Normal Conducting RF Cavity R&D for Neutrino Factory or Muon Collider

Thomas Jefferson National Laboratory Facility

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Thomas Jefferson National Laboratory Facility

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University of Mississippi

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Outline

- **Introduction**
  - Muon Ionization Cooling
  - International Muon Ionization Cooling Experiment (MICE)
- **Experimental study program**
  - 805 MHz cavity design
  - Fabrication
  - Coupler design
  - Achievable accelerating gradient under a few Tesla magnetic fields
  - Button tests with different materials and coatings
- **Thin beryllium windows for RF cavity**
  - Pre-stressed flat windows, grids
  - Curved Be windows
- **201 MHz Cavity Program**
  - Cavity design
  - Fabrication techniques
    - Spinning
    - Extruding
    - E-beam welding
    - Cleaning and electro-polishing (EP)
  - Loop coupler and conditioning
  - Preliminary test results of the cavity
- **Some of the US MICE responsibilities**
- **Summary**

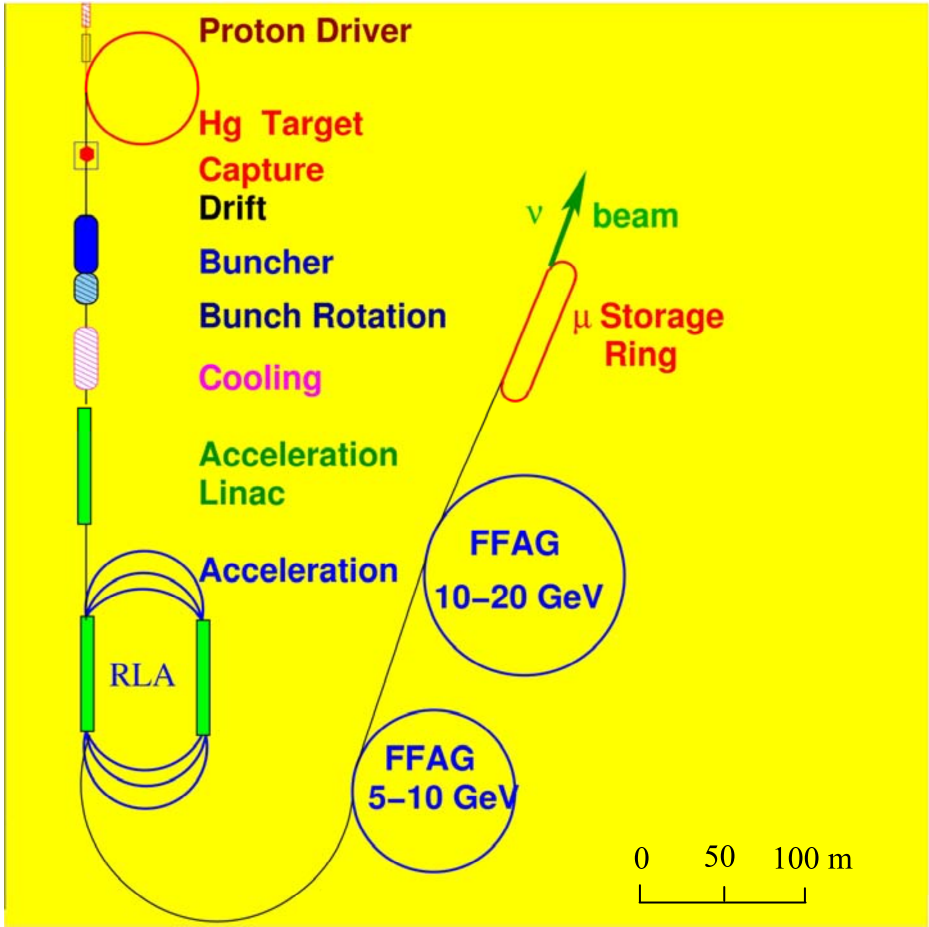
Introduction

- R&D program under auspices of the U.S. Neutrino Factory and Muon Collider Collaboration (NFMCC)
- Three leading national laboratories (BNL, FNAL, LBNL) + JLab and other university research groups
  - Production, acceleration and storage of intense muon beams (hardware and software)
    - Technology and engineering solutions
    - Accelerator physics of intense muon beams
- Support from DOE, NSF, Illinois State and U.S.-Japan
- R&D progress enhanced significantly by corresponding programs in Europe and Japan
- Long term goals
  - Continue evaluating physics opportunities afforded by intense muon beams from Neutrino Factory through a Muon Collider
- Near term goals
  - Muon cooling R&D (software and hardware)
  - International Muon Ionization Cooling Experiment (MICE)
  - Cost effective Neutrino Factory Design

Neutrino Factory Ingredients

Neutrino Factory comprises

- Proton Driver
  - primary beam on production target
- Target, Capture, and Decay
  - Create π; decay into μ
- Bunching and Phase Rotation
  - Conditioning: reduce ΔE of bunch
- Cooling
  - Reduce transverse emittance
  - *MICE*
- Acceleration
  - 130 MeV ~ 20–50 GeV
- Storage Ring
  - Store for ~ 500 turns; long straight

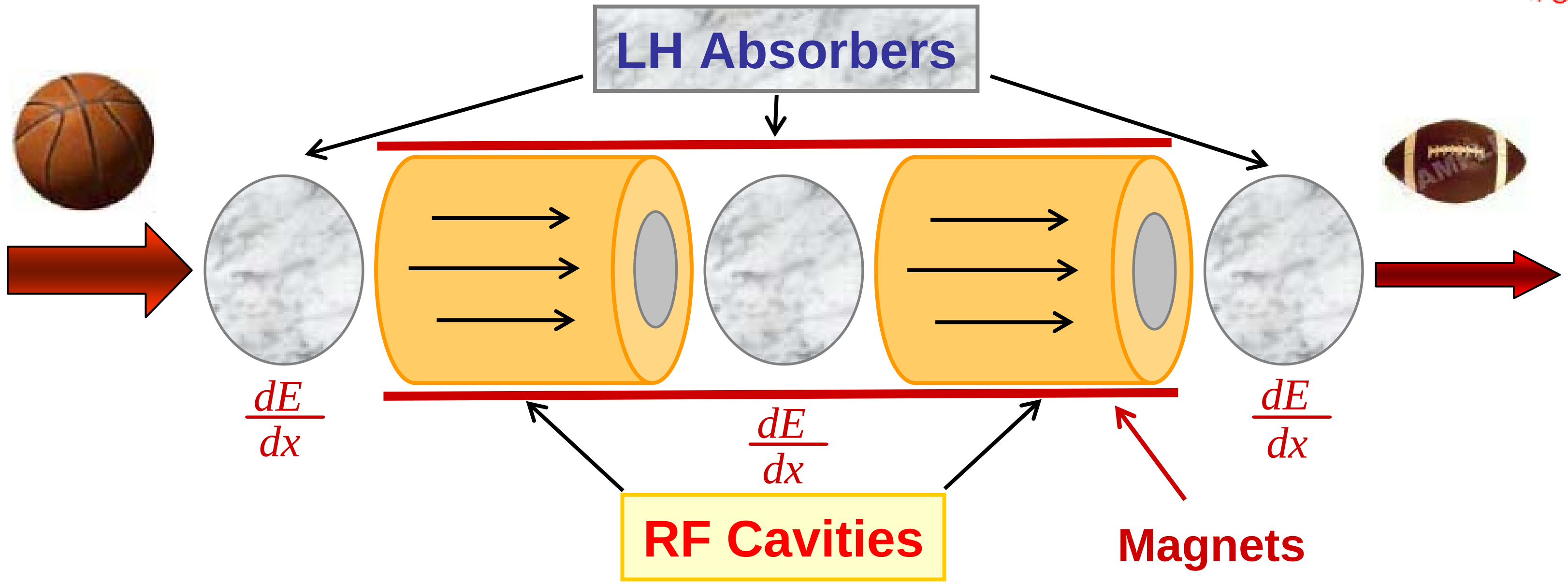


Challenging, but no show stoppers!

Cooling R&D Programs

- Cooling
  - Components R&D: NC RF cavities, absorbers and solenoids
  - Normal conducting RF cavity studies:
    - Experimental studies at 805 MHz using a pillbox cavity
    - Be windows R&D
      - Thermal and mechanical stabilities at high accelerating gradients
      - Scattering and limits
    - Tests are being conducting now at MTA (MUCOOL Test Area), FNAL
    - 201 MHz cavity design, fabrication and tests
  - Absorbers (ICAR, Japan-US funding)
    - Absorbers, windows and safety issues
    - Design and FEA simulations of absorber windows
    - Absorber tests at MTA, FNAL
  - SC solenoids (magnets)
  - International MICE experiment

Muon Ionization Cooling



- High gradient RF cavities to compensate for lost longitudinal energy
- Strong magnetic field to confine muon beams
- Energy loss in LH_2 absorbers

Goal:

- Development of NC 201-MHz cavity operating at ~ 16 MV/m in a few-Tesla solenoidal *B* field (~ 30 MV/m at 805-MHz)

Demand for High Gradient RF

Technical challenges

- Muon beam is unstable, and has short decay time (~ 2 μs at rest)
- Muon beam is created with LARGE 6-D phase space
  - Muon beam manipulation must be done quickly including cooling

→ Highest possible gradient normal conducting RF cavity

- Requirements of RF cavity for muon beams
  - High cavity shunt impedance, high gradient and high field
    - Gradient at 201 MHz: ~ 16.5 MV/m {Kilpatrick criterion: 15 MV/m}
    - Gradient at 805 MHz: ~ 30 MV/m {Kilpatrick criterion: 26 MV/m}
  - RF cavity with closed iris (iris terminated by Be window)
    - Higher shunt impedance
    - Independent phase control, higher transit factor
    - Lower peak surface field

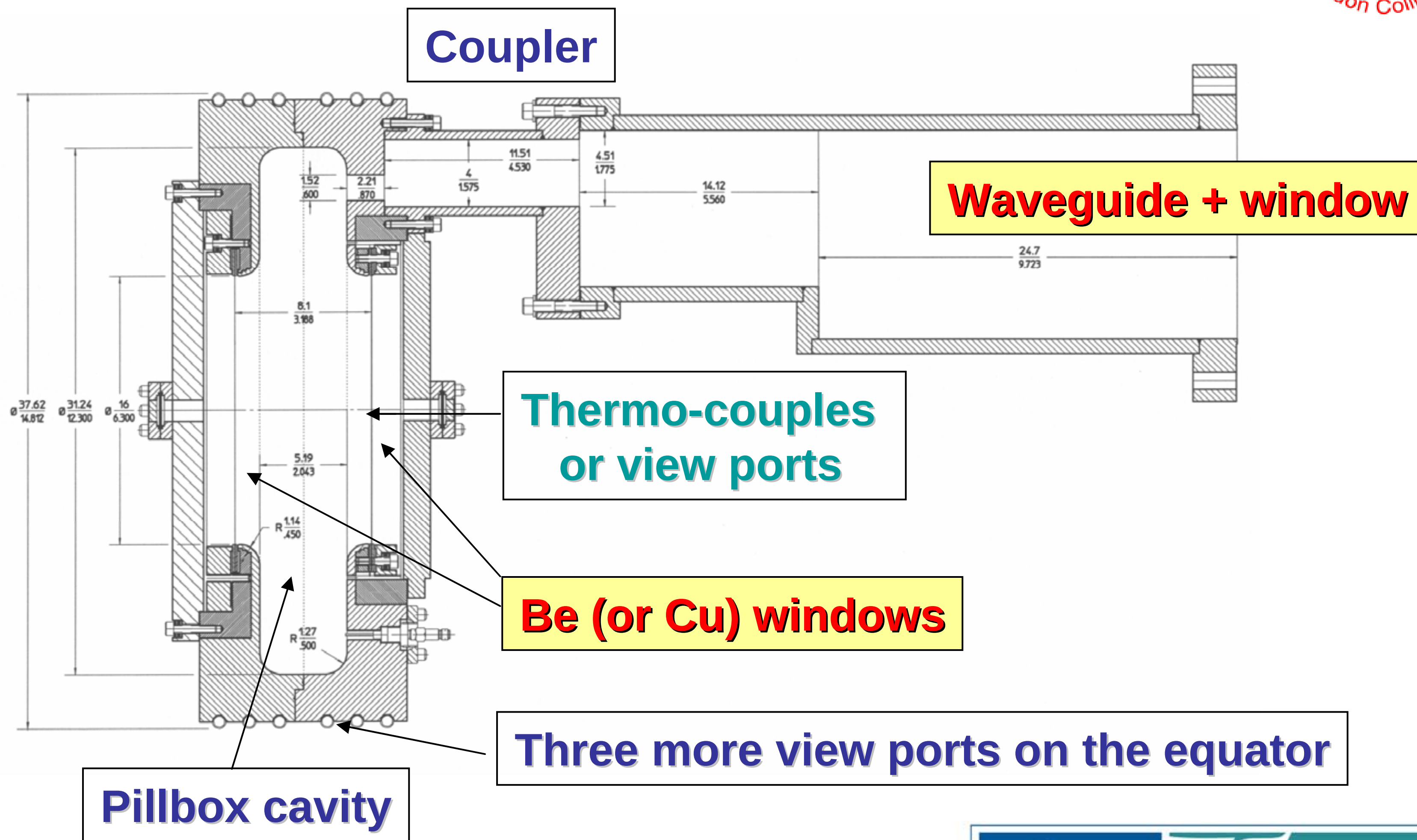
Experimental Studies at 805 MHz

LBNL 805-MHz pillbox cavity design, fabrication and tests

Experimental Programs at 805-MHz

- Development of the 805 MHz Pillbox cavity
  - Design and fabrication of the cavity
  - Highest possible shunt impedance and high acceleration gradient at the order of ~ 30+ MV/m
  - Allowing for testing of Be windows with different thickness, coatings, and other windows as well
    - Copper windows, Be windows, Grids and curved Be windows
  - Study RF cavity operation and conditioning under the influence of strong external magnetic fields (a few Tesla) at both the solenoid and gradient modes
- Be windows R&D
  - Mechanical stabilities and thermal stress under RF heating
  - Prototype and FEA modeling
  - Evolutions of Be windows

Cavity Design and Fabrication

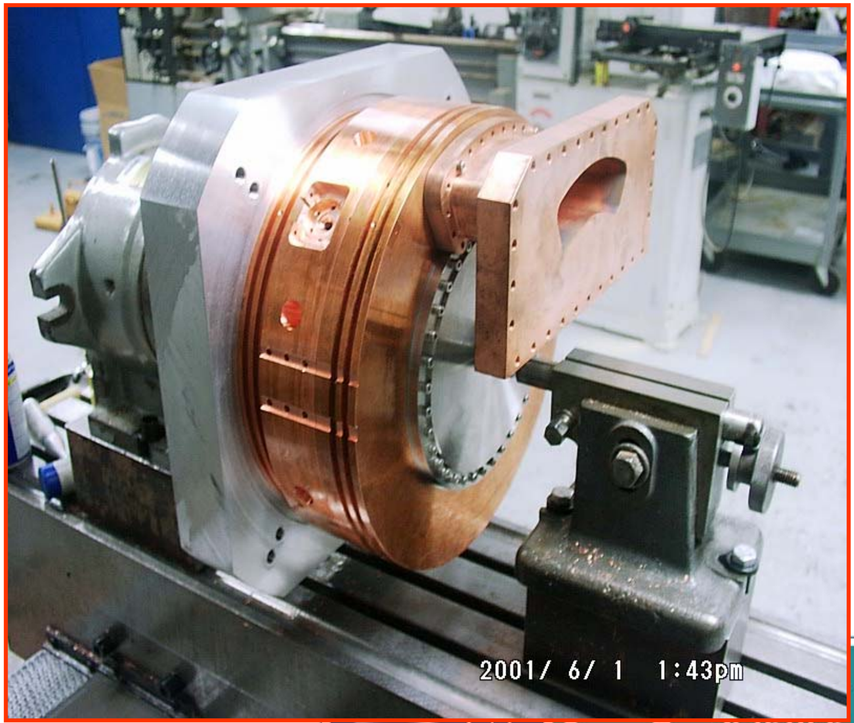


Cavity Design Parameters

- **Frequency: 805 MHz**
- **Shunt Impedance:**
  - **38 MΩ/m (Z_0); 32 MΩ/m (ZT^2); {definition used: $Z = V^2/P$}**
- **Quality factor: Q_0 = 18,800**
- **Coupling Constant:**
  - **Critical coupling at β_c = 1.0**
  - **Accelerating gradient of 30 MV/m requires 2 MW peak power**
  - **350 watts average on cavity body, 52 watts on two windows (66 watts if Be windows) at a duty factor of 1.8×10^{-4} (12 μs pulse length and 15 Hz repetition rate)**
- **Up to 12 MW peak power available at MTA**
- **Tests started 3 years ago, with interruptions in between, but have just resumed recently**

Manufacturing of the cavity

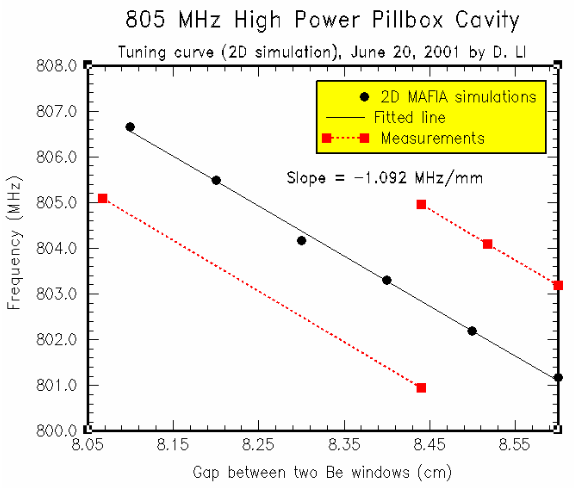
The cavity was designed and engineered at LBNL, fabricated at University of Mississippi, and brazed at Alpha Braze Comp.



Cavity and coupler tuning

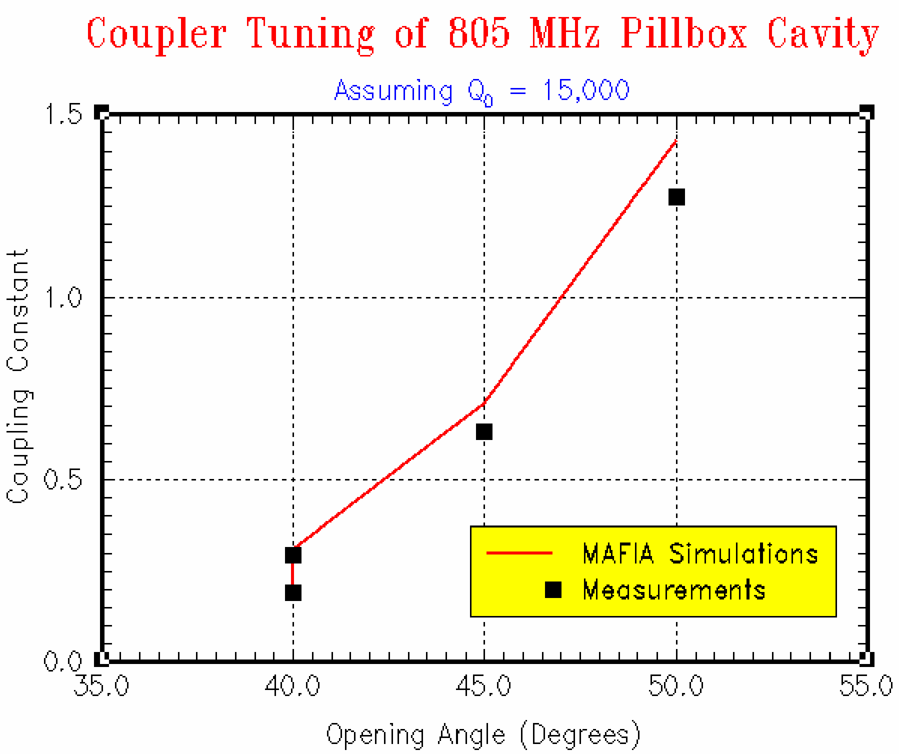
- The cavity final tuning for frequency and coupling at University of Mississippi
  - Before tuning: f = 803.198 MHz, β_c = 0.12
  - After tuning: f = 805.486 MHz, Q_{ext} = 12,800
  - Shipped to Alpha Braze, California for brazing
  - Measurements after final brazing (before shipping to FNAL):

f = 804.946 MHz, β_c = 1.3, Q_0 = 15, 000

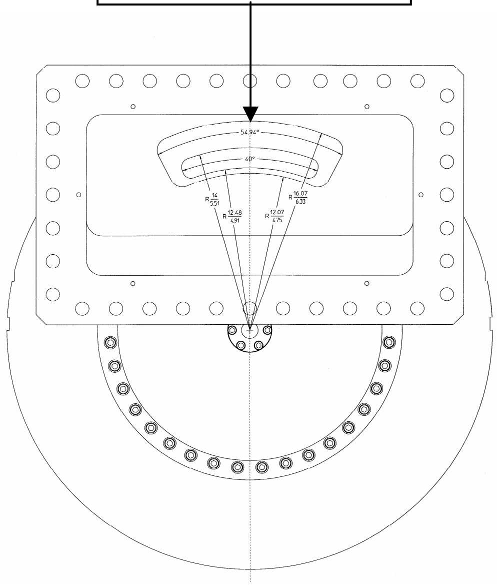


Cavity Coupling Adjustments

- Frequency tuning (shortening the gap)
- Coupler tuning (widening coupling slot and shortening the transition waveguide)
- Good agreements between simulations and measurements



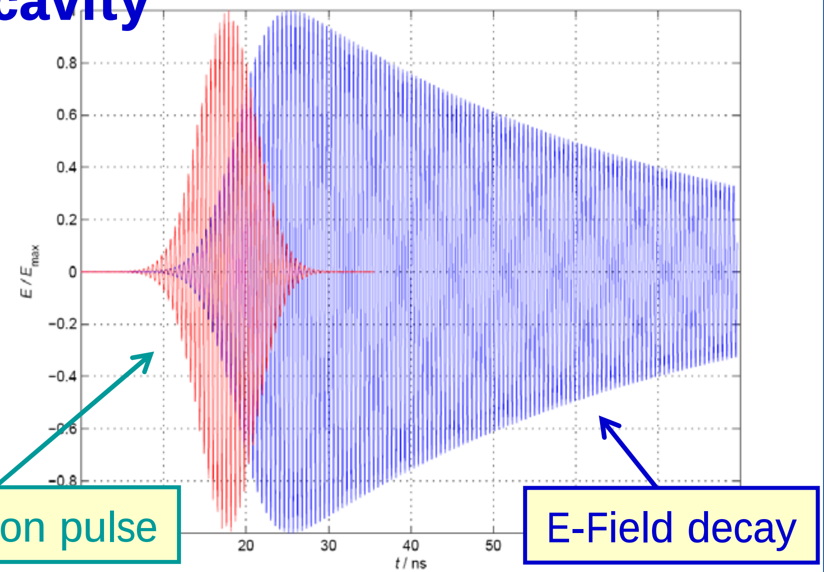
Coupling slot



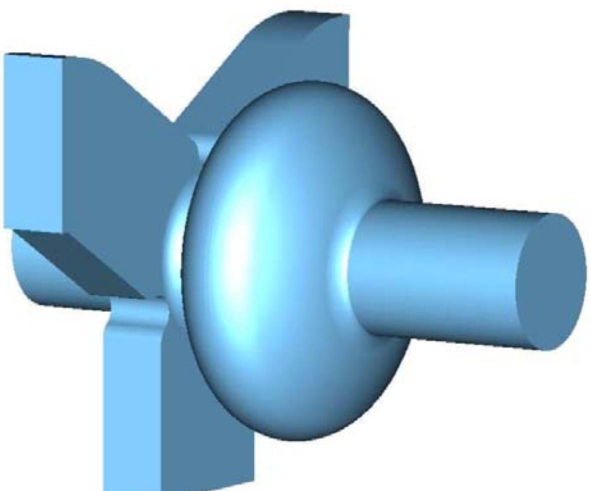
External Q calculations by MAFIA and MWS

Method has been benchmarked again against measurements for the JLab HOM damped cold test cavity

- MWS simulations in time domain
- Waveguide boundary conditions at ports
- Excite cavity from one RF (HOM) port
- Record and observe field (energy) decay as a function of time inside the cavity
- External Q is calculated from decay time



MWS model of the J-Lab Cavity



$$\rho(s) = \frac{Q}{\sqrt{2\pi}\sigma_s} e^{\frac{(s-s_0)^2}{2\sigma_s^2}}, \left[\frac{\mathrm{C}}{\mathrm{m}}\right],$$

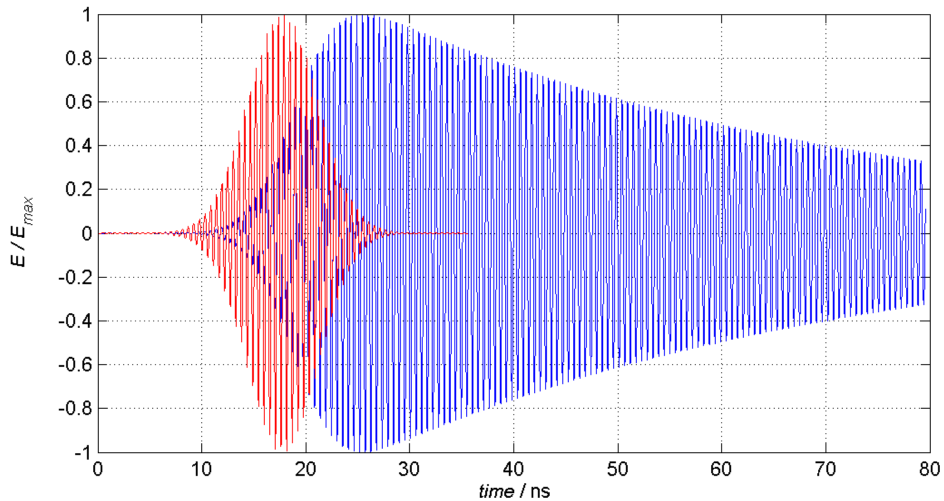
$$i(t) = \frac{Qc}{\sqrt{2\pi}\sigma_s} e^{\frac{(t-t_0)}{2(\sigma_s/c)^2}}, [\mathrm{A}],$$

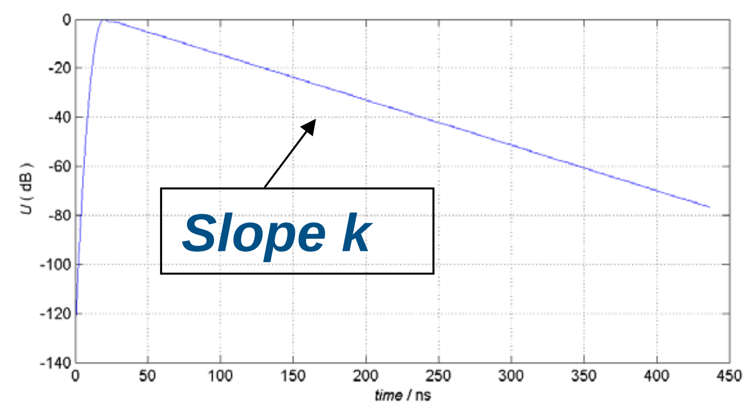
$$i(\omega) = Q e^{\frac{\omega^2}{2(c/\sigma_s)^2}}, [\mathrm{C}].$$

MS Calculated		Measured	
f/GHz	Q_{load}	f/GHz	Q_{load}
1.84727	276	1.848006	317
1.84764	264	1.848252	227
2.03046	719	2.029628	996
2.03055	746	2.030226	667
2.43190	2750	2.426183	2878

CST MWS External Q Calculations

- **Energy in the cavity decays with time**
- **Time decay constant depends on the coupling strength**



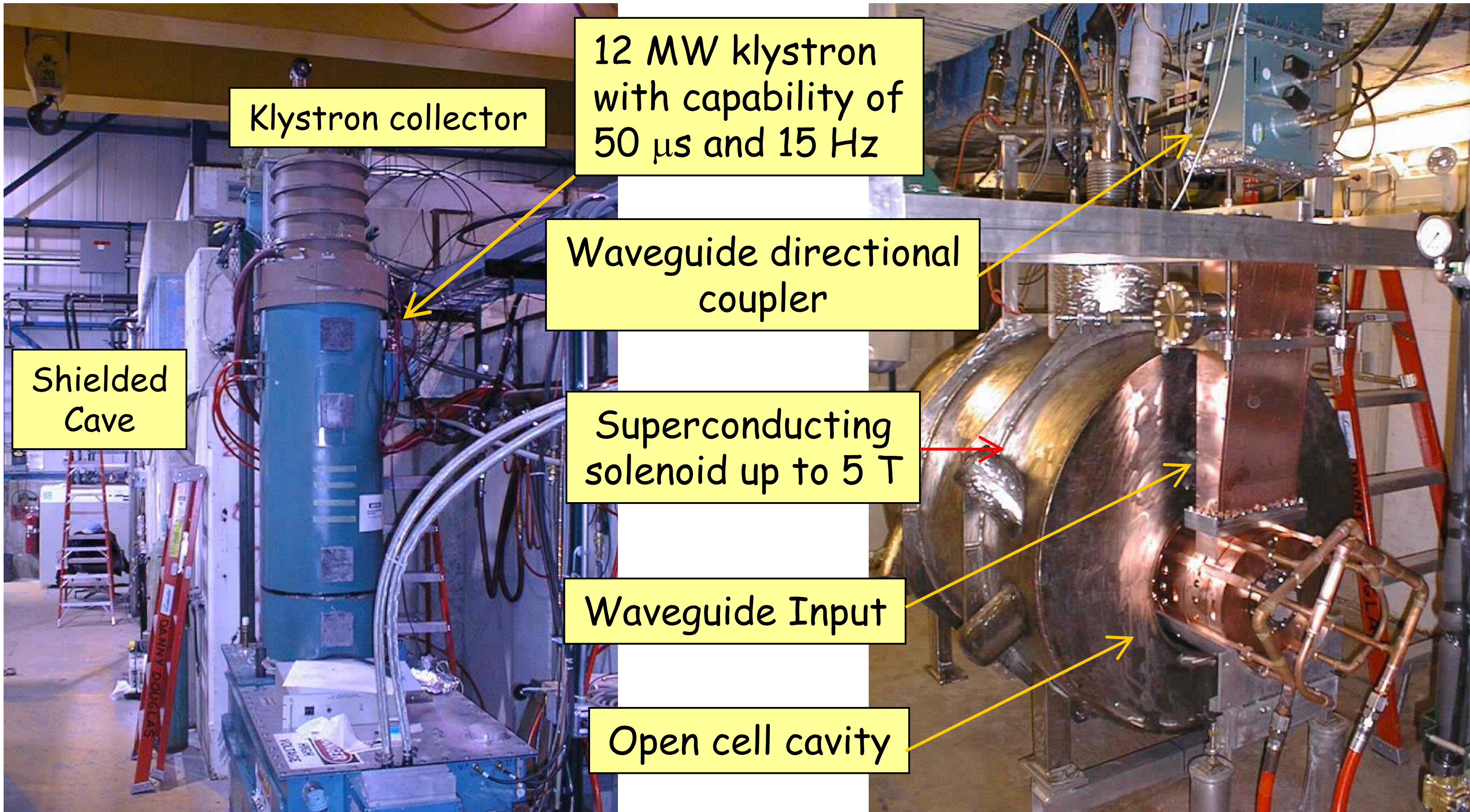


$$U(t) = U_0 \exp\left(-\frac{\omega t}{Q_{load}}\right)$$

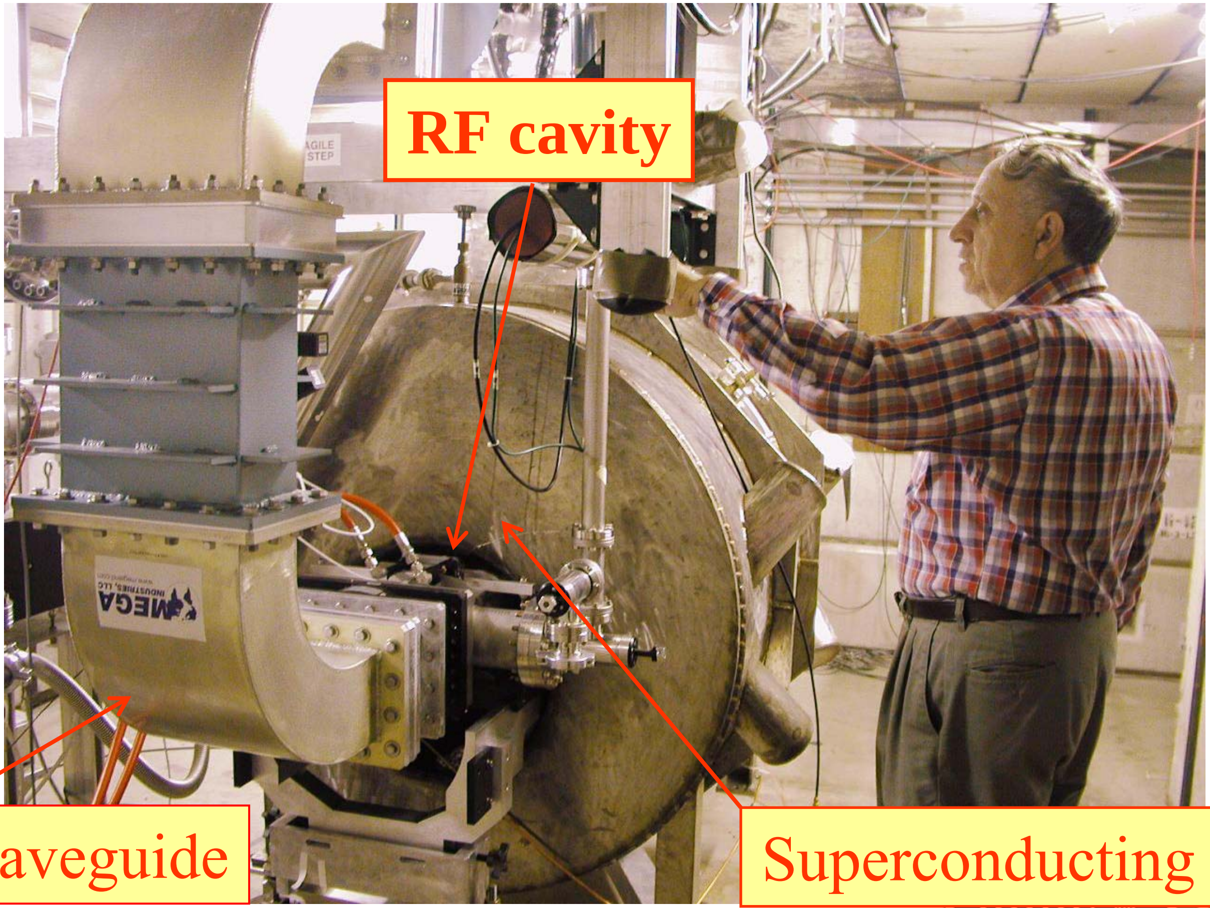
$$Q_{load} = -\frac{10\lg e \cdot \omega}{k}$$

Simulation agrees with measurements

Test setup at Lab G



Test setup at Lab G (cont'd)



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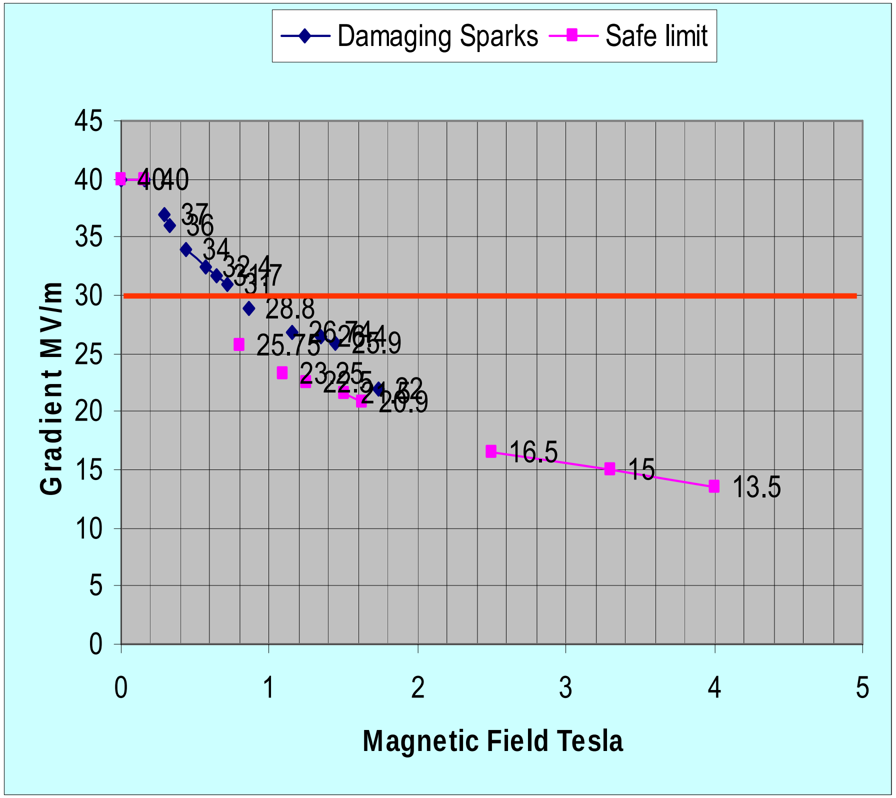
Experimental Study Results

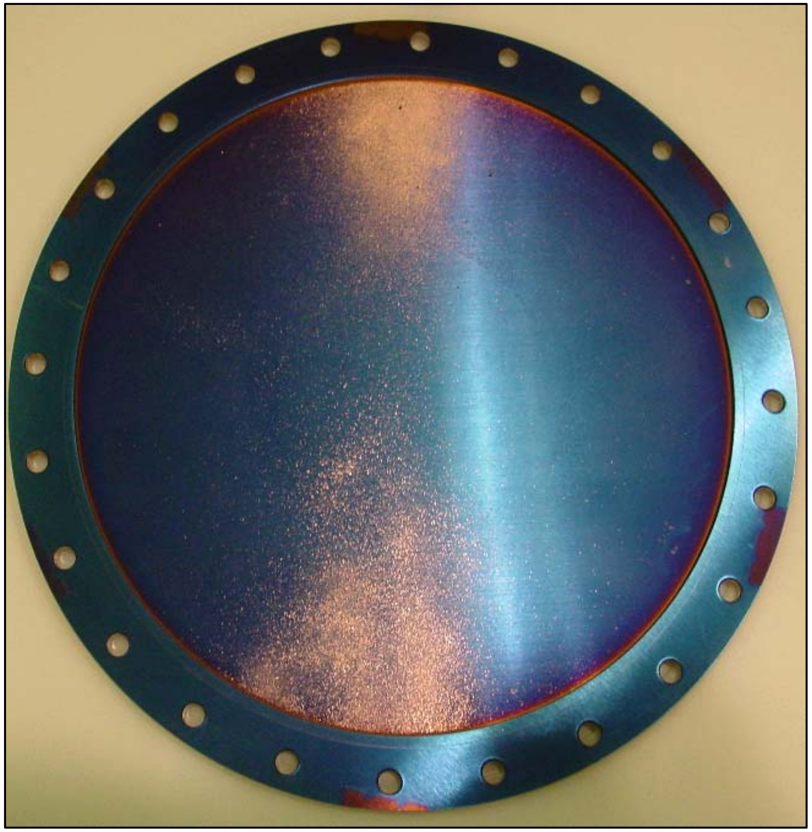
We have conducted experimental studies at 805 MHz for nearly three years at Lab G and has resumed recently at MTA, FNAL

- Open 5-cell cavity reached 25 MV/m gradient (54 MV/m surface field)
- Large dark current with surface and window damage
- Pillbox cavity test exceeded its design gradient of 30 MV/m with no magnetic field and reached up to 40 MV/m
- Thin Be windows with TiN-coated surface have been tested versus magnetic fields up to 4 Tesla
  - No surface damage was found on the **Be windows**
  - Little multipacting was observed; accelerating gradient limit is a function of the external magnetic field



Windows after Conditioning

Copper window

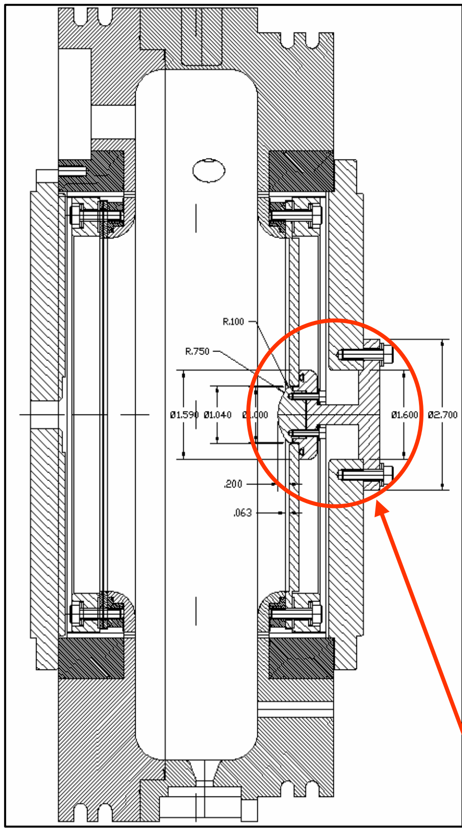


Be window

These windows (surface damage) have been analyzed at ANL and JLab

Button and Window Study Using the 805 MHz Pillbox Cavity

Neutrino Factory Muon Collider

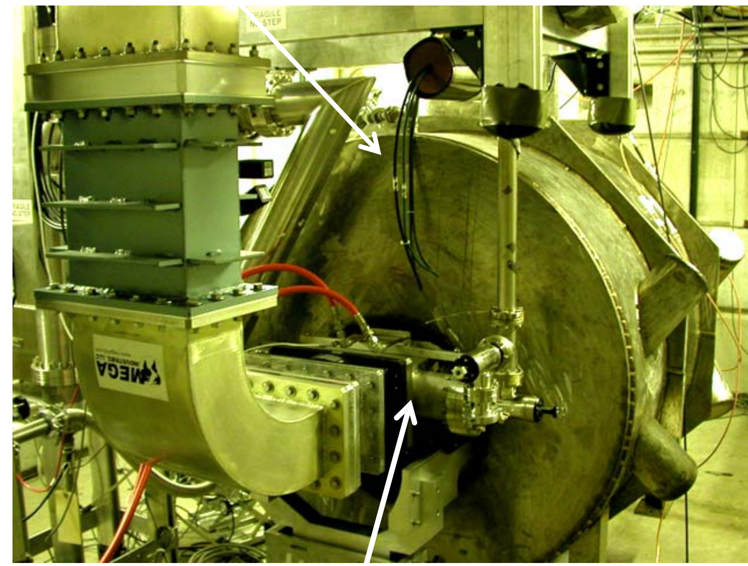


- Curved Be windows
- Button study
  - Completed design and fabrication
  - Ratio of peak surface field (on the button) versus accelerating field on-axis ≈ 1.7 with ~ 0.5 MHz shift
  - New materials
    - many buttons
    - SS, Cu with coatings, ...
  - Different coatings

Demountable button

Up to 12 MW peak power

SC Solenoid



805 MHz pillbox cavity inside the SC solenoid

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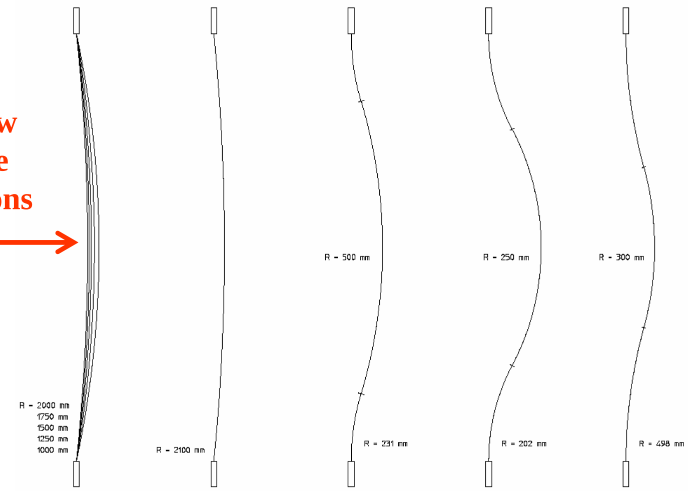
RF Cavity Iris Terminations

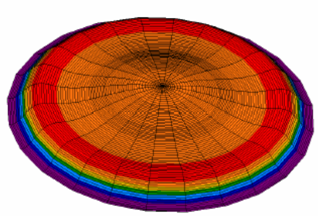
Thin Be Windows R&D

Be Windows R&D

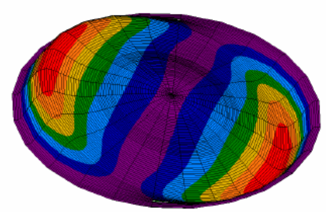
- Ideal windows (physicist's dream)
  - Transparent to muon beams
  - Perfect electric boundary to RF field
  - No detuning to cavity frequency
- Engineering solutions
  - Pre-stressed flat Be windows
  - **Pre-curved Be windows**
  - Grids

Window profile evolutions



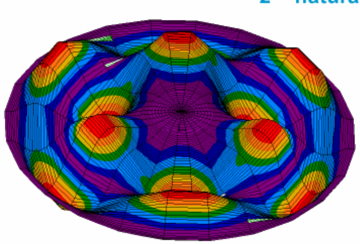


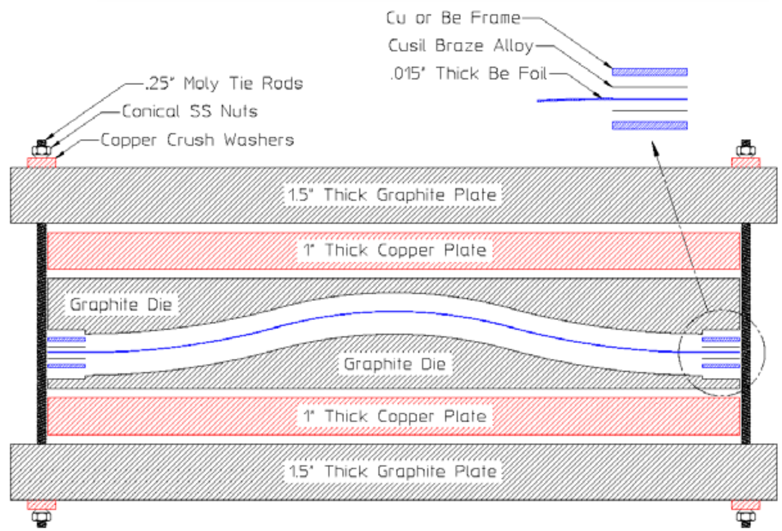
1st natural frequency: 530 Hz.



2nd natural frequency: 673 Hz

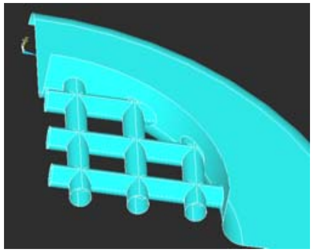
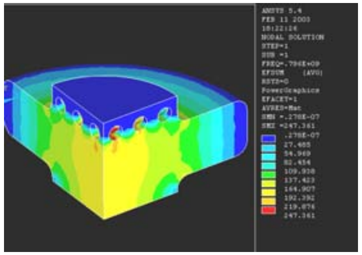
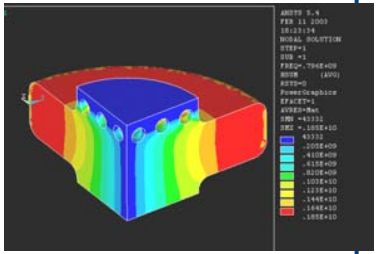
A pre-curved Be window: 0.25 mm thick and 21 cm in radius



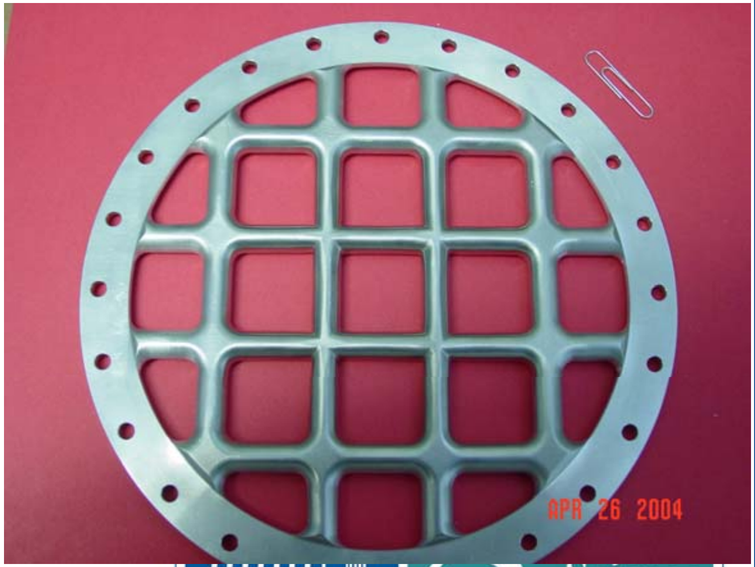


Tube-Grid Study

- ANSYS study of tube grid design and prototype for 805 MHz pillbox cavity (Ph.D thesis at IIT)
  - Tests at MTA soon
  - Field enhancement between 1.4 & 3.6
  - RF Heating on tubes

Grid Model	Electric Field	Magnetic Field
		

First prototype of solid Al grid



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		

Setup for Window Formation

- The graphite die in Al fixture (room or high temperatures)
- 10 S.S sheets (10 mils) and 3 Be foils (10 mils) have been ordered for the pre-form tests
- Halogen lamp heating tests may be conducted at the 805 MHz low power test cavity to benchmark the FEA models

Curved S.S. Windows

Succeeded in the S.S. window with Cu frame for 805 MHz cavity

Pre-formed at room temperature by holding foil edge then braze the Cu frame

A finished curved S.S. window with brazed Cu frame

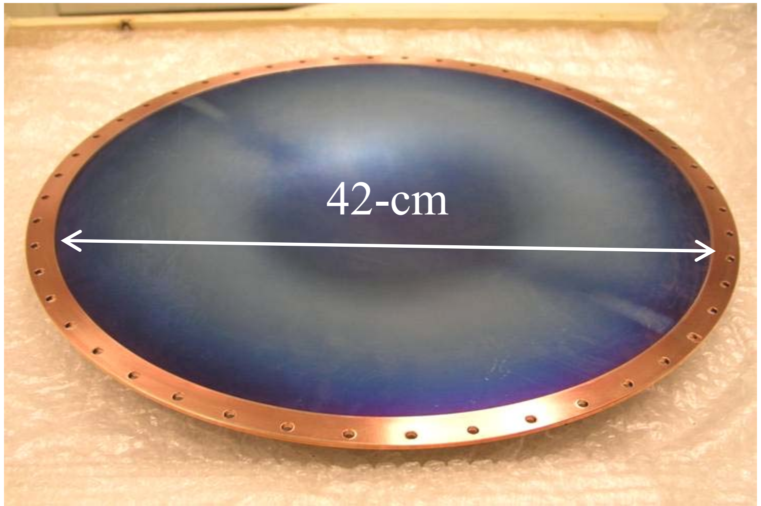
Curved Be Window

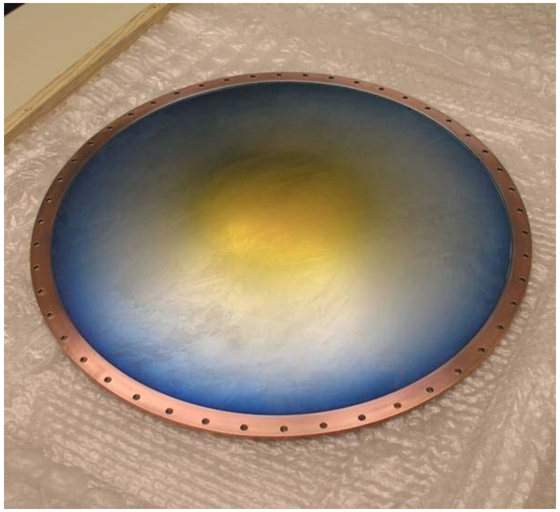
Failed in forming Be window at room temperature

However, we believe the curved Be windows can be formed at higher temperature at that time. It turns out that the windows can be formed and brazed at Brushwellman Company *without significant cost increases*. We have succeeded in making these windows and have three (805 MHz cavity) and two (for 201 MHz) of them ready for use for high power tests.

Curved Be Windows

- **Two windows available now**
  - 21-cm and 0.38-mm thick
  - "Good" braze (between annular frames and foil)
  - Achieved ~ 95 % of the designed profile
  - Thin Ti-N coatings
- **Windows installed pointing to the same direction in the cavity**
- **Ready for HP tests**





201 MHz RF Cavity R & D

Cavity design, fabrication and preliminary tests at MTA

201 MHz RF Cavity R&D

Building and operating a real piece of muon cooling hardware to explore engineering, fabrication and operational challenges

- Prototype cavity for MUCOOL/MICE
  - Designs
  - Couplers and ceramic RF windows
  - Engineering
  - Fabrication: cavity body, ports, tuners, etc.
  - Large, pre-curved and thin 42-cm diameter Be windows
- Commissioning and operation
  - RF Conditioning and background (for MICE only)
  - High gradients (~ 16 MV/m) and high RF power
  - With the thin Be windows
  - With external magnetic fields

The Cavity Body Profile

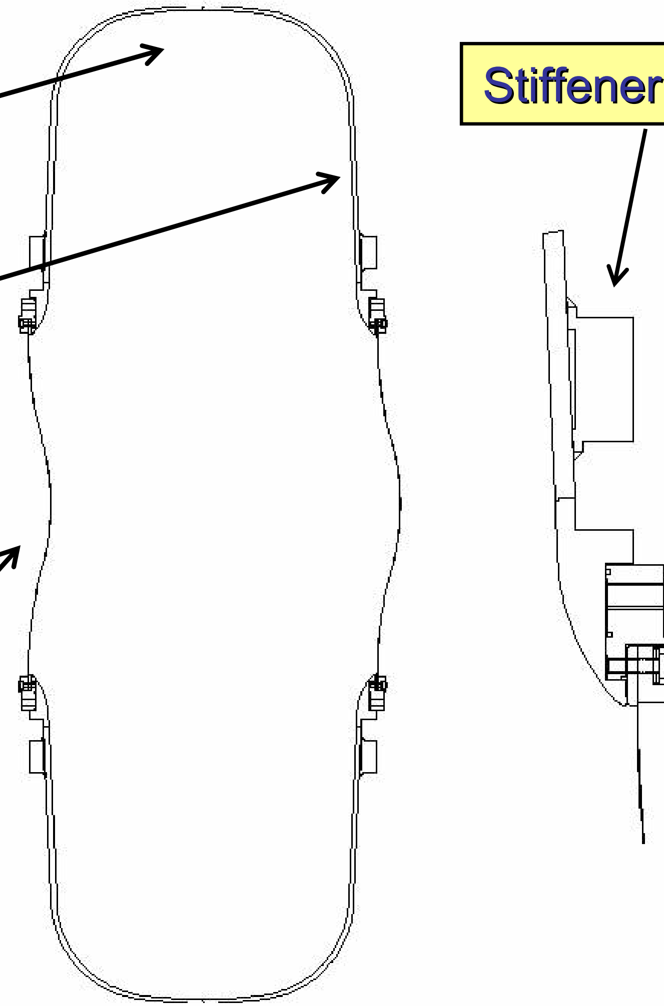
Spherical section at the equator to ease addition of ports (± ~ 6°)
Elliptical-like (two circles) nose to reduce peak surface field

2° tilt angle

6-mm Cu sheet allows for uses of spinning technique and mechanical tuners similar to SCRF ones

De-mountable Pre-curved Be windows to terminate RF fields at the iris

Stiffener ring

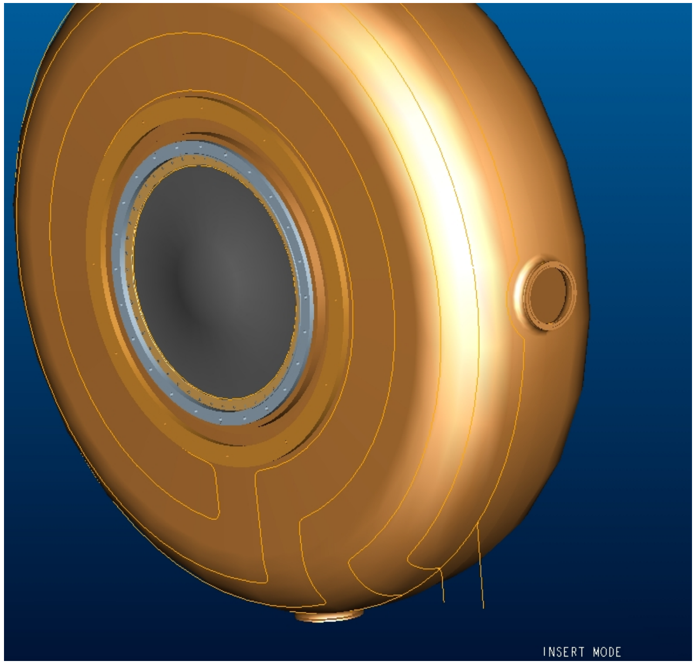


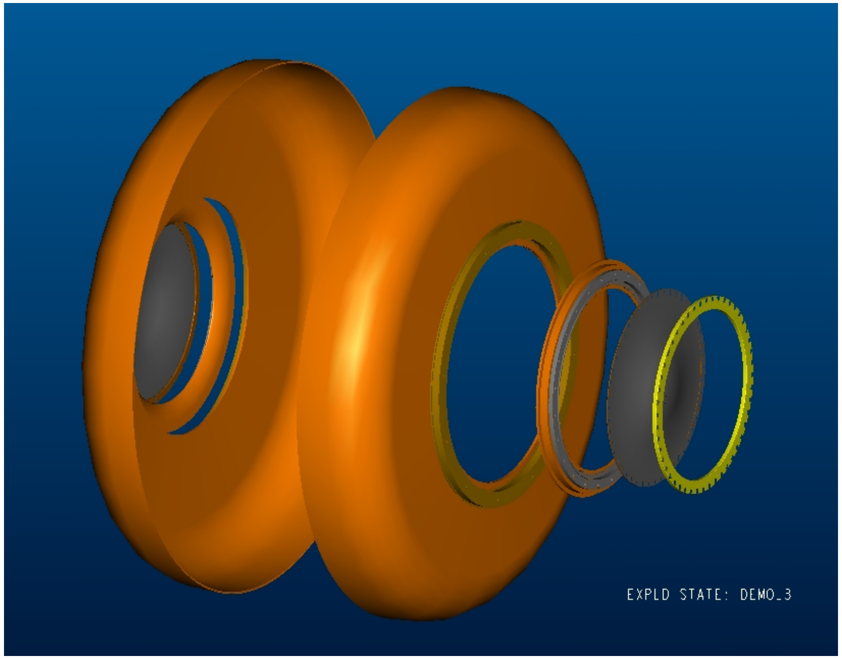
Cavity Design Parameters

- **The cavity design parameters**
  - Frequency: 201.25 MHz
  - $\beta = 0.87$
  - Shunt impedance (definition used: VT^2/P): ~ 22 MΩ/m
  - Quality factor (Q_0): ~ 53,500
  - Be window radius and thickness: 21-cm and 0.38-mm
- **Nominal parameters for cooling channels in a muon collider or a neutrino factory**
  - ~ 16 MV/m peak accelerating field
  - Peak input RF power ~ **4.6 MW** per cavity (85% of Q_0, 3τ filling)
  - Average power dissipation per cavity ~ **8.4 kW**
  - Average power dissipation per Be window

    ~ **100 watts**

201 MHz NC Cavity Concept





Spinning of half shells using thin copper sheets and e-beam welding to join the shells

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

Shells Spun at ACME Company

An example of using spinning technique !

Spinning a bowl

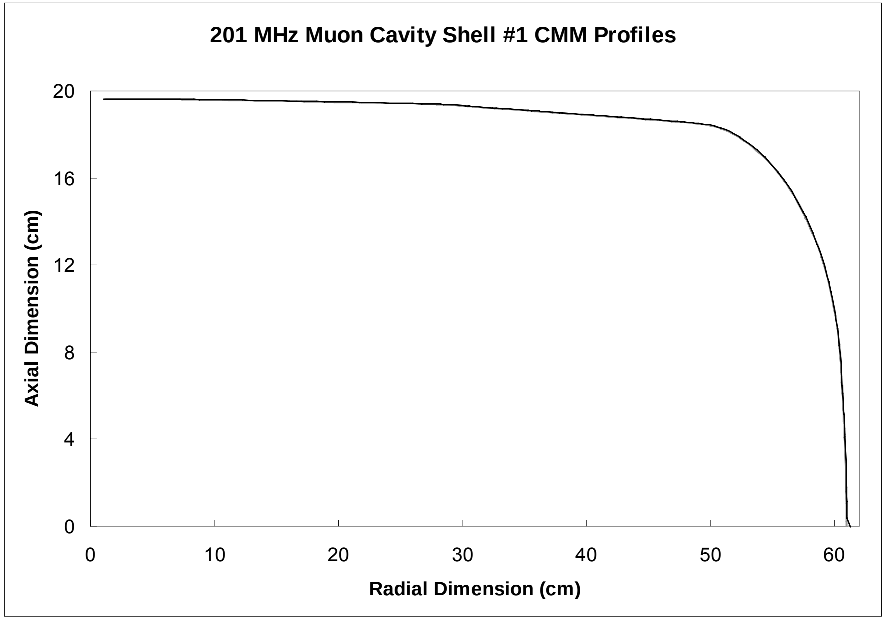
Spinning tools

Shell Measurements at LBNL

- CMM scans to measure the spun profiles of shells
- Frequency and Q measurements
- Copper tapes for better RF contacts

Measured frequency of shell-1: 196.97 MHz

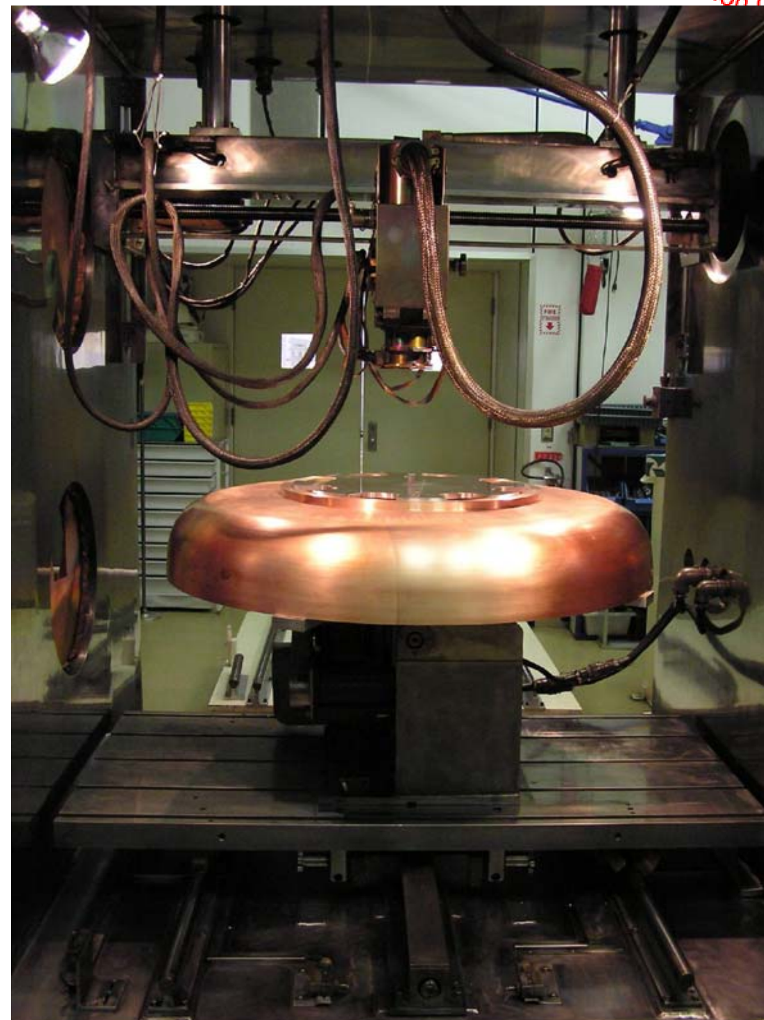
(simulated frequency: 197.32 MHz)



Profile measurements:

3 CMM scans per half shell conducted at 0°, 45°, 90°, respectively

E-beam Welding at J-Lab

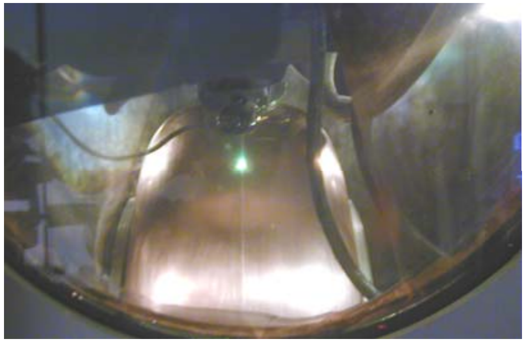


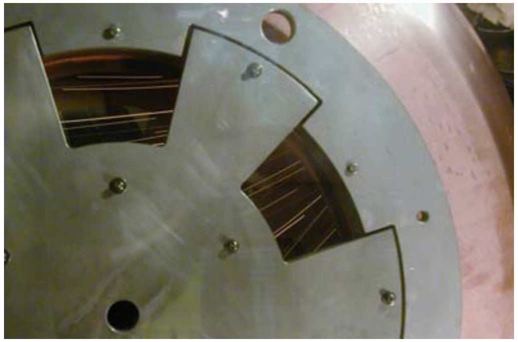
E-beam Welding of Stiffener Ring

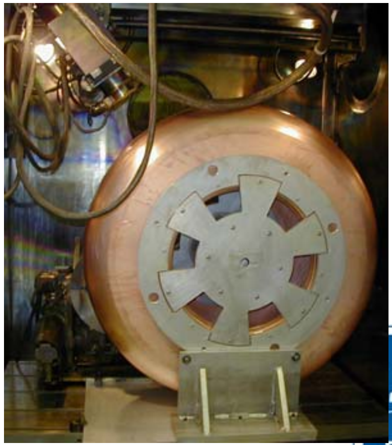
Mechanical cleaning of the cavity inner surface right after e-beam welding of the stiffener ring (above)

Cavity Equator Welding

- Cavity and fixture system is mounted and assembled on a plate and placed on the welder sliding table
- External structural weld is near full penetration and is achieved in three offset passes
- A final cosmetic/vacuum weld is performed on the inside of the joint with the cavity mounted on a horizontal rotary table

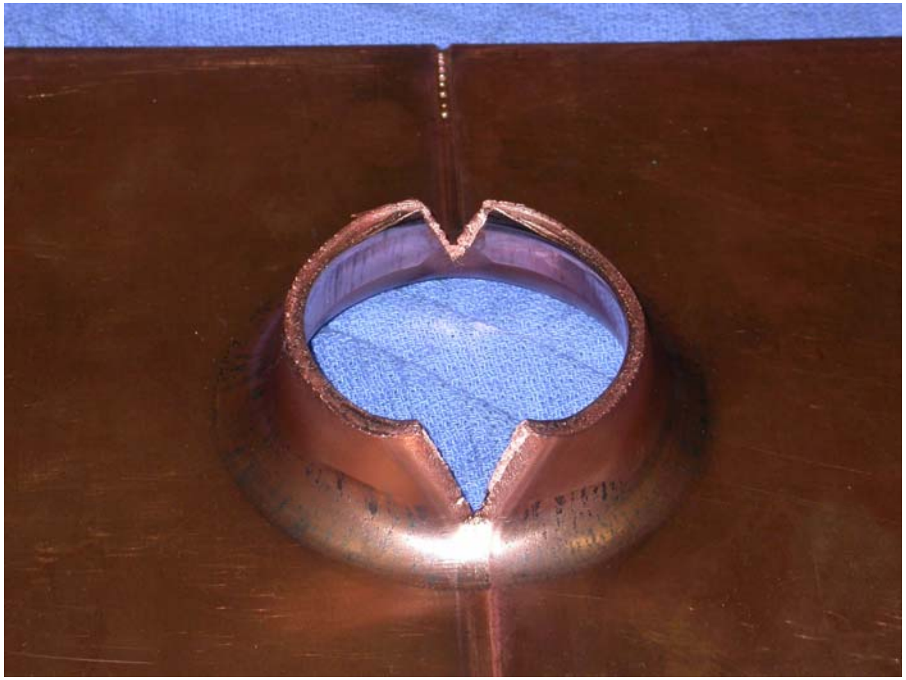






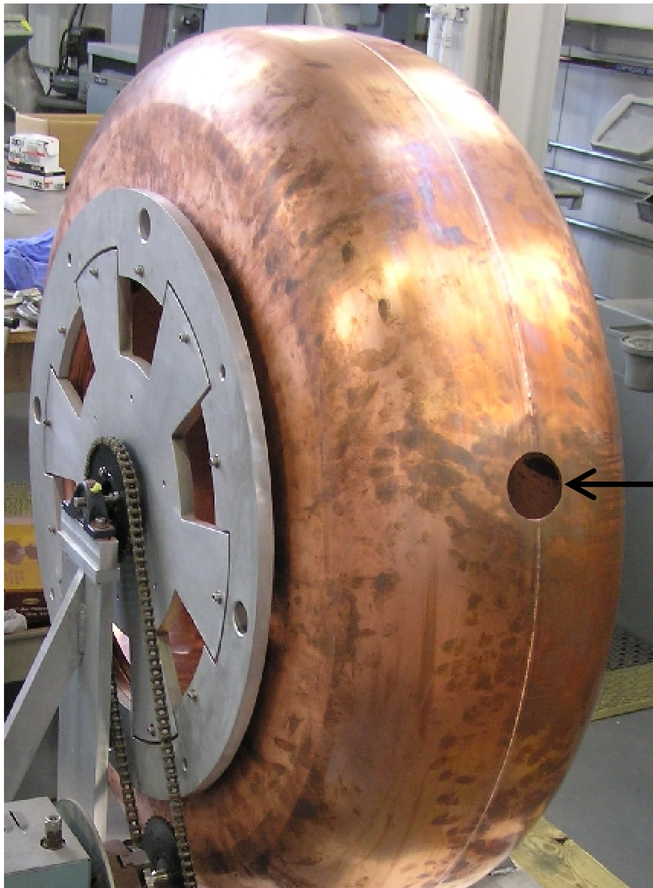
RF Port Extruding Tests at J-Lab

Extruding RF ports through e-beam joints: tests on flat copper plates going through e-beam joints



Possible improvement: Anneal around the extruding area + combination between pilot hole dimensions and lid heights, …

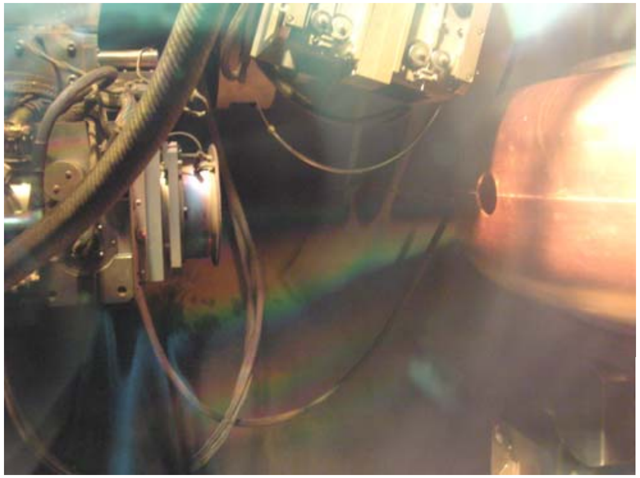
RF Ports: Extruding at J-Lab



Port extruding

We have successfully developed techniques to extrude ports across e-beam welded joints.

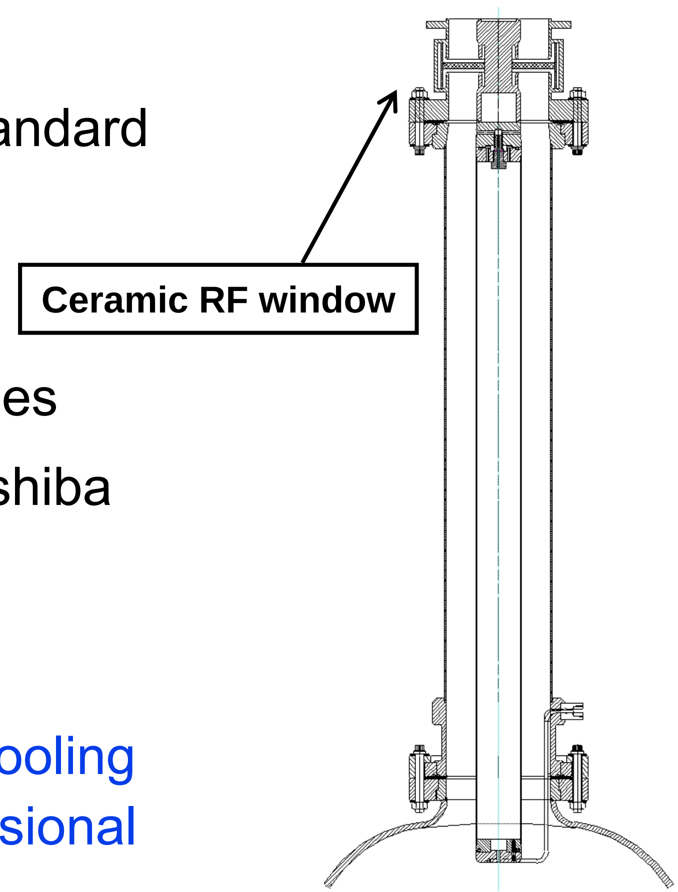
Cavity Port Forming




- Local annealing is achieved by repeatedly passing a diffuse e-beam around port
- Softening of copper must be local to preserve cavity overall strength
- Port pulling tool is used in a horizontal orientation
- A weld prep is machined into the port lip using a numerically controlled mill

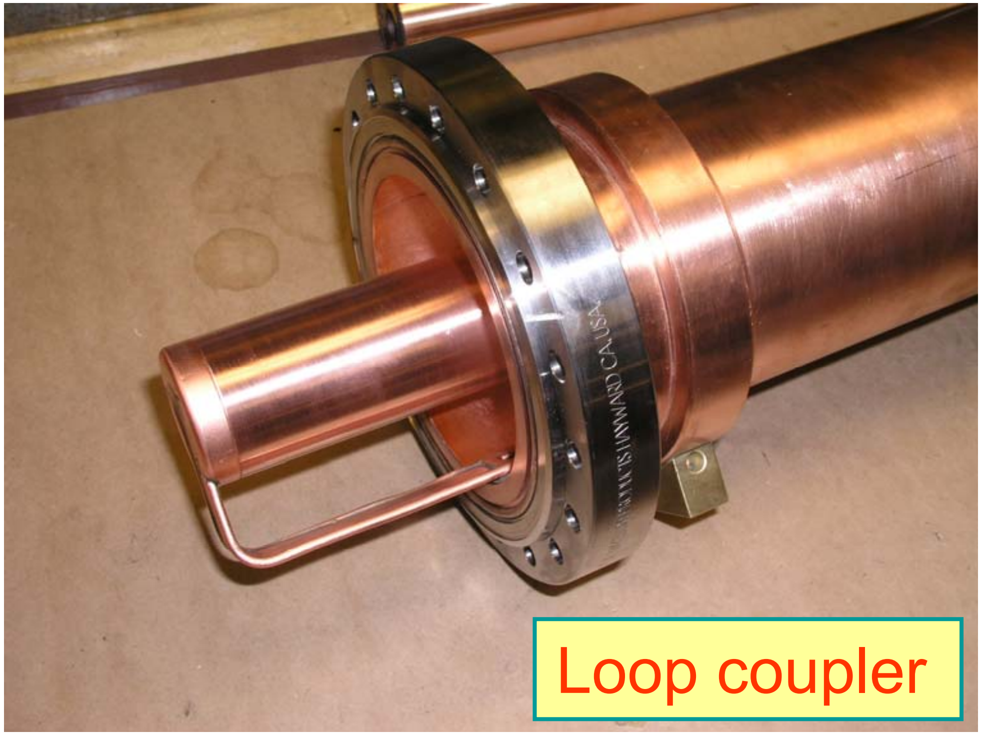
RF Coupler Design

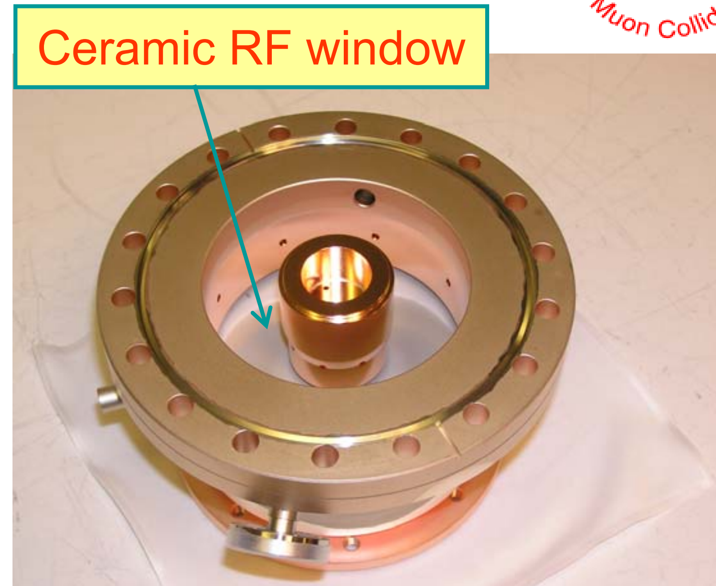
- ☐ Loop coupler at critical coupling
- ☐ Prototype coupling loop design uses standard off-the-shelf copper co-ax
- ☐ Parts were joined by torch brazing
- ☐ Coupling loop has integrated cooling lines
- ☺ Two SNS style RF windows mfg. by Toshiba received (no cost to us !)
- Two couplers with RF windows
- Bellows connection required on MICE cooling channel (Study-II) for thermal and dimensional reasons

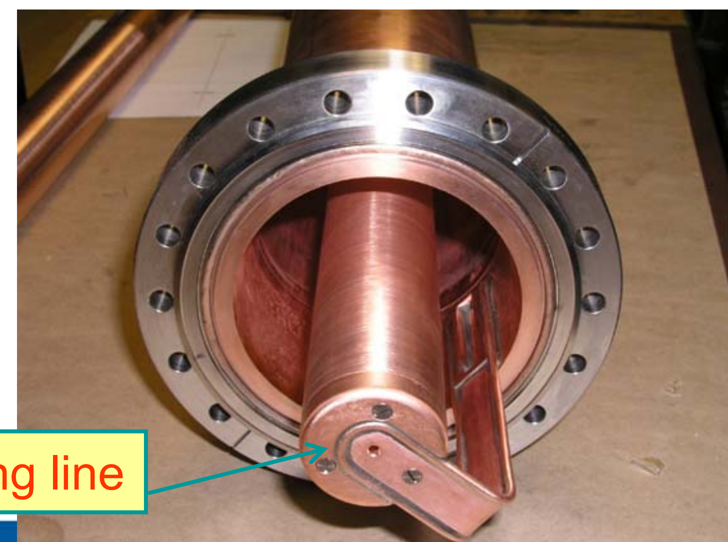


Loop Coupler Design

Fabrication of the Coupler

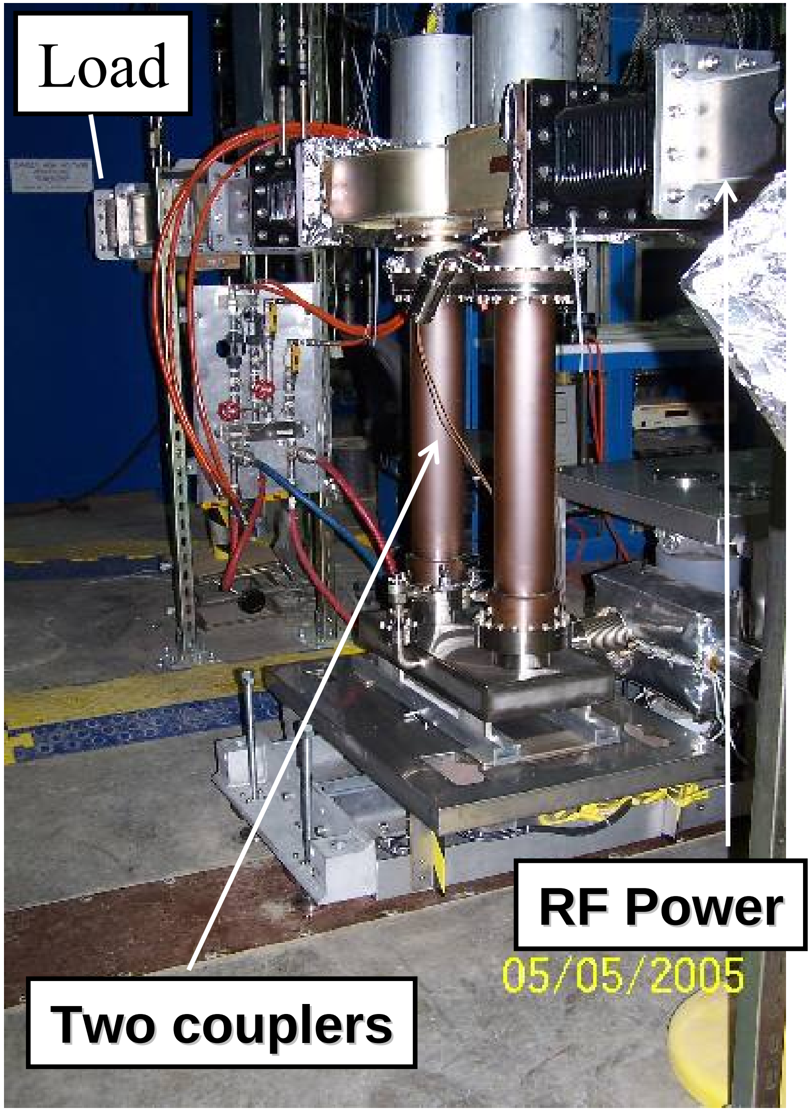






- The coupling can be adjusted by rotating the loop
- Water cooling line goes around the loop

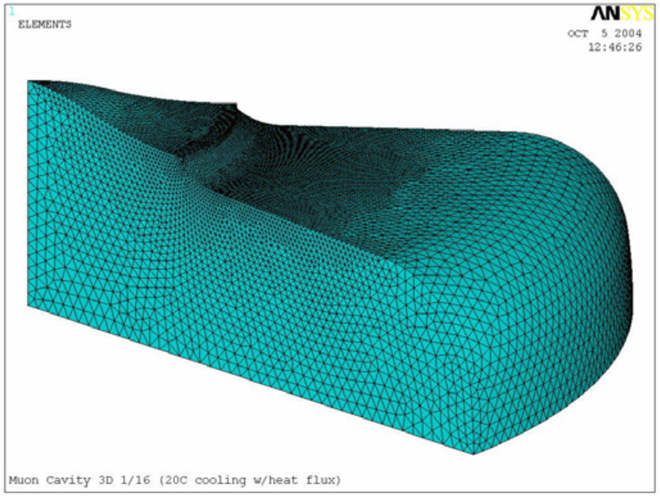
RF Coupler Conditioning

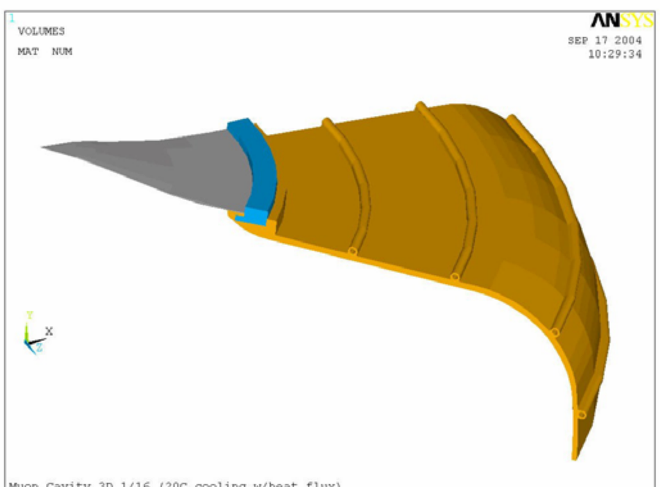


Two loop couplers

- Conditioning started during at SNS, ORNL
- Good vacuum ~ low 10^{-8} T
- Achieved 600 kW in TW mode (matched load)
- Achieved 10 kW average power (~ 9 kW for nominal NF parameters)
- Achieved 2.4 MW peak power in SW mode (at variable short positions)
- Ceramic windows work perfectly within two weeks of the conditioning

Finite Element Analysis



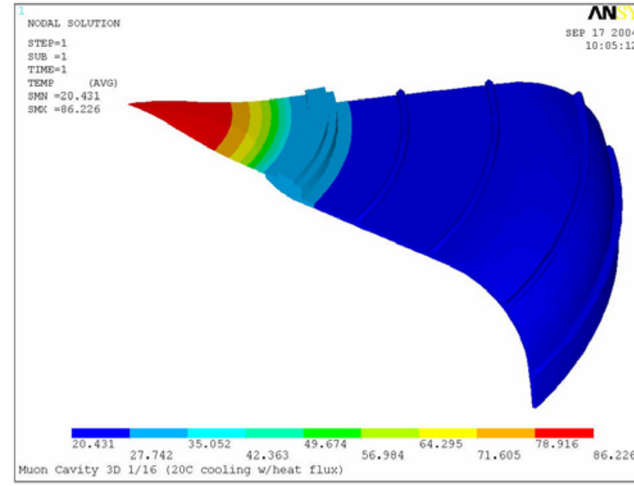


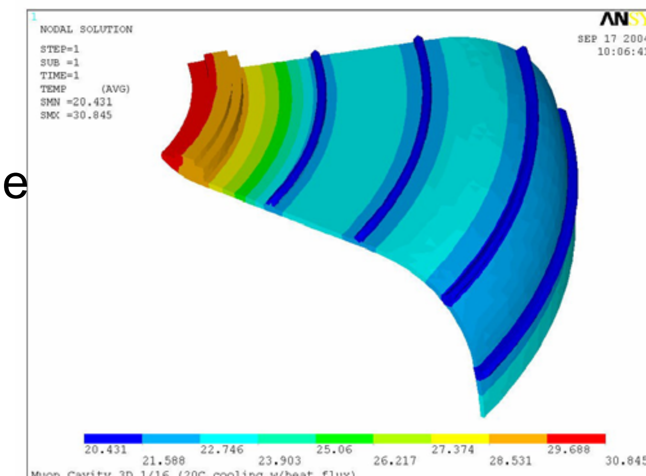
The thermal solution provides temperature distribution throughout the cavity and the beryllium window

The peak temperature occurs at the center of the beryllium window (86 ºC)

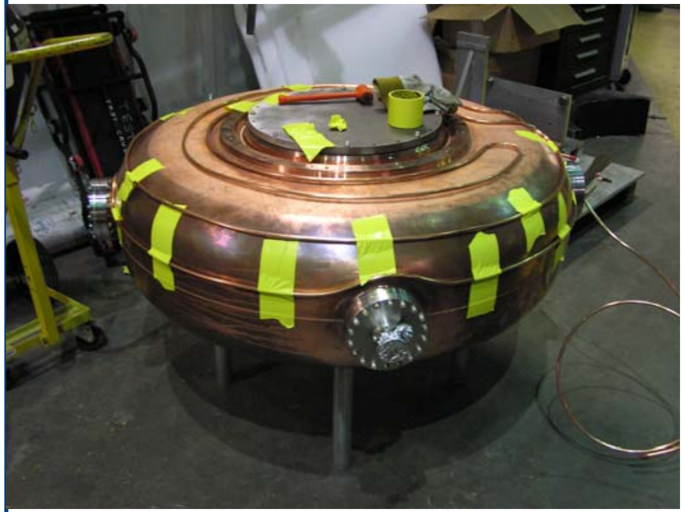
FEA helps to determine designs for:

→ Cooling tubes
→ Be window thickness





TIG Braze of Cooling Tubes



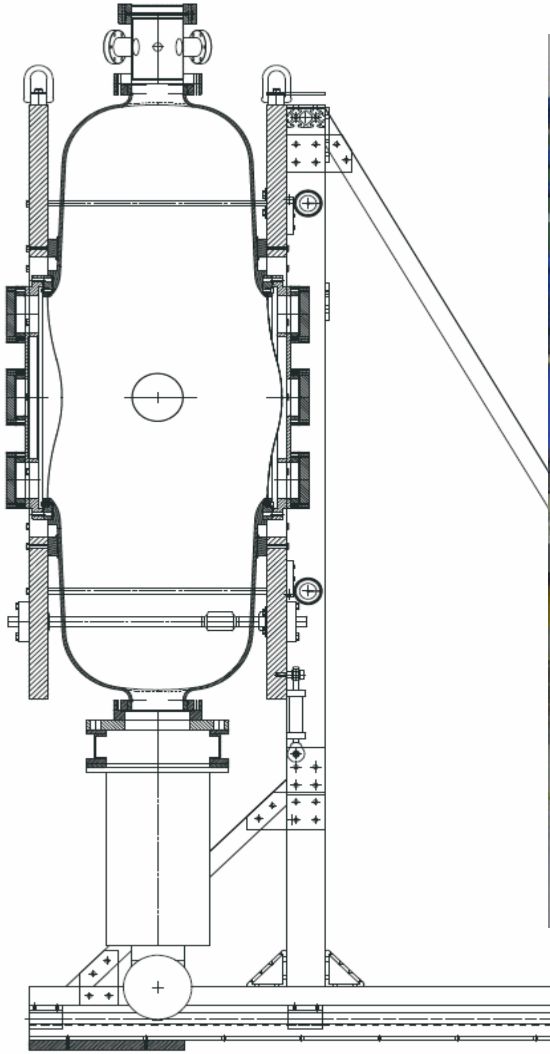
Requirement:

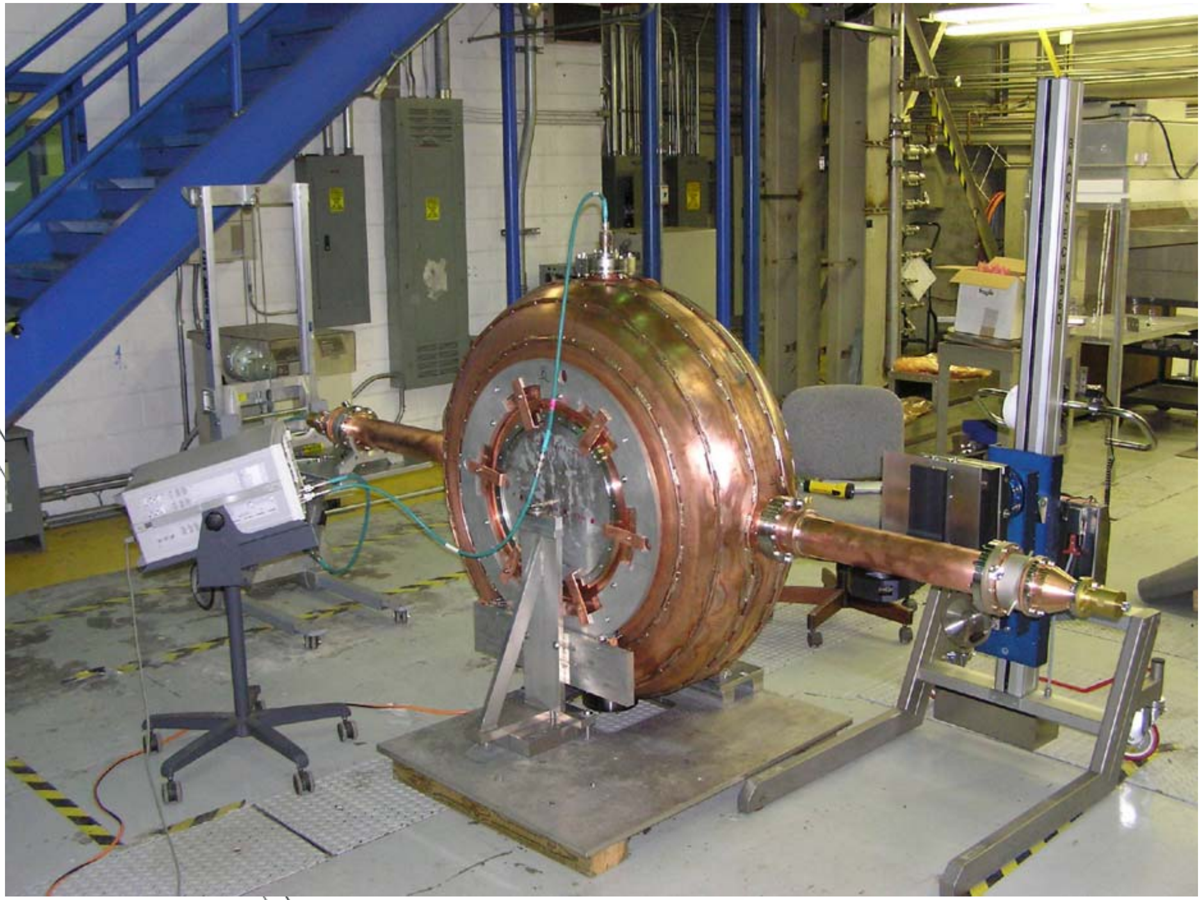
- Good thermal conduction
- No distortion on the cavity body
- Welding material
- Welding speed and temperature

We have developed the technique and achieved the design goal

Silicon-Bronze with helium gas torch + argon gas flowing in the cooling tubes

Cavity & Supporting Structure





First measurement: f ~ 199.5 MHz with β_C (max) ~ 5

Final Interior Buffing

- Final interior buffing of cavity is performed to ensure the surfaces are ready for electropolishing
- Less buffing needed near equator where fields are lower
- An automated process of buffing was developed using a rotary buffing wheel and a cavity rotation fixture
- Some local hand work required to clean up some areas
- A series of pads with graduated coarseness was used
- Goal was scratch depth shallow enough for EP removal

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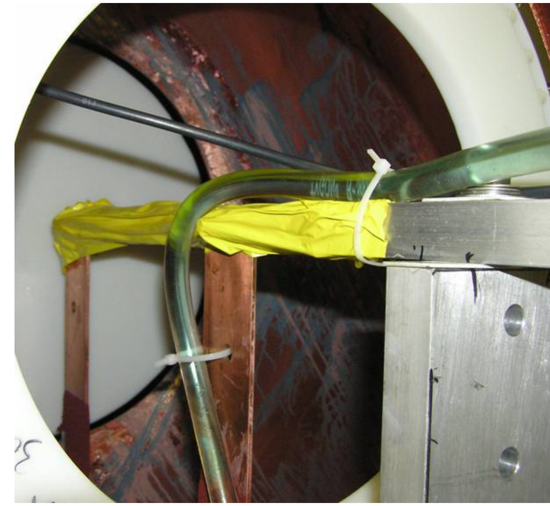
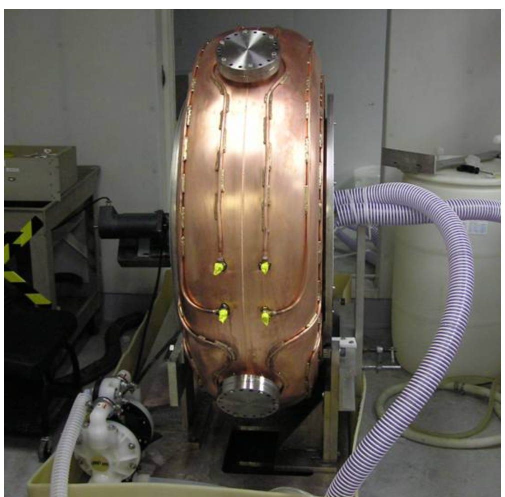
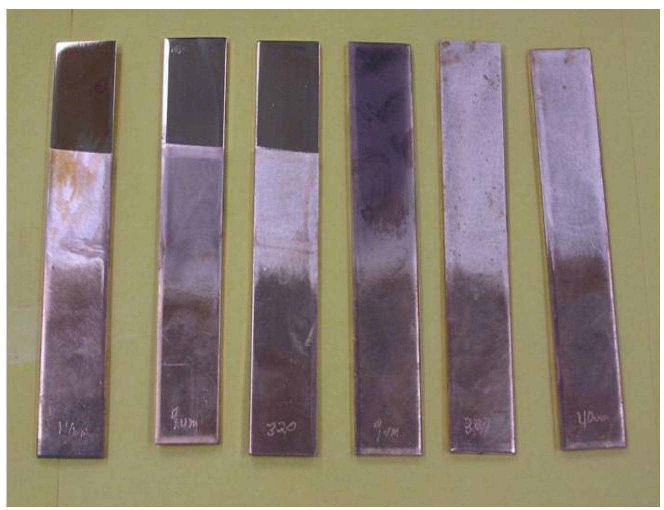
Interior Surface Electropolish

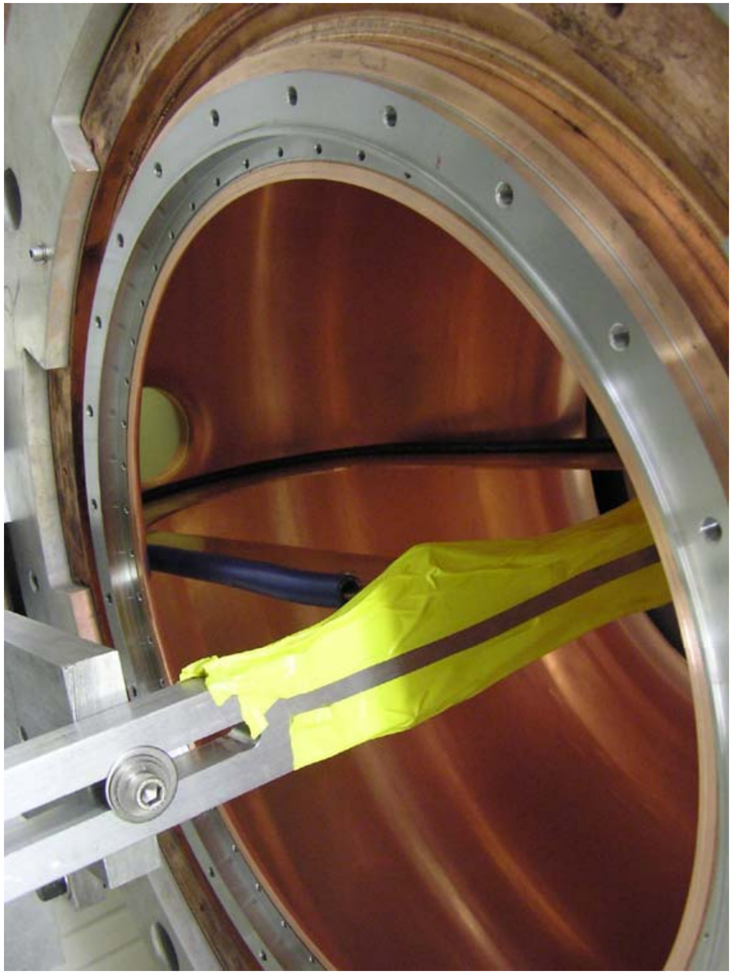
- After buffing, cavity underwent a chemical cleaning process
- Test bars with various degrees of buffing were run through an electropolish process
- Cavity was rotated with a U-shaped electrode fixed in place
- Initial polish failed due to depletion of the solution, and rebuffing was required
- 2nd EP successfully removed scratches in high field regions
- Final process is a high pressure water rinse of cavity surface







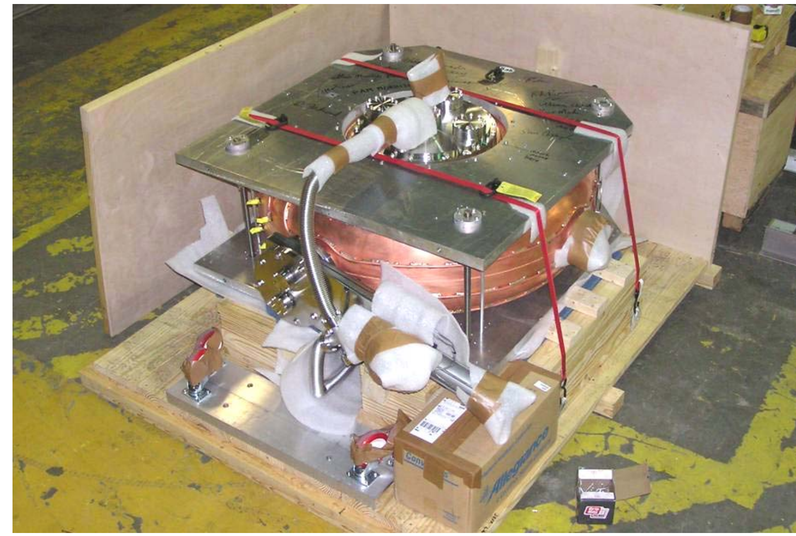
Electro-polishing (EP) Setup

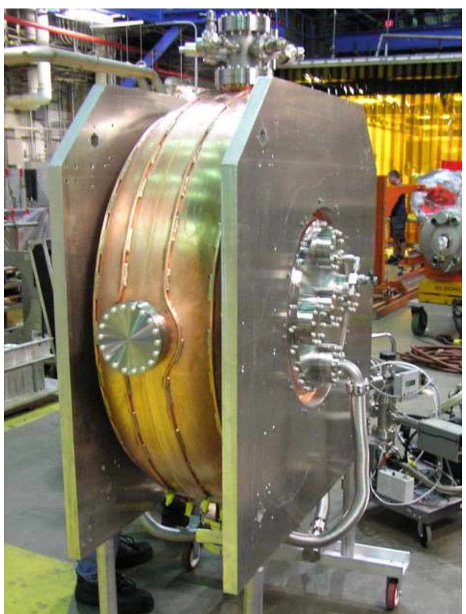


EP setup and the U-shape electrode for EP at J-Lab

Shipment to the MTA at FNAL

- System assembly included: tuner plates, port blank-offs, diagnostic spool, window cover plates, gate valve and window pump-out tubes
- Final leak check conducted prior to shipping
- Cavity was back-filled with nitrogen in its assembled state and packaged in a custom made crate for shipping to the MTA

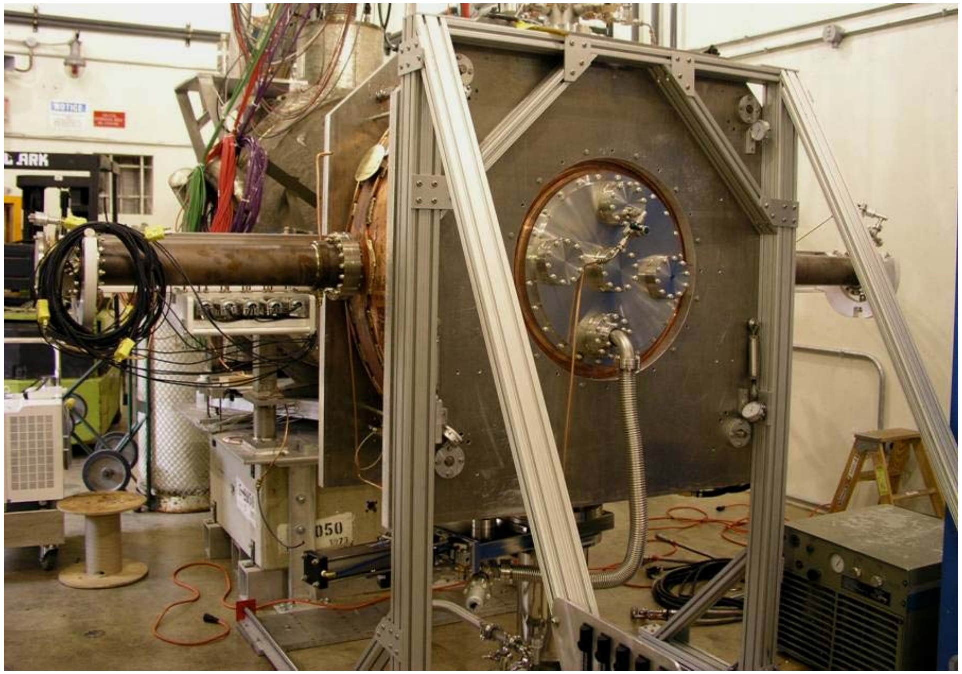





Couplers

Final Assembly & Measurement at MTA

- Cavity assembly was mounted on the support and couplers were installed in a portable clean room
- Dummy copper windows (flat) are used initially
- Couplers were set and frequency was measured
- Bakeout system hardware was installed
- System is leak tight



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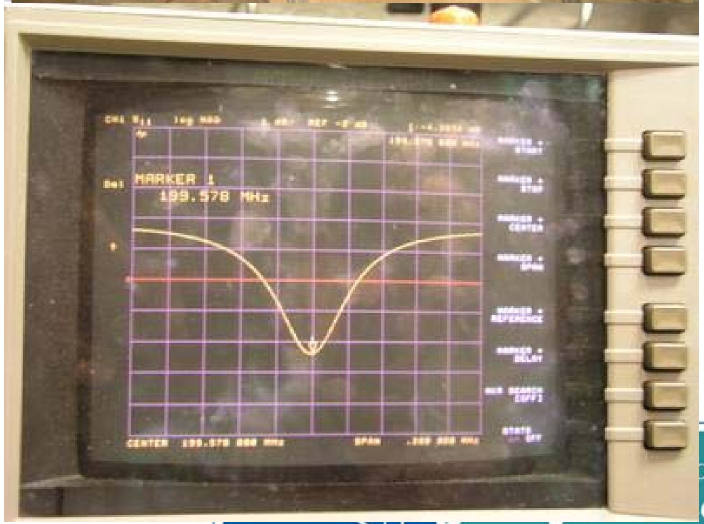
Low Power Measurements

f **= 199.578 MHz**

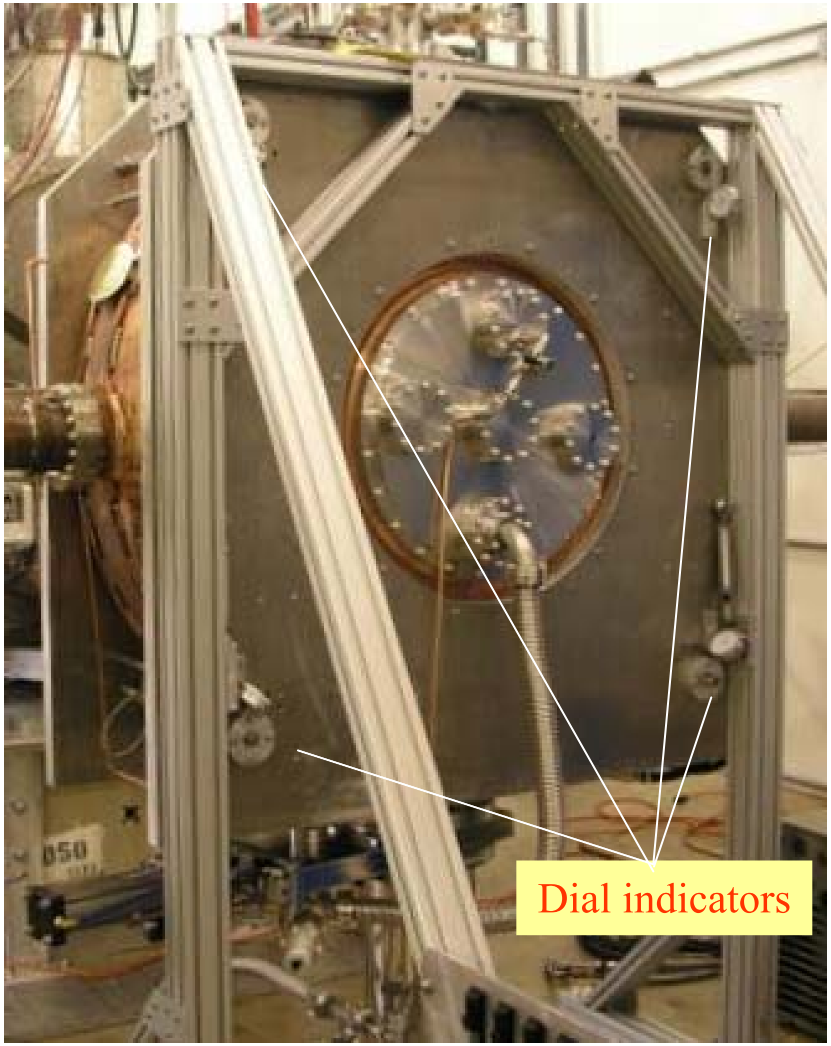
Q_0 **= 49,000 ~ 51,000 (better than 90 % of the design value)**

Two couplers

- **balanced**
- **coupling adjustments**

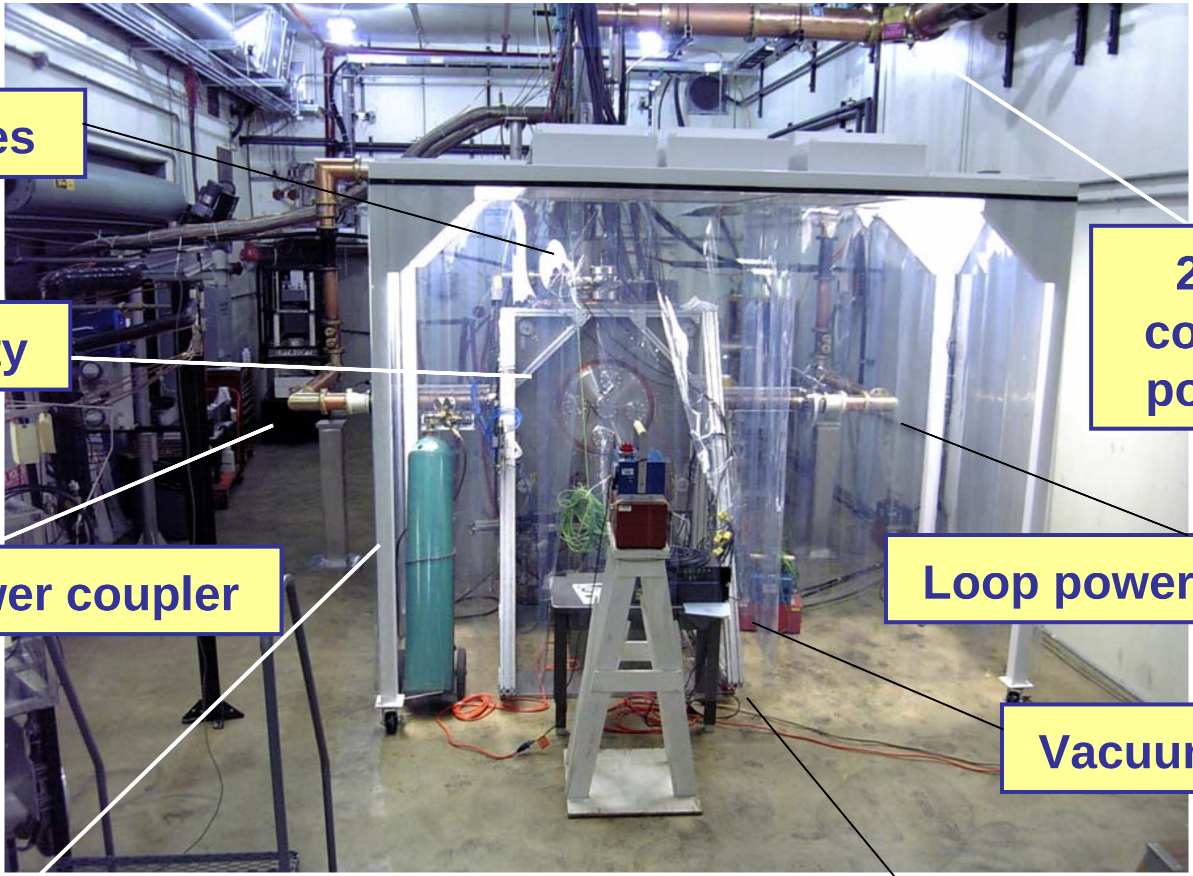


Tuner Measurements



- Mechanical tuning plates at four locations
- Dial indicators to measure displacement between Al plates
- Tuning measurement in air
  - Equivalent to MICE cavity under vacuum
- Adjusted up to 2-mm with 8 steps of 0.25-mm each
- Measured tuner sensitivity
  - ~ 78 kHz/mm
- Calculated tuner sensitivity
  - 115 kHz/mm
  - Disagreements are due to deflection of the Al plates

High Power Test Setup at MTA



RF probes

The cavity

Loop power coupler

Portable clean room

201 MHz coaxial RF power line

Loop power coupler

Vacuum pump

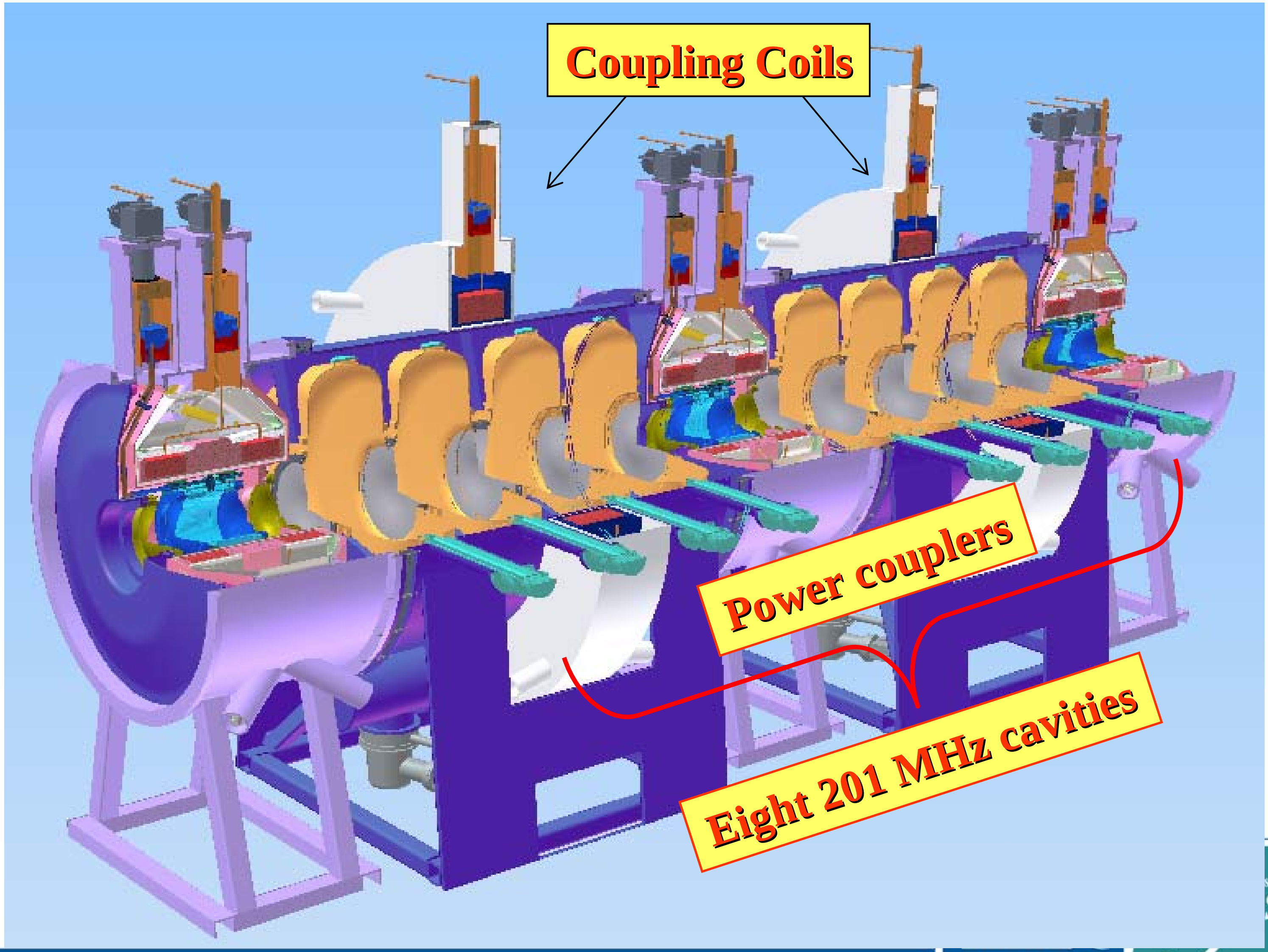
Movable cavity support

High Power Test Results

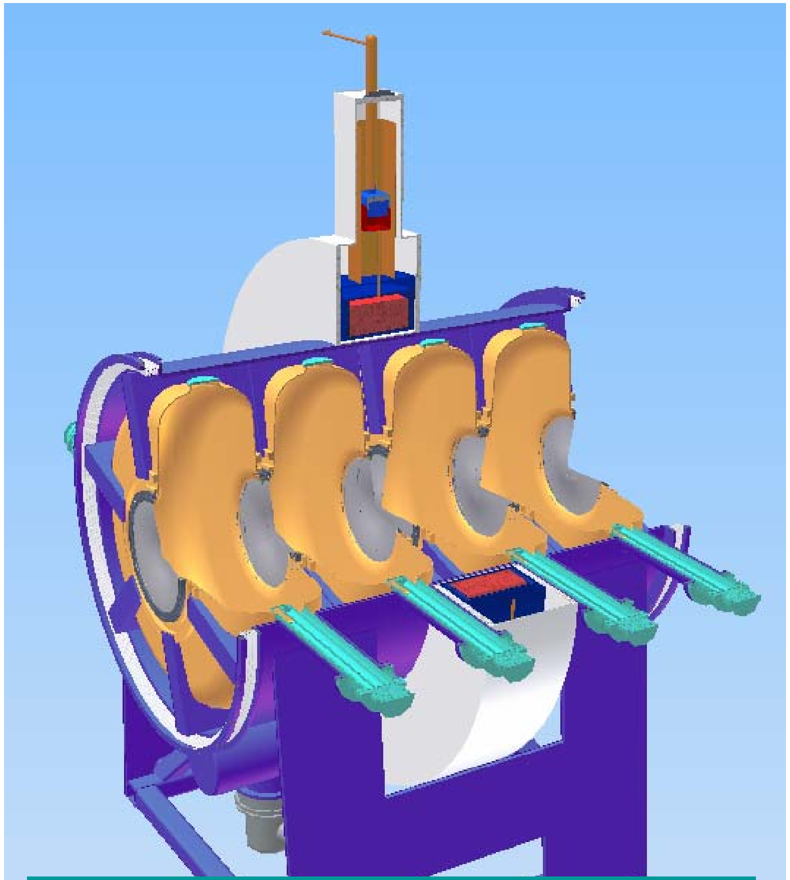
- **Conditioning started late Feb. 2006 with**
  - Flat copper windows (plates) with Ti-N coatings
  - RF diagnostics
  - Good vacuum ~ high 10^{-9} Torr
- **Without external magnetic field, the cavity conditioned very quietly and quickly to reach**

  ~ 16 MV/m
- **Gradient limited by available RF power of 4.2 MW, could not go higher**
- **Curved Be windows will be installed for future tests**

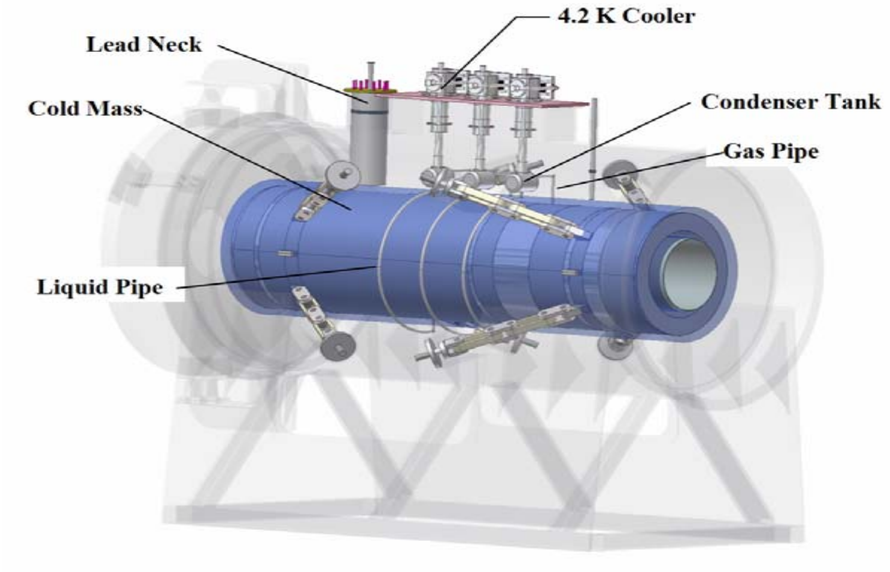
MICE Cooling Channel



RFCC Module and Spectrometer Solenoid



Three quarter section of 3-D view of the RFCC module



- RFCC is US MICE deliverable
- Spectrometer solenoid
  - Purchased superconducting materials
  - Bids for RFP returned May 15, 2006
  - Vendor selection by mid-June-2006

Summary

- **NFMCC has continued to make good technical progress in R&D for intense muon beam accelerator**
- **R&D Programs**
  - RF cavity R&D
  - Be window R&D
  - SC magnets and system integration
- **Experimental studies at 805 MHz using the pillbox cavity are being conducting now at MTA**
- **The 201 MHz test cavity fabrication completed; tests will continue**
  - **Reached 16 MV/m quickly without magnetic field**
- **Continue to develop and test hardware for μCOOL and MICE**

Thank you !