Design and fabrication of RF cavities for muon cooling

Tianhuan Luo

Accelerator Technology and Applied Physics Division, LBNL

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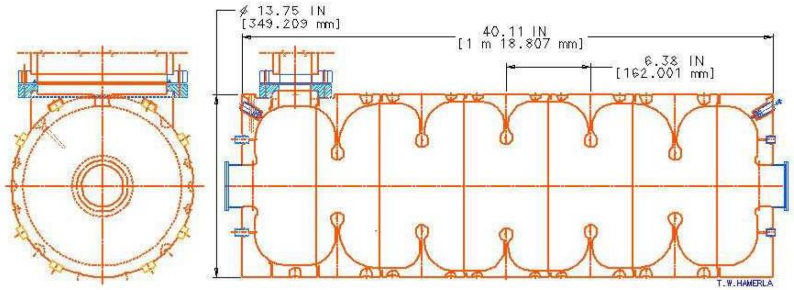
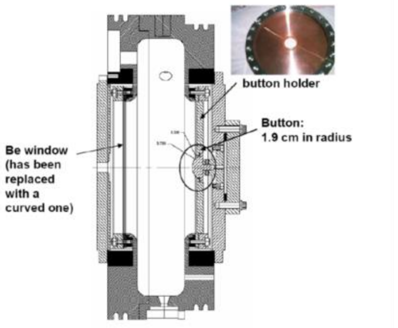
Several NC RF cavities have been designed and built to study the RF breakdown in multi-Tesla environment and its mitigation to achieve stable operation at required accelerating fields in US MuCool and MAP R&D

805 MHz iris loaded cavity with a beam envelope matched aperture.

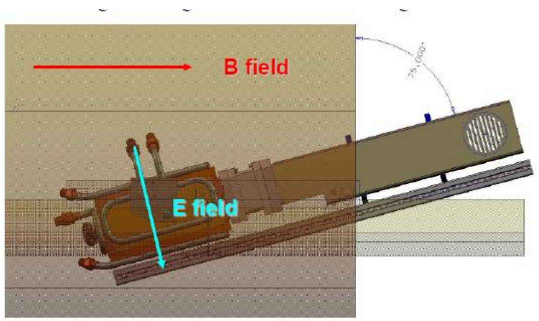


805 MHz Cavity Button test



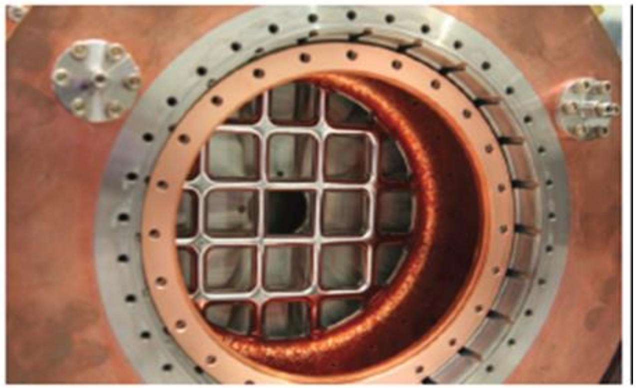
To find materials and coatings that can withstand high surface electric field in strong magnetic field.

805 MHz Box cavity



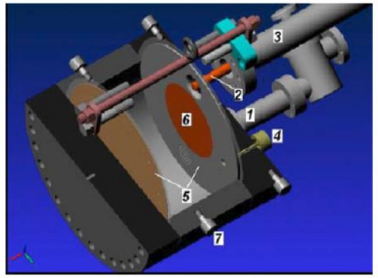
To study the breakdown mechanism with adjustable angle between E, B field directions

805 MHz Cavity with grid windows



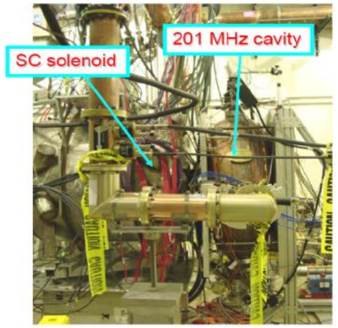
Alternative to the fully covered Be windows

805 MHz all-season cavity



A versatile cavity for both vacuum and high-pressure test.

201 MHz prototype cavity

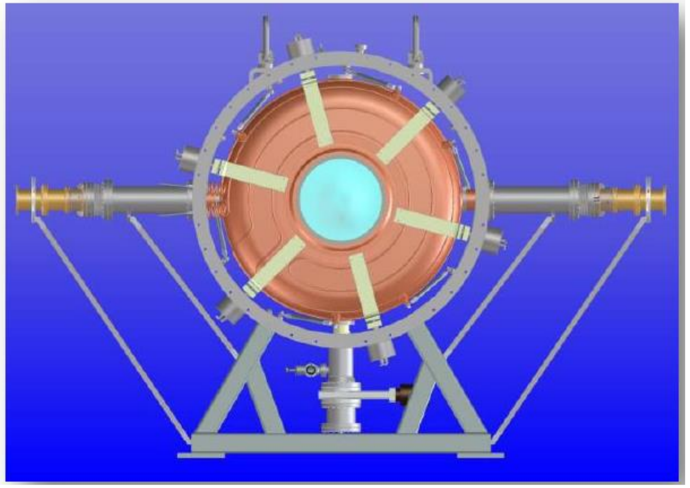


201 MHz Normal Conducting RF Cavity for MICE

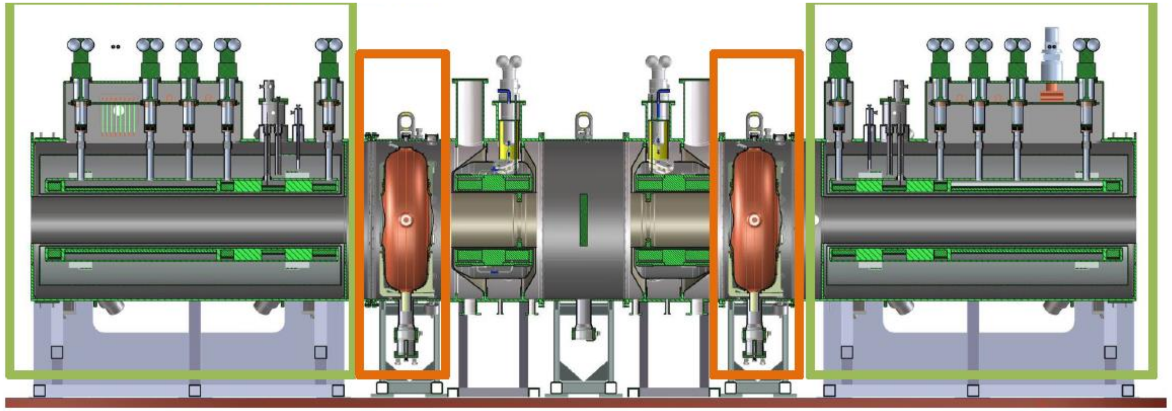
- Muon Ionization Cooling Experiment at RAL UK aims to demonstrate the ionization cooling experimentally.
- 201 MHz cavity in MICE to replenish the energy loss in absorber.

Cavity length	430	mm
Cavity inner radius	610	mm
Cavity body thickness	6	mm
Be window diameter	420	mm
Be window thickness	0.38	mm
Cavity shunt impedance	22	MΩ/m
Cavity quality factor Q_0	53,000	

- MICE cavity is based on the R&D of US MuCool cavity.
- Original MICE includes 2 RFCC module, each including 4 cavities.
- Re-baselined MICE includes 2 single cavity module, as shown below.
- Due to limited resources and tight schedule, MICE eventually didn't include RF. Nevertheless the design, production and test of MICE cavity provide valuable experience for future cavity development.



f0 (MHz)	E_peak	P_peak	Pulse length	Duty factor	B (on axis)
201.25	10.3 MV/m	2 MW	1.0 ms	0.1%	~ 1 T



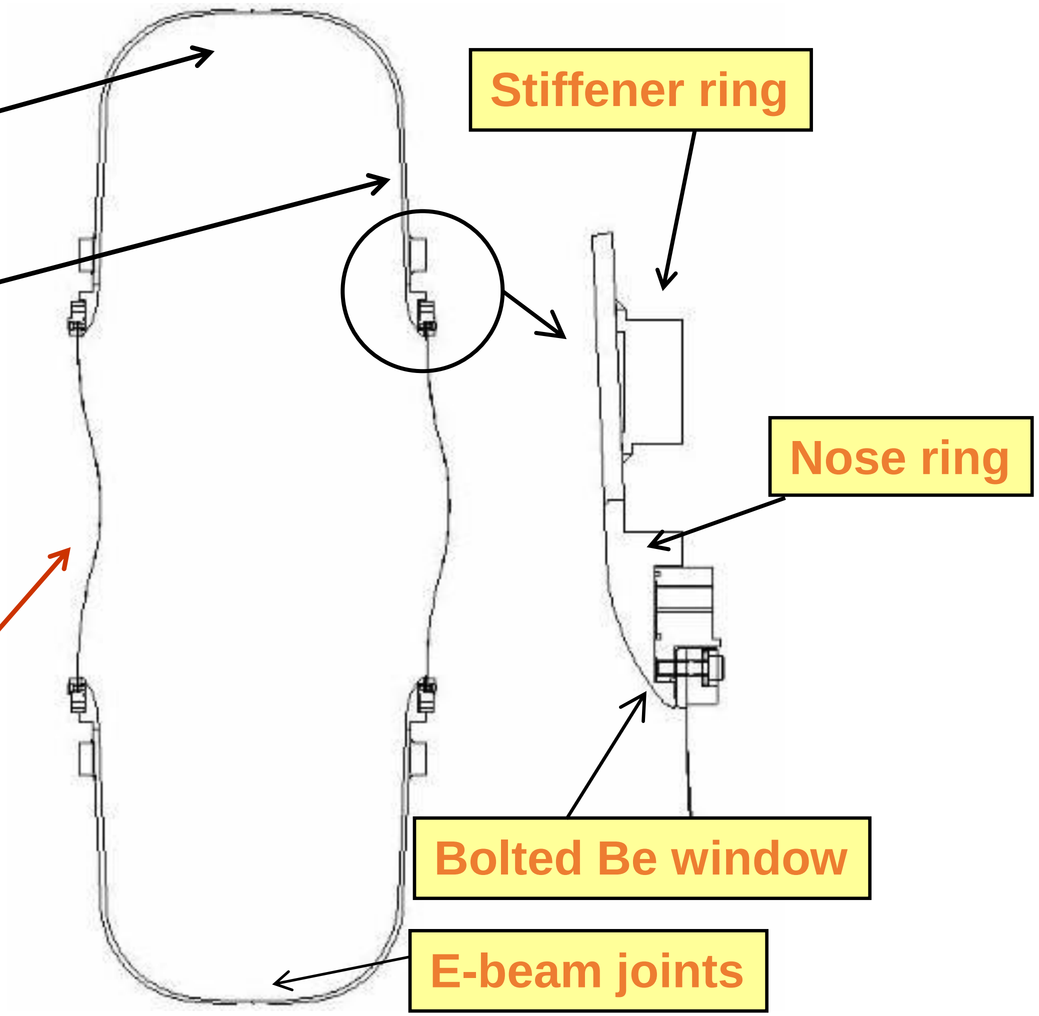
Cavity body design overview

Spherical section at the equator to ease addition of ports ($\pm \sim 6^{o}$)
Elliptical-like (two circles) nose to reduce peak surface field

2^{o} tilt angle to avoid multipacting

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

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

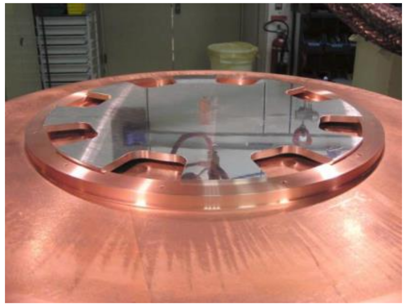


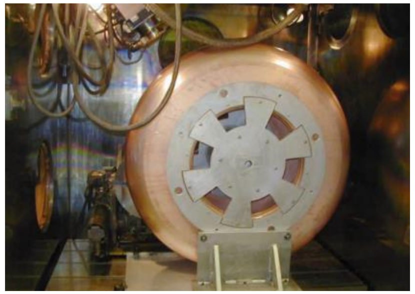
Low peak surface field, MP suppression and easy fabrication

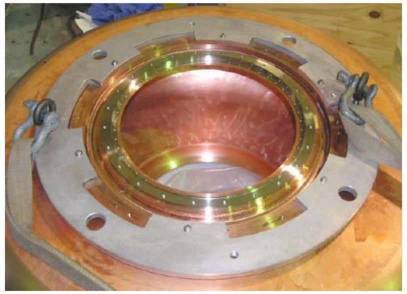
Several novel fabrication methods offer significant cost savings

- The cavity body is made from two half-shells that were fabricated from flat plates by metal spinning.
- Each half shell has a stiff tuner ring attached by e-beam welding before the cavity halves are joined together. This ring is initially used for handling and as a datum and will later be used as the mounting point for the tuner mechanism.
- The center of the shell is cut out for the later installation of the “nose ring” (similar to the nose-cones in a conventional cavity, though there are none in this case).
- The equator weld consists of a full penetration weld from the outside and a cosmetic pass on the inside to leave a smooth surface.
- Next, the nose rings were joined to the cavity with a similar two-sided weld. All of the e-beam weld parameters were developed through sub-scale testing.
- The cavity ports were pulled or extruded directly out of the cavity body. The port flanges are joined to the cavity by copper to copper e-beam welds.


Spun cavity half-shell


Stiff ring ready for e-beam welding


Outer equator weld in the JLab e-beam welder


Nose ring welding

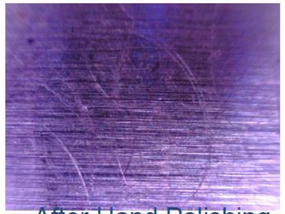

Cavity port extrusion

Smooth surface to suppress field emission

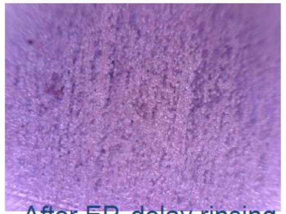
- Previous RF breakdown studies indicate the importance of the surface smoothness for lowering the field emission.
- For MICE cavity, we carried out an SRF-type polishing procedure to smooth the cavity surface thus to suppress the field emission: mechanical polishing -> pre-cleaning -> electropolishing -> bright wipe.
- Mirror-like smoothness is achieved after the polishing procedure.
- High pressure rinsing at Fermilab before installation.

Electropolishing at LBL

Coupon test at different polishing steps



After Hand Polishing



After EP, delay rinsing

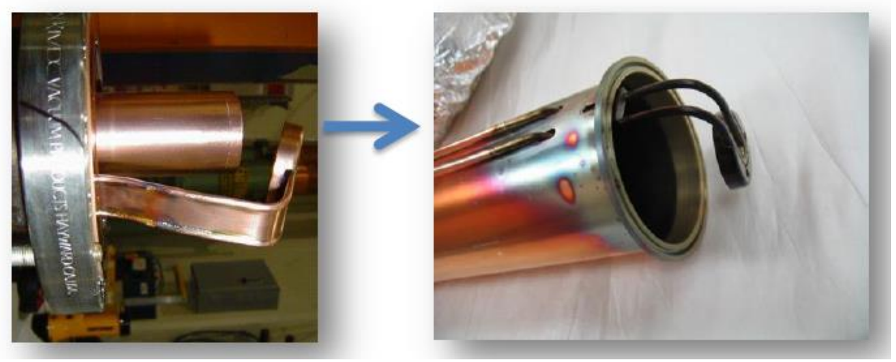
After bright wipe

Mirror-like cavity surface after polishing

Geometry design and TiN coating to suppress MP

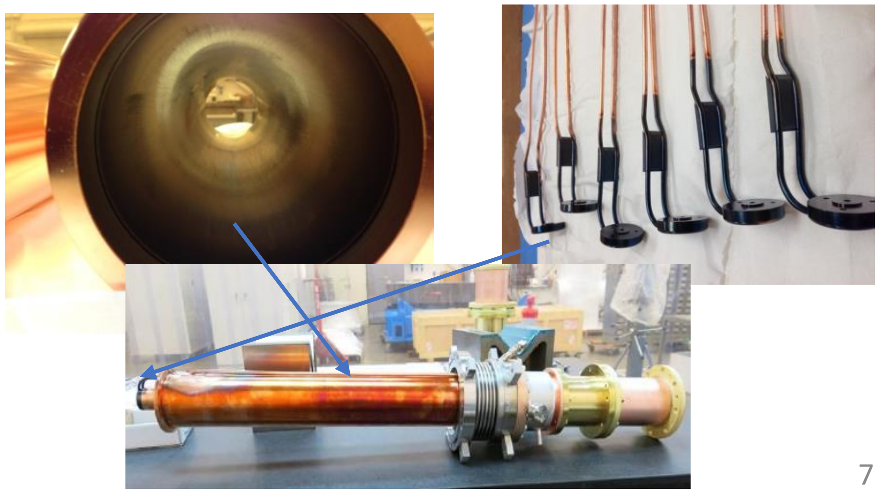
- Even though MICE is operated with pulsed mode, its 1ms pulse length is long and considerable MP can build up. Also its Q is quite high -> relatively slow rise/fall time.
- External magnetic field complicates the MP situation.
- The cavity body design avoids parallel planes which can lead to hazardous MP.
- The MP simulation shows MP patterns in the coaxial waveguide and the loop coupler especially at the lower power range. To mitigate:
  - Remove the strip at the loop coupler.
  - TiN-coat the waveguide outer tube and the loop coupler.

Modification of the loop coupler

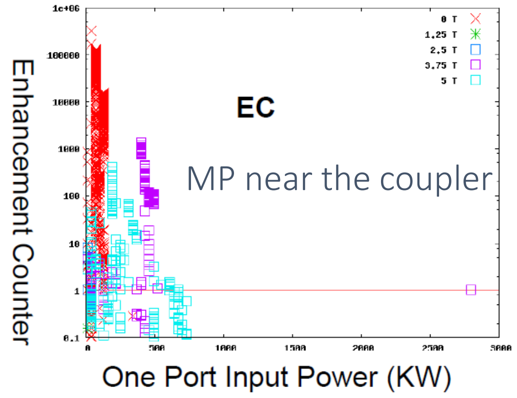


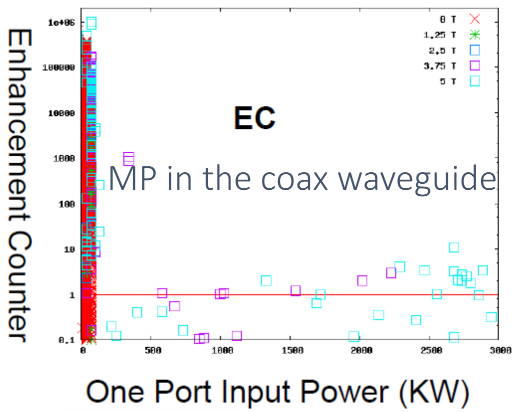
Simulation shows removing the strip doesn't affect the coupling angle much.

TiN coating with PVD at LBNL



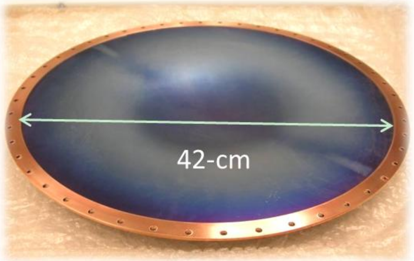
MP simulation with Track3P with background solenoid field strength





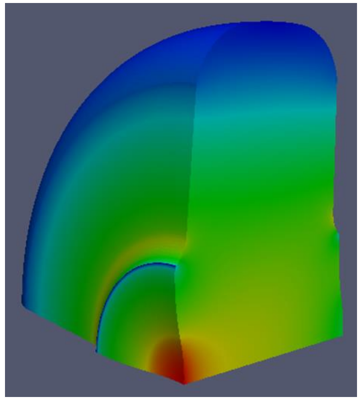
Be windows to enhance cavity acceleration efficiency

- Be windows to cover the cavity irises to significantly increase the cavity shunt impedance.
- Advantages of Be: low thermal stress for a given temperature gradient, lower density (less material and less scattering), mechanically stiff and relatively low cost of manufacture.
- Be windows have to be thin (0.38mm for MICE cavity), to minimize the interaction with muon beam.
  - Thin window -> small thermal conduction & small mechanical rigidity.
- Double curvature profile to lower thermal stress and to control the thermal expansion direction of the window.
  - Unsymmetric Ez field along the central axis, field enhancement on the convex window.
  - Uneven heating on the two windows -> uneven distortion -> frequency drift.
- Lorentz force detuning: not a concern for MICE operation but could become significant for thinner Be windows or higher operation E field.

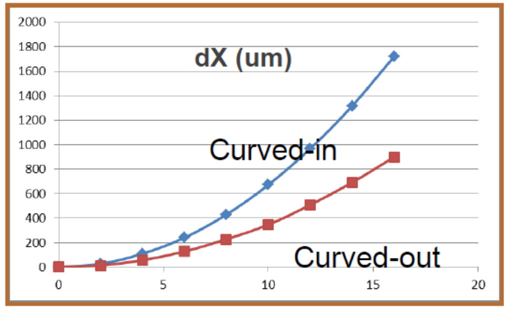


The windows are hot formed into the curved shape from flat Be foil. A 30 nm TiN coating is deposited on the Be surfaces.

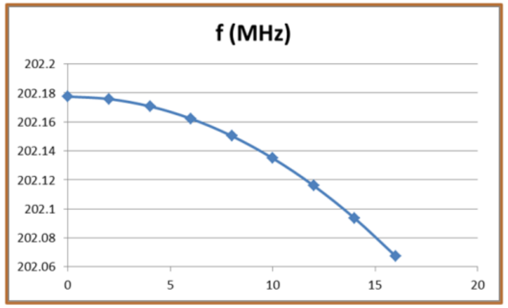
E field



Displacement at the center of Be windows and the frequency drift due to thermal expansion

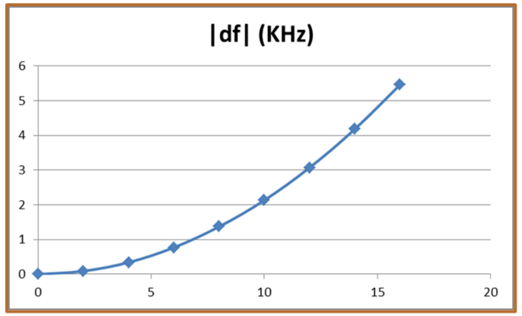


E_eff (MV/m)



E_eff (MV/m)

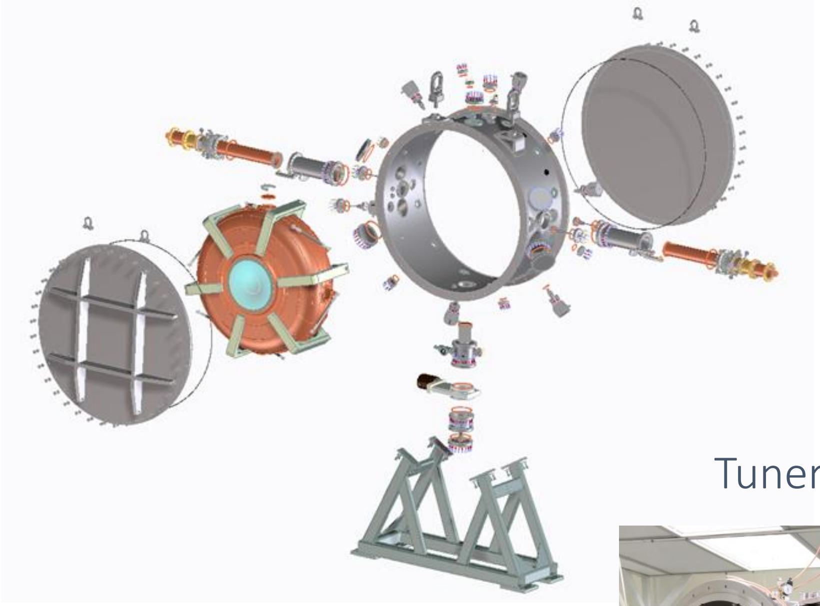
LFD



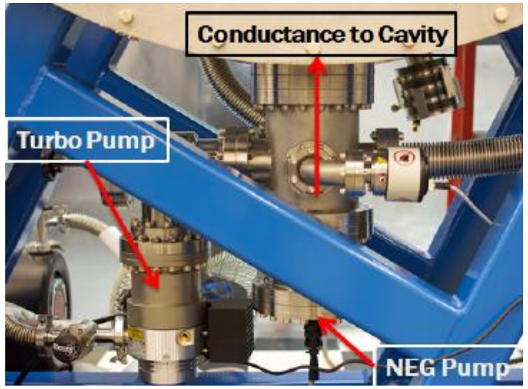
E_eff (MV/m)

Vacuum and frequency tuning

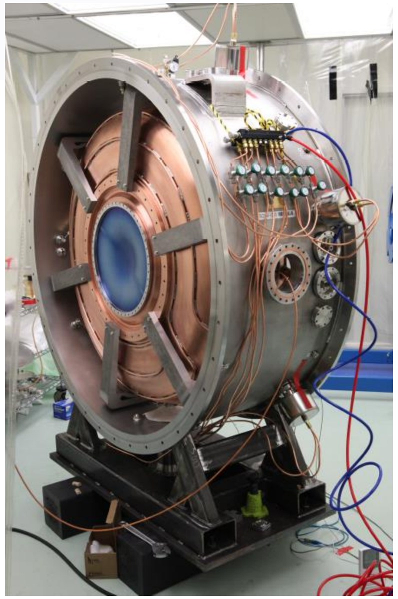
- The cavity is enclosed in a vacuum environment. Target vacuum is 10e-8 Torr for the cavity and 10e-6 Torr for the vessel.
  - •Two separated vacuum volumes with limited conductance between them.
  - •A differential pressure box was designed and constructed to protect the beryllium window during pump-down, vent, and possible system failure.
- The frequency is tuned by six tuner arms around the cavity body, each squeezed by a pressurized actuator to deform the cavity shape.
  - •Tuning system can achieve a frequency tuning range of +/- 200 kHz at least.
  - •The actuator has passed the functional test and the lifetime test.
  - •The tuning system has been validated in high power cavity operation.



Vacuum test

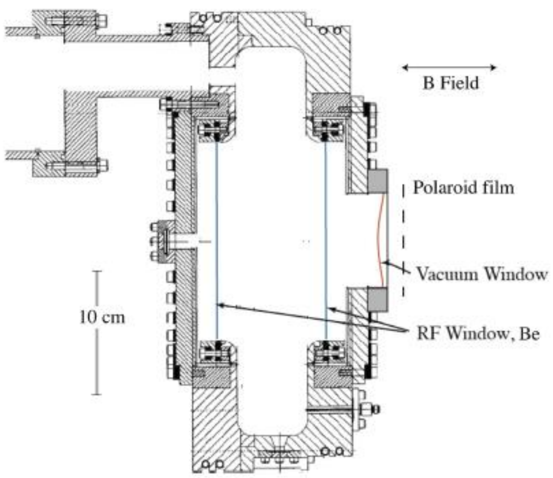


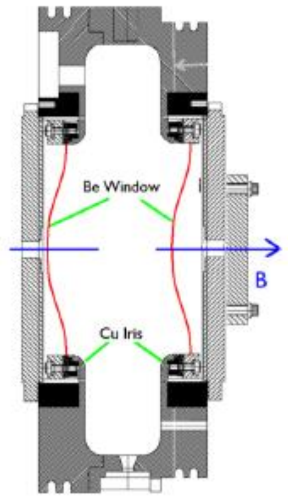
Tuner test

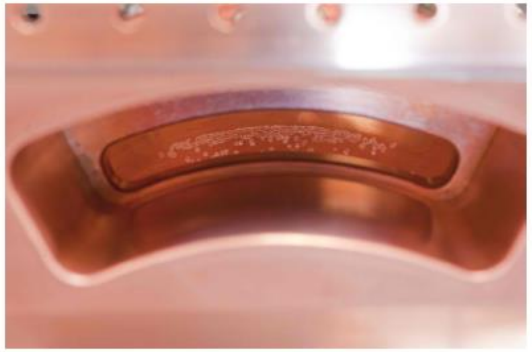


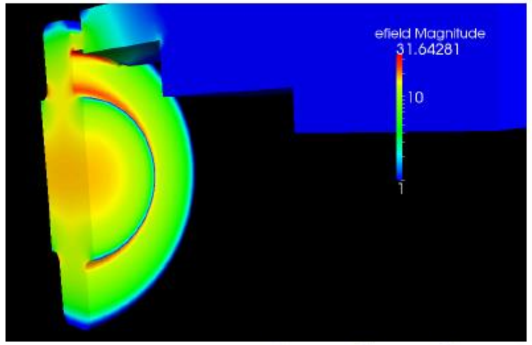
Previous 805 MHz modular cavity

805 MHz LBL cavity with demountable windows









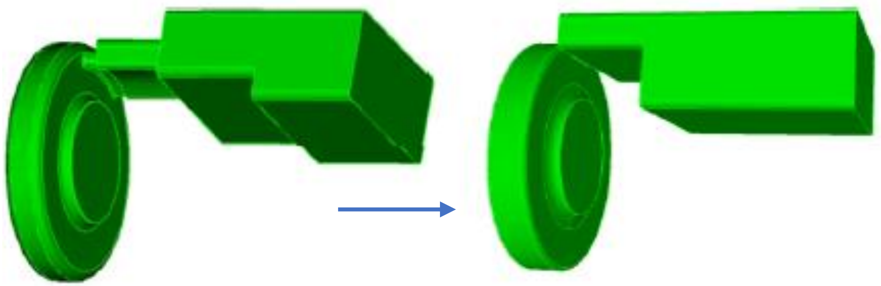
Left: surface damage near coupler iris;
Right: E field strength map.

Previous 805 MHz cavity with demountable windows:

- Coupling from the cavity sidewall: strong field enhancement at the coupler iris;
- window covers the sidewall partially, strong field enhancement around the window opening.

Both fields are higher than the E field at the window center, thus complicating the interpretation of the RF breakdown data.

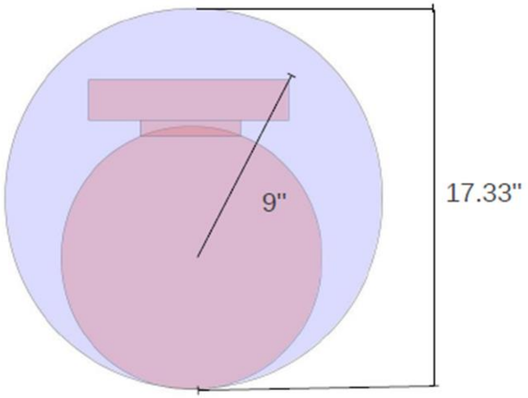
Optimizing the shape of the coupling slots and the window opening corner can reduce their local fields significantly, but still comparable to the center E-field.



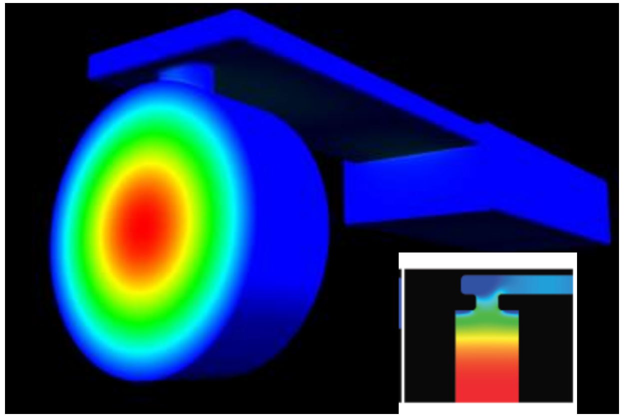
This study also shows the coupler E field decreases as the coupling slot is moved towards the edge.

MAP 805 MHz modular design

- Moving the coupler to the equator.
  - The E field at coupler slot is reduced to less than 1/5th of the center E field.
  - Also enabling the window to cover the whole side, thus eliminating the field enhancement at the window mounting iris.
  - Fitting into the tight space of MTA Lab-G magnet: cavity center and solenoid field center are slightly off; narrow waveguide in magnet and transition to WR975 outside Lab-G mag.
- Modularized components.
  - Demountable end plates to study different materials, surface treatments, etc. Cu and Be endplates have been tested and studied. Easy for inspection.
  - Replaceable central torus to study the effect of transit time and stored energy with different cavity lengths.



Evaluating the clearance in the early design phase.



E field magnitude map

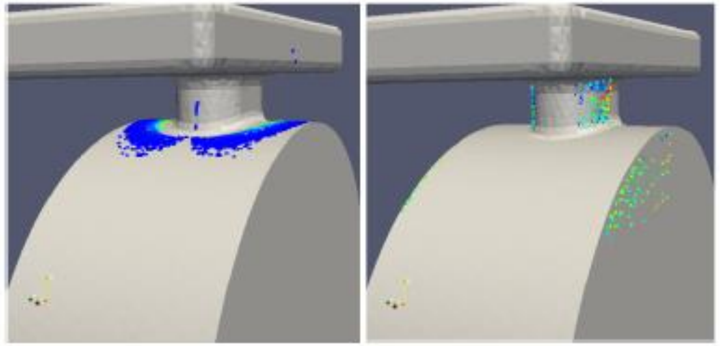
Parameter	Value	Units
Frequency	805.0	MHz
Radius	142.25	mm
Length	104.4	mm
Q_0	20500	
Q_{ext}	15600	
Coupling coefficient, β	1.3	
Field ratio	5.4	

for Be endplates (Q_0, Q_{ext}, β)

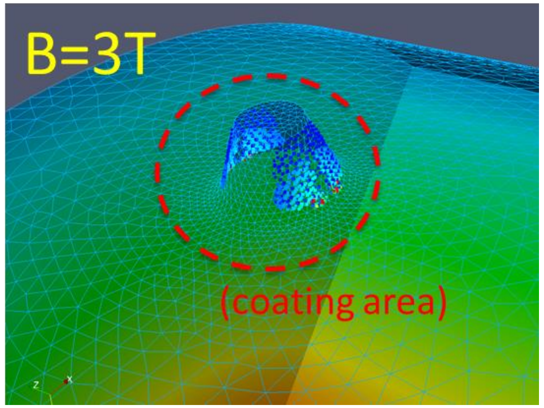
Counting the clamping loss (β)

RF design parameters

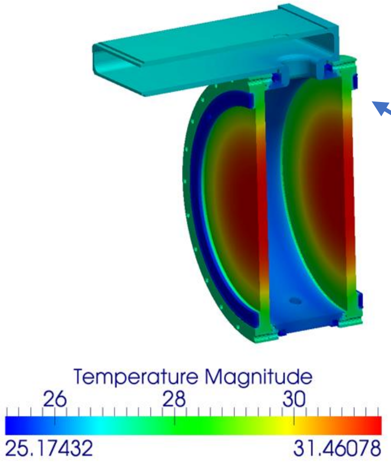
MAP 805 MHz modular cavity design



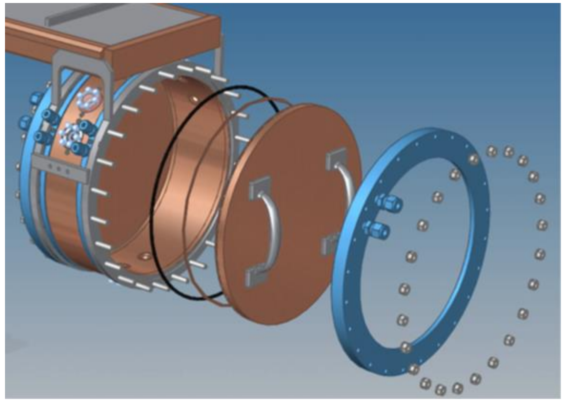
Possible MP in B=0 (left) and B=3T (right)
Coupling iris geometry optimized for minimal MP across a range of B-field strengths



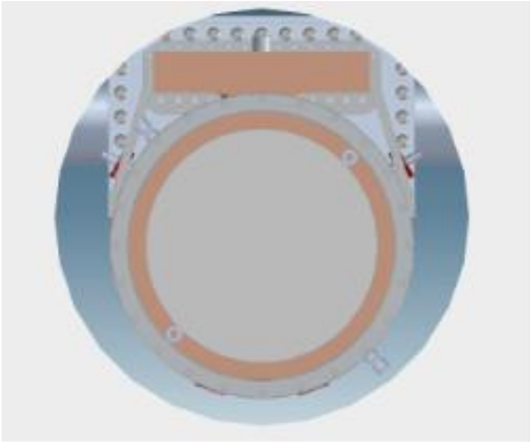
MP at the view port



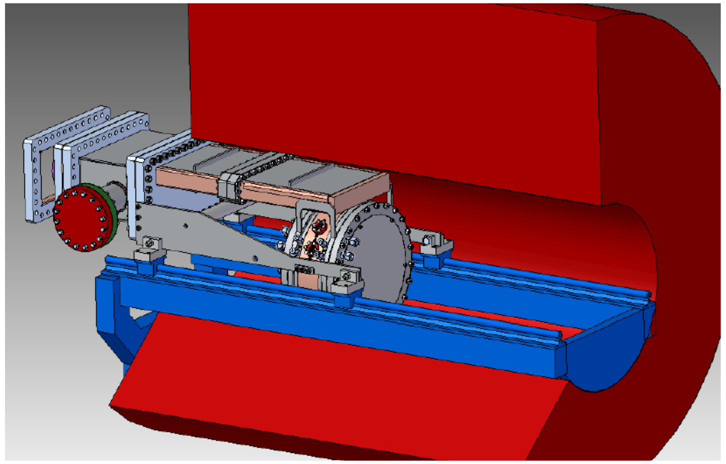
Cooling passage to minimize ΔT across the Be endplate



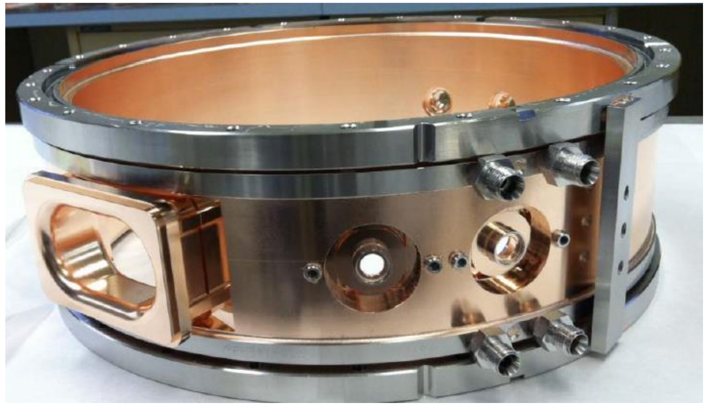
- Annealed copper gasket for RF seal.
- Viton o-ring for vacuum seal.
- Design for multiple mounting/dismounting cycles.



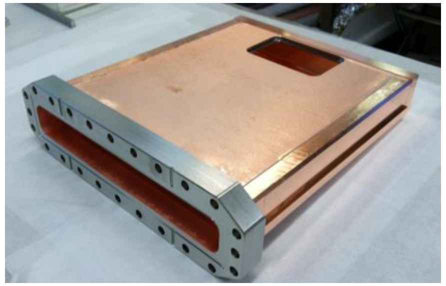
A tight fit in Lab-G mag with 44cm ID, min clearance ~ 6mm



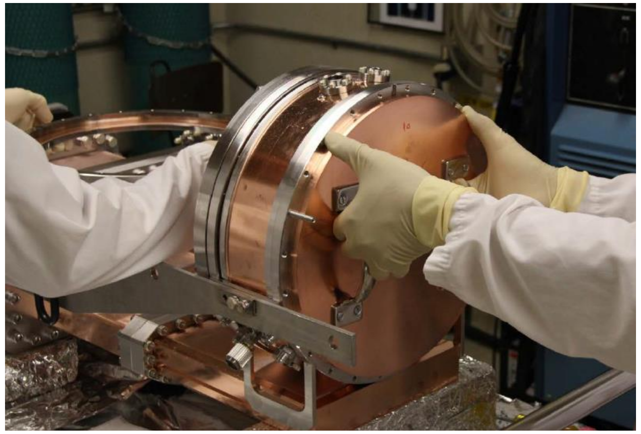
Modular cavity fabrication: collaboration between SLAC, Fermilab and LBNL



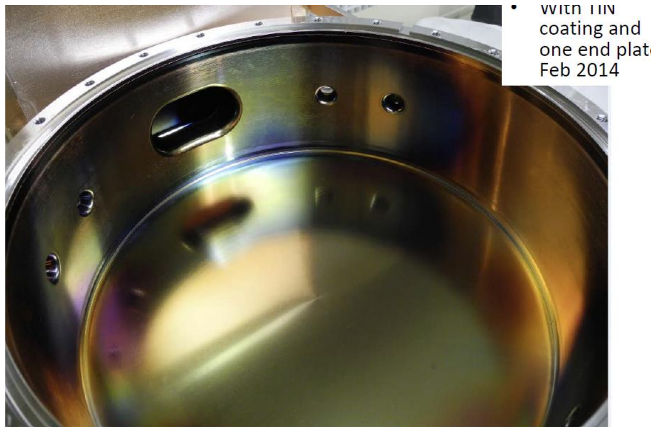
Cavity main body final braze



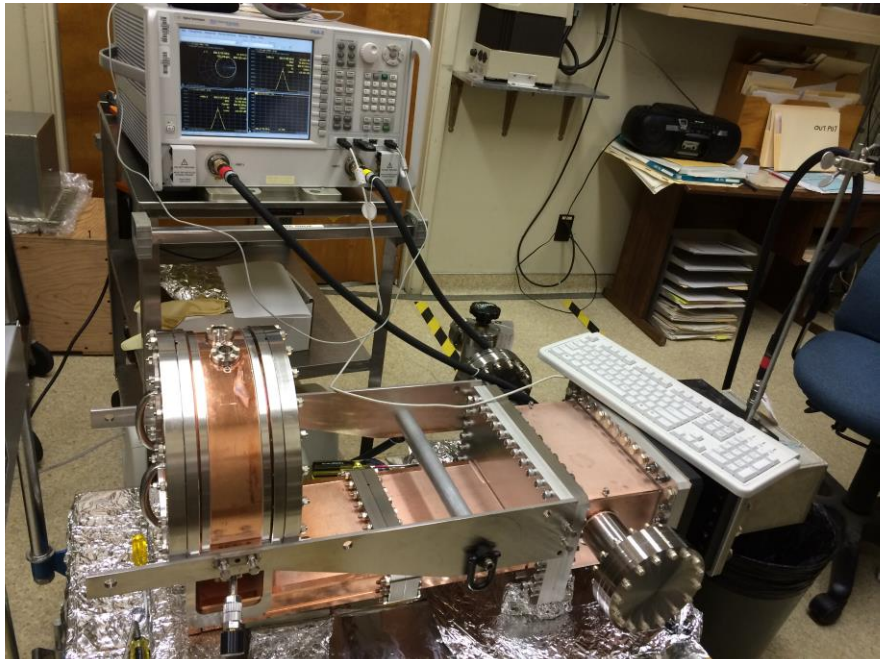
Narrow waveguide



Cavity assembly



TiN coating on cavity wall, endplates, view ports, coupler iris and waveguide.



Low power RF measurement after the build completed.
RF parameters achieved design values.
The coupling with clamped Cu endplates is ~ 1.2.

Summary

- In this talk we briefly reviewed two NCRF vacuum cavities developed for muon ionization cooling.
- MICE 201 MHz cavity
  - A complete functional product for MICE operation.
  - RF design focuses on low peak field, MP suppression and easy fabrication, with curved Be windows covering the side walls.
  - Novel fabrication methods.
- MAP 805 MHz modular cavity
  - A cavity built for R&D study on RF breakdown in strong B field.
  - Modularized design for systematically testing different variables and being convenient for inspections.
- For both cavities, particular efforts were made to achieve good surface finishing and suppress MP.
- Both cavities achieved or even exceeded their target gradients within corresponding B field configurations. The design and fabrication of both cavities provide valuable experience for future cavity developments.

Main References

- D. Li et al, "201 MHz cavity R&D for MuCool and MICE", EPAC2006.
- T. Luo et al, "Progress on the MICE RF module at LBNL", IPAC2016.
- D. Bowring et al, "A modular cavity for muon ionization cooling R&D", IPAC2013.
- Z. Li et al, "MuCool Cavity RF Simulation Studies", presented at MAP Collaboration Meeting, June 2013.

- Google drive (in progress): https://drive.google.com/drive/folders/1Pa1W6m5L-iExeDBx51J_9_7u2kJKdrpX?usp=drive_link