Muon Collaboration

MuCool Results and Plans

Muon Cooling R&D

NuFact 03

A. Bross

Muon Collaboration

The MuCool Collaboration

- **Mission**
  - Design, prototype and test all cooling channel components
  - Perform high beam-power engineering test of cooling section
  - Support MICE (cooling demonstration experiment)

- Consists of 18 institutions from the US, Europe, and Japan

RF Development
ANL
Fermilab
IIT
LBNL
Univ. of Mississippi

Beam Diagnostics
ANL
Fermilab
IIT
Princeton
Univ. of Chicago

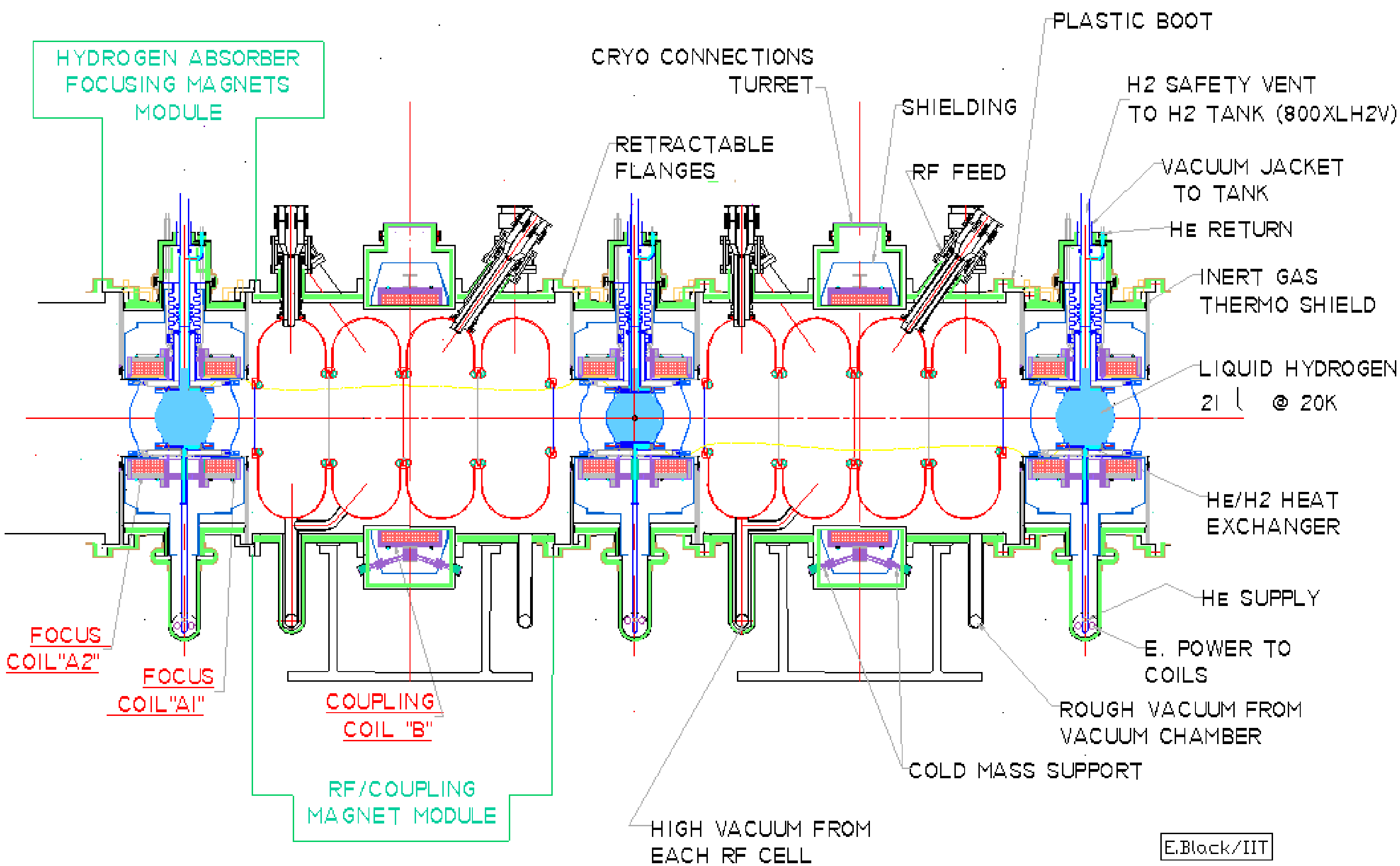
Absorber R&D
Fermilab
IIT
KEK
NIU
Oxford
UIUC
Univ. of Mississippi
Univ. Osaka

Solenoids
LBNL

Cooling Demonstration (MICE)
ANL
BNL
Fermilab
Fairfield
IIT
Iowa
JLab
LBNL
NIU
UCLA
UC Riverside
UIUC
Univ. of Chicago
Univ. of Mississippi

SFOFO Cooling Lattice

- R&D Focus of MuCool
  - *Component testing Fermilab*
    - High Power
      - Both RF and Beam
  - *System test as shown in MICE @ RAL*



Research and Development Challenges

- Can NCRF cavities be built that provide the required accelerating gradients?
  - AND operate in multi-tesla fields!
- Can the heat from *dE/dx* losses be adequately removed from the absorbers?
  - On the order of 100's W for a neutrino factory
- Can the channel be engineered with an acceptably low thickness of non-absorber material in the aperture?
  - Absorber, RF, & safety windows
- Can the channel be designed & engineered to be cost effective?

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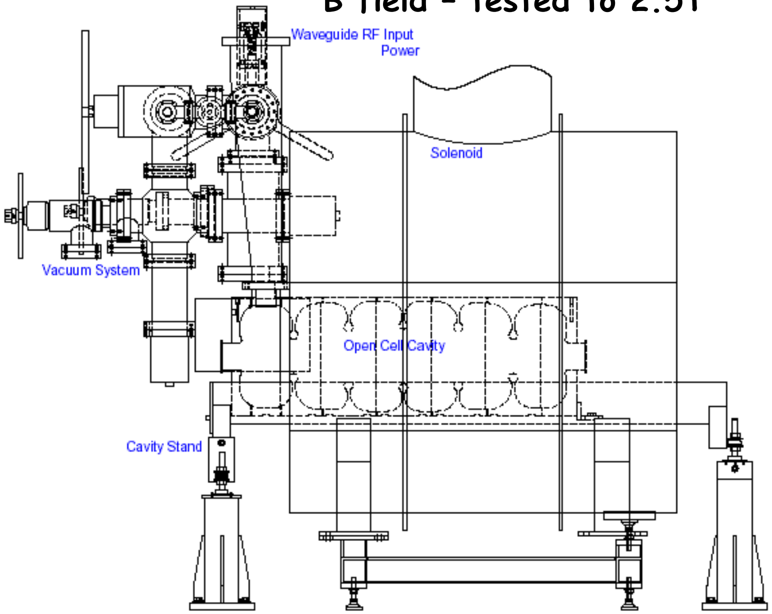
RF Cavity R and D

ANL/FNAL/IIT/LBNL/UMiss

RF Cavity R&D – Prototype Tests

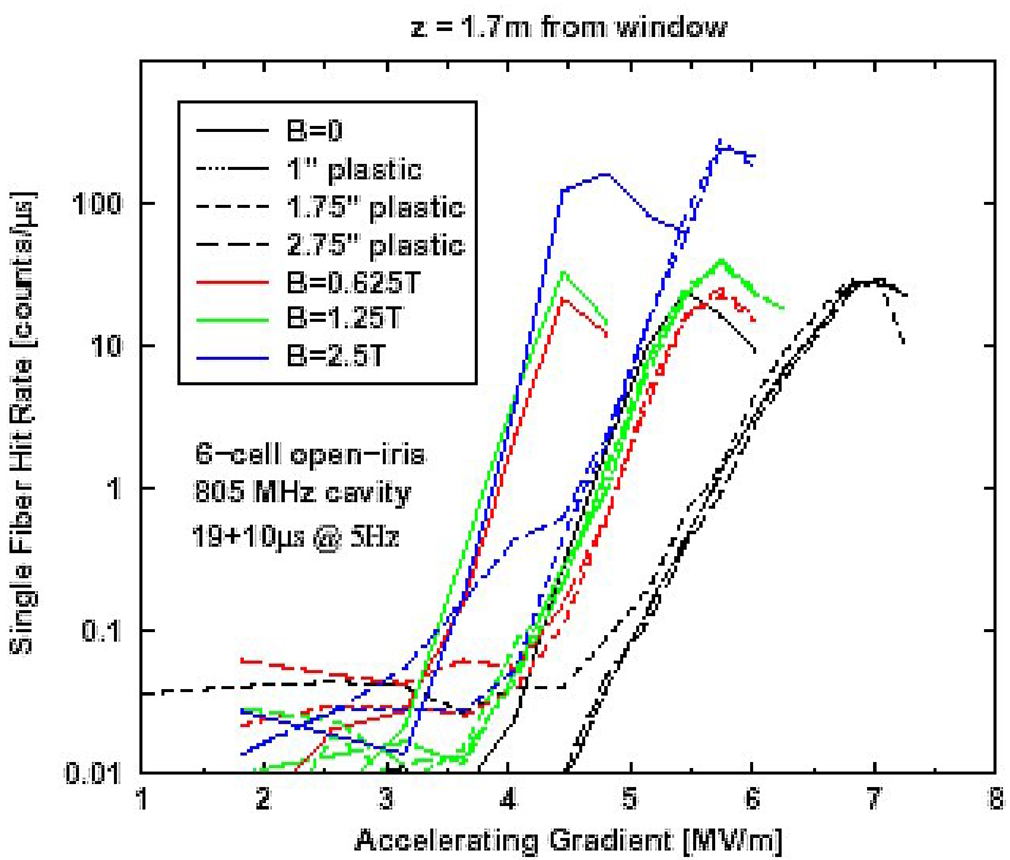
Lab G RF Cave showing 5T SC Magnet
44 cm bore

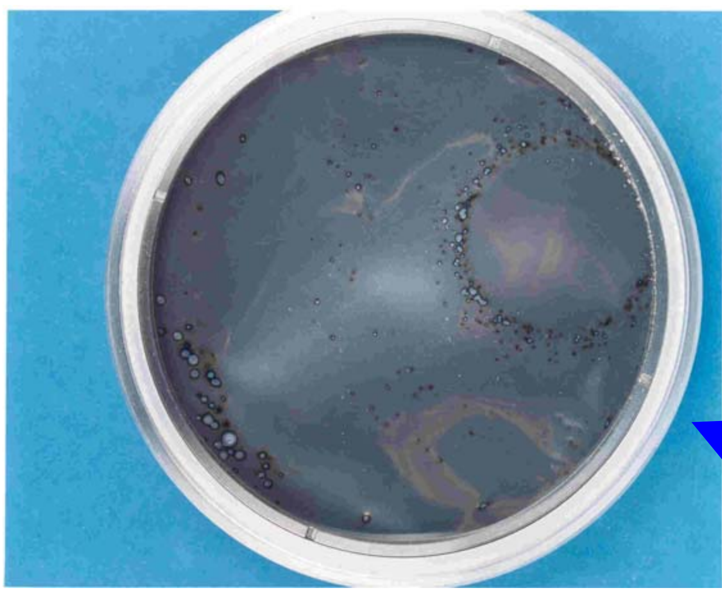
- Work to date has focused on using 805 MHz cavities for test
  - Allows for smaller less expensive testing than at 201 MHz
  - Lab G work at Fermilab
    - Phase I
      - Open Cell cavity reached 54 MV/m surface field (25 MV/m on axis)
        - Large dark currents increased with B field – tested to 2.5T



RF Cavity Prototype Tests 805 MHz Open Cell

- Reached peak surface field of 54 MV/m (25 on axis)
- Large dark currents
  - Damage to windows
  - In worst case, Power loading to LH absorbers = to that from high intensity beam





Ti window (125 mm) showing spark damage

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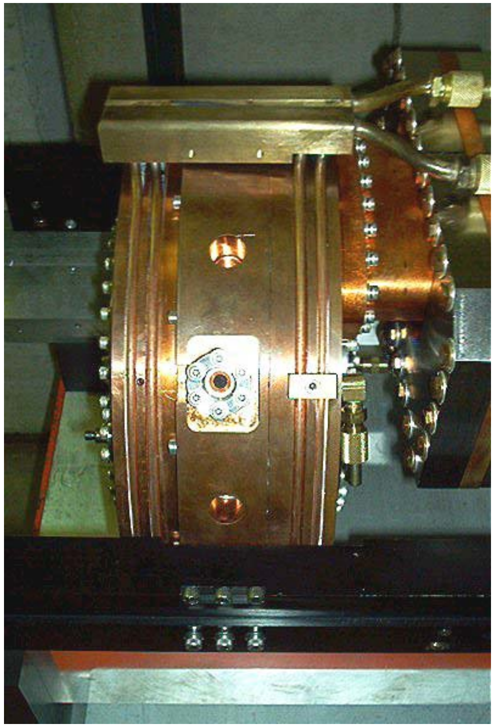
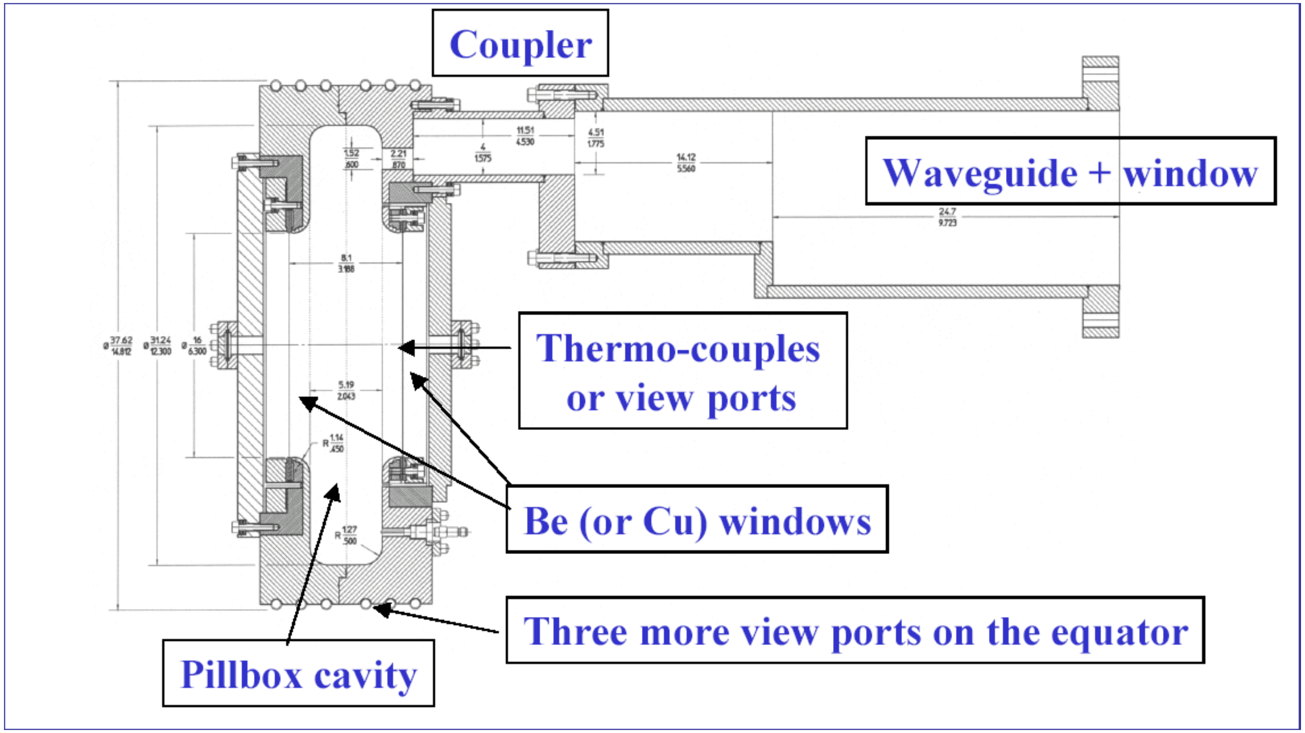
RF Cavity Prototype Tests 805 MHz Pillbox

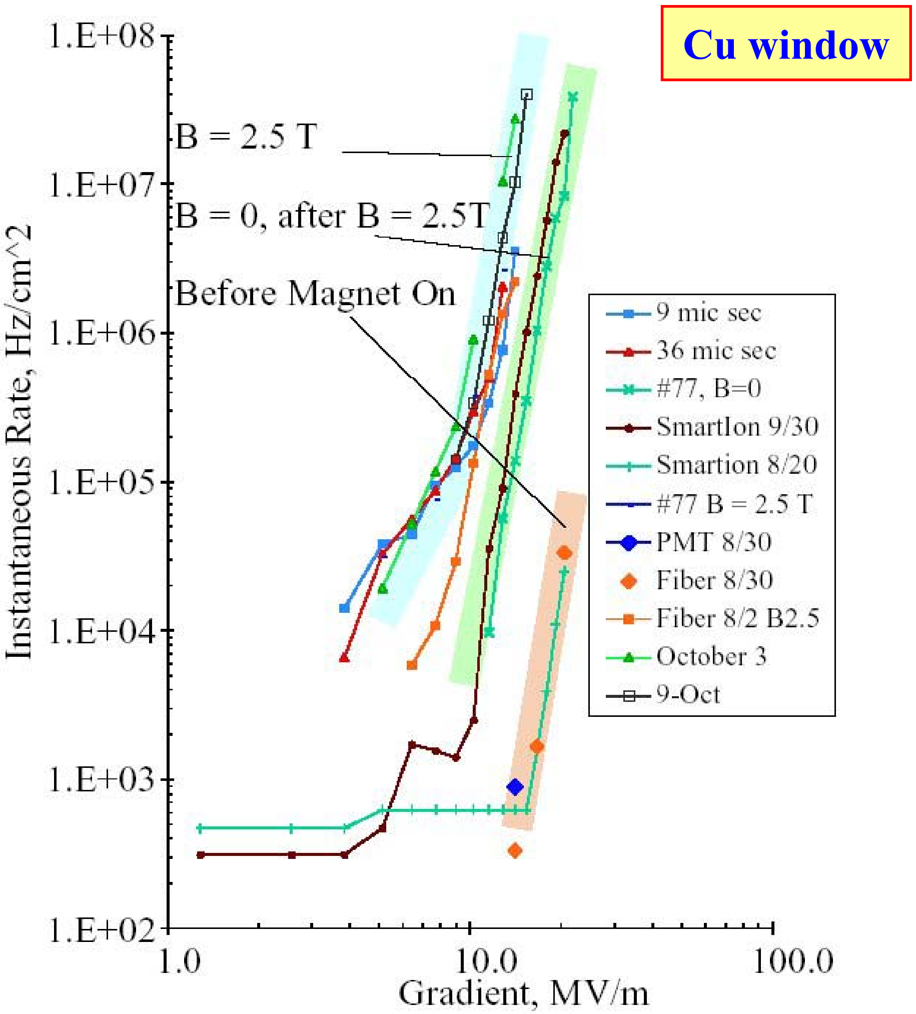
- Lab G Tests Phase II
  - Closed Cell (pillbox) - E_{acc}/E_{surf} = 0.99
  - Reached 34MV/m with little sparking and low background
    - Thick Cu windows
    - B=0





RF Cavity Prototype Tests
805 MHz Pillbox

- **With Solenoidal field**
  - Thin (0.015") Cu windows
    - Dark currents much larger, damage seen
      - Pitting
    - Dark currents reduced via conditioning
    - Conditioned to 20 MV/m
  - Be windows (0.010")
    - TiN coated
    - Conditioned to 16MV/m
      - Dark currents then rose
    - However, no damage in evidence to Be
      - Copper contamination
        - From iris/flange surface
    - At 8MV/m dark currents very low
      - Acceptable for MICE



RF Cavity Prototype Tests
805 MHz Pillbox

- Be surface showed very little damage to the Be
  - Cu "blobs" re-solidified on Be surface
    - Tips of Emitters in high-field regions get hot
      - Break or melt and form conducting path
      - Accelerated into window
- Ge Detector
  - Energy distribution of detected e^- and γ

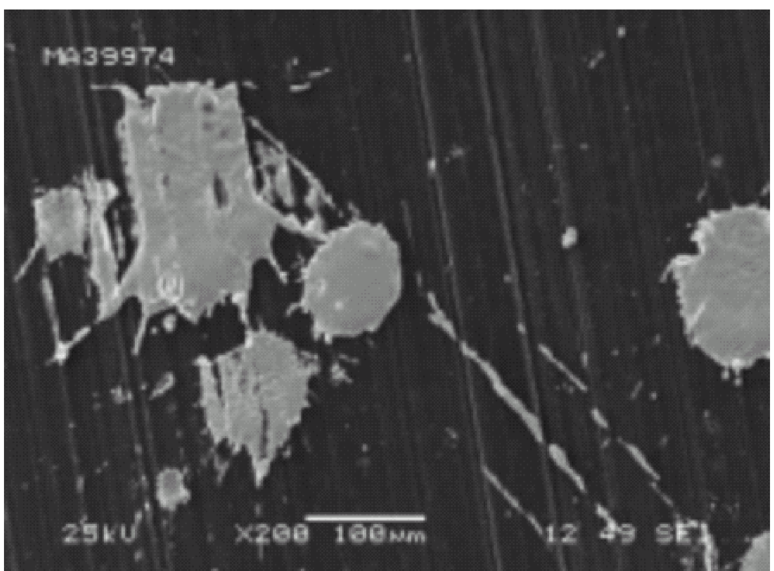
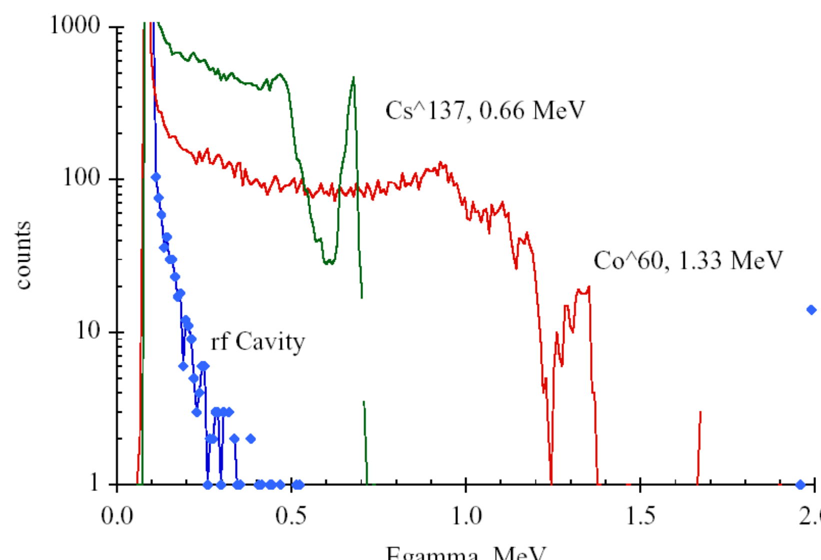
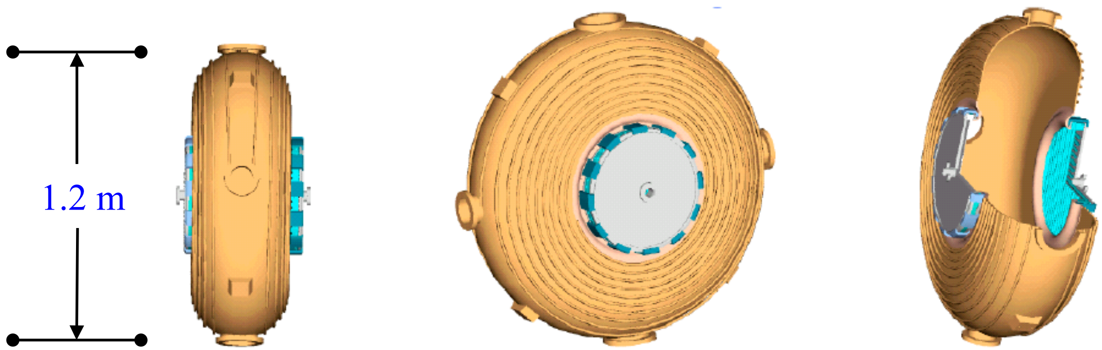


Fig 7, SEM image of Be Windows showing copper.

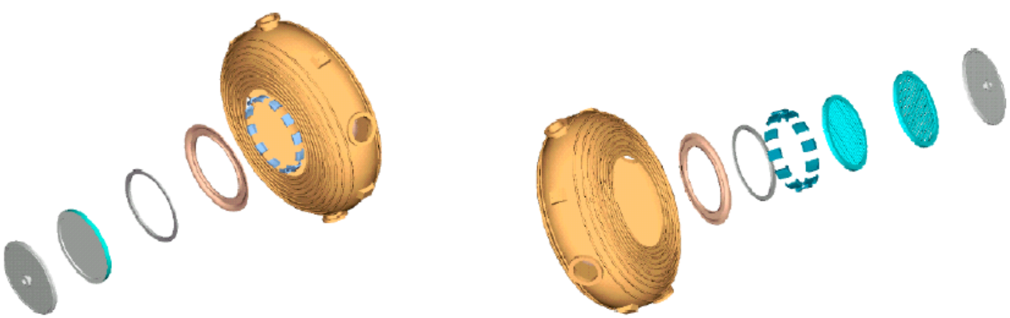


RF R&D – 201 MHz Cavity Design

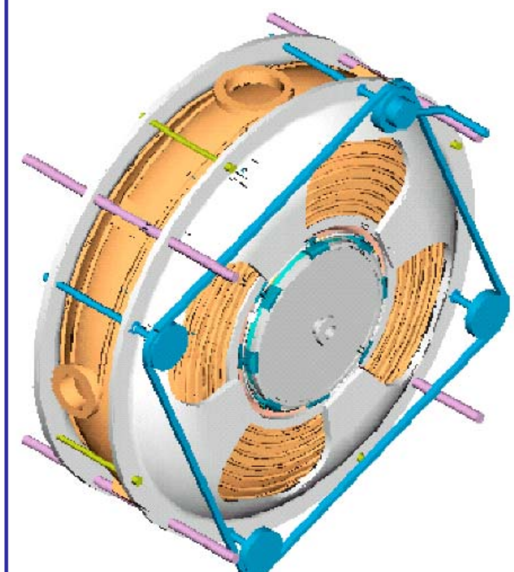
- Design Complete
  - Electrical, Mechanical, and thermal analyses have been done
    - E^{pk}_{surf} = 26.5 MV/m
  - Fabrication has started
  - Goal is to have a 201 MHz cavity under test at Fermilab 04



201.25 MHz cavity conceptual design

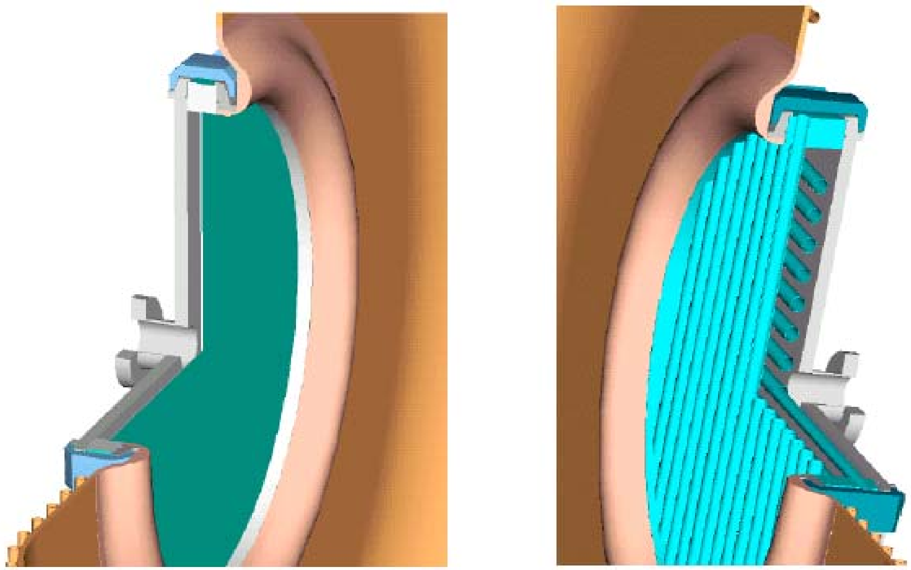


Exploded views showing foil and grid mounting hardware



RF R&D – 201 MHz Cavity Design

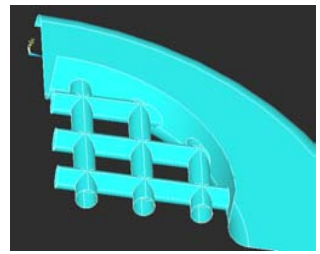
- 201 MHz design accommodates either solid Be windows or tube-grid structure
  - The large aperture (≈ 20 cm radius)
    - Heat load requires Be widows of ≥ 1 mm thickness
      - Concern with pre-stressed flat windows
      - "Inflected" bellows design
    - Al tube grid structure (gas cooled) is an option

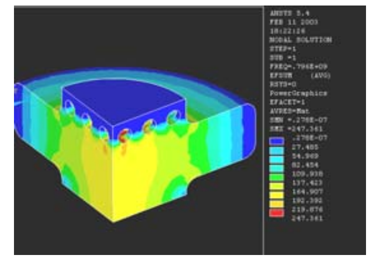


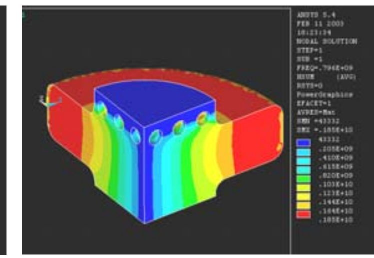
RF R&D – 201 MHz Cavity Design
Tube-Grid Aperture Study

- Finite Element analysis of tube grid design
  - First applied to electromagnetic model of 805 MHz cavity
    - For Lab G tests
  - Field enhancement between 1.4 and 3.6 depending on configuration
    - = Emax at tube surface/E at cavity center

Grid Model **Electric Field** **Magnetic Field**







Maximum Surface Field Enhancement

Grid \ Tube DIA (cm)	0.50	1.00	1.25	1.50
4x4-Connected	3.60			
4x4 -Waffle	2.30	1.80		
6x6 -Waffle		1.64	1.40	1.39
6x6 Middle-Concentrated/Waffle		1.40		

Absorber R and D

IIT/KEK/NIU/Osaka/Oxford/UIUC/UMiss

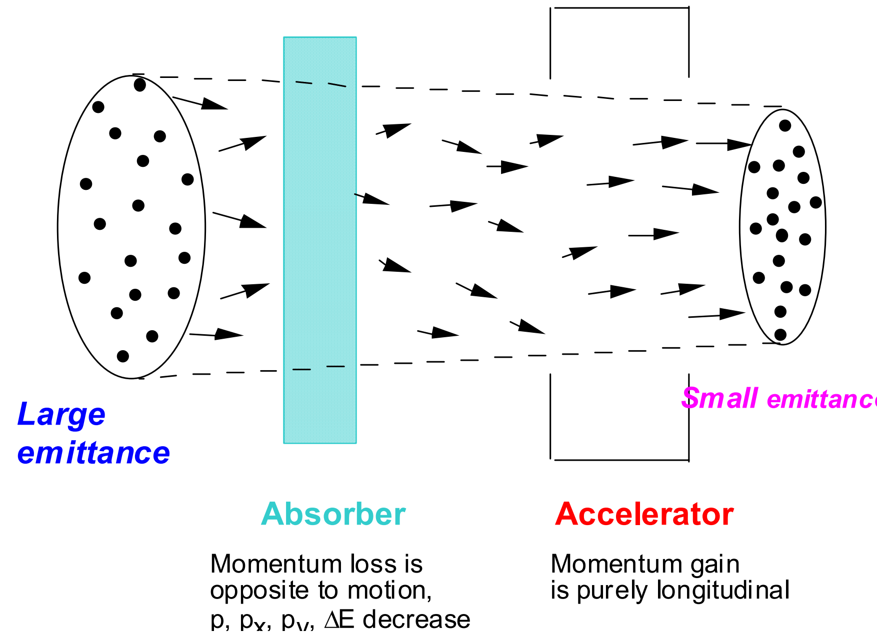
Absorber Design Issues

- **2D Transverse Cooling**

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

and

$$\epsilon_{N,\mathrm{min}} = \frac{\beta_\perp (14\ \mathrm{MeV})^2}{2\beta m_\mu \frac{dE_\mu}{ds} L_R}$$



- **Figure of merit: $M = L_R dE_\mu/ds$**

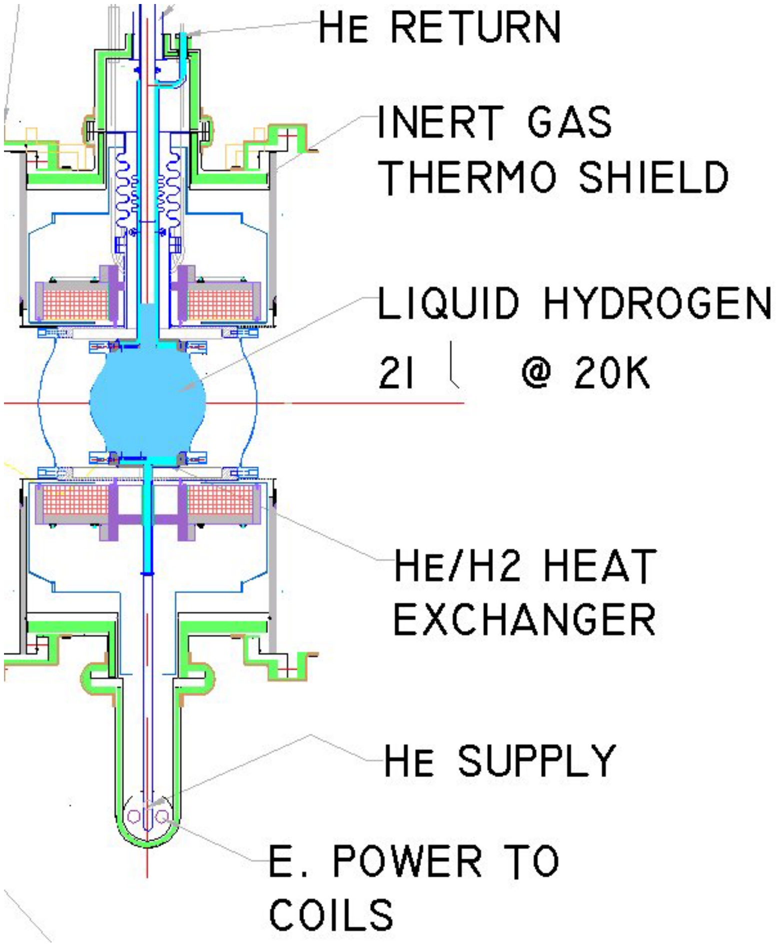
M^2 (4D cooling) for different absorbers

Material	$\langle dE/ds\rangle_{\mathrm{min}}$ (MeV g^{-1}cm^2)	L_R (g cm^{-2})	Merit
GH_2	4.103	61.28	1.03
LH_2	4.034	61.28	1
He	1.937	94.32	0.55
LiH	1.94	86.9	0.47
Li	1.639	82.76	0.30
CH_4	2.417	46.22	0.20
Be	1.594	65.19	0.18

H_2 is clearly Best -
Neglecting Engineering Issues
Windows, Safety

Absorber Design Issues

- **Design Criteria**
  - High Power Handling
    - Study II – few 100 W to 1 KW with "upgraded" (4MW) proton driver
    - 10 KW in ring cooler
      - Must remove heat
  - Safety issues regarding use of LH_2 (or gaseous H_2)
    - Window design paramount
      - H_2 containment
    - Proximity to RF adds constraints (ignition source)
  - Window material must be low Z and relatively thin in order to maintain cooling performance



H_2 implies engineering complexity

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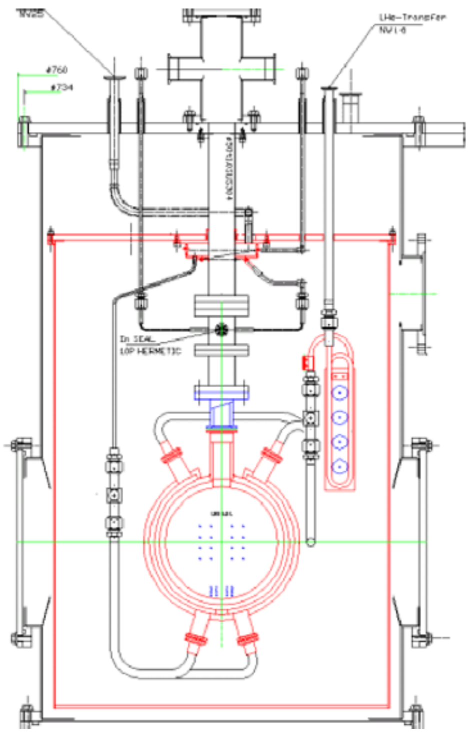
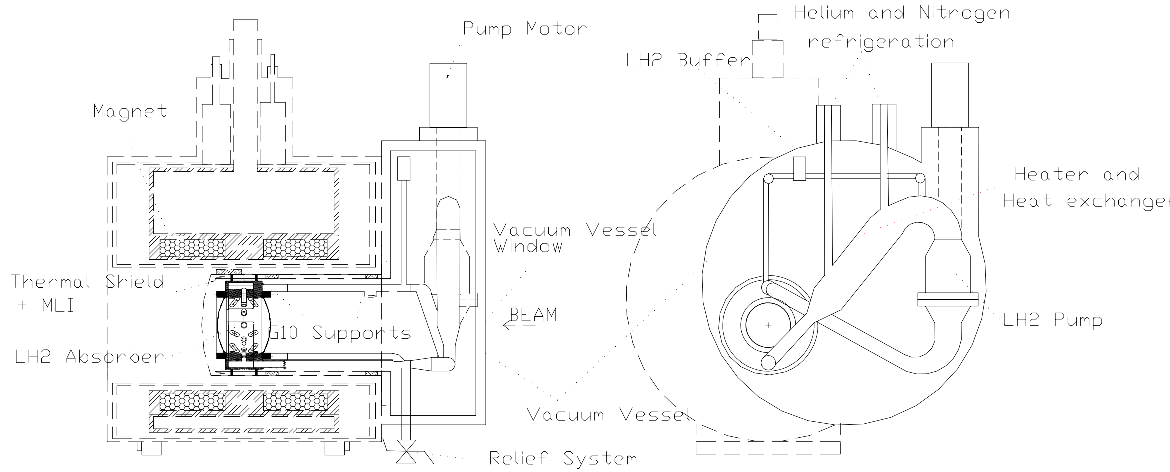
Absorber R&D

- Two LH_2 absorber designs are being studied
  - Handle the power load differently



Forced-Convection-cooled. Has internal heat exchanger (LHe) and heater



Forced-Flow with external cooling loop

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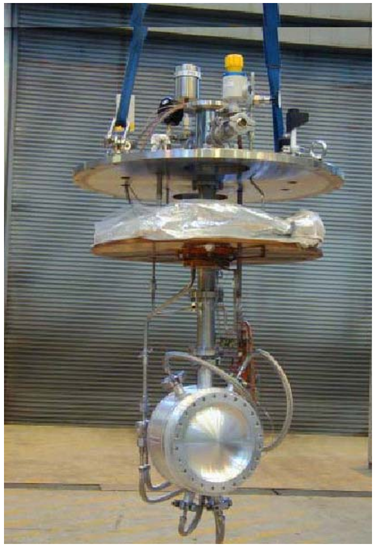
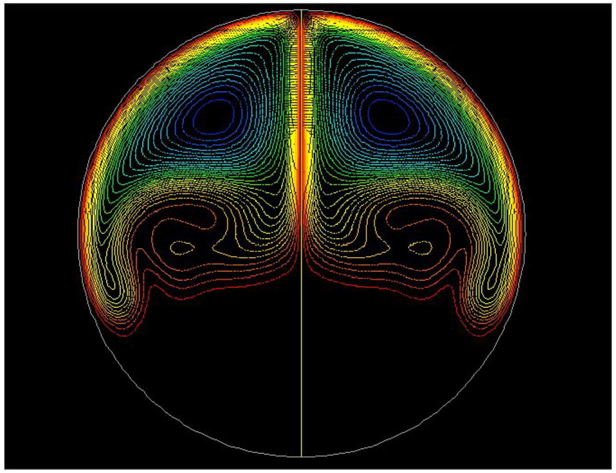
Convection Absorber

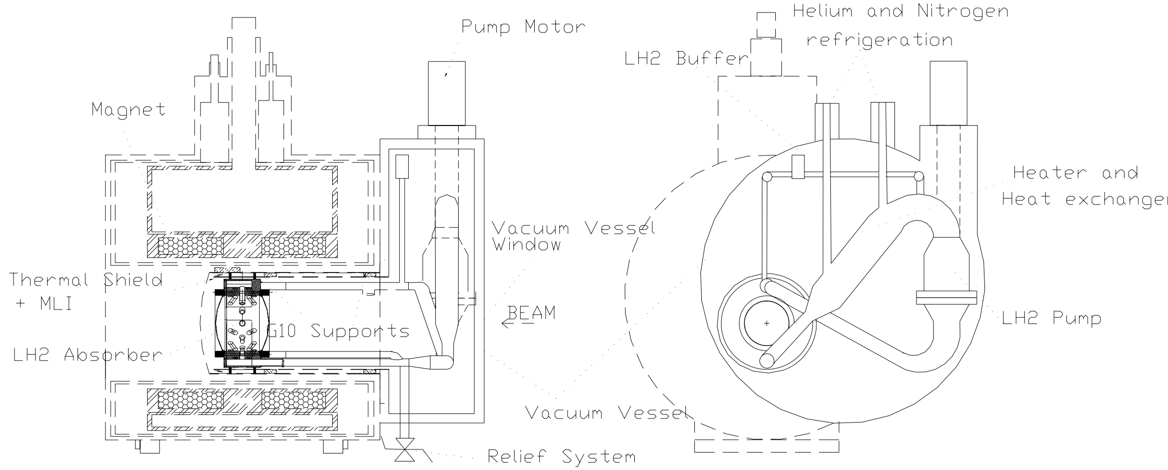
- Convection is driven by beam power and internal heaters
- LHe heat exchanger removes heat from absorber walls
- Two-dimensional Computational Fluid Dynamics calcs
  - Flow essentially transverse
  - Max flow near beam
  - Heaters required to setup convective loops

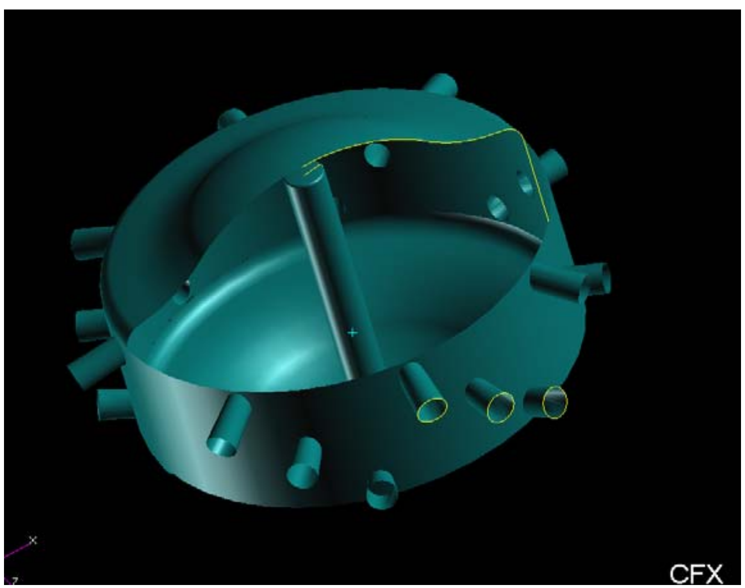


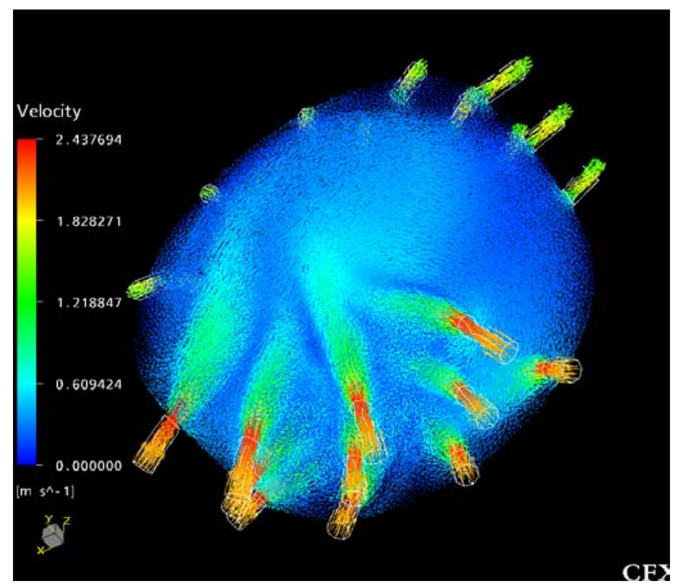


Forced-Flow Absorber

- **Heat removed with external heat exchanger**
  - LH_2 pumped from absorber to heat exchanger
  - Nozzles in flow path establish turbulent flow
  - Simulation via 2D and 3D FEA

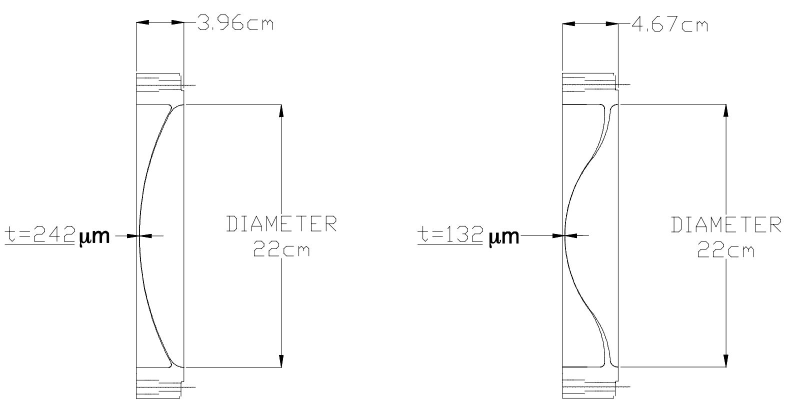






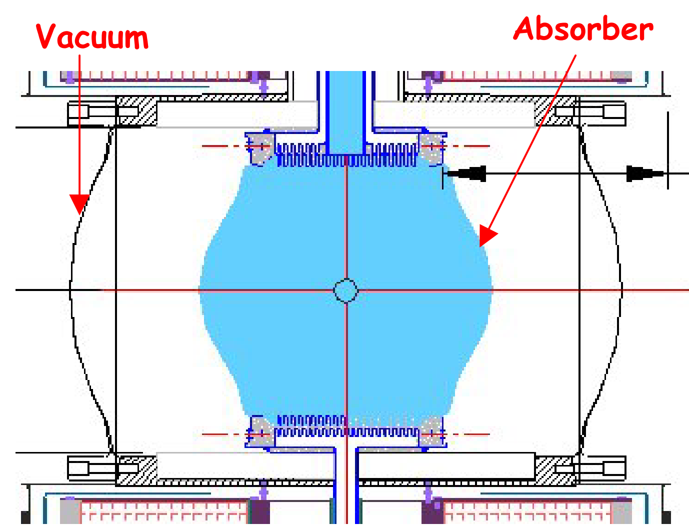
Absorber Windows

- Thin windows are required in all absorber designs
  - Critical design issue
    - Performance
    - Safety
  - First examples made with AL T6061
  - Maybe even thinner with
    - Al-Li alloy - 2195



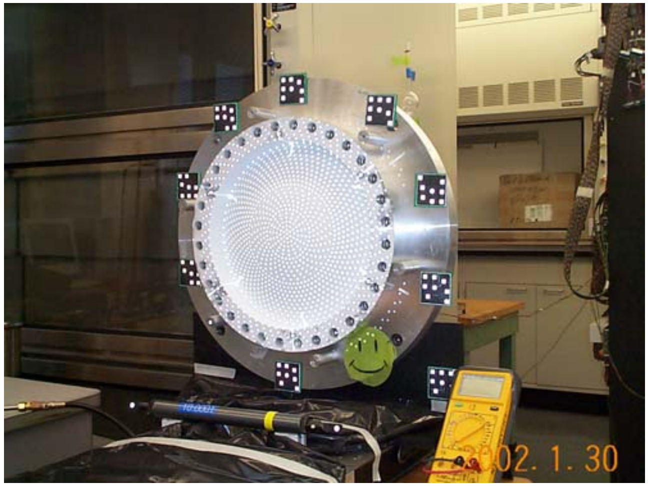
Design Iteration
HemiSpherical - Inflected

Containment Windows



Absorber Windows

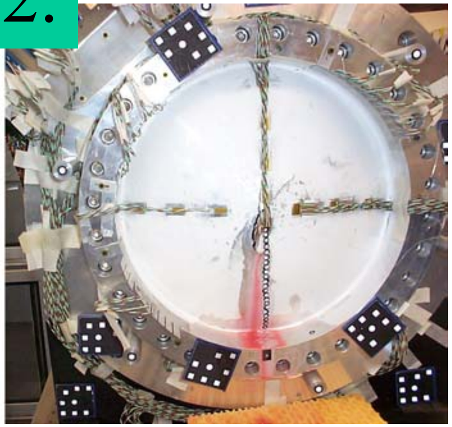
- Window design relies on FEA analysis
  - No closed-form analysis
- Photogrammetry used to verify "as-built" parameters
- Safety Requirements require destructive testing of windows
  - FEA analysis ⇔ Photogrammetry
    - Conformation
    - Photogrammetry and FEA predictions agree to within 5%
  - 4 Destructive tests have been done
    - Thinnest meets pressure specification



1. 130 μ window

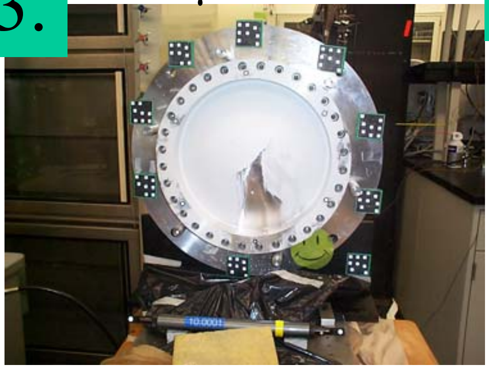
44 psi

2. 350 μ window



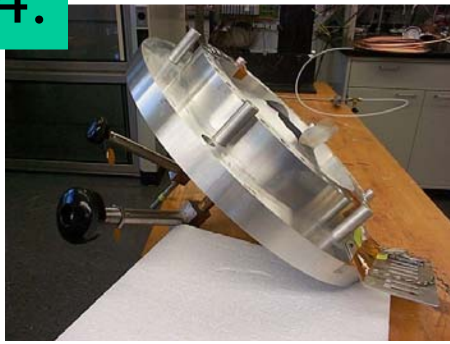
120 psi

3. 340 μ window



120 psi

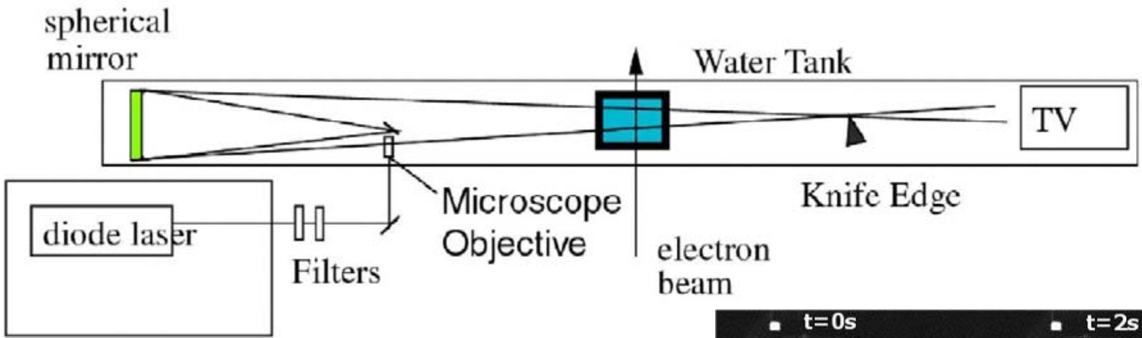
4. 350 μ window

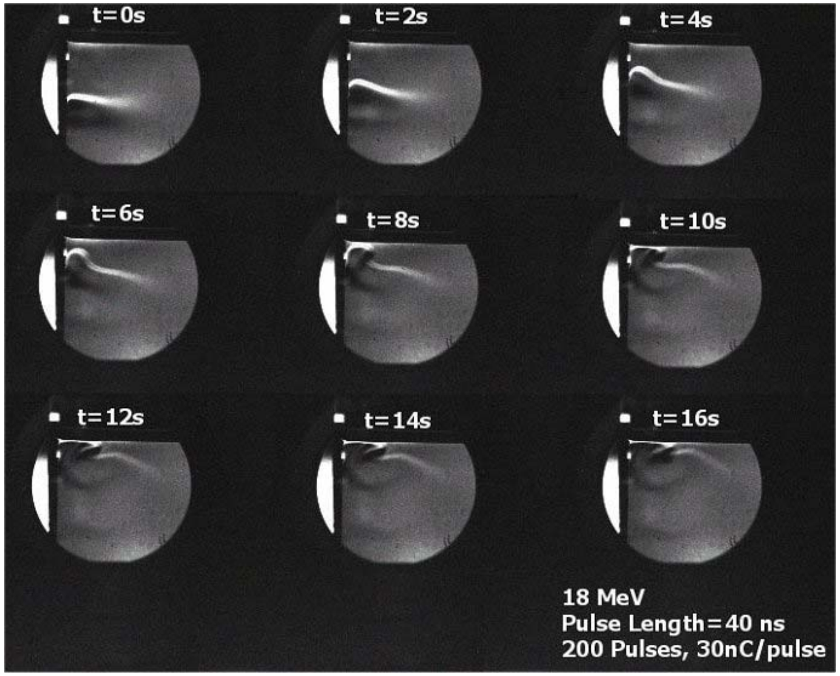


Cryo-Test
152 psi

Absorber R&D – Flow Studies

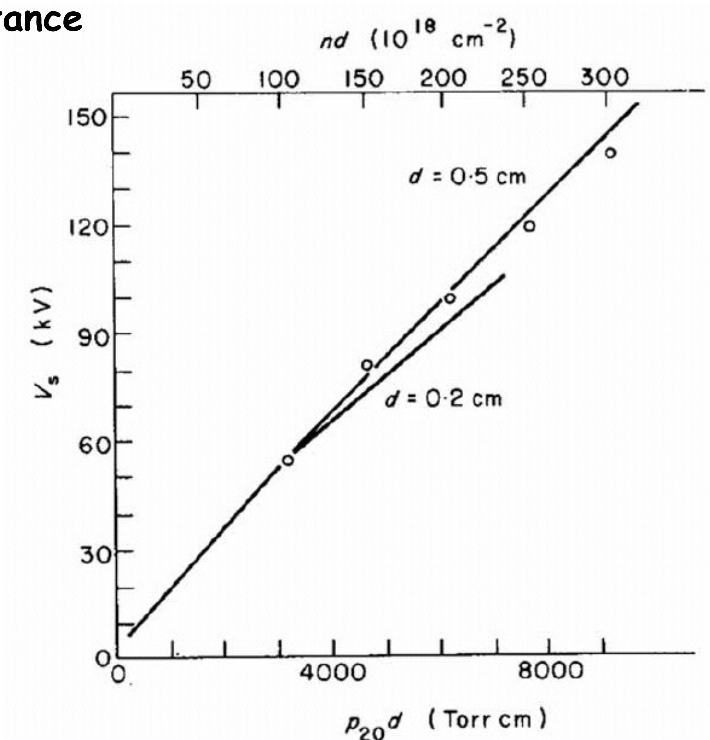
- Schlieren testing of convective flow (water) at ANL using 20 MeV e⁻ beam (J. Norem, L. Bandura)
  - Intial measurement indicate data can be used to validate flow calculations





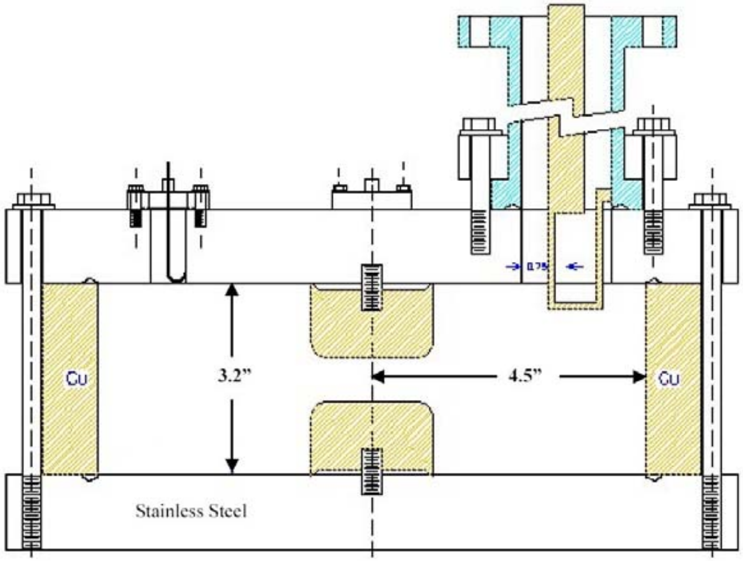
Absorber R&D – Gaseous Absorber

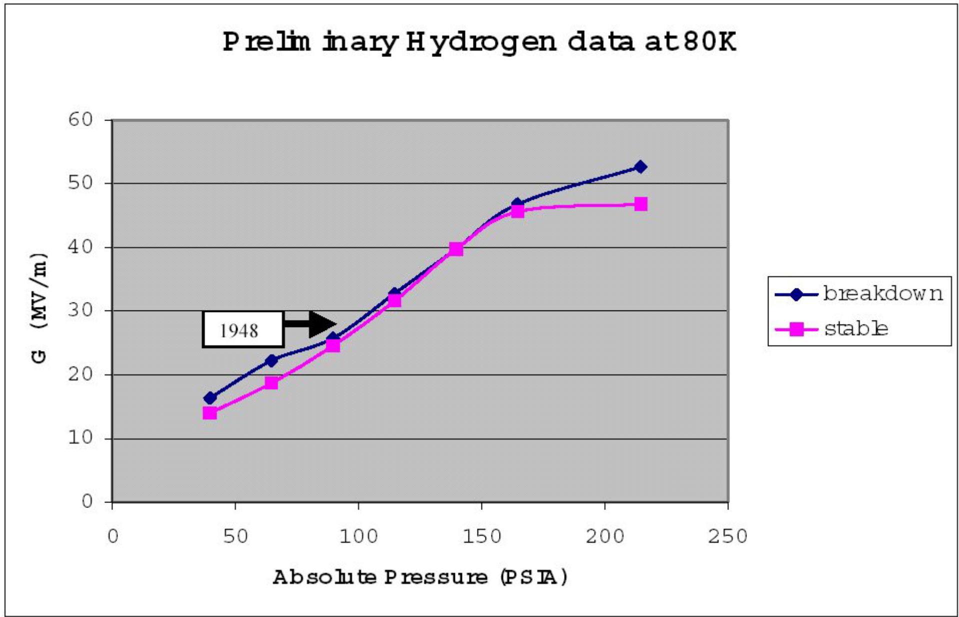
- Complications imposed by window design and flow characteristics can by addressed by considering a gaseous absorber
  - Absorbers migrate into RF cavities – Fill cavities with high pressure H_2
    - Most windows can be eliminated
    - Heat removal, flow characteristics simplified
      - 80K operation at 100 Atm (½ density of LH_2)
        - Also improved (lower) Cu surface resistance (X20 @ 200 MHz)
    - Large Potential impact on channel
      - Higher gradient RF
      - Shorter channel
    - Breakdown governed by Pashen Law
      - $V_s = 0.448(nd) + 0.6(nd)^{1/2}$
        - d = gap thickness
        - n = number density of gas molecules
        - At high P ∝ n
      - At high P
        - MFP extremely short
        - Difficult to initiate avalanche



Gaseous Absorber – Muon's Inc

- Work on Phase I STTR
  - 805 MHz test cell
    - Tested at Lab G
  - Cell conditioned at 450 psig @ 80K
  - Max stable gradient
    - 47 MV/m
  - Data agree well with Pashen Law up to ≈ 170 psig
  - From 170-500 psig no increase in max gradient
    - Surface breakdown
      - Improve electrode surface qualities
  - Data extrapolate to almost 240 MV/m at 80K & 100 atm





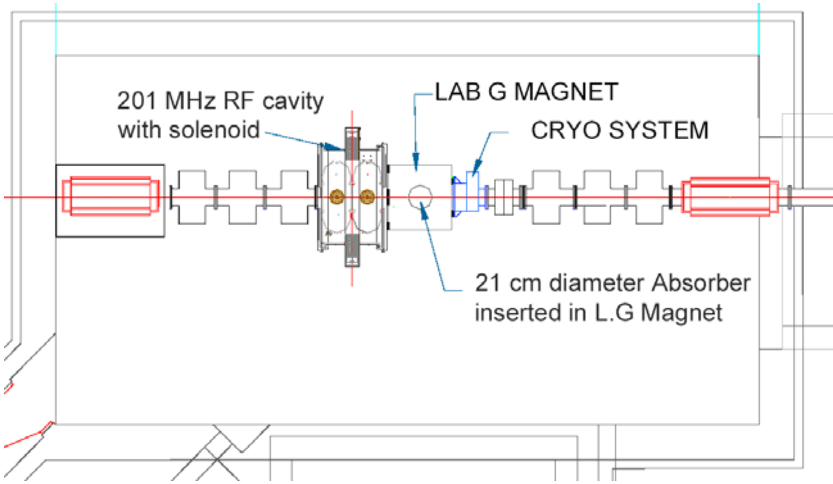
Muon Collaboration

MuCool Test Area

400 MeV High-Intensity Proton Beam line

MuCool Test Area (MTA)

- Facility to test all components of cooling channel (not a test of ionization cooling)
  - At high beam power
    - Designed to accommodate full Linac Beam
    - 1.6 X 10^{13} p/pulse @15 Hz
      - 2.4 X 10^{14} p/s
      - ≈ 600 W into 35 cm LH_2 absorber @ 400 MeV
  - RF power from Linac (201 and 805 MHz test stands)
    - Waveguides pipe power to MTA



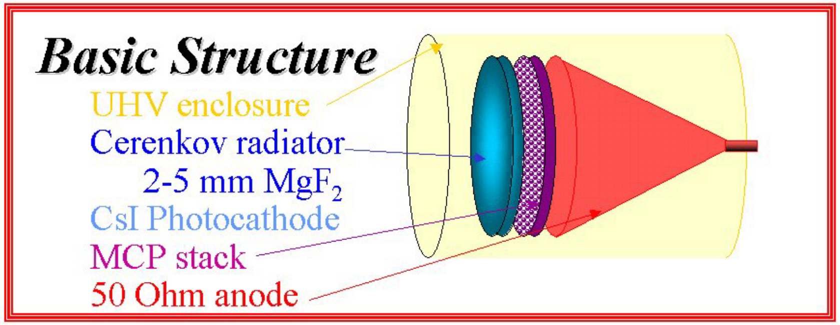
MuCool Test Area (MTA)

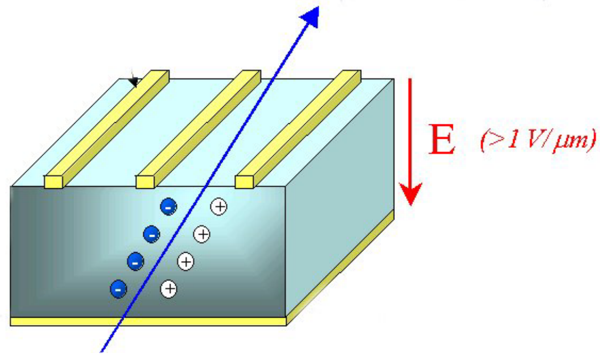
- Construction of facility slightly ahead of schedule
- Beneficial occupancy is expected to be in September
- First Use
  - Convective LH_2 absorber tests
- 201 and 805 MHz RF testing towards end of FY 04
  - Installation of LH_2 and LHe systems in FY 04 depends on funding
- Beam to area in FY 06

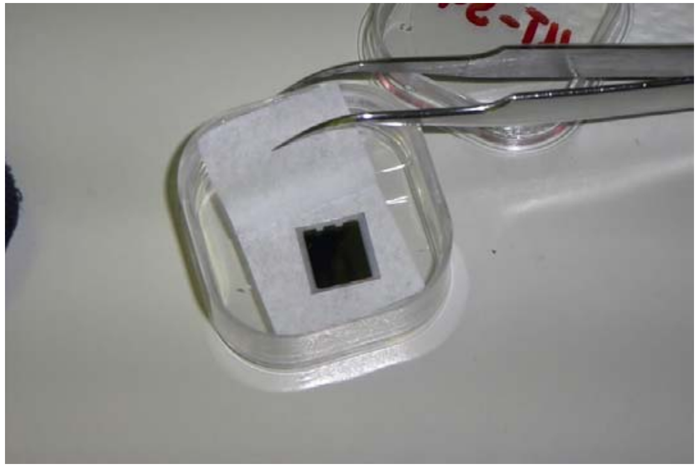
Status as of May 20

Beam line Instrumentation

- A number of areas have been investigated
  - Ultra-fast timing
    - Cerenkov –Photocathode-MCP
    - $\sigma_\tau = 6.5$ ps (intrinsic)
  - Beam Profile Monitors
    - Bolometry
      - Thin films applied to absorber windows
        - Ni & C films tested at ANL e beam showed promising results
        - Pt may be a better choice
    - CVD Diamond
      - For beam diagnostics can be very thin
        - Lots of charge – 36 e-h/μm-mip
      - Rad Hard
      - Low-quality (small *mfp*) might be useable
      - First strip prototype ready for test







Simulation Work

- Cooling Components as mentioned
  - Absorbers – 2D and 3D Finite Element Analysis (FEA)
    2D Computational Fluid Dynamics (CFD)
  - RF – Electromagnetic modeling of Be windows and grids
    FEA modeling of window deflection/stress
- Quad-focused cooling channel
- Study II cooling channel
  - GEANT4 simulation including latest window design
- MICE
  - GEANT4 framework developed

MuCool and MICE

- Muon Ionization Cooling Experiment (MICE)
  - Demonstration of "Study II" cooling channel concept
- MuCool Collaboration interface to MICE
  - Design Optimization/develop of Study II cooling channel
    - Simulations
  - Detailed engineering
    - Full component design
    - Systems integration
    - Safety
  - RF cavity development, fabrication, and test
  - Absorber development, fabrication, and test
  - Development of beam line instrumentation
  - MuCool will prototype and test cooling hardware including MICE pieces which the collaboration is responsible
- High-intensity Beam Tests are responsibility of MuCool and are, of course, fully complementary to MICE

MuCool Plans

- Continue 805 MHz RF studies in Lab G
  - Window and grid tests
  - Surface treatment/materials tests
    - Effect on dark current and breakdown
- Continue development of thin windows for absorbers
  - Already within the material budget of Study II even with the extra windows
- Begin work in the MuCool Test Area (MTA)
  - First work in MTA to be test fill of LH_2 absorber (convective)
- In FY04
  - Provide 201 & 805 MHz capability for MTA
  - Provide as much of the cryo infrastructure as funding allows
  - Fabricate first 201 MHz cavity and bring to MTA for test
  - Possibly move Lab G magnet to MTA for test with cavity
- In FY05
  - Complete MTA cryo (if needed)
  - Fabricate coupling-coil prototype
  - Begin installation of 400 MeV beam line from Linac
- In FY06
  - Bring high intensity beam to MTA
    - Test complete set of cooling components in high intensity beam

Conclusion

- Excellent progress has been made in the last year
  - On-going NCRF R&D has demonstrated High Gradient low dark current operation
    - R&D continues in order to continue to push HG Low DC operation in B field
      - Use of Be RF windows looks promising
  - Design of LH_2 absorbers and windows has matured
    - "Thin" window required spec appears to have been met
  - Detailed engineering of components has matured
  - MuCool Test Area construction is on (slightly ahead) of schedule
- Speed of progress in FY04+ will depend on funding
- MuCool is a thriving International Collaboration
  - Absorbers – Japan
  - Absorber/Window design – UK
  - Addressing many of the needs of MICE