High Pressure, High Gradient RF Cavities for Muon Beam Cooling

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ABSTRACT

High intensity, low emittance muon beams are needed for new applications such as muon colliders and neutrino factories based on muon storage rings. Ionization cooling, where muon energy is lost in a low-Z absorber and only the longitudinal component is regenerated using RF cavities, is presently the only known cooling technique that is fast enough to be effective in the short muon lifetime. RF cavities filled with high-pressure hydrogen gas bring two advantages to the ionization cooling technique. First, the energy absorption and energy regeneration happen simultaneously rather than sequentially, and second, higher RF gradients and better cavity breakdown behavior are possible due to the Paschen effect. A first step in a program to develop ionization cooling using pressurized cavities is the measurement of RF breakdown of hydrogen at high density. In the study reported here, the linear dependence of breakdown on pressure was verified in an 800 MHz hydrogen-filled test cavity up to 80 MV/m, which was the surface gradient limit of the molybdenum electrodes of the cavity. We note that the conditioning of the electrodes was unusually fast in the gas and needed only a few hundred thousand pulses. Planned research includes experimental measurements of pressurized RF cavity behavior in strong magnetic and ionizing radiation fields. Analytical and simulation calculations are also being made to examine how these cavities might be used in a practical cooling channel, effectively a complex Linac.

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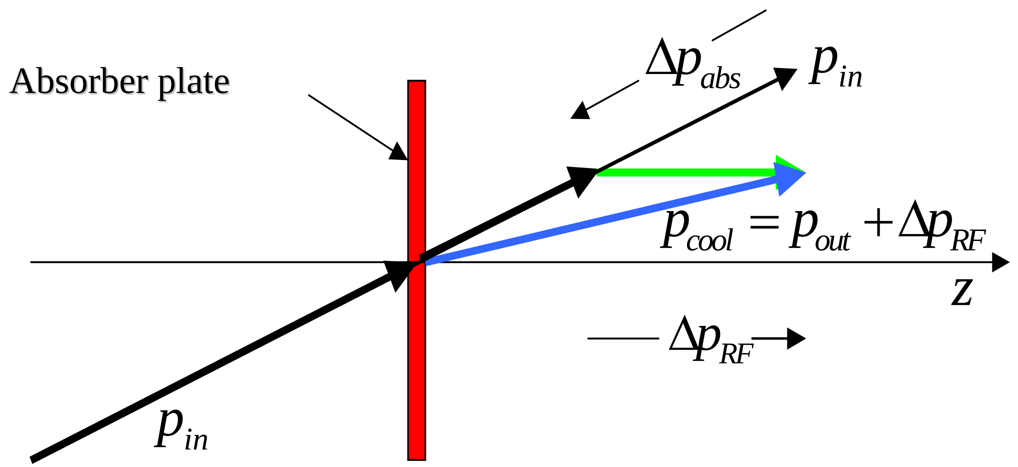
Pressurized RF for Muons

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

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.

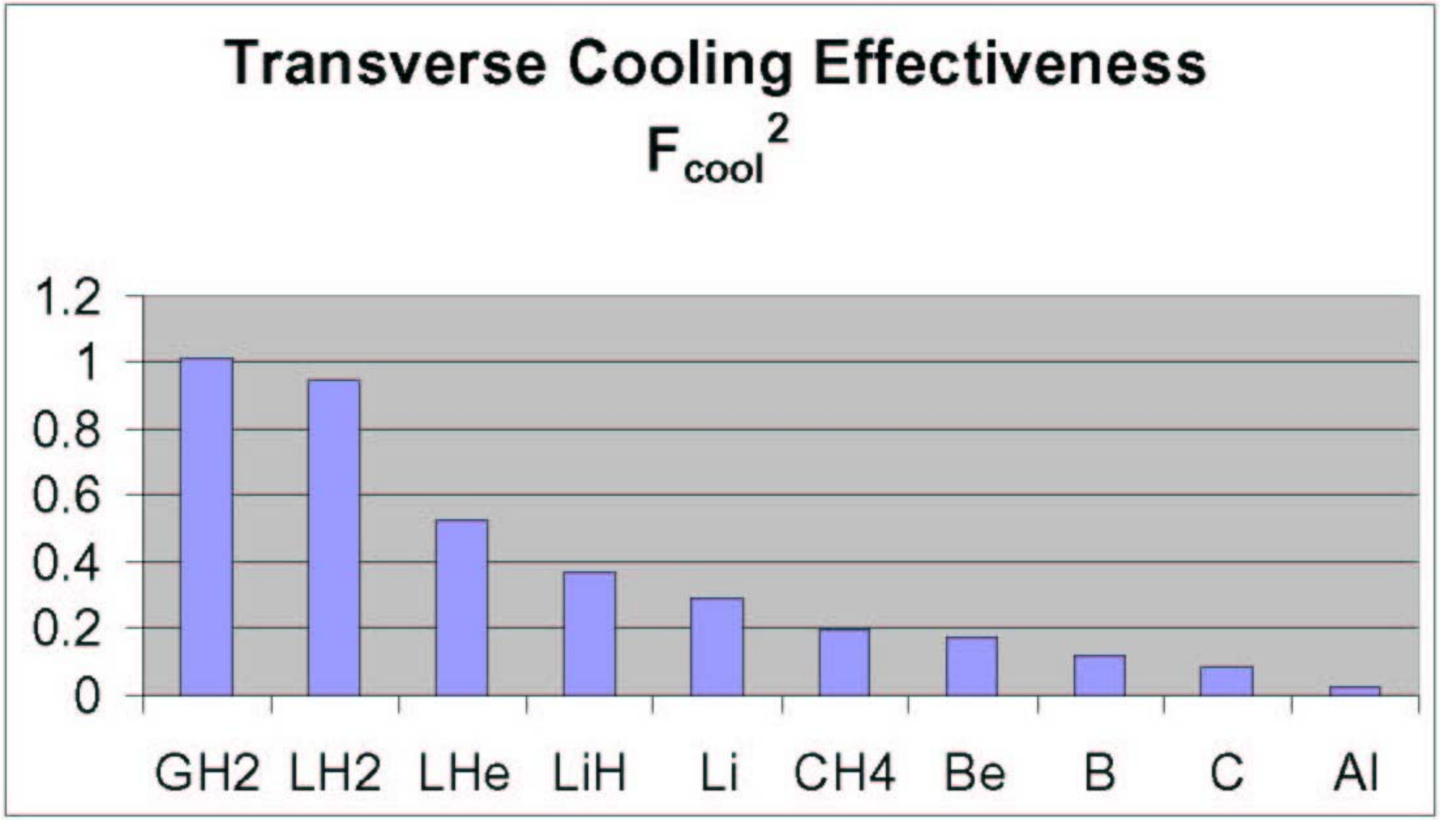
I. C. Figure of Merit

- 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



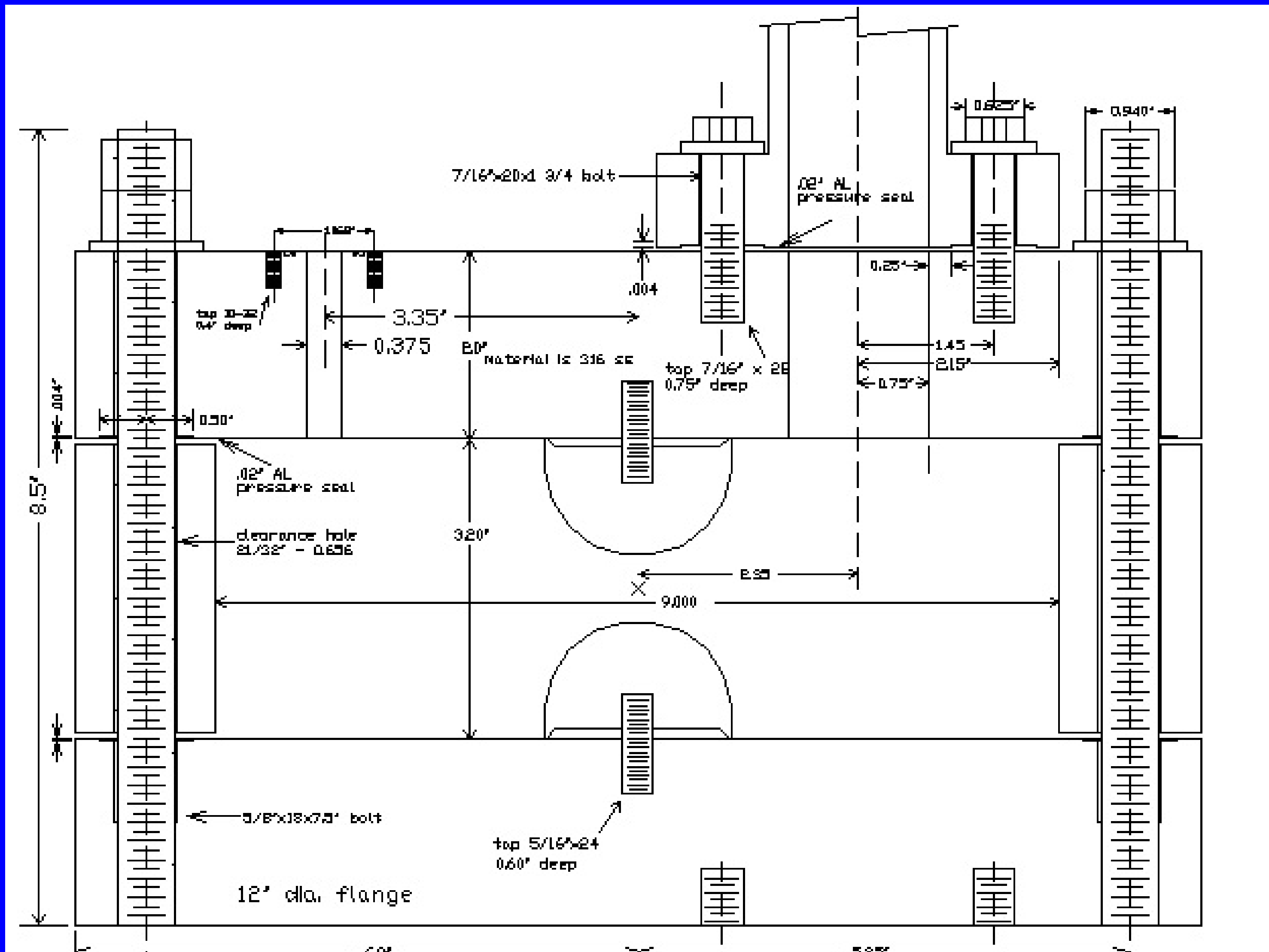
Hydrogen Gas Virtues/Problems

- 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

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*

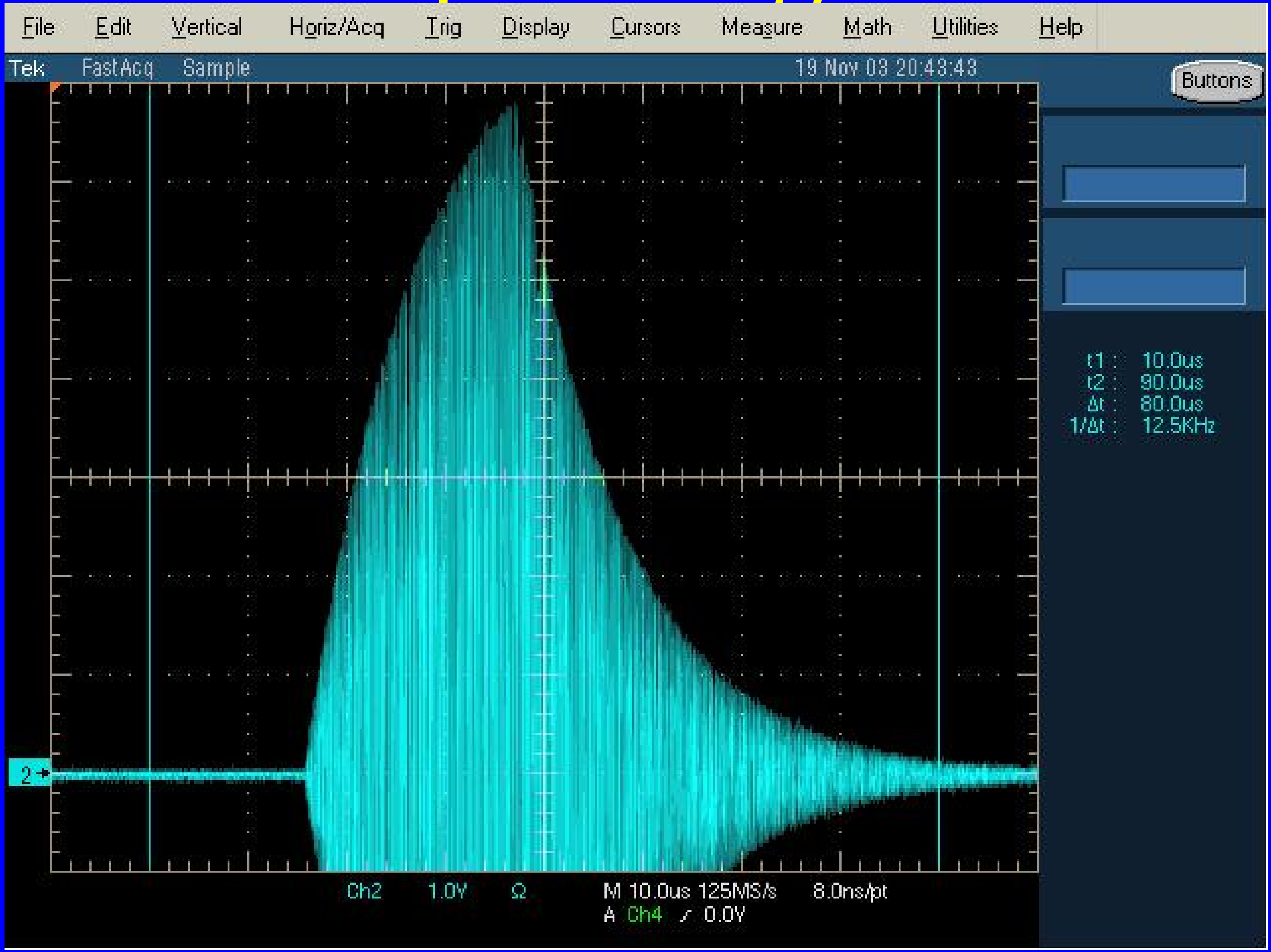
Mark II 805 MHz RF test cell



New TC; 2000PSI @ 77K

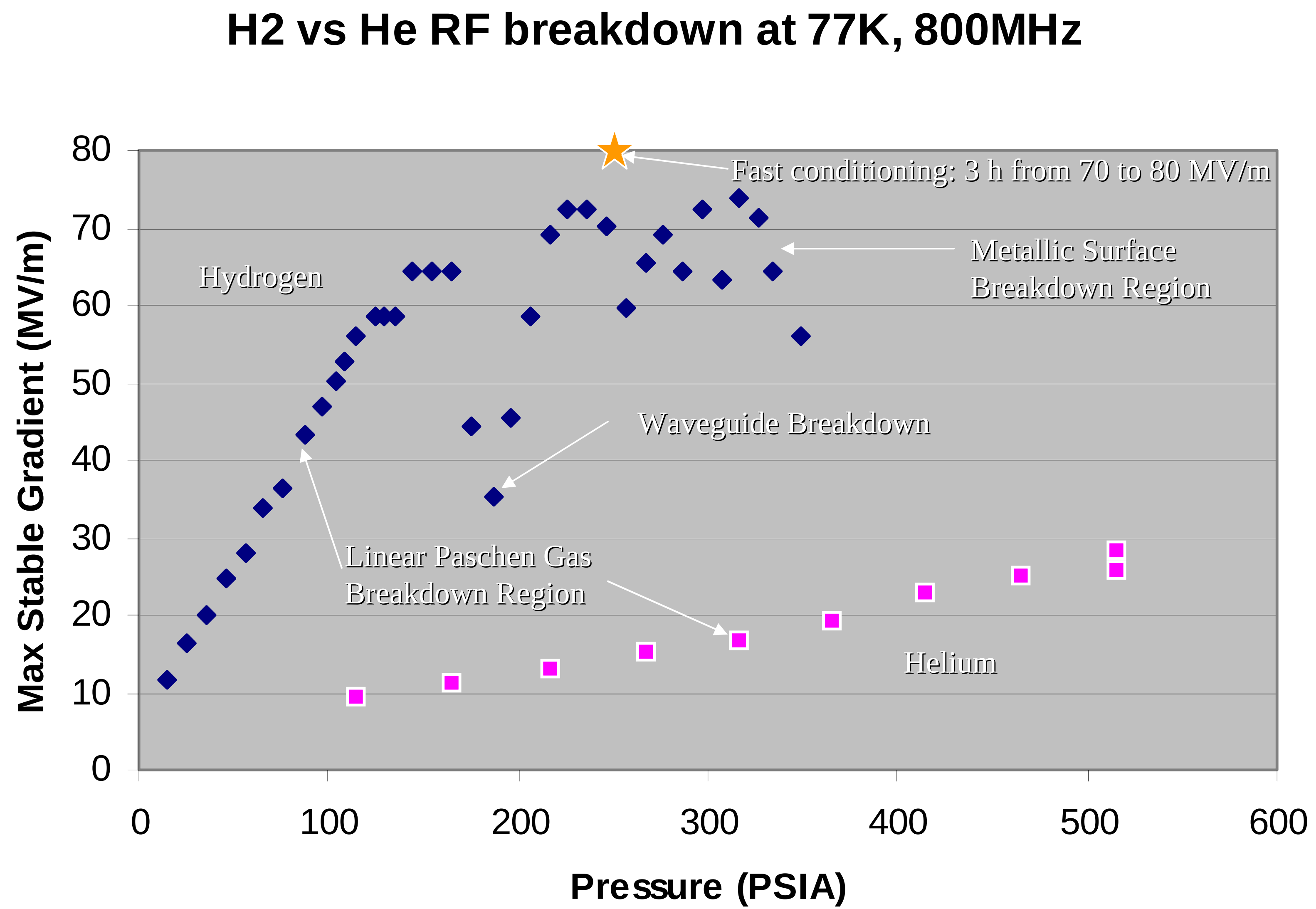

4/9/2003

RF probe signal



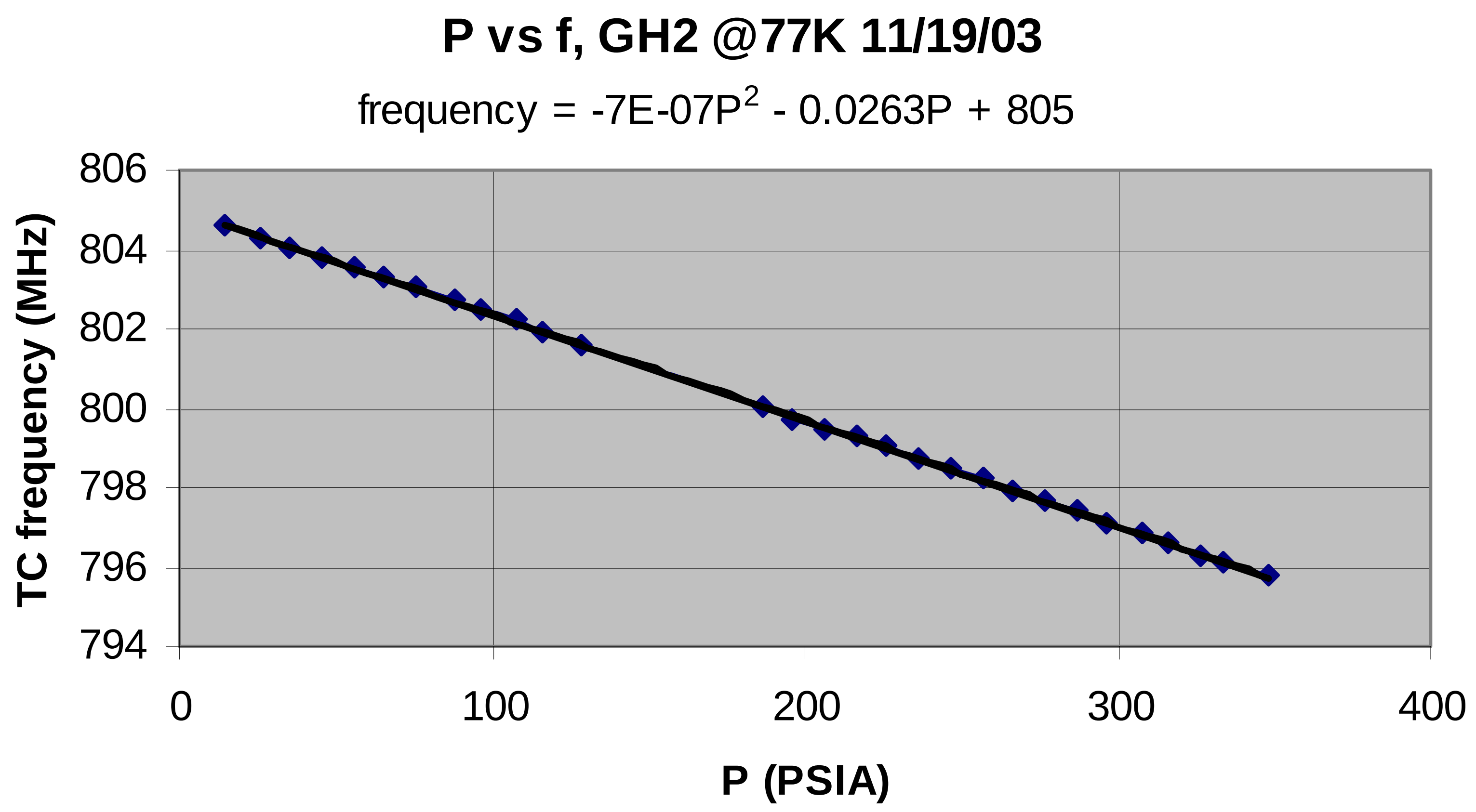
The probe signal taken during the last hours of operation at 250PSI and 77K. The pulse time of 20 μs corresponds to the rising part of the 800MHz envelope. The required pulse length is a few microseconds for a neutrino factory, while a collider may only require a few nanoseconds.

11/19/03 Lab G Results, Molybdenum Electrode



Gas density and dielectric increase with pressure causing frequency to decrease

Test Cell Pressure vs frequency



Cell is not tunable except by shimming doorknob electrodes. Klystron range for low power is 796 to 812 MHz.

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 Hardware Activities

- Moving from Lab G to MTA
- 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 (w Dave Harding)
  - Want radiation test of GH2 RF in 2005

Example of HP RF Linac Design: Emittance Exchange With GH2

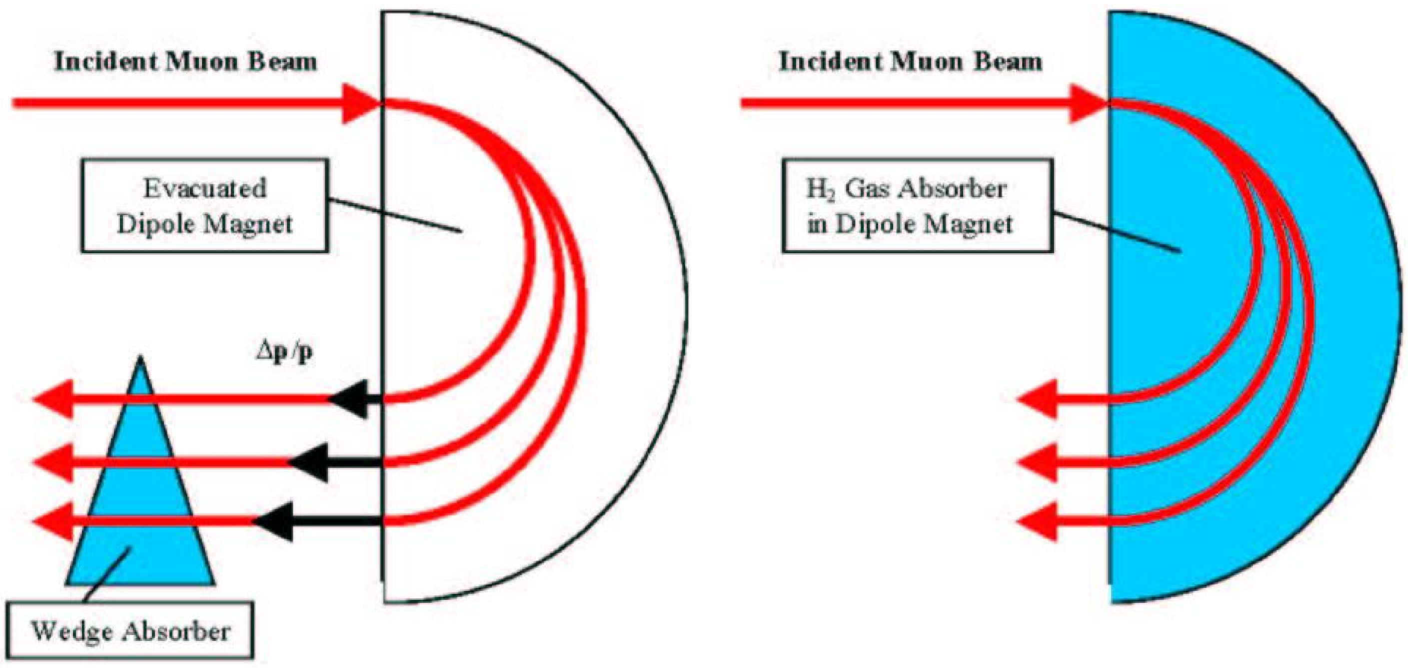


Figure 1. Use of a Wedge Absorber for Emittance Exchange

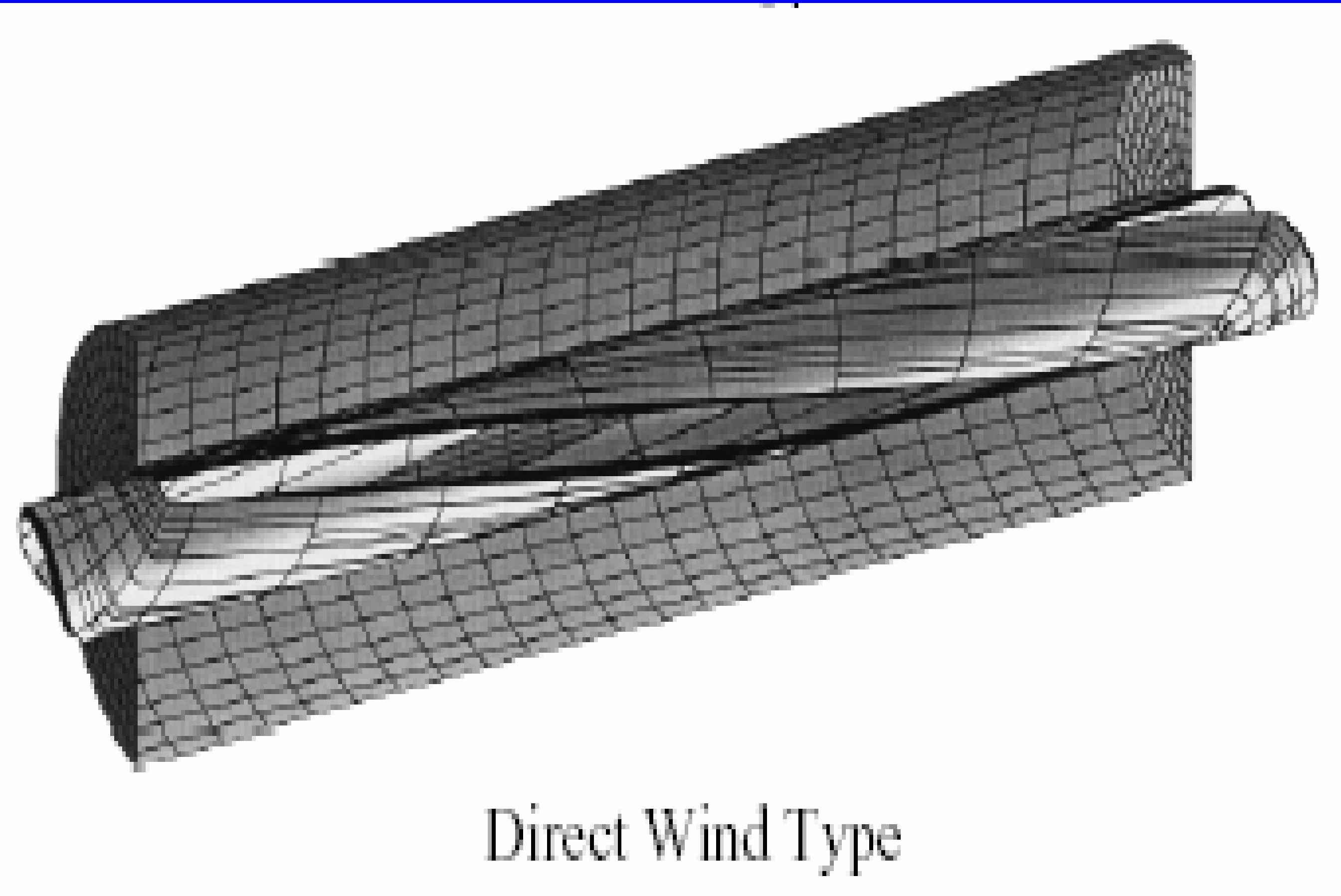
Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

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

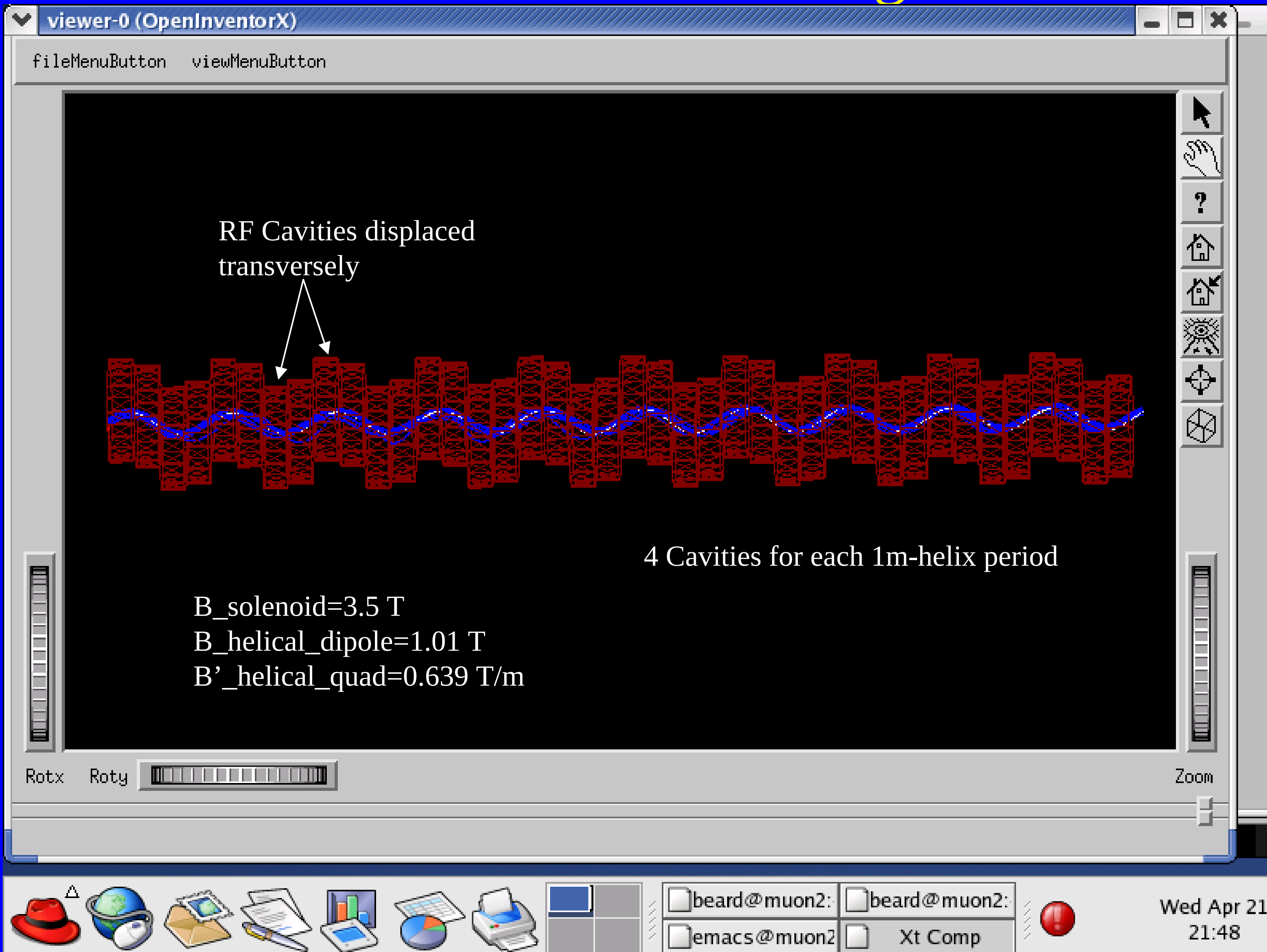
Derbenev Channel for 6D Cooling

- 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

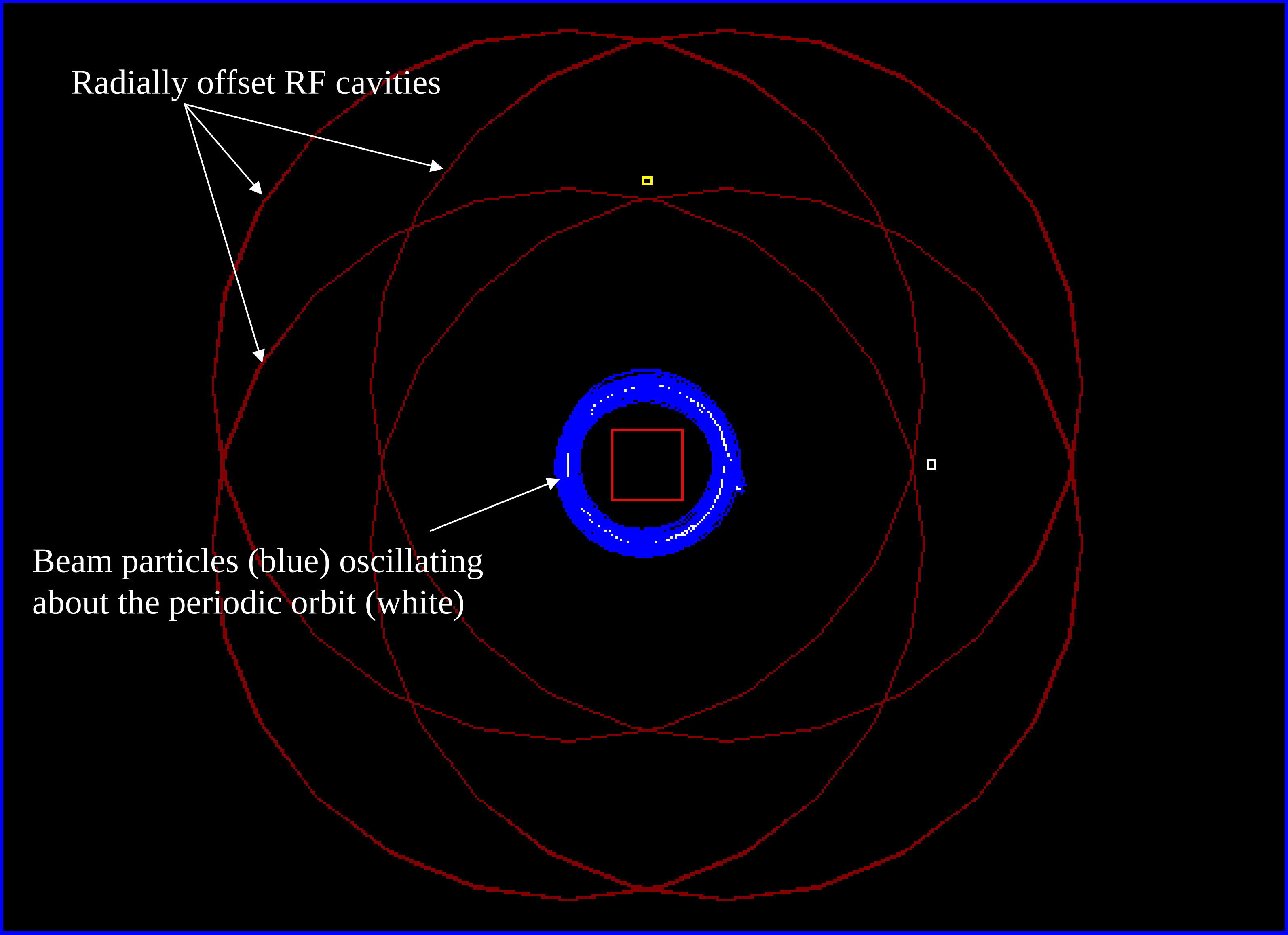
Helical Dipole Magnet (c.f. Erich Willen at BNL)



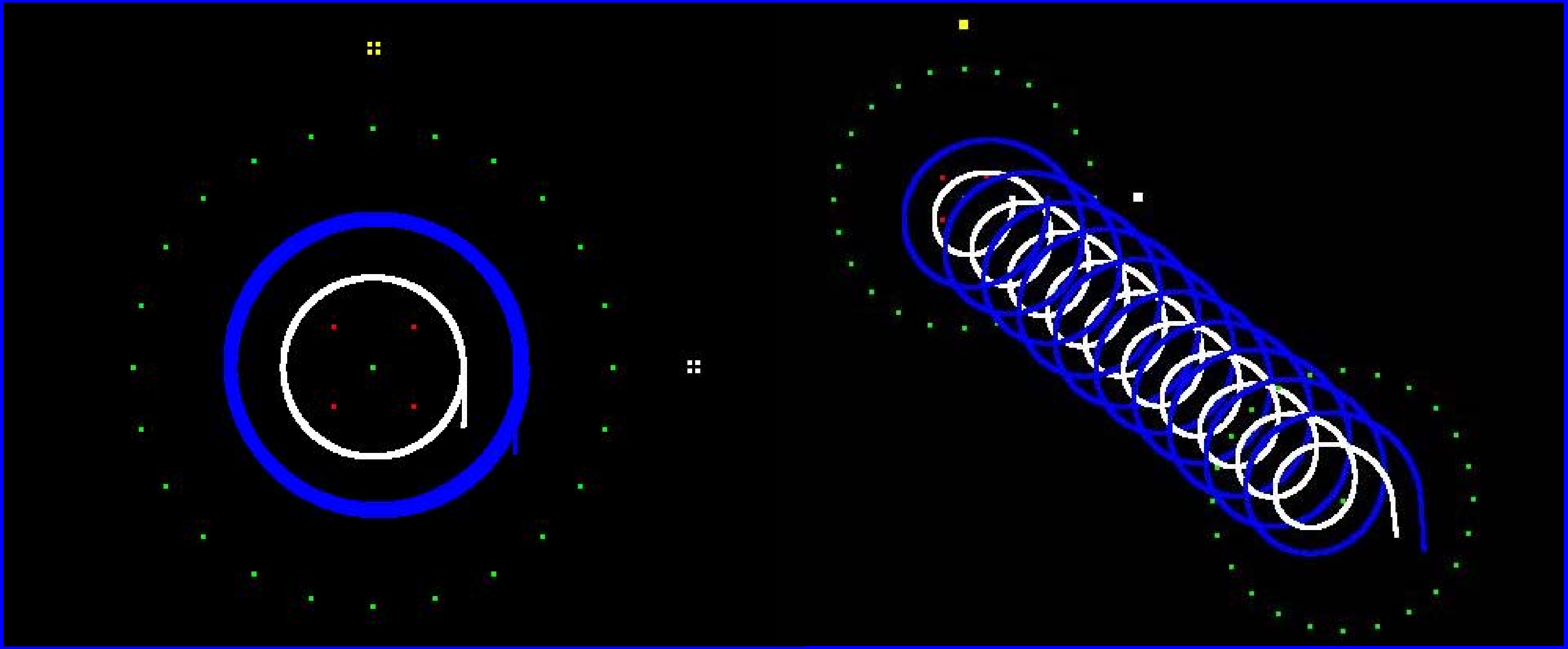
G4BL 10 m helical cooling channel



G4BL End view of 200MeV HCC



G4BL HCC Dispersion Measurement: $r_{250} = (1+0.25D)\, r_{200}$, D=2.93



200MeV/c (white), 250 MeV/c (blue) periodic orbits

Status

Muons, Inc., IIT, Fermilab, and Jefferson Lab under the DOE SBIR program are developing new muon beam cooling concepts. The funded projects:

1) high-pressure, high-gradient RF cavities,
2) six-dimensional beam cooling using a helical dipole magnetic channel and GH2 absorber,
3) a plan for a demonstration muon beam cooling experiment using gaseous absorber,
4) a cryostat for muon cooling that incorporates high-T SC magnets and a hydrogen refrigerator,
5) a new method of ionization cooling using parametric resonances.