Muon Ionization Cooling R&D

1. Cooling channel ingredients / R&D Issues
2. RF
3. Liquid Hydrogen Absorbers
4. Solenoid Design
5. Summary / Remarks

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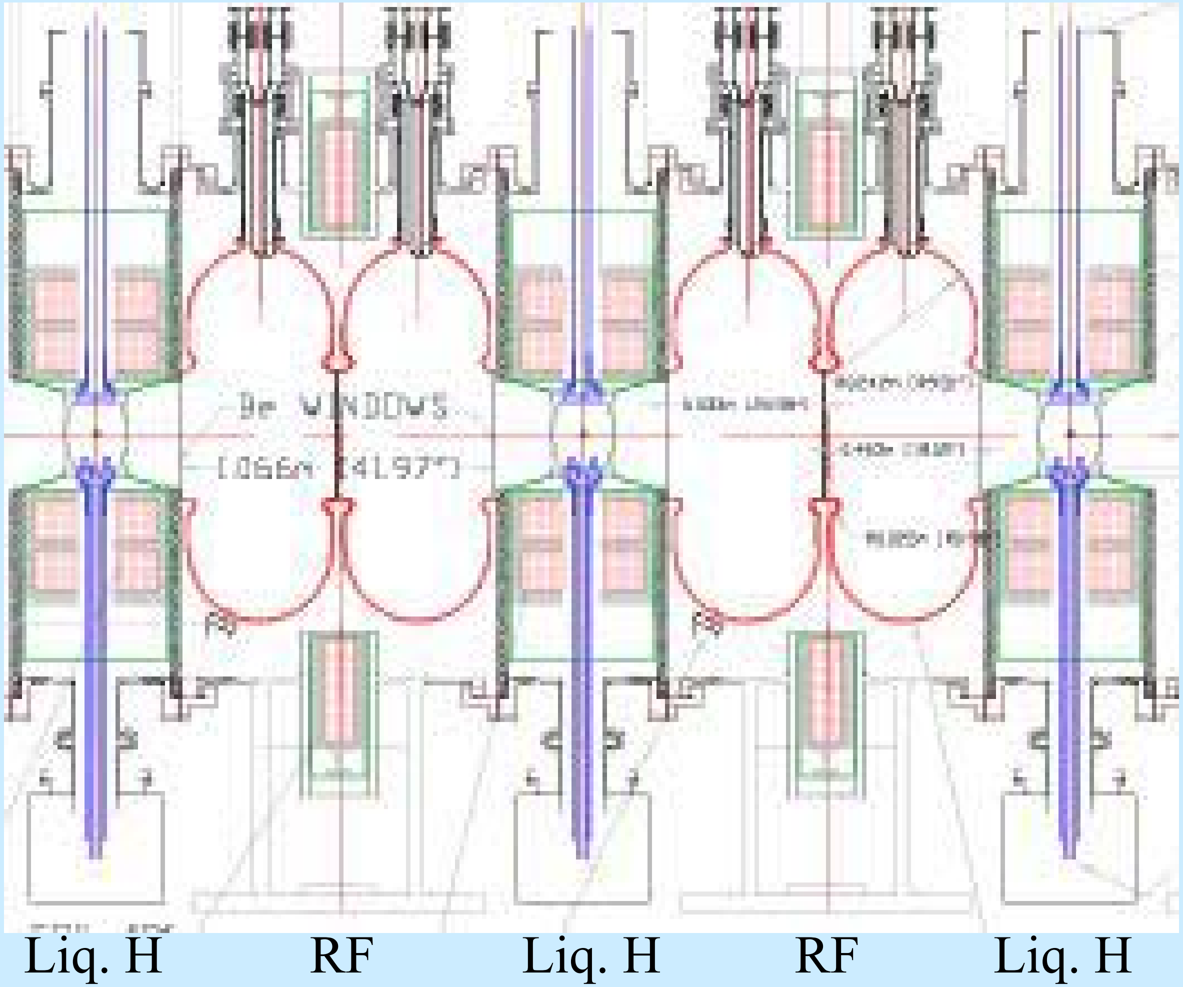
Muon Cooling R&D

Muon cooling channels (for Neutrino Factories and/or Muon Colliders) require high-gradient NCRF cavities, liquid hydrogen absorbers, and a lattice of multi-Tesla solenoids.

Detailed simulations have established that an ionization cooling channel will work provided its components meet the aggressive performance criteria that are assumed in the design.

Muon ionization cooling R&D is required to develop components that can meet the required performance criteria, establish that there are no unforeseen issues, and demonstrate the performance of a test channel.

Muon Cooling Channel Ingredients



Basic Ingredients:

Absorbers – presently assumed to be liquid hydrogen

RF Cavities – presently Assumed to operate at 200 MHZ

A lattice of SC Solenoids providing on-axis fields of a few Tesla

R&D Issues

The cooling channel component parameters depend on the cooling channel lattice details, and will evolve with time as designs improve. However, many of the basic R&D issues do not depend on the lattice details.

1. Can NCRF cavities be built that provide the required peak accelerating gradients, and operate within multi-Tesla fields?

2. Can the heat from dE/dx losses be adequately removed from the absorbers?

3. Can the channel be engineered with an acceptable amount of additional (non-absorber) material (absorber-, RF-, & safety-windows) in the channel?

4. Can the channel be disgned/engineered so that it is cost-effective?

RF Requirements

The RF fields must restore the longitudinal momentum lost in the absorber AND keep the muon bunch captured longitudinally.

To keep the bunch captured it must arrive away from the RF crest.

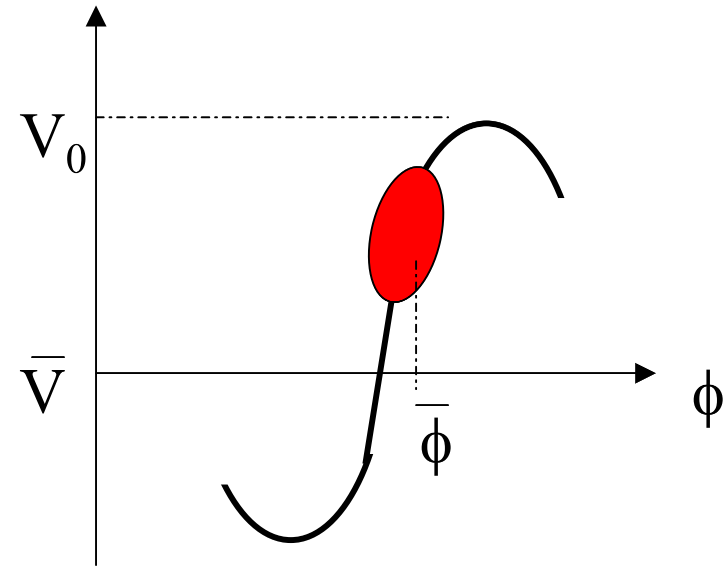
The peak gradient E_0 must be sufficient to keep the muons captured.

The cavity transverse dimensions must be sufficient to contain the beam → low frequency cavities.

Detailed simulations determine acceptable cavity parameters :

200 MHz Cavities with V_0 = 17 MV/m
→ Peak surface field $E_S \sim 26$ MV/m

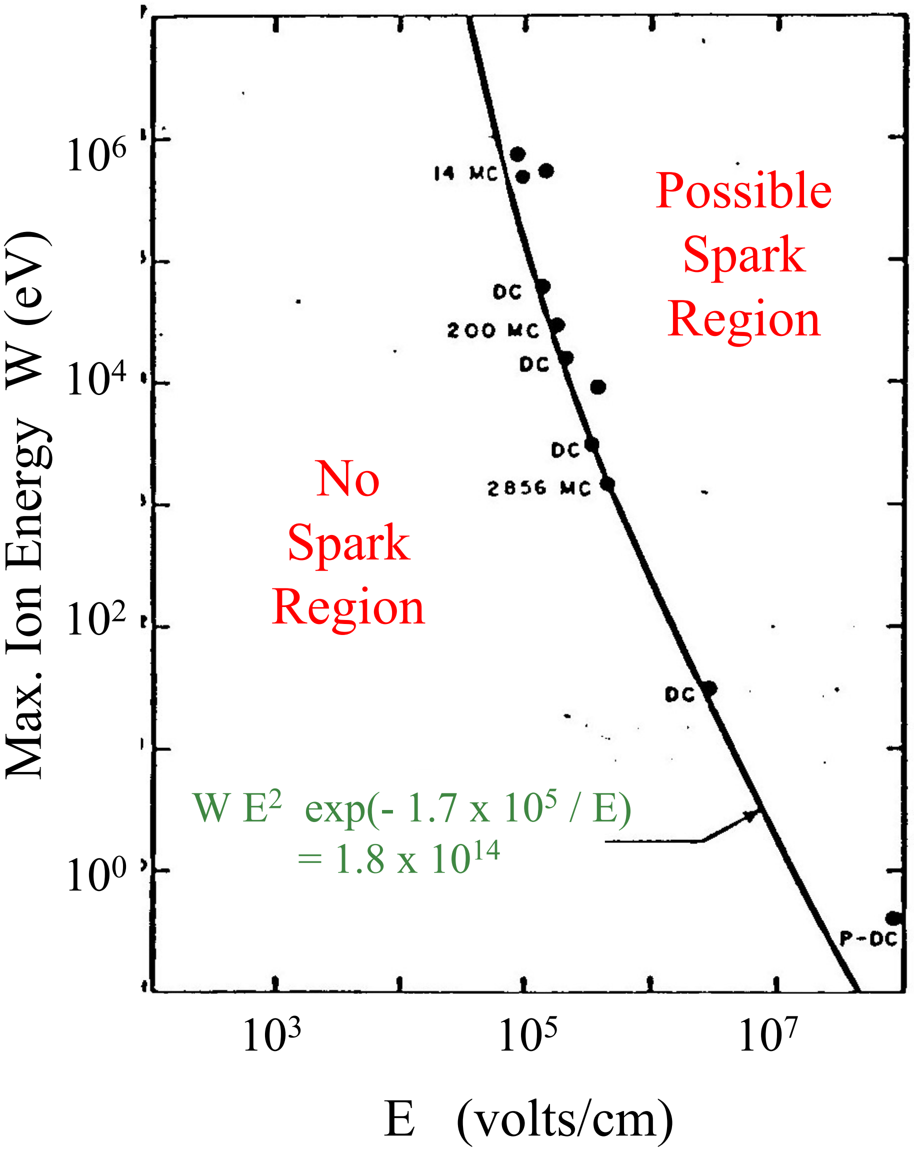
$$V_{rf} = V_0 \cos(2\pi f_{rf} t + \phi)$$



Typically $\bar{\phi} \sim 10$ - 20^o

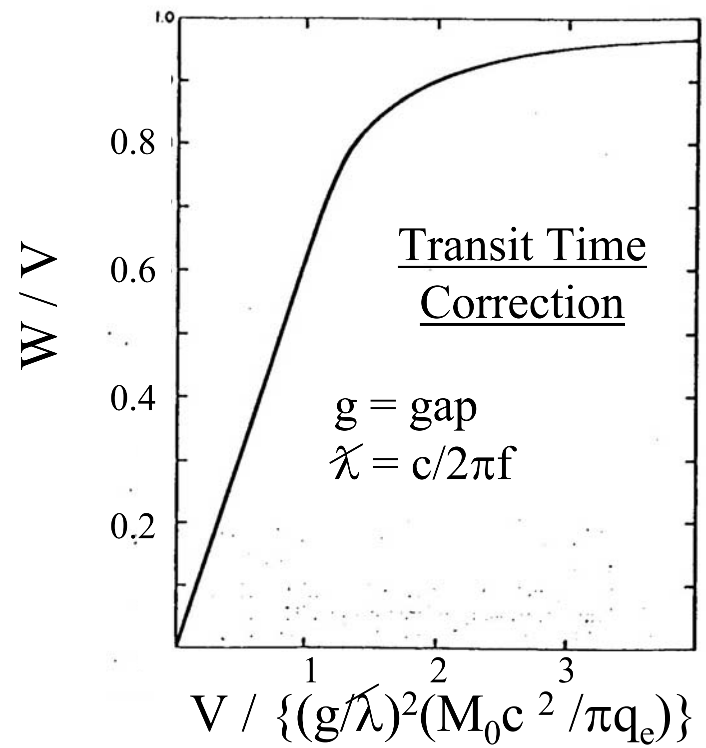
→ $\bar{V} \sim 12$ MV/m

RF Breakdown - 1



Criteria for sparking in a vacuum was addressed by Kilpatrick (Rev. of Scientific Instruments 28 (1957) 824) → empirical relation based on electron field emission probability and a linear dependence of secondary emission on ion energy.

For RF breakdown, the maximum ion energy W must include a correction for transit time & phasing effects:



RF Breakdown - 2

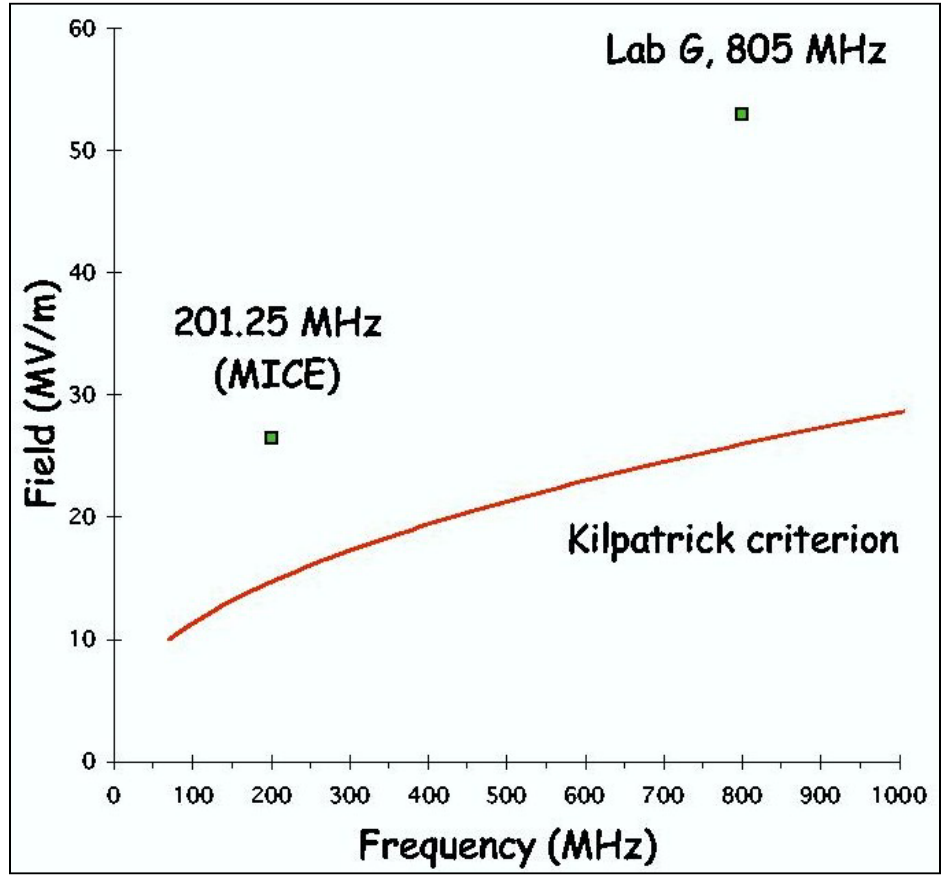
For a surface field E_S, the Kilpatrick criteria:

$E_S \exp(-4.25 / E_S) = 24.7 \; [f(\mathrm{GHz})]^{1/2}$ MV/m

These days, with aggressive RF "processing" we can do much better than the Kilpatrick limit. An updated empirical criteria is that the maximum surface field that can be maintained before the onset of breakdown is:

$$E_S = 220 \; [f(\mathrm{GHz})]^{1/3} \; \mathrm{MV/m}$$

This criteria is based on data in the GHz to tens of GHz region, and is empirical with no deep theoretical foundation.



What about the few x 100 MHz range ?
→ Interesting R&D to be done.

RF Power Issue

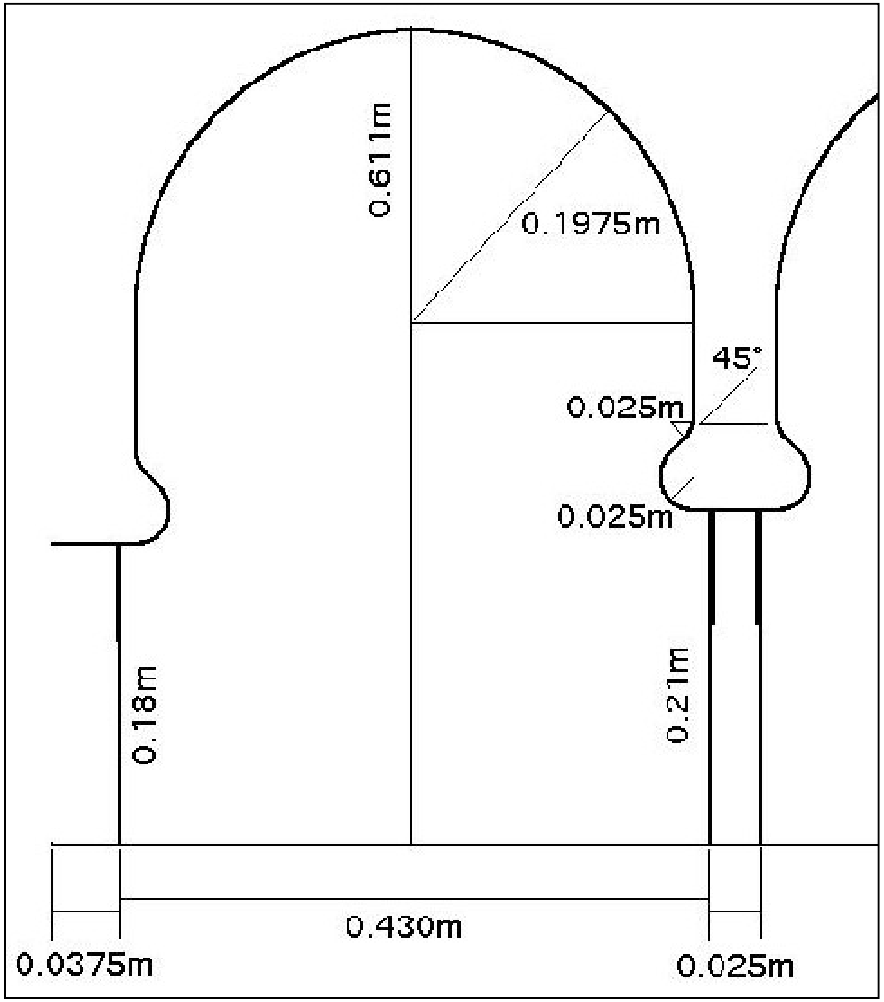
RF power sources are expensive, and are currently estimated to account for ~ 1/3rd of the total cost of the cooling channel. We need to minimize the number of power sources we require.

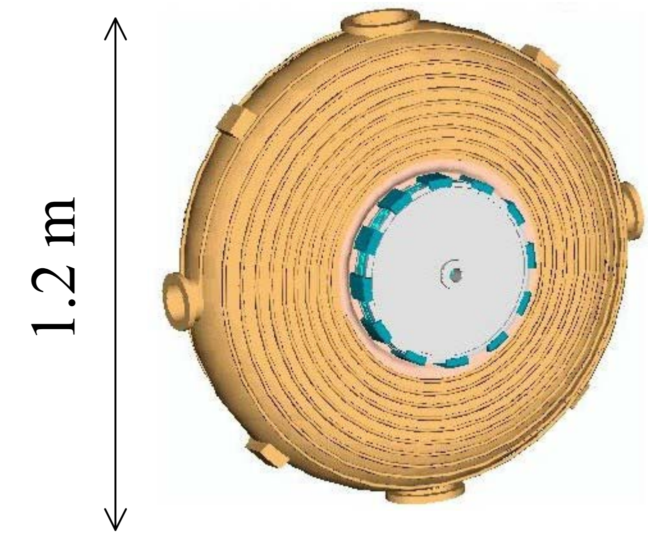
The number of power sources is determined by the total peak power requirements.

RF cavities usually have open apertures. However muons are penetrating particles and we can therefore close the aperture with a thin low-Z (minimize scattering) conducting membrane → "pillbox cavity".

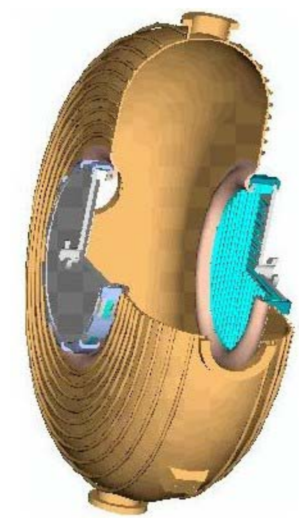
The advantage of a pillbox cavity is that, for a given peak power, the accelerating gradient on axis is double that of an open cell cavity.

200 MHz Cavity Design



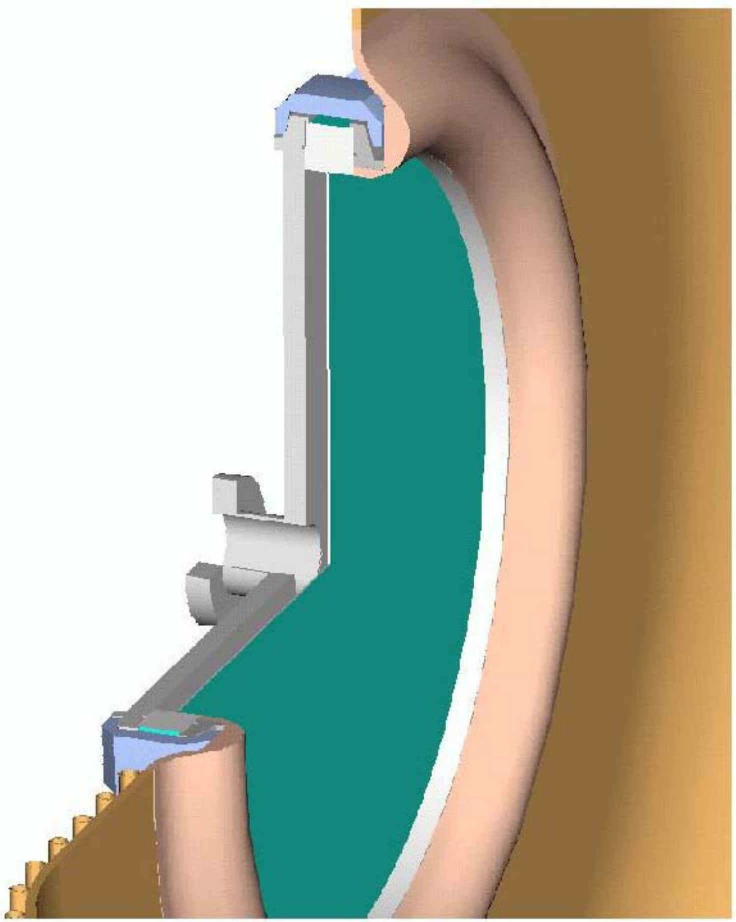


NOTE: 200 MHz cavities are BIG !

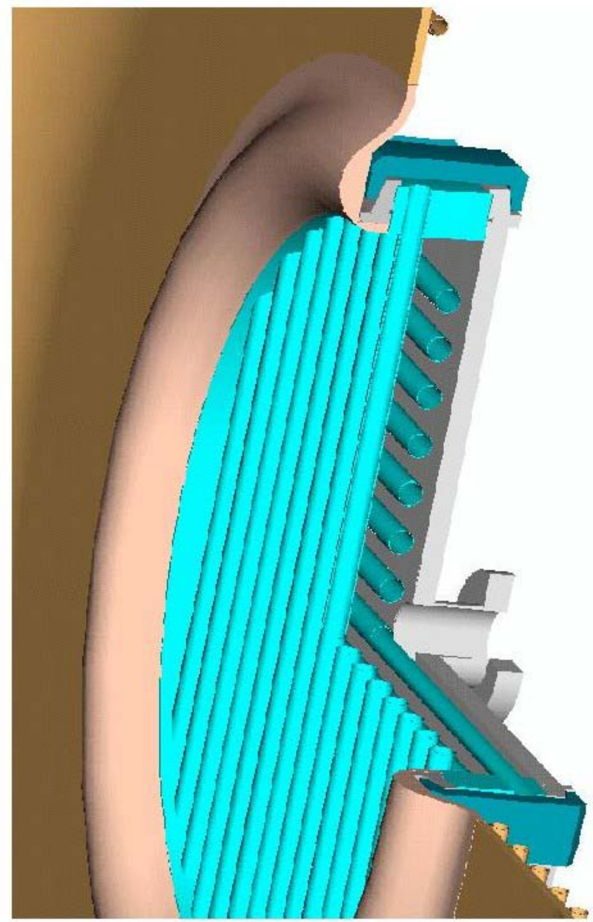


RF Cavity Design: Windows or Grids

Two alternative "membrane" designs are being pursued:



Thin Beryllium foils



A Grid of Thin Hollow Tubes

RF R&D Issues

1. RF currents will heat the foils/grids. If they move too much the cavity will be detuned. Foil/grid support and cooling are R&D issues.

2. Can the desired peak gradients be attained ? Breakdown (sparking) ultimately limits the achievable gradient. The higher the gradients we can safely achieve the better the performance of the cooling channel. What is the highest achievable gradient ?

3. Is the desired gradient achievable in a multi-Tesla magnetic field ? Is it achievable if there is a large magnetic field gradient ? The answers to these questions may place constraints on cooling channel lattice design.

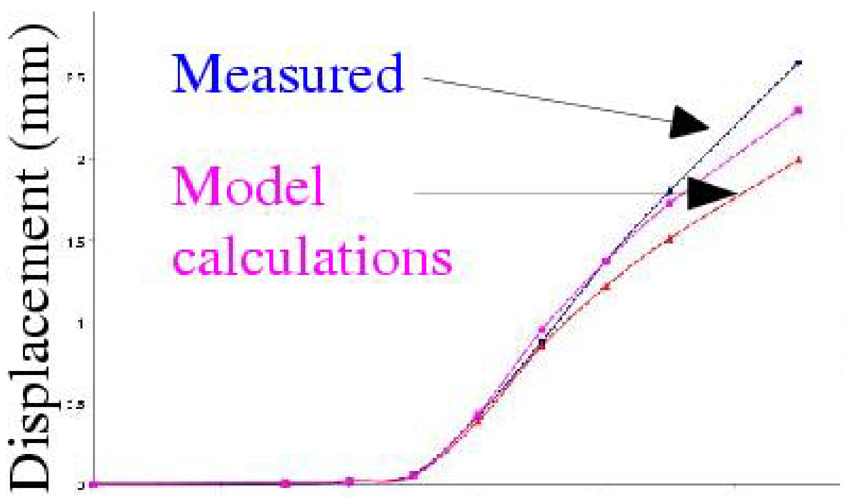
4. When there is a breakdown (there is always some sparking) what happens to the foils/hollow tubes ?

5. Is there a problem with multipactoring given the "parallel plate" type of geometry (multipactoring = resonant phenomenon in which electrons emitted are accelerated to opposite surface, hit the surface to produce more electrons which are accelerated to initial surface, etc.)

Be Window Tests

It is easier to test the cavity design concepts with smaller cavities. For historical reasons we chose 805 MHz cavities (we have power sources at Fermilab for 805 MHz and 201 MHz cavities).

Build an 805 MHz test cavity with 0.005" thick Be windows, heat the windows up with a heat lamp, and measure the window displacement.

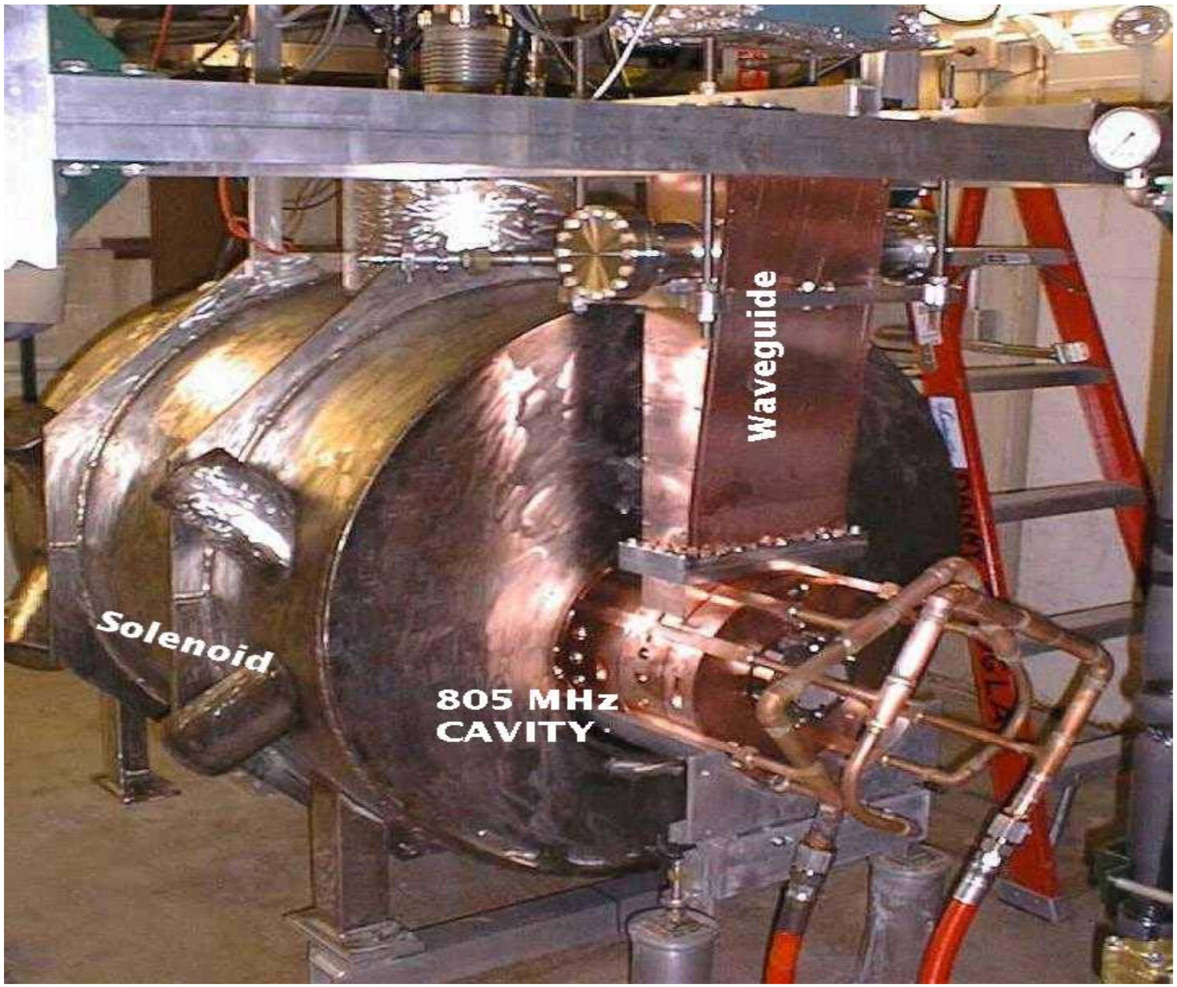


Window Displacement vs Power dissipated

The window is pre-stressed so low powers do not displace it. Beyond a threshold the window displacement is linear with power dissipation … and this can be reproduced by calculations. At large powers the increase in displacement is non-linear.

MUCOOL 805 MHz Test Setup

To study achievable RF gradients and breakdown issues we need a high power test facility …



Located at Fermilab Lab G

12 MW klystron

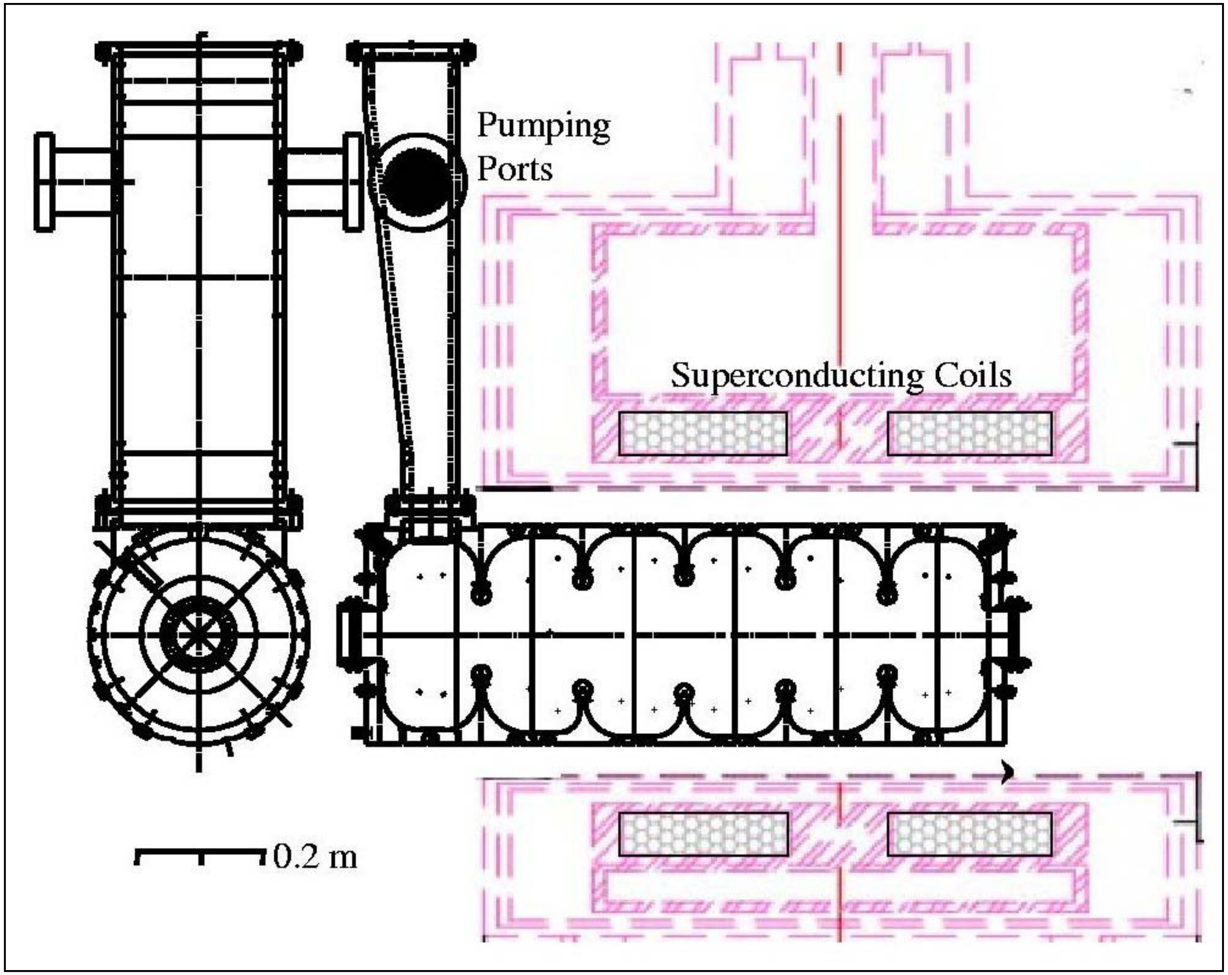
Linac-type modulator & controls

X-Ray cavern

5T two-coil SC Solenoid

Dark-current & X-Ray instrumentation

MUCOOL 805 MHz Open Cell Cavity Test



The first high-power tests were made with a 6-cell copper cavity – open cells.

Cavity geometry is a little complicated for the initial studies, but enabled the first look at dark current & breakdown issues and the effect of having the cavity within a multi-Tesla axial magnetic field.

RF breakdown mechanisms are not well understood in detail → systematic studies can teach us more

First MUCOOL RF Results

(i) The cavity was operated with no magnetic field (Peak Surface gradient: 53 MV/m, peak cell accel. gradient: 23.5 MV/m for end cells)

(ii) With magnetic field on the cavity needed to be re-conditioned. After reconditioning the dark currents were roughly (factor few) comparable to their field-off values.

(iii) Cavity operated at full power with B = 2T.

(iv) Breakdown punched a hole through the 0.005” Ti window during conditioning with B=2.5T.

Results described in J. Norem et al., submitted to PRST/AB

Dark Current

Dominant source of dark current is from field emission of electrons from specific sites where E is high. The current density (A/m^2) for conduction electrons tunneling through a modified potential barrier at an ideal clean flat metal surface in an applied electric field is described by the Fowler-Nordheim equation:

$$j(E) = \frac{A_{FN}(\beta_{FN}E)^2}{\phi} \exp\left(\frac{B_{FN}\,\phi^{3/2}}{\beta_{FN}E}\right)$$

$A_{FN} = 1.54 \times 10^6$, $B_{FN} = 6830$

E = electric field (MV/m)

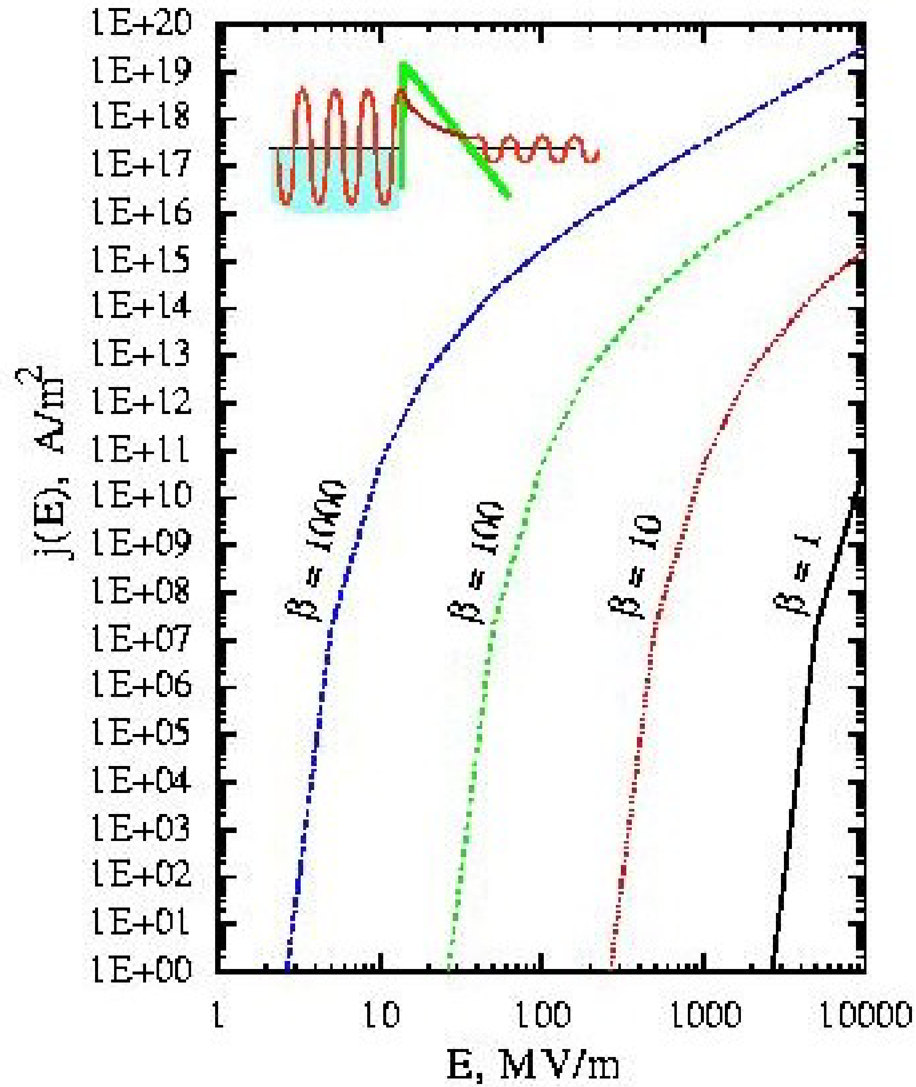
ϕ = work function of the material (eV)

β_{FN} expresses enhancement of the local electric field at the assumed pointlike source

$$I(E) = A_{rf}\, A_e\, j(E) \quad \text{amps}$$

A_e = emitter area

A_{rf} corrects for the sinusoidal field



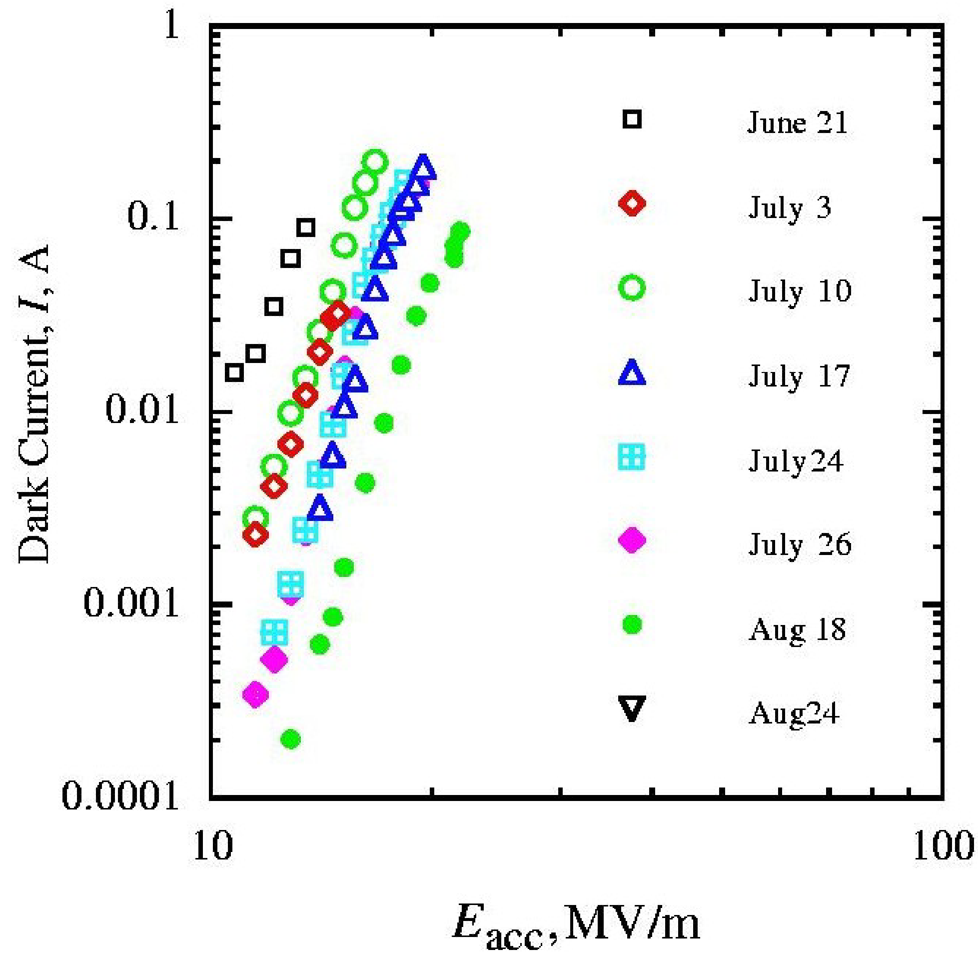
Cavity Conditioning

When a new cavity is first powered the maximum achievable field is relatively modest, limited by radiation levels and/or sparking. After running for some time at these lower fields, the field can be increased … then run some more, then increase again etc.

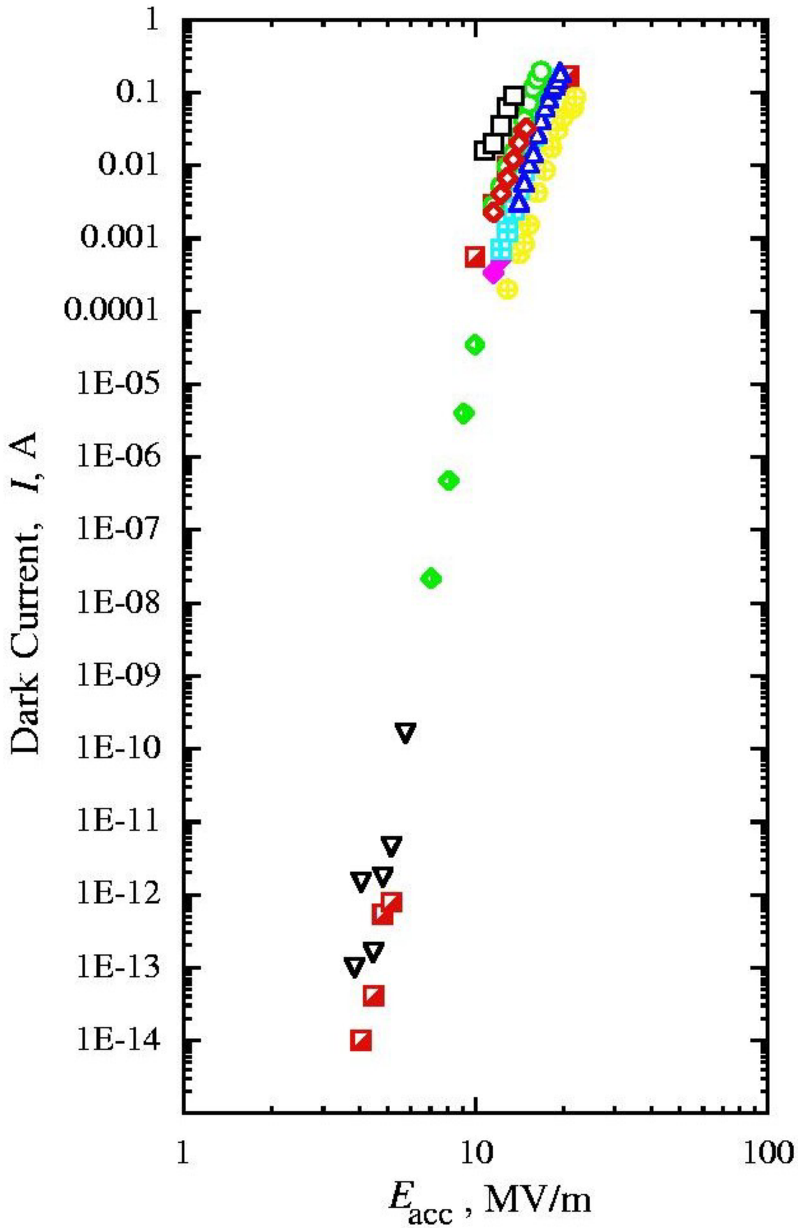
The belief is that, in this conditioning process, imperfections on the cavity surface are being "burnt off".

Conditioning can take days or weeks. For the MUCOOL open cell cavity it took several weeks, during which the dark current dropped by about two orders of magnitude.

Conditioning history for the MUCOOL open cell 805 MHz cavity

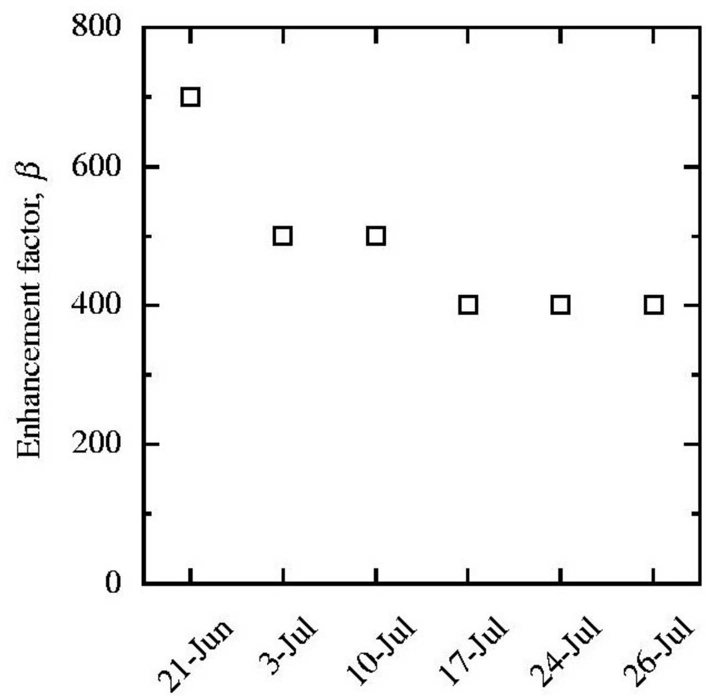


Dark Current Results



The measured E-dependence is consistent with the Fowler Nordheim equation … the dark current increases roughly as $E^9 - E^{10}$.

Fitting the data for and yields A_e (plagued with normalization systematics) and the field enhancement factor β_{FN} :



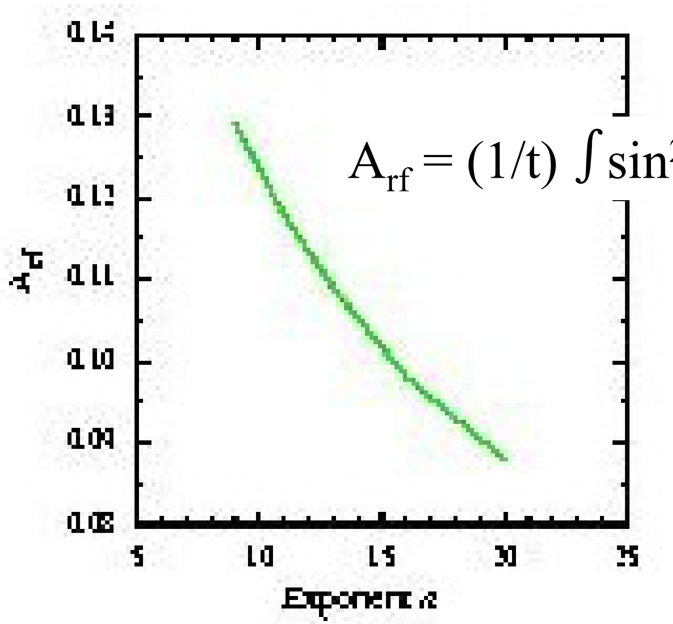
These values are large.

Typically values of β_{FN} = 40 – 100 are obtained.

Dark Current Pulse Shape

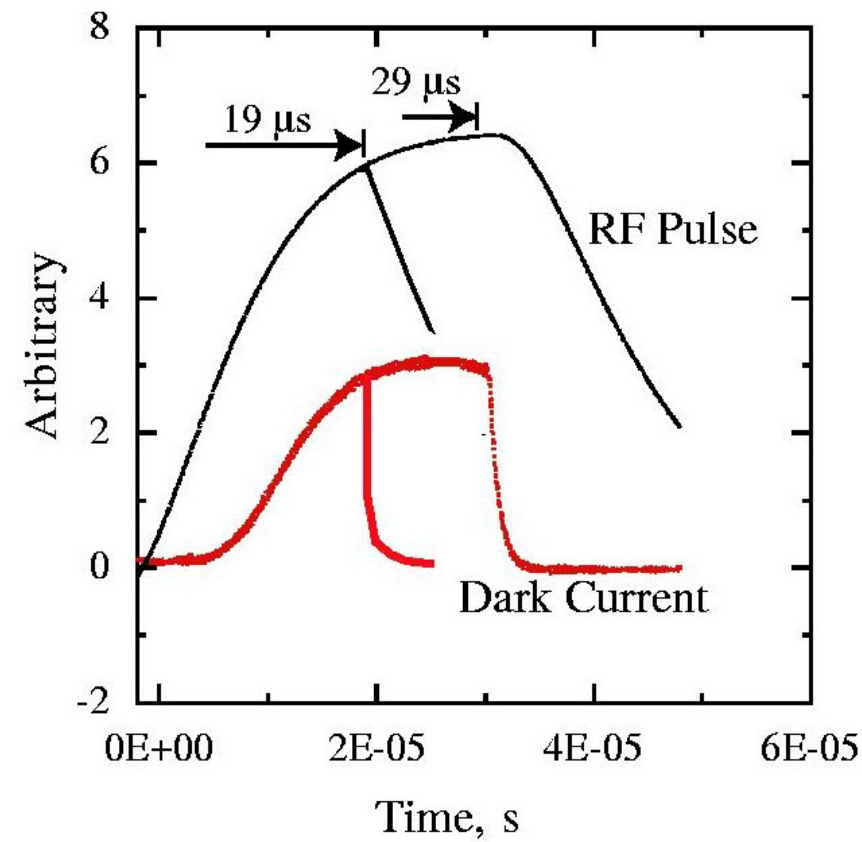
The dark current emerging from the cavity window (0.005" Ti, 0.125" Al) can be measured with a current transformer.

The dark current becomes significant only at times when the RF pulse has developed significant fields within the cavity, & then increases rapidly as the cavity fields increase. The dark current pulse for the MUCOOL test lasted ~ 1/10th of the rf cycle



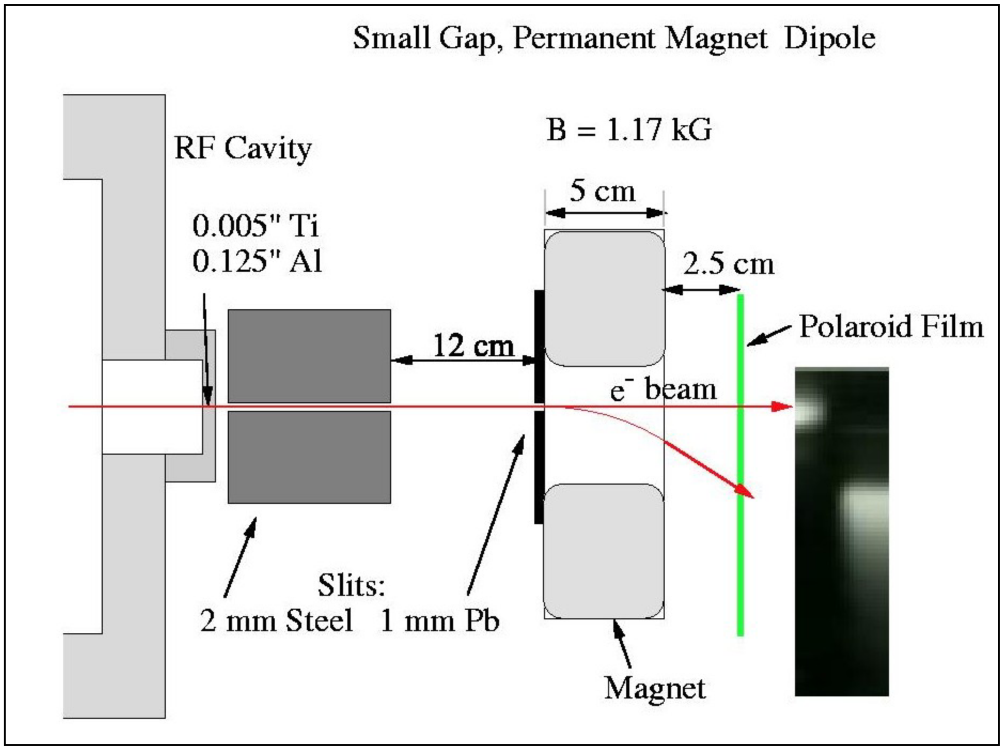
$$A_{rf} = (1/t) \int \sin^2 t \, dt \sim 0.1$$

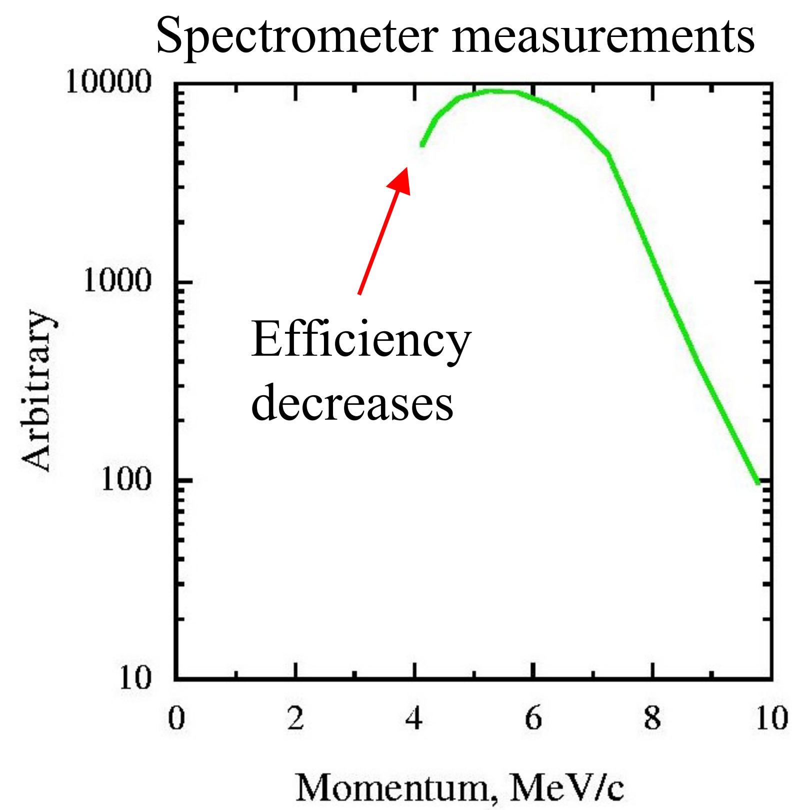
Dark current measured with current transformer



Dark Current Energy Spectrum

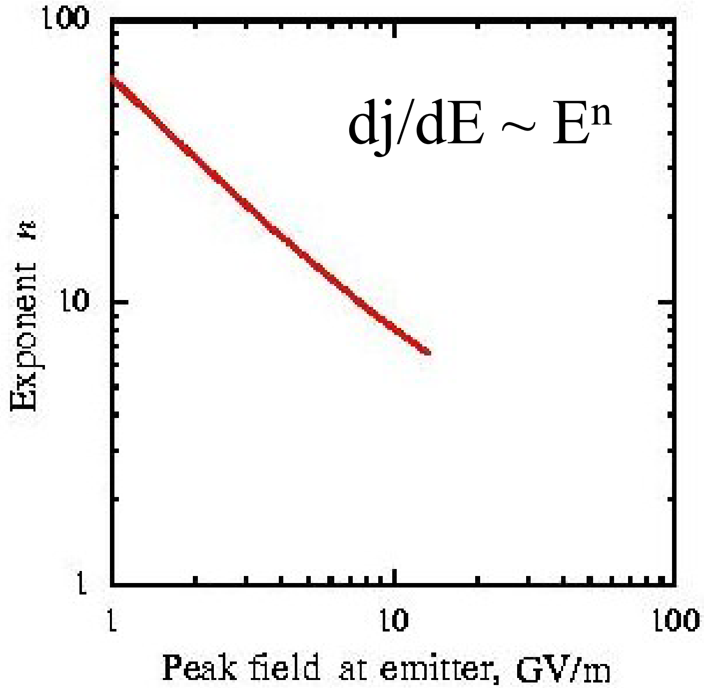
Measure end-point with a magnetic spectrometer, and full spectrum by making range measurements.

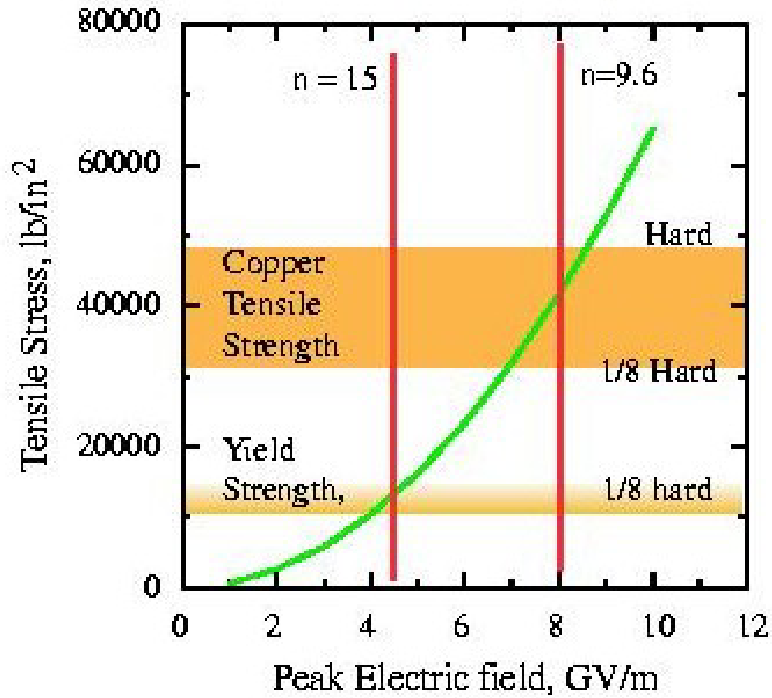




Electron end-point ~ 0.5 E_{acc} L_{cav} which is expected for electrons accelerated in a cavity design for muons with velocity $\beta = 0.85$.

Stress at Emitter Sites





Fowler-Nordheim equation enables us to deduce the field at the emitter, which depends on the exponent n of the dark current field dependence.

Significant dark current implies the emitter field is at least a few GV/m

Tension: $T = 0.5\,\varepsilon_0\,E^2$

For the MUCOOL copper cavity,
T ~ 380 Mpa ~ 40,000 lb/in^2
which is comparable to the tensile strength of copper.

Cavity Damage

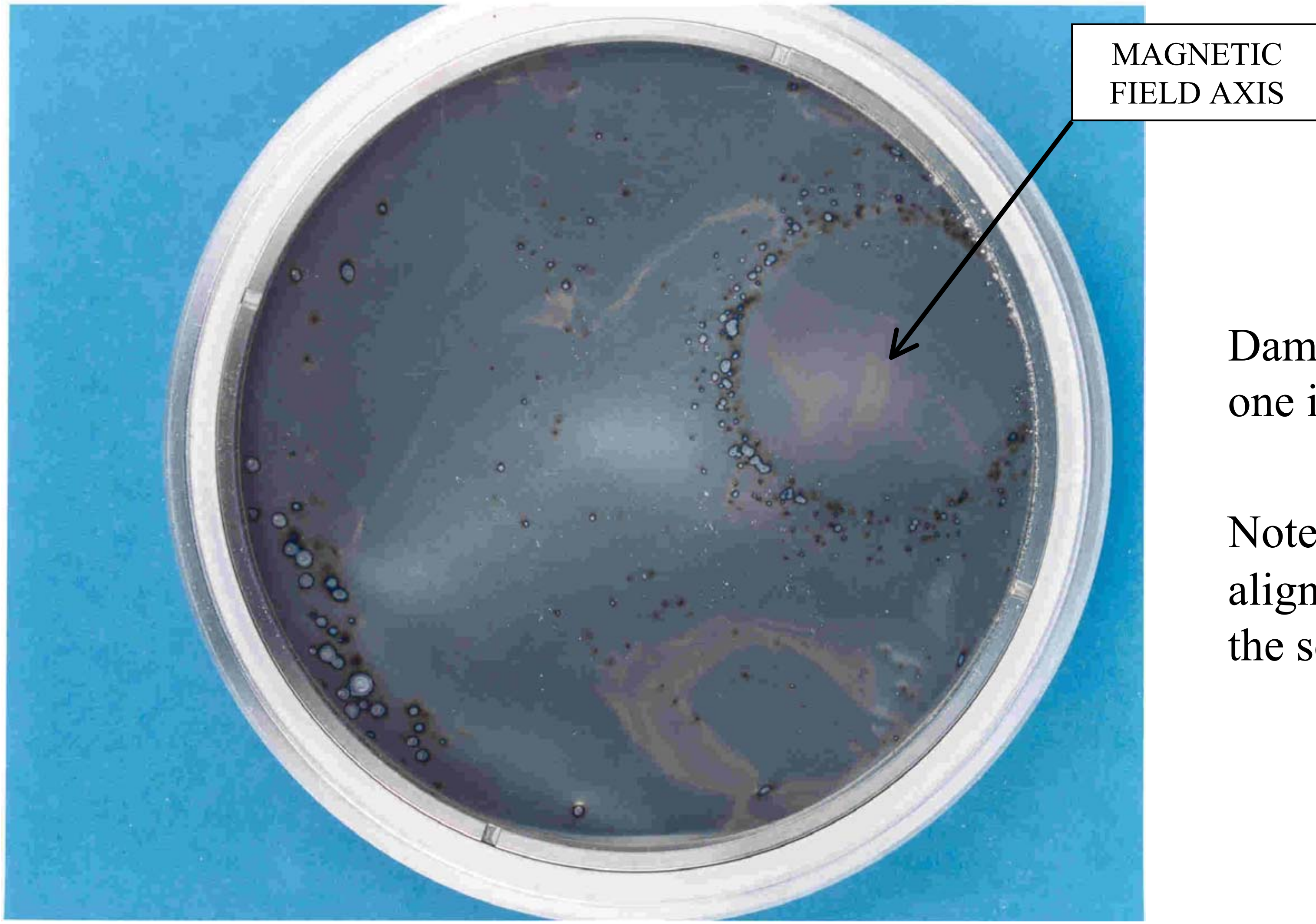
When there is a lot of energy stored in an RF cavity, sparking can cause mechanical damage.

There is always some sparking (1 in 100,000 pulses for example), but if we have thin foils or hollow tubes we must be sure sparking doesn’t destroy them.

After several months of operating the open cell cavity there was a vacuum failure, Which was caused by a 100 micron size hole punched through the 0.005” thick Titanium end-window.

This “event” happened with peak surface fields and gradients much higher than we require for the 200 MHz cavity. However, it gives us an opportunity to learn what can happen if there are large dark currents, and to begin to work on reducing these dark currents and the related sparking rates.

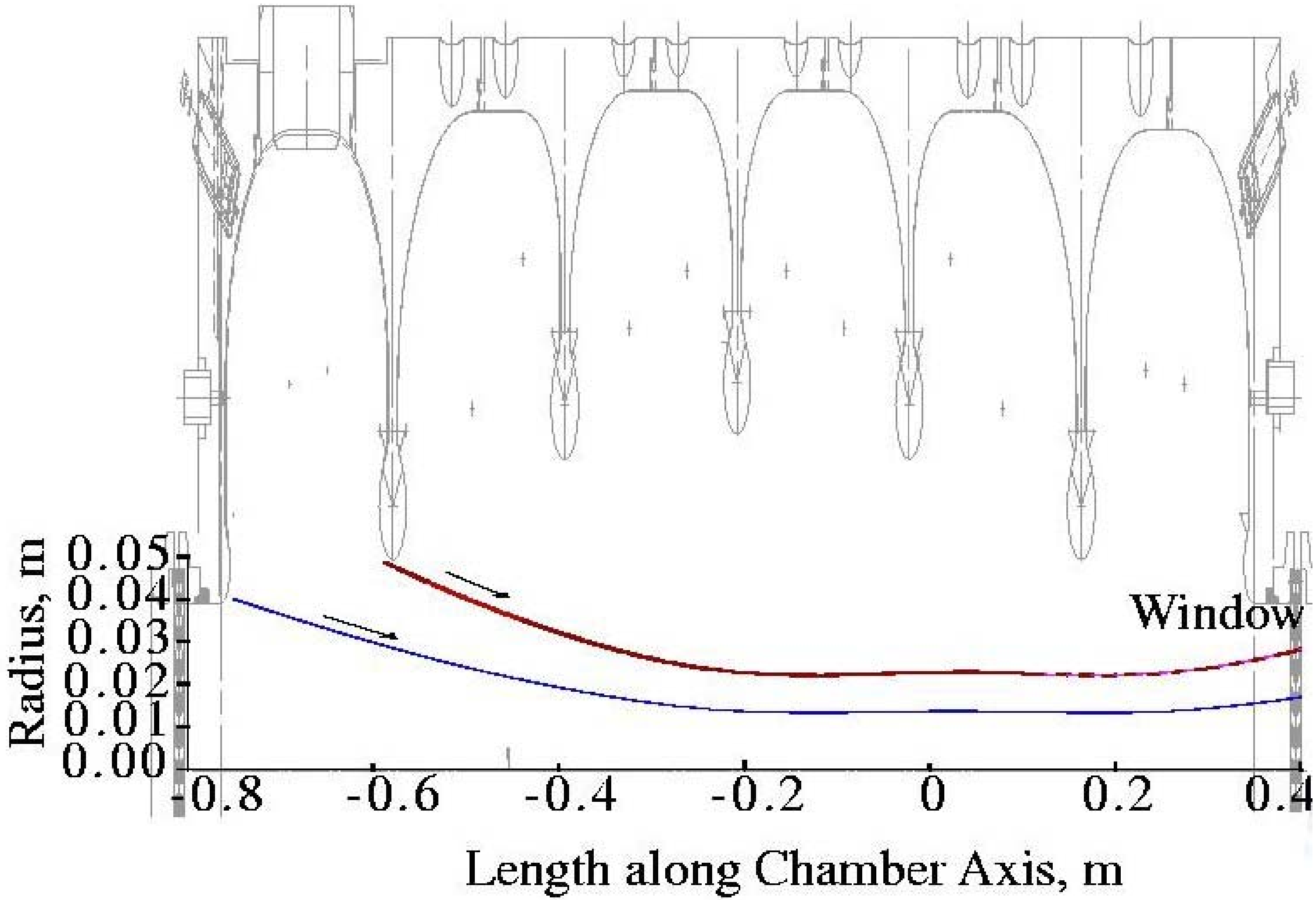
Window Damage



Damaged end is the one inside solenoid

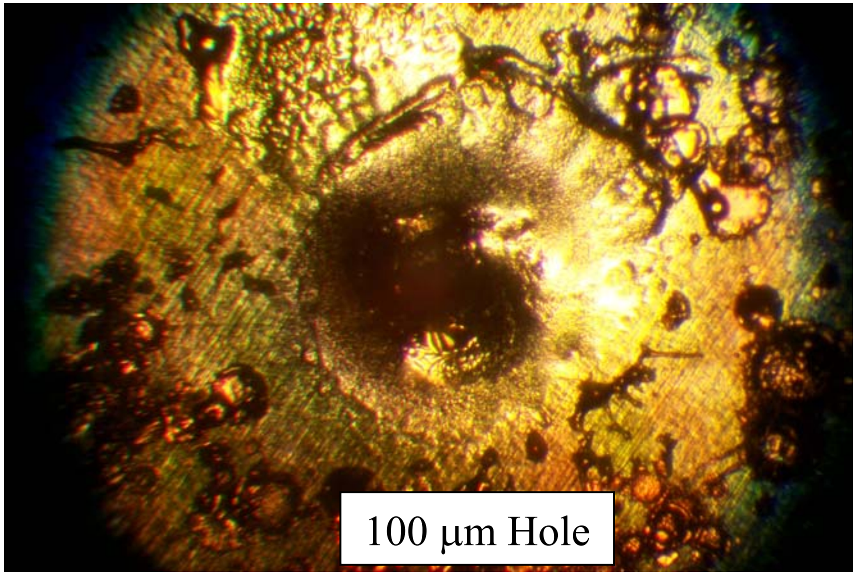
Note: Cavity was not aligned exactly along the solenoid axis

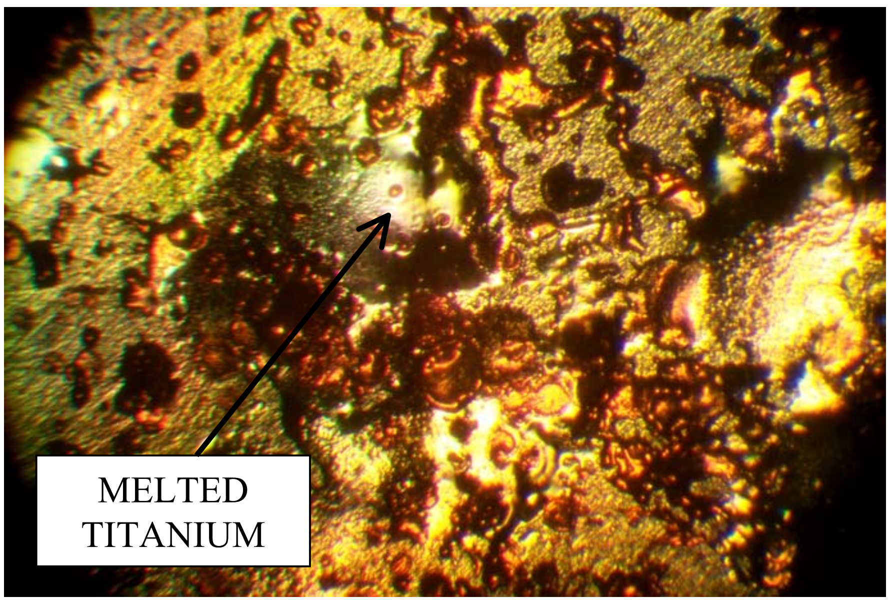
Rings



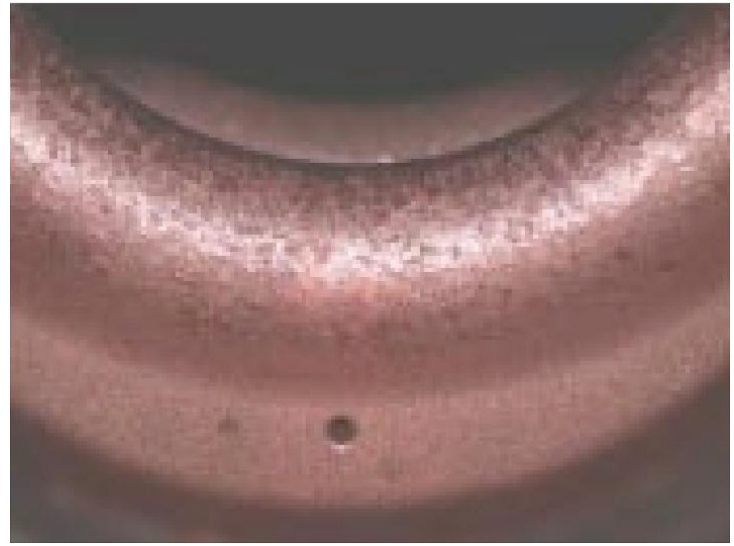
Radius, m
0.05
0.04
0.03
0.02
0.01
0.00
Window
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
Length along Chamber Axis, m

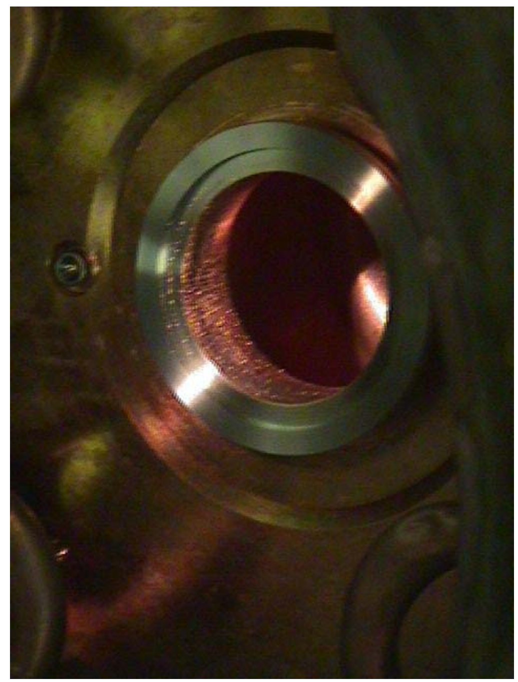
Window Damage

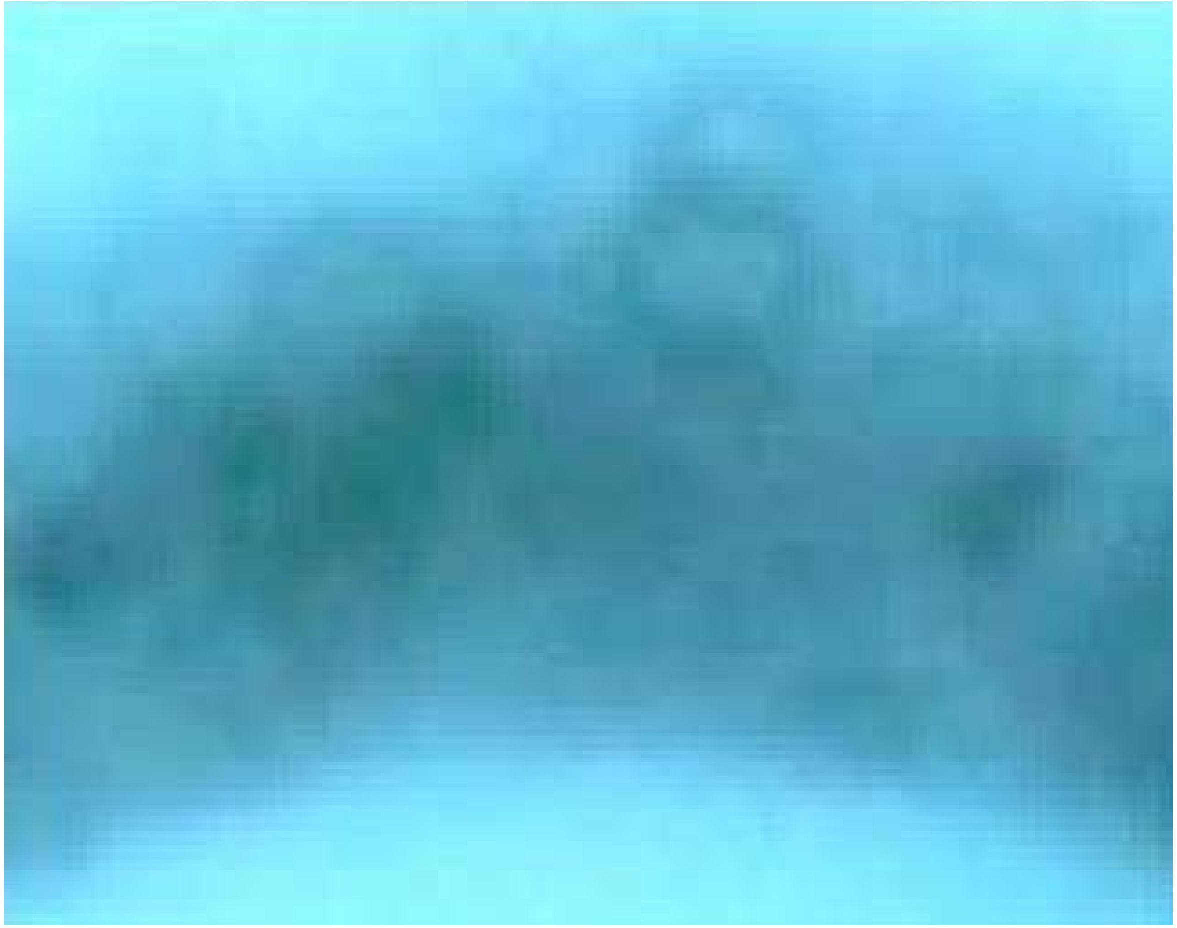




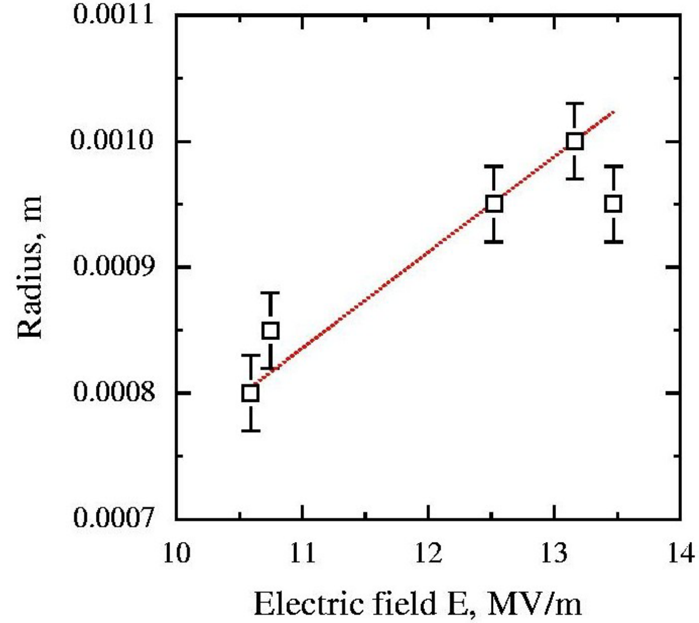
Iris Damage

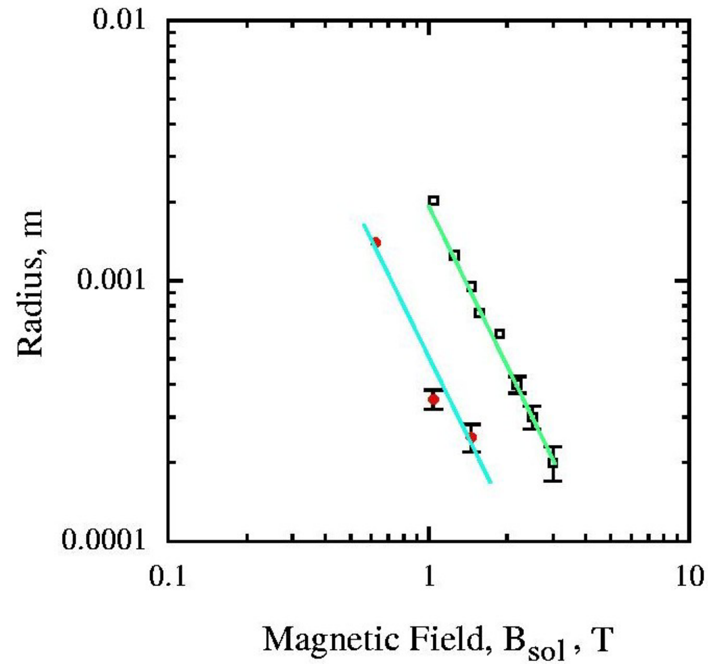






Ringlets on a glass plate exposed to the dark current exiting the end of the cavity



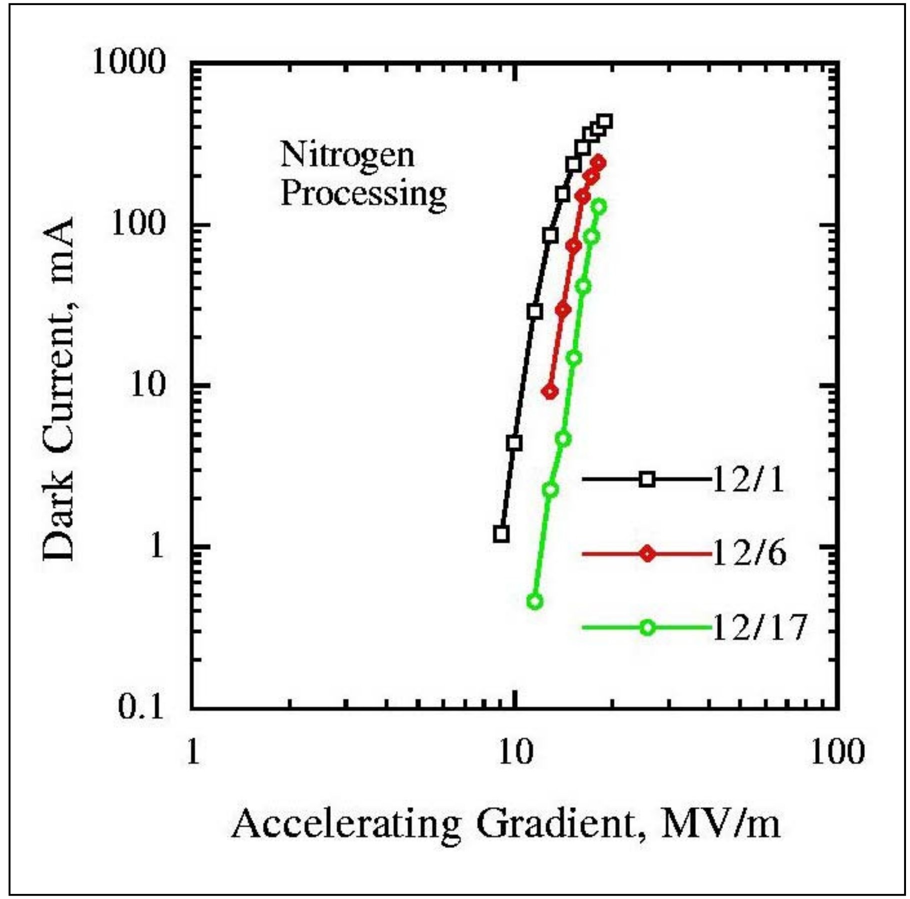


Nitrogen Conditioning

Discharge in a low pressure gas can help clean the surface of a cavity.

After the field studies were complete, the Ti window replaced, the cavity was recondit-ioned with a nitrogen atmosphere, 10^{-5} Torr.

The dark currents were reduced by about 2 orders of magnitude.



Surface Treatment

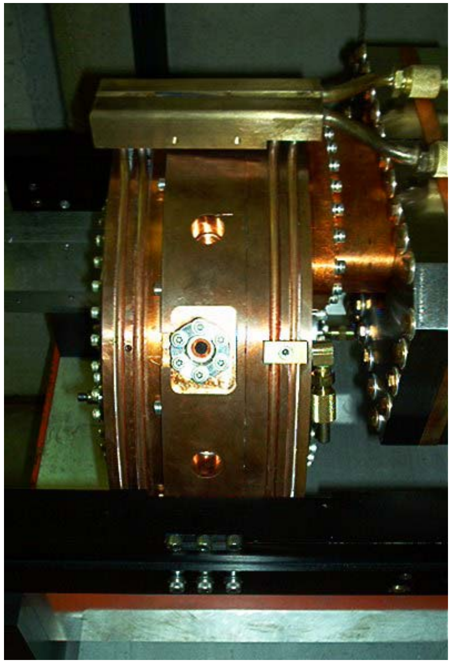
Dark currents, and breakdown rates, can be reduced with carefull preparation of the cavity surface. The recipe used for the open cell cavity:

> Machined using water-soluble lubricant, then cleaned with a micro degreaser, Citronox rub & warm Citronox bath (30 mins) followed by di-water rinse & alcohol rinse. Components bagged in Nitrogen & brazed.

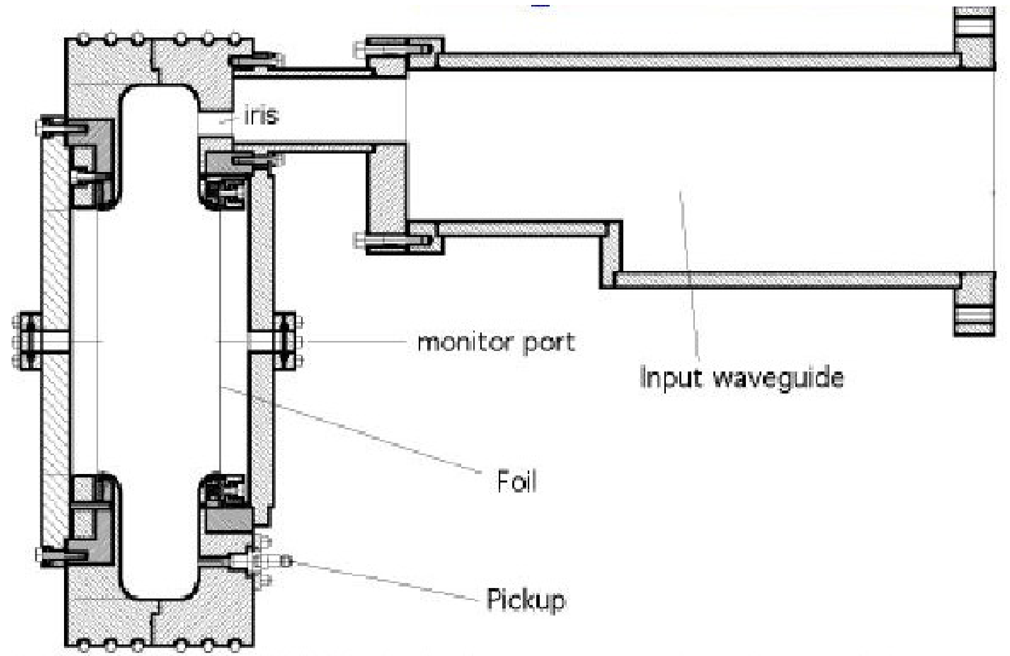
… was not really state-of-art. High-pressure pure water rinse, electro-pollishing … are expected to improve the surface and the cavity performance.

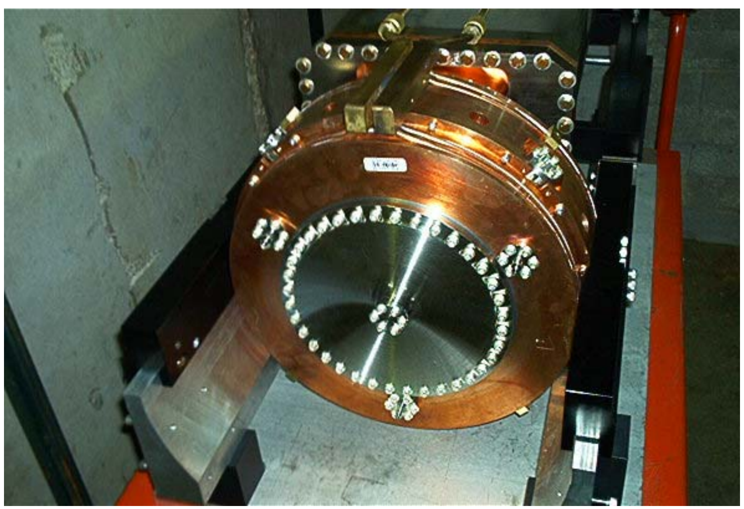
In the next few months R&D will be pursued to study the effects of different surface treatment on dark currents & cavity performance.

Pillbox Cavity with Thick End-Plates



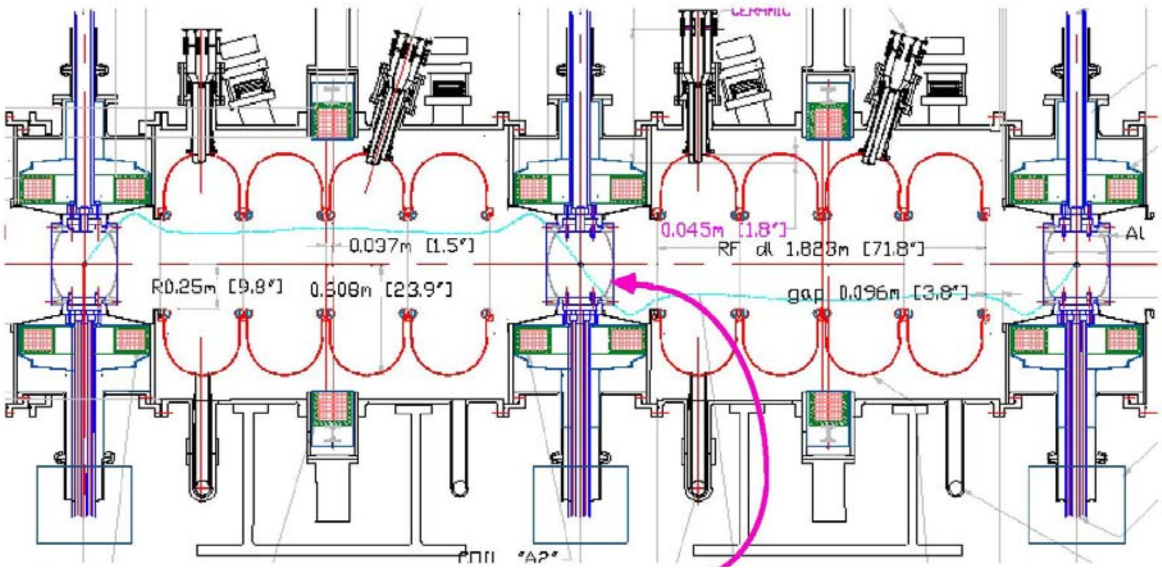
We have just successfully conditioned our 2nd prototype cavity (pillbox cavity) at Lab G, and are proceeding to study dark currents and performance in multi-Tesla fields.





R&D program expected to go on for a couple of years, ending with the testing of a 200 MHz cavity for the MICE experiment

Liquid Hydrogen Absorber Design Issues



In study 2, the absorbers had Al windows that were 360 µm (220 µm) thick for lattice 1 (2) and no additional pressure windows.

1. We must remove the heat deposited by dE/dx
2. The asborber must operate safely within the confines of the solenoid lattice, and adjacent to an RF cavity (potential ignition source)
3. The safety codes require absorber windows and pressure vessel windows that must have strengths exceeding specified criteria.
4. To minimize scattering, windows must be made of low Z material & be very thin.

Absorber Choice: Liquid Hydrogen

To minimize the effects of scattering we must chose a low Z absorber.

Mat'l	ρ	M.P.	B.P.	dE/dx	dE/dx/cm	L_R	merit
	(g/cm^3)	(K)	(K)	($MeV/g{\cdot}cm^2$)	(MeV/cm)	(cm)	$(L_R\, dE/dx)$
LH_2	0.0708	14	20	4.05	0.29	866	1
LHe	0.125		4	1.94	0.24	755	0.51
LiH	0.78	956		1.94	1.59	106	0.44
Li	0.53	454	1615	1.64	0.88	155	0.28
CH_4	0.42	91	112	2.42	1.03	46.5	0.19
Be	1.848	1560	2744	2.95	2.95	65	0.17

Rate at which 4D phase space is cooled

If the cooling rate is in the scattering dominated regime (close to the equalibrium emittance) then liquid hydrogen is a factor of 2 better than its closest rival.

Liquid Hydrogen Absorbers – Heat Removal

Absorber	Length (cm)	Radius (cm)	Window thickness (μm)	Number needed	FS-II power (kW)	"Rev.-FS-II power (kW)
Minicool?	175	30	?	2	≈5.5	≈22
SFOFO 1	35	18	360	16	≈0.27	≈2
SFOFO 2	21	11	220	36	≈0.1	≈0.9

← Not LH_2

– First, estimate rate of bulk temperature rise if no flow:

$c_p = 1.1 \times 10^4$ J/kg·K

$$\Delta T/\mathrm{s} = \frac{\langle P\rangle}{c_p V\rho} = \frac{\langle P\rangle / L}{c_p A\rho}$$

$$= \frac{0.27 \quad \mathrm{kW} / 0.35 \mathrm{~m}}{1.1 \times 10^4 \mathrm{~J/kg} \cdot \mathrm{K} \times \pi(0.16\mathrm{m})^2 \times 70.8 \mathrm{~kg/m}^3}$$

$$\approx \quad 0.01 \mathrm{~K/s}$$

⇒ 0.1 volume change/s sufficient to keep $\Delta T \lesssim 0.1$ K

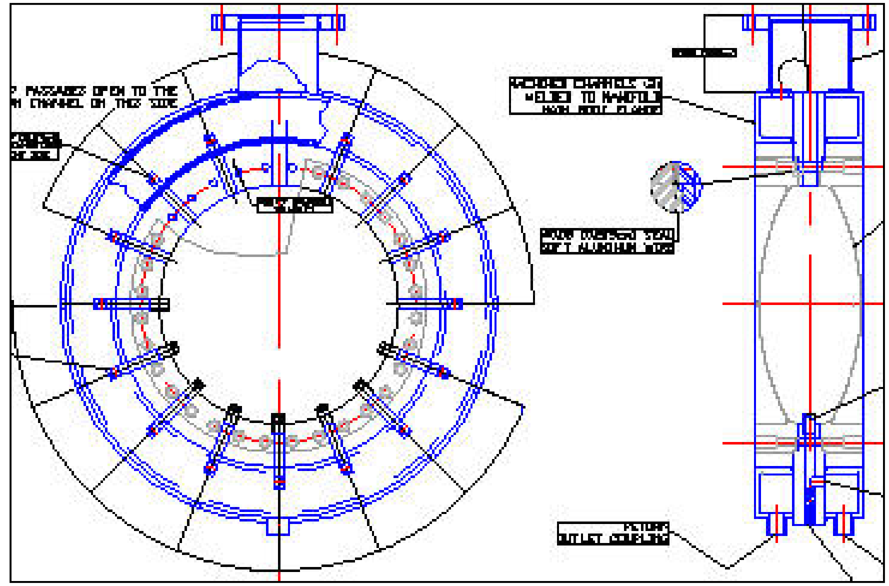
≈ 3 *l*/s SFOFO1 (35-cm) absorber

Note:
Good
transverse
mixing
is required

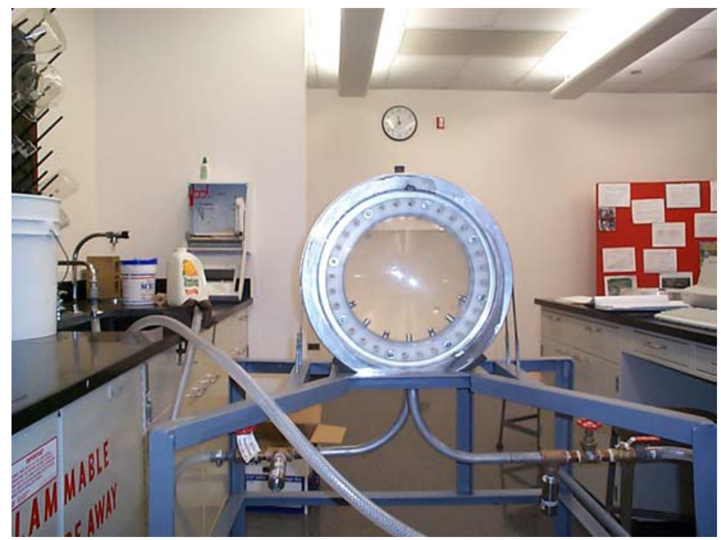
Forced Flow Liquid Hydrogen Absorber Design

Forced flow through nozzles.

R&D Issue: the nozzle design is complicated → must make sure there are no dead spaces in the flow pattern.



- → Prototype built
- → Flow pattern under study
- → Absorber will be filled with Liq. H_2 and tested at Fermilab

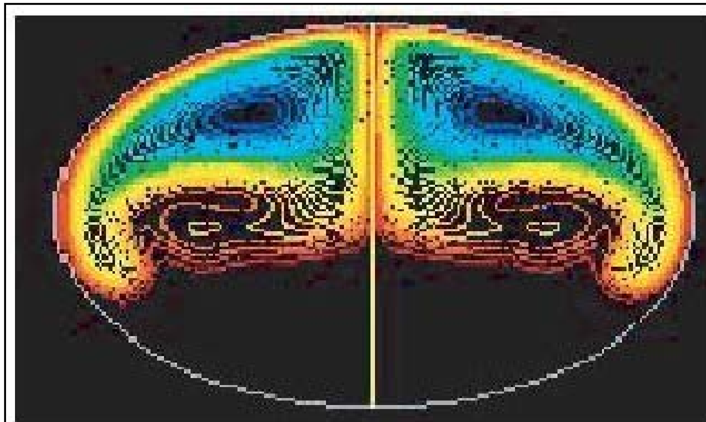


Flow study test setup

Forced Convection Absorber Design

Heat exchanger is on the body of the absorber. Liquid mixed using convection driven by a heater at the bottom of the absorber vessel.

R&D Issue: The coefficient of heat transfer between the liquid and heat exchanger is not measured for LH_2 – just a guess.



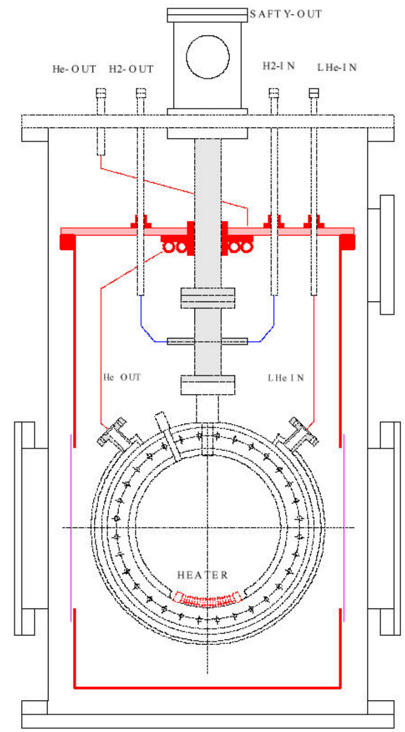
Computational Fluid Dynamics Simulation

→ Prototype being built by KEK & Osaka

→ Tested with Liq. Neon and heat deposited with wire array (low power) suggests 100W cooling OK

→ 100W test planned

→ Absorber will be filled with Liq. H_2 and tested at Fermilab

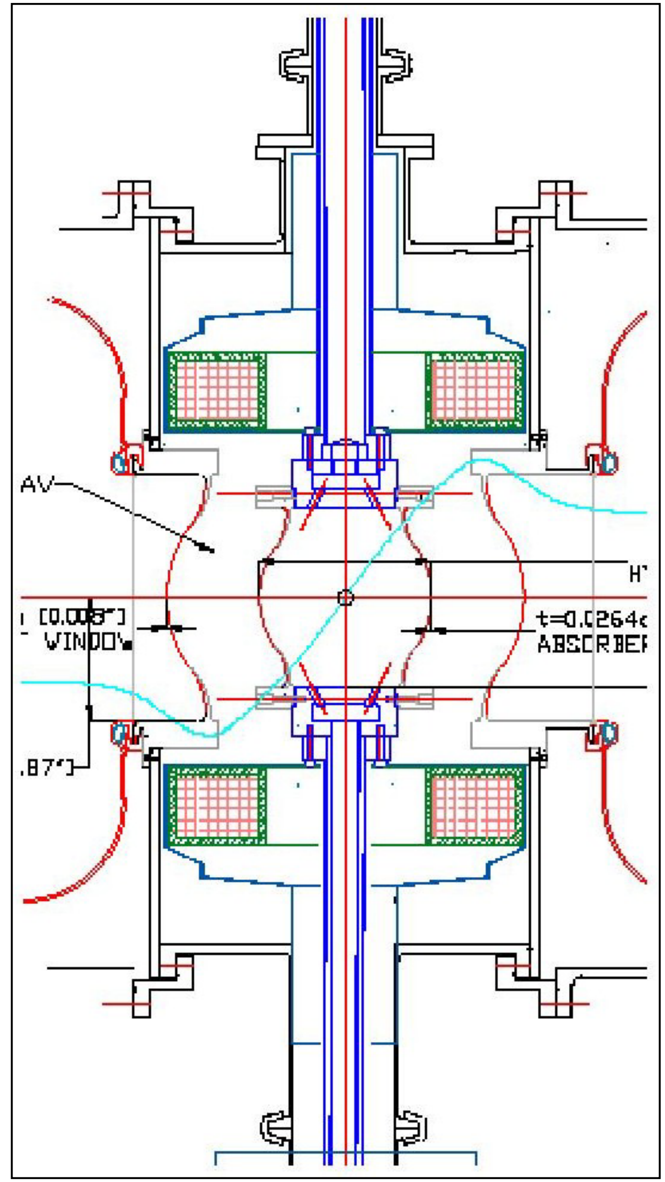


Liquid Hydrogen Absorber Windows

In study 2, the absorbers had Al windows that were 360 µm (220 µm) thick for lattice 1 (2) and no additional pressure windows.

Subsequent engineering & safety studies have taught us that we must allow for two failures and still be safe → the hydrogen vessel must be contained within a pressure vessel. Hence two sets of windows to worry about.

Window shape chosen to maximize strength Whilst fitting within the available space.



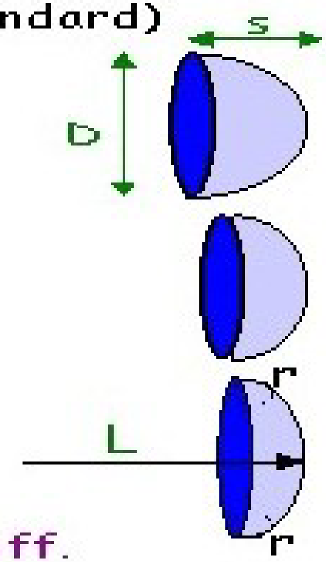
Liquid Hydrogen Absorber Windows

- Minimum thickness depends on shape (ASME Standard)

Hemispherical: $t = \dfrac{0.5PL}{SE - 0.1P} \Longrightarrow s = 0.5D$

Ellipsoidal: $t = \dfrac{0.5PD}{SE - 0.1P} \Longrightarrow s = .25D$

Torispherical: $t = \dfrac{0.885PD}{SE - 0.1P} \Longrightarrow s = .169D$



t = min. thickness   s = sagitta

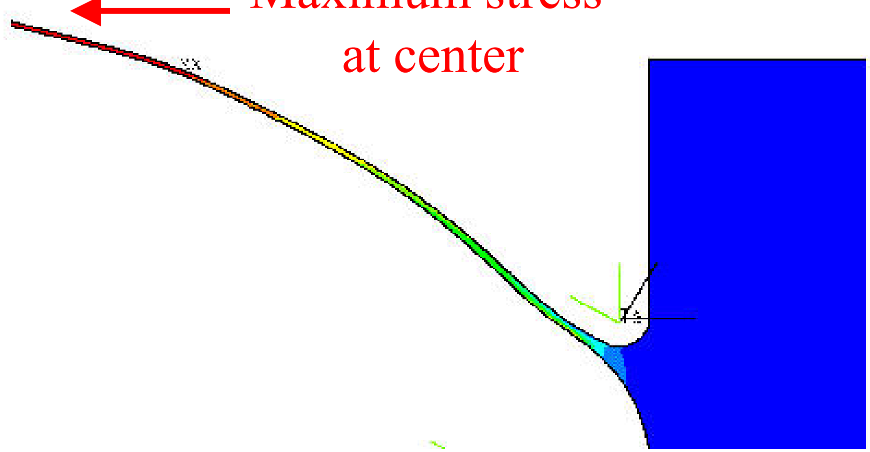
P = pressure diff.   S = max. stress   E = weld eff.

- Needs to meet FNAL safety standards: $S < S_u/4,\ S_y/1.5$

Window	Max int. pressure (psid)	Max ext. pressure (psid)	Safety factor (rupture)	Safety factor (yield)	Min rupture pressure (psid)
Absorber	25	-	4	1.5	100
Vac. vessel	30	15	2.5	1.5	75

Window Tests

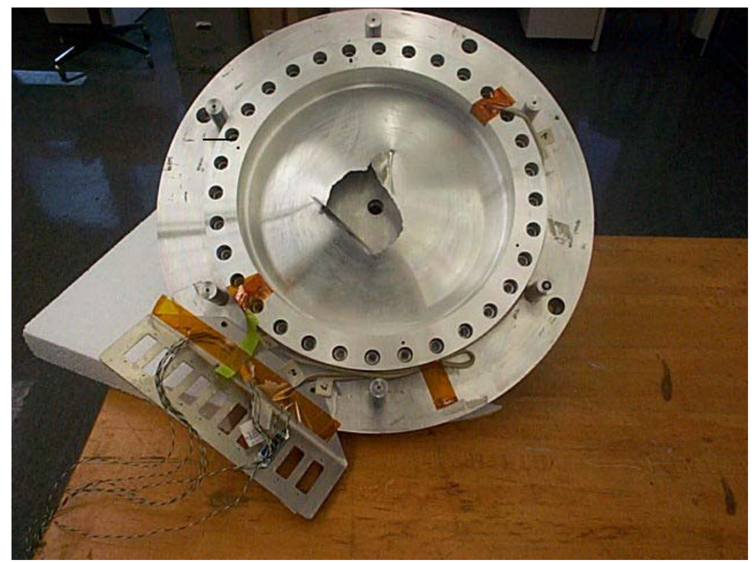
Maximum stress
at center



330 μm Al windows made (Mississippi)

Safety code requires we pressure test to dest-
ruction 4 windows to demonstrate their strength

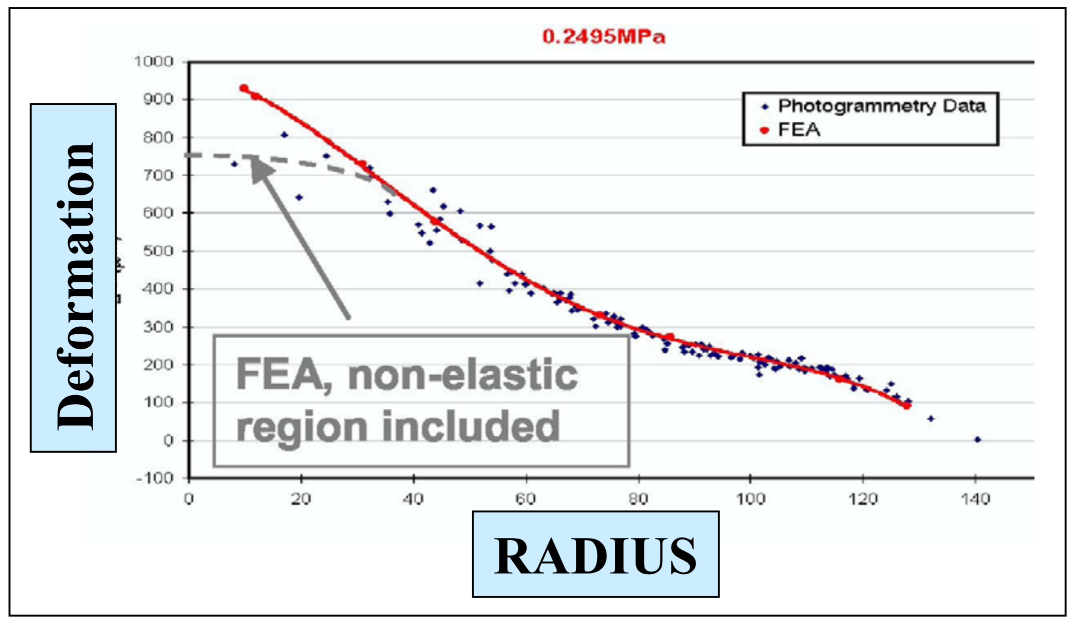
Pressure tests performed (NIU) on 4 windows
Including one at LN_2 temp.



Window Measurements

The windows are bolted to a back-plate and water is injected to pressurize the window. As a function of pressure, the window shape is measured using photogrammetry.

Photogrammetry is a technique in which an array of spots is projected onto a surface, and then viewed from several positions with a camera. Triangulation is used to reconstruct the surface in 3D.



FEA calculations give a good description observed window deformation and the rupture pressure.

Future Window R&D

Simulations indicate that with our present window designs the cooling channel will cool, but most of the advantage of using liquid hydrogen is lost through the scattering in the windows.

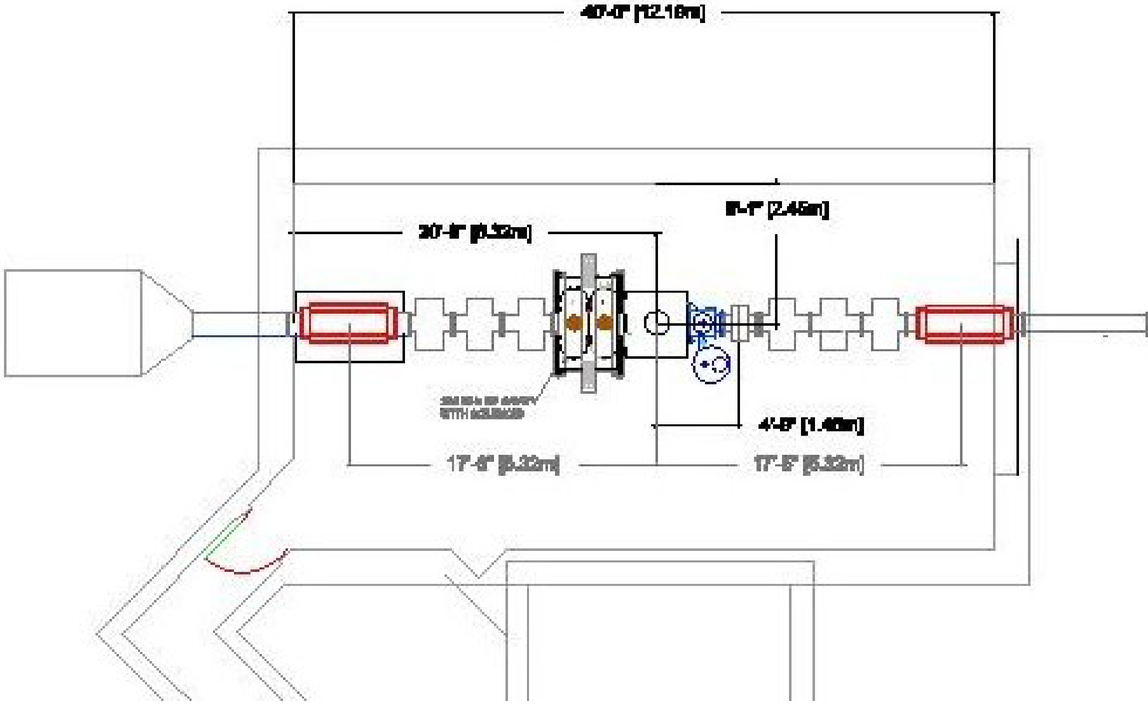
Better designs are under way:

-- Better shapes with less material in the center where most of the beam is, and more material (to maintain strength) at larger radii

-- Better materials with higher strengths, lower effective Z

The real test is to build an absorber system, and operate it in an ionizing beam.

New Fermilab MUCOOL Test Facility



Fill & test absorbers
HP 201 MHz (& 805 MHz ?) Tests
Integrate components into a unit
Test in intense ionizing beam

Solenoid Design - 1

A cooling channel, as presently envisioned, has about 100 m of multi-Tesla solenoids. There are no special R&D issues for these solenoids, but they are expensive, accounting for about 1/3rd the total cost of the cooling channel. Some solenoid cost reduction R&D might eventually be worthwhile.

Cooling channel solenoids are large enough to be stress-strain limited.

Axial field: $B_Z = \mu_0 nI$

Current density: $J = nI/t = B_Z / \mu_0 t$ for coils on thickness t

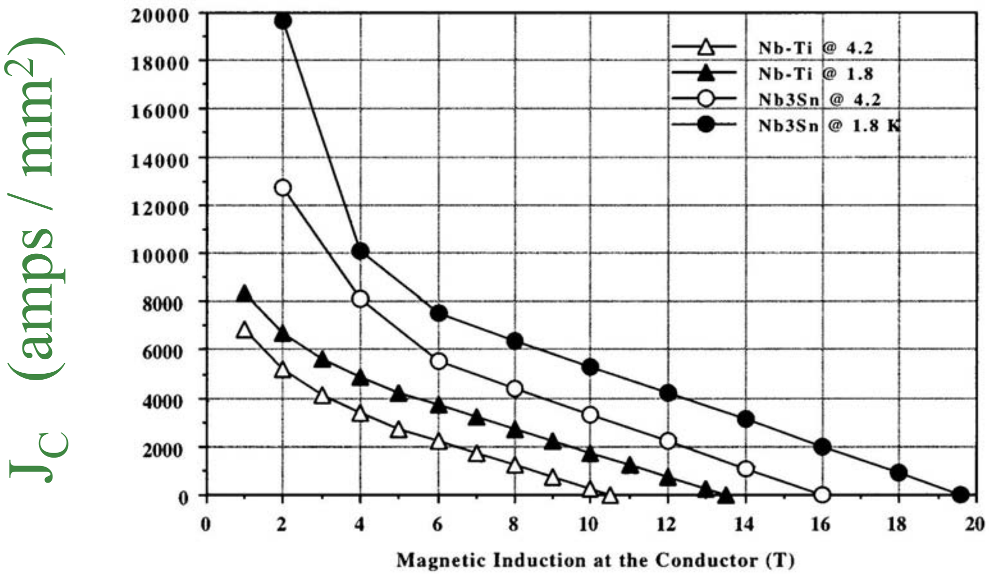
Stress in coil: $\sigma = (B_Z^2 / 2\mu_0) R / t = B_Z J R$ for coil of radius R

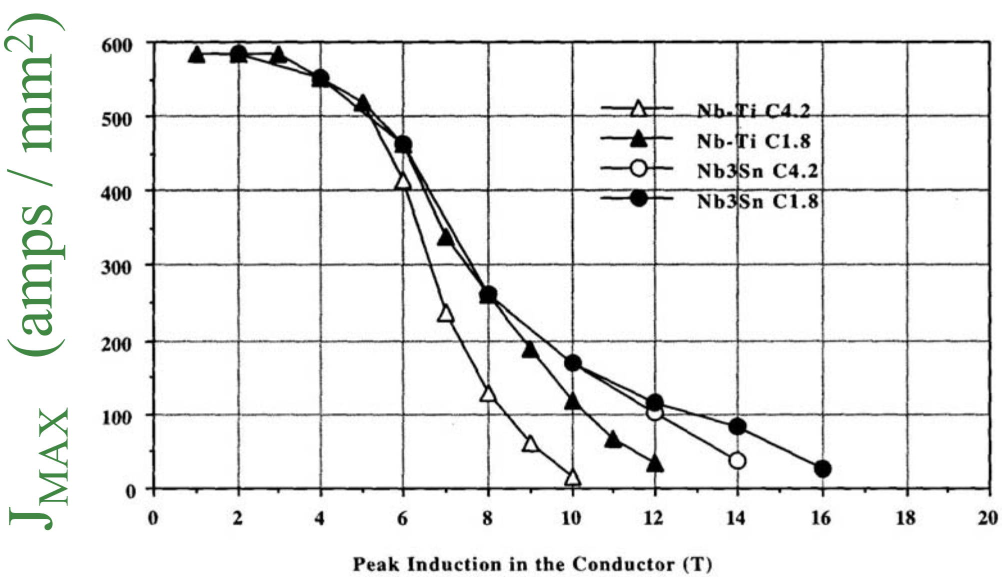
This gives rise to the "BJR" design rule-of-thumb. To ensure mechanical stability of the coil, the Current density should not be such that the stress exceeds ~350 Mpa : $B_Z J R < 350$ MPa

Stored Energy / unit length: $E = (B_Z^2 / 2\mu_0) \pi R^2$ for infinitely long solenoid

Hence stress is related to the stored energy: $\sigma = E / (\pi RT)$

Solenoid Design - 2





The current density must be much lower than the critical current density J_C for the super-conductor, which depends on the magnetic field at the conductor. In practice, the Maximum current density J_{MAX} should be safe by a factor of a few.

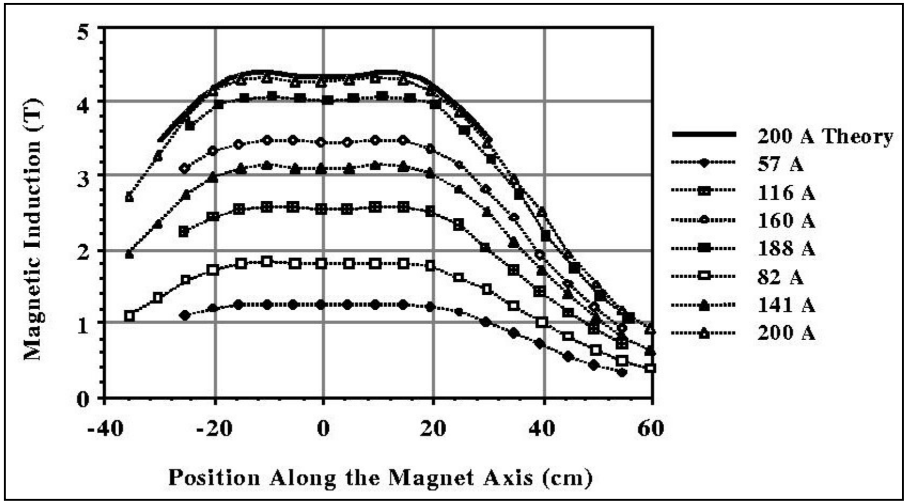
Minimizing cost is always an important criteria. An empirical relationship, based on many built solenoids:

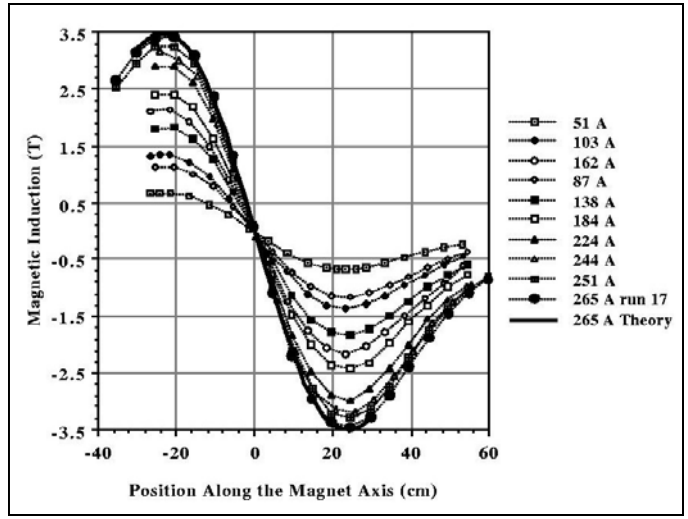
$$\text{Cost (M\$)} = 0.53 \ [E(MJ)]^{0.70}$$

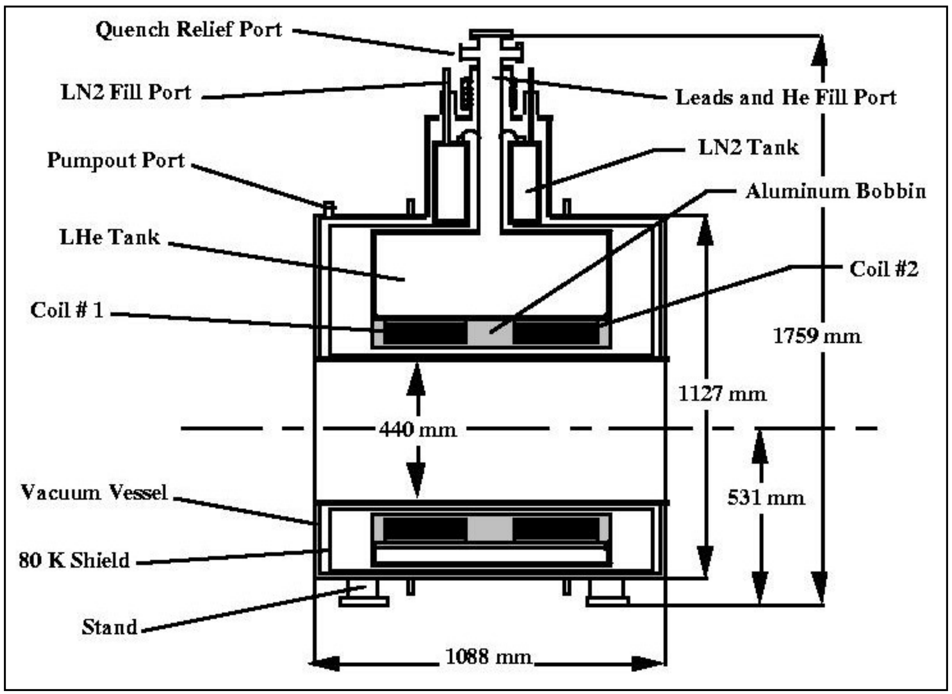
▲ Year 2000 Dollars

To a first approximation, cost depends only on stored energy $E = (B_Z^2 / 2\mu_0) \ \pi R^2$

MUCOOL Test Solenoid



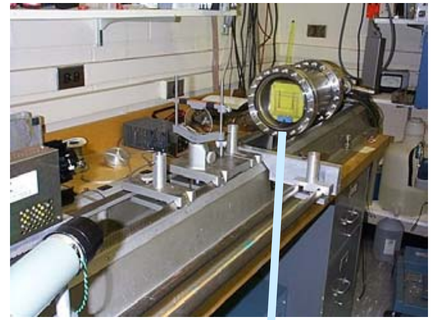




	Single Coil	Solenoid Mode	Gradient Mode
Physical Parameters			
Active Coil Package Length (mm)	250	640	640
Location of the Peak B Point on the Axis (mm)	±195	±105	±240
Electrical Parameters			
Magnet Design Current I_d (A)	270	230	265
Probable Short Sample Quench Current (A)	not known	286	323
Design Margin along the Load Line at 4.2 K	not known	0.803	0.821
Induction on Axis at I_d at R=0 and Z=0 (T)	~3.24	4.99	0.00
Maximum Induction on Axis at I_d (T)	4.64	5.04	3.48
Maximum Induction at R=20 cm at I_d (T)	not known	5.85	5.13
Maximum Induction in the Coil at I_d (T)	not known	6.82	6.52
Maximum Gradient on Axis Z=0 at I_d ($T\ m^{-1}$)	-NA-	-NA-	24.0
Coil Average Current Density at I_d ($A\ mm^{-2}$)	150.55	128.24	147.76
S/C Matrix Current Density J at I_d ($A\ mm^{-2}$)	171.34	145.96	168.17
Magnet Self Inductance (H)	41.67	98.22	68.46
Magnet Stored Energy E at I_d (MJ)	1.519	2.598	2.404
EJ Limit for the Magnet at I_d ($J\ A^2\ m^{-4}$)	4.46×10^{22}	5.54×10^{22}	6.78×10^{22}

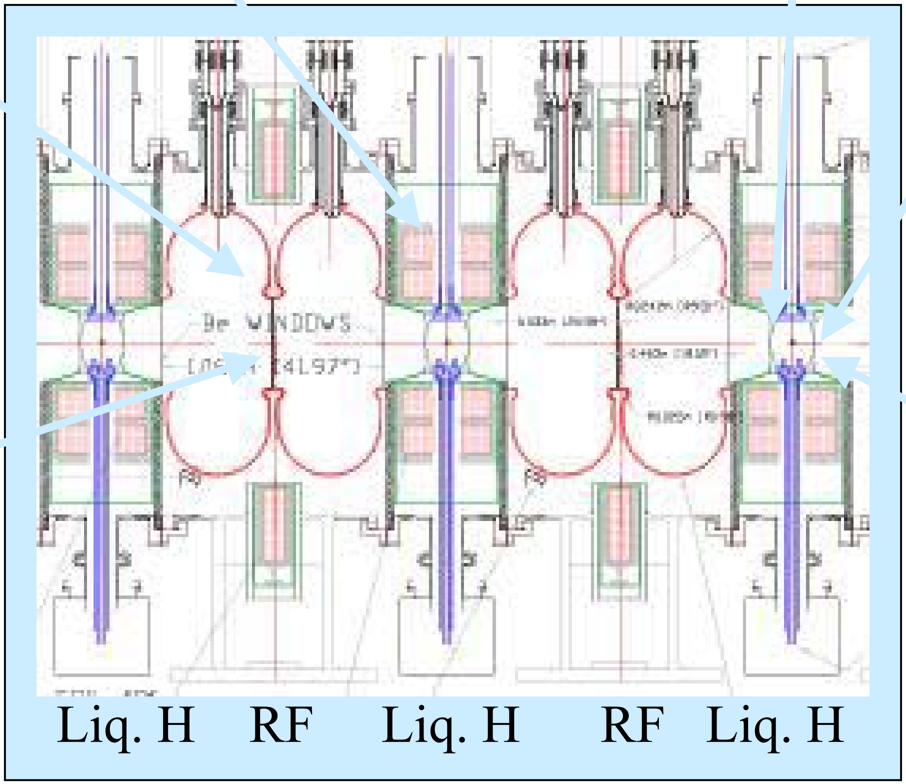
MUCOOL R&D: Summary

5T Cooling Channel
Solenoid – LBNL
& Open Cell NCRF Cavity
operated at Lab G – FNAL



Bolometer detectors for
Window Beam profile
Measurements– U. Chicago

Liq.H Absorber – KEK
To be tested at FNAL



Tested Be-Windows for
RF Cavities -- LBNL

Thin absorber windows
Tested – new technique
– ICAR Universities

Final Remarks

The plan is, in the next few years, to develop all the components required for a cooling channel, test them individually, and then test them integrated together → engineering test of a short section exposed to an intense charged beam (400 MeV protons).

On the way there is much interesting R&D to be done.

Meanwhile the cooling channels we are designing are evolving (ring coolers for example) … to some extent the R&D is iterative between paper designs and hardware development. Still lots of potential for new ideas.

After MUCOOL comes MICE (see Dan Kaplans Talk)

After MICE comes, we are hoping, a Neutrino Factory.