Muon Collaboration

MuCool and Neutrino Factory R&D

Fermilab Accelerator LRP Open Session

A. Bross

November 18, 2003

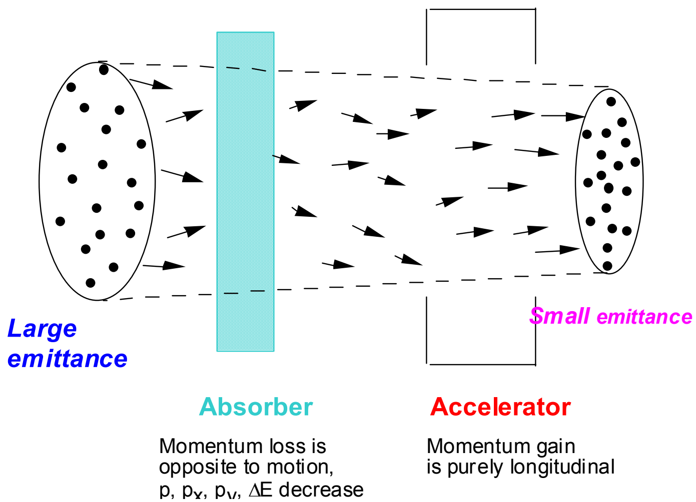
Muon Collaboration

Introduction

- Neutrino Oscillation Physics has created a revolution in HEP in recent years
- Quite possibly the ultimate tool for studying neutrino oscillations (and neutrino interactions in general) is the so-called Neutrino Factory (see S.Geer's talk)
- The Fermilab community is actively involved in the international Neutrino Factory R&D effort
  - Physics studies
  - Accelerator design and simulation
  - Accelerator component design, construction, and test
- The MuCool Collaboration is focusing on R&D on components for a particular implementation of a Neutrino Factory
  - Muon Ionization Cooling

Muon Ionization Cooling

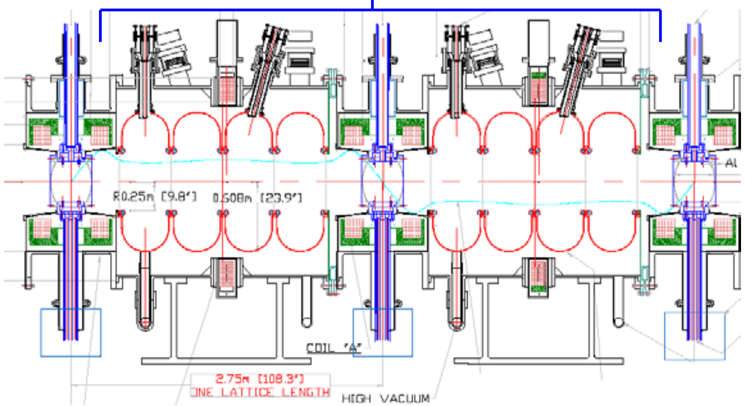
- Although the concept of muon ionization cooling is relatively straightforward (transverse, at least)
  - Muons pass through material losing energy
  - They are then accelerated regaining only longitudinal momentum



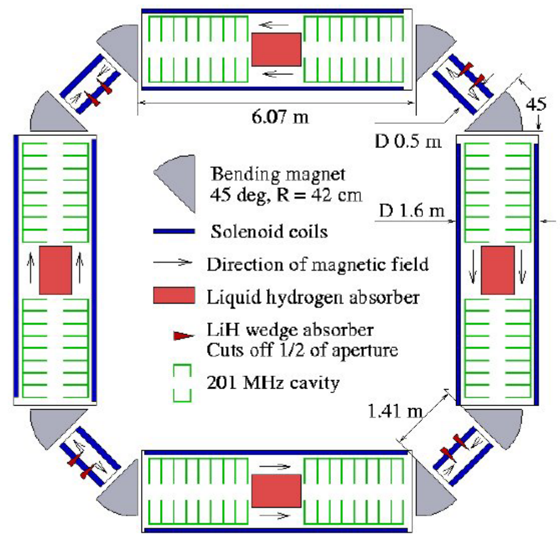
- However, theory is sometimes much simpler than reality

Muon Ionization Cooling

- There are both linear and ring implementations proposed for muon ionization cooling …

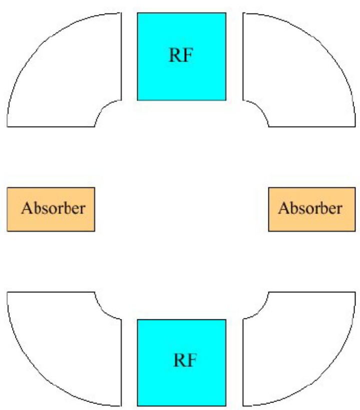


SFOFO



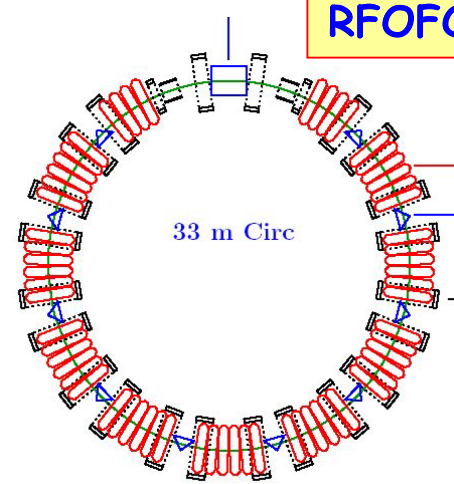
Solenoid Focused Ring

RFOFO



Graded Dipole

Note: Rings provide 6D cooling and therefore present some differences in implementation



Muon Ionization Cooling

- … They all require high-gradient Normal-Conducting RF, some sort of absorber, and high field magnets
- The theory, and now detailed and quite extensive simulations show that ionization cooling can work
  - Still some problems to be solved with 6D cooling
    - Injection and extraction
- However, engineering a real system is a daunting task
  - Performance criteria in design/simulation – quite aggressive
  - Many of the specifications push state-of-the-art
  - System integration problems are formidable
  - Operational safety concerns are an issue
- Before building a complete cooling channel an extensive R&D program is required in order to
  - Demonstrate there are no unforeseen problems
  - Verify performance criteria are met
    - With high-intensity beam in many cases
  - Demonstrate cooling in a test channel
- *Note*
  - For Neutrino Factories and Muon Colliders these same statements can be made regarding:Proton Driver, Targetry, Acceleration
    - No off-the-self items!

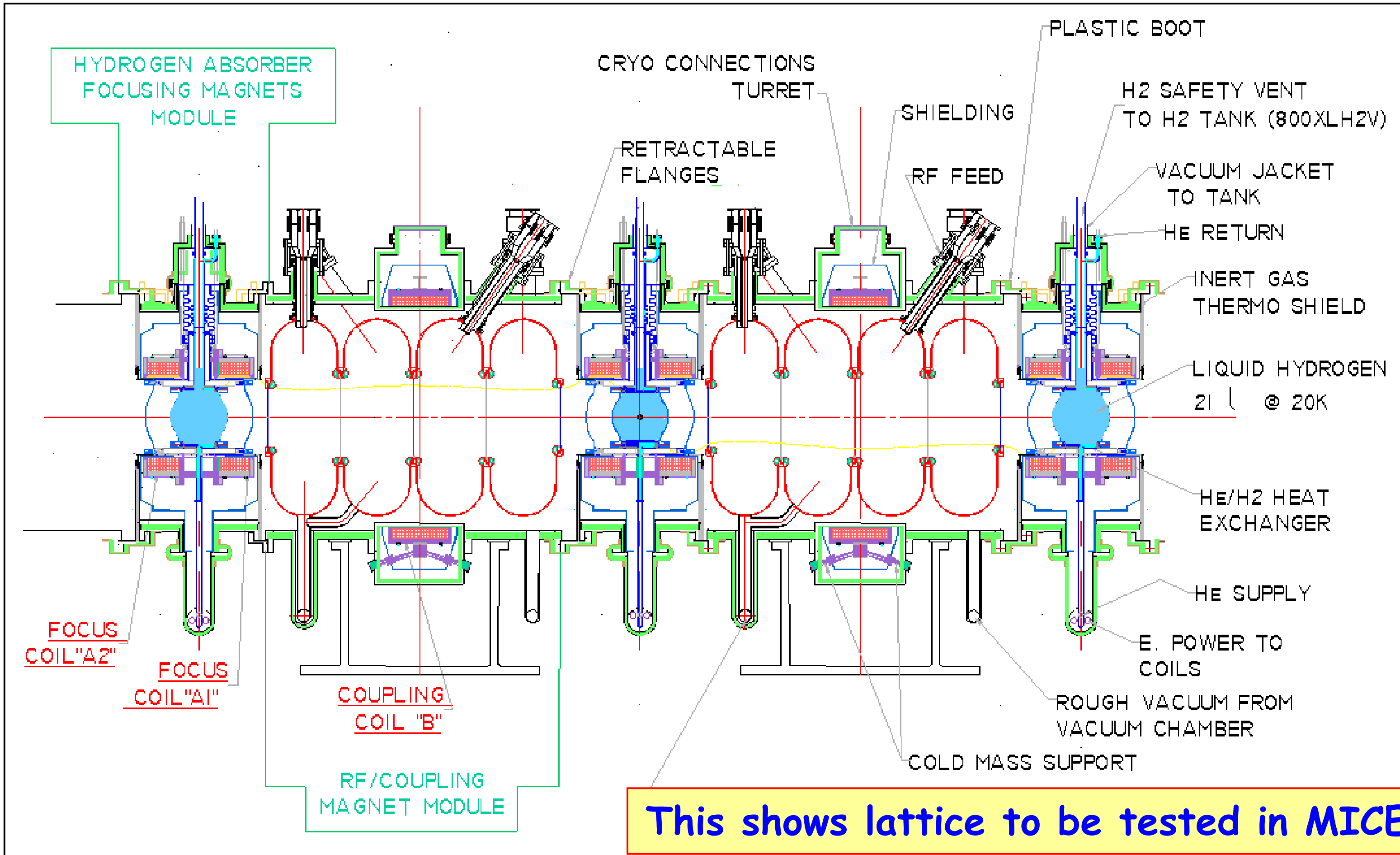
The MuCool Collaboration

- MuCool Mission
  - Design, prototype and test all components of a muon ionization cooling channel
  - Perform high beam-power engineering test of cooling section
  - Support MICE (cooling demonstration experiment)
    - Successful MuCool + MICE programs will provide key technical input to decision on Neutrino Factory

- Consists of 70 scientists from 18 institutions from the US, Europe, and Japan
- Primary Support for MuCool comes from non-base program funds
  - Accelerator R&D through broader Muon Collaboration
- Fermilab staff are involved in essentially all aspects of the R&D program
- Fermilab staff key members of the Neutrino Factory Design Effort (Muon Collaboration)

The Details - SFOFO Cooling Lattice

- Basic Components
  - Absorbers – Most likely LH_2
  - 201 MHz RF
  - Superconducting Solenoids (On-axis fields up to ≈ 3-4T)



This shows lattice to be tested in MICE

Muon Collaboration

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
    - kW for ring cooler designs
- 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?

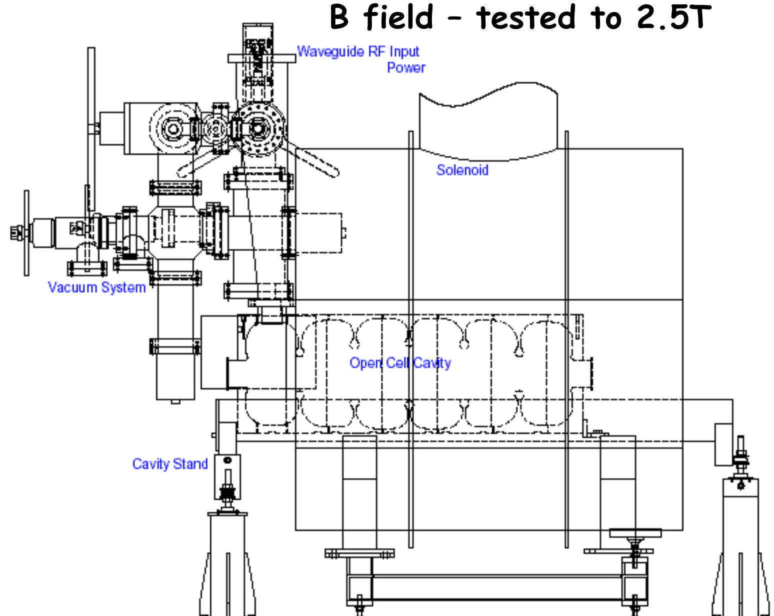
RF Cavity R and D

ANL/FNAL/IIT/LBNL/UMiss

RF Cavity R&D – Prototype Tests

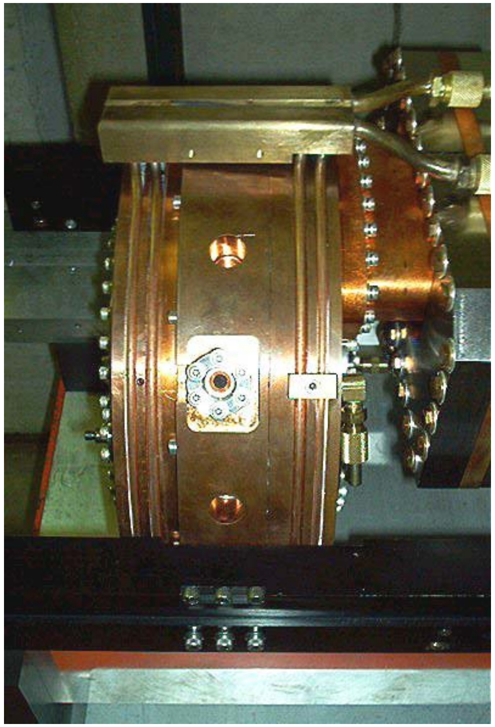
Lab G RF Cave showing 5T SC Magnet 44 cm bore

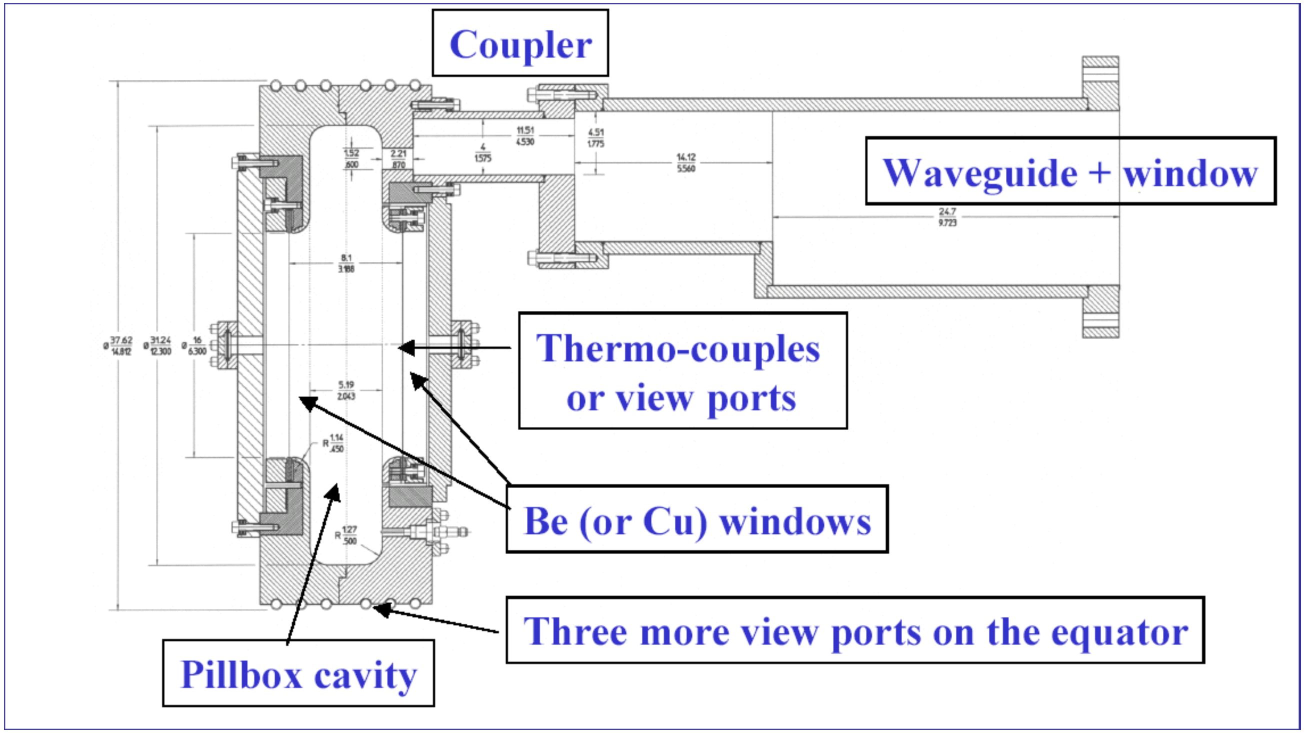
- Work to date has focused on using 805 MHz cavities for test
  - Allows for smaller less expensive testing than at 201 MHz
  - Lab G work at Fermilab
    - Phase I
      - Open Cell cavity reached 54 MV/m surface field (25 MV/m on axis)
        - Large dark currents increased with B field – tested to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



RF Cavity Prototype Tests
805 MHz Pillbox

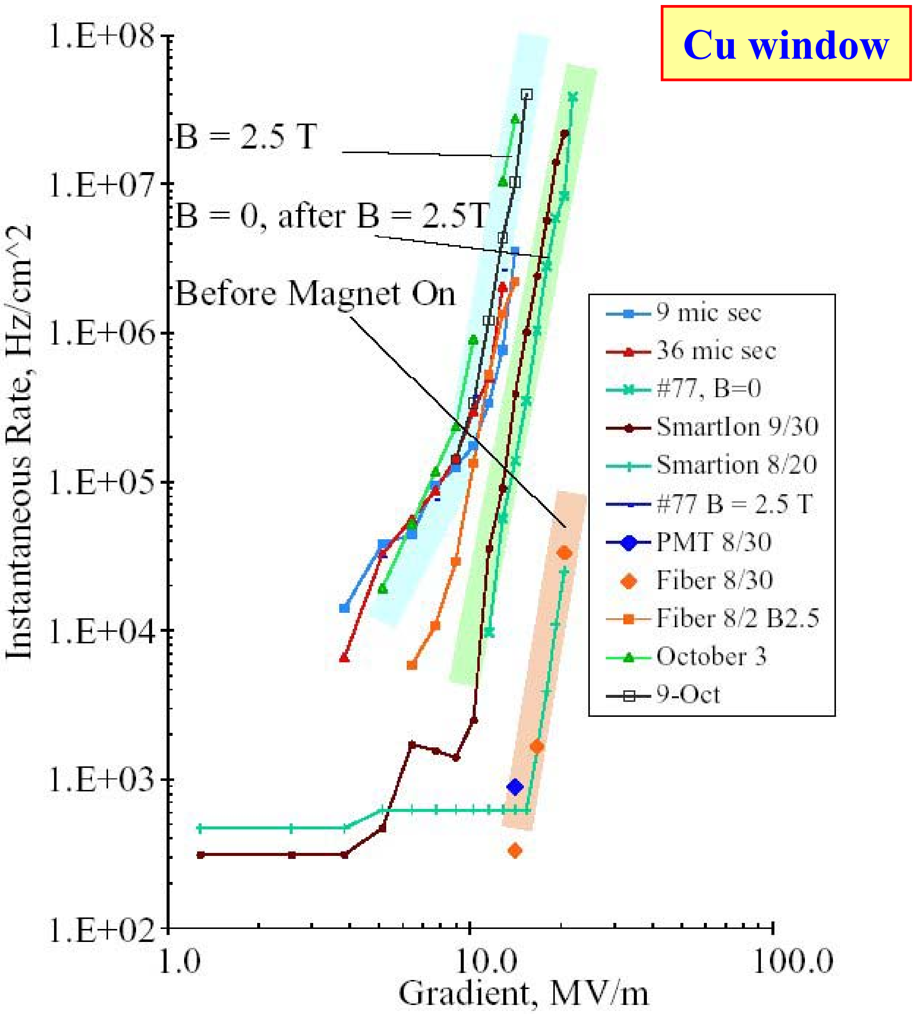
- Lab G Tests Phase II
  - Closed Cell (pillbox) - E_{acc}/E_{surf} = 0.99
  - Reached 34MV/m with little sparking and low background
    - Thick Cu windows
    - B=0





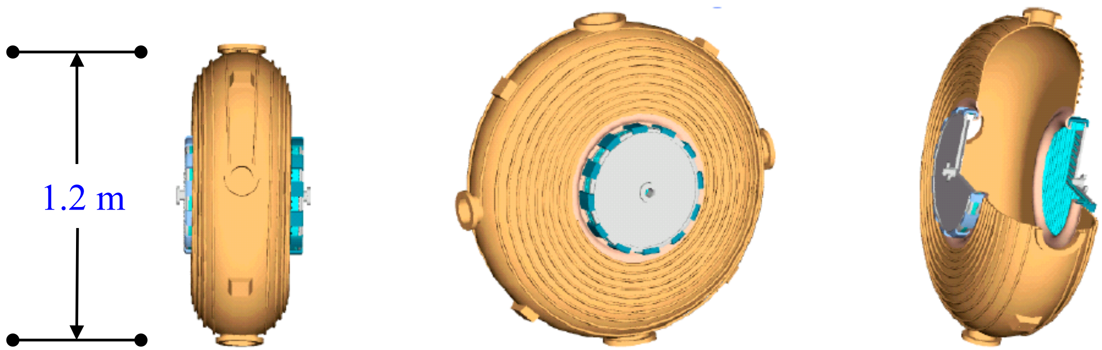
RF Cavity Prototype Tests 805 MHz Pillbox

- 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

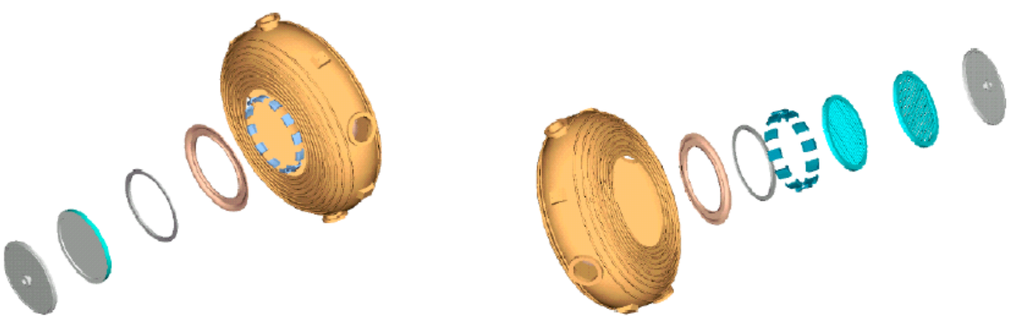


RF R&D – 201 MHz Cavity Design

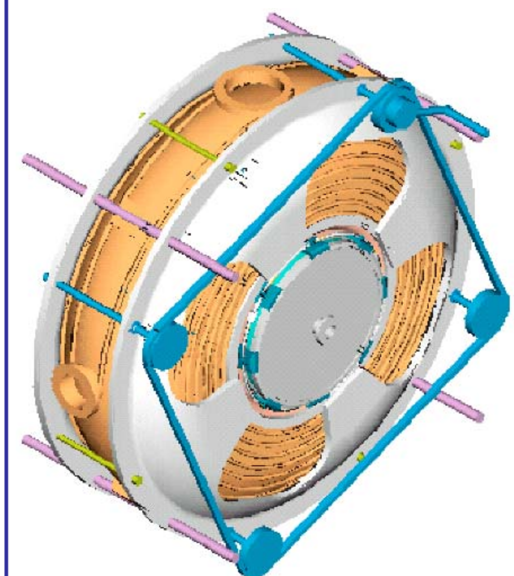
- Design Complete
  - Electrical, Mechanical, and thermal analyses have been done
    - E^{pk}_{surf} = 26.5 MV/m
  - Fabrication has started
  - Goal is to have a 201 MHz cavity under test at Fermilab 04



201.25 MHz cavity conceptual design



Exploded views showing foil and grid mounting hardware



Absorber R and D

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

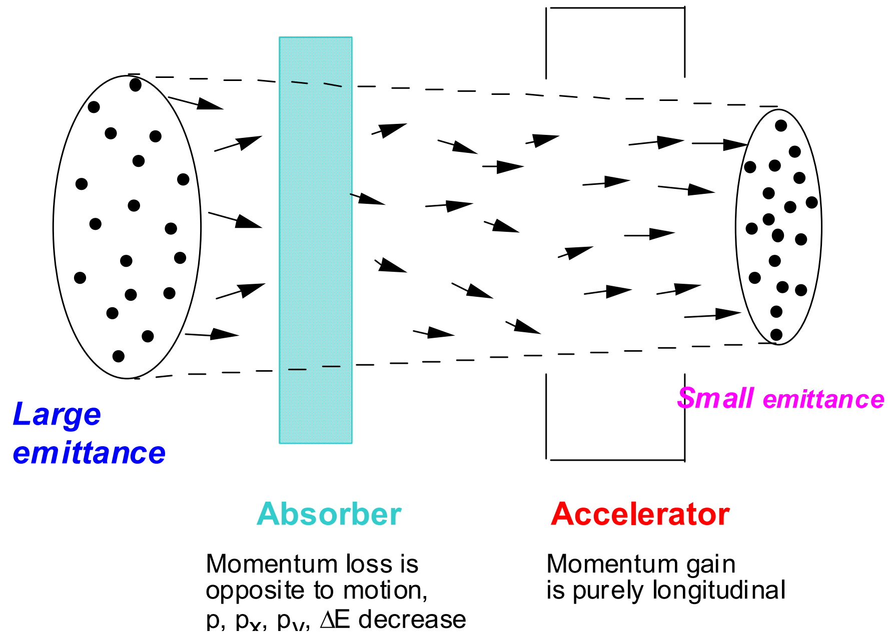
Absorber Design Issues

- **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

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



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

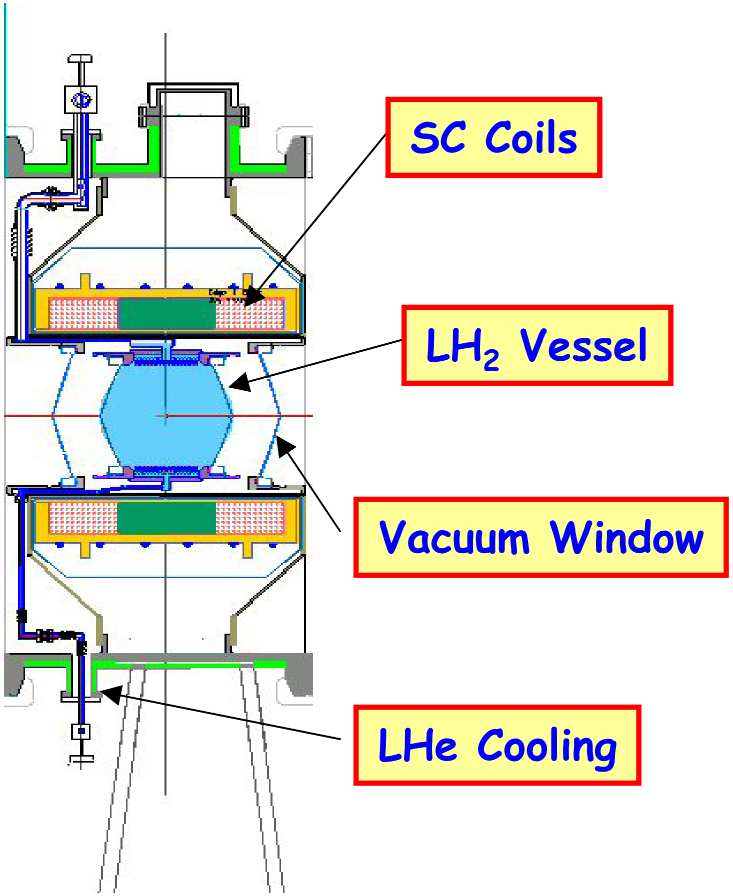
M^2 (4D cooling) for different absorbers

Material	$\langle dE/ds\rangle_{min}$ (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

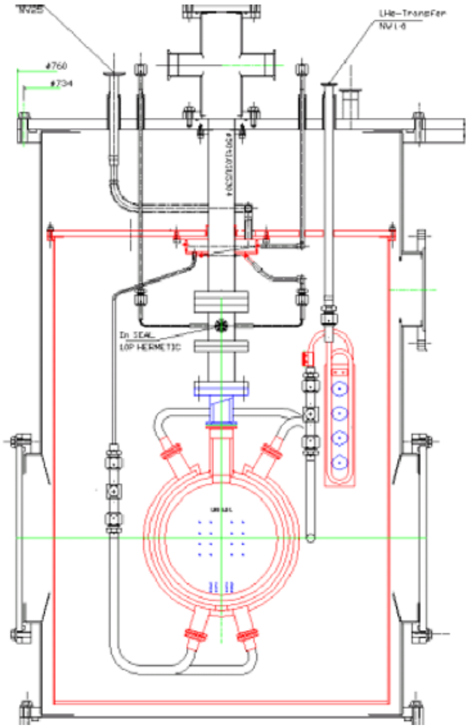
- Design Criteria
  - High Power Handling
    - Study II – few 100 W to 1 KW with "upgraded" (4MW) proton driver
    - 10 KW in ring cooler
      - Must remove heat
  - Safety issues regarding use of LH_2 (or gaseous H_2)
    - Window design paramount
      - H_2 containment
    - Proximity to RF adds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



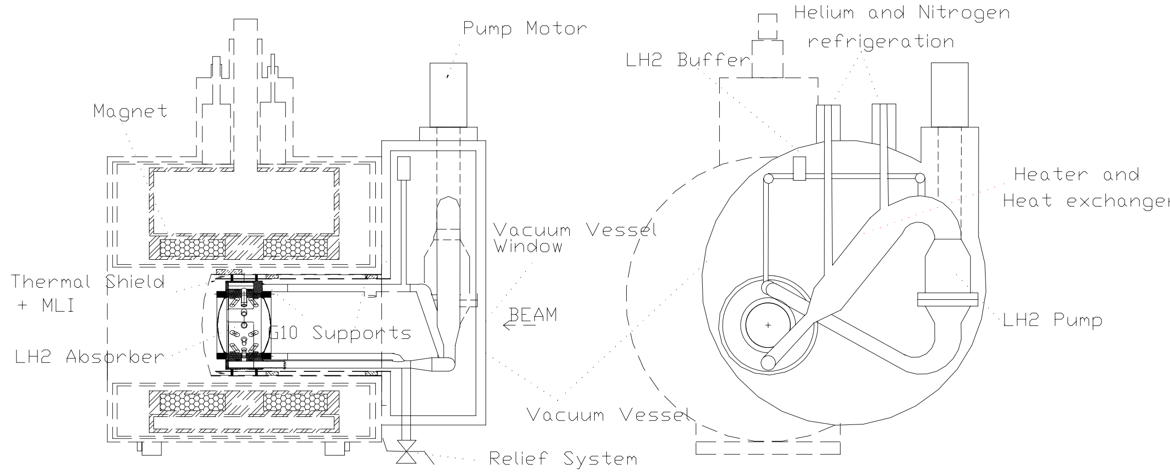
H_2 implies engineering complexity

Absorber R&D

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



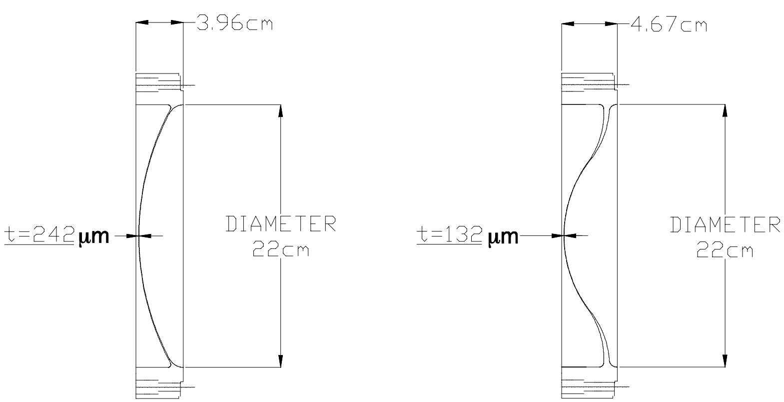
Forced-Convection-cooled. Has internal heat exchanger (LHe) and heater



Forced-Flow with external cooling loop

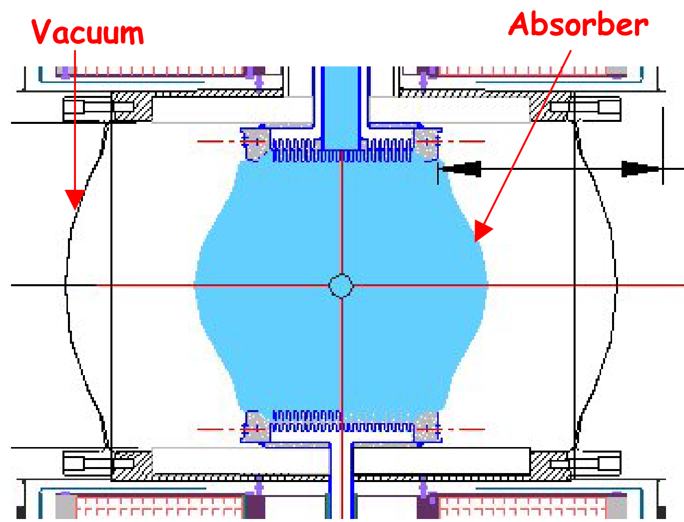
Absorber Windows

- 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



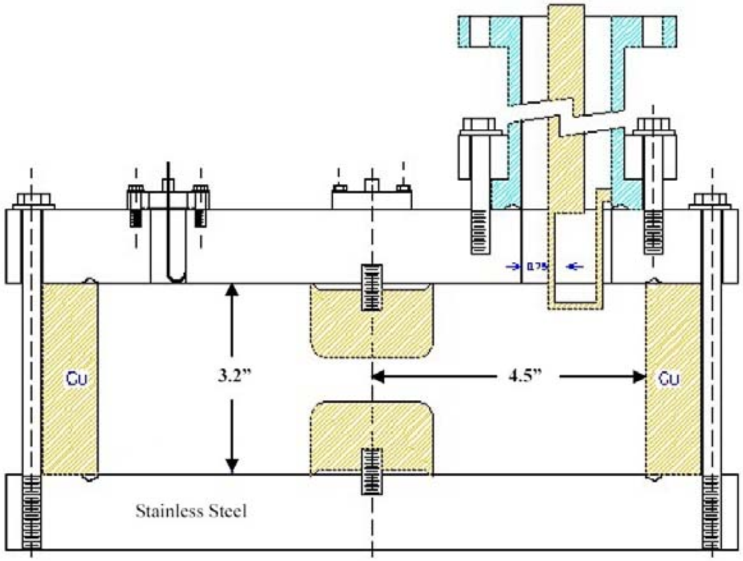
Design Iteration
Tori-Spherical - Inflected

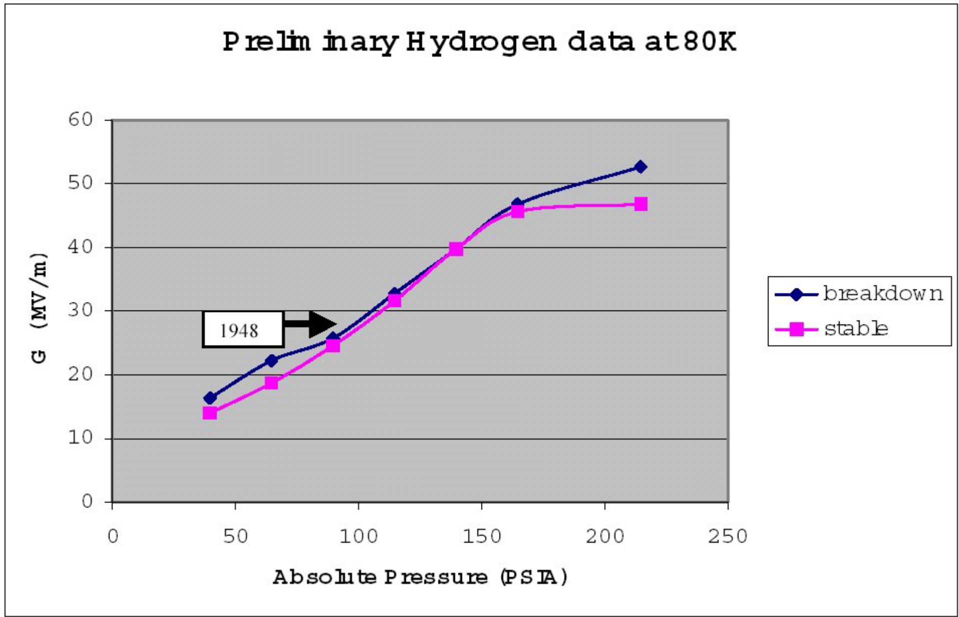
Containment Windows



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

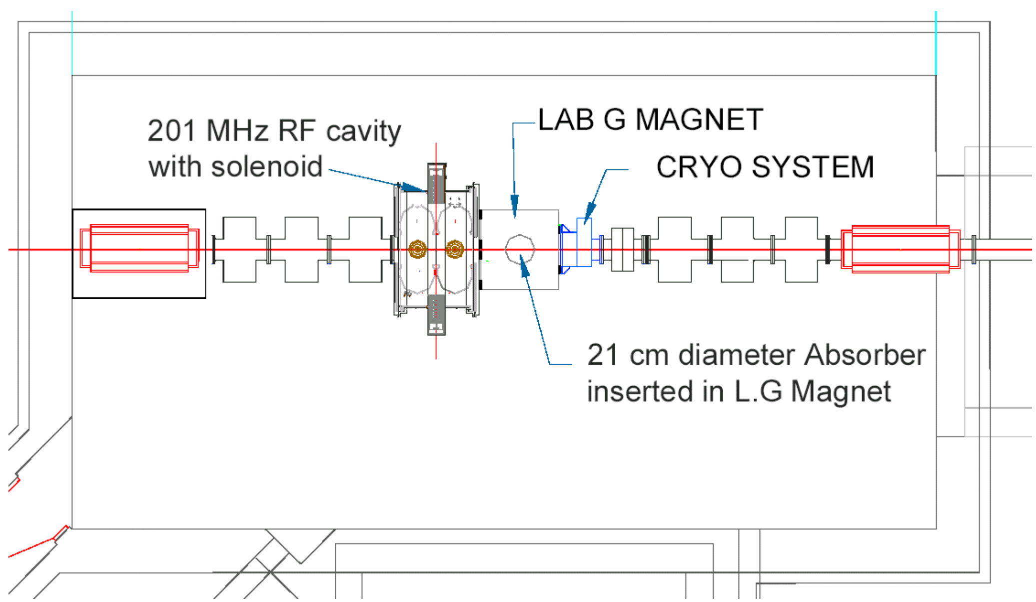
MuCool Test Area

MuCool Test Area (MTA)

- Facility to test all components of cooling channel (not a test of ionization cooling)
  - RF power from Linac (201 and 805 MHz test stands)
    - Waveguides pipe power to MTA
  - LHe refrigeration plant for tests of LH_2 absorbers and for superconducting magnets
  - Hydrogen gas facility

MuCool Test Area (MTA)

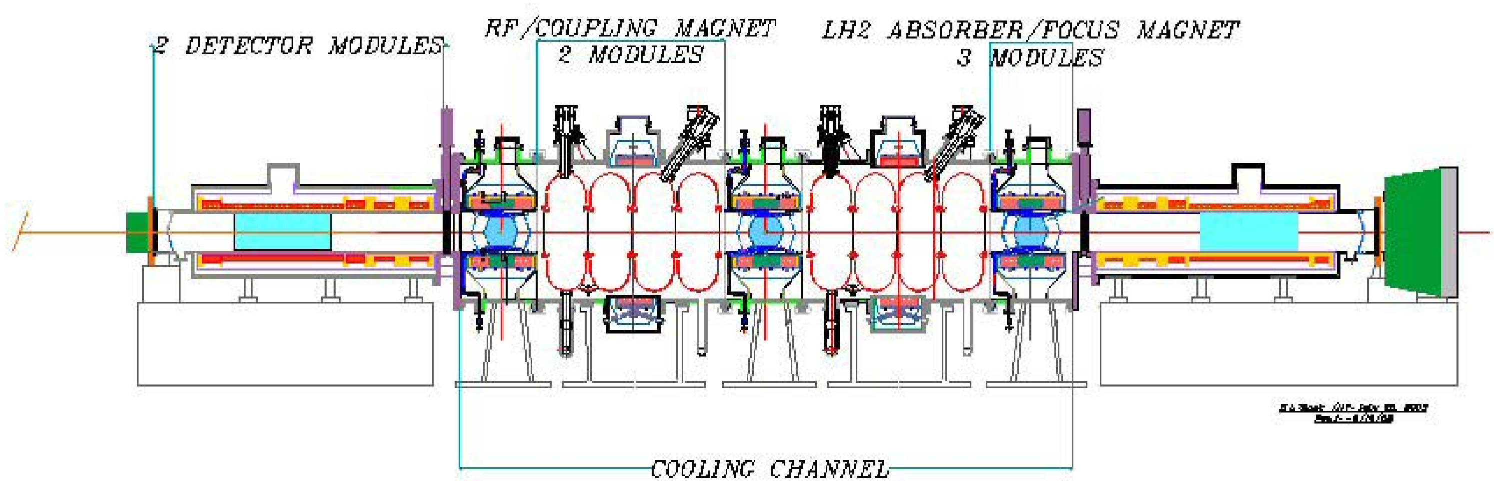
- First Experiment in MTA is now setting up
  - LH_2 Convective-flow absorber (KEK)
- We eventually wish to bring Linac Beam out the area
  - Designed to accommodate full Linac Beam
  - 1.6 X 10^{13} p/pulse @15 Hz
    - 2.4 X 10^{14} p/s
    - ≈ 600 W into 35 cm LH_2 absorber @ 400 MeV
- This will allow us to test cooling components at high beam current



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
    - Has Now Received Scientific Approval from the UK!
- MuCool Collaboration interface to MICE
  - Design Optimization/develop of Study II cooling channel
    - Simulations
  - Detailed engineering
    - Full component design
    - Systems integration
    - Safety
  - RF, 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 ultimately the 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
- MuCool Test Area (MTA)
  - First work in MTA has started - 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
  - Initiate Full beam-line design and complete shielding assessment
    - Dependent on availability of Laboratory resources
- In FY05
  - Complete MTA cryo (if needed)
  - Fabricate coupling-coil prototype (funding driven – Lab help)
  - Begin installation of 400 MeV beam line from Linac
    - Dependent on availability of Laboratory resources
- In FY06
  - Bring high intensity beam to MTA (again dependent on Lab resources)
    - Test complete set of cooling components in high intensity beam

Conclusion

- Excellent progress has been made on the design and engineering of ionization cooling components
  - 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
      - This work is of general interest to HEP Accelerator R&D
  - 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 is complete and first experiment is being setup
- Speed of progress in FY04+ will depend on funding
  - Beam to the MTA will have to be addressed by the laboratory
- MuCool is a thriving International Collaboration
  - Absorbers – Japan
  - Absorber/Window design – UK
  - Closely coupled to and working with the MICE collaboration