HELICAL COOLING CHANNEL PROGRESS*

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(and many other SBIR-STTR collaborators)

We describe the design and construction plans for a 1-m, 20-cavity prototype Helical Cooling Channel (HCC) segment, including the development of oxygen-doped hydrogen-pressurized RF cavities that are loaded with dielectric, fed by magnetrons, and operate in a superconducting helical solenoid magnet. A 300 m long cooling channel composed of similar segments will reduce the 6D emittance of a muon beam by almost a factor of one million.

Please visit http://www.muonsinc.com/

Overview

In 20 minutes, I will try to describe the outcome of ten years of developing new concepts for muon ionization cooling.

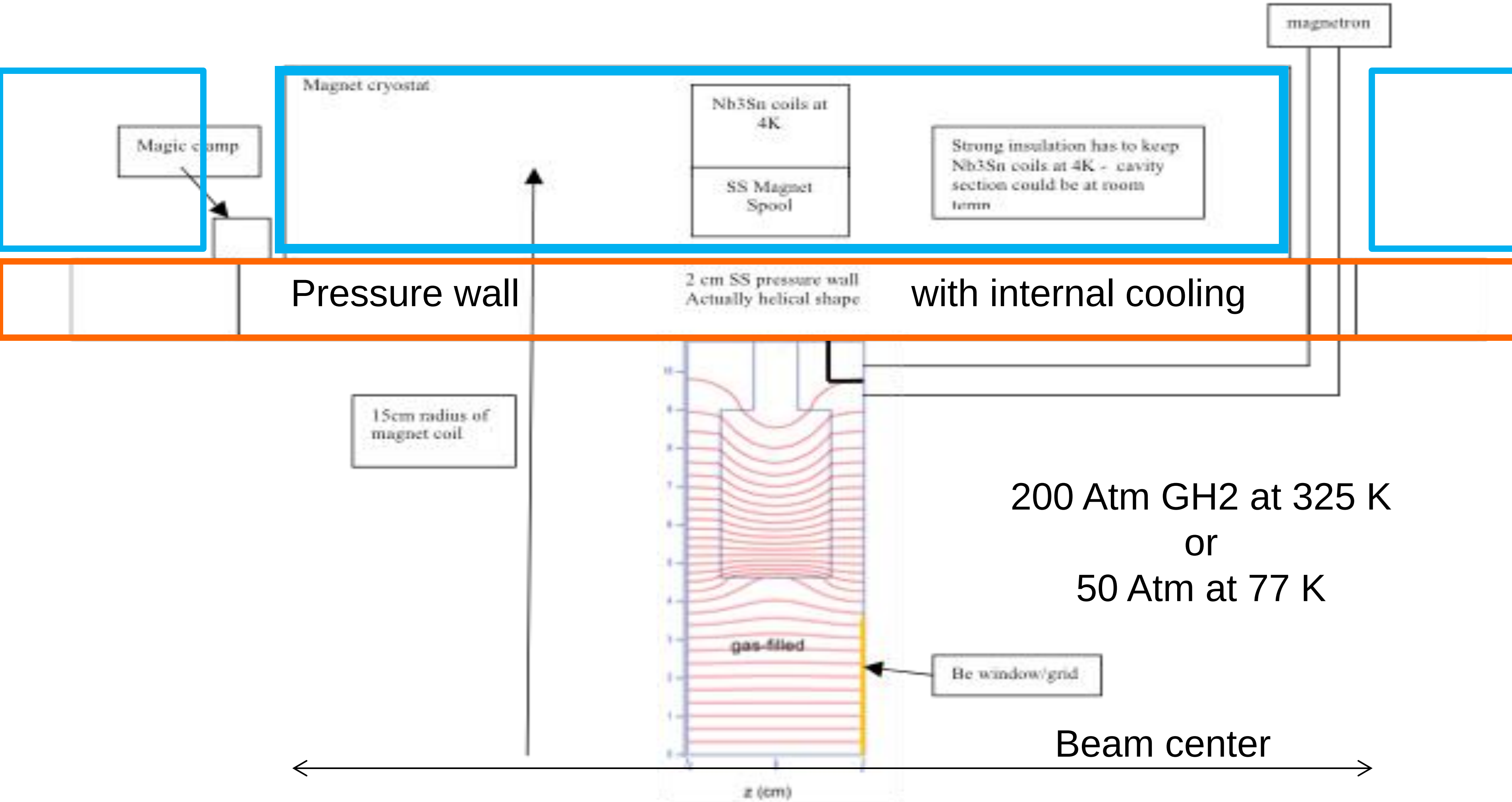
The ideas that are basic to the prototype being designed are new for this millennium:

Hydrogen-pressurized RF cavities,
- doped with oxygen,
- loaded with dielectric,

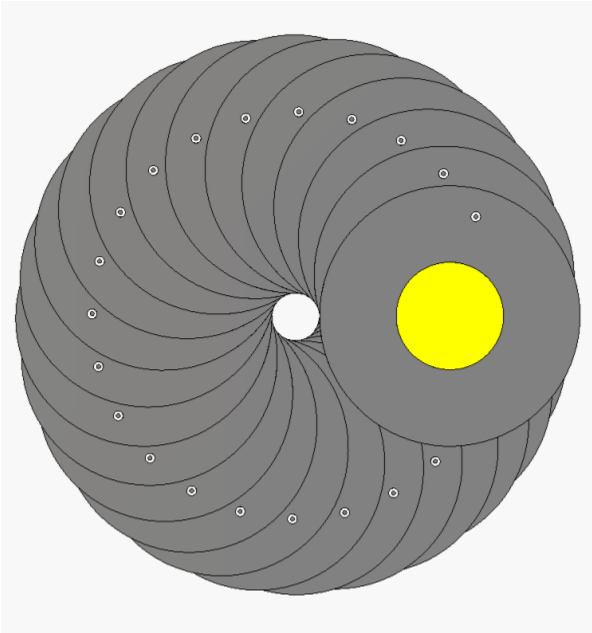
Helical Ionization Cooling theory using Siberian snake fields in Helical Solenoid magnets, generating 6d cooling using emittance exchange with a continuous homogeneous absorber

In the style of a patent application, I will describe the device, the features that make it work, and the experiments and numerical simulations that support the application.

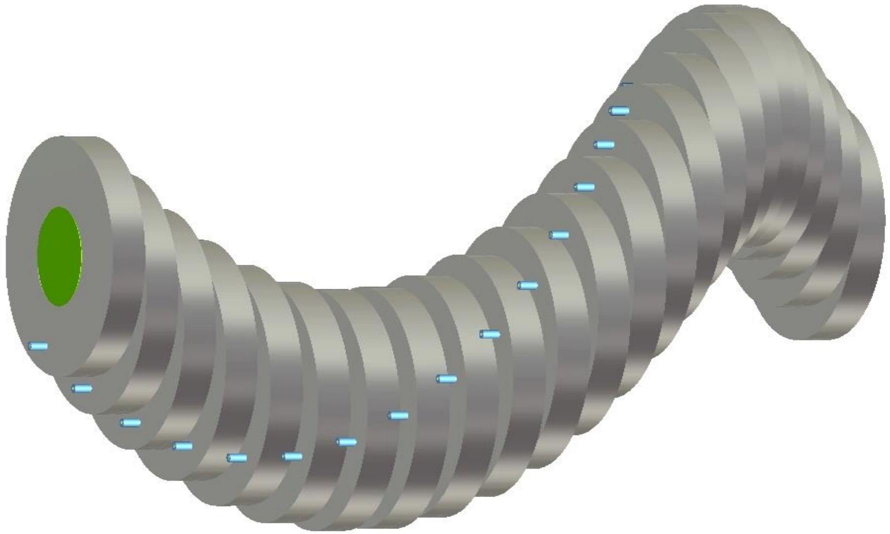
Concept of HCC Segment



5-cm Pillbox Cavities in HCC



End view, yellow is beam region



Side view, green is Be grid to keep RF in pillbox and allow GH2 to pass

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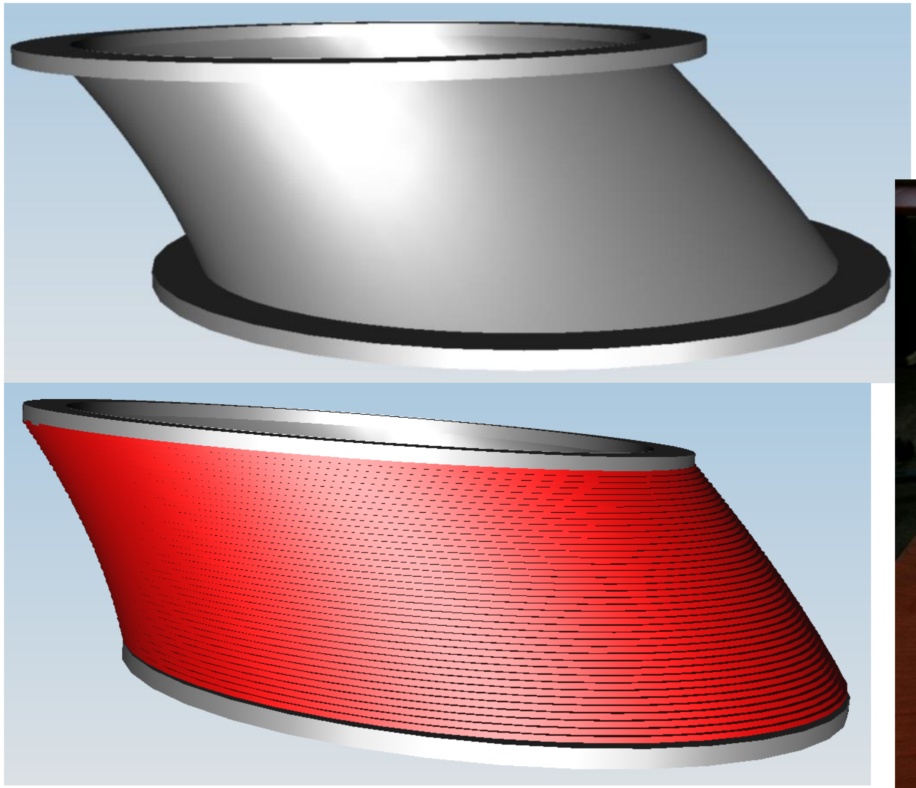
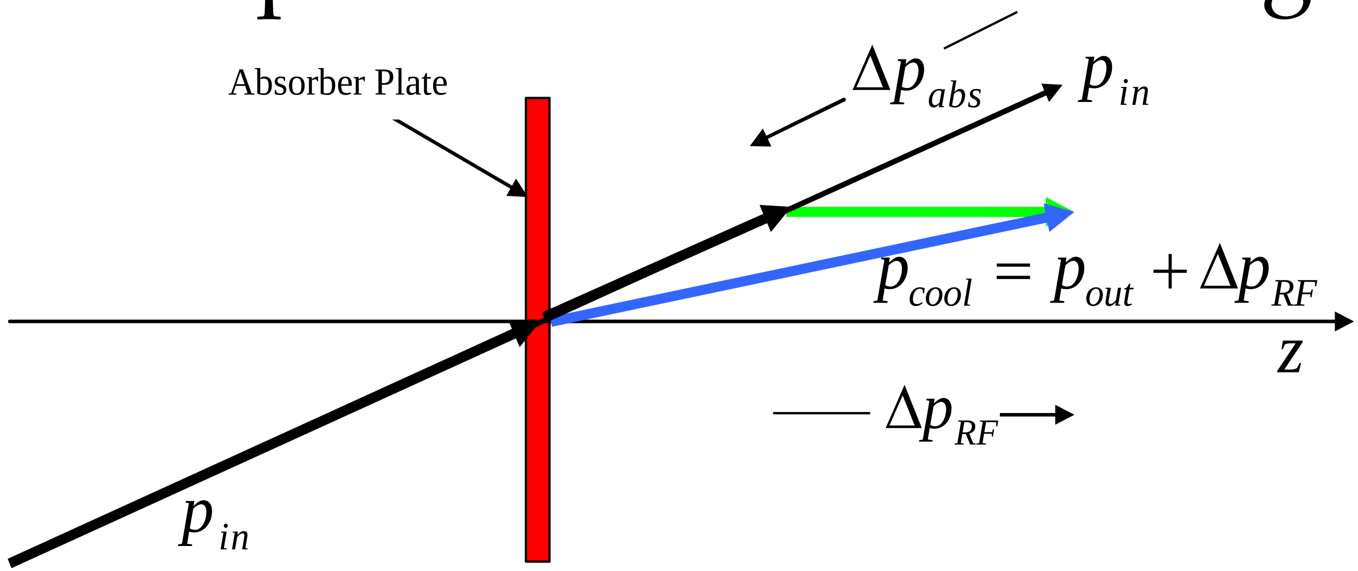
R&D for HCC magnet



- Make smooth coil structure to reduce a discontinuity of helical field
- Use Nb_3Sn for this test

The helical solenoid provides the required B, b, and db/dr if the dimensions are correct. To put lower frequency RF cavities inside the magnet coils, the cavities are loaded with dielectric to reduce their radial dimension.

Principle of Ionization Cooling



- Each particle loses momentum by ionizing a low-Z absorber
- Only the longitudinal momentum is restored by RF cavities
- The angular divergence is reduced until limited by multiple scattering
- Successive applications of this principle with clever variations leads to small emittances for many applications
- Early work: Budker, Ado & Balbekov, Skrinsky & Parkhomchuk, Neuffer

Transverse Emittance IC

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

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

Bethe-Bloch Moliere (with low Z mods)

- 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.

Wedges or Continuous Energy Absorber for Emittance Exchange and 6d Cooling

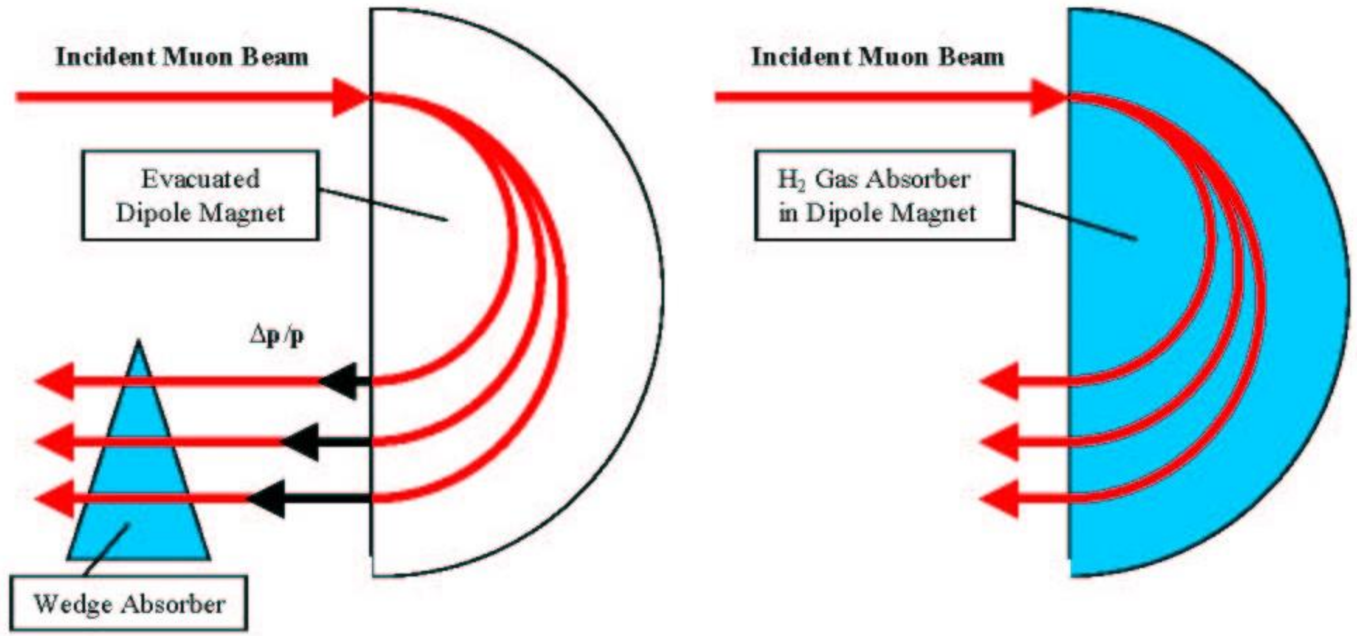


Figure 1. Use of a Wedge Absorber for Emittance Exchange

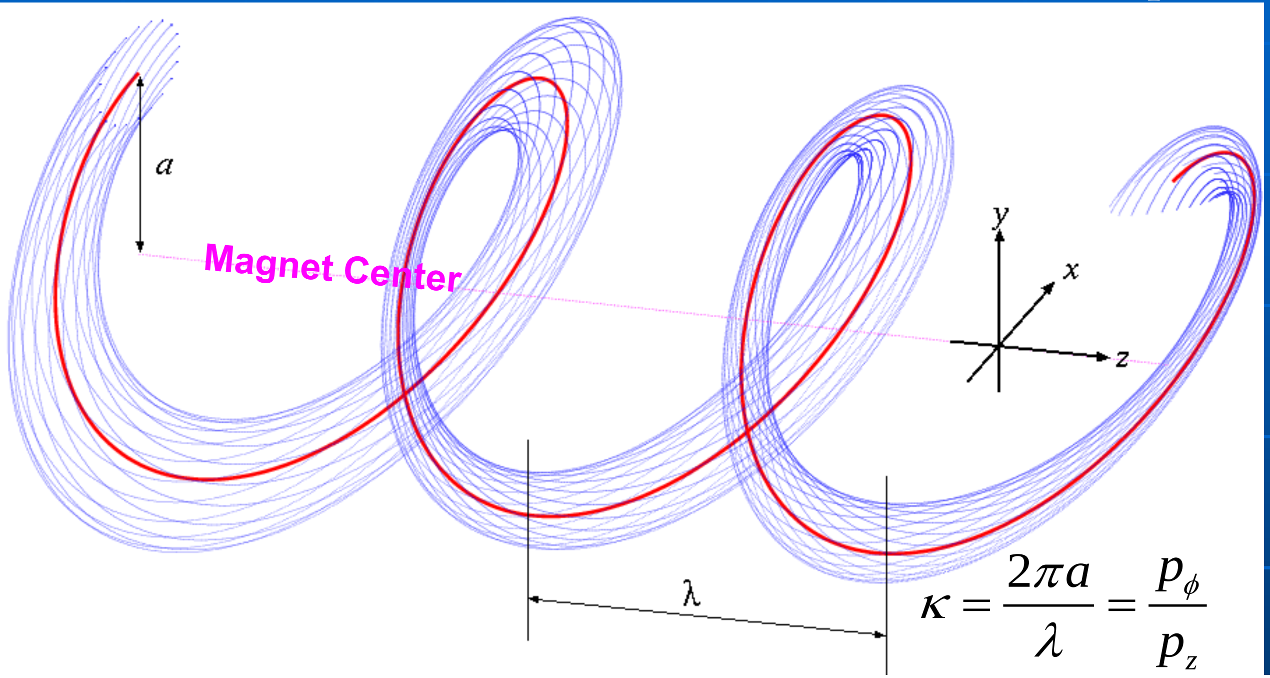
Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

Ionization Cooling is only transverse. To get 6D cooling, emittance exchange between transverse and longitudinal coordinates is needed.

Particle Motion in a Helical Magnet

Combined function magnet (invisible in this picture)

Solenoid + Helical dipole + Helical Quadrupole



$$\kappa = \frac{2\pi a}{\lambda} = \frac{p_\phi}{p_z}$$

Red: Reference orbit

Blue: Beam envelope

Dispersive component makes longer path length for higher momentum particles and shorter path length for lower momentum particles.

Opposing radial forces

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

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

Transforming to the frame of the rotating helical dipole leads to a time and z – independent Hamiltonian

b' added for stability and acceptance

Some Important Relationships

Hamiltonian Solution
$$p(a)=\frac{\sqrt{1+\kappa^2}}{k}\left[B-\frac{1+\kappa^2}{\kappa}b\right] \qquad k=2\pi/\lambda \qquad \kappa=ka$$

Equal cooling decrements
$$q\equiv\frac{k_c}{k}-1=\beta\sqrt{\frac{1+\kappa^2}{3-\beta^2}} \qquad k_c=B\sqrt{1+\kappa^2}/p$$

Longitudinal cooling only
$$\hat{D}\equiv\frac{p}{a}\frac{da}{dp}=2\frac{1+\kappa^2}{\kappa^2} \qquad q=0$$

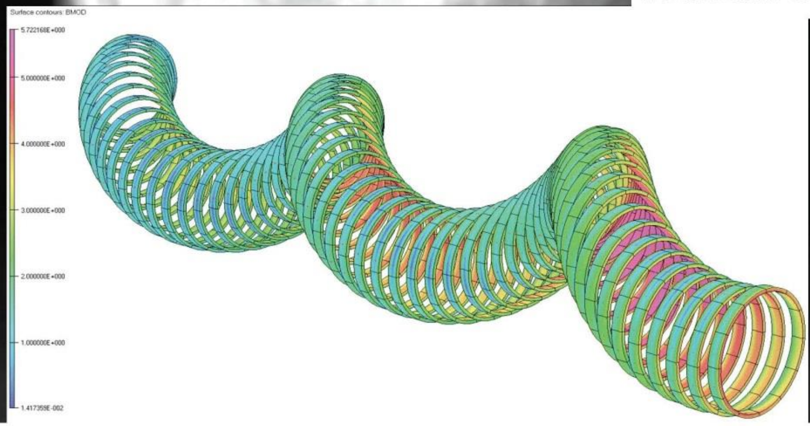
~Momentum slip factor
$$\eta=\frac{d}{d\gamma}\frac{\sqrt{1+\kappa^2}}{\beta}=\frac{\sqrt{1+\kappa^2}}{\gamma\beta^3}\left(\frac{\kappa^2}{1+\kappa^2}\hat{D}-\frac{1}{\gamma^2}\right) \qquad \frac{\kappa^2}{1+\kappa^2}\hat{D}\sim\frac{1}{\gamma^2_{transition}}$$

Hardware Development

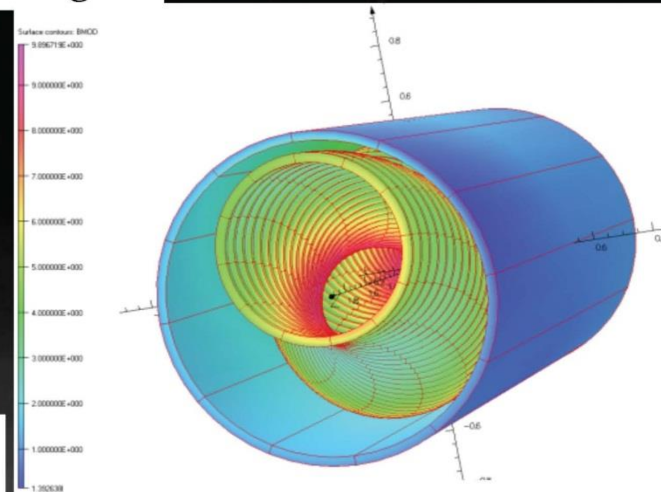
- Helical Solenoid invention to get HCC fields
  - 4-coil NbTi HS model tested (1^{st} 6d HCC segment)
  - 6-coil YBCO HS model tested (last 6d HCC segment)
- High Pressure H_2 Cavity development
  - Test cell shows no HV max dependence on external B
  - First beam tests show agreement with models
    - No RF breakdown
    - Ionization electrons move far enough to heat H_2 – reduce Q
    - Mitigated with 0.01% SF_6 dopant
    - Oxygen shown to be a good dopant with less corrosion

Helical Magnet

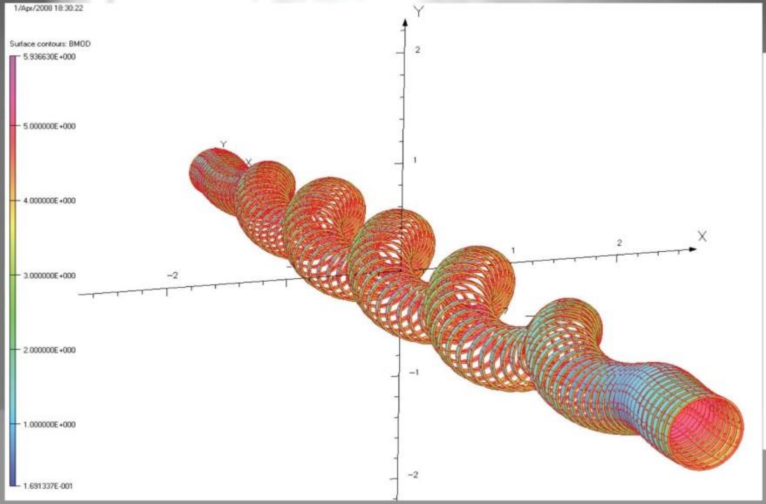
Helical solenoid magnet



- Coil center follows on the helical reference track
- It generates proper helical dipole + field gradient



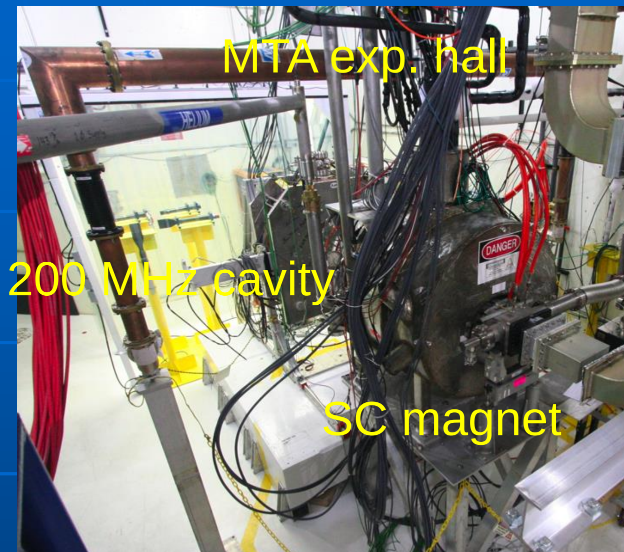
- By adding a solenoid coil, it tunes all three field components (b, b', bz)



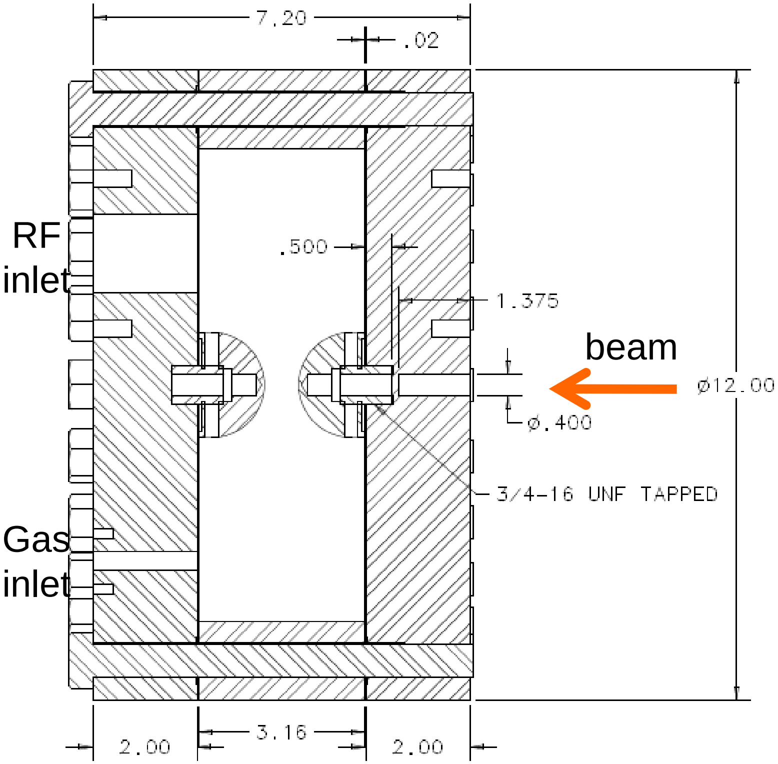
- By modulating the coil position, it can make a beam adapter to connect between straight and helical magnet sections.
- Helical solenoid magnet generates more uniform field than analytical field.
- It means that helical solenoid magnet has larger acceptance than analytical one.

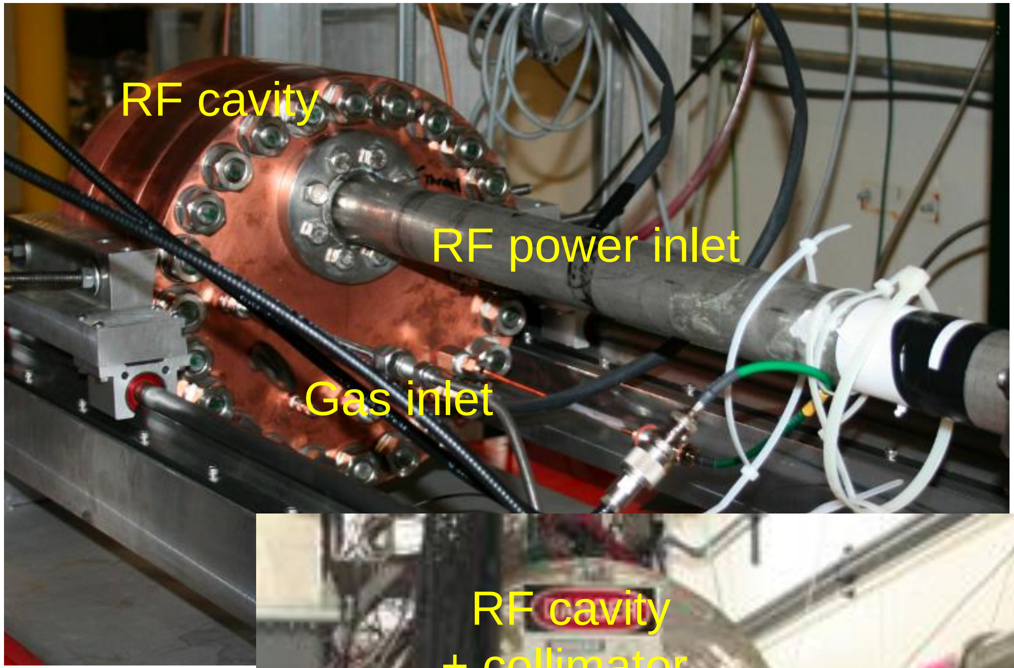
Mucool Test Area (MTA) & work space

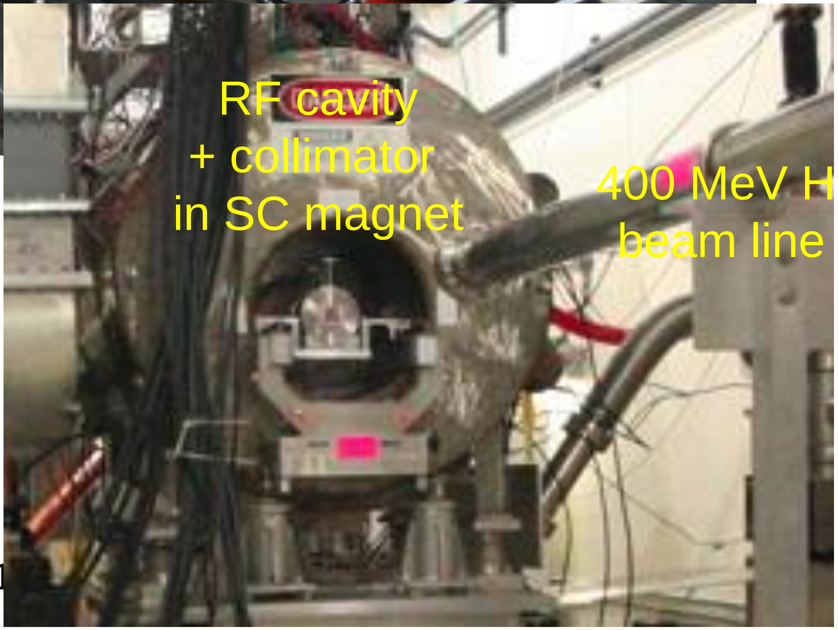
Multitask work space to study RF cavity under strong magnetic fields
& by using intense H^- beams from Linac



First results HPRF cavity in beam

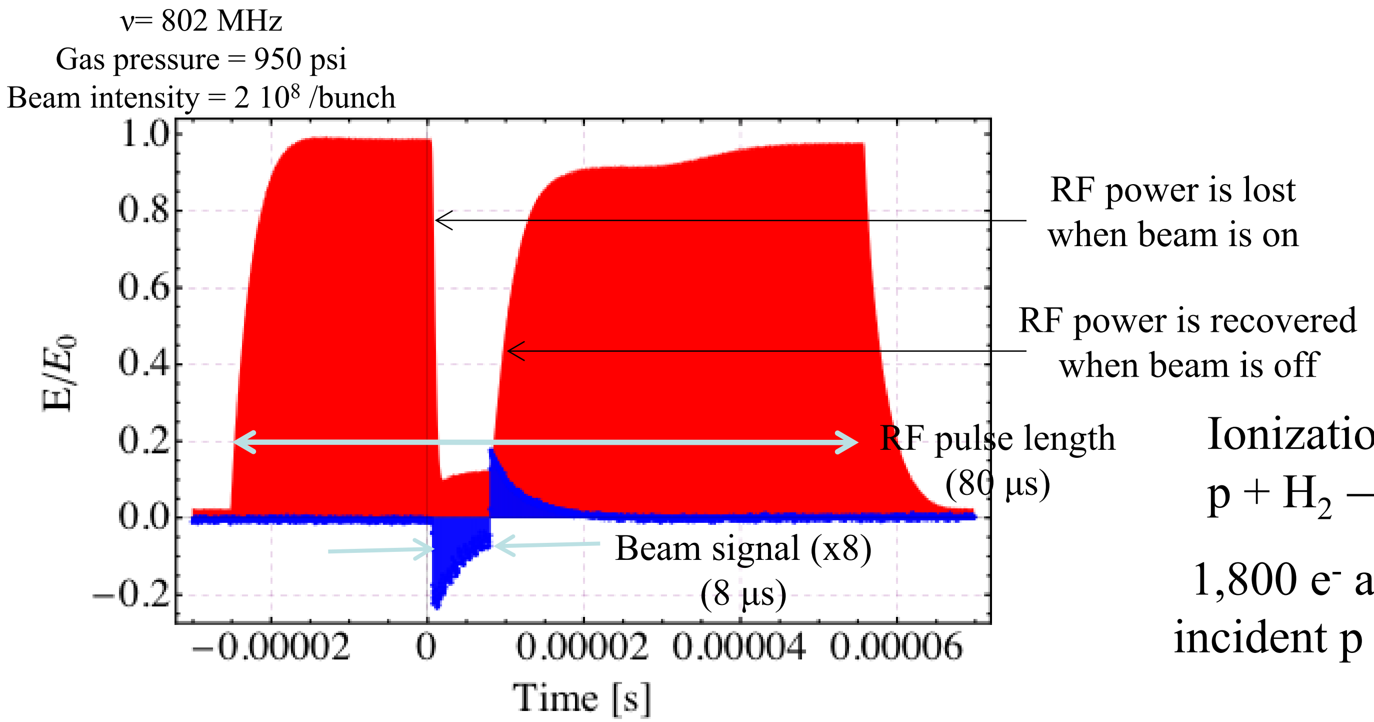






- 400 MeV H^- beam
- Beam pulse length 7.5 µs
- 5 ns bunch gap
- 10^9 H^-/bunch
- 18 % of transmission in collimator system
- 1.8 10^8 protons/bunch reaches to the cavity

Study interaction of intense beam with dense H2 in high gradient RF field



Ionization process

$p + H_2 \rightarrow p + H_2^+ + e^-$

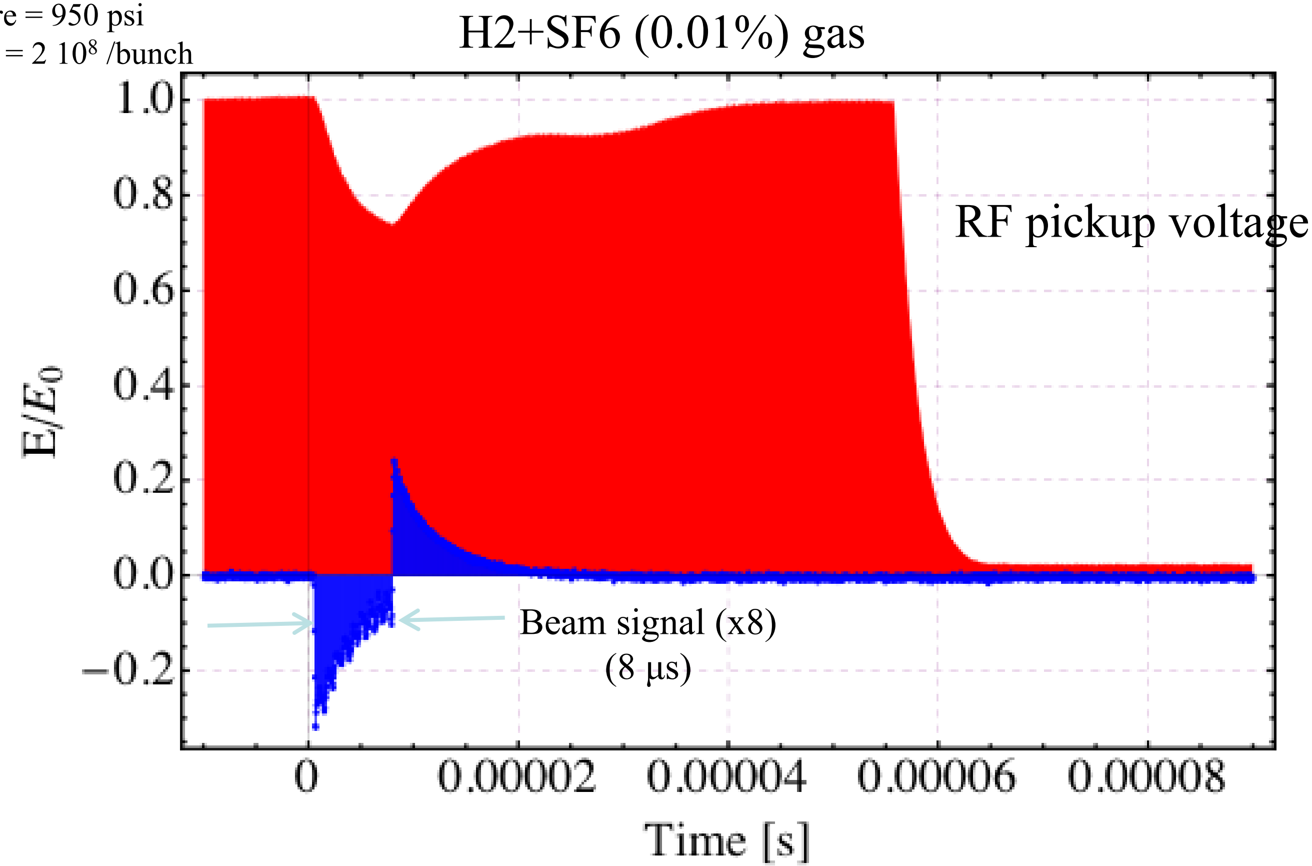
1,800 e^- are generated by incident p @ K = 400 MeV

Huge RF power lost due to electrons' power consumption

But, No Breakdown!!

Electronegative gas

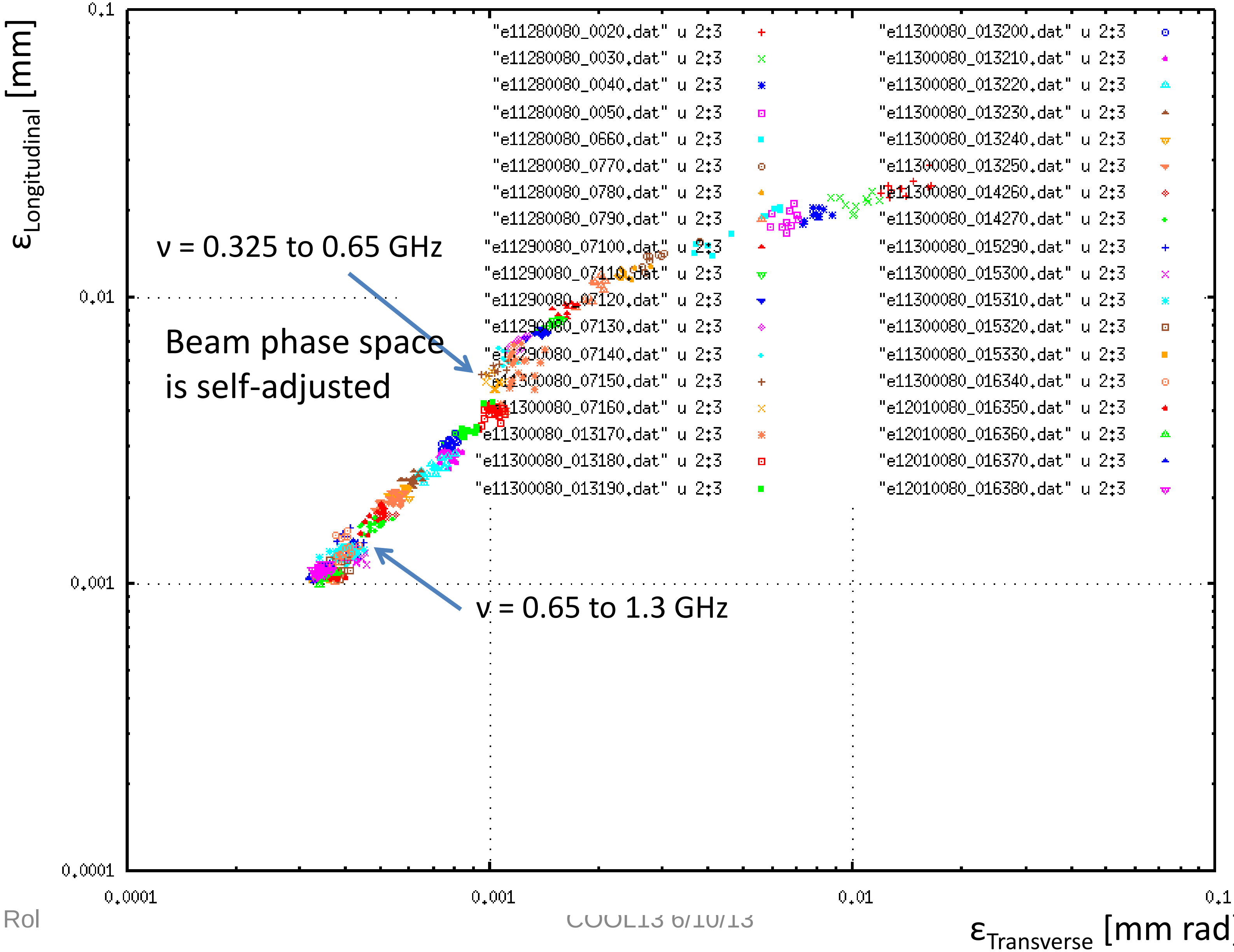
ν= 802 MHz
H2 + SF6 (0.01 % condensation)
Gas pressure = 950 psi
Beam intensity = 2 10^8 /bunch



SF6 removes a residual electron
Great improvement!

HCC parameter from cooling simulation

(MC design workshop ’09@BNL)



Parameter of cooling channel with Cary's correction (IPAC'13, TUPFI060)

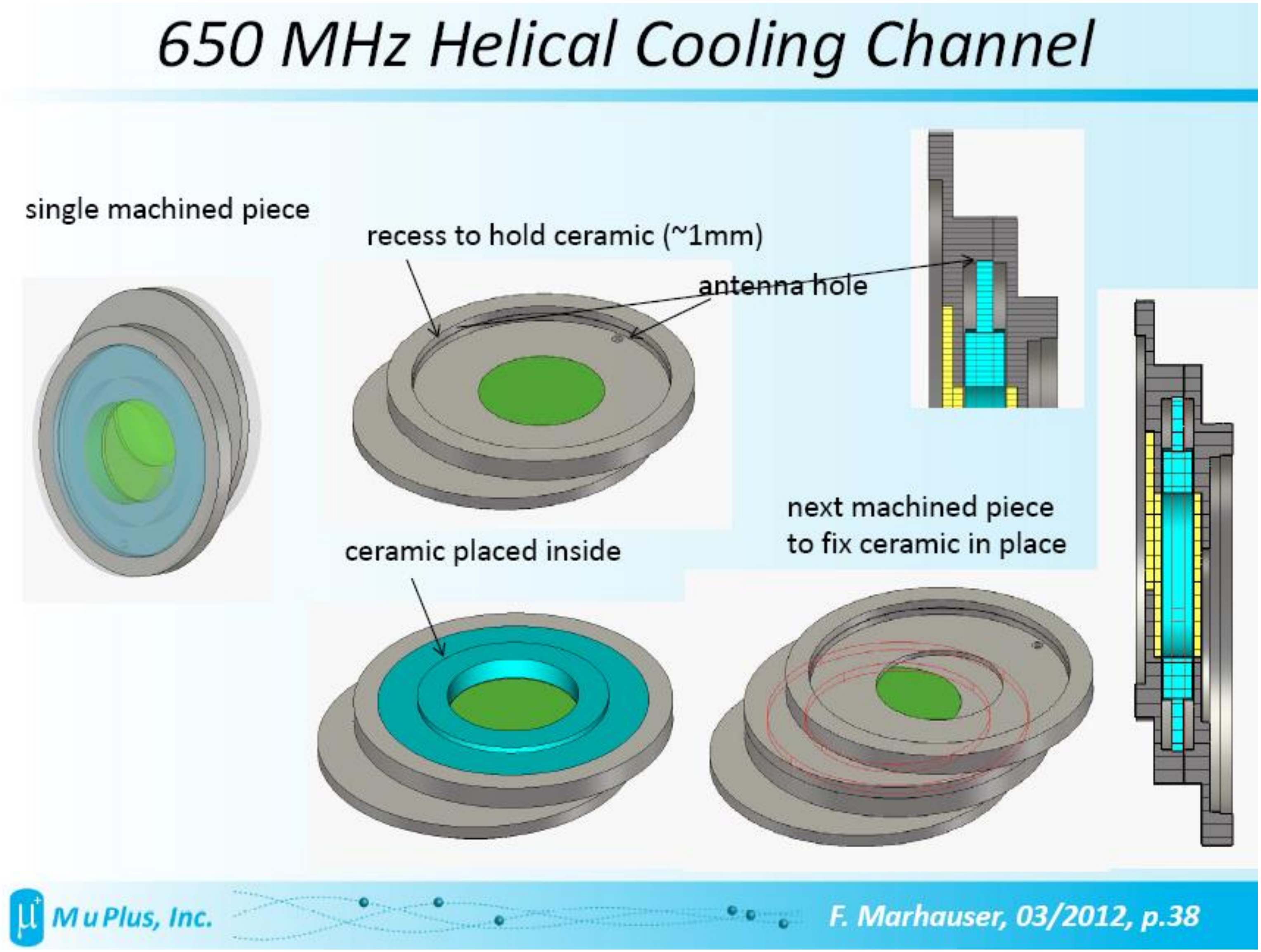
	Z	b	b'	b_z	λ	ν	ε_T	ε_L	ε_{6D}	ε
unit	m	T	T/m	T	m	GHz	mm rad	mm	mm3	Transmission
1	0	1.3	-0.5	-4.2	1.0	0.325	20.4	42.8	12900	
2	40	1.3	-0.5	-4.2	1.0	0.325	5.97	19.7	415.9	0.92
3	49	1.4	-0.6	-4.8	0.9	0.325	4.01	15.0	10.8	0.86
4	129	1.7	-0.8	-5.2	0.8	0.325	1.02	4.8	2.0	0.73
5	219	2.6	-2.0	-8.5	0.5	0.65	0.58	2.1	3.2	0.66
6	243	3.2	-3.1	-9.8	0.4	0.65	0.42	1.3	0.14	0.64
7	273	4.3	-5.6	-14.1	0.3	0.65	0.32	1.0	0.08	0.62
8	303	4.3	-5.6	-14.1	0.3	1.3	0.32	1.0	0.07	0.60

- Use analytical EM field
- GH2 pressure = 160 atm
- 60 μm Be RF window
- E ~ 27 MV/m

A big mismatching appears due to RF frequency change

Schematic view of HCC RF segment

F. Marhauser



Recent result of dielectric loaded gas-filled RF cavity

L. Nash et al., IPAC'13 TUPFI068

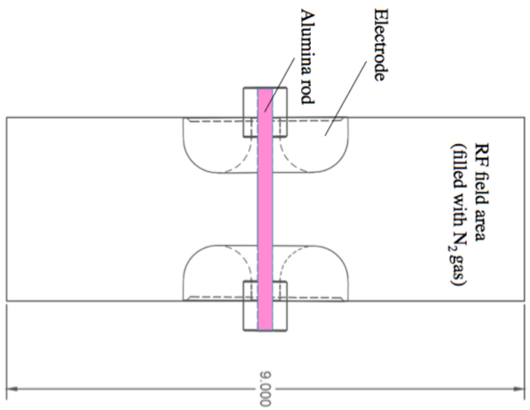
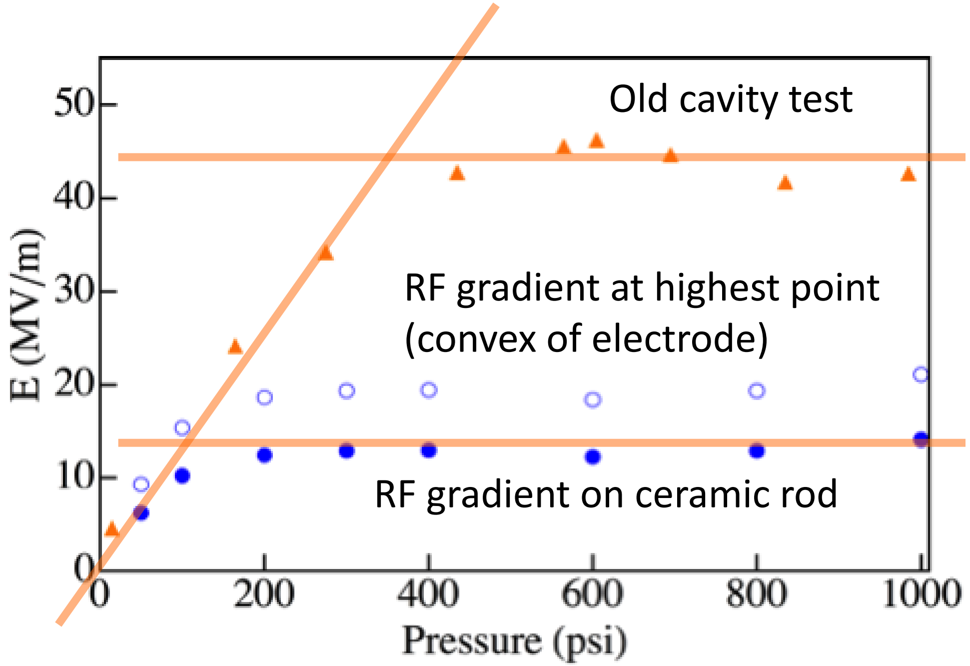


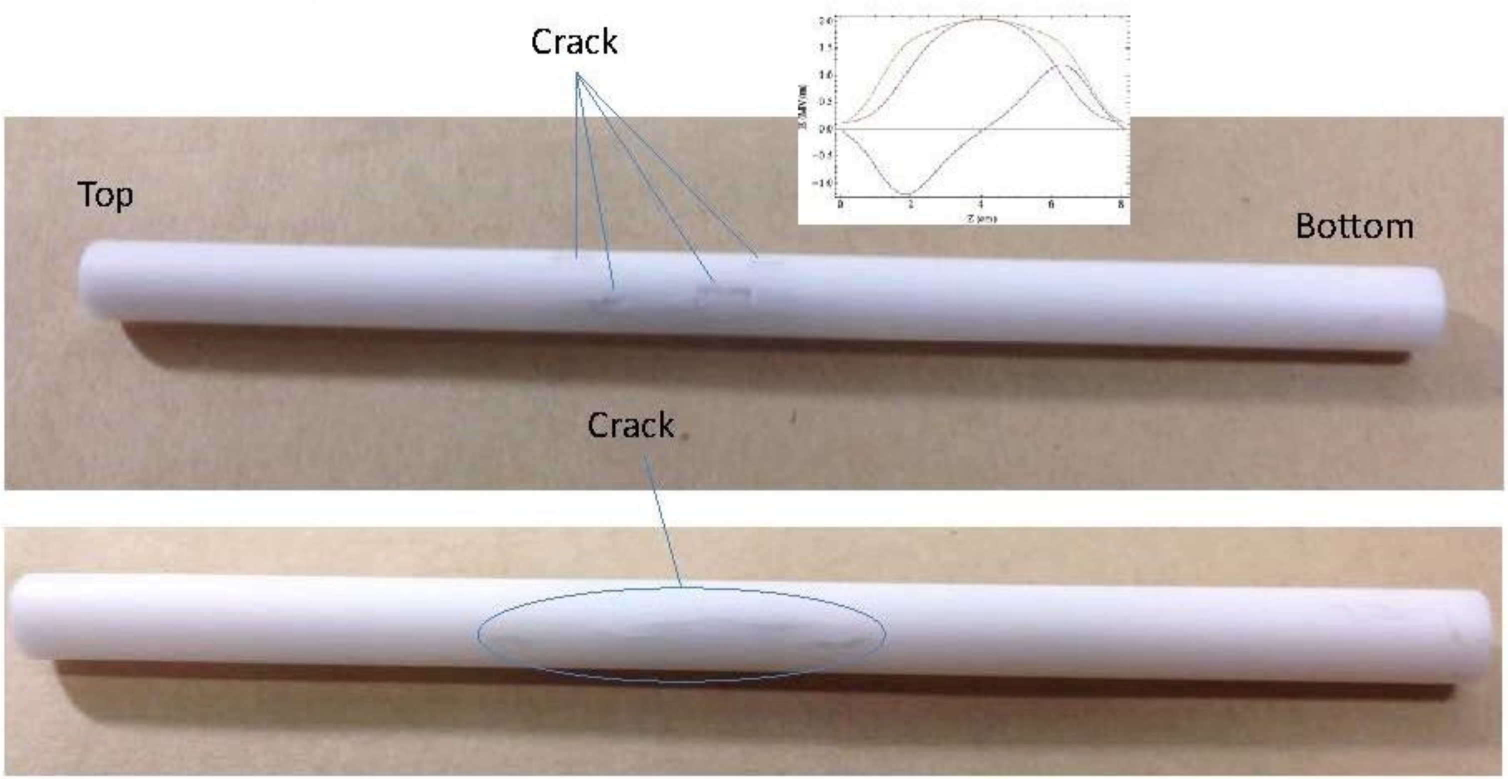
Table 1: Specification of tested alumina (Al_2O_3) rod.

Property	Value	Unit
Length	4	inch
Width	0.25	inch
Purity	99.8	%
Relative dielectric constant	9.6	
Loss tangent	10^{-4}	
Dielectric strength	16.7	MV/m



- Open blue circle: peak E at electrode
  Close blue circle: surface E
- Compare old result (orange)
- At p < 200 psi, observed peak E (open circle) shows gas BD
- At p > 200 psi, observed peak E shows a plateau
- This limit seems to be determined by the surface E since it is close to the dielectric strength

High pressure gas suppresses breakdown even when alumina dielectric fails at 12 to 14 MV/m in test cell



- Since bottom part of rod is inserted to the rod holder deeper than top location of cracks is the middle of cavity that is the highest RF gradient

4/24/13 Dielectric loaded HPRF test 9

Summary of RF activity

- Gas filled RF cavity seems to be feasible even most severe muon collider beam parameters
  – Investigate collective & space charge effects in PIC simulation
- Surface breakdown of dielectric material seems to be suppressed by buffer gas in the cavity
  – Need dielectric material with higher dielectric strength
- Magnetron seems to be a good RF source for HCC RF
  – Inexpensive (<$2/W vs $5 to $10/W for klystron or IOT)
  – Efficient (~85% vs 50-60% for klystron or IOT)
  – Frequency and phase stabilization are an issue for accelerators
  – Muons, Inc. has several relevant projects underway.

In next 18 months

- Construct part of a Nb_3Sn HCC segment
- Continue studies of gas filled RF cavities
  - Find and test better dielectric materials
  - Investigate possible 77 K operation
  - Develop magnetron RF source
- Mechanical design of 1-m HCC segment
  - Make everything fit and easy to build and maintain
  - Cryostat design with constraints
  - GH2 containment and pressure system code requirements
- Simulations and calculations
  - Optimize design for 6D cooling demo, study tolerances,…