Muons, Inc. Status: Six SBIR/STTR Projects

Rolland Johnson, Jan 30, 2004

- HP HG GH2 RF
  - Ph II, w IIT, DK
- 6D Cooling on Helix
  - Ph I, w Jlab, YD
- Pulse Compression
  - Awarded, abandoned
- MANX
  - Proposed w FNAL, DF
- H2 Cryostat
  - Proposed w FNAL, DF
- PIC
  - Proposed w Jlab, YD

Thanks to Excellent Collaborators

- IIT; Dan Kaplan, Katsuya Yonehara, Mohammad Alsharo’a
- JLab; Slava Derbenev, Alex Bogacz, Kevin Beard
- Fermilab; Chuck Ankenbrandt, Al Moretti, Milorad Popovic, Dave Finley, Victor Yarba
- Employees; Bob Hartline, Moyses Kuchnir

Project 1: HP HV RF Cavities Ph II, Dan Kaplan, IIT

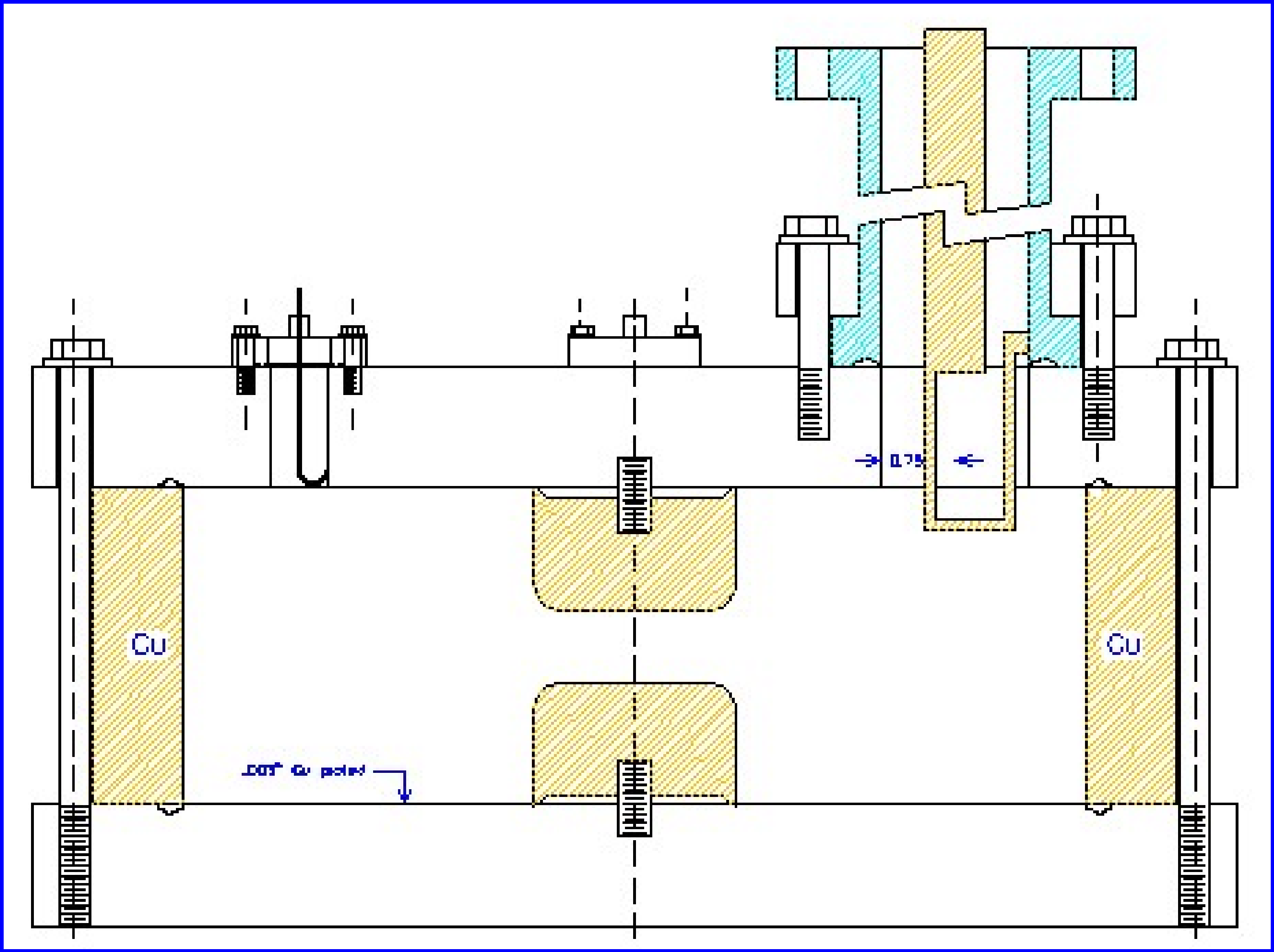
- Dense GH_2 suppresses high-voltage breakdown
  - Small MFP inhibits avalanches (**Paschen's Law**)
- Gas acts as an energy absorber
  - Needed for ionization cooling
- Only works for muons
  - No strong interaction scattering like protons
  - More massive than electrons so no showers

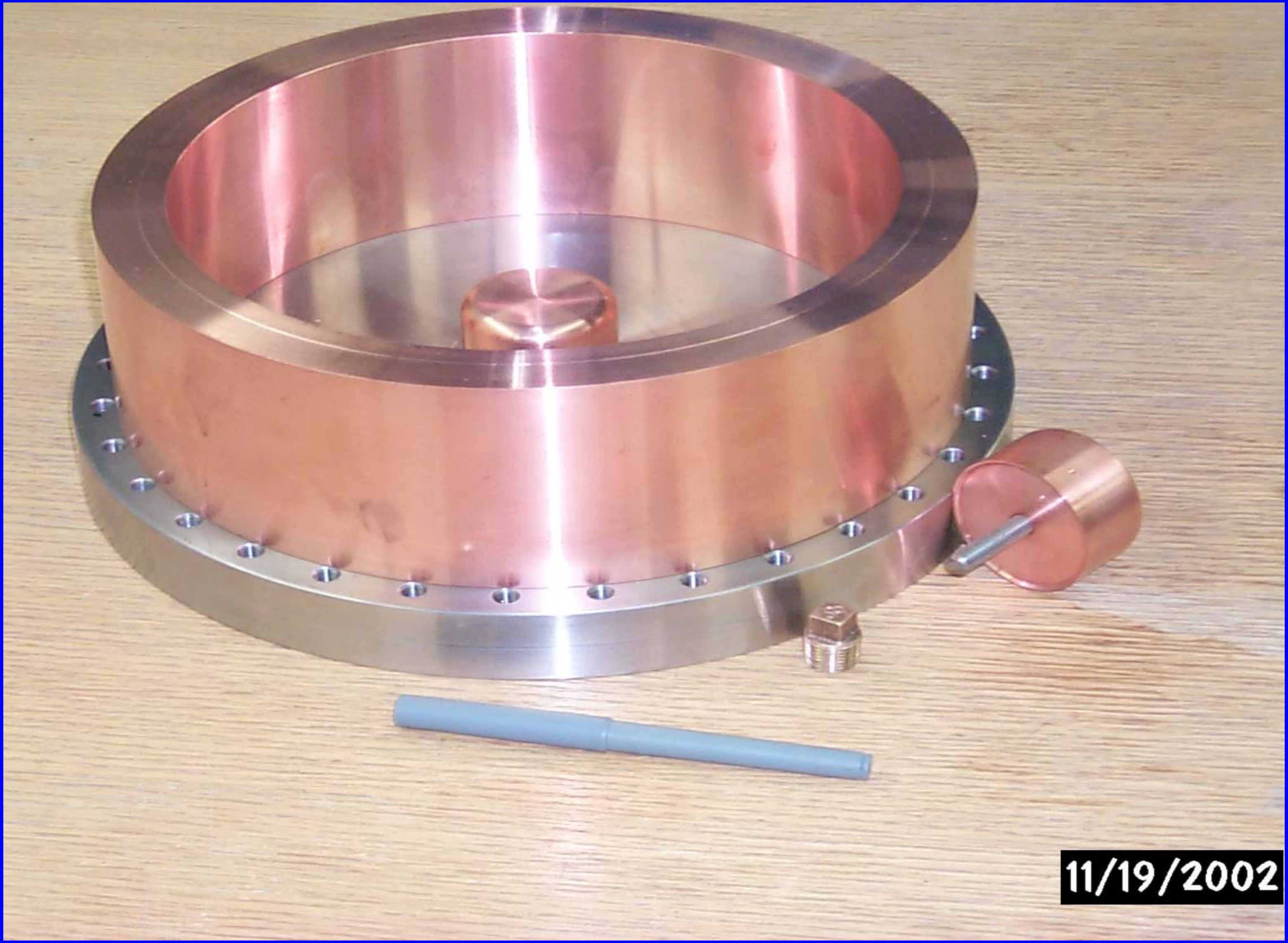
2002 STTR Phase I Project

To build an RF test cell for testing breakdown characteristics of gases for ionization cooling.

For use in Phase II for the exploration of Paschen's Law, relating breakdown voltages to gas density, over a range of temperatures, pressures, external magnetic fields, and ionizing particle radiation at Lab G and the Linac Test Area.

First 805 MHz RF test cell




11/19/2002

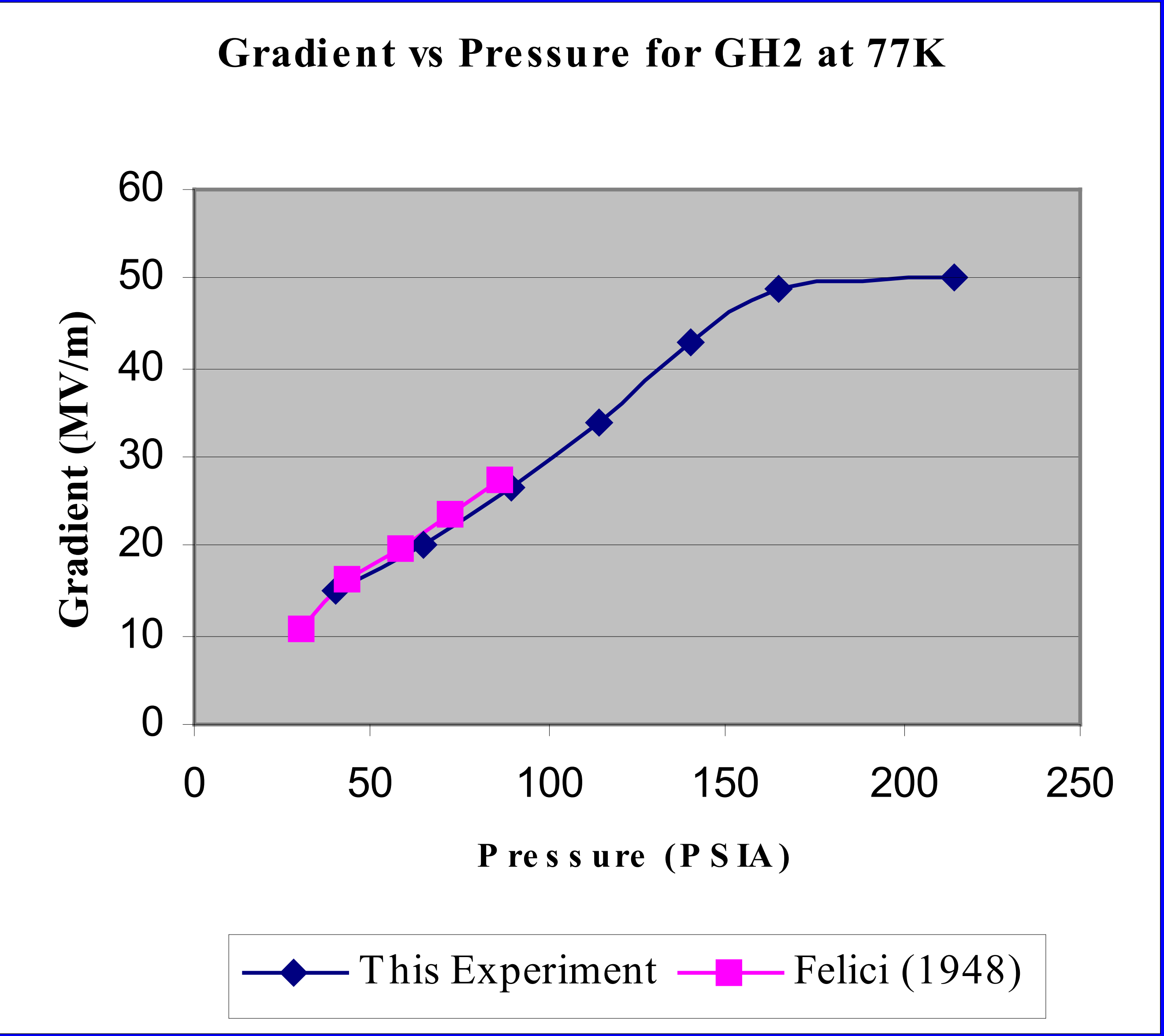

HOT
9/4/2002


10/11/2002


HANDLE WITH CARE
DELICATE
INSTRUMENTS
FRAGILE
10/13/2002


4/9/2003

April 2003, copper electrodes, first test cell. Published in PAC2003.



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

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

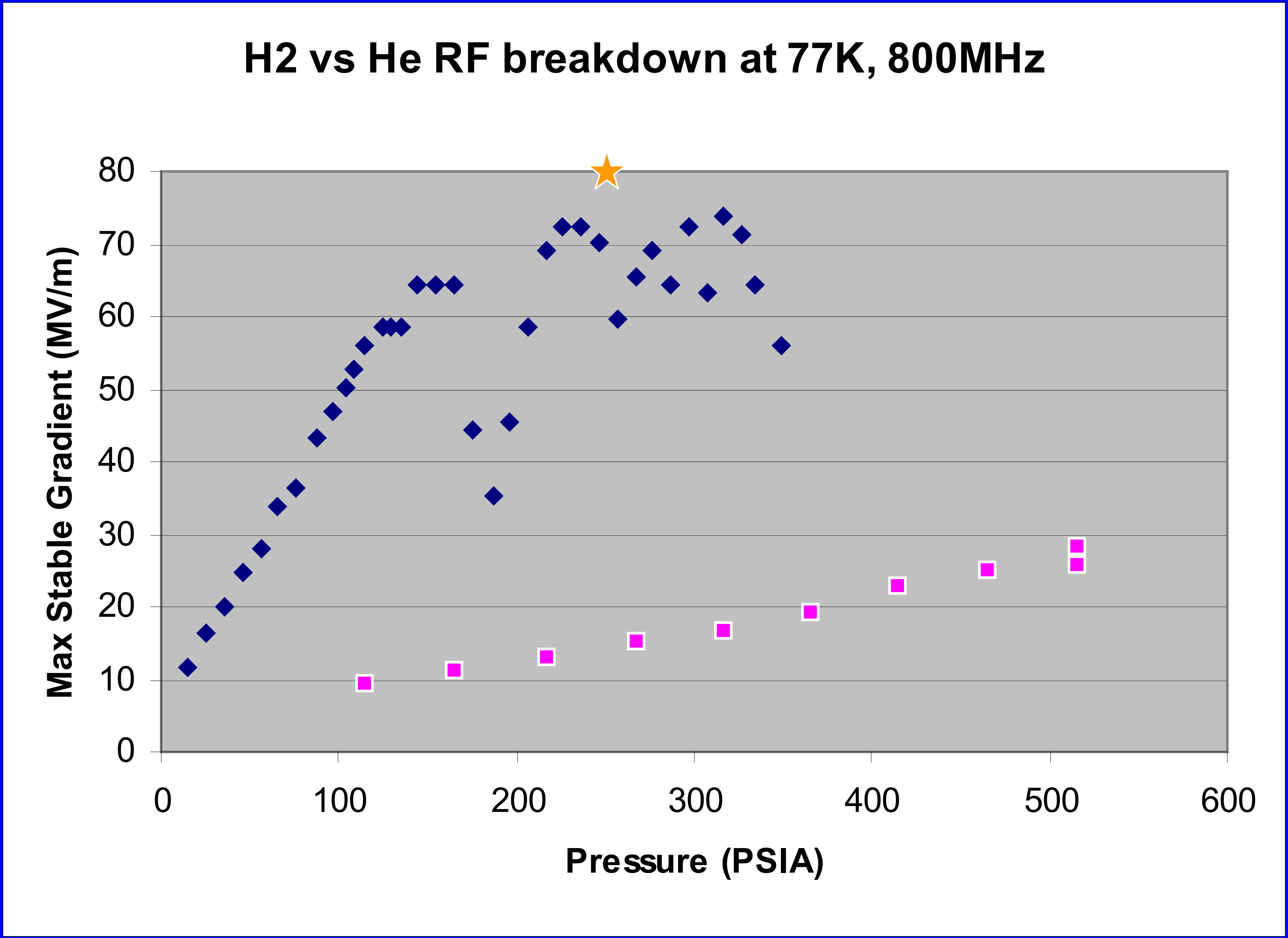
C. M. Ankenbrandt, A. Moretti, M. Popovic
Fermilab

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

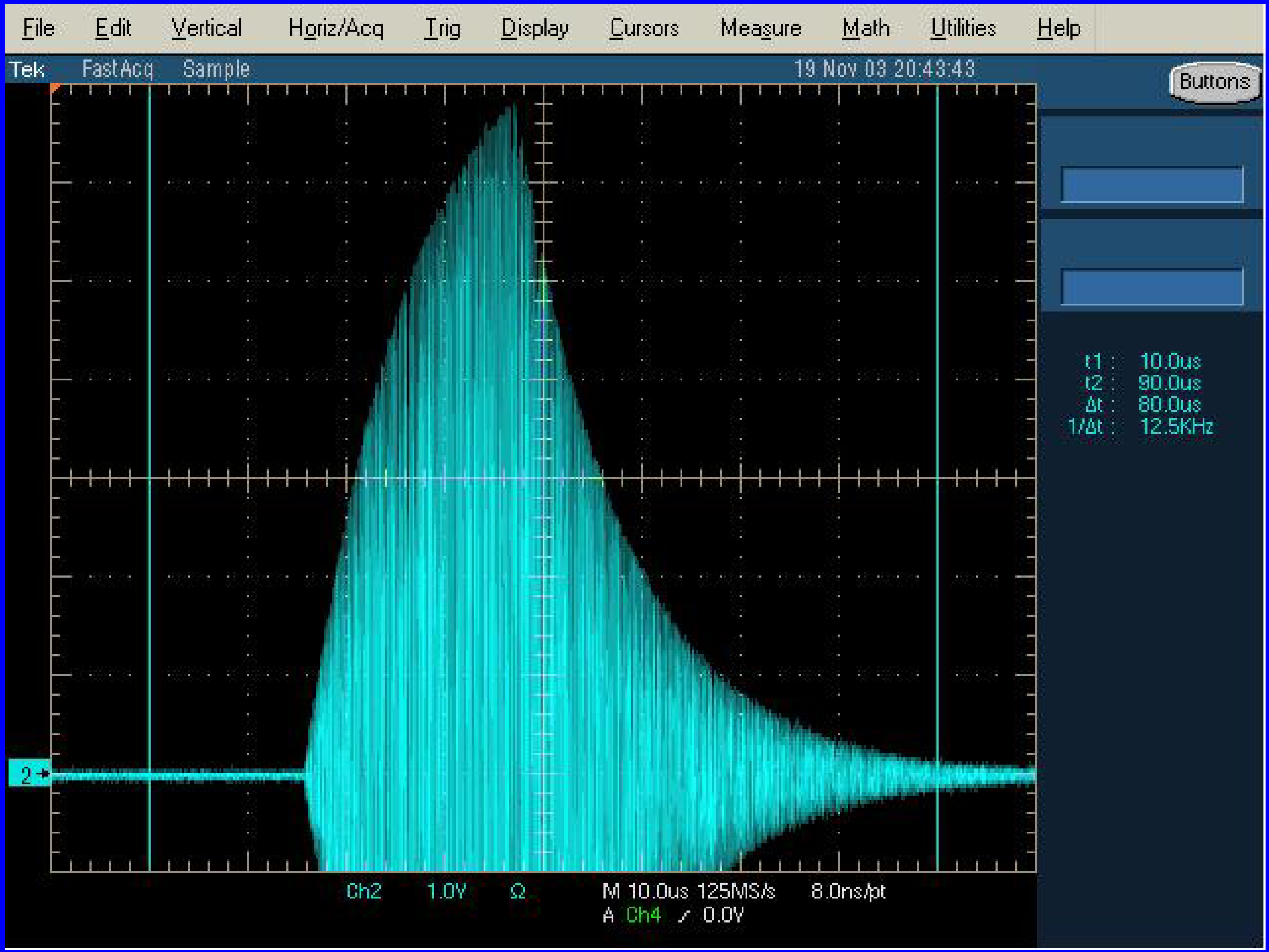
See MuCool Note 285 for paper

New TC; 2000PSI @ 77K

11/19/03 Lab G Results, Molybdenum Electrodes



Mark II Lab G at 80 MV/m




9/17/2003

Study of RF Breakdown in Gases

- Origin of plasma physics ('40-'60)
  - Pressurized coaxial RF transmission lines
- Properties of gases
  - First Townsend Coefficient
- Properties of metallic electrodes
  - Second Townsend Coefficient
- Gas as another variable
  - to investigate metallic breakdown mechanisms

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
- Studying RF breakdown with copper, molybdenum, and chromium electrodes
- Planning Test Cell for Operation in the LBL 5 T solenoid at 1600 PSI and 77K
- Ensure MUCOOL Test Area Beam Line is available in 2005

Project 2, with JLab, Derbenev Emittance Exchange With GH2

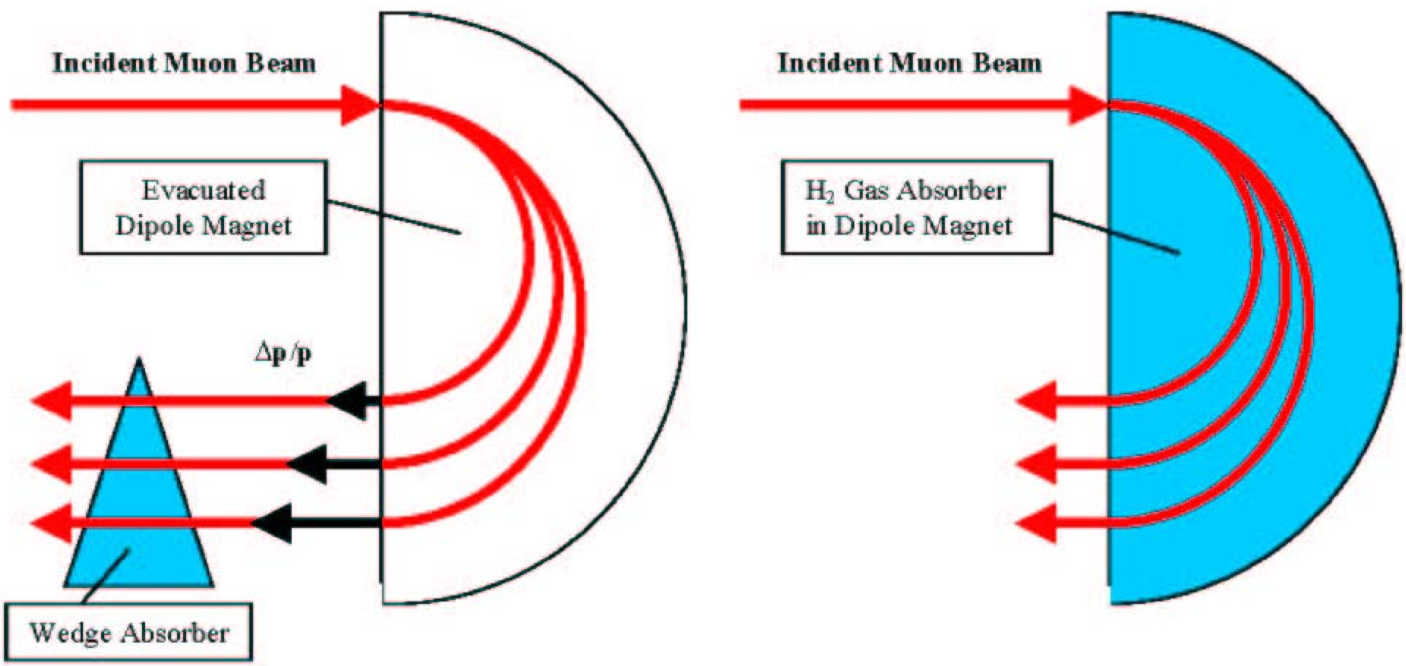


Figure 1. Use of a Wedge Absorber for Emittance Exchange

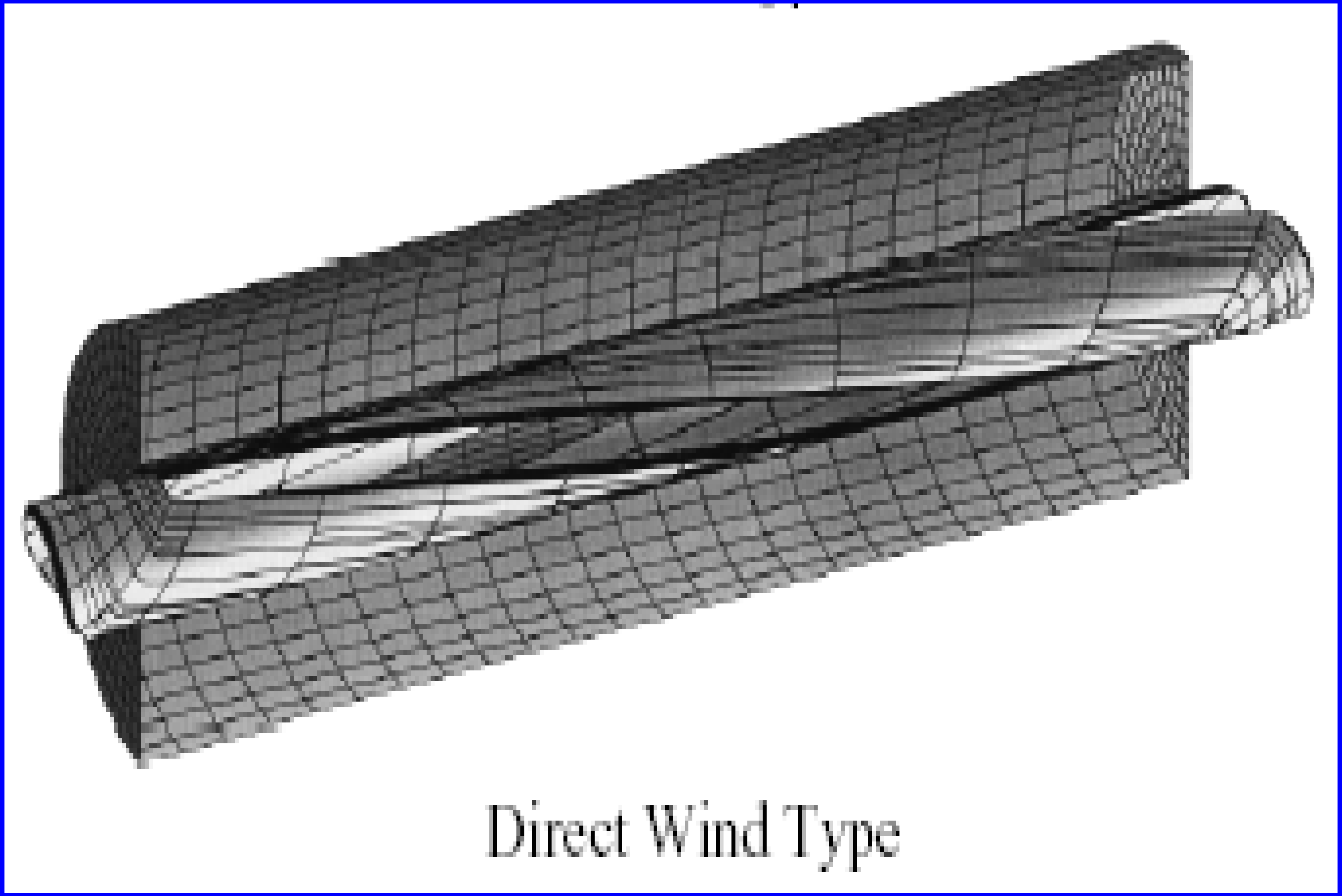
Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

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

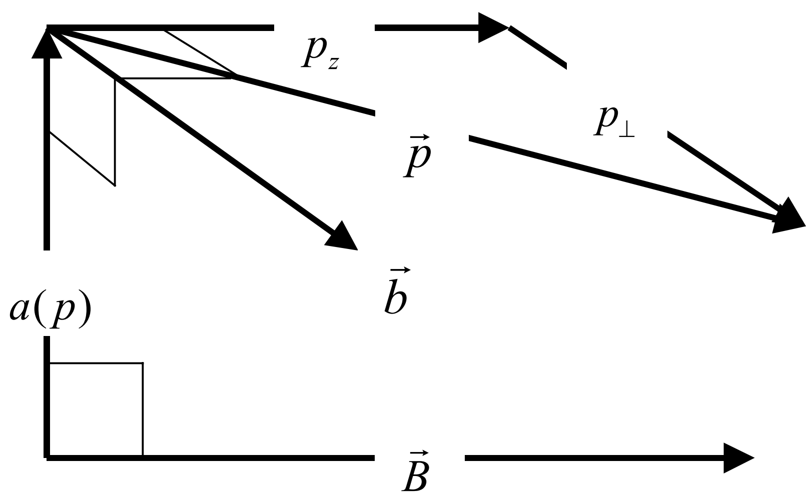
6D Cooling with GH2

- Derbenev channel: Solenoid plus transverse helical dipole and quadrupole fields
- Analytically predict exceptional 6D cooling
  - MC284 (submitted to PRSTAB)
- Avoids ring problems
  - Injection and Extraction simpler
  - No Multi-pass Beam loading or Absorber heating
  - Can adjust channel parameters as beam cools

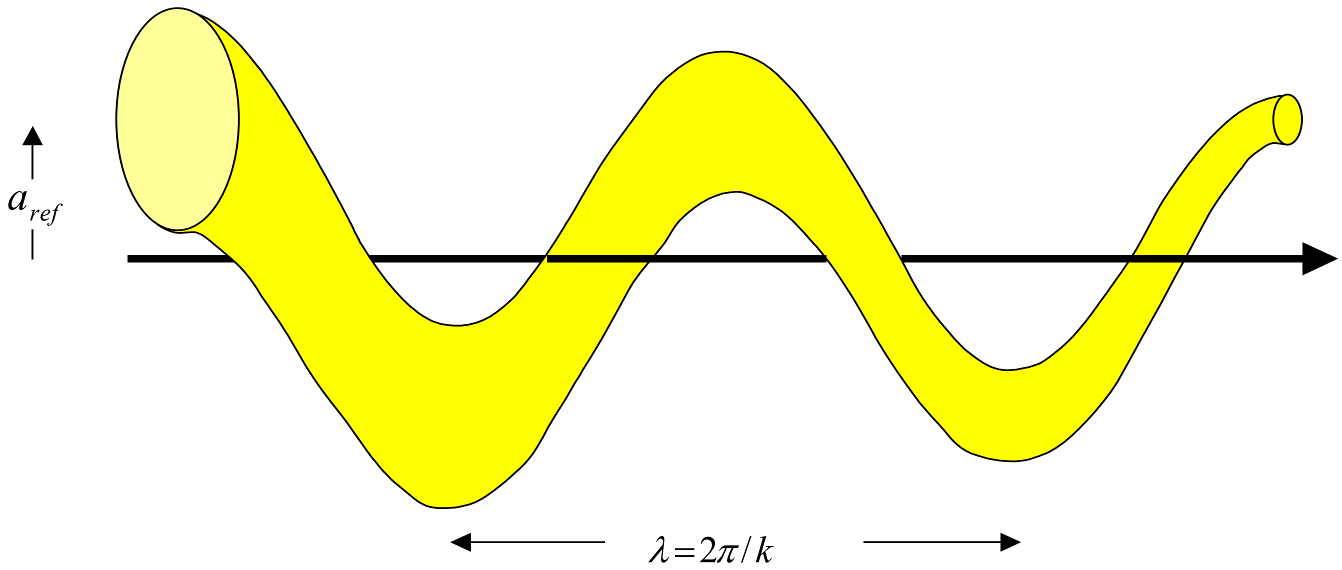
Helical Dipole Magnet (c.f. Erich Willen at BNL)



Particle momentum in a helical dipole and solenoidal field



Helical channel beam envelope



Note that the helical channel is not like an alternating solenoidal transverse cooling channel.

More like a synchrotron with tune-sensitive behavior, requiring careful injection matching.

Transverse Field Harmonics

the rate the dipole is twisted in turns/m and we **define *k* = 2*π* turns/m**

$$B_\varphi \propto \cos \ell(\varphi - kz),\ \ell = 1, 2, 3, 4....,$$

$$B_\rho \propto \sin \ell(\varphi - kz)$$

$$B_Z = -k\rho B_\varphi$$

$$x + iy = \rho e^{i(\varphi - kz)}$$

Periodic Orbit Solution

$$\kappa = \left[\frac{p_\perp}{p_Z} \right] = ka = \frac{1+\kappa^2}{k - k_C} \frac{B_\varphi}{p_Z}$$

where $e = c = 1$,

$$k_C = B_S / p_Z$$

$$p / p_Z = \sqrt{1+\kappa^2}$$

Translational Mobility, η

$$\eta = \frac{d}{d\gamma}\frac{1}{\beta_Z} = \frac{\sqrt{1+\kappa^2}}{\gamma\beta^3}\left(\frac{1}{\gamma_{tr}^2} - \frac{1}{\gamma^2}\right)$$

, where

$$\gamma_{tr}^2 \equiv \frac{1+\kappa^2}{\kappa^2}\hat{D}^{-1}$$

Cooling Decrements

$$\Lambda_6 = \Lambda_\gamma + \Lambda_2 + \Lambda_3 = 2\left(\frac{dE}{dz}\right) / \gamma mc^2$$

$$\Lambda_\gamma = \frac{dE/dz}{\gamma\, mc^2 \beta^2}\left[-\frac{2}{\gamma^2} + \hat{D}\frac{\kappa^2}{1+\kappa^2}\right]$$

Equal Decrements

Equating the three decrements leads to two conditions:

$$\hat{D} = \frac{2\left(1+\kappa^2\right)}{\kappa^2}\left(1-\frac{2}{3}\beta^2\right)$$

and, as follows from formulae for transverse decrements in reference [9],

$$\frac{k_C}{k} = 1 + \sqrt{\frac{\beta^2}{3-\beta^2}\left(1+\kappa^2\right)}$$

Estimated parameters of a helical 6D cooling channel

Parameter	*Unit*	*Initial*	*Middle* ****)	*Final*
Beam momentum,	**MeV/c**	**100**	**100**	**100**
Solenoid field	**T**	**3.5**	**8**	**14**
Helix period	**m**	**1**	**0.44**	**0.22**
Transverse field at beam	**T**	**0.7**	**1.6**	**3.0**
Helix orbit radius	**cm**	**15**	**6**	**3**
Dispersion	**cm**	**37**	**15**	**7.5**
Accelerating RF field	**MV/m**	**40**	**40**	**40**
Frequency	**GHz**	**0.2**	**0.8**	**1.6**
Absorber energy loss rate	**MeV/m**	**14**	**14**	**14**
Synchrotron emittance	**cm**	**1.5**	**0.15**	**3.10^{-2}**
Relative momentum spread	**%**	**7.5**	**3**	**2**
Bunch length	**cm**	**30**	**7.5**	**1.1**
Beam width	**cm**	**3**	**0.56**	**0.15**
Transverse emittances	**cm x rad**	**1.7/1.7**	**0.2/0.2**	**$(1/3)10^{-2}$**

The cooling effect in this calculation in terms of reduction of the 6D emittance is $5x10^5$. The total energy loss in absorber is about 1.12 GeV. For a channel of continuous dense hydrogen gas with 14 MeV/m of energy loss, this implies a 6D cooling channel length, $L = \frac{1.12}{.014} / \sqrt{1+\kappa^2} = 56$ m.

Status of 6D cooling project

- G4Beamline (Tom Roberts, IIT) version of Geant4 has helical channel
  – Modifying C++ code
- Studying helix as precooler (no RF)
- ICOOL has helical channel
  – Will try to understand previous simulations
- Preparing Phase II proposal (April 21,2004)

Cryogenic Pulse Compressor Project Ph I, Dave Finley, Fermilab

These are seven foot diameter spheres for 200 MHz

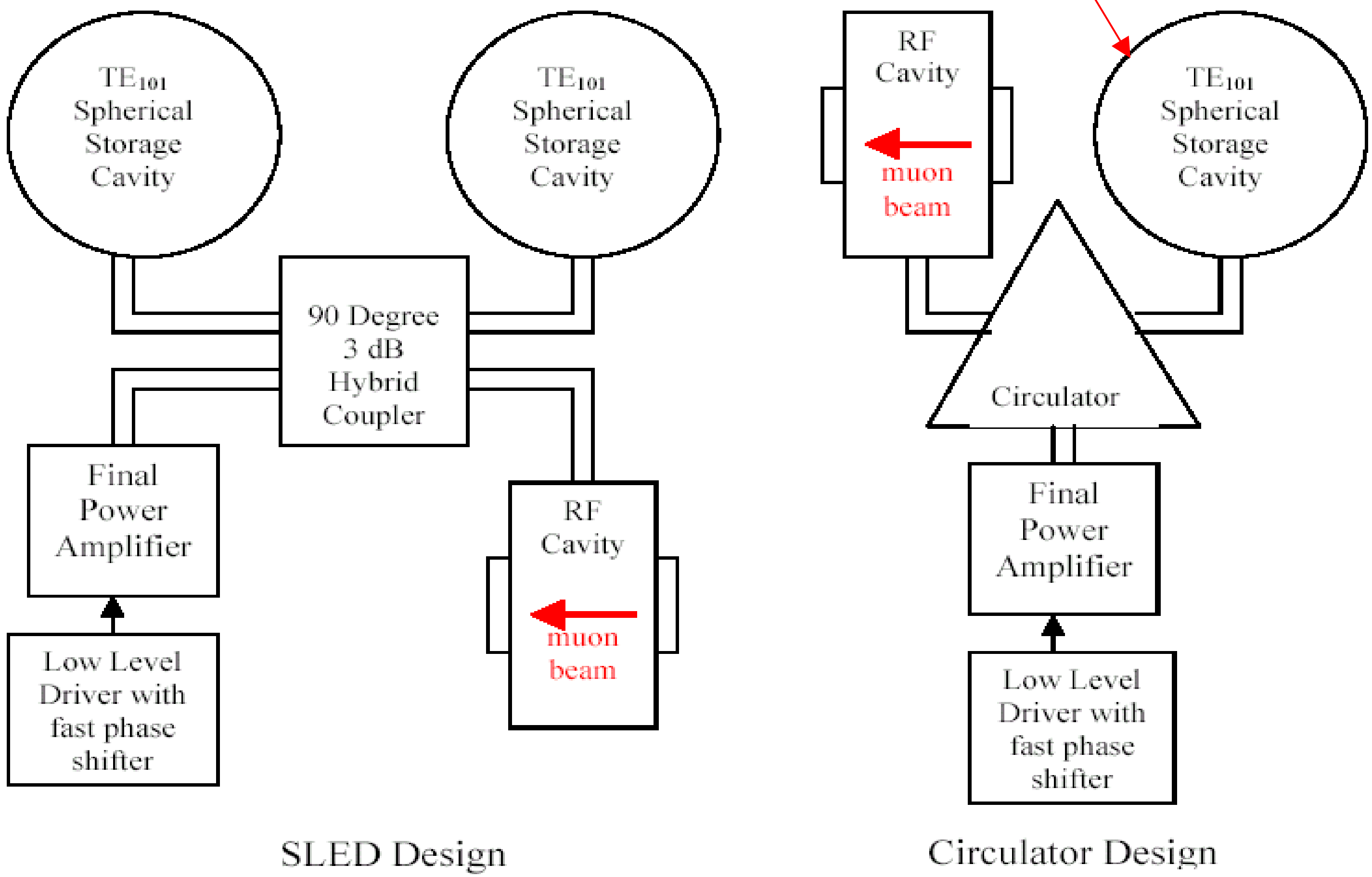


Figure 1. A comparison of the SLED and Circulator designs.

Magic of Pulse Compression

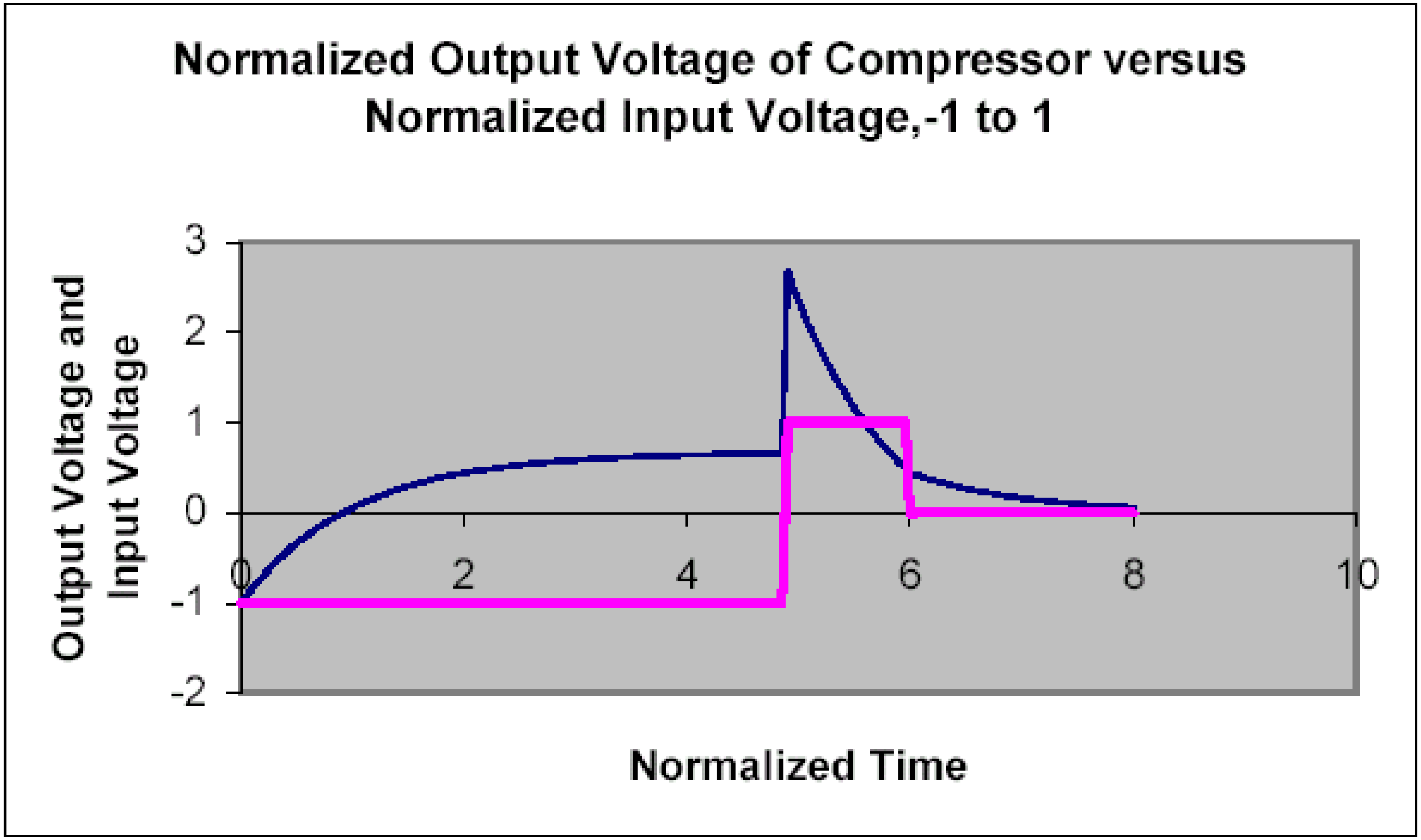


Figure 2. Input and output voltage of a compressor as a function of time.

Status of Cryogenic Pulse Compressor Project

- Phase I grant awarded 5/03, not consummated in good time, abandoned
- 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

Muon Collider And Neutrino Factory eXperiment Proposal

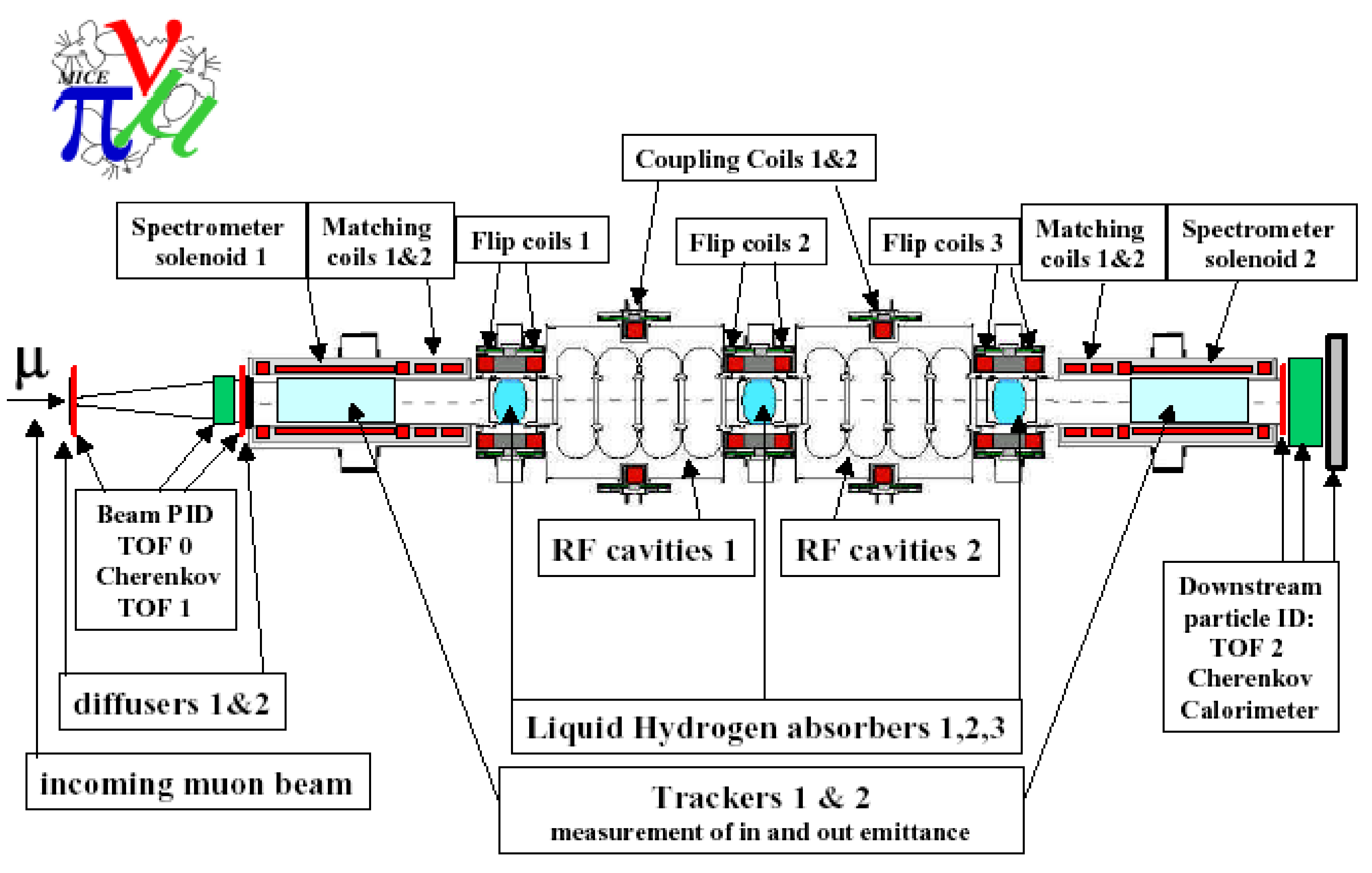
Ph I, Dave Finley, Fermilab

- 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



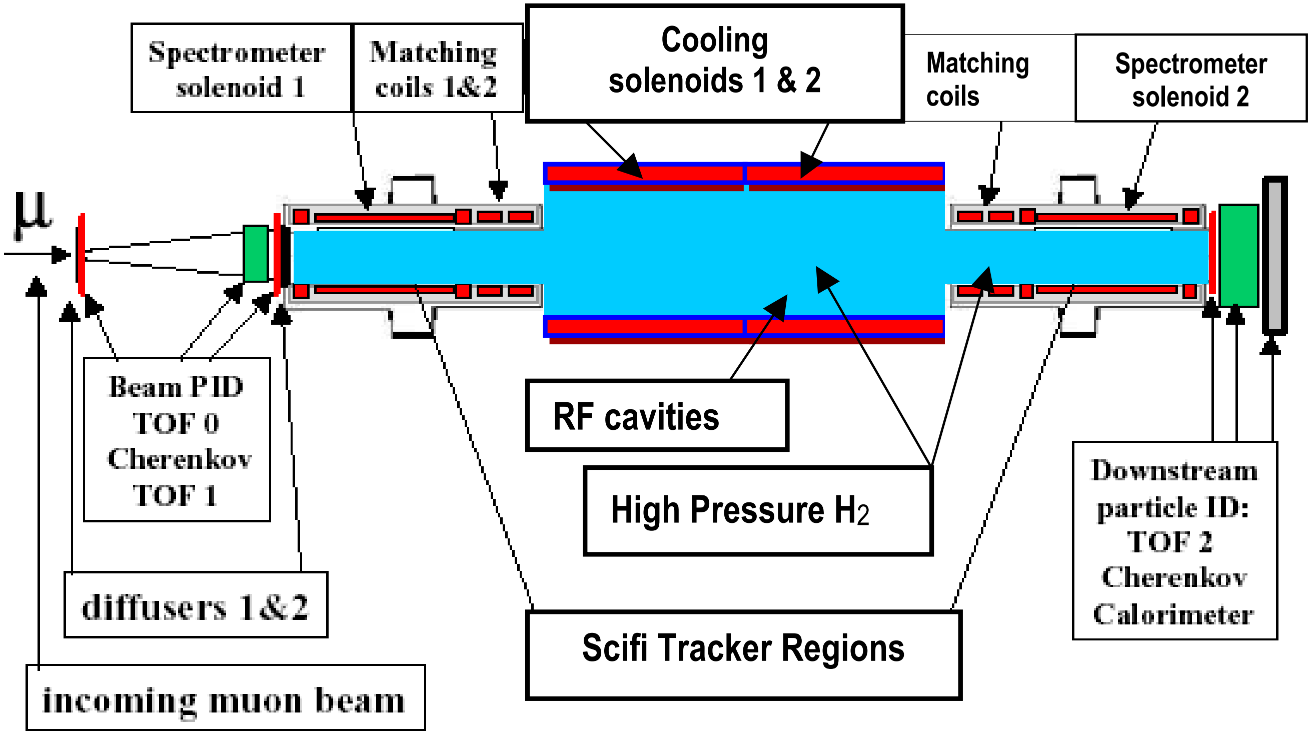
MICE
Coupling Coils 1&2
Spectrometer solenoid 1
Matching coils 1&2
Flip coils 1
Flip coils 2
Flip coils 3
Matching coils 1&2
Spectrometer solenoid 2
μ
Beam PID
TOF 0
Cherenkov
TOF 1
RF cavities 1
RF cavities 2
Downstream particle ID:
TOF 2
Cherenkov
Calorimeter
diffusers 1&2
Liquid Hydrogen absorbers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

MICE changes into MANX

- Continuous GH2 replaces LH2 flasks
  - High density from P and/or T
- Opposing solenoids
  - Simple picture of “single-flip” lattice
- Detectors (scifi) in gas
  - No pressure windows to obscure cooling
- Different hydrogen safety solution

MANX is GH2 version of MICE

MANX

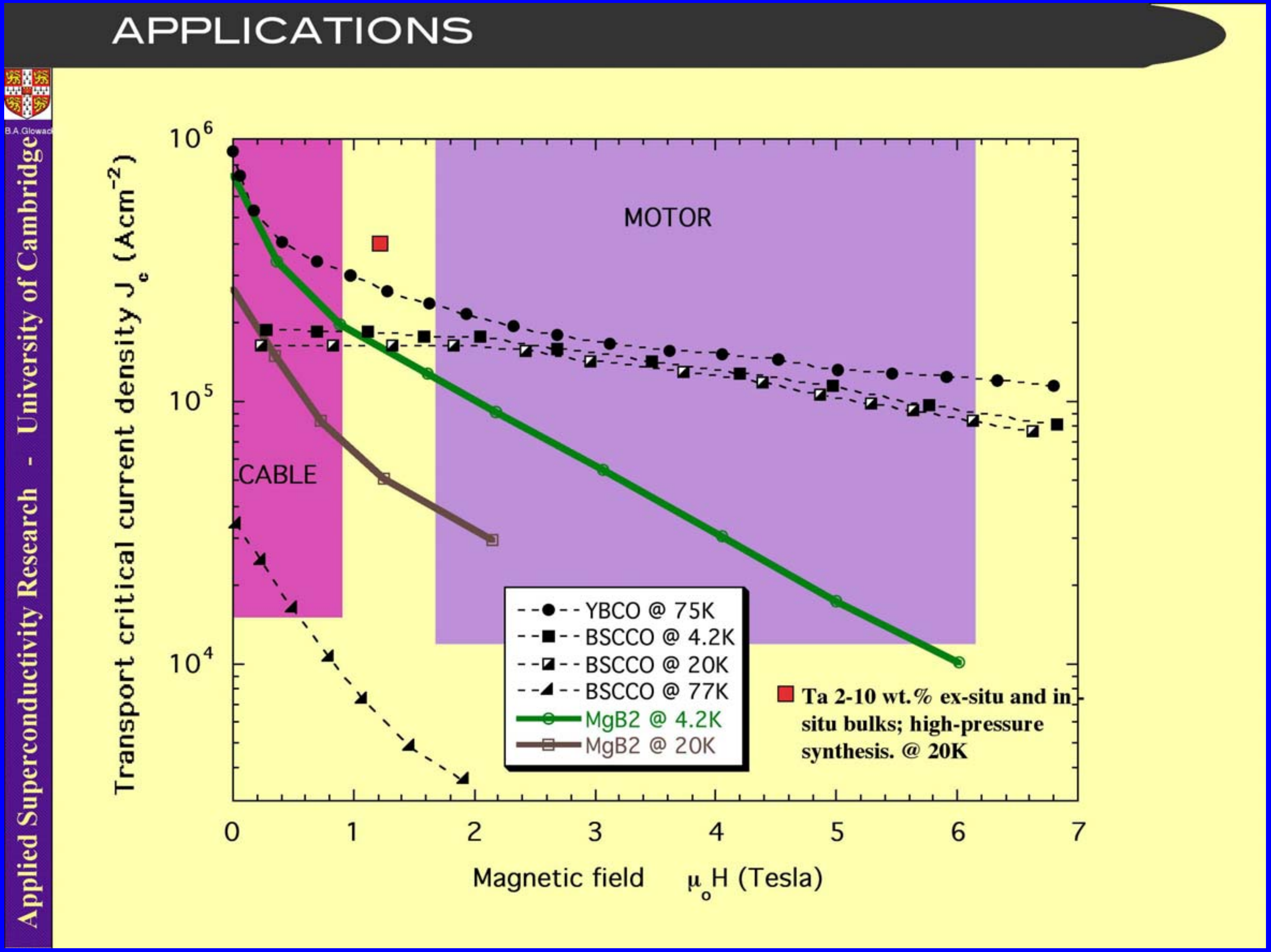


Hydrogen Cryostat Proposal

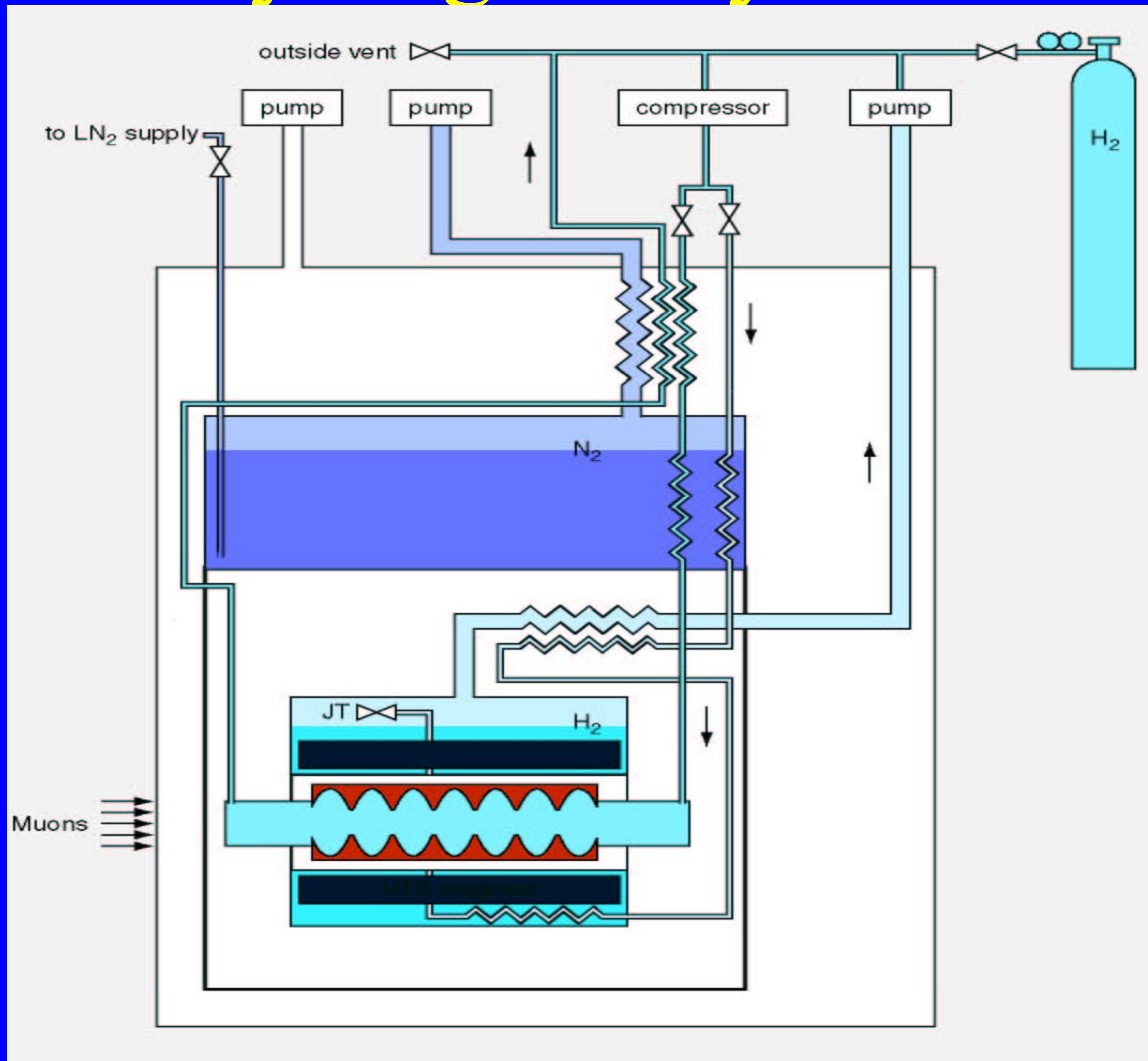
Ph I, Dave Finley, Fermilab

- 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})
10^6
10^5
10^4
MOTOR
CABLE
0
1
2
3
4
5
6
7
Magnetic field $\mu_o H$ (Tesla)
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

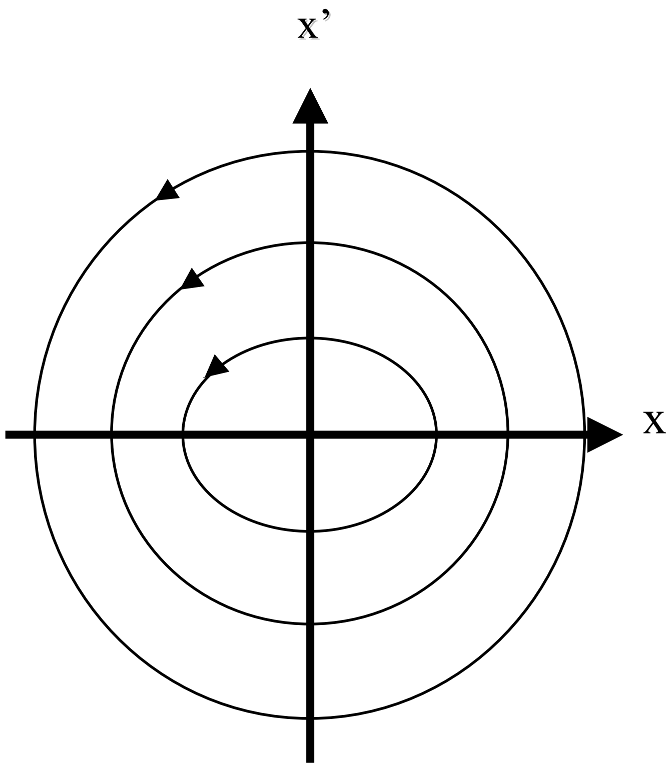
Hydrogen Cryostat

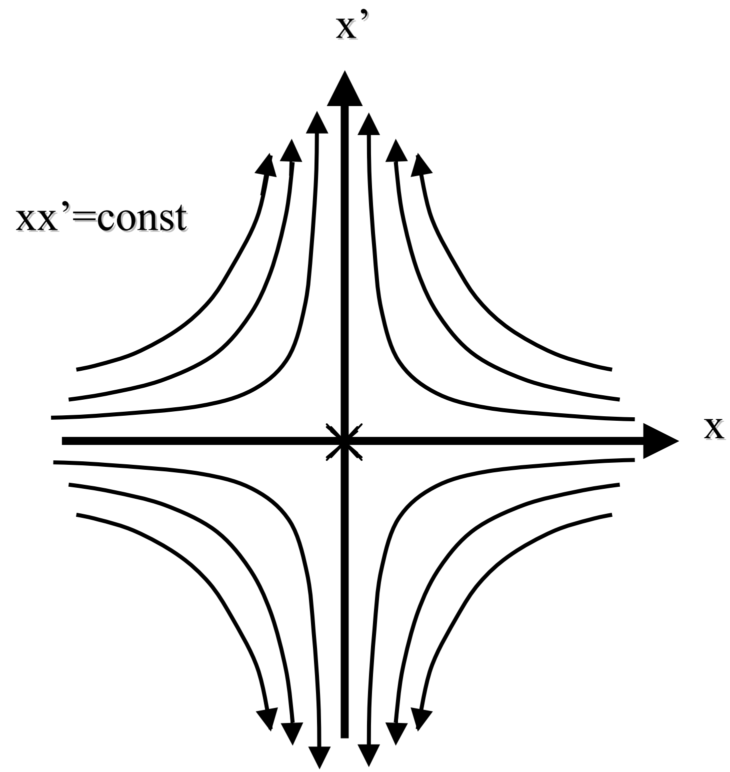


Phase Ionization Cooling (PIC) Proposal Ph I, Slava Derbenev, JLab

- Derbenev Idea
  - 6D cooling allows new IC technique
  - 1 to 2 orders smaller emittance than conventional IC
  - Fewer muons to get high luminosity
    - Easier proton driver and production target
    - Fewer detector backgrounds
    - Less neutrino radiation from storage rings
- Excite parametric resonance (xx'=const)
  - Like vertical rigid pendulum
  - Or ½-integer extraction from synchrotron
  - reduce x, increase x'
- Use IC to reduce x'

Hyperbolic phase space motion





IC constrains x’

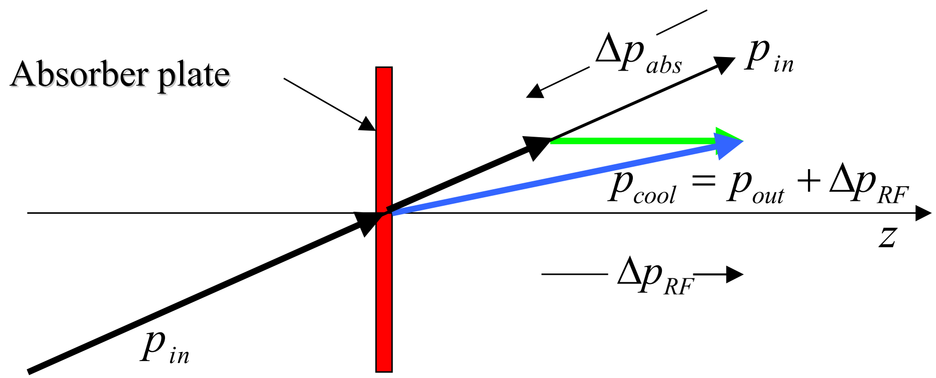
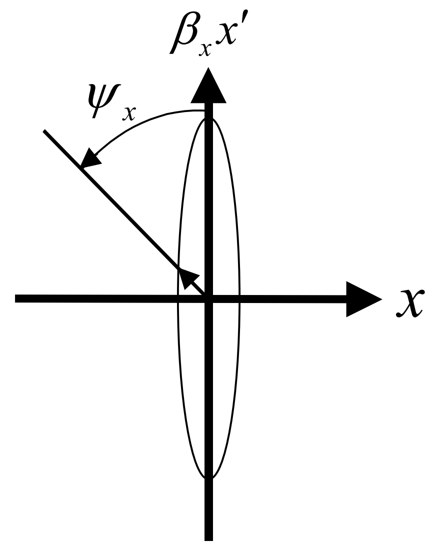
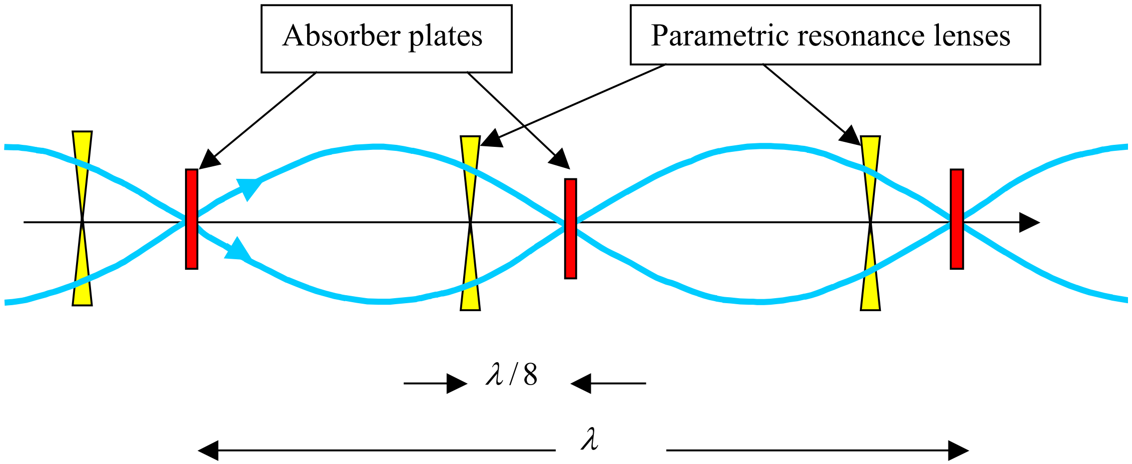


Fig. 3 Phase space compression. The spread in x diminishes due to the parametric resonance motion while the spread in x' diminishes due to ionization cooling. The area of the occupied phase space ellipse is reduced as the particles are restricted to a narrow range of phase angle, psi.



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.

Summary

- SBIR/STTR supports a vigorous R&D effort
  - Innovation requirement demands creativity
  - Scientific interests well-served
    - Government---expands project choices with most value
    - Academic---leads to best projects, support of researchers
    - Business---allows small business to take part in big science
- GH2 an enabling technology for μ machines
  - HG RF for less-expensive, more efficient beam cooling
    - Takes advantage of unique properties of muons
  - Emittance exchange with homogeneous absorber
    - 6D Cooling makes Muon Collider possible, maybe PIC
    - Less expensive acceleration for Neutrino Factory