MuCool

Mary Anne Cummings

Nufact'04

July 31, 2004

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

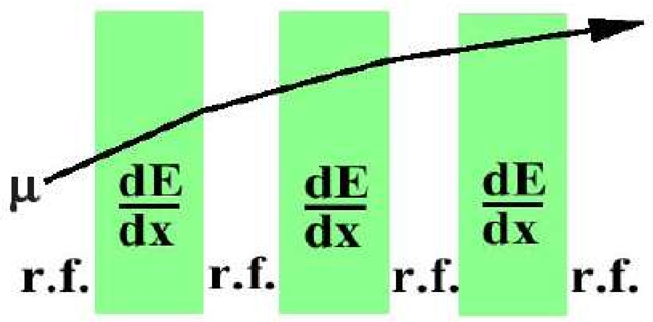
Cooling Demonstration (MICE)
ANL
BNL
Fermilab
Fairfield
IIT
Iowa
JLab
LBNL
NIU
UCLA
UC Riverside
UIUC
Univ. of Chicago
Univ. of Mississippi

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
  - **Small projects, shifting budgets/schedules/resources –**

MAJOR PROGRESS

Ionization cooling



G. I. Budker and A. N. Skrinsky, Sov. Phys. Usp. **21**, 277 (1978)
A. N. Skrinsky and V. V. Parkhomchuk, Sov. J. Part. Nucl. **12**, 223 (1981)

- Muons can focus going through matter
- **Transverse (4D) cooling** – sufficient for neutrino factories
  - Lose energy in all three dimensions – reducing the particle density
  - Longitudinal momentum restored using RF

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

per dimension

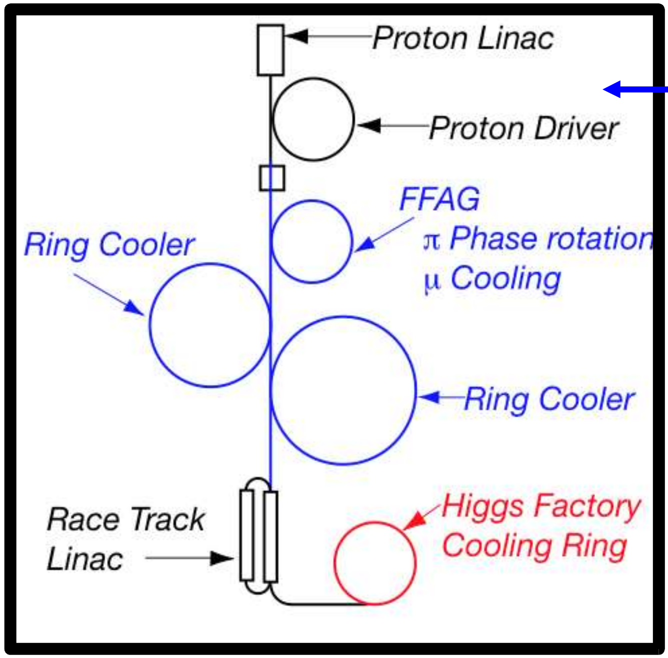
cooling dE/dx

heating coulomb sc.

Beam divergence reduced while average energy maintained

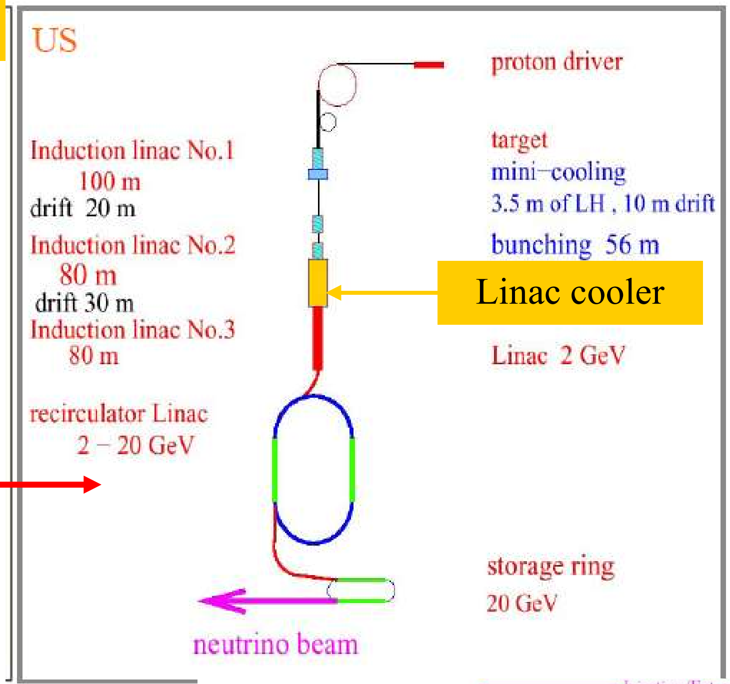
The next generation ν,μ machines…

Cooling channels in a variety of configurations

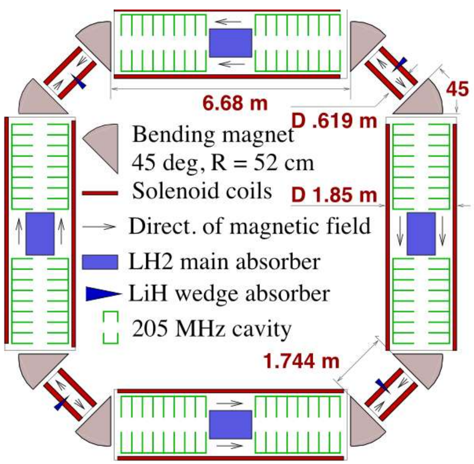


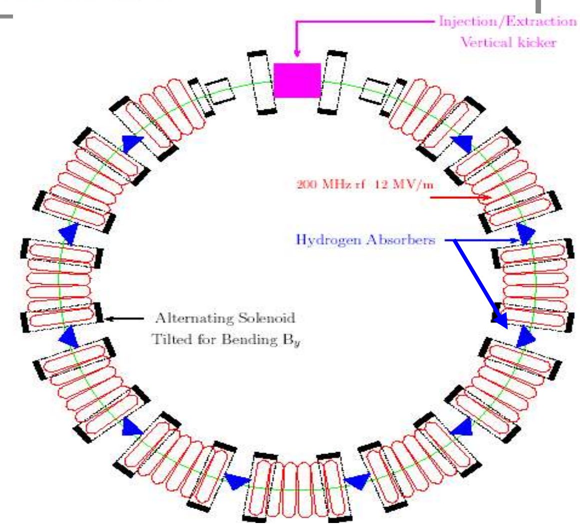
Muon collider

Neutrino factory



- Different geometries
- Different cooling cell designs
- Possible 6D cooling channels
- Solenoidal and toroidal!

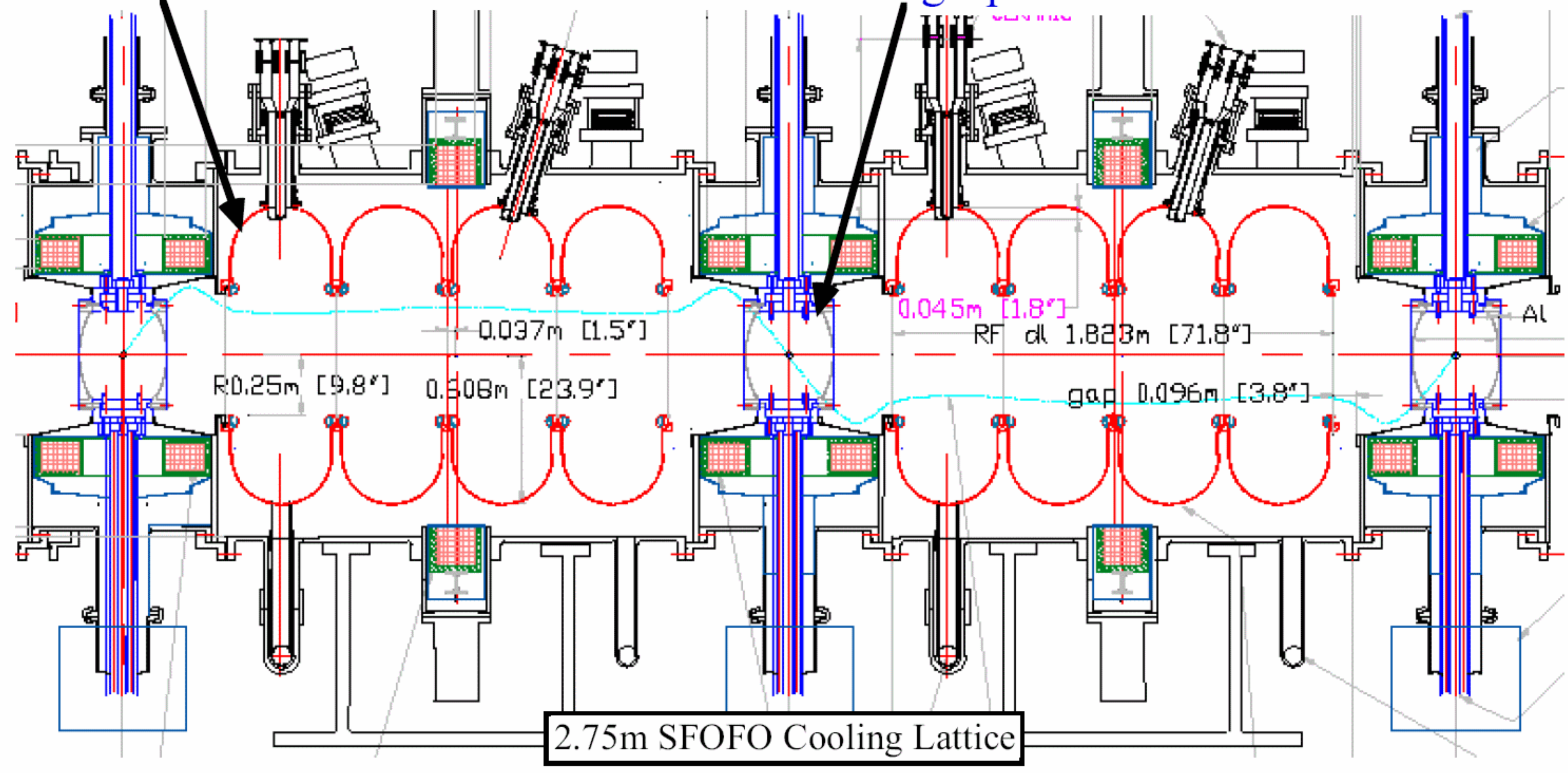




R&D Focus of MuCool

- SFOFO Cooling Lattice – transverse cooling for ν factories
  - Component testing Fermilab: high power, both RF and Beam
  - System test - MICE @ RAL

- High-gradient normal-conducting RF
- High-power LH2 absorbers



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?
- Can a definitive, timely decision be made on the technology?
  - **Physics driving accelerator choices..**

MuCool Test Area

The MuCool Collaboration Enters a new Era

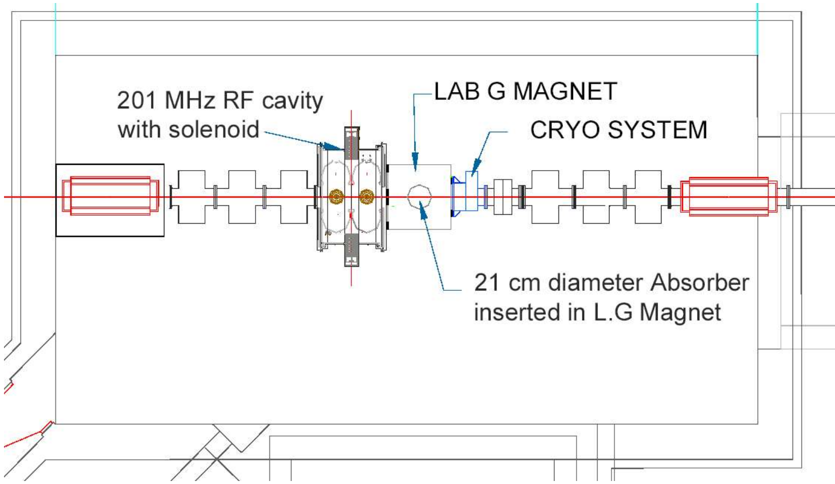
MTA Tour

View from Wilson Hall
RF Trench visible

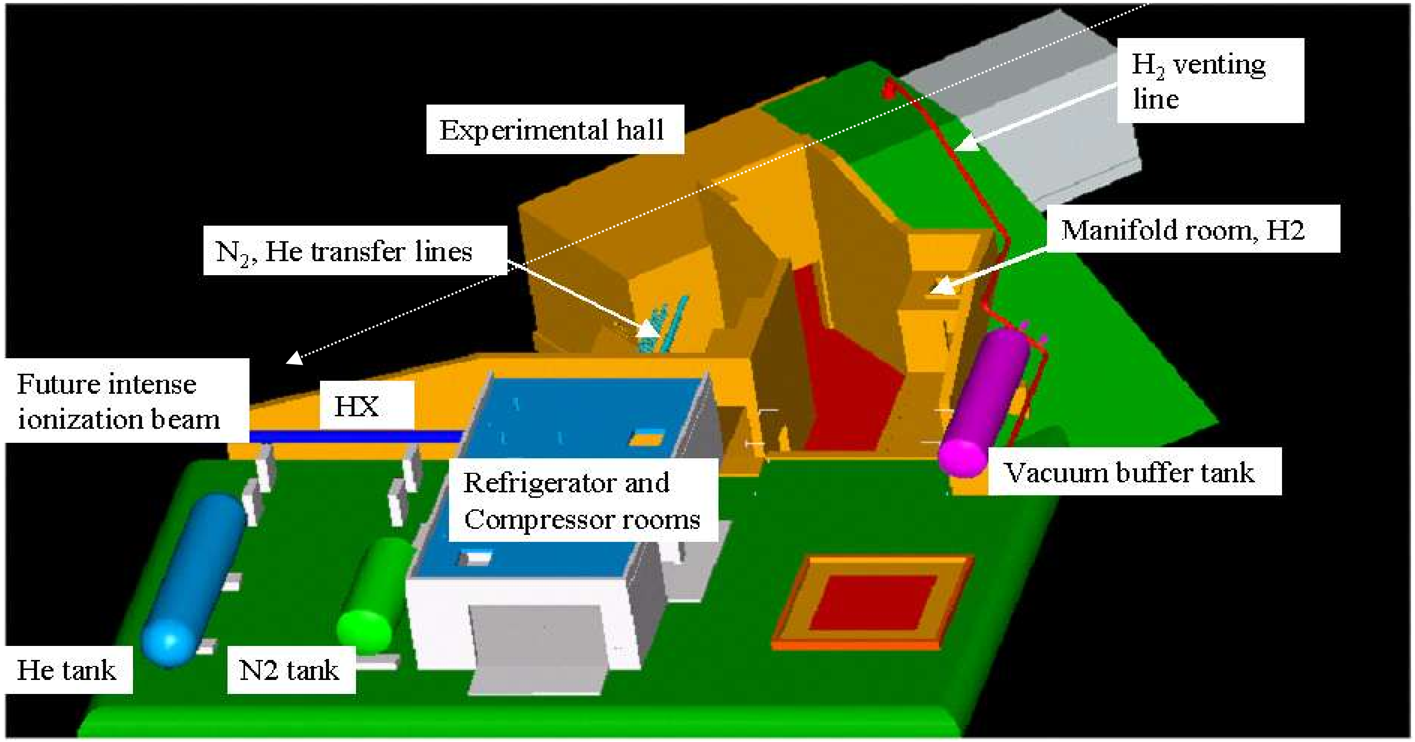
MuCool Test Area

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

LH2 gas house

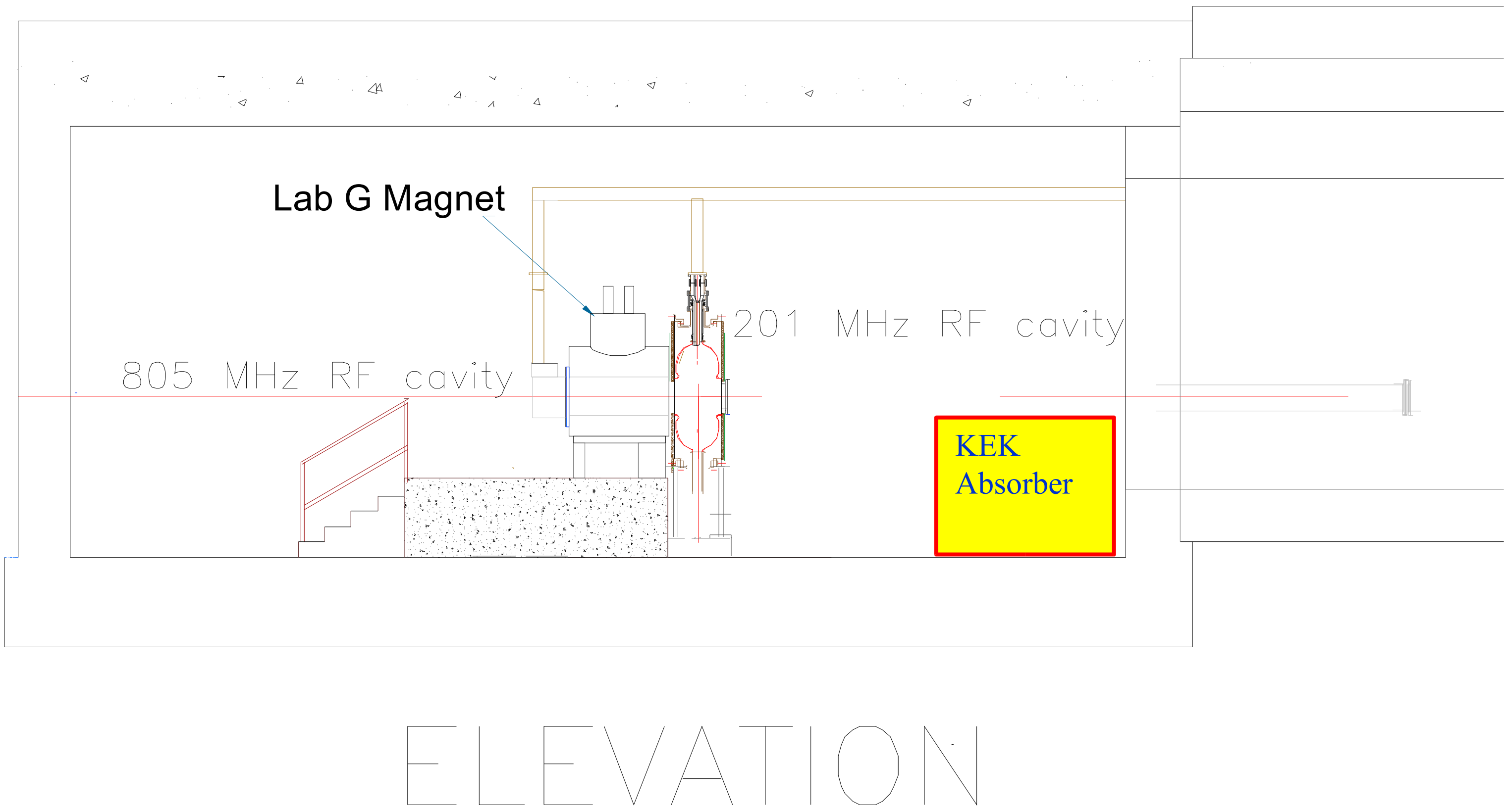
L-He Dewar, Transfer line, Valve box

MTA Tour

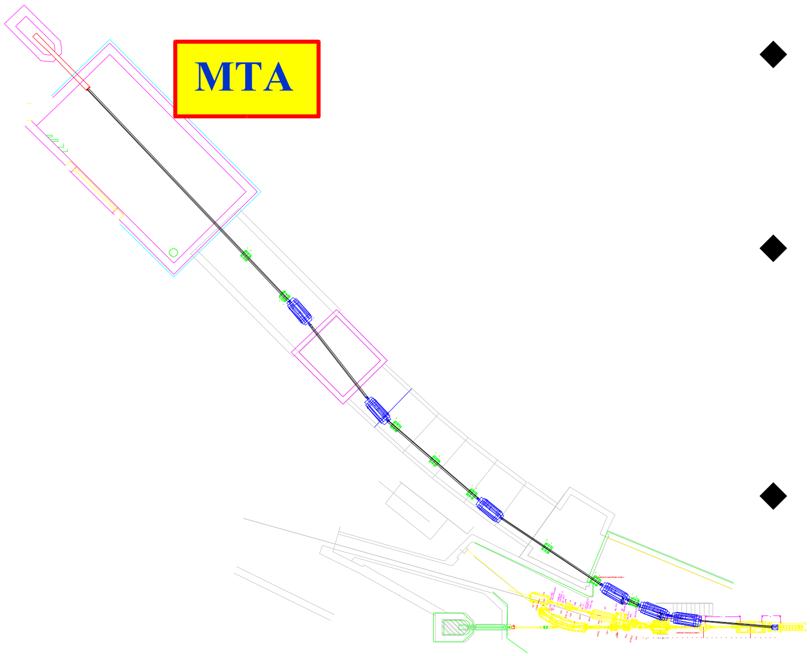
MTA Experimental Hall
(from Linac)
Lots of Activity

KEK test cryostat at MTA/FNAL

MTA – RF Configuration

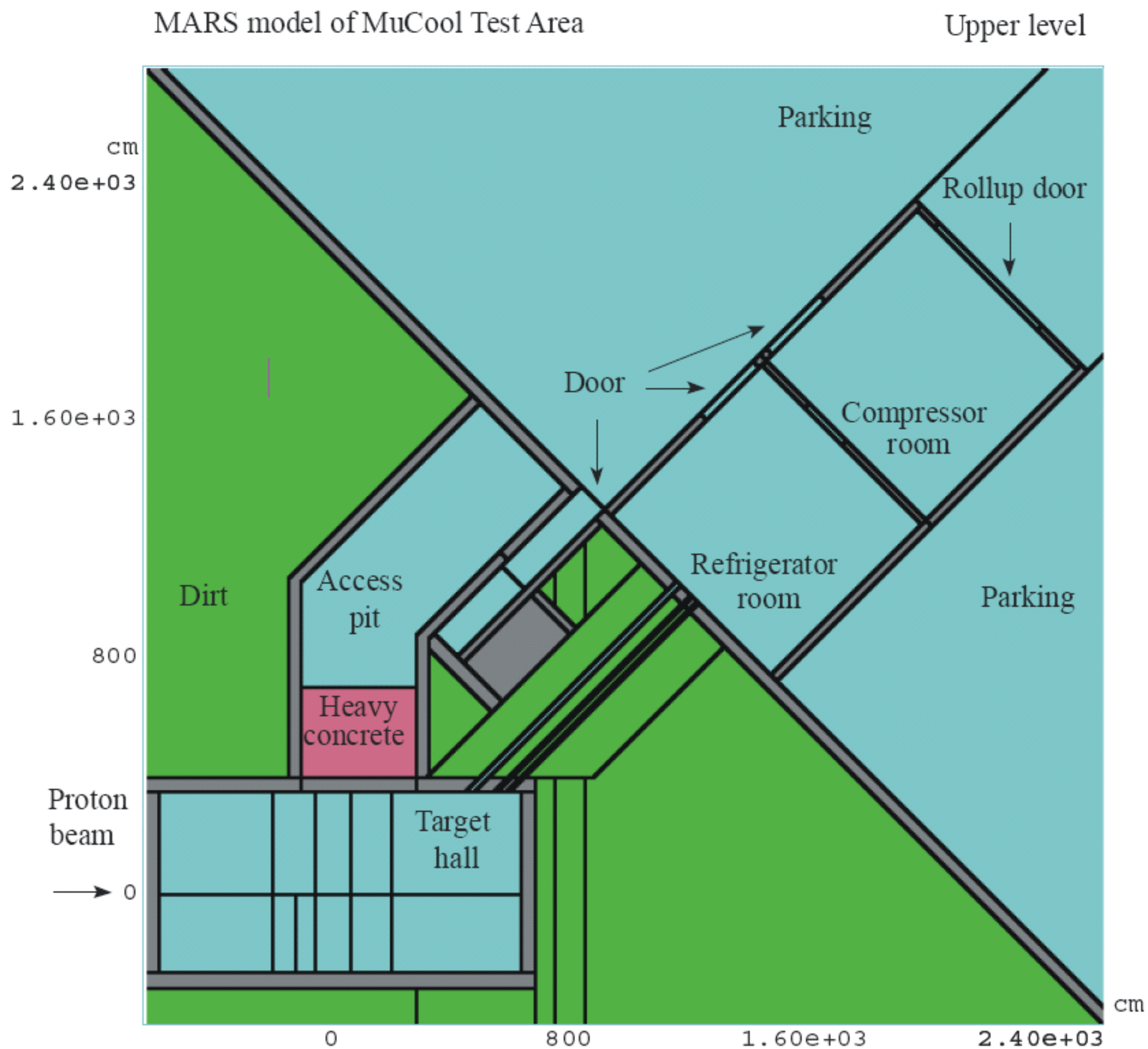


MTA High Intensity Beam Tests



- 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
  - **Beam options**
    - "Spin" beam in order to provide large (30 cm) aperture
    - Available large quads may be sufficient (21 cm absorbers)
  - **Timeline still driven by resource availability**

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).**

RF Cavity R and D

ANL/FNAL/IIT/LBNL/UMiss

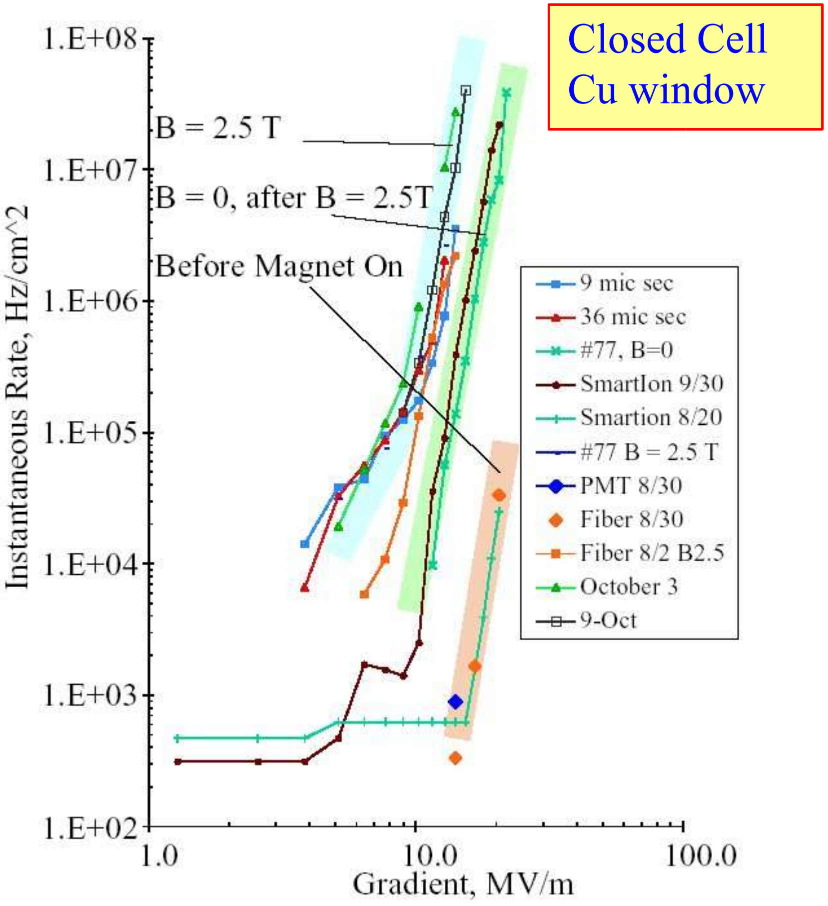
RF Cavity R&D – Prototype Tests

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

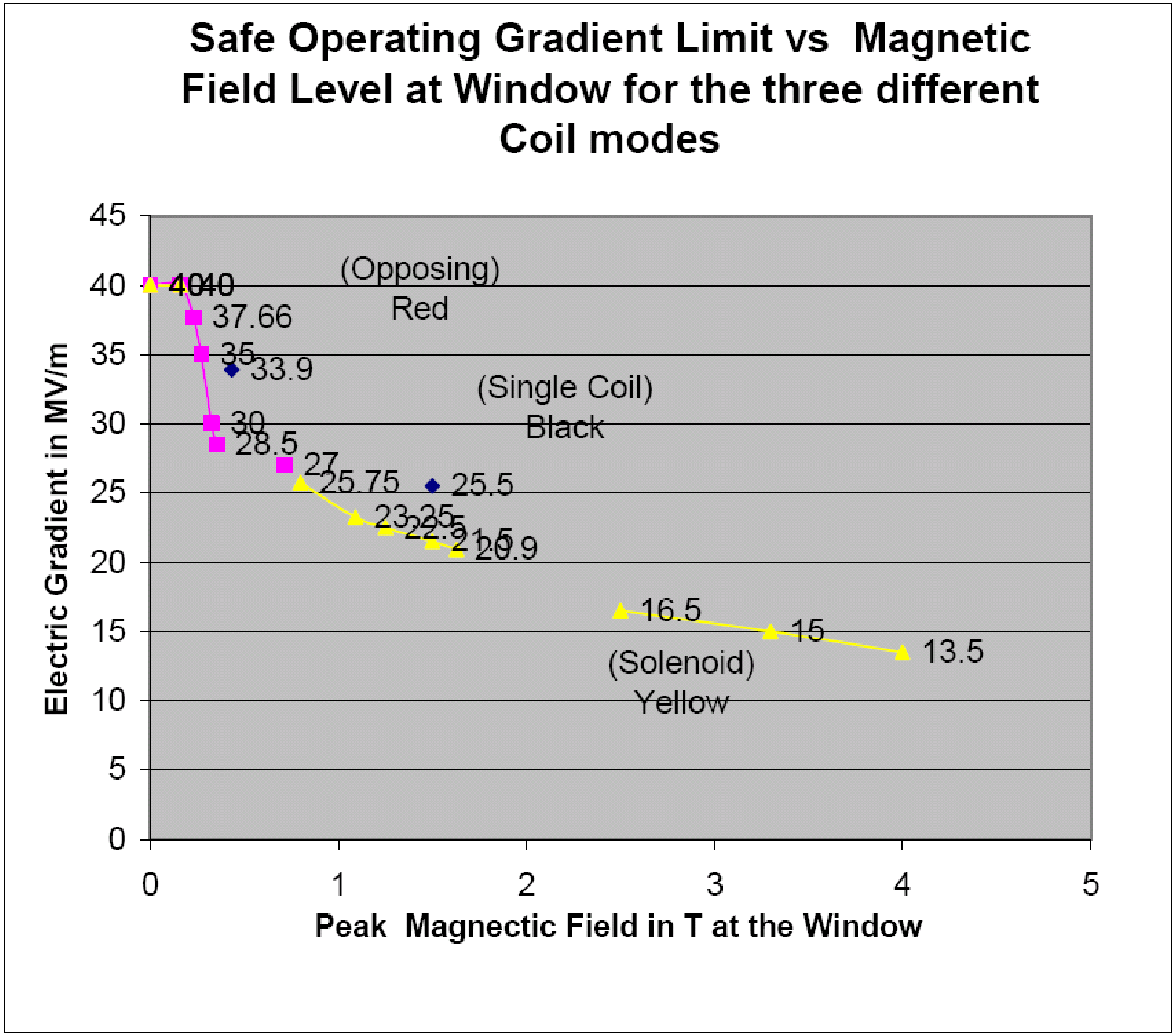
- Work to date has focused on using 805 MHz cavities for test
  - **Allows for smaller less expensive testing than at 201 MHz**
  - **Lab G work at Fermilab**
- Unfortunately due to a Klystron failure in the Linac, the Lab G Klystron had to be moved back to the Linac
  - **As of December 25, 2003 the 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



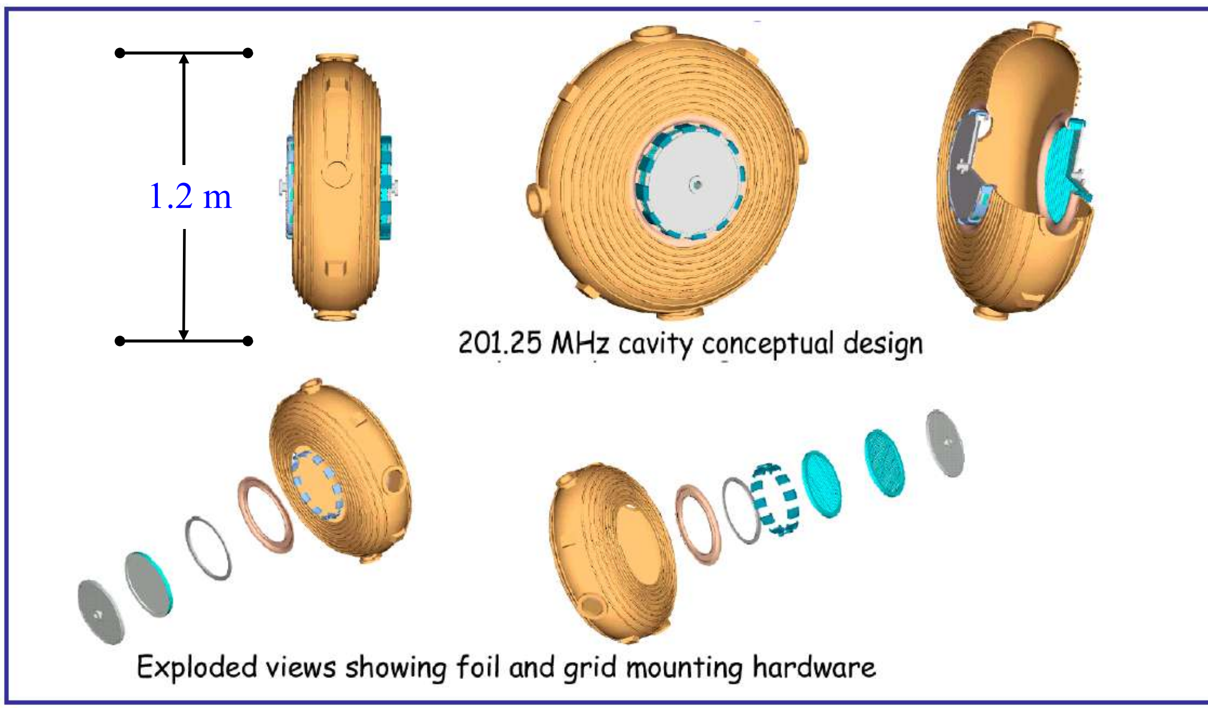
RF Cavity Closed Cell Magnetic Field Studies



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

RF R&D – 201 MHz Cavity Design

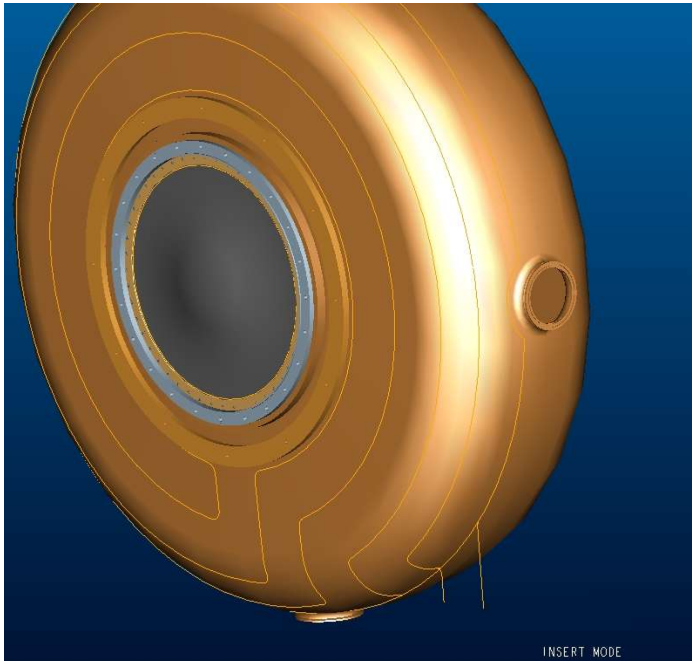
- Design Complete and Fabrication well under way
  - **Expect E^{pk}_{surf} = 26.5 MV/m**
  - **Now has curved windows**
  - **Goal is to have a 201 MHz cavity under test at Fermilab in the Fall**

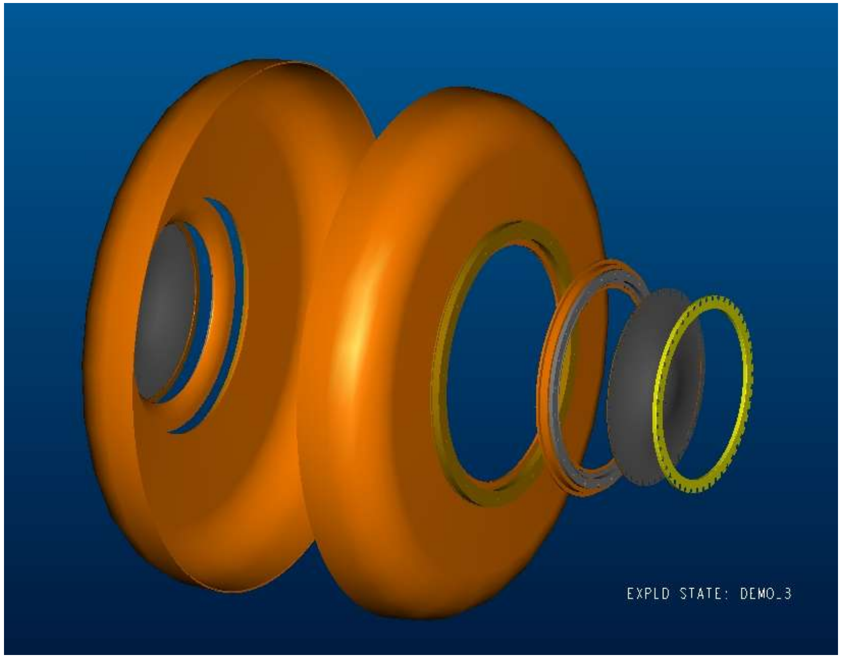


201.25 MHz cavity conceptual design

Exploded views showing foil and grid mounting hardware

201 MHz Cavity Design Features





Spinning of half shells using thin Cu sheets and e-beam welding to join the shells. Four ports across the e-beam joint at equator.

Cavity design uses pre-curved Be windows, but also accommodates different windows or grids.

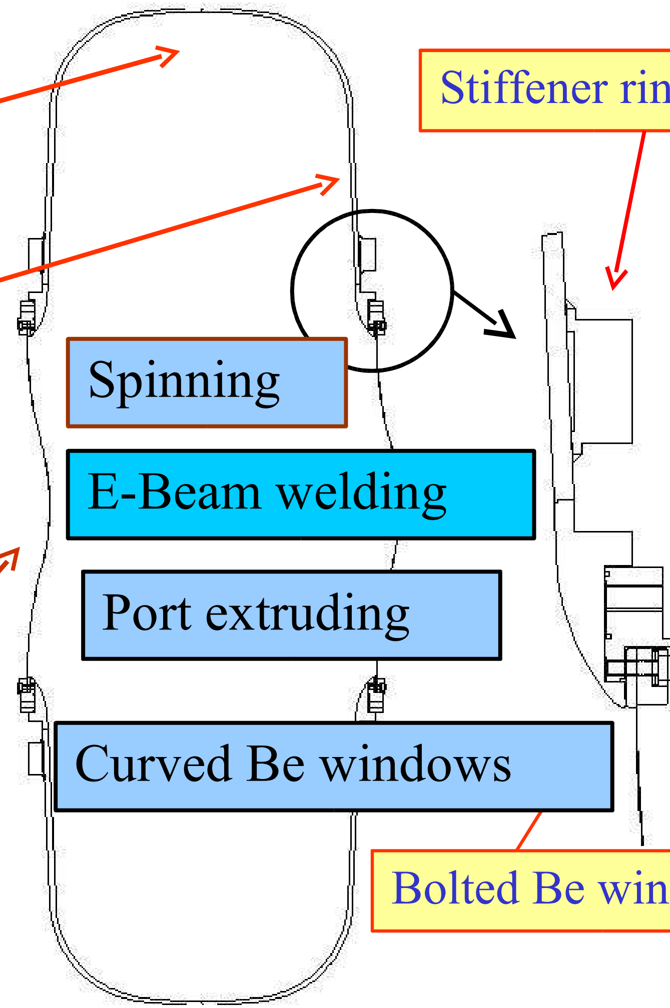
Cavity Body Profile

Spherical section at the equator to facilitate fabrication of ports (± ~ 6°)
Elliptical-like nose shape to further reduce peak surface field

2° tilt angle

6-mm Cu sheet permits spinning technique and mechanical tuners similar to SCRF ones

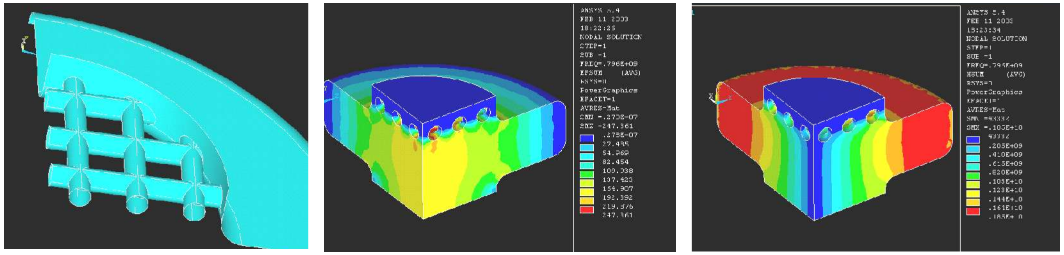
De-mountable pre-curved Be windows pointing in the same direction to terminate RF fields at the iris



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

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

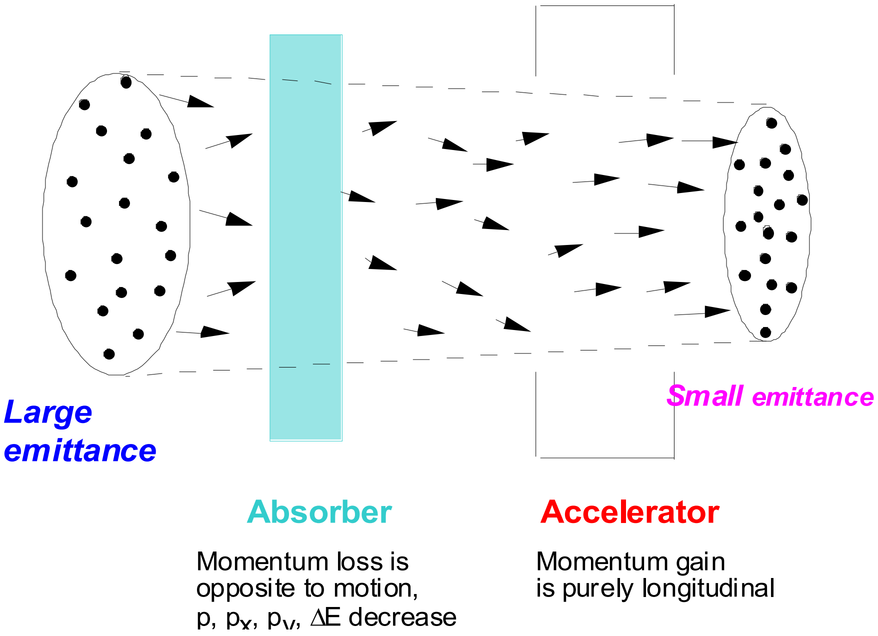
and

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

- 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

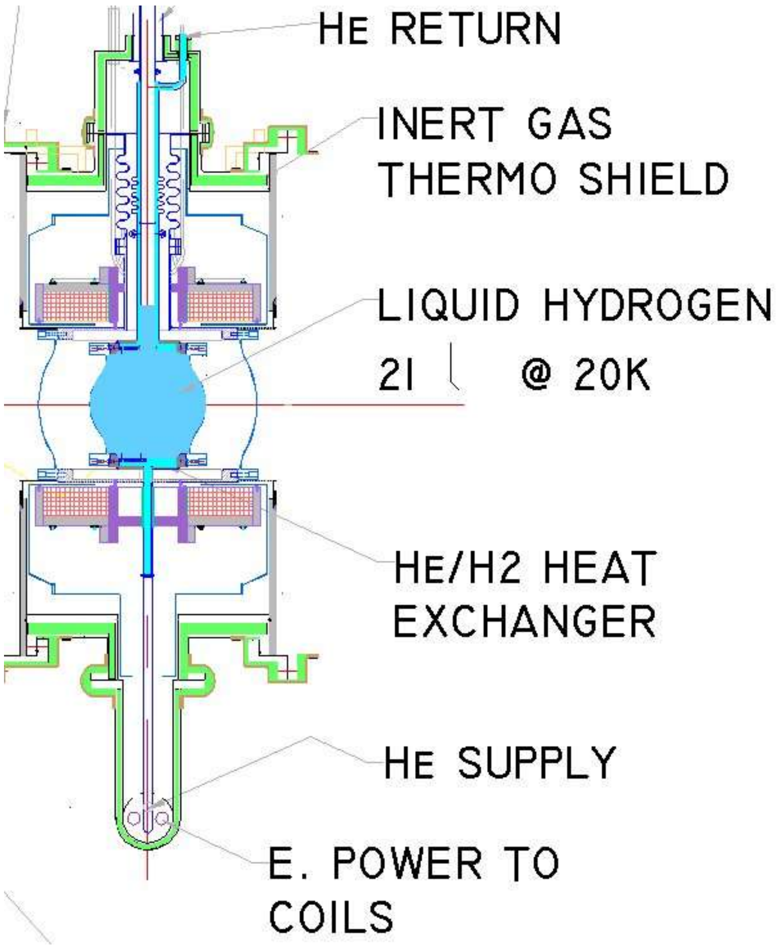


H_2 is clearly Best -
Neglecting Engineering Issues

Windows, Safety

Absorber Design Issues

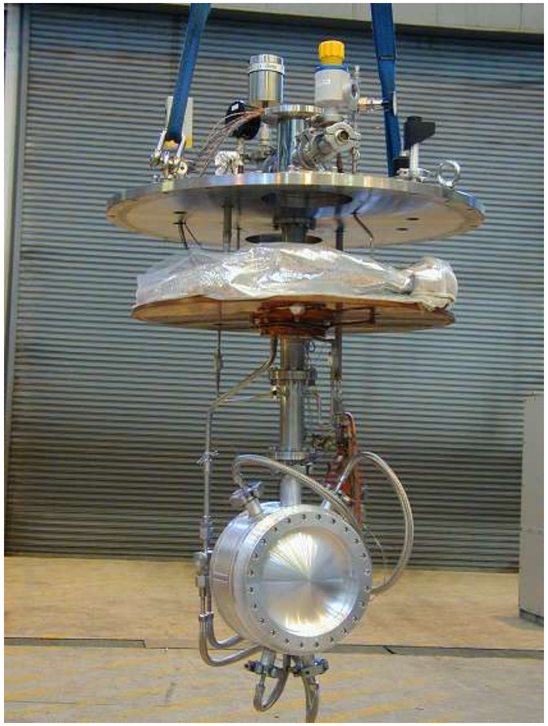
- Design Criteria
  - **High Power Handling**
    - Study II – few 100 W to 1 KW with “upgraded” (4MW) proton driver
    - 10 KW in ring cooler
      - Must remove heat
  - **Safety issues regarding use of LH_2 (or gaseous H_2)**
    - Window design paramount
      - H_2 containment
    - Proximity to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



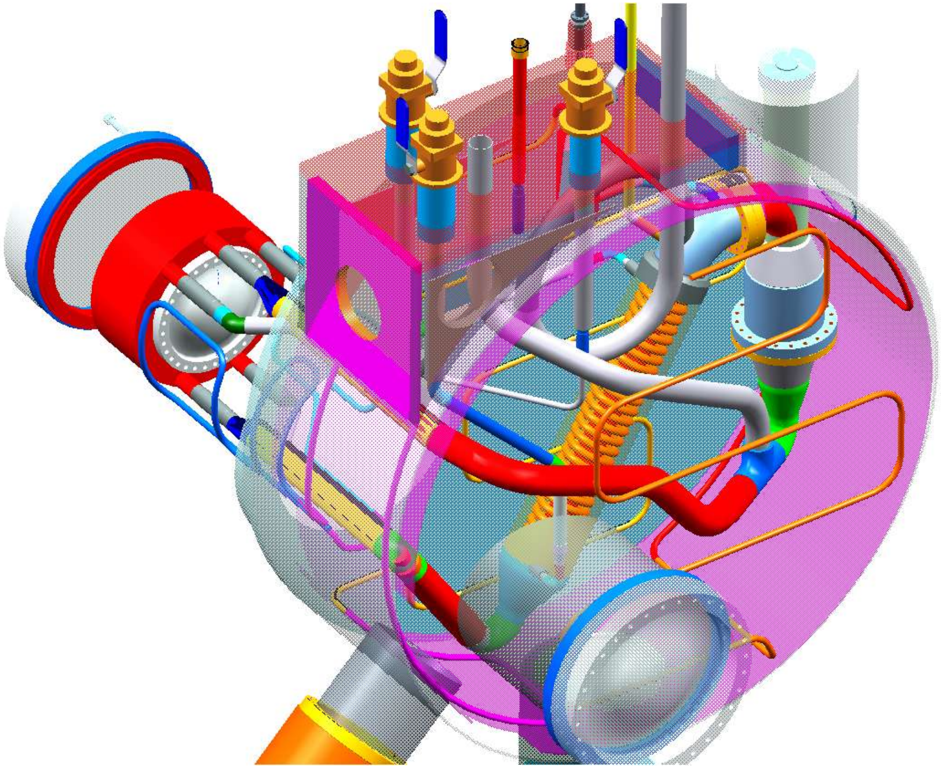
H_2 implies engineering complexity

Absorber R&D

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



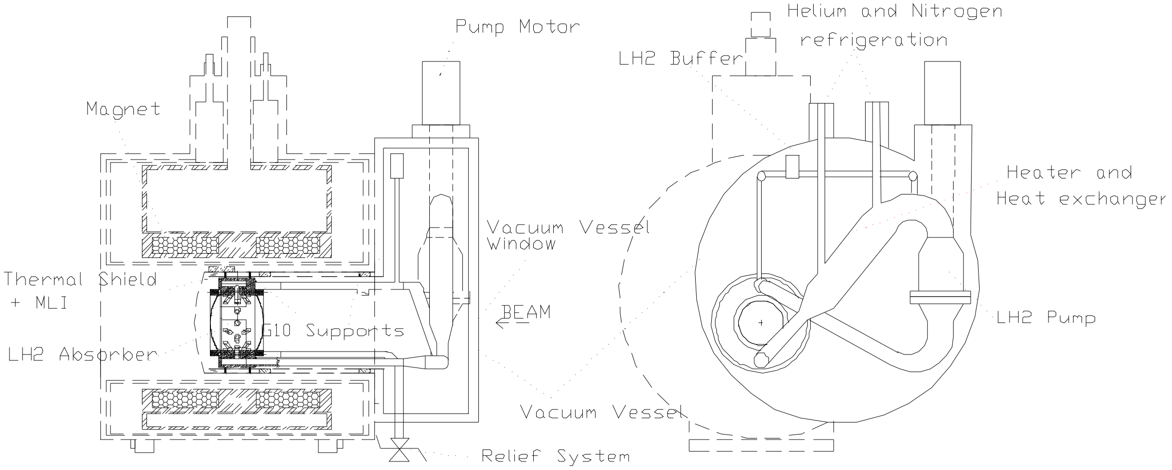
Convection-cooled. Has internal heat
exchanger (LHe) and heater –
KEK System

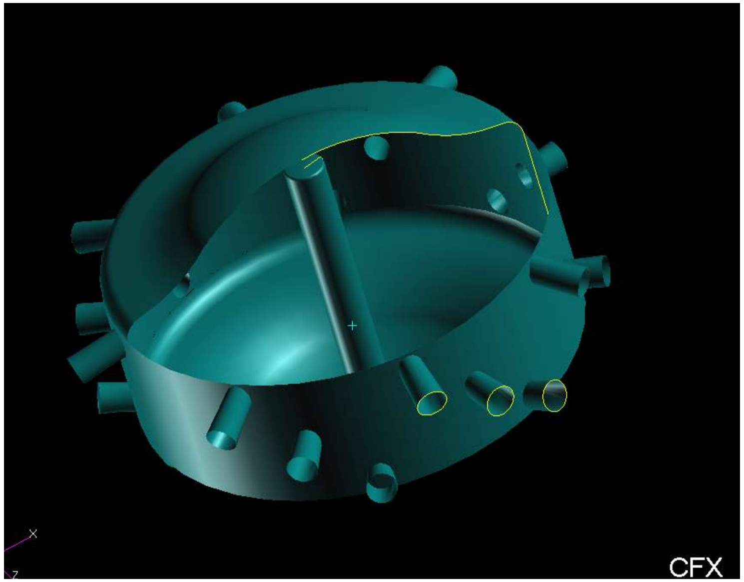


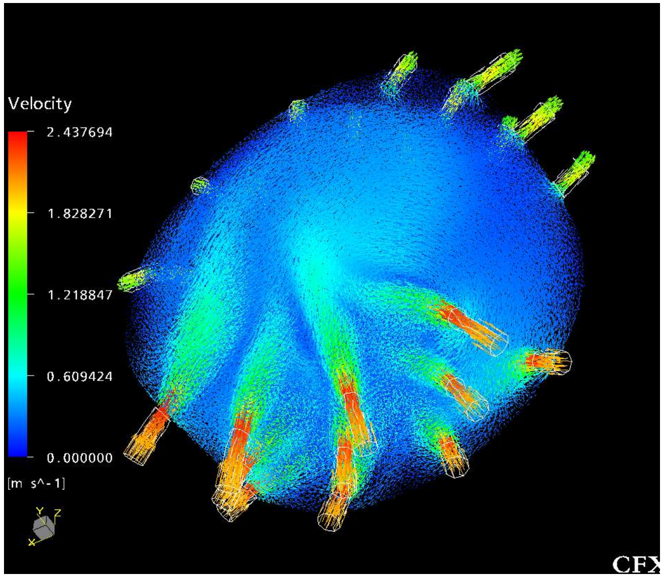
Forced-Flow with external cooling loop

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

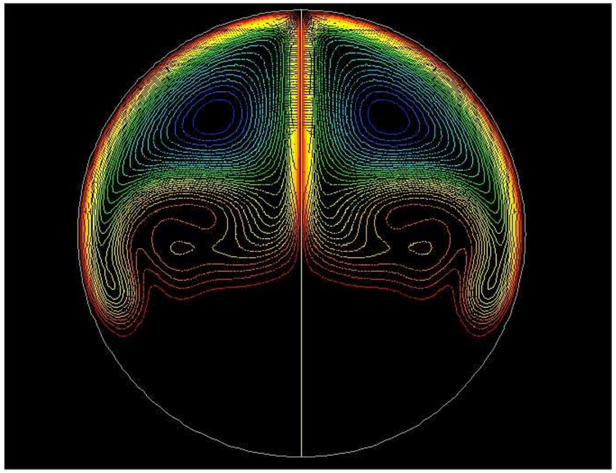






Convection Absorber

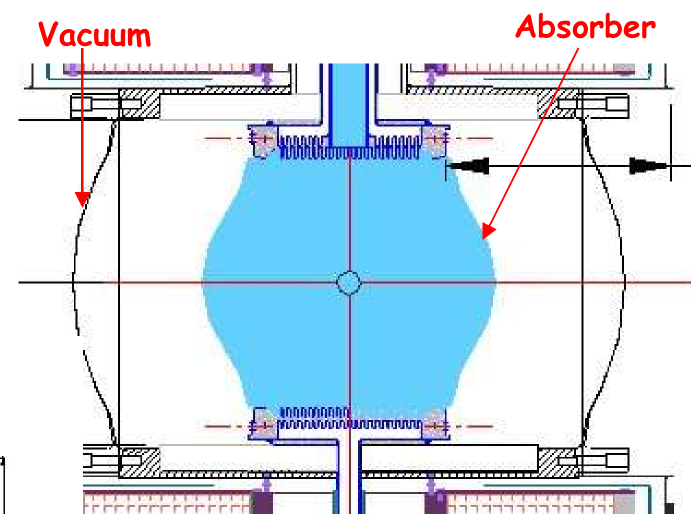
- Convection is driven by beam power and internal heaters
- GHe heat exchanger removes heat from absorber walls
- Two-dimensional Computational Fluid Dynamics calcs
  - Flow essentially transverse
  - Max flow near beam
  - Heaters required to setup convective loops



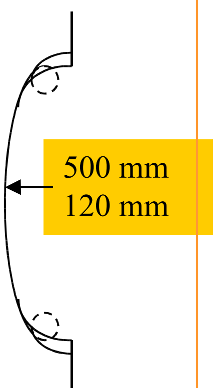
Absorber Windows

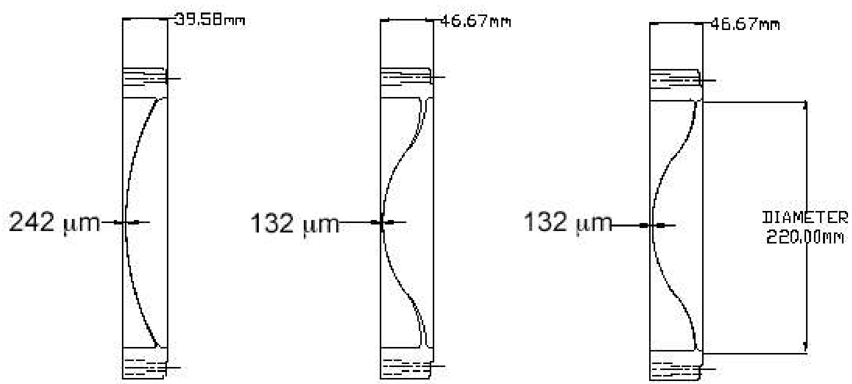
- Thin windows are required in all absorber designs
  - **Critical design issue**
    - Performance
    - Safety
  - **First examples made with AL T6061**
  - **Maybe even thinner with**

Containment Windows



Originally..



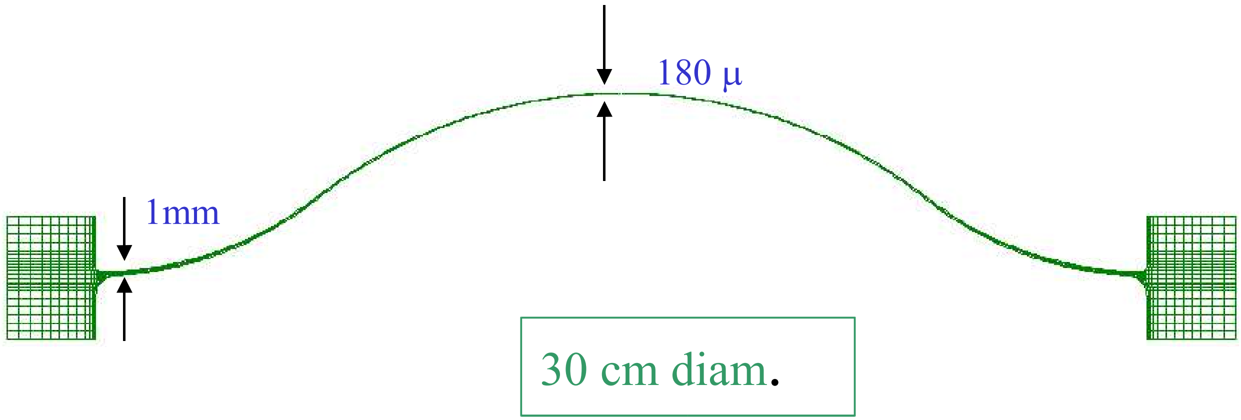


Design Iteration
Hemispherical – Inflected
(Now also used for RF)

FEA results on current bellows window design

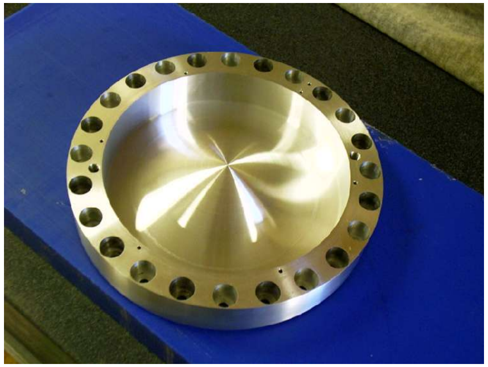
The current window design has a double curvature to ensure that the thinnest part is membrane stress dominate

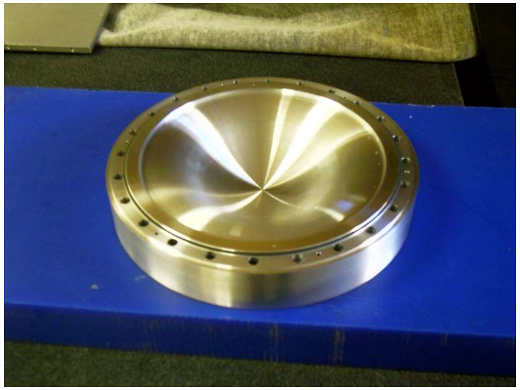
Here is the FEA model on the Absorber window. (Note that in the MICE experiment both the Absorber and the Safety windows now have the same pressure load requirements!)



Learning to manufacture new window

First window (above)!
Second window (below)





"Bellows" Window

(FNAL/Oxford)

Current Photogrammetic Test Setup (FNAL)

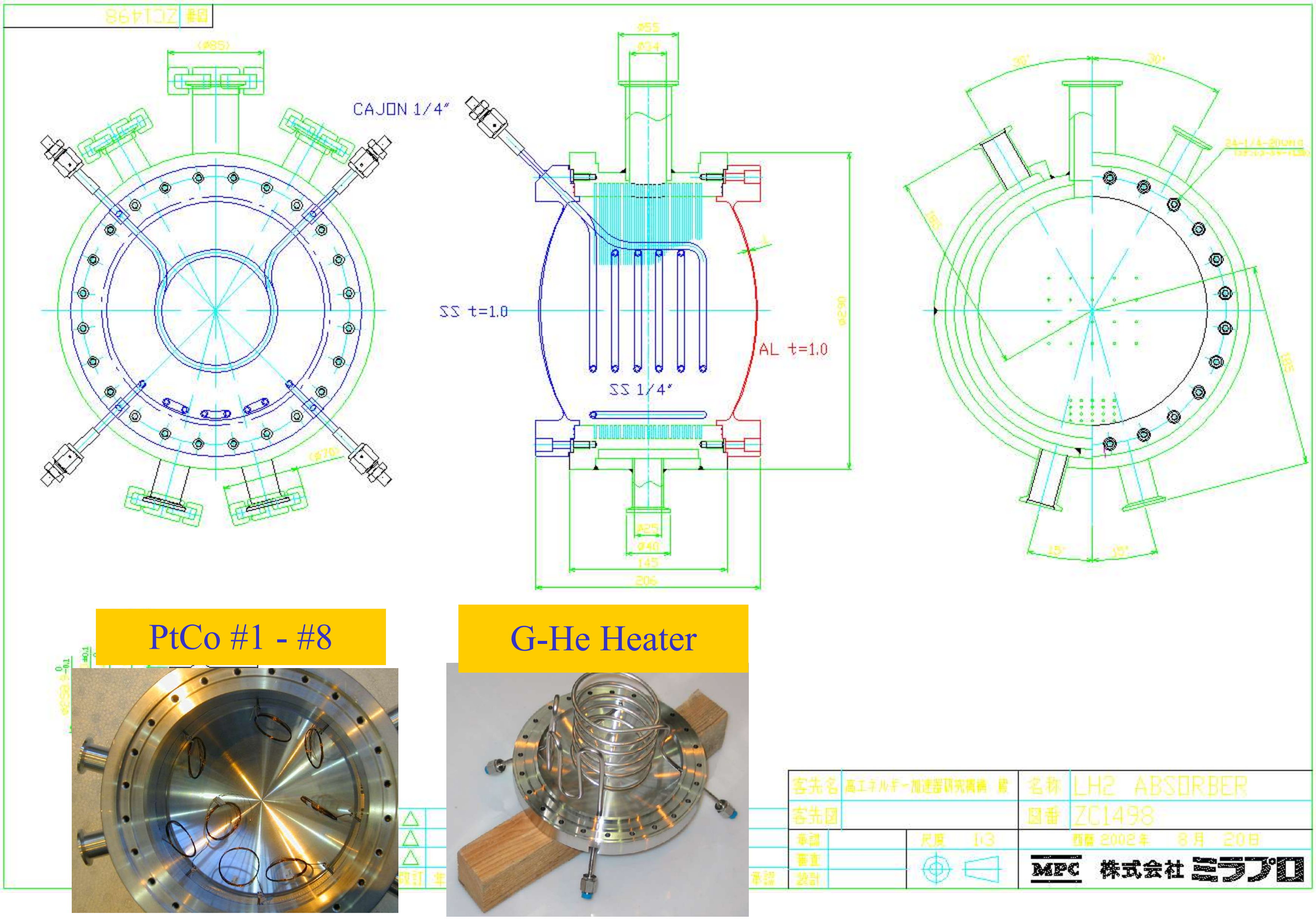
Granite block (seismically stable)

Measurement from two sides

Window wrap-up

- Both software and testing methods are maturing
  - **Equipment upgrades**
  - **Vapor deposition coating**
  - **Certification standard developed**
- 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)

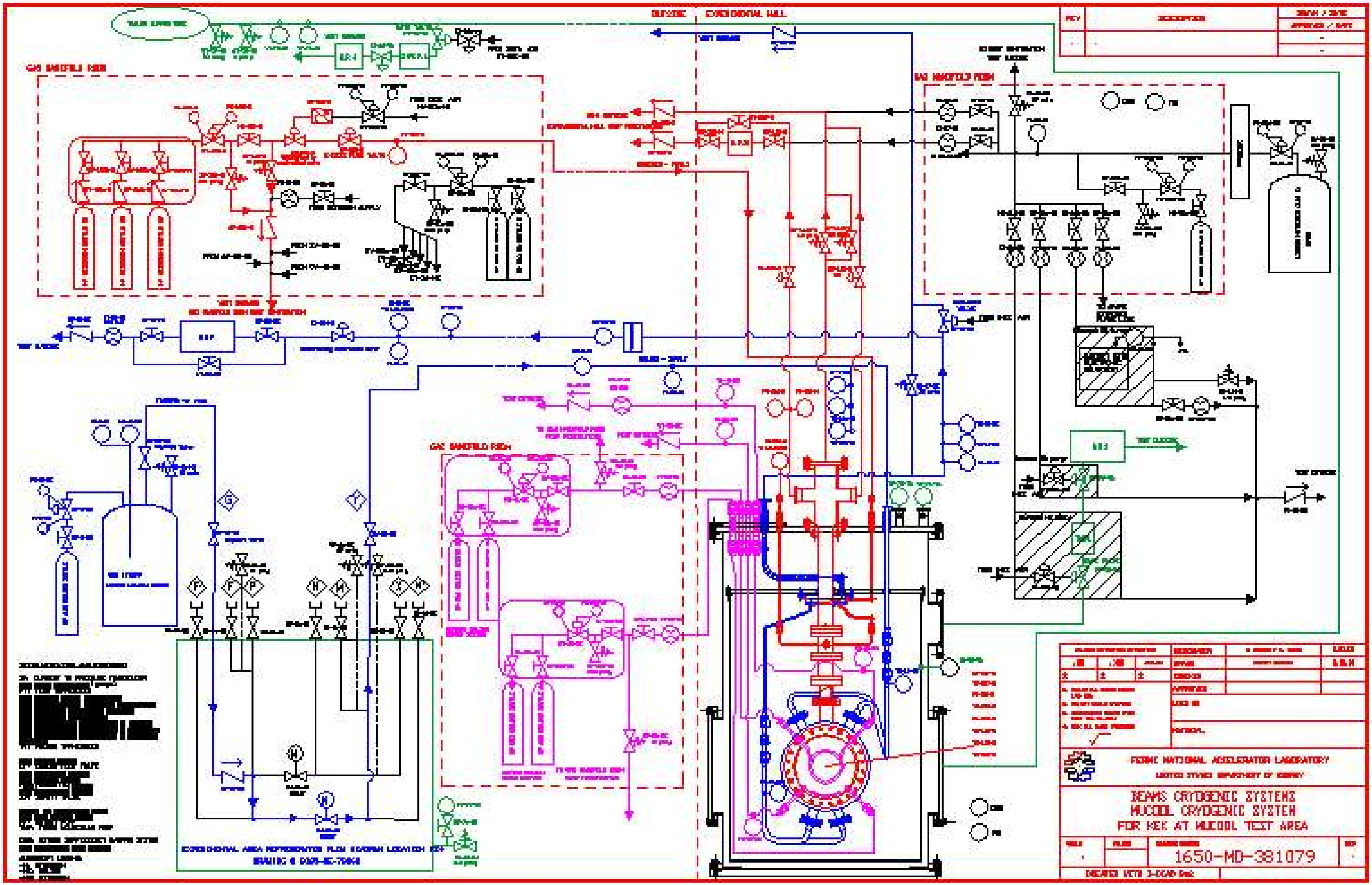
KEK absorber II



Muon Collaboration

KEK absorber test at MTA /FNAL

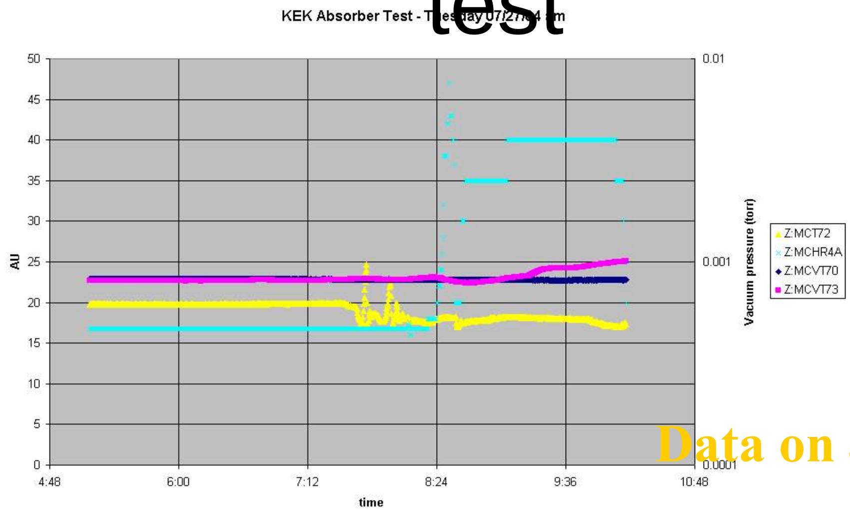
Complete controls system



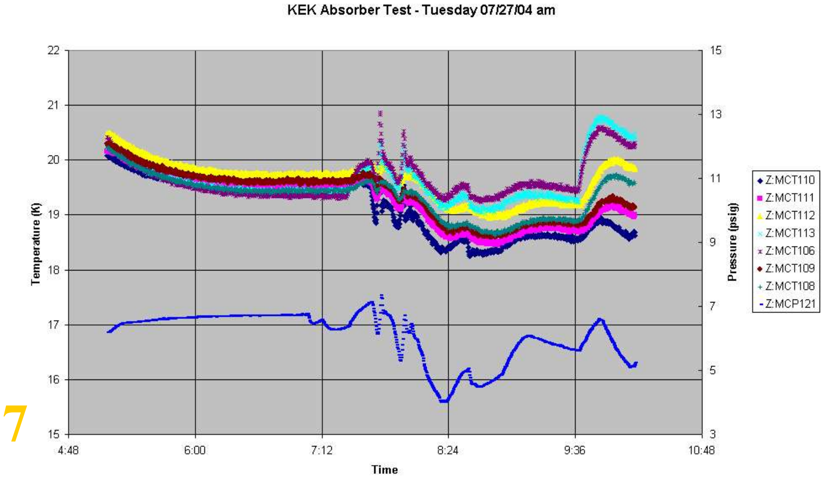
Muon Collaboration

½ fill on Jul-9 ; no leak at 20K

First data from MTA KEK absorber test

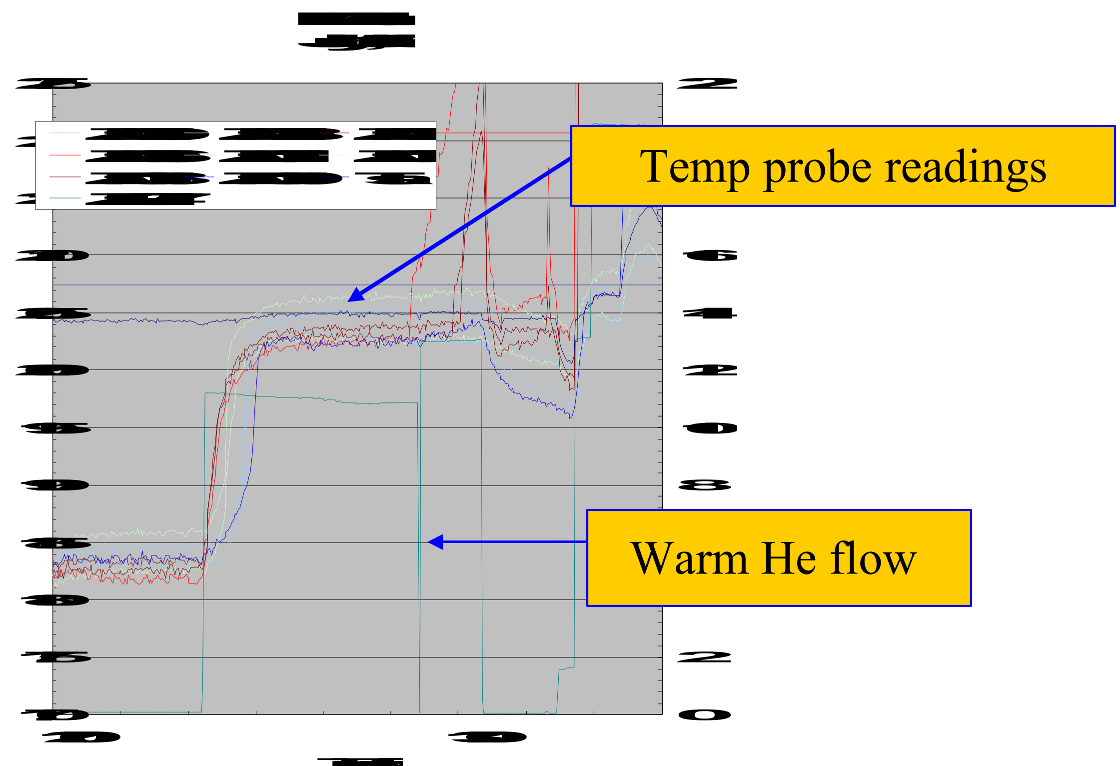


Data on July 27



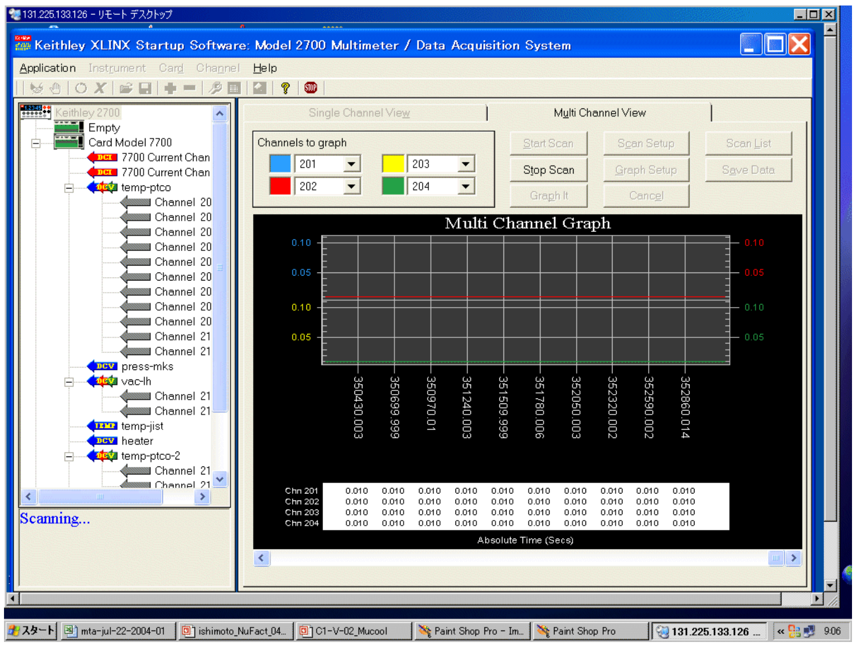
Heater; 35-40 W
Goal: more heat absorption with stable operation

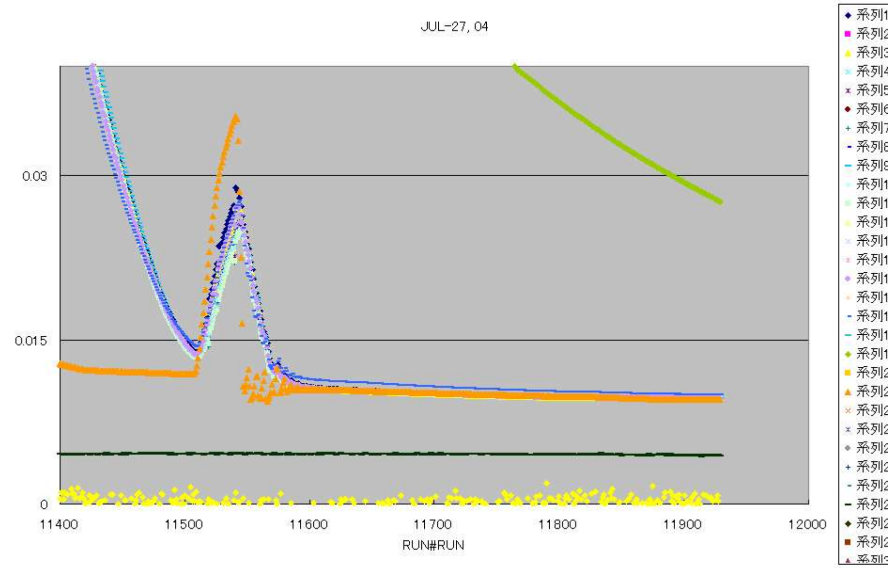
July 15, 40W heat, stable temps



The cooling test continues…

Remote access from KEK
and data on Jul-27





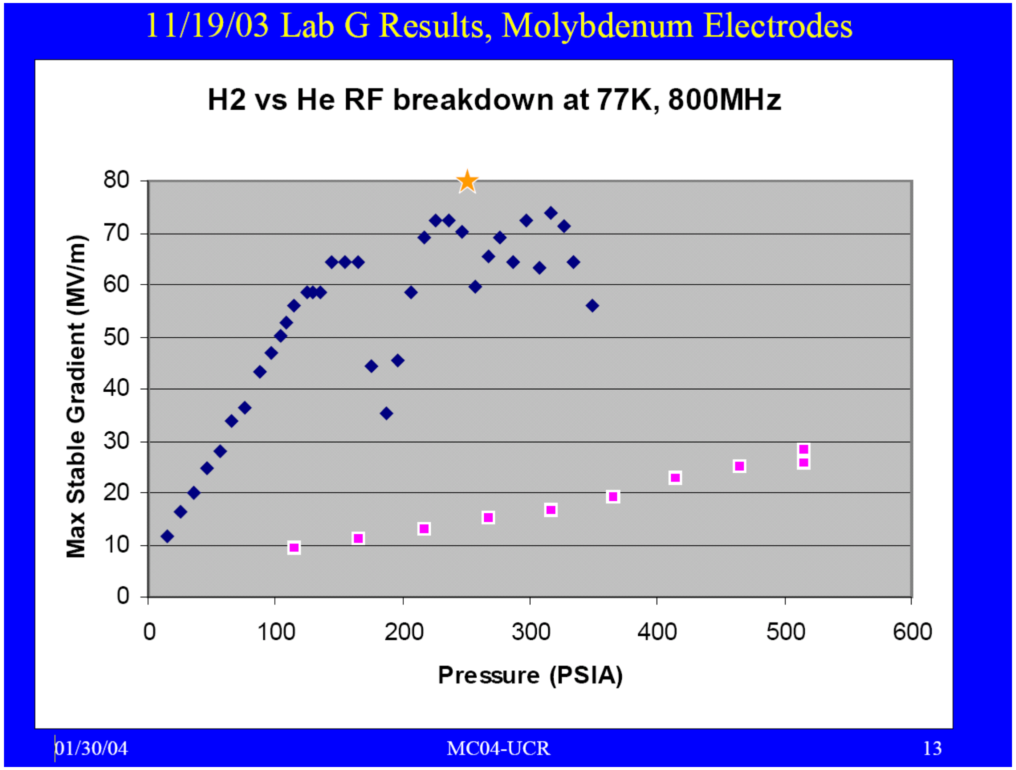
Strong FNAL cryo team

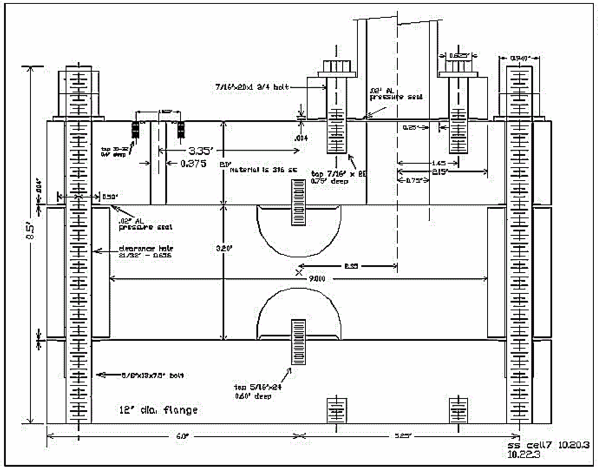
MTA KEK Summary

1. Cold-He Cooling test has been started, and many problems were successfully solved.
2. Large heat input ~23 W to ~20 m transfer tube made thermal vibration. → Solved by cold G-He system
3. High temperature G-He was sent to absorber when Dewar was changed. → 2 Dewar (500 L) were used simultaneously.
4. The absorber was filled of L-H2 full without leak, and it was well controlled continuously without heat input.
5. The FNAL cryo-group is now operating the absorber with G-He heater.
6. Valuable experience for Mucool and MICE.
7. Next test:
    1. New absorber instrumentation
    2. Better heat exchange regulation (optimization)

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-August**
  - **Provide 201 & 805 MHz capability for MTA**
  - **Move Lab G magnet to MTA**
  - **Continue 805 MHz RF studies in Lab MTA (starting fall)**
    - Window and grid tests
    - Surface treatment/materials tests - effect on dark current and breakdown
  - **Provide as much of the cryo infrastructure as funding allows**
  - **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
    - Absorber testing underway
    - RF test program to begin in Fall '04 (805 and then 201)
      - **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**