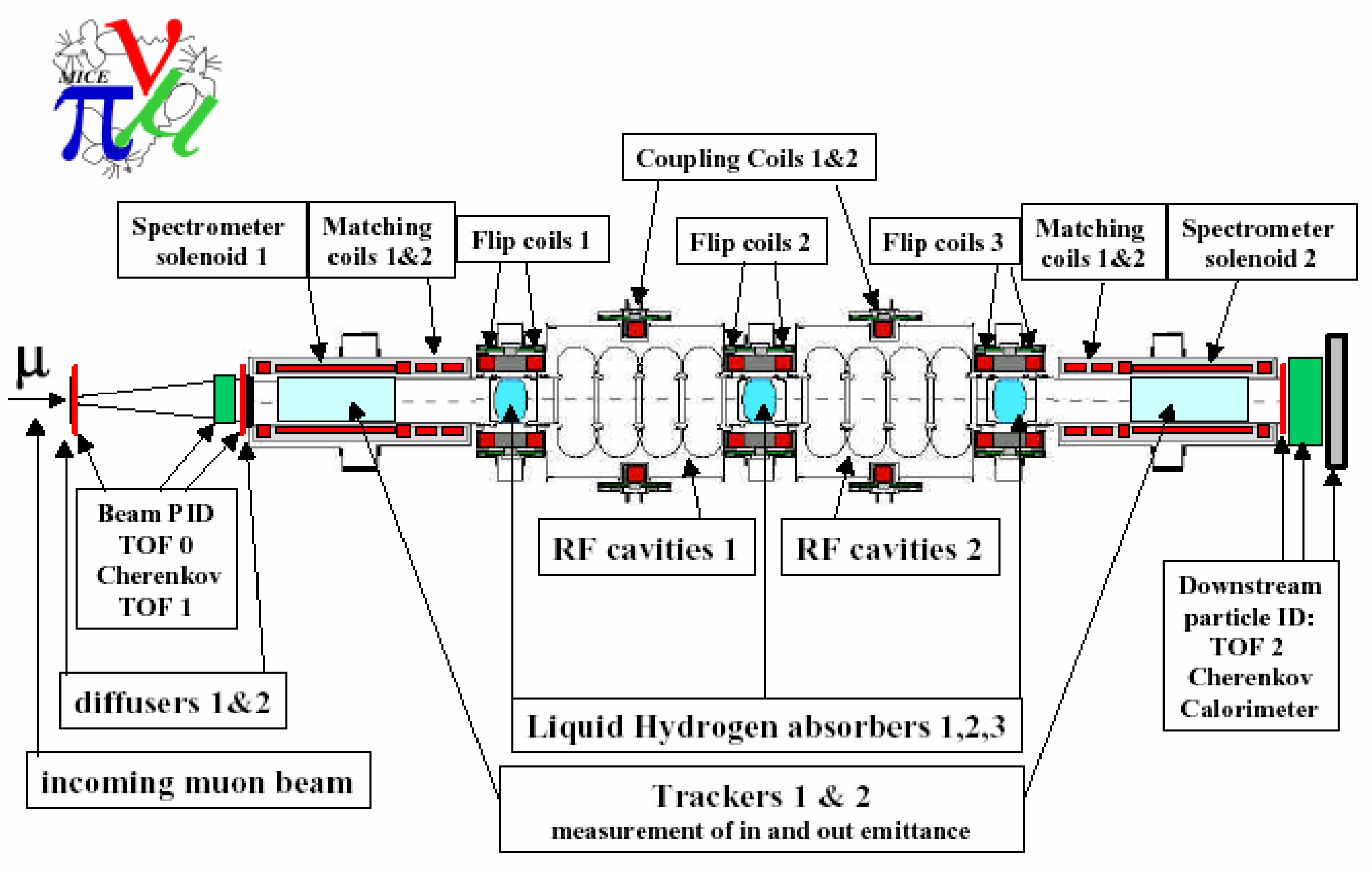
Ph I, w Victor Yarba, Fermilab

- Hi-Pressure GH2
- Continuous Absorber
- Continuous low-β
  - Single-flip Solenoids
- Internal Scifi detectors
  - Minimal scattering
- MANX follows MICE
  - Engineering proof

MANX comparison to MICE

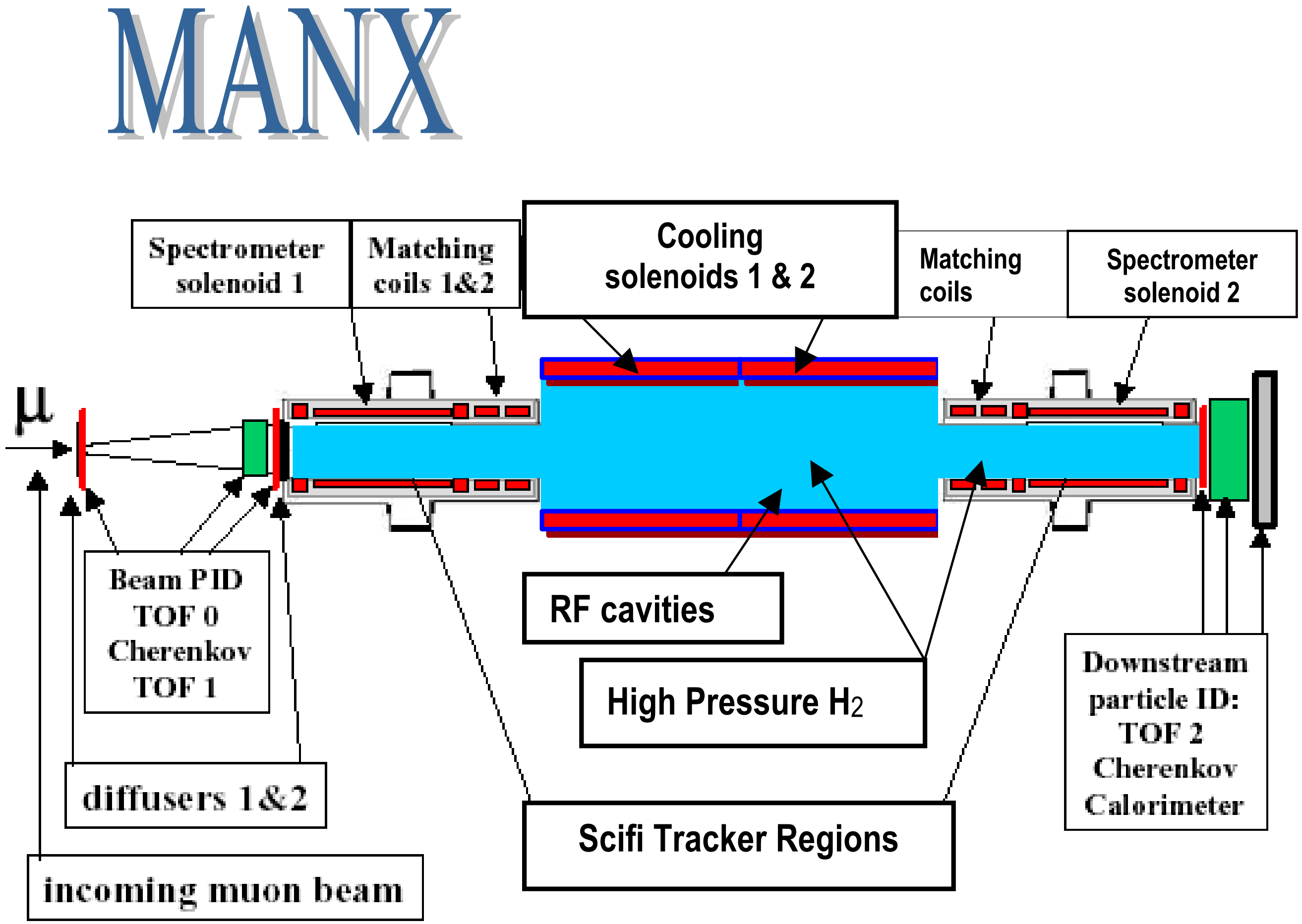
- Conventional LH2 cooling channel
  - Liquid hydrogen absorbers between RF cavities
  - Placed at low β locations, where solenoidal fields change direction
- Proposed GH2 cooling channel
  - Continuous dense hydrogen absorber fills RF cavities
  - Low β is continuous along channel

MICE



MICE
μ
Coupling Coils 1&2
Spectrometer solenoid 1
Matching coils 1&2
Flip coils 1
Flip coils 2
Flip coils 3
Matching coils 1&2
Spectrometer solenoid 2
Beam PID
TOF 0
Cherenkov
TOF 1
RF cavities 1
RF cavities 2
Downstream particle ID:
TOF 2
Cherenkov
Calorimeter
diffusers 1&2
Liquid Hydrogen absorbers 1,2,3
incoming muon beam
Trackers 1 & 2
measurement of in and out emittance

MANX is GH2 version of MICE



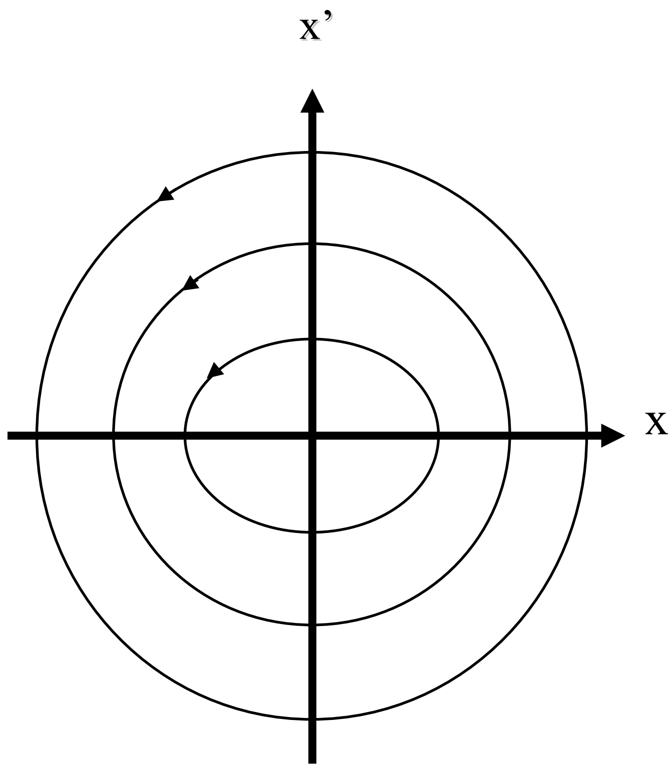
New 2004 Project!!

Phase 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



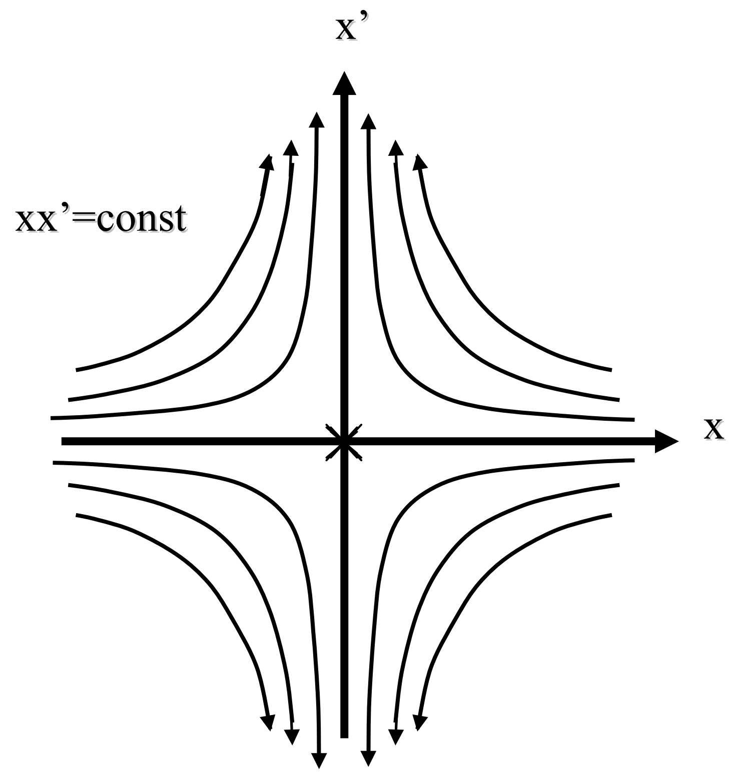
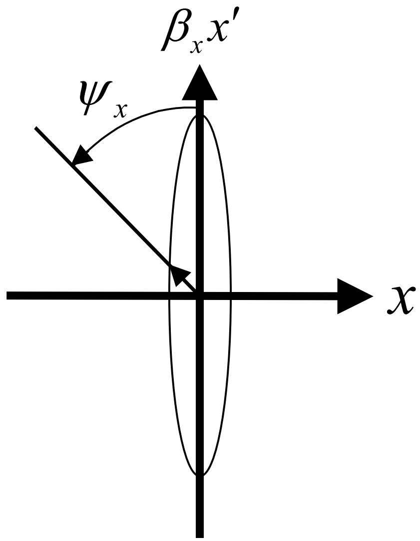
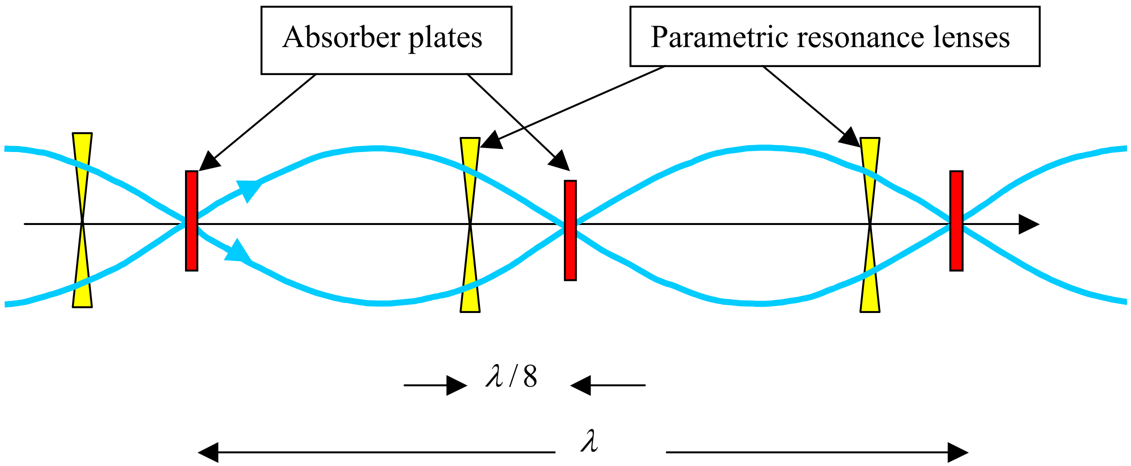


Fig. 3 Phase space compression. The spread in x diminishes due to the parametric resonance motion while the spread in x' diminishes due to ionization cooling. The area of the occupied phase space ellipse is reduced as the particles are restricted to a narrow range of phase angle, psi.



PIC concept first appears in our 2004 SBIR proposal! First paper EPAC2004, YD,RJ.

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.

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:
  - HCC Magnets with BNL
  - RevEmEx with Jlab
  - G4BL with IIT
  - Muon Precooling, bunching with Fermilab

REMEX starting point.
Basic 6D Cooling;
Estimated final parameters of a helical 6D cooling channel

Parameter	*Unit*	*equilibrium rms value*
Beam momentum, *p*	MeV/c	100
Synchrotron emittance,	µm	300
Relative momentum spread	%	2
Beam width due to d*p/p*	mm	1.5
Bunch length	mm	11
Transverse emittances,	mm-mr	100/300
Beam widths,	mm	4.5/2.8

Figure 1. Emittance Exchange

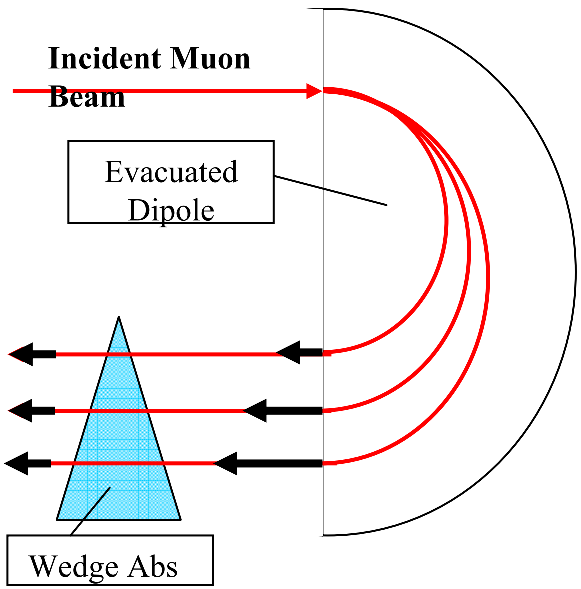


Figure 2. Reverse Emittance Exchange

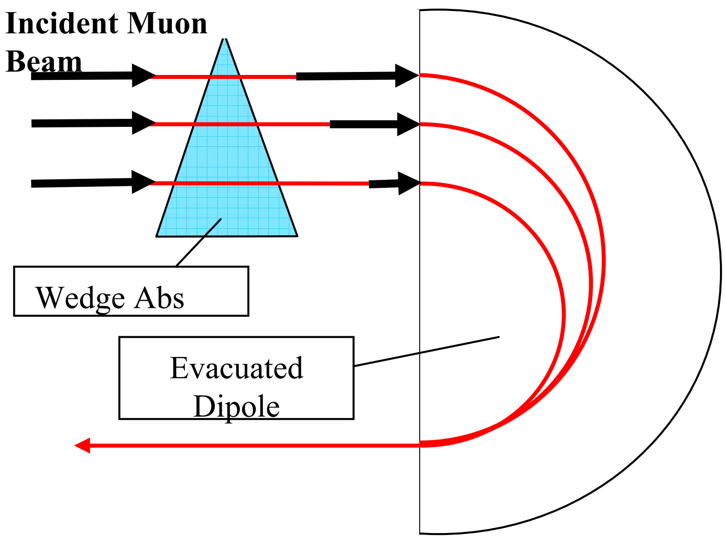


Figure 1. Conceptual diagram of the usual mechanism for reducing the energy spread in a muon beam by emittance exchange. An incident beam with small transverse emittance but large momentum spread (indicated by black arrows) enters a dipole magnetic field. The dispersion of the beam generated by the dipole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

Smaller ε_T means fewer μ

$$\mathcal{L} \approx \frac{N_{\mu^+} N_{\mu^-}}{\beta_\perp \varepsilon_N}$$

Factor of 100 lower emittance means factor 10 fewer muons needed.
Then, proton driver needs 400kW, not 4MW on target (new Linac * MI)
Neutrino radiation problem reduced.
Detector backgrounds reduced.
Take advantage of $(m_\mu/m_e)^2$=40,000 s-channel Higgs production cross-section.
Needs Booster sized ring.

After the Higgs factory, the next step is an energy frontier muon collider using Tesla cavities (perhaps with recirculation) to feed a 2 (or more) TeV ring.

GOAL: Higgs Factory at Fermilab using new muon beam cooling ideas

- μ cooling technique
  - Initial Precooling implies
  - 6D cooling in helix
    - Needs HPRF
  - Parametric resonance Ionization Cooling
  - Reverse emittance exchange (next SBIR proposal)

- ε_N transverse (mm-mr)

  10^4

  10^2 (usual IC limit)

  6D cooling is 10^6

  10

  1

Summary

- Take advantage of unique properties of muons
  - Pressurized RF Cavities
  - 6D Cooling with homogeneous absorber
    - May make Muon Collider possible
    - Less expensive acceleration for Neutrino Factory
- Once 6D cooling is achieved, use other tricks
  - Parametric Resonance Ionization Cooling
  - Reverse Emittance Exchange
- Is a Higgs Factory an intermediate step to an Energy Frontier Muon Collider?