MuCool

ICAR Meeting

May 19, 2004

Mary Anne Cummings

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

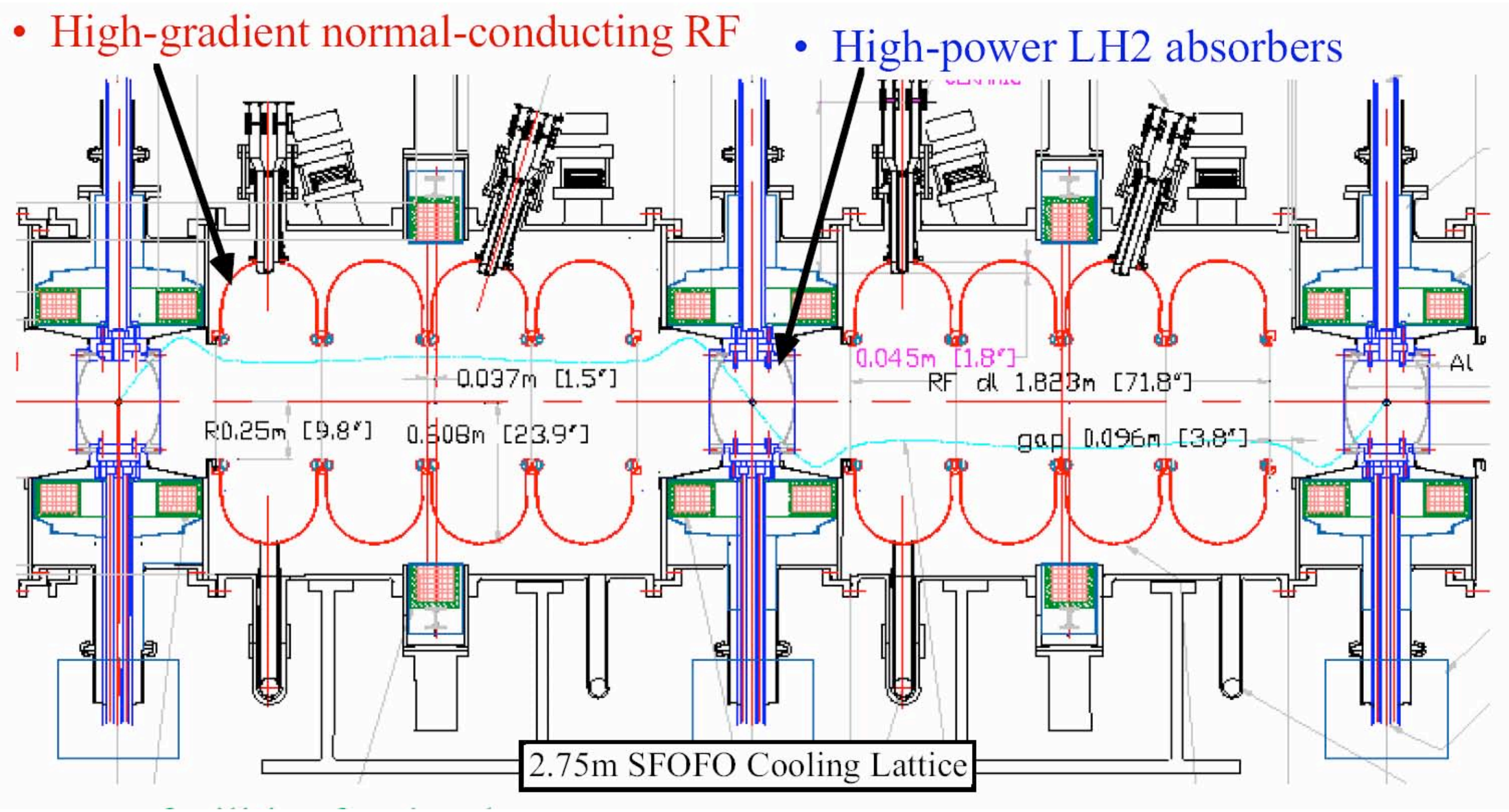
Cooling Demonstration (MICE)
ANL
BNL
Fermilab
Fairfield
IIT
Iowa
JLab
LBNL
NIU
UCLA
UC Riverside
UIUC
Univ. of Chicago
Univ. of Mississippi

MuCool Management Structure

- Rather loose – A WBS structure has not yet been inflicted on the collaboration:
  - **Spokesperson:** **Alan Bross**
  - **Technical Area Leaders:**
    - RF: Al Moretti, FNAL
      Derun Li, LBNL
    - RF Diagnostics: Yagmur Torun, IIT
    - Absorbers: Mary Anne Cummings, NIU
    - MuCooL Test Area: Milorad Popovic, FNAL

SFOFO Cooling Lattice

- R&D Focus of MuCool
  - Component testing Fermilab
    - High Power, both RF and Beam
  - System test - MICE @ RAL



Research and Development Challenges

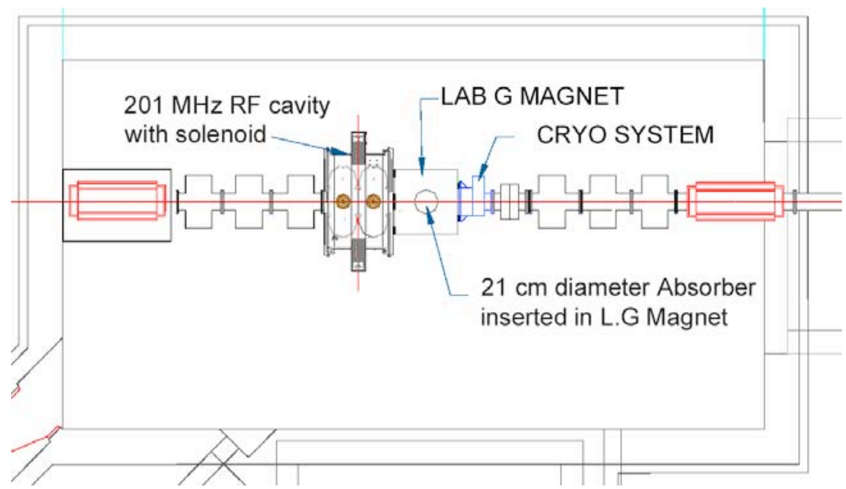
- Can NCRF cavities be built that provide the required accelerating gradients?
  - **AND operate in multi-tesla fields!**
- Can the heat from *dE/dx* losses be adequately removed from the absorbers?
  - **On the order of 100's W for a neutrino factory**
- Can the channel be engineered with an acceptably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

MuCool Test Area

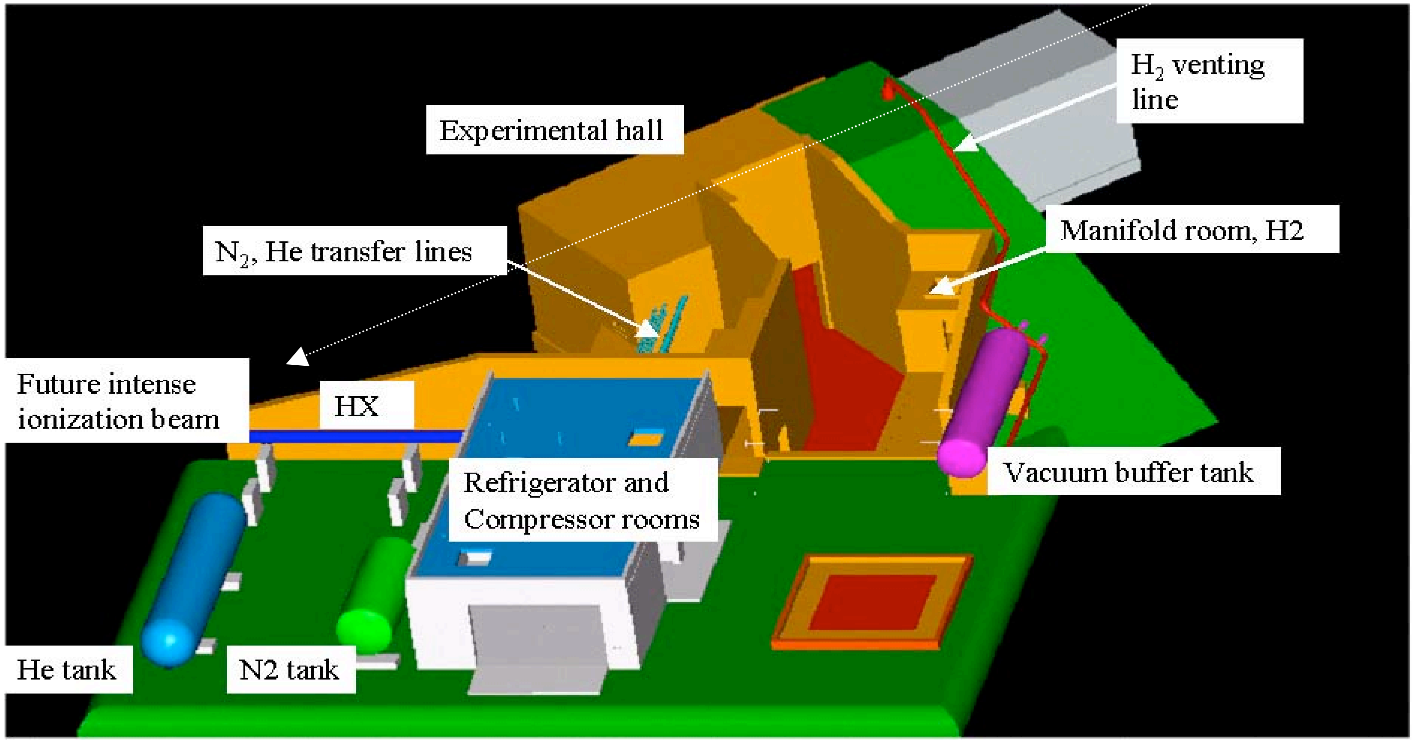
The MuCooL Collaboration Enters a new Era

MuCool Test Area

- 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



MTA



- The MTA is becoming our focus of Activity
  - **LH_2 Absorber tests**
  - **RF testing (805 and 201 MHz)**
  - **Finish Cryo-Infrastructure**
  - **High pressure H_2 gas absorbers**
  - **High Intensity Beam**

MTA Tour

Compressor Room Access Pit

MTA Tour

H_2 Buffer Tank
H_2 Manifold Room

MTA Tour

Access Pit

MTA Tour

MTA Experimental Hall

MTA Tour

KEK LH_2 Absorber

MTA Tour

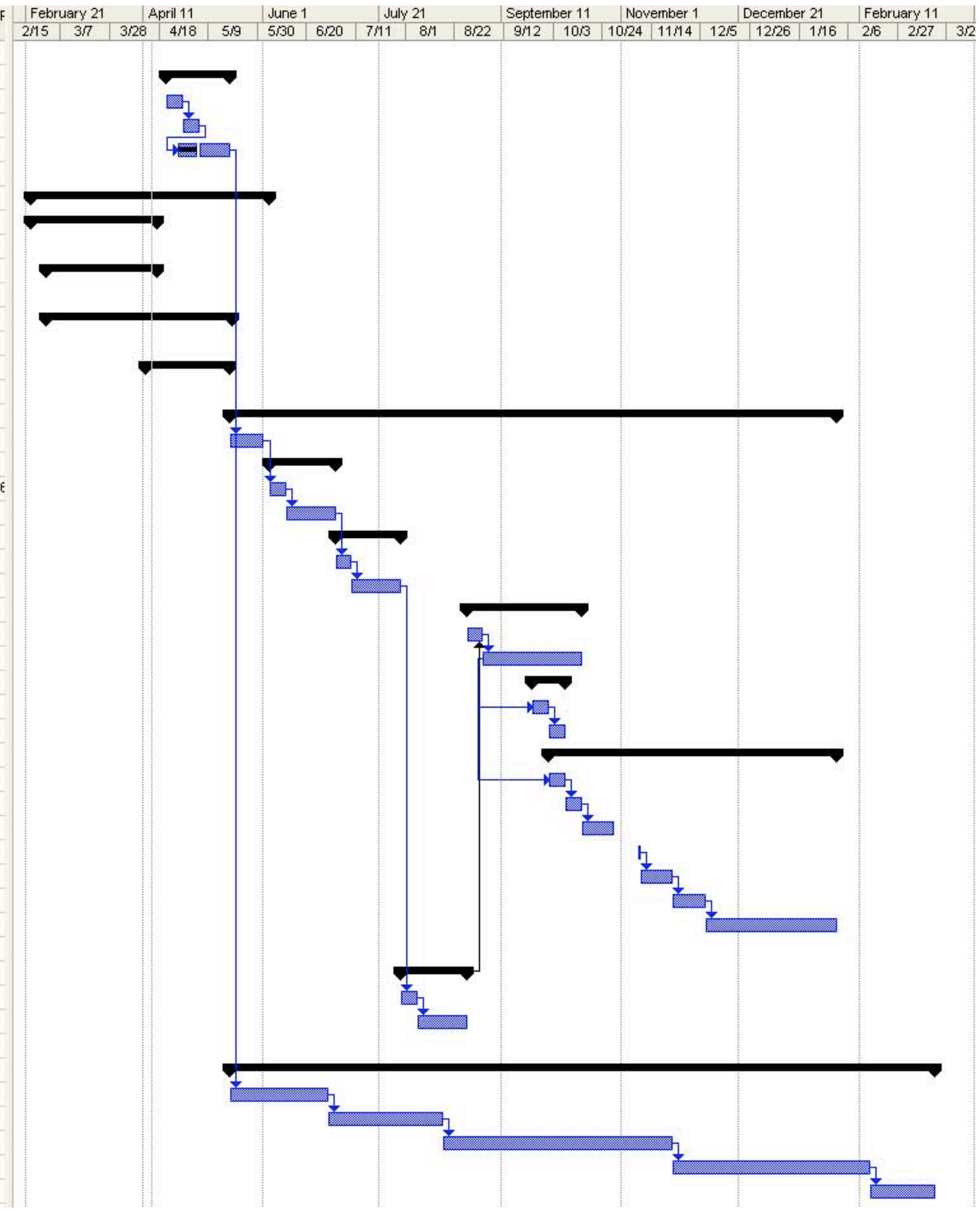
MTA Experimental Hall
From Linac
(Lots of Activity)

MTA Tour

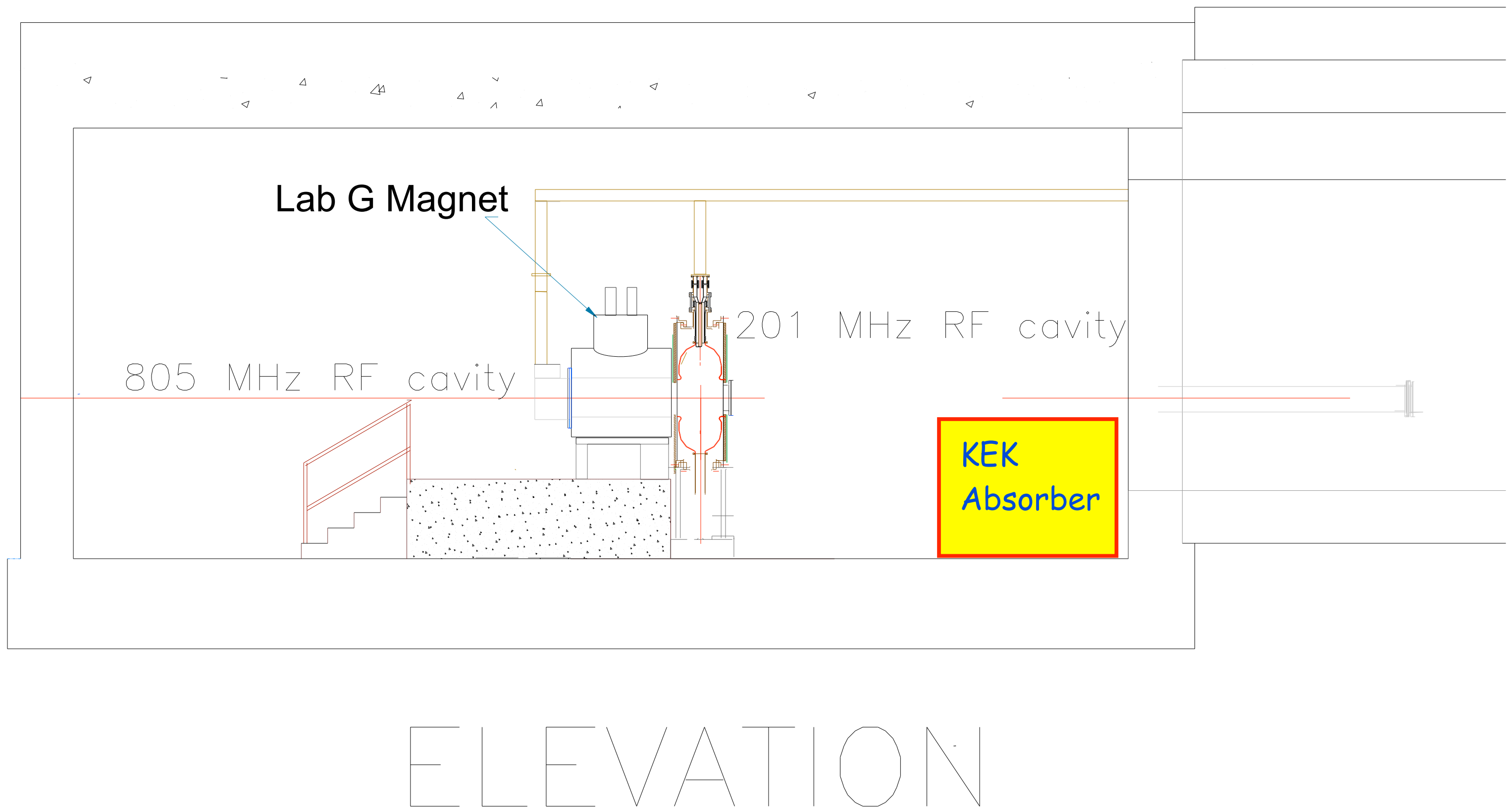
View from Wilson Hall
RF Trench visible

MTA – Near Term Schedule

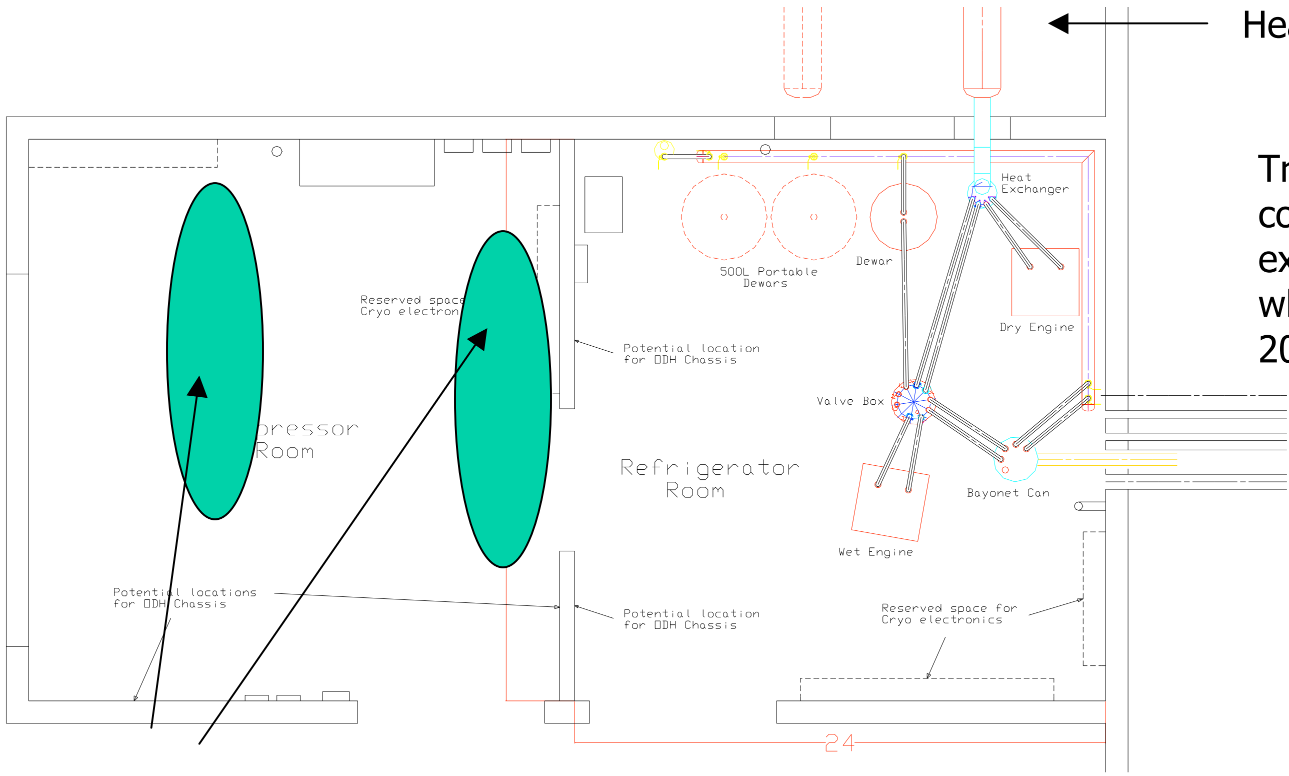
Task Name	Start	Finish
KEK Absorber Cooldown	**Wed 4/21/04**	**Mon 5/17/04**
Walkthru	Wed 4/21/04	Tue 4/27/04
Cooldown Helium only	Wed 4/28/04	Tue 5/4/04
Cooldown Hydrogen	Mon 4/26/04	Mon 5/17/04
201 and 805 MHz RF Installation	**Mon 2/23/04**	**Thu 6/3/04**
Water	**Mon 2/23/04**	**Fri 4/16/04**
Power	**Mon 3/1/04**	**Fri 4/16/04**
RF Controls and Instrumentation	**Mon 3/1/04**	**Tue 5/18/04**
HVAC	**Mon 4/12/04**	**Mon 5/17/04**
RF Experimental Program	**Tue 5/18/04**	**Mon 1/31/05**
Install Waveguides from MTA drop to cavity	Tue 5/18/04	Mon 5/31/04
Al Waffle Grid	**Fri 6/4/04**	**Thu 7/1/04**
Installation	Fri 6/4/04	Thu 6/10/04
Data Run	Fri 6/11/04	Thu 7/1/04
Curved Be Window Test	**Fri 7/2/04**	**Thu 7/29/04**
Installation	Fri 7/2/04	Thu 7/8/04
Data Run	Fri 7/9/04	Thu 7/29/04
Button Chamber	**Fri 8/27/04**	**Thu 10/14/04**
Installation	Fri 8/27/04	Thu 9/2/04
Data Run	Fri 9/3/04	Thu 10/14/04
Muon's Inc Magnet Test	**Fri 9/24/04**	**Thu 10/7/04**
Installation	Fri 9/24/04	Thu 9/30/04
Data Run	Fri 10/1/04	Thu 10/7/04
201 MHz Tests	**Fri 10/1/04**	**Mon 1/31/05**
Install New Vacuum System	Fri 10/1/04	Thu 10/7/04
Install Stands	Fri 10/8/04	Thu 10/14/04
Prepare Instrumentation	Fri 10/15/04	Thu 10/28/04
Prototype Delivery	Mon 11/8/04	Mon 11/8/04
RF and Vacuum Installation	Tue 11/9/04	Mon 11/22/04
Install Instrumentation and test	Tue 11/23/04	Mon 12/6/04
Conditioning and Background Measurements	Tue 12/7/04	Mon 1/31/05
KEK Absorber Test II	**Fri 7/30/04**	**Thu 8/26/04**
Setup	Fri 7/30/04	Thu 8/5/04
Data Run	Fri 8/6/04	Thu 8/26/04
MTA Cryo-Infrastructure	**Tue 5/18/04**	**Mon 3/14/05**
Engineering for Piping	Tue 5/18/04	Mon 6/28/04
Go out for Piping Bid	Tue 6/29/04	Mon 8/16/04
Piping Contract	Tue 8/17/04	Mon 11/22/04
Wet Engine Installation and Setup	Tue 11/23/04	Mon 2/14/05
Commissioning	Tue 2/15/05	Mon 3/14/05



MTA – RF Configuration



MTA Cryo-Infrastruture



Heat exchanger

Transfer line connections to experimental hall which includes 5K, 20K, 80K circuits

Towards Experimental Hall

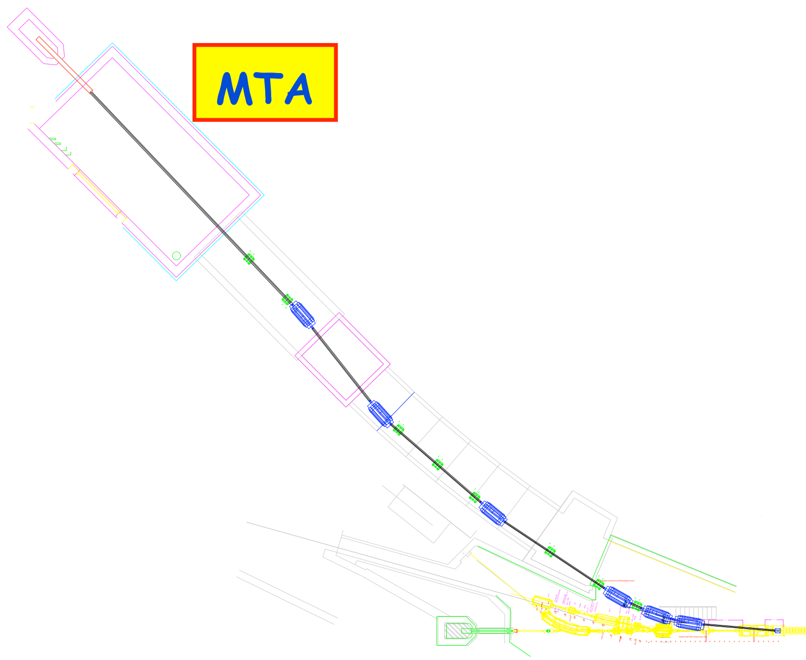
Compressor Room

- Two 400 HP 2-stage oil injected screw compressors

Refrigerator Room

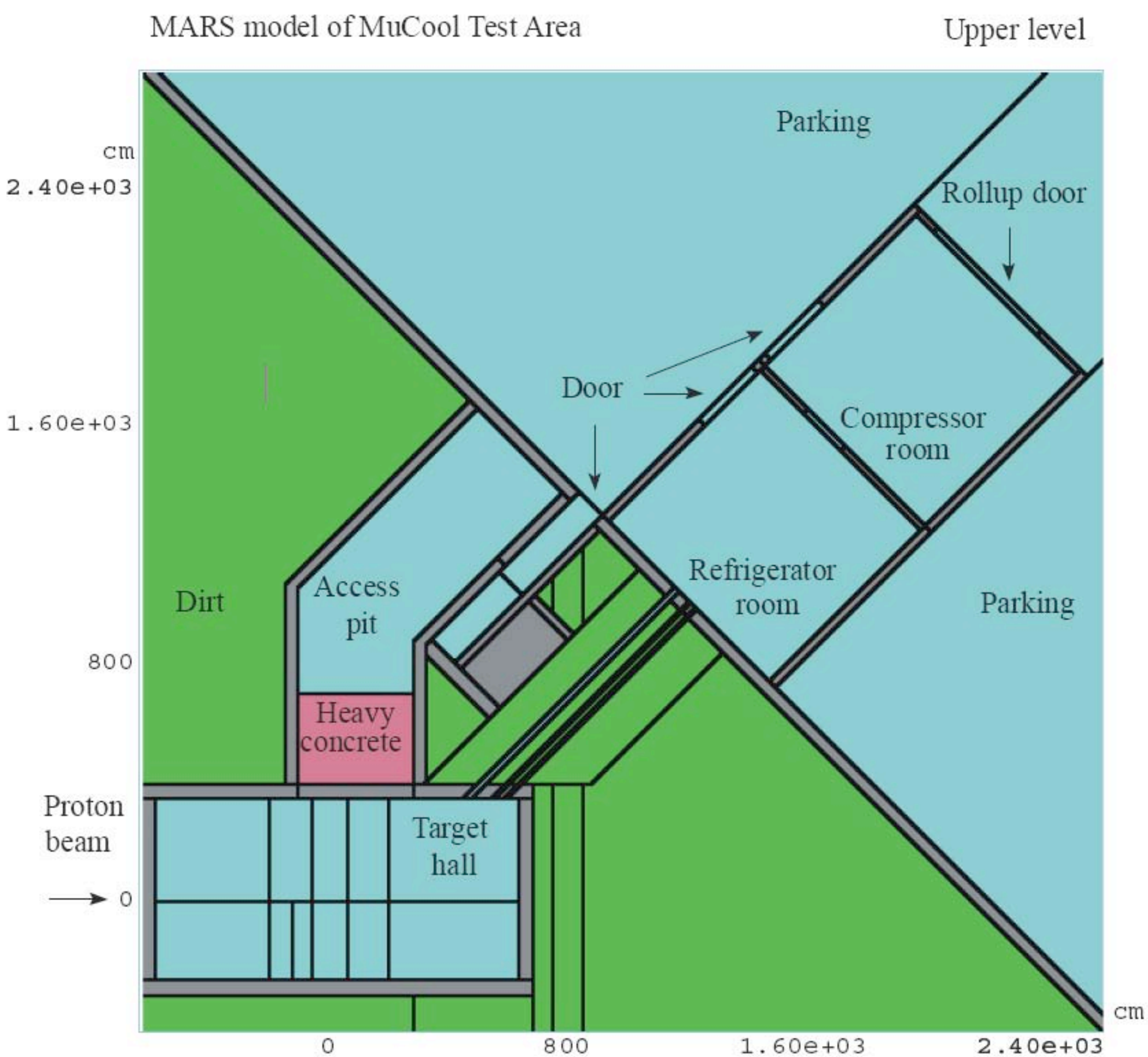
- Tevatron satellite refrigerator to be operated on 5 K mode and 14 K mode (3” DE, 3” WE)
- Helium and nitrogen Dewar

MTA High Intensity Beam Tests



- FNAL Study group has been formed to design 400 MeV beamline for the MTA
  - Under Craig Moore
    - External Beams Department
  - Develop Engineering Design
    - Cost
    - Schedule
  - Safety Analysis
    - Linac Area and Beamline
    - Shielding Assessment for MTA
      - Essentially Complete
  - Preliminary thoughts
    - "Spin" beam in order to provide large (30 cm) aperture
      - Instead of large Quads
      - Simpler and therefore Cheaper
  - Timeline still driven by resource

MTA Shielding Assessment



- Conclusions from Present Study
  - **A credible beam accident at MTA is less severe than normal operation.**
  - **At normal operation the following classification is suggested (Fermi RCM):**
  - **• Berm above target hall – Controlled Area of minimal occupancy (0.25 – 5 mrem/hr);**
  - **• Access pit – Radiation Area with rigid barriers/locked gates (5 – 100 mrem/hr);**
  - **• Cryo room - Radiation Area with rigid barriers/locked gates (5 – 100 mrem/hr);**
  - **• Compressor room - Controlled Area of minimal occupancy (0.25 – 5 mrem/hr);**
  - **• Parking lot – Normal (not controlled) area (dose rate below 0.05 mrem/hr).**

fact Muon Collaboration

RF Cavity R and D

ANL/FNAL/IIT/LBNL/UMiss

RF Cavity R&D – Prototype Tests

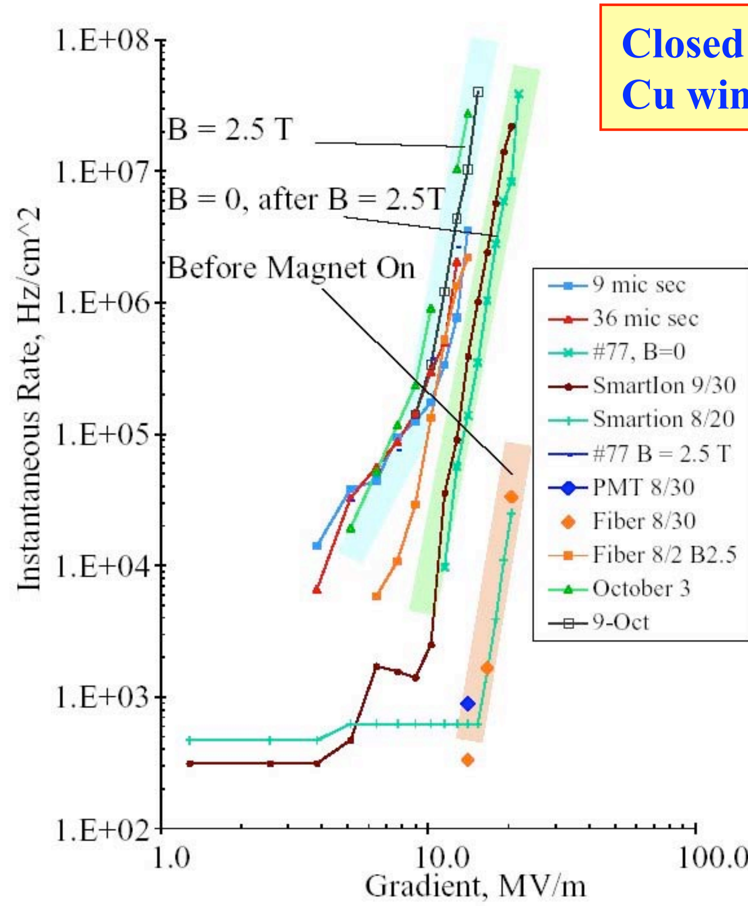
Lab G RF Test Cave showing 5T SC Magnet
44 cm bore
R.I.P.

- 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**
- Unfortunately due to a Klystron failure in the Linac, the Lab G Klystron had to be moved back to the Linac
  - **As of December 25, 2003 the Lab G facility ceased operation**
- We are now moving as rapidly as possible (with a great deal of support from the Fermilab Beams Division) to bring up 805 and 201 MHz RF test capability to the MTA
  - **Moving Vacuum, power, etc systems to MTA**
  - **Move Magnet to MTA**

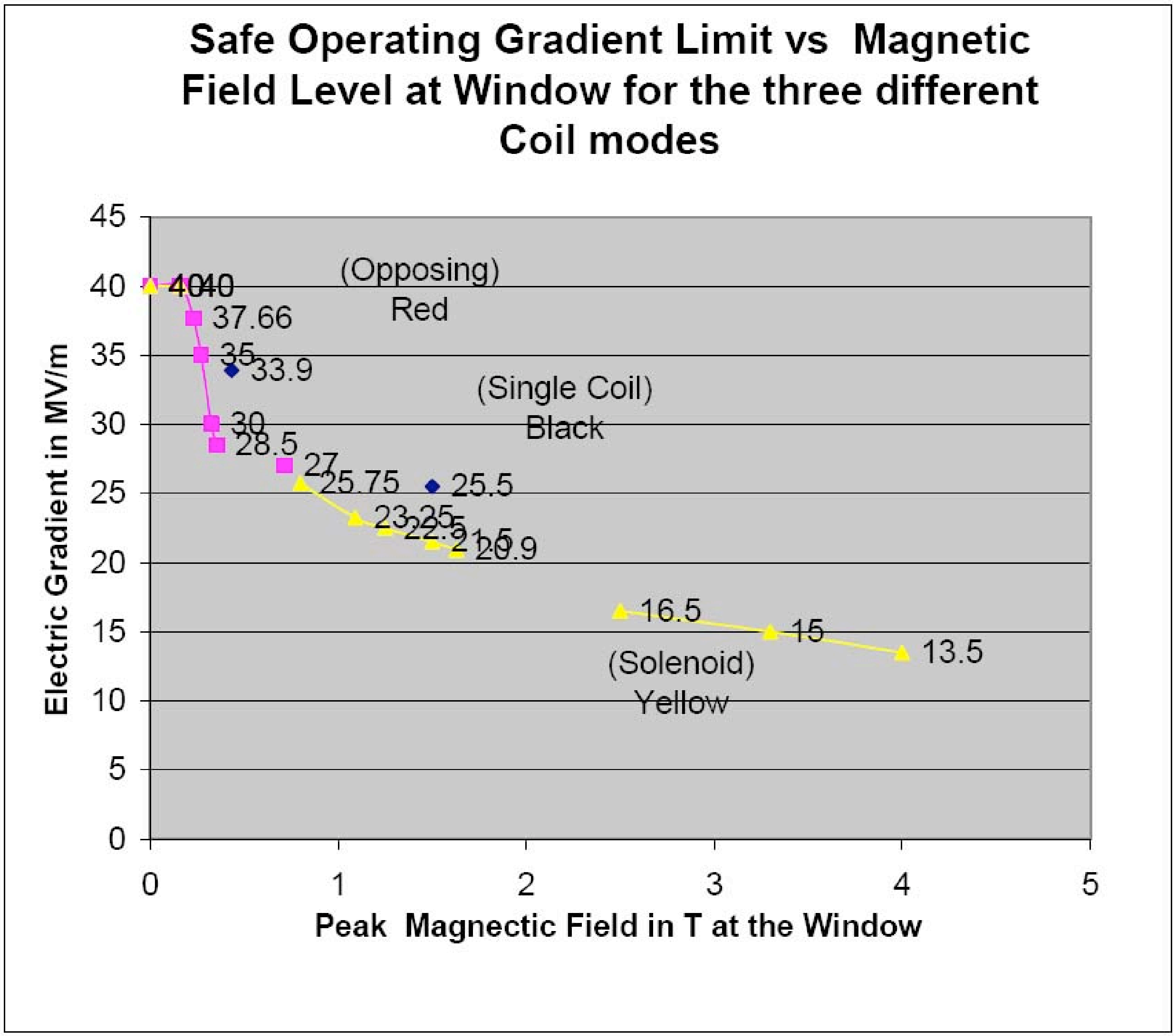
RF Cavity R&D – Quick Review

- Open cell cavity reached peak surface field of 54 MV/m (25 on axis)
  - **Large dark currents**
    - Damage to windows
    - Punctured Ti window in worst case
- Closed Cell (single) cavity
  - **B=0, Cu window – Low Bkg.**
    - Reached 34MV/m
  - **With B field**
    - TiN coated Be window (0.01")
    - 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

Closed Cell Cu window



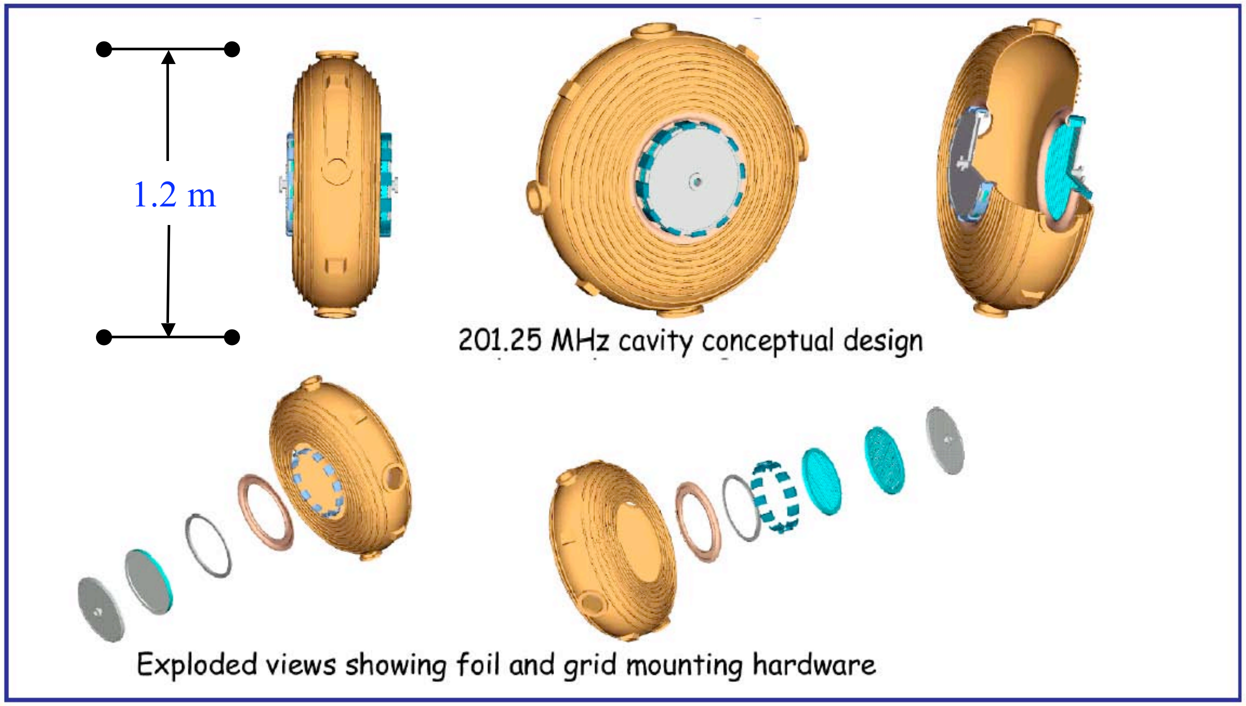
RF Cavity Closed Cell Magnetic Field Studies



- Data seem to follow universal curve
- Sparking limits max gradient
- Copper surfaces the problem

RF R&D – 201 MHz Cavity Design

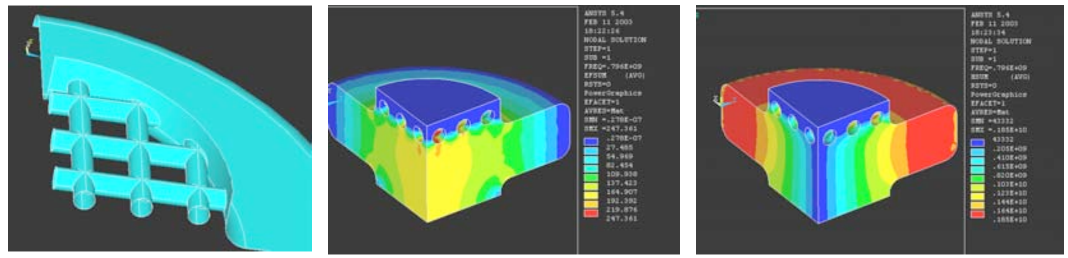
- Design Complete and Fabrication well under way
  - **Expect E^{pk}_{surf} = 26.5 MV/m**
  - **Now has curved windows**
  - **Goal is to have a 201 MHz cavity under test at Fermilab in the Fall**



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

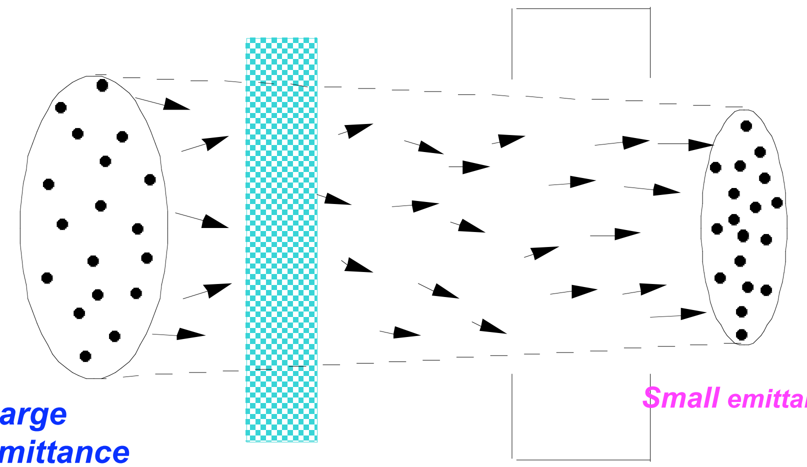
Absorber Design Issues

- 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

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



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

M^2 (4D cooling) for different absorbers

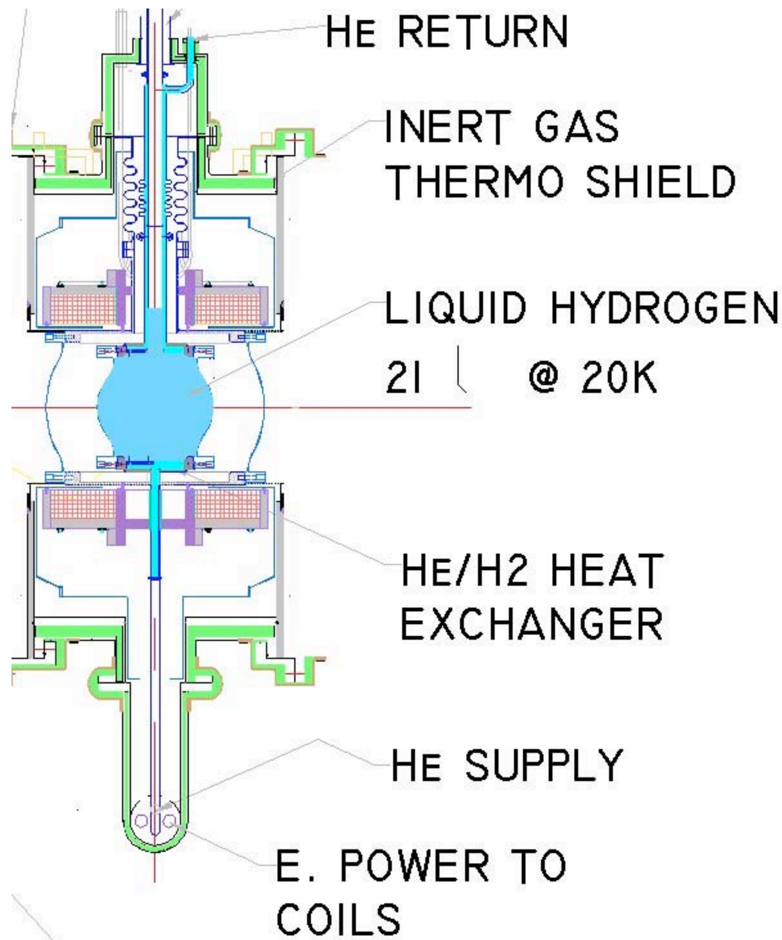
Material	$\langle dE/ds \rangle_{min}$ (MeV g^{-1}cm^2)	L_R (g cm^{-2})	Merit
GH_2	4.103	61.28	1.03
LH_2	4.034	61.28	1
He	1.937	94.32	0.55
LiH	1.94	86.9	0.47
Li	1.639	82.76	0.30
CH_4	2.417	46.22	0.20
Be	1.594	65.19	0.18

H_2 is clearly Best - Neglecting Engineering Issues

Windows, Safety

Absorber Design Issues

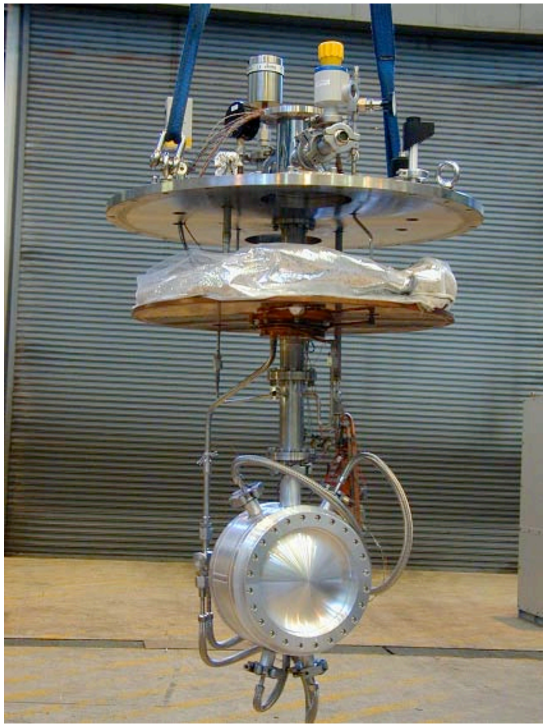
- Design Criteria
  - **High Power Handling**
    - Study II – few 100 W to 1 KW with “upgraded” (4MW) proton driver
    - 10 KW in ring cooler
      - ***Must remove heat***
  - **Safety issues regarding use of LH_2 (or gaseous H_2)**
    - Window design paramount
      - ***H_2 containment***
    -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



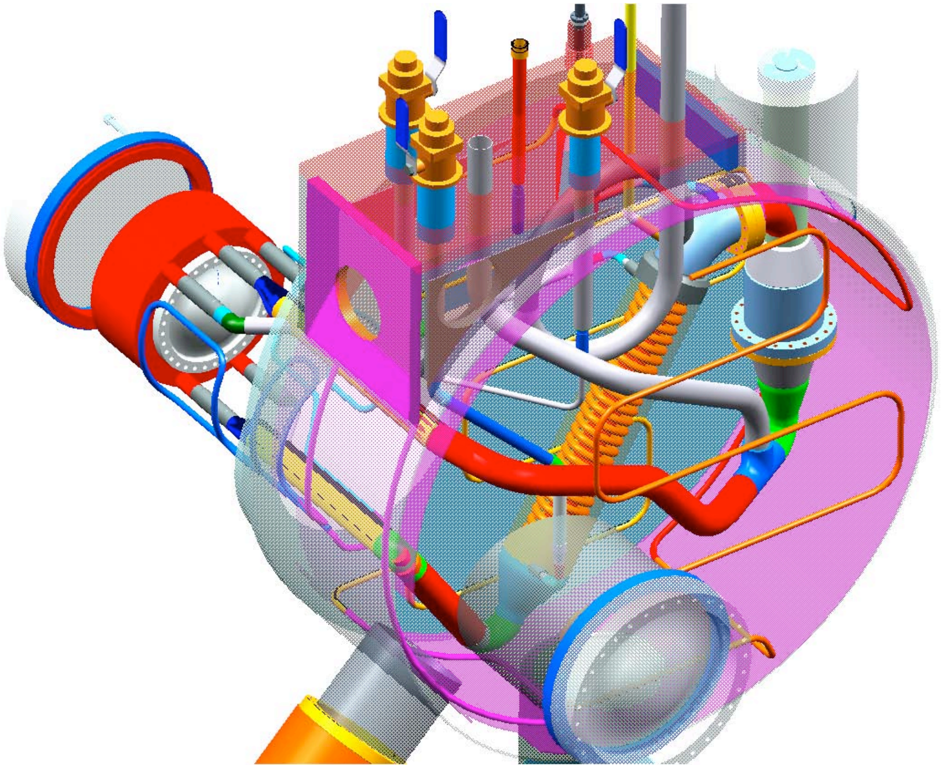
H_2 implies engineering complexity

Absorber R&D

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



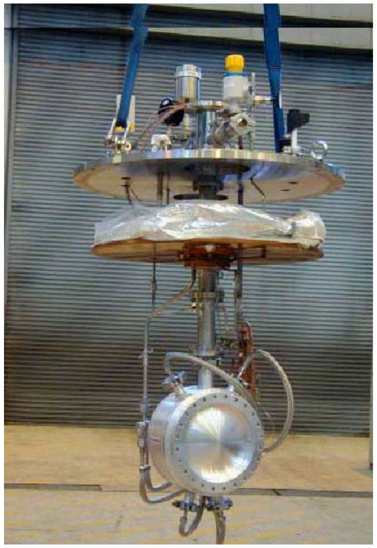
Forced-Convection-cooled. Has internal heat exchanger (LHe) and heater – KEK System

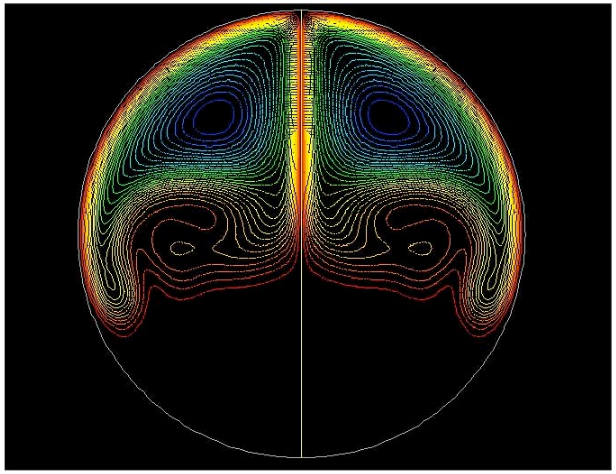


Forced-Flow with external cooling loop

Convection Absorber

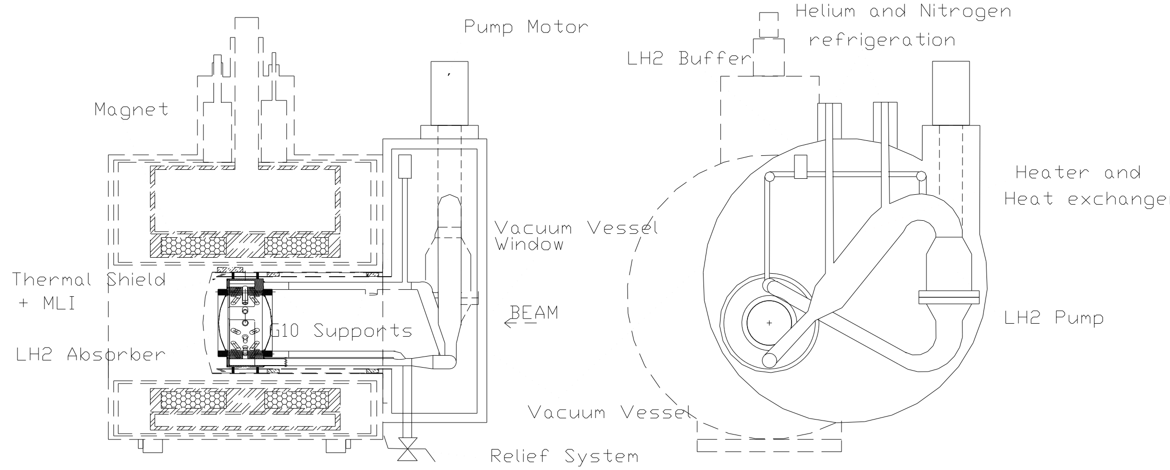
- Convection is driven by beam power and internal heaters
- LHe heat exchanger removes heat from absorber walls
- Two-dimensional Computational Fluid Dynamics calcs
  - **Flow essentially transverse**
  - **Max flow near beam**
  - **Heaters required to setup convective loops**

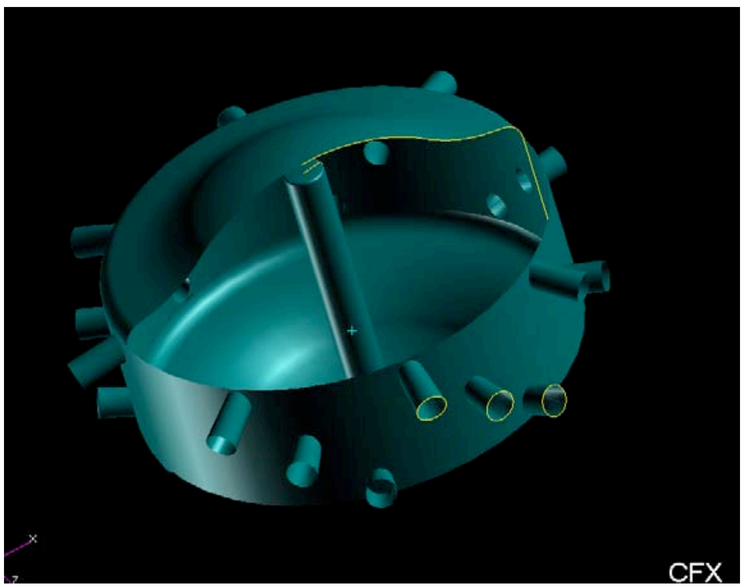


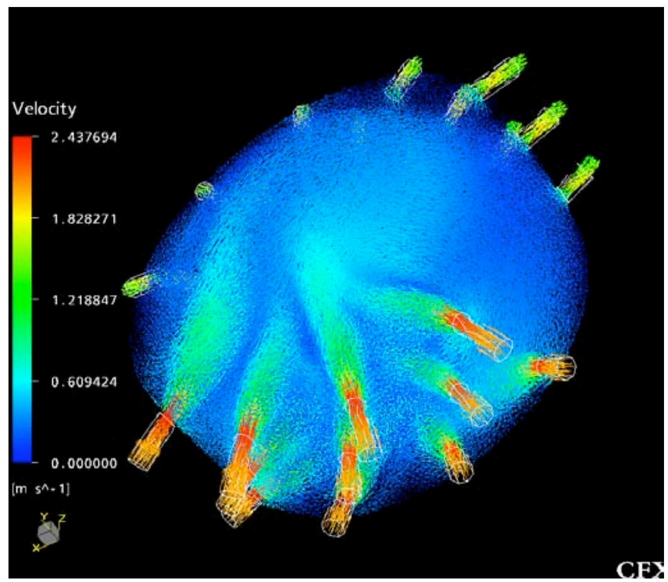


Forced-Flow Absorber

- 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



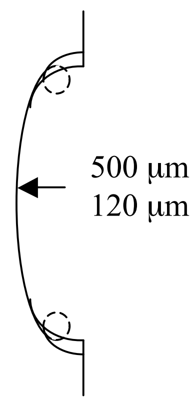


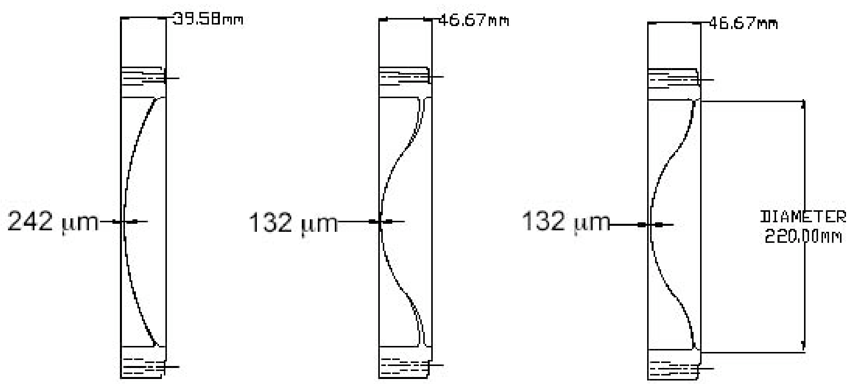


Absorber Windows

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

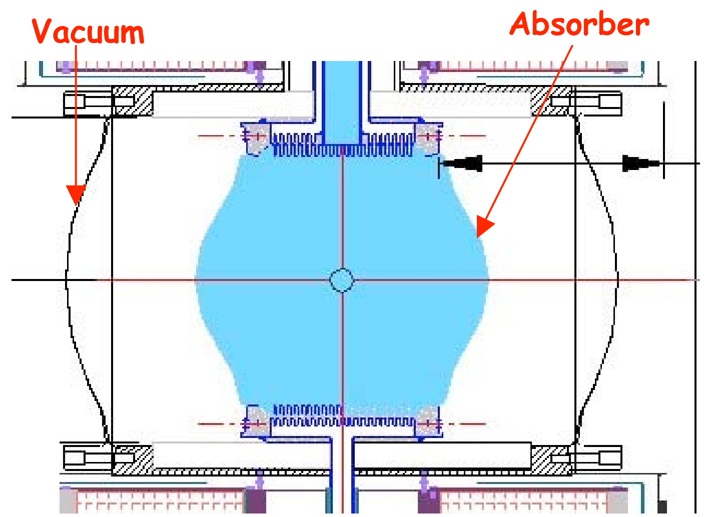
Originally..





Design Iteration
HemiSpherical – Inflected
(Now also used for RF)

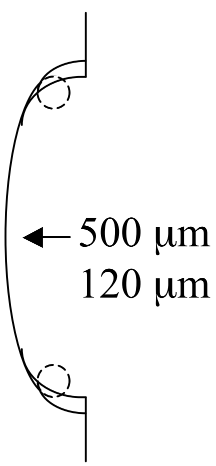
Containment Windows

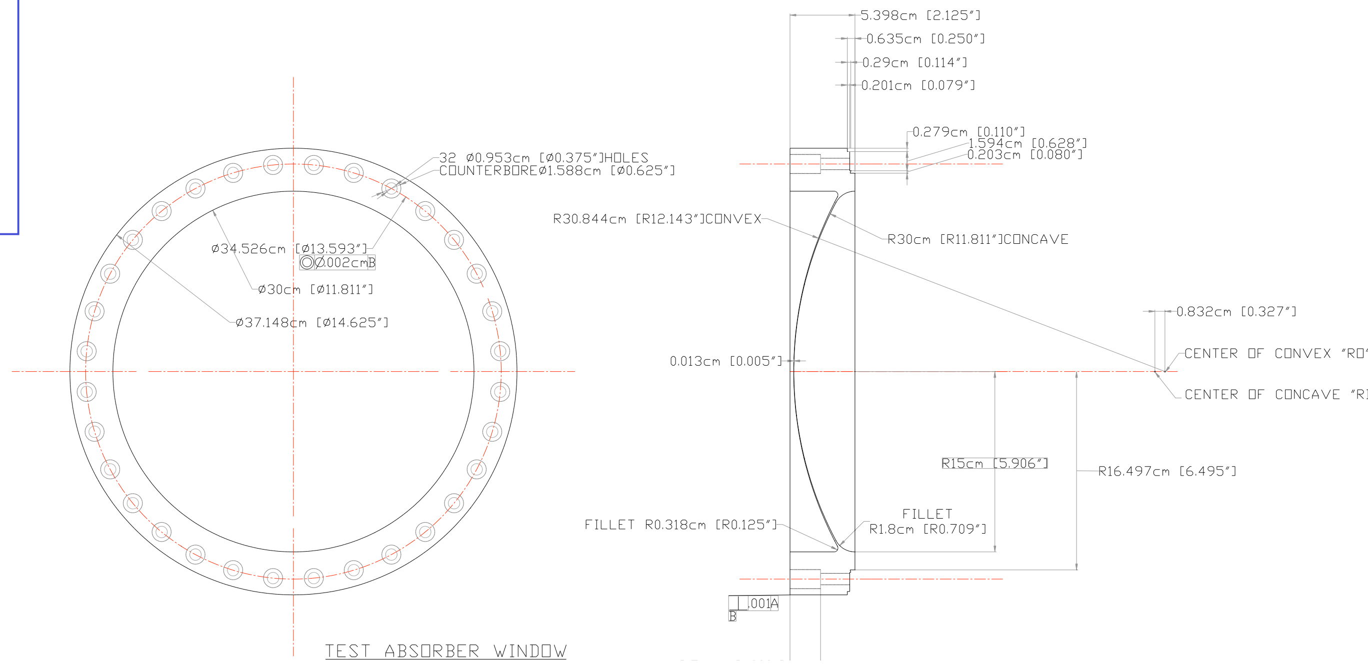


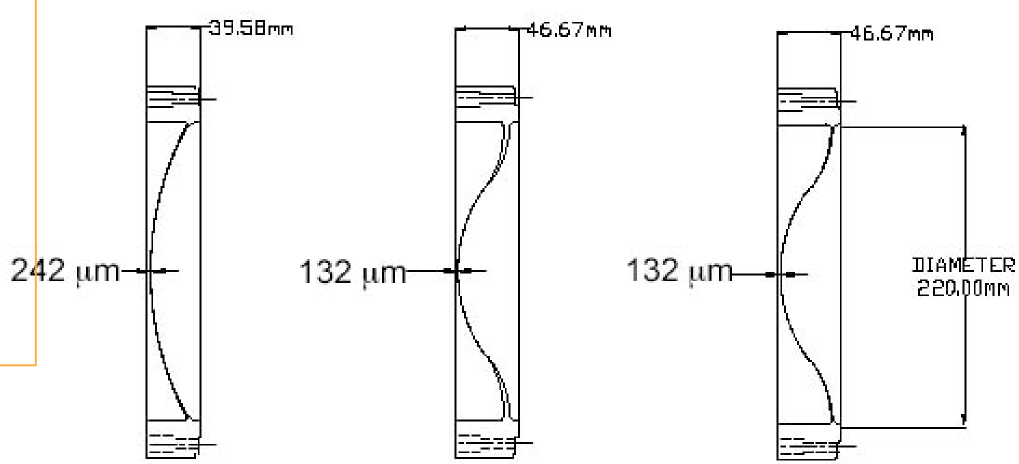
Thin Windows Design

Tapered thickness from window edges can further reduce the minimum window thickness near beam:

Originally..



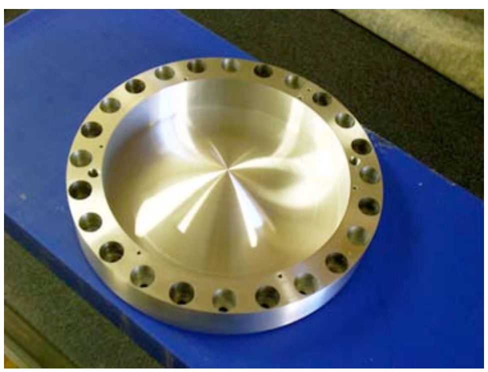


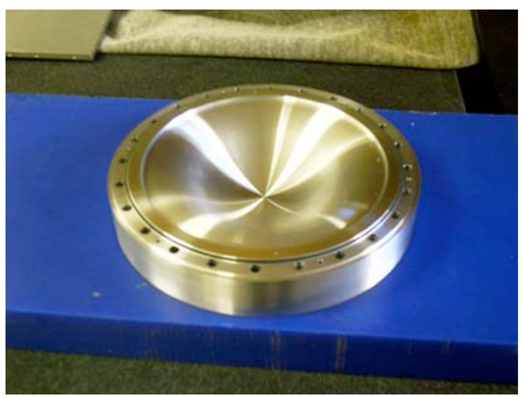


Progression of window profiles:
torispherical (1)
"tapered" (2) and
"bellows" (3 & 4)

Learning to manufacture new window

First window (above)!
Second window (below)



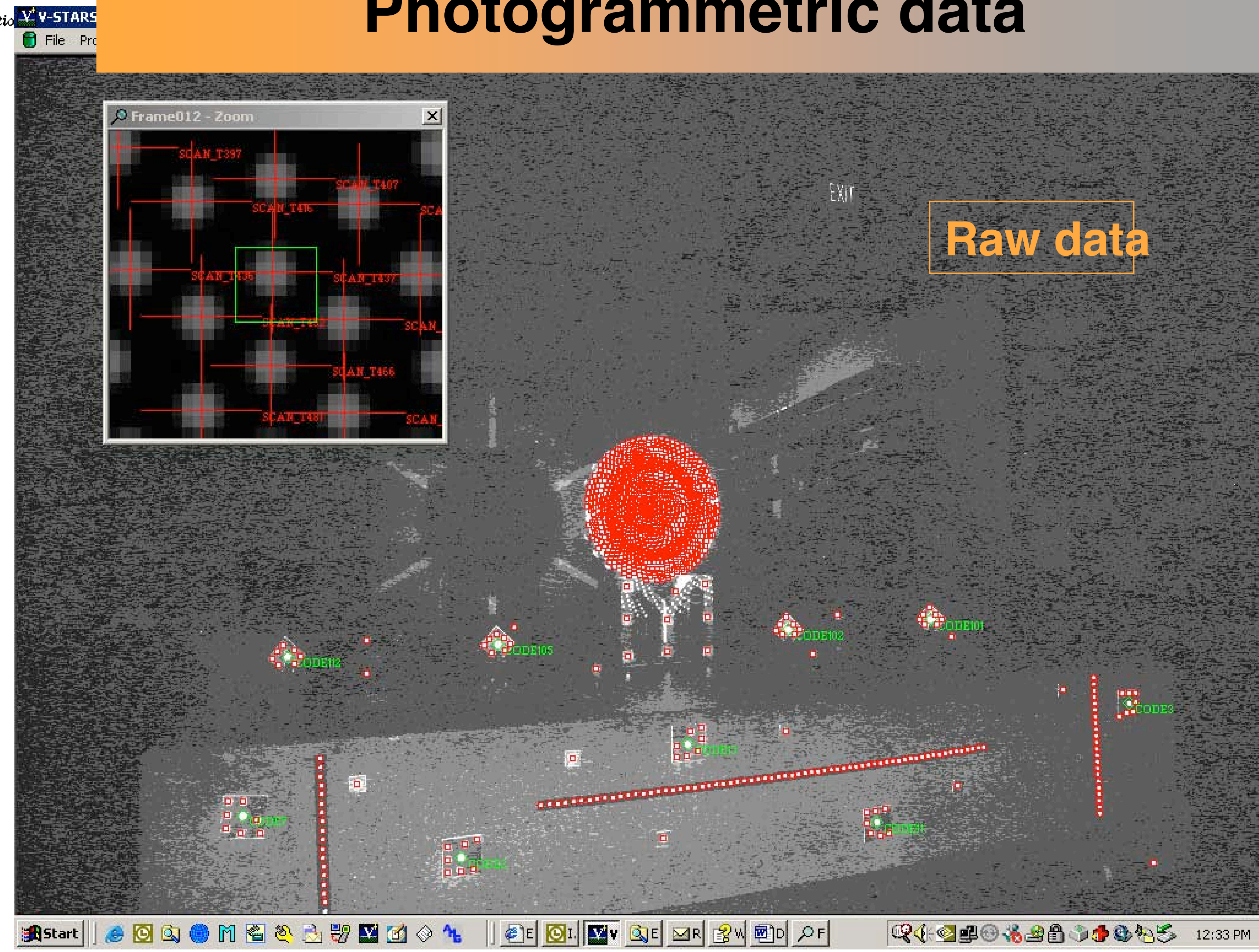


"Bellows" Window

(FNAL/Oxford)

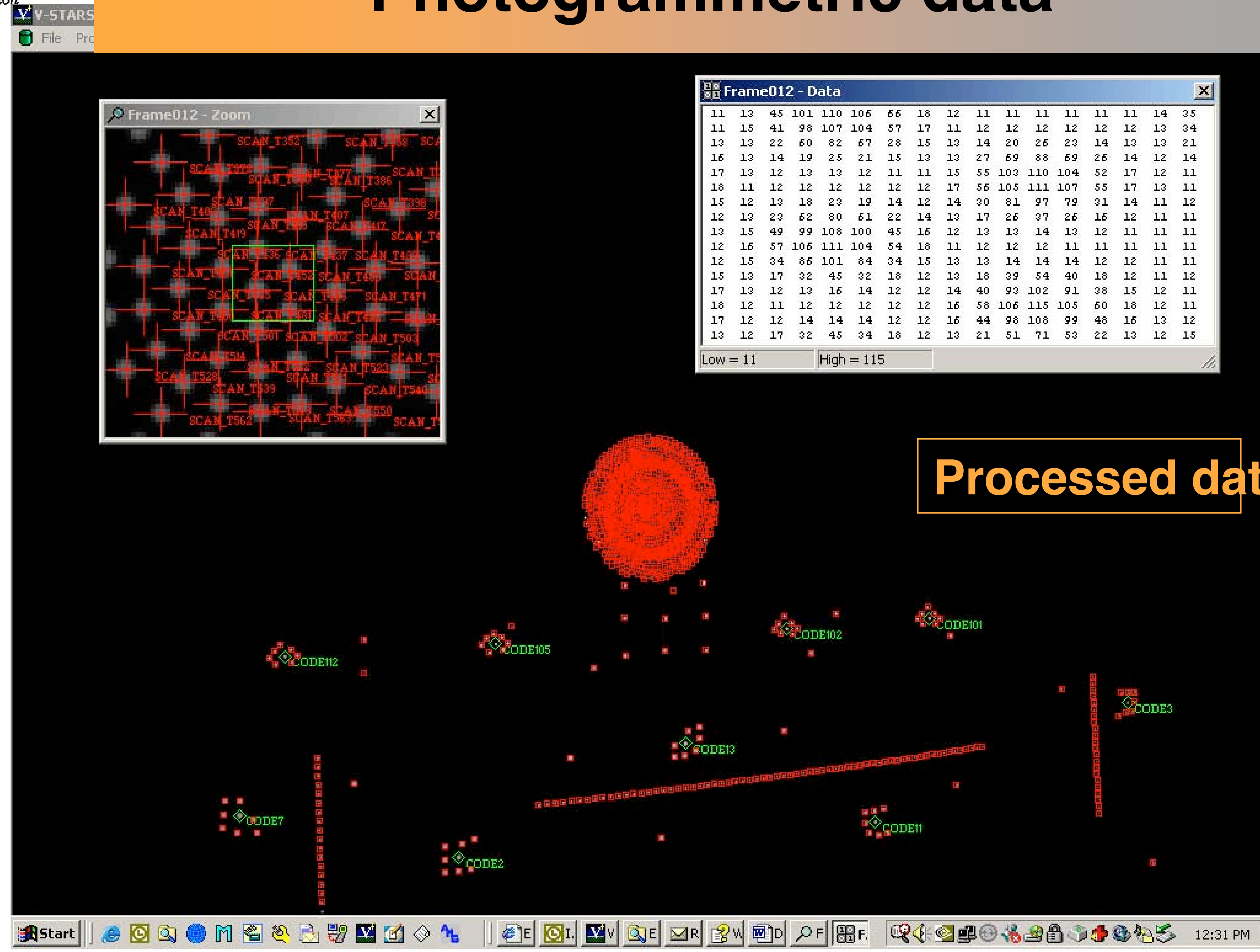
Current Photogrammetic Test Setup (FNAL)

Photogrammetric data



Raw data

Photogrammetric data

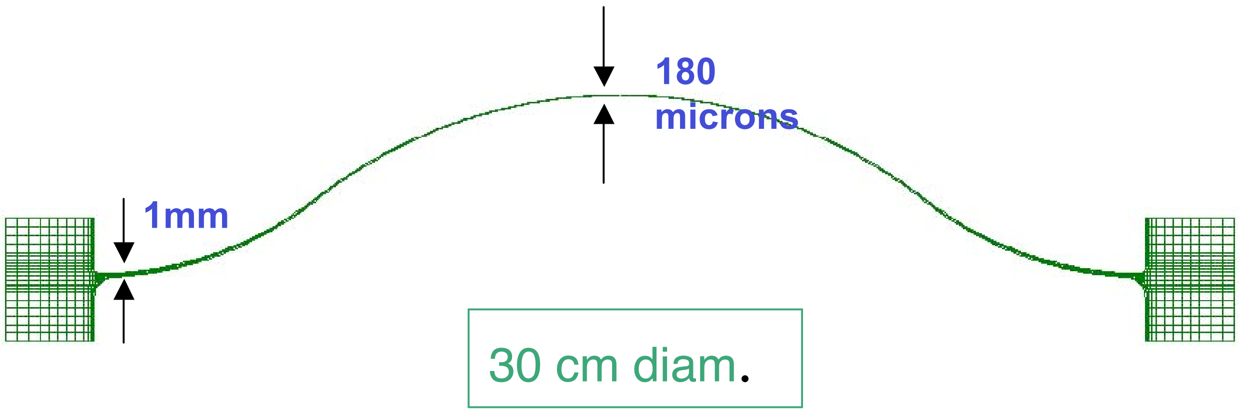


Processed data

FEA results on current bellows window design

The current window design has a double curvature to ensure that the thinnest part is membrane stress dominate

Here is the FEA model on the Absorber window. (Note that in the MICE experiment both the Absorber and the Safety windows now have the same pressure load requirements!)

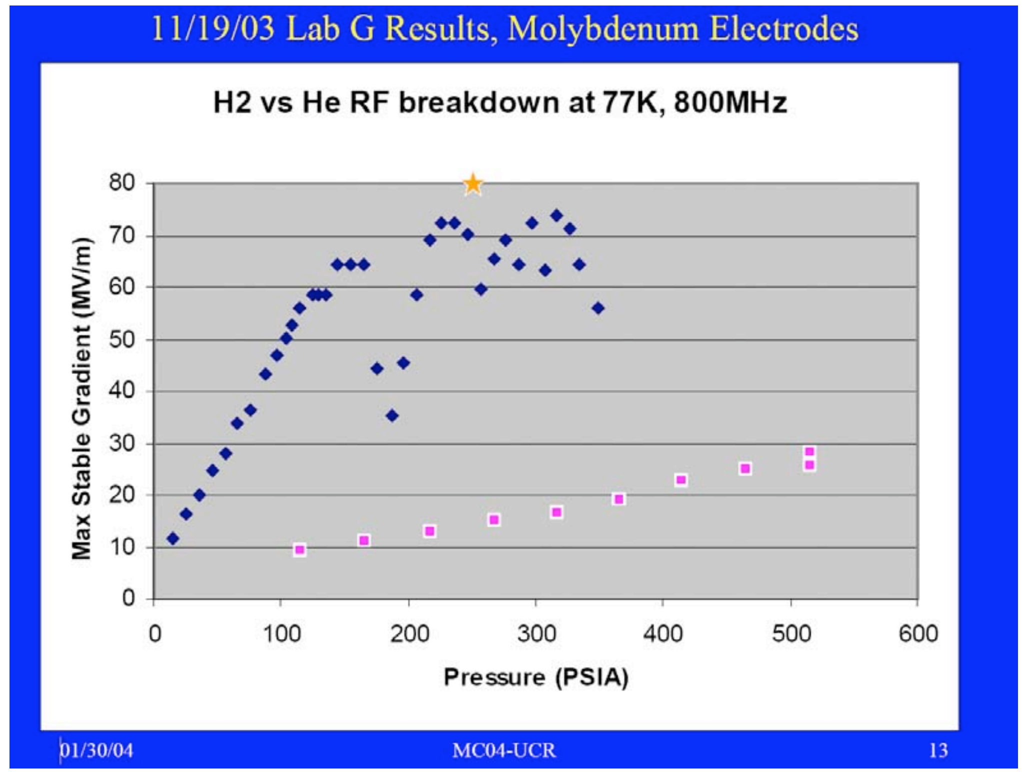


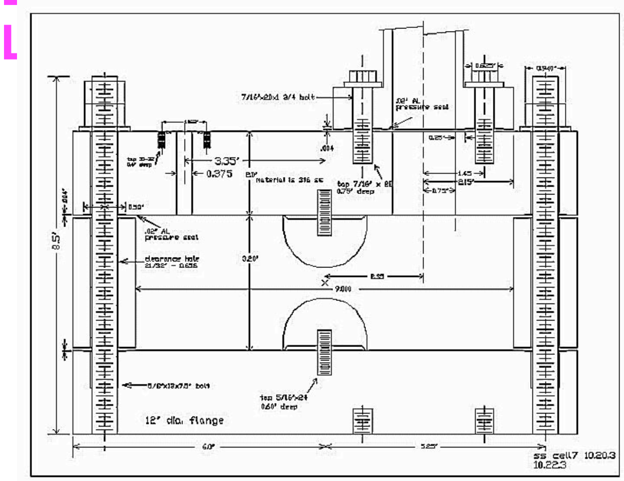
Window wrap-up

- Both software and testing methods are maturing
- Have standardized requirements for Mucool and MICE experiments
- Mucool window approach has passed MICE safety review
- FEA analyses developed for absorber windows now used in other aspects of cooling channel designs (i.e. RF windows)

Gaseous Absorber – Muon's Inc

- Serendipitous exploitation of:
  - **19th century science**
  - **Muons unique cooling quality**
- Work on STTR Phase II
  - **805 MHz test cell**
    - Tested at Lab G
  - **Cell conditioned at 450 psig @ 80K**
  - **Max stable gradient**
    - ≈ 80 MV/m
  - **Data agree well with Pashen**
    L





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 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)
  - **KEK LH_2 absorber test first. Phase I complete by mid-May, second set of tests in August**
  - **Provide 201 & 805 MHz capability for MTA**
  - **Move Lab G magnet to MTA**
  - **Continue 805 MHz RF studies in Lab MTA (starting in June)**
    - Window and grid tests
    - Surface treatment/materials tests
      - Effect on dark current and breakdown
  - **Provide as much of the cryo infrastructure as funding allows**
    - Very likely ALL of it
  - **Fabricate first 201 MHz cavity and bring to MTA for test**
    - On Schedule for delivery in Fall
- In FY05
  - **Start 201 MHz RF test program in MTA**
    - 805 MHz testing likely to continue interleaved with 201 testing
  - **Complete MTA cryo (if needed)**
  - **Fabricate coupling-coil prototype**
    - If funding is available
  - **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
  - **MTA is complete**
    - On budget and on schedule
      - **HVAC is late**
    - Absorber testing underway
    - RF test program to begin in June (805 and then 201 in Fall)
      - **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
    - Technological innovation in photogrammetry measurements
  - **Detailed engineering of components has matured**
- MuCool is a thriving International Collaboration
  - **Absorbers – Japan**
  - **Absorber/Window design – UK**
  - **Addressing many of the needs of MICE**