RF Design and Operation of a Modular Cavity for Muon Ionization Cooling R&D

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for the
US Muon Accelerator Program

International Particle Accelerator Conference
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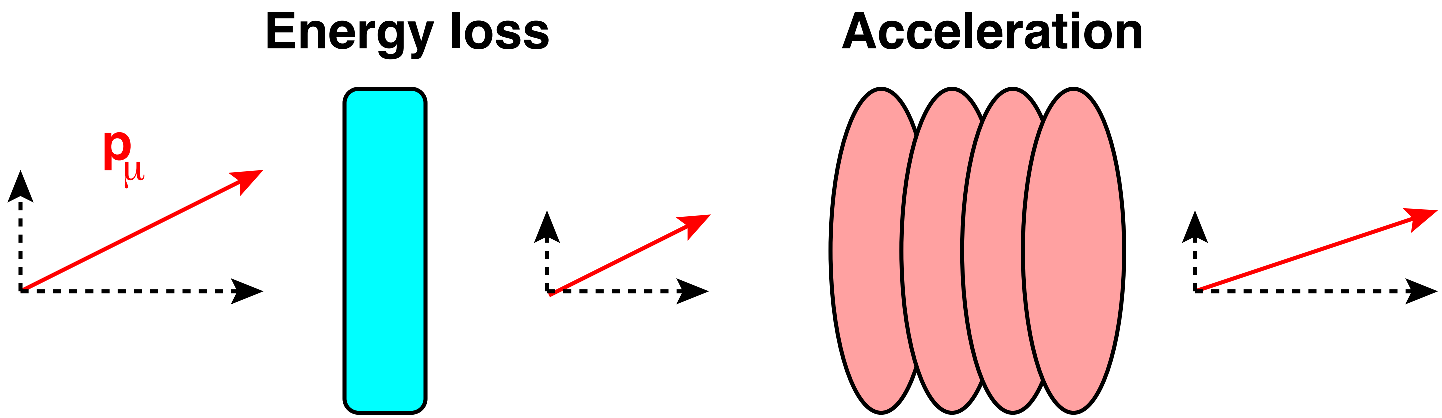
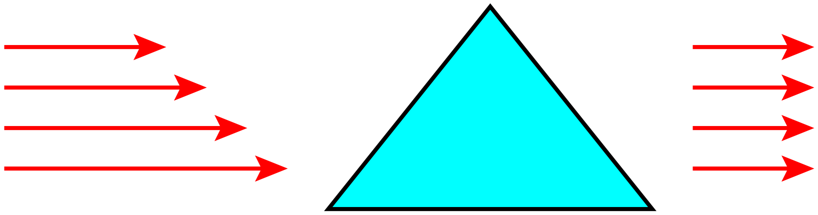
Ionization Cooling

- The only muon cooling scheme that appears practical within the muon lifetime (2.2 μs)





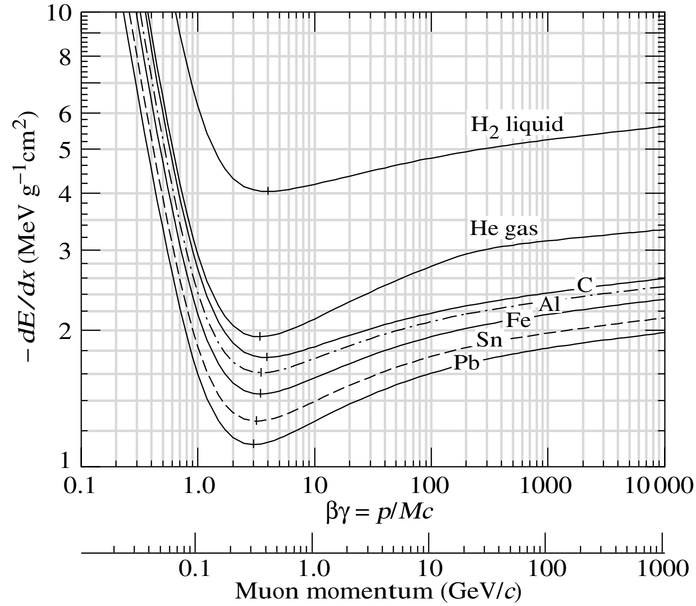
- Longitudinal cooling requires momentum dependent path length through the energy absorbers

Ionization Cooling

- Normalized transverse emittance ε of muon beam in solenoidal channel

$$\frac{d\varepsilon}{ds} \simeq \frac{\left\langle \frac{dE}{ds} \right\rangle}{\beta^2 E} (\varepsilon - \varepsilon_0), \quad \varepsilon_0 \simeq \frac{0.875\text{MeV}}{\left\langle \frac{dE}{ds} \right\rangle X_0} \frac{\beta_\perp}{\beta}$$

- ε_0: equilibrium emittance
  - multiple scattering ~ cooling
- Efficient cooling requires
  - Absorbers with large ΔE per radiation length
    - LH2: 29 MeV/m x 8.9 m
  - Strong focusing (high B): $\beta_\perp \sim p/B$
  - RF cavities in high B-field
  - Tight packing to minimize decay losses
  - Low muon momentum

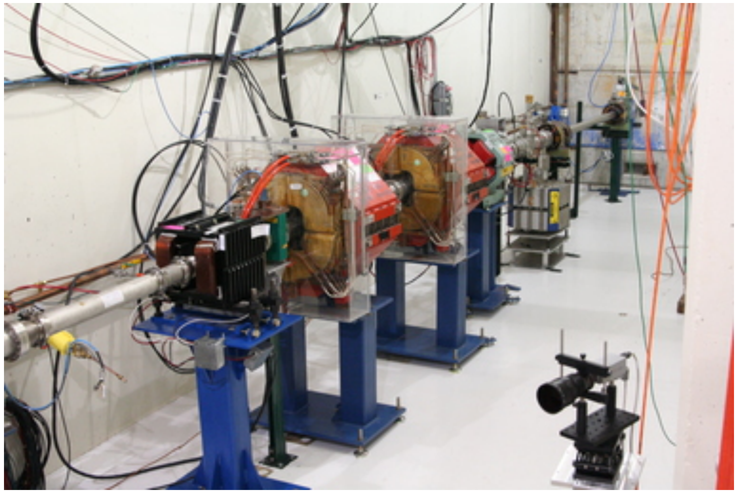


MuCool Test Area
http://mice.iit.edu/mta/

Dedicated facility for muon cooling R&D

- At the end of the Fermilab Linac
- RF power
  - 12 MW @ 805 MHz
  - 4.5 MW @ 201 MHz
- Large-bore 5T SC solenoid
- LHe cryogenic plant
- 400-MeV H- beamline and instrumentation
- Class-100 portable clean room
- Radiation monitors
- Extensive diagnostics for RF cavity tests

Unique in the world



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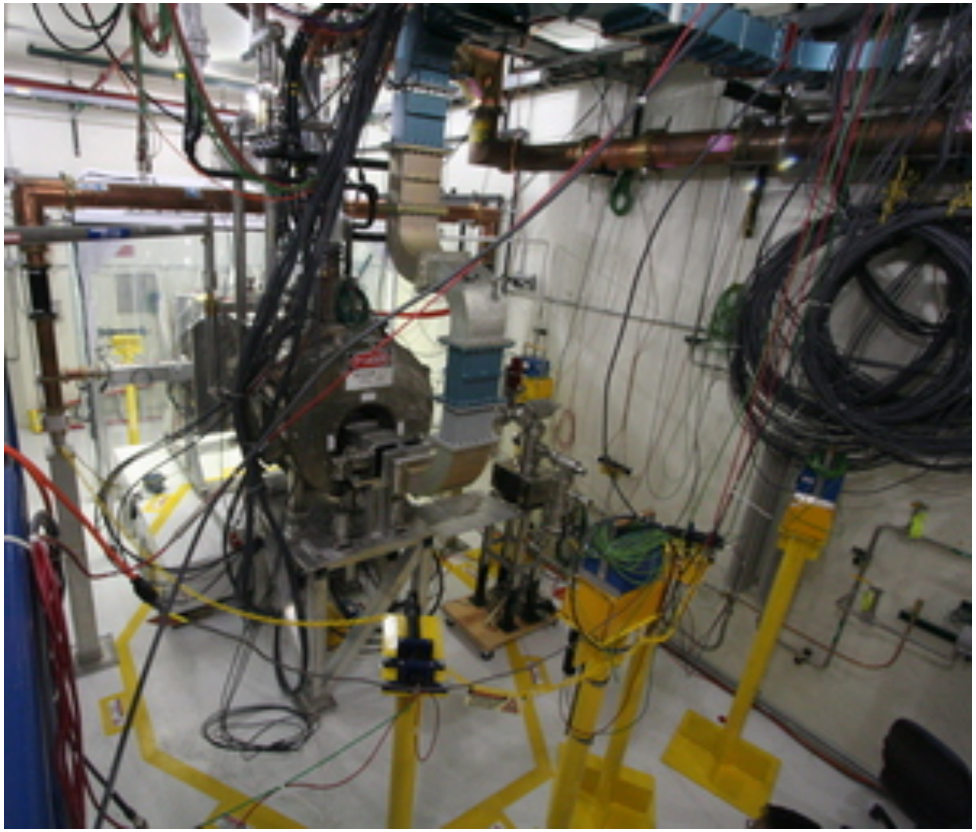

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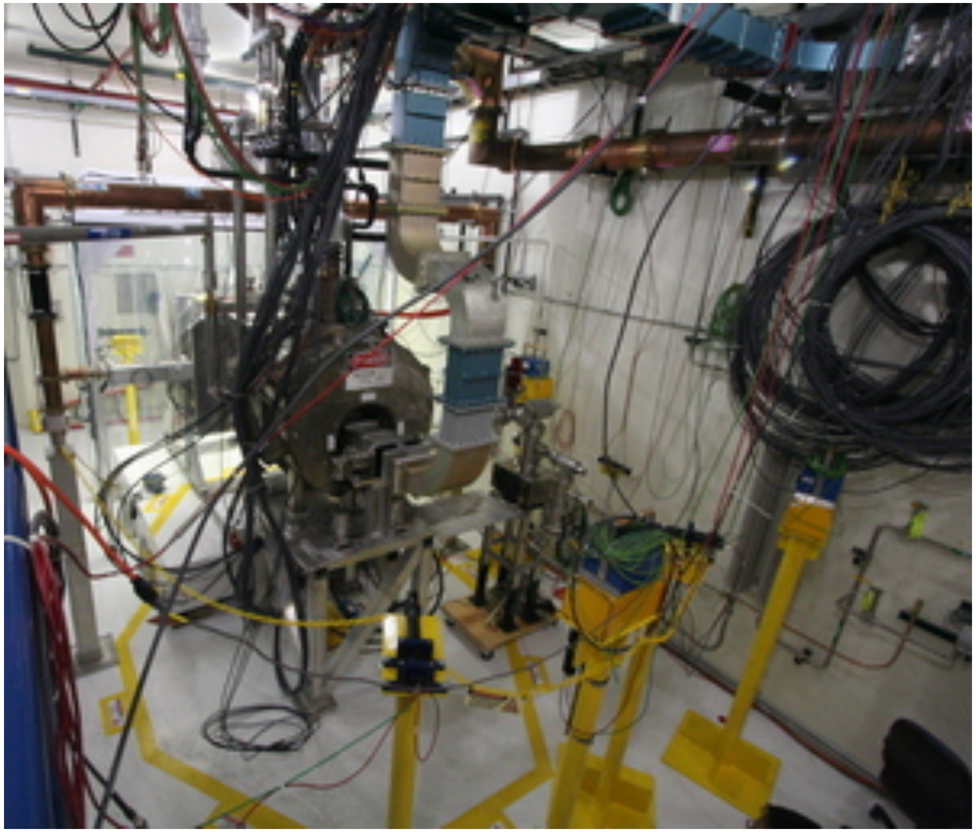

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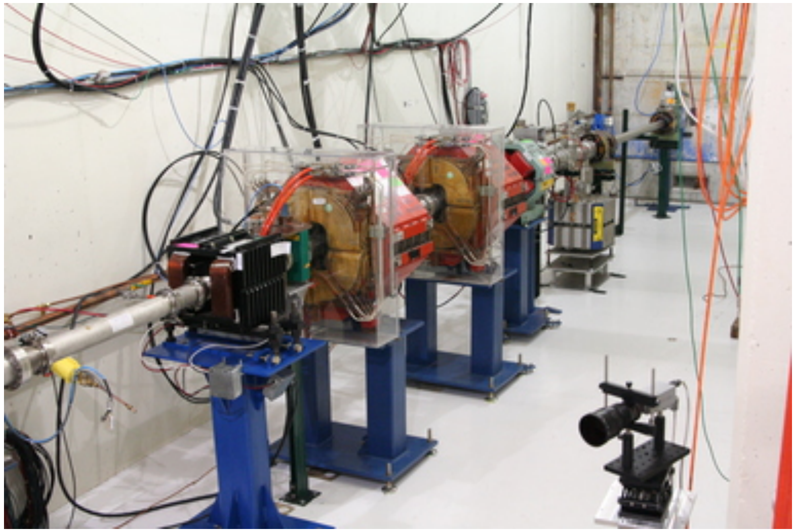

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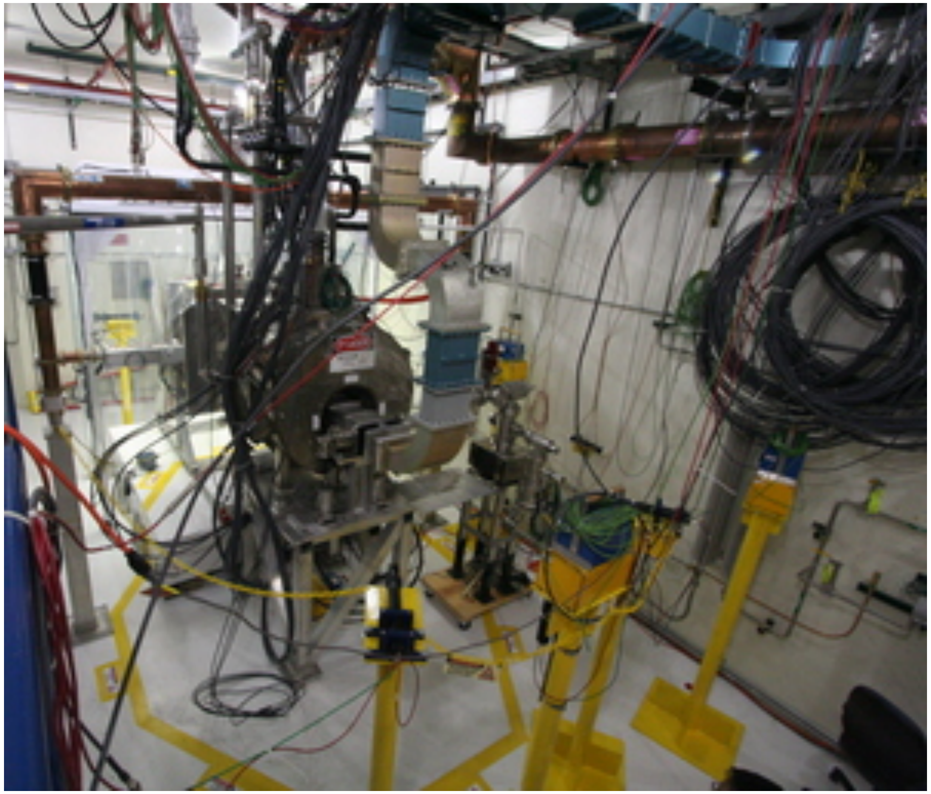

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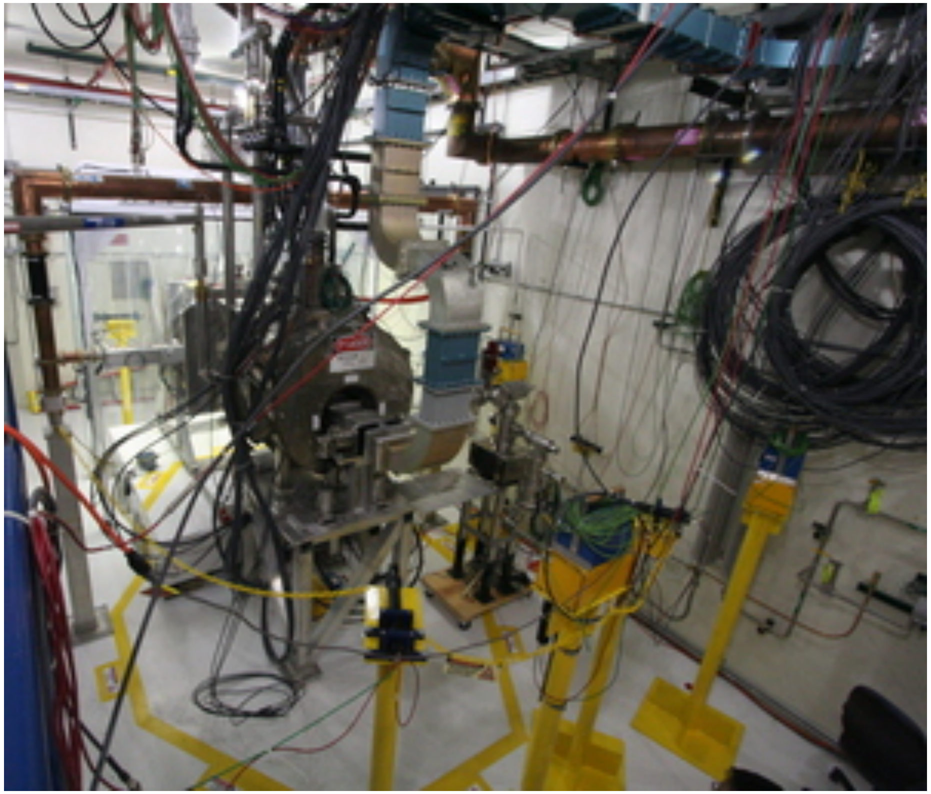


Muon Accelerator Program: NCRF Performance Requirements

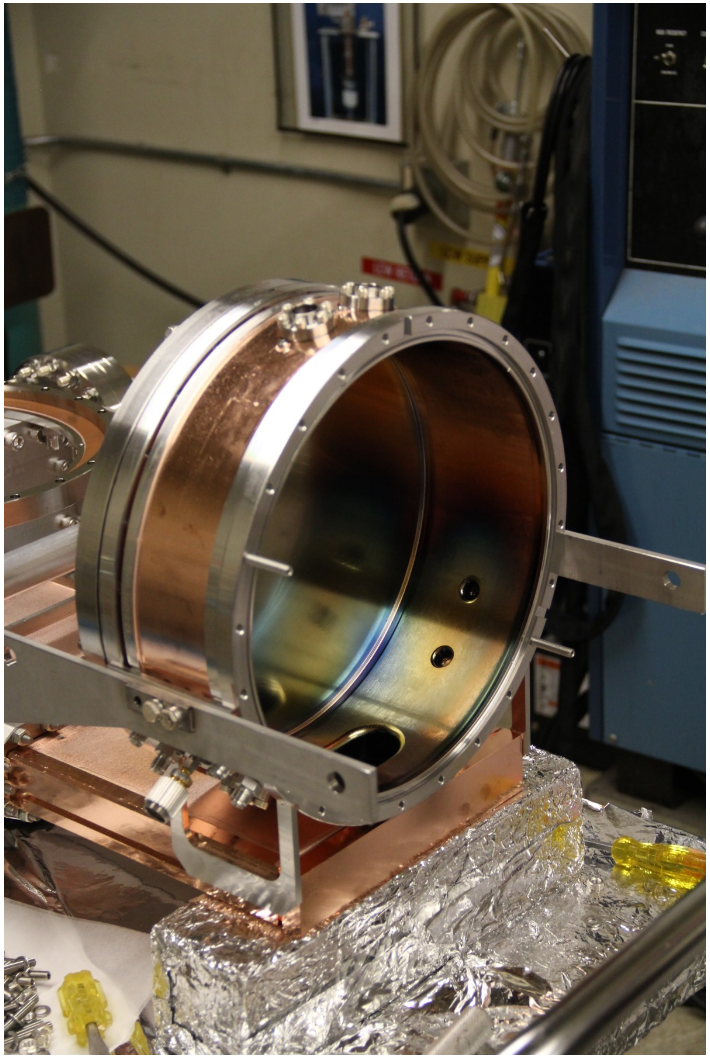
- Normal conducting RF requirements for muon beams: muon capture, bunching, phase rotation, ionization cooling require
  - Low frequency normal conducting RF cavities
  - High RF gradient operation in a few-T to 14 T on-axis magnetic fields

Parameter	Value	Unit
Buncher cavity frequency range	365 – 490	MHz
Maximum buncher cavity gradient	0.3 - 15.0	MV/m
Phase rotation cavity frequency range	326 – 364	MHz
Maximum phase rotation cavity gradient	20	MV/m
6D cooling channel cavity frequency	325	MHz
6D cooling channel cavity gradient	22	MV/m
6D cooler (later stages)	650	MHz
RF cavity gradient for 6 D cooler	30	MV/m
HCC HPRF frequencies	325, 650, 975	MHz
HCC HPRF gradient	20	MV/m

Mission / Talk Outline

1. Advance ***ionization cooling technology R&D***
   Help design, prototype, test components:
      Gridded cavity windows
      Modular pillbox cavity
      Dielectric-loaded HPRF cavity
2. Support the ***Muon Ionization Cooling Experiment*** *(MICE)* at Rutherford Appleton Laboratory
   Single-cavity system assembly, instrumentation, testing
3. Ongoing effort informs ***muon accelerator design***
   MICE cavity operation and analysis
   805 MHz modular cavity R&D
   Further gas-filled cavity testing
   Dielectric-loaded gas-filled 805 MHz cavity

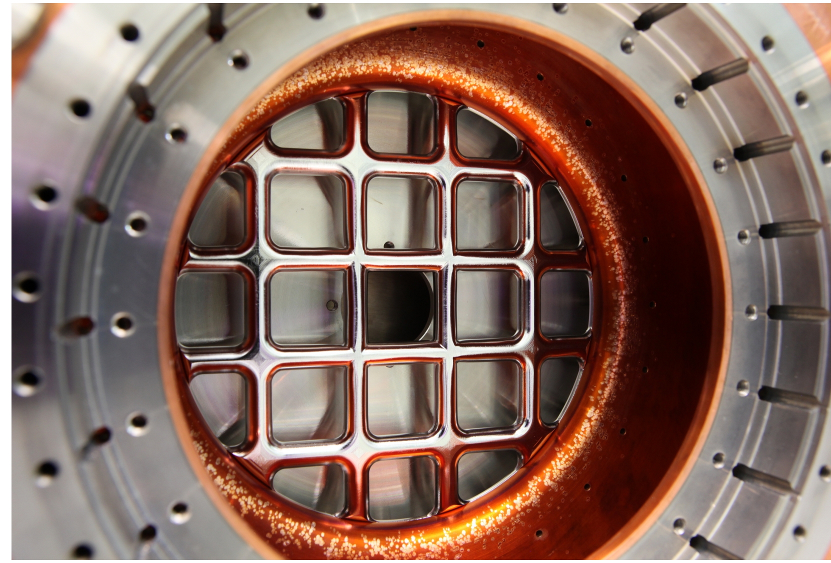
1: Technology R&D

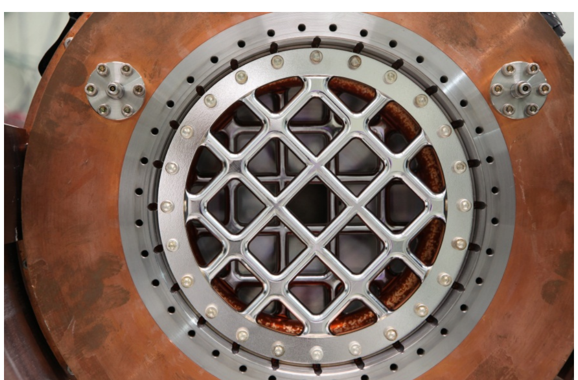


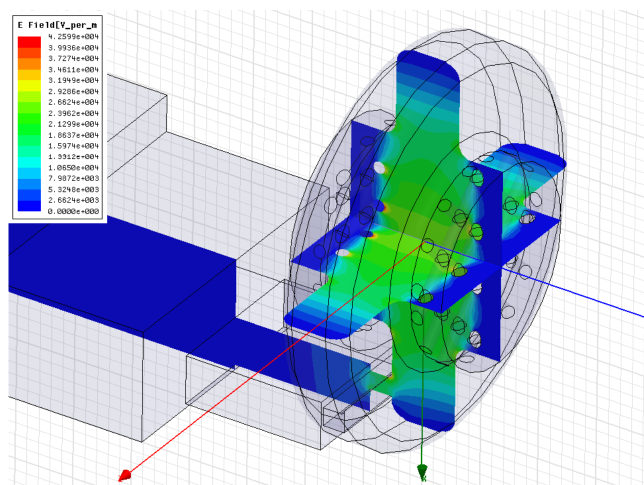
Technology R&D: Gridded Windows

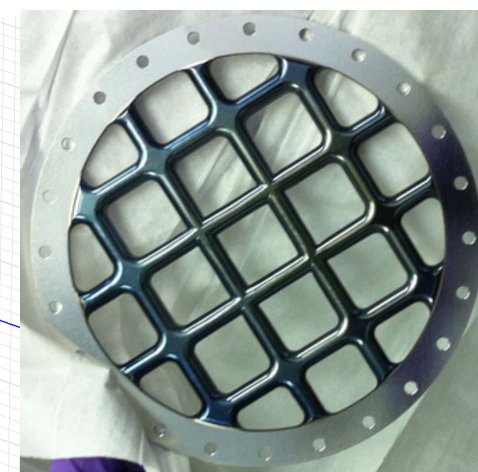
Gridded windows on 805 MHz pillbox cavity

- Based on M. Alsharo'a's 2004 PhD thesis (IIT)
- 25+ MV/m (surface) at B=0
- 22-23 MV/m for up to B=5 T
- Breakdown rate sensitive to large forward power ramp rates – suggests multipacting





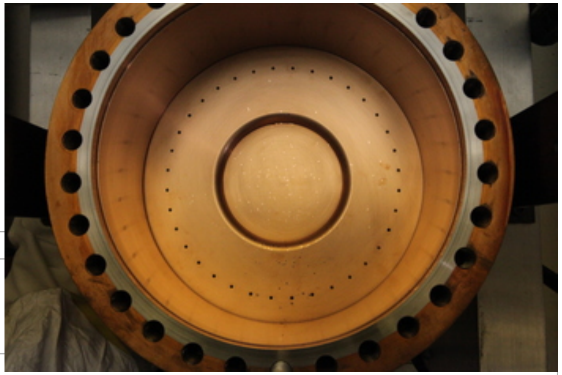


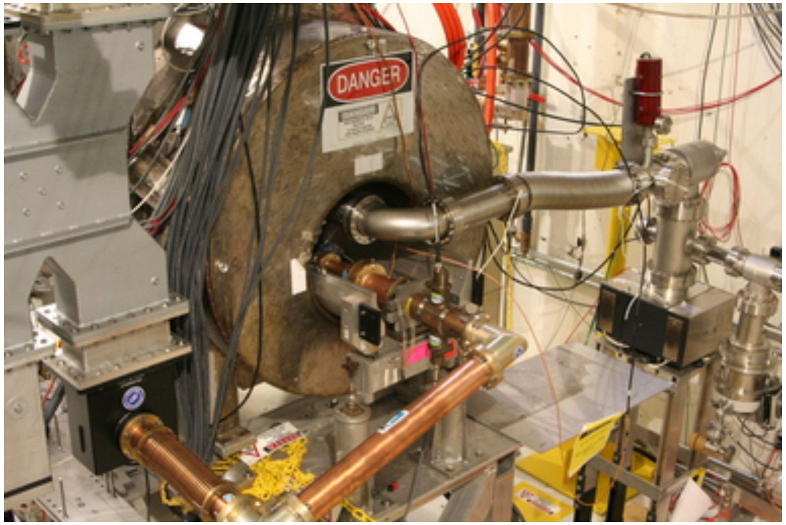


Technology R&D: Vacuum RF

"All Seasons" Cavity

- Successor to original MTA 805 MHz pillbox cavity
  - Operated in magnet (FY11 results):
    - ~ 25 MV/m at B=0, 3 T
  - Re-run with RF pickup in FY13
    - Confirmed B=0 data
    - ≥ 20 MV/m to 5T

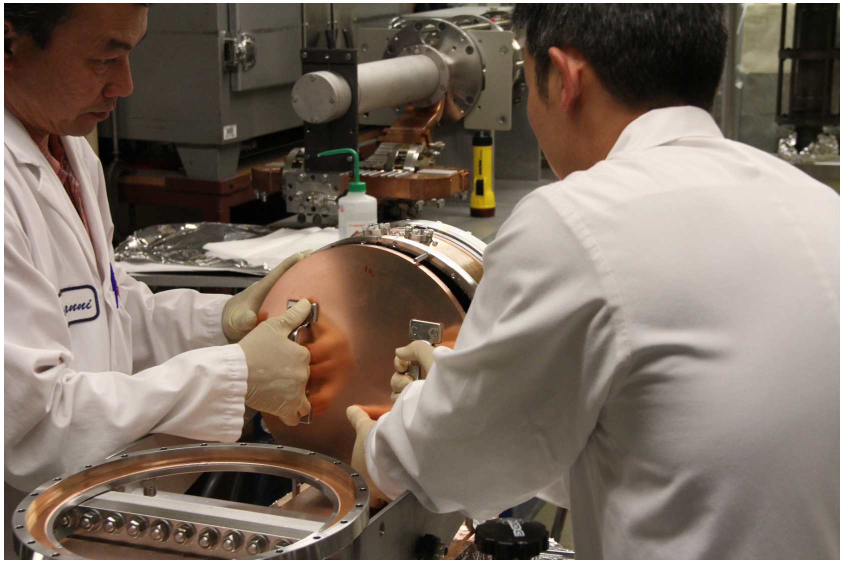


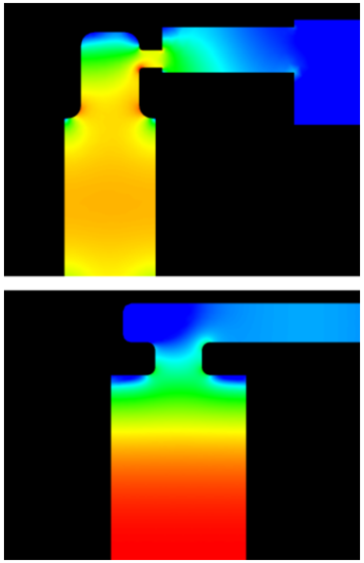


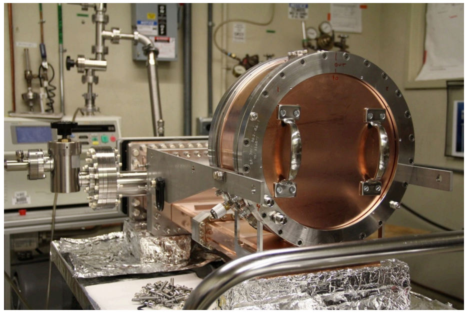
Technology R&D: Vacuum RF Cavities

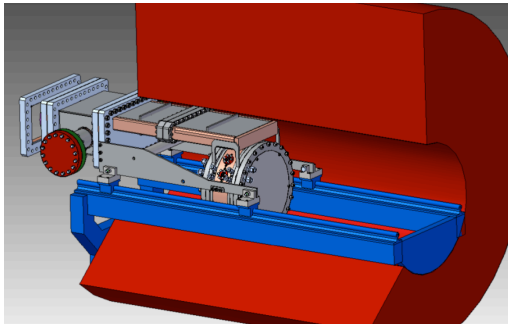
805 MHz “Modular” Cavity

- Well-controlled systematics
- Incorporates all lessons learned from previous cavity efforts
- Removable endplates for easy assembly, inspection, replacement (eg, alternative cavity materials/surface treatments)
- Coupler designed so longitudinal axis is the “weakest link” during breakdown
- RF design validated by extensive ACE3P simulation
- Incorporates dedicated instrumentation ports
- Fabrication complete at SLAC, MTA infrastructure ready





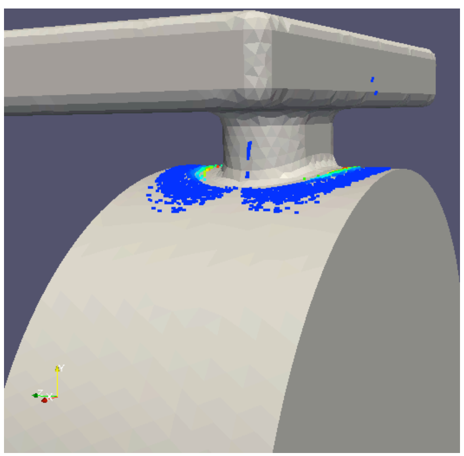




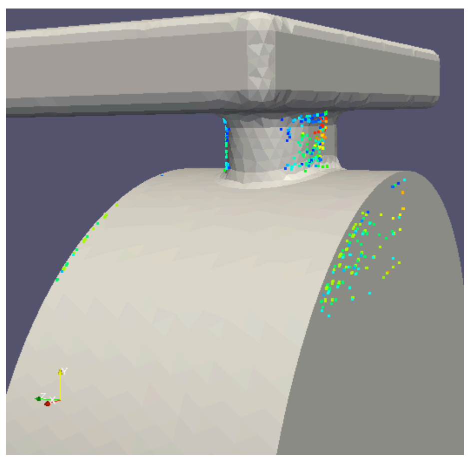
805-MHz Modular Cavity

Multipacting Simulations (Track3P)

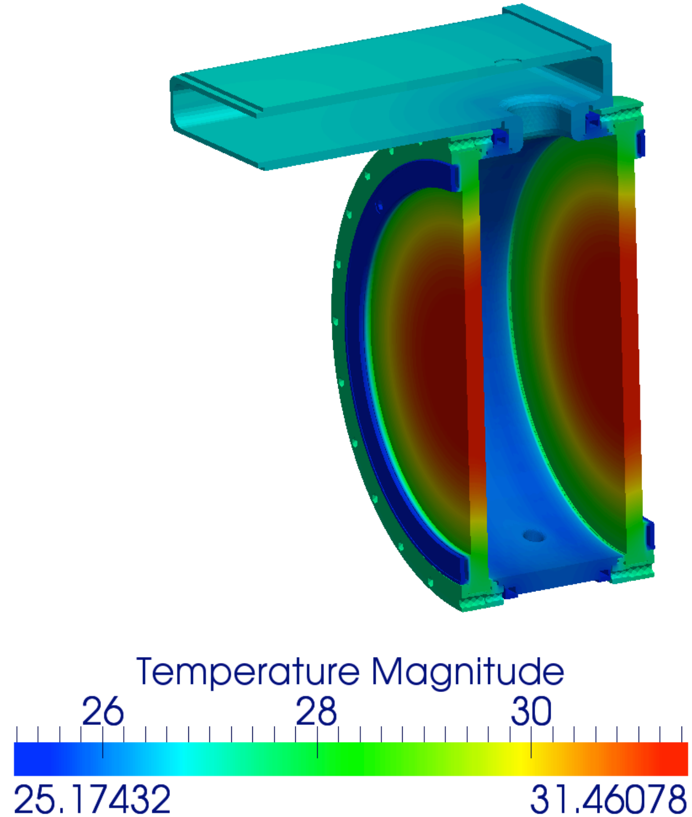
- Coupling iris geometry optimized for minimal multipacting across a range of B-field strengths
- Dot color corresponds to impact energy for a resonant trajectory



B = 0 T



B = 3 T



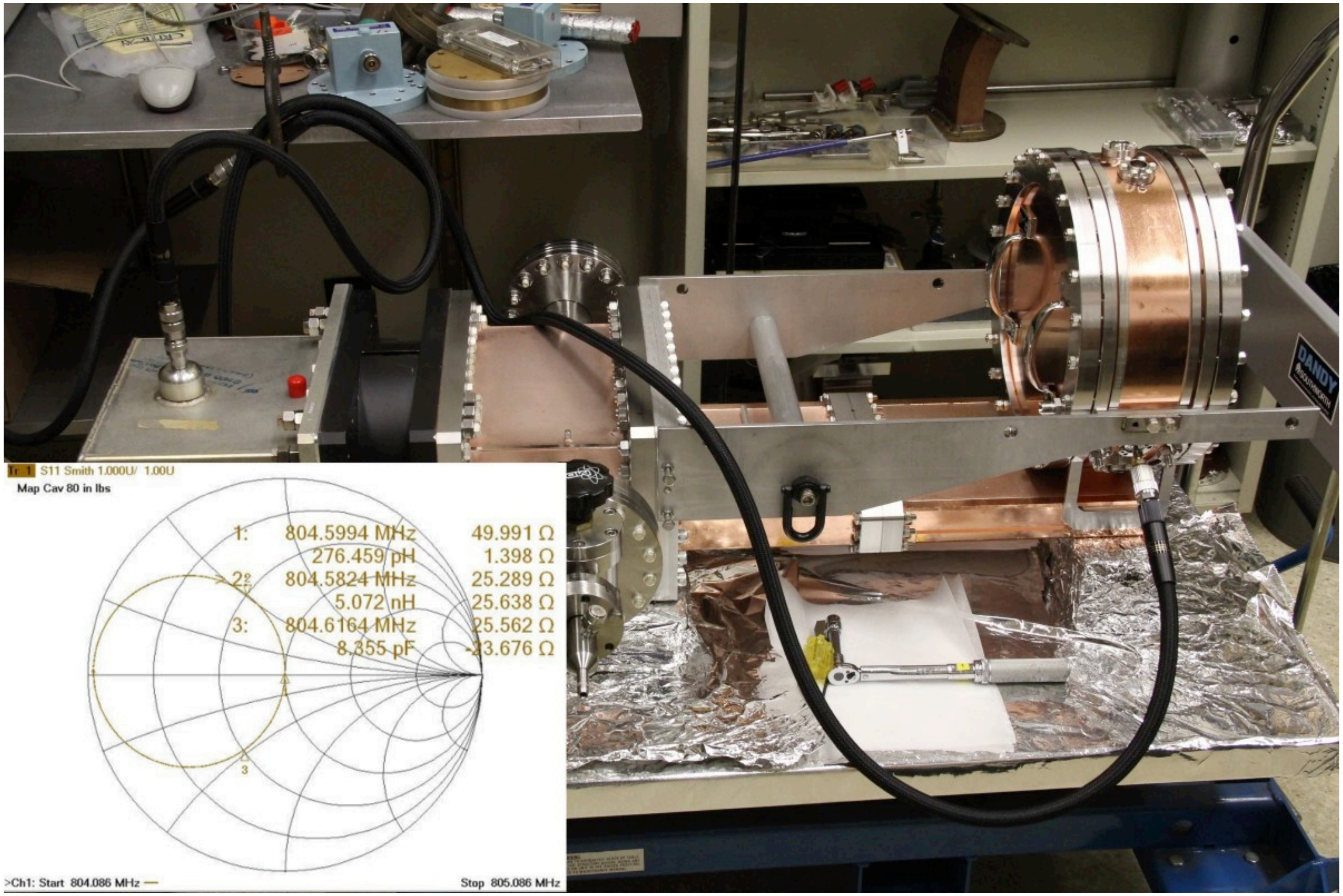
Thermal & Mechanical (Tem3P)

- Multiple coolant channels limit thermal gradient across Be plates
  - ΔT ~ 4 K

805-MHz Modular Cavity

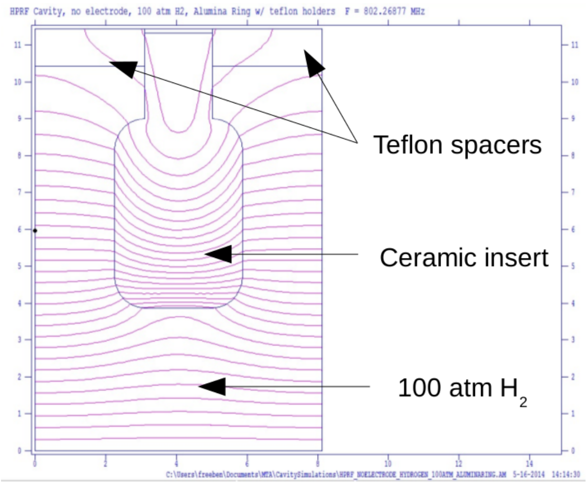
Muon Accelerator Program

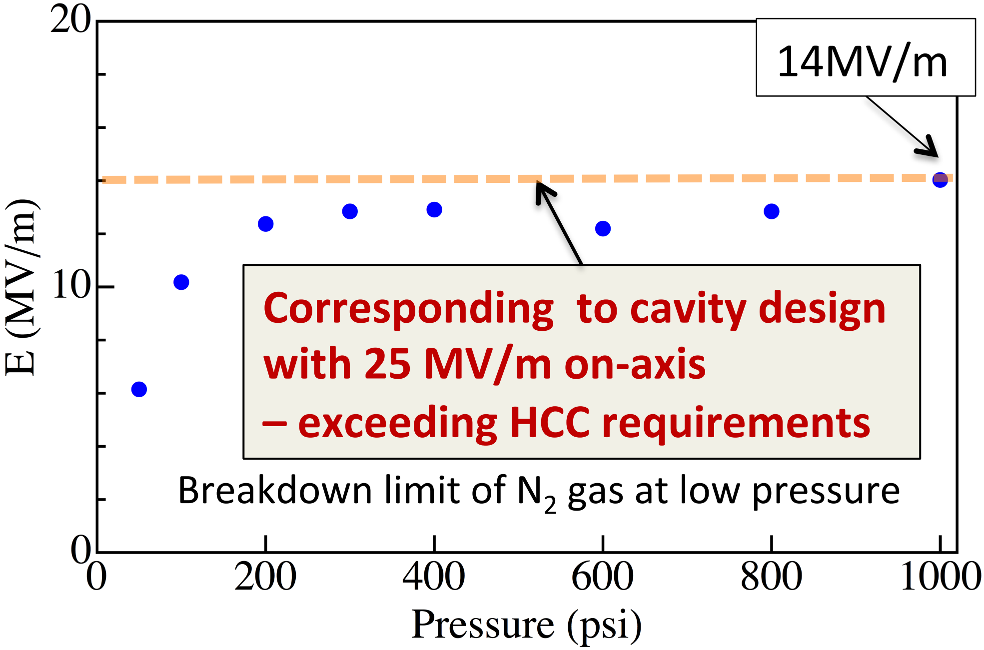
Measured RF parameters match design: 804.7 MHz, critical coupling



Technology R&D: Dielectric-Loaded HPRF

- High-pressure H2 gas filled RF (HPRF) cavities shown to work in B-field (~ 1 MV/m / atm) and beam induced plasma loading measured in the MTA
- Dielectric inserts under study to shrink cavity/magnet sizes in Helical Cooling Channel (HCC) design
- Alumina sample tested to surface breakdown limit (14 MV/m) in a 805 MHz RF Test Cell
- Current dielectric sample testing evaluates dielectric samples under low power HPRF conditions.
- In the future:
  - ➢ High-power RF test of sample(s)
  - ➢ Dielectric-loaded cavity beam test

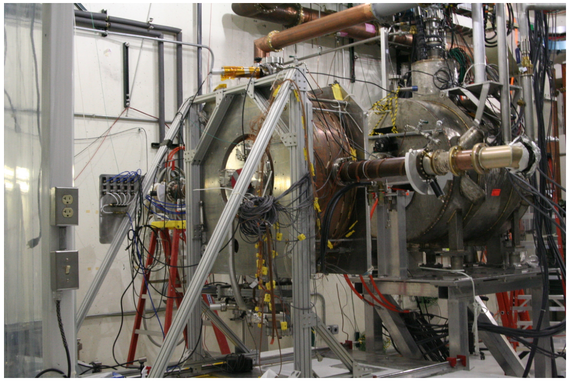


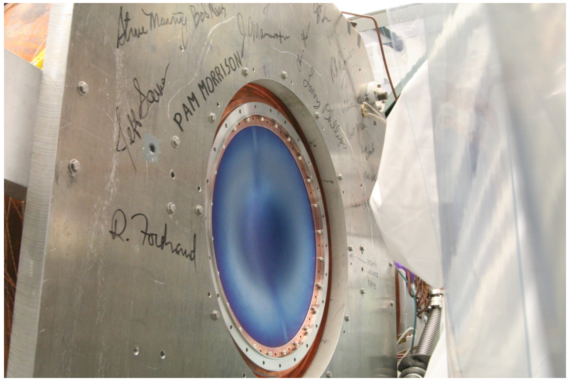


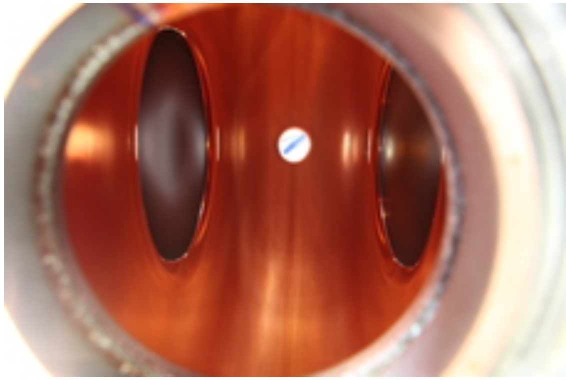
2: Supporting MICE

201-MHz Vacuum RF Program

- New 201-MHz MICE prototype cavity now ready for test
  - ➢ Incorporates SRF-like surface treatment (EP, HP rinse)
  - ➢ New coupler design
- Original Prototype (2005):
  - ➢ Conditioned to design gradient quickly
  - ➢ Demonstrated operation with large, curved Be windows
  - ➢ Somewhat reduced RF gradient in fringe field of solenoid.
  - ➢ Radiation output measured (MICE detector backgrounds).
  - ➢ Some evidence for sparking in the coupler
    - – ACE3P multipacting studies (T. Luo) led to coupler redesign.
    - – New coupler incorporates TiN coating.



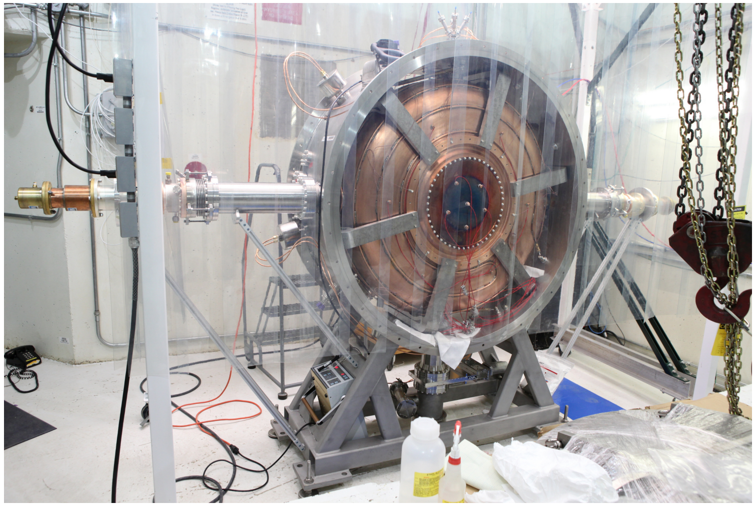




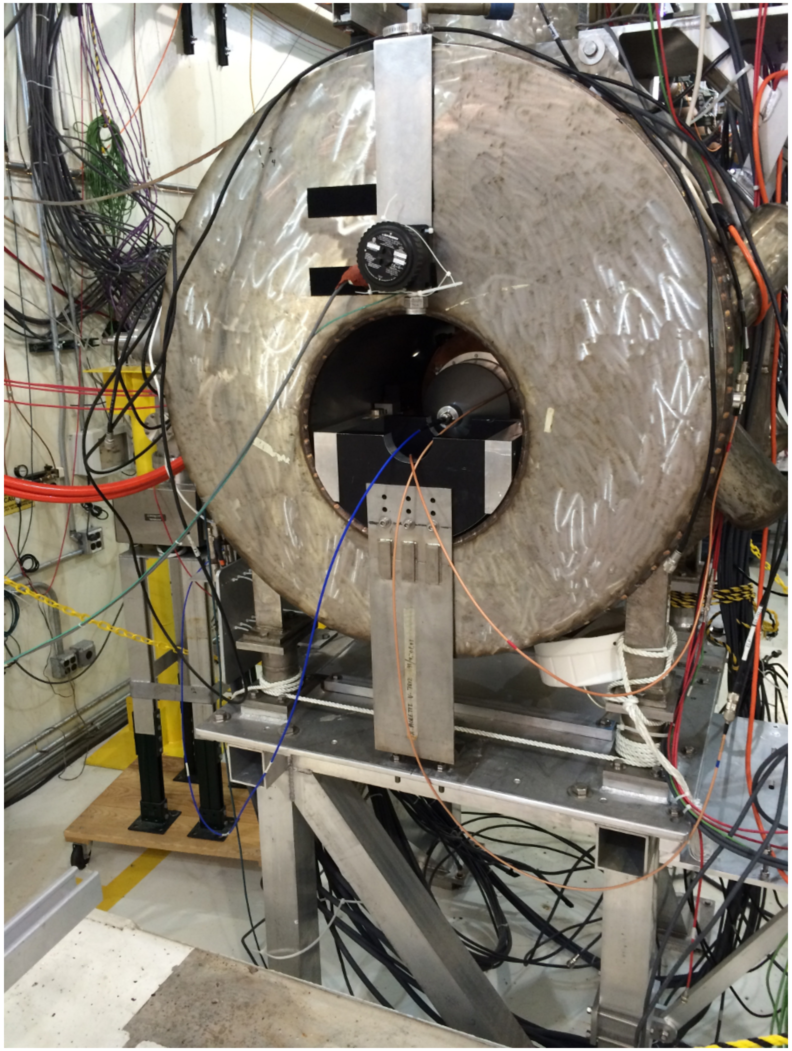
201-MHz Cavity & Vacuum Vessel

MICE Single Cavity Test Stand:

- Initial assembly completed at Fermilab's Lab 6.
- Fixtures built, tested during assembly.
- Full tuning system assembled, tested, characterized for the first time.
  - L. Somaschini MSc thesis (INFN Pisa)
- First pair of MICE redesigned prototype input couplers installed, tuned.
- Transported to MTA hall in early May.
- Installation in progress. High-power testing in near future.
- Large diameter magnet (coupling coil) needed for field configuration closer to MICE/cooling channel.



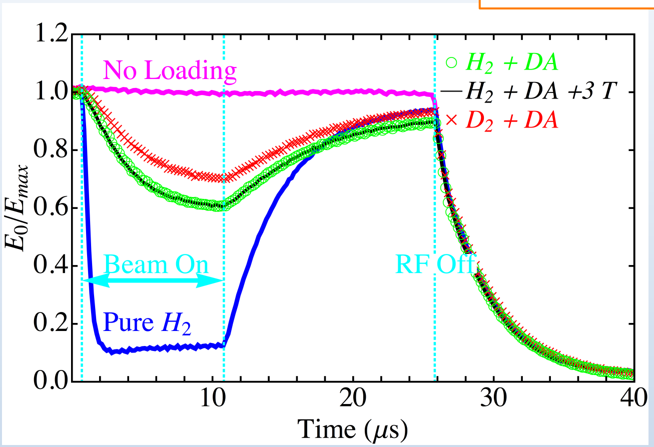
3: Ongoing / Future Effort



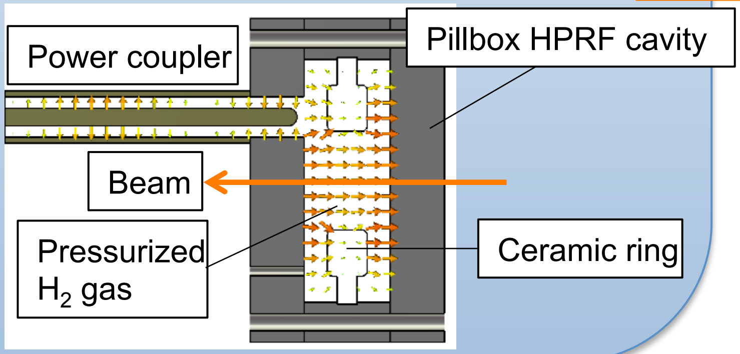
Ongoing HPRF Effort

Experimental efforts

- Pressurized H_2 RF Cavities in ionizing beams and magnetic fields PRL **111**,184802 (2013)



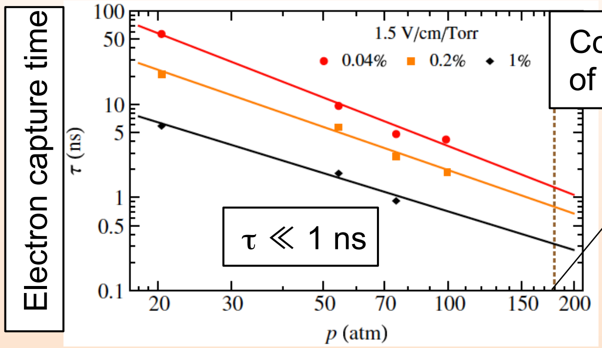
- Verify dielectric insert compact RF concept in high gradient gas-filled RF cavity THPME054



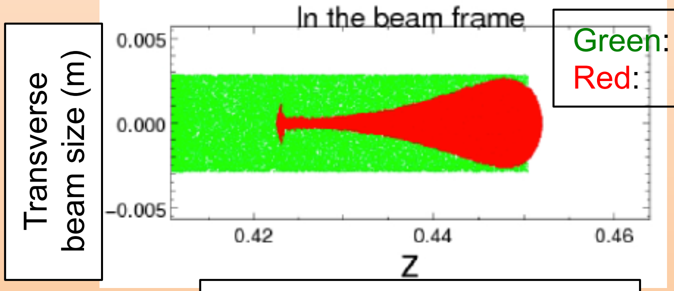
Interpret test result

Analytical investigations

- Investigate plasma process with muon collider beam THPRI064



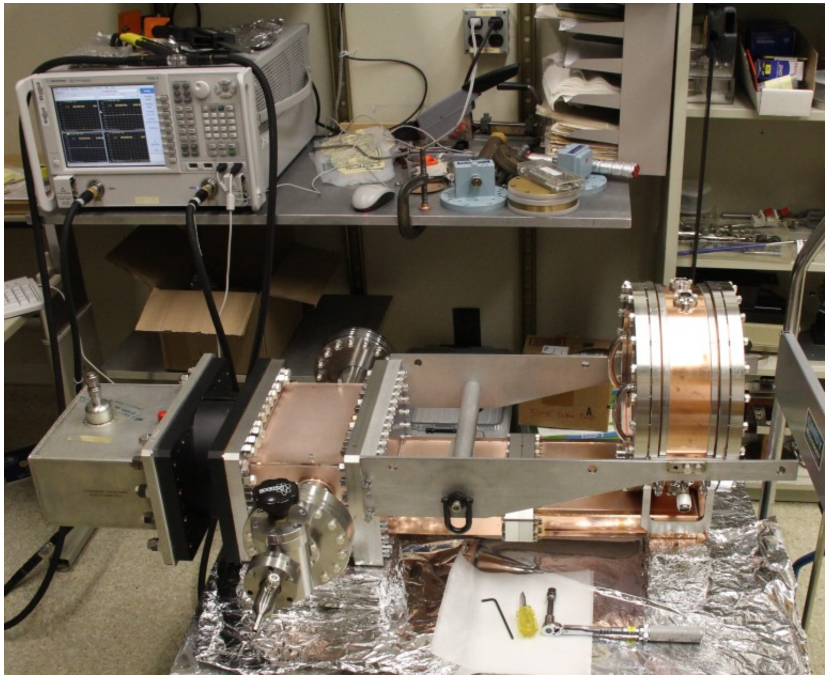
- Study RF performance with muon collider beam MOPME043, THPRI065
  - ▶ Beam loading effect
  - ▶ Beam-plasma interaction (plasma lens)



Ongoing Vacuum RF Effort

Modular Cavity program: systematic exploration of basic performance issues in muon acceleration

- What is a realistic accelerating gradient on which to base our designs?
- How do material choice and surface preparation affect breakdown rates?
- What is the operating lifetime of a clean cavity surface under these conditions?
- Other considerations: gap length, frequency scaling



Outlook

- Operating point for 805-MHz vacuum RF in 0-5T established
  - Preparations complete for next step: Modular Cavity
    - Enabling systematic studies of all critical issues
    - Installation and test program to start late Summer 2014
- MICE cavity assembly complete
  - Commissioning under way
  - Test program planned over next year
- Plasma loading for HPRF in beam evaluated
  - Electronegative dopants shown to mitigate beam-induced plasma loading
  - Projections to NF and MC operating intensities appear reasonable
- Proof-of-principle dielectric loading test complete
  - Provides route to reduced size cavities for a high-pressure gas-filled cooling channel
  - Required surface gradients achieved
  - Follow-on program to study material choices ready to begin

Acknowledgement

- Material provided by Daniel Bowring, Mark Palmer, Katsuya Yonehara

IPAC'14 MTA Posters

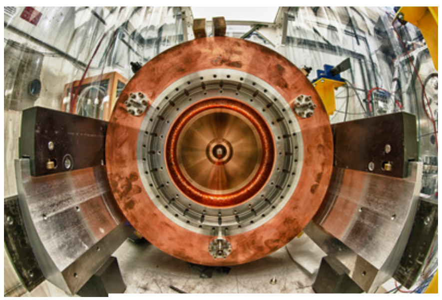
- Tuner System simulation and tests for the 201-MHz MICE Cavity, L. Somaschini *et al.*, THPRI070
- Plasma Chemistry in a High Pressure Gas Filled RF Test Cell for use in a Muon Cooling Channel, B. Freemire *et al.*, THPRI064
- Installation and Commissioning of the MICE Single-Cavity Module, Y. Torun *et al.*, THPRI067
- Instrumentation for characterizing 201-MHz MICE Cavity at Fermilab, M. Chung *et al.*, THPRI071
- Acoustic localization of breakdown in the MICE Single-Cavity Module, P. Lane *et al.*, THPRI029
- Extended RF Testing of the 805-MHz Pillbox "All-Season" Cavity for Muon Cooling, Y. Torun *et al.*, THPRI068
- Tube-Grid Windows for Pillbox Cavities, A. Moretti *et al.*, THPRI069
- The Fermilab MuCool Test Area and Experimental Program, Y. Torun, THPRI072

Supplemental Material

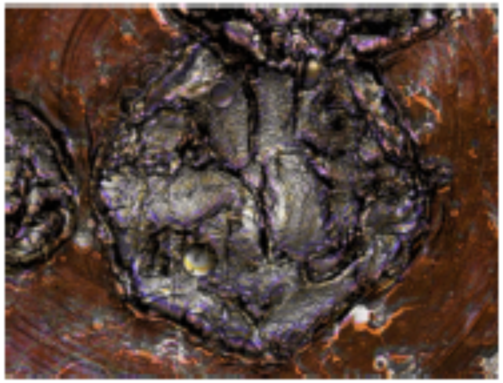
805-MHz Vacuum Cavity Program

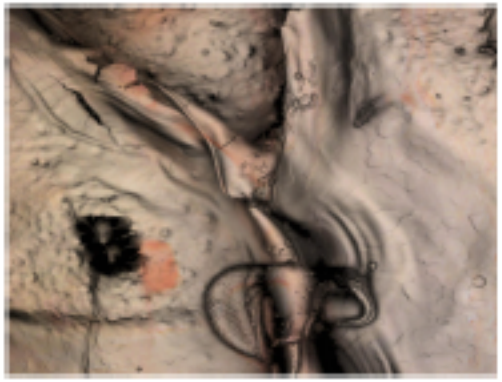
[Magnetic Field] [Surface Processing]
[Cavity Materials] [Window Options]

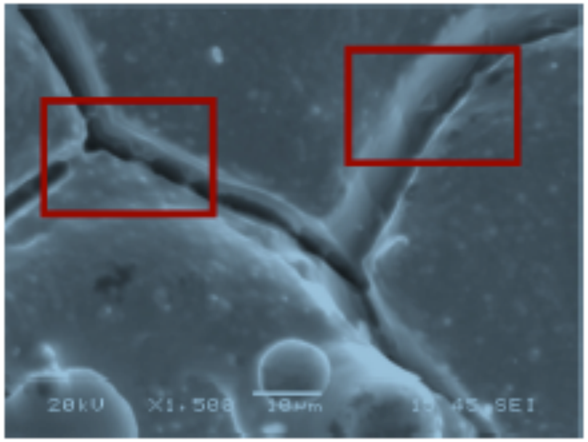
- Original LBNL pillbox
- Removable electrode inserts
- Used to study
  - B-field dependence of gradient
  - Feasibility of thin windows (Cu, Be)
  - Potential cavity materials (Cu, Be, Mo, W)



- Be vs Cu buttons & flat Cu endplates
  - Higher gradient with Be buttons
  - Minimal surface damage on Be
  - Surface microscopy
    - Bowring et al., IPAC13







805-MHz Vacuum RF Program: Button Pillbox Cavity

- Jana et al., NAPAC13

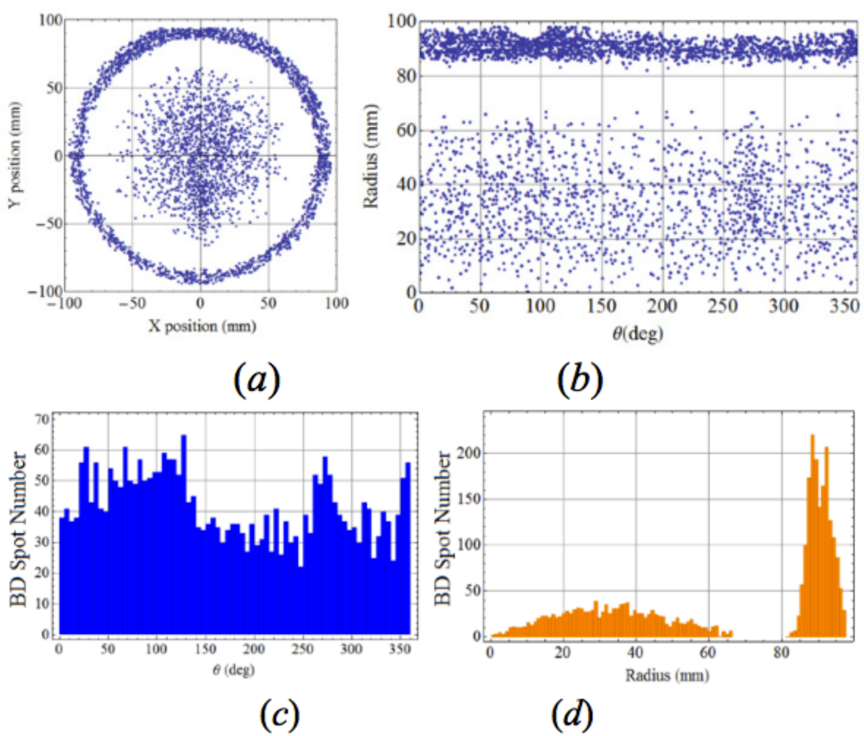
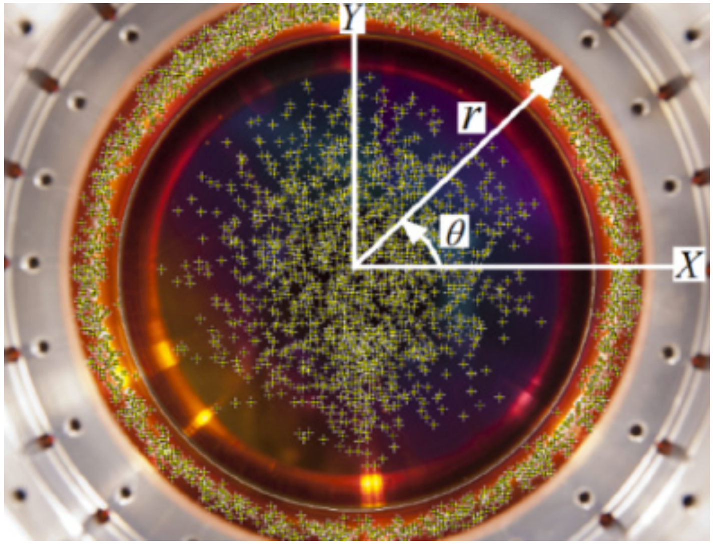


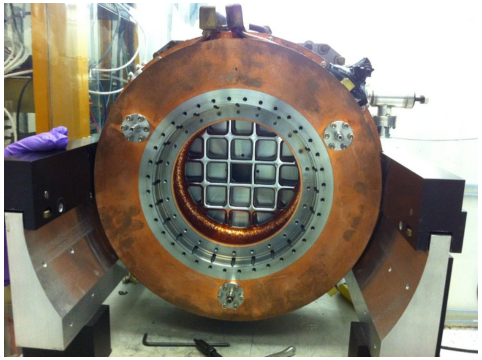
Figure 4: BD spot distribution in X-Y plane (*a*) and r-θ plane (*b*), BD spot no. vs θ plot (*c*) with bin size: 5° and BD spot no. vs *r* plot (*d*) with bin size 0.9 mm.

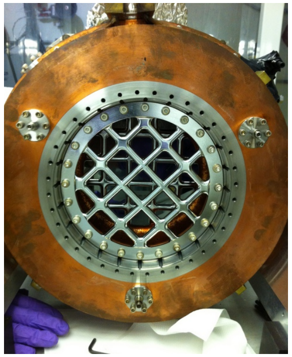
- Breakdown spot distribution consistent with E-field

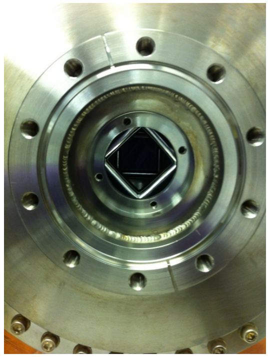


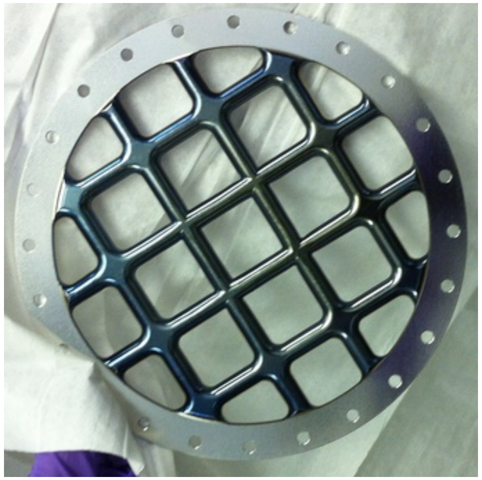
805-MHz Vacuum RF Program: Button Pillbox Cavity

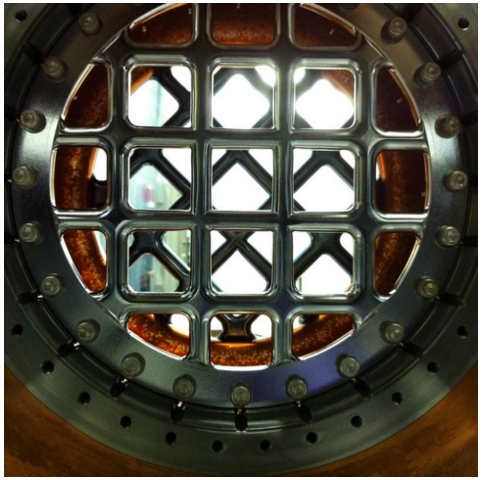
- Windows: low radiation length, good electrical and thermal conductivity
  - Flat thick Cu ✔
  - Thin pre-stressed flat Be ✖
  - Thin curved TiN/Be ✔
  - Exploring alternative: gridded tube windows
    - Solid Al
    - Electro-polished
    - TiN coated (one face)
    - Cavity assembled with grids (and spacer)
    - Also ran with flat Cu plate on one side
  - M. Alsharo’a Ph. D. thesis, IIT, 2004





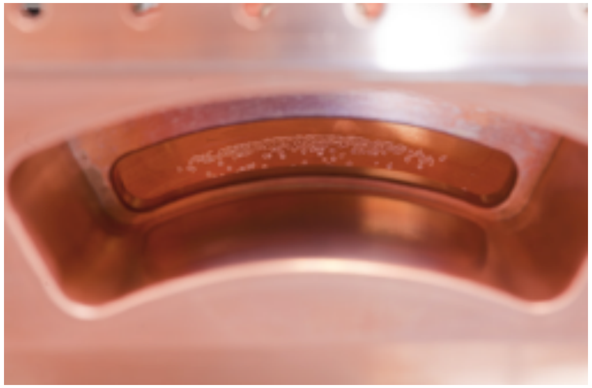






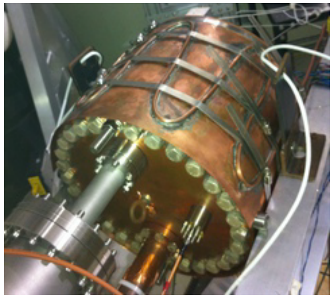
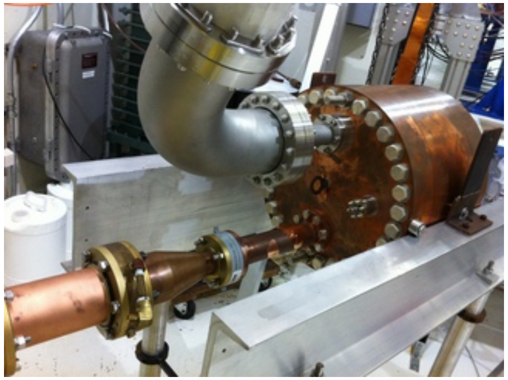
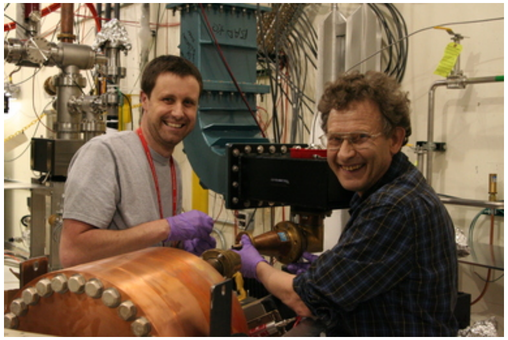
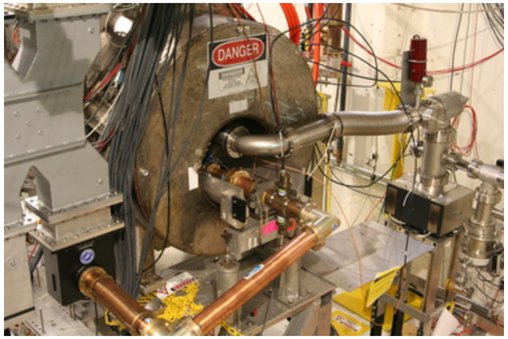
805-MHz Vacuum Button Pillbox Cavity
Looking back

- Gradient limited by high field in coupler region
  - originally to protect Be windows
- Demountable windows and electrodes reached through external cover plates
  - flexible assembly
  - *transformed* for many uses
  - last test completed
- Some vacuum seal problems
- Practical instrumentation
  - RF pickup probes
  - viewports for breakdown light
  - thin external windows for dark current, x-ray measurement



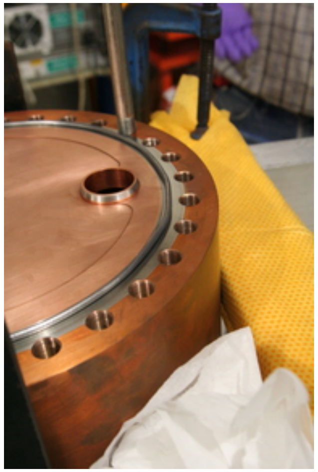
805-MHz Vacuum Cavity Program
[Long pillbox]

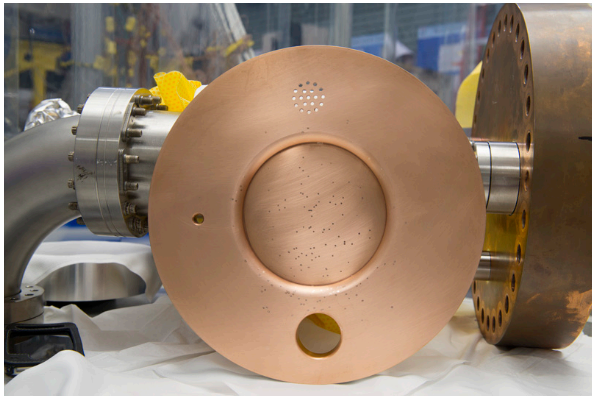
- "All-season" cavity (Muons Inc, LANL)
  - Modular pillbox with replaceable endplates
    - Designed for both vacuum and high pressure
    - 316SS with 25um Cu coating
    - 3.9/6.6/2.7cm-thick center ring/outer/inner plates
  - Φ29.1 x 12.9cm inner RF volume
  - 1-5/8" coax coupler
  - Q ~ 28k, frequency 810.+ MHz
  - 1.2MW @ 25 MV/m
  - No active cooling in design
    - Tried external water blanket, did not work
    - Limited rep rate: 5/2/1/0.5 Hz @ 10/15/20/25 MV/m
    - Ran ~24/7 from late March 2013 (RF control software upgrade)
  - No RF pickup
    - Used gas port

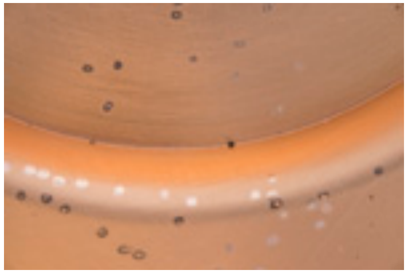






805-MHz Vacuum RF Program: All-Season Cavity

- Operated in magnet:
  25 MV/m at B=0, 3 T
- Re-run with RF pickup
  - Confirmed B=0 data
  - 20-22 MV/m at 3T
- Inspection
  - coupler damage (repaired)
  - mm-size spots on endplates
- Reassy: poor Q
  - shape distortion at high power
  - used Cu wire for RF contact
  - Pb wire for vacuum seal
  - Replaced pickup (failed shortly after)
- Recovered Q and vacuum seal
  - completed measurements at 0-5T

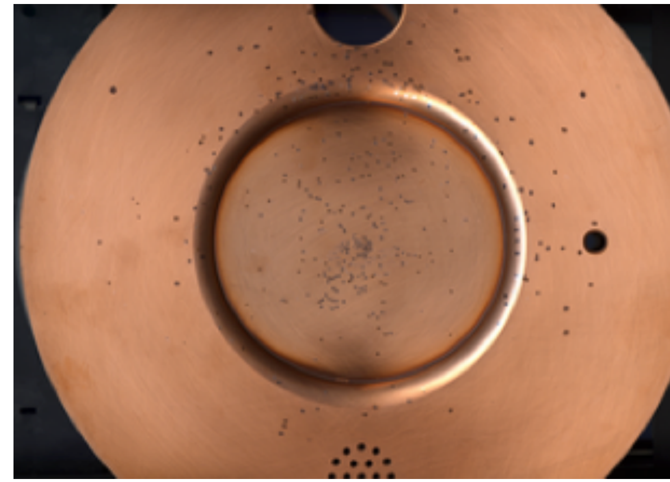


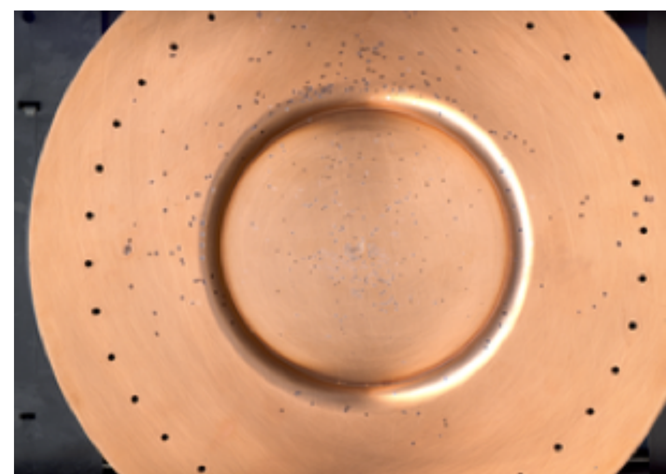


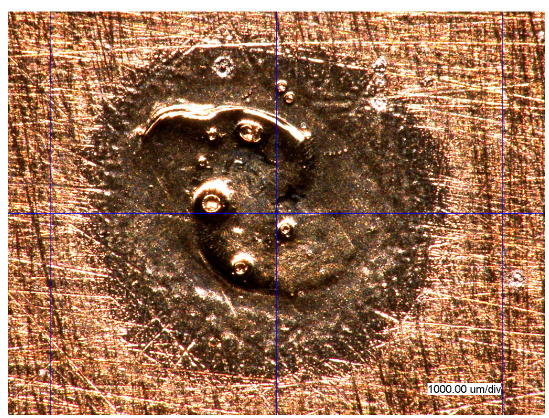


805-MHz Vacuum RF Program: All-SeasonCavity

- Last run
  - 25 MV/m at B=0
  - 20-22 MV/m @ B=0.25-5T [preliminary] (sparking rate ≤ 1 in 10^5)
- Inspection
  - similar spots on endplates
  - more around coupler
  - scanner & microscope tested
- Data analysis in progress
  - publication draft soon
  - cavity removed from MTA

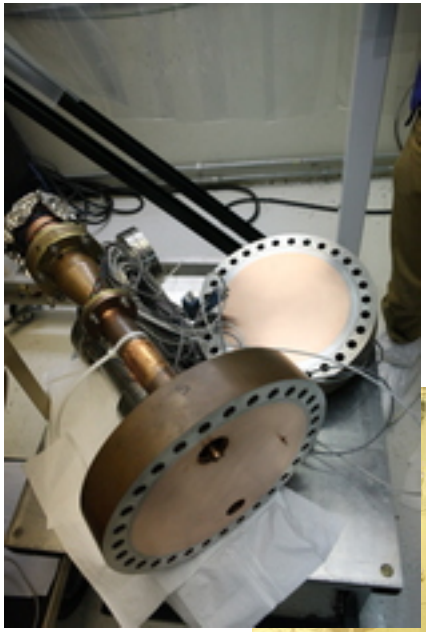






805-MHz All-Season Cavity Looking back

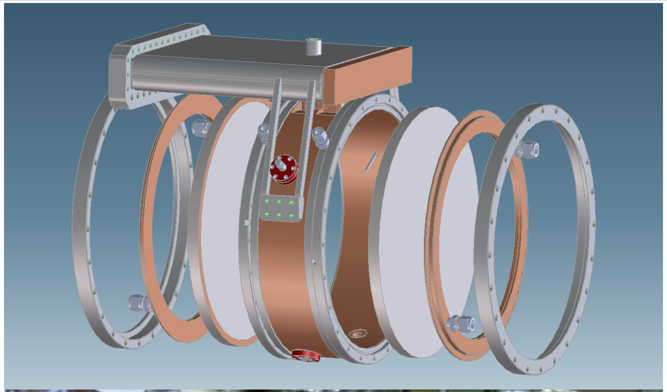
- Did operate it in all seasons!
- Limited by lack of cooling
- No heat treatment after machining
  - distorted during high-power operation
  - loss of contact/Q, vacuum seal problems
- Heavy-duty construction for high pressure
  - assembly/handling challenge
  - Limited clearance/provision for instrumentation
- Drop-in test plates clamped by external cover plates
  - simple bolt-together design (many bolts!)
- Many input configurations
  - hybrid, circulator
  - coupling issues at high power
- Practical experience
  - clean room assembly
  - optical inspection
  - control software, data analysis

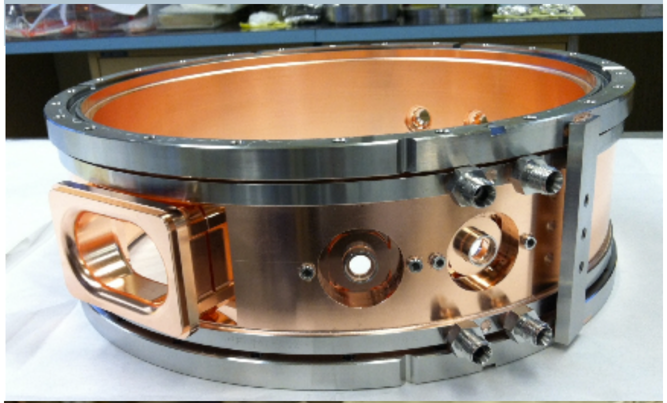


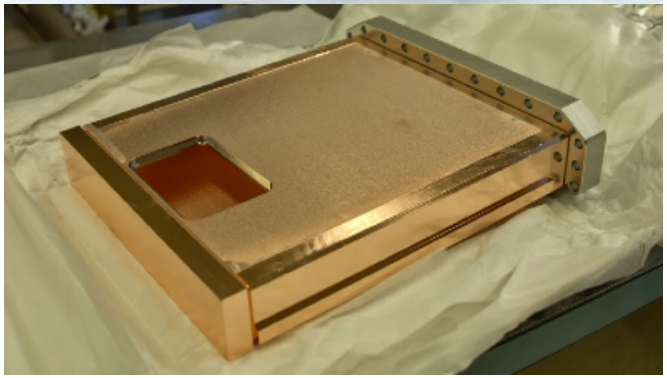
805-MHz Vacuum Cavity Program

Moving forward

- New modular cavity for detailed systematic studies (SLAC, LBNL)
  - Modular design for easy assembly, inspection, parts replacement
  - Removable endplates (initially Cu; Be, other materials, treated surfaces)
  - Coupling iris moved to center ring and field reduced (*more realistic design for cooling channel*)
  - RF design validated by detailed simulation
  - Ports for instrumentation
  - Inspection setup under preparation
  - Fabrication close to completion
  - Expected delivery to MTA: FY14 Q4
- Incorporates all lessons learned



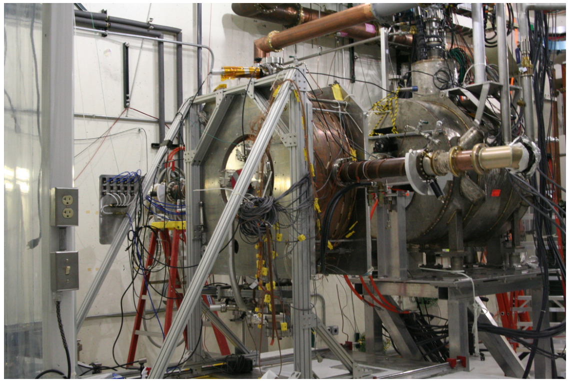


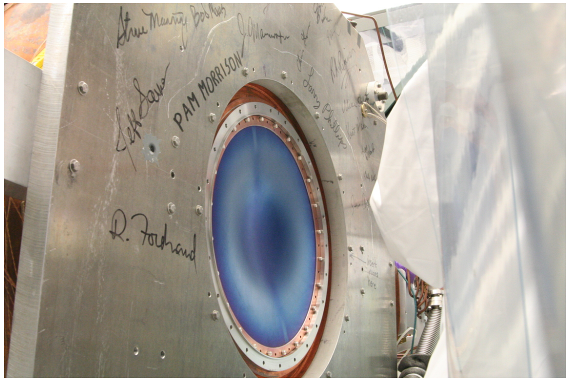


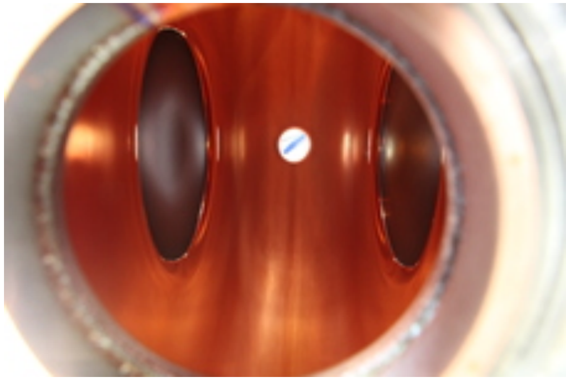
201-MHz Vacuum RF Program [Surface treatment, NF channel, MICE]

Muon Accelerator Program

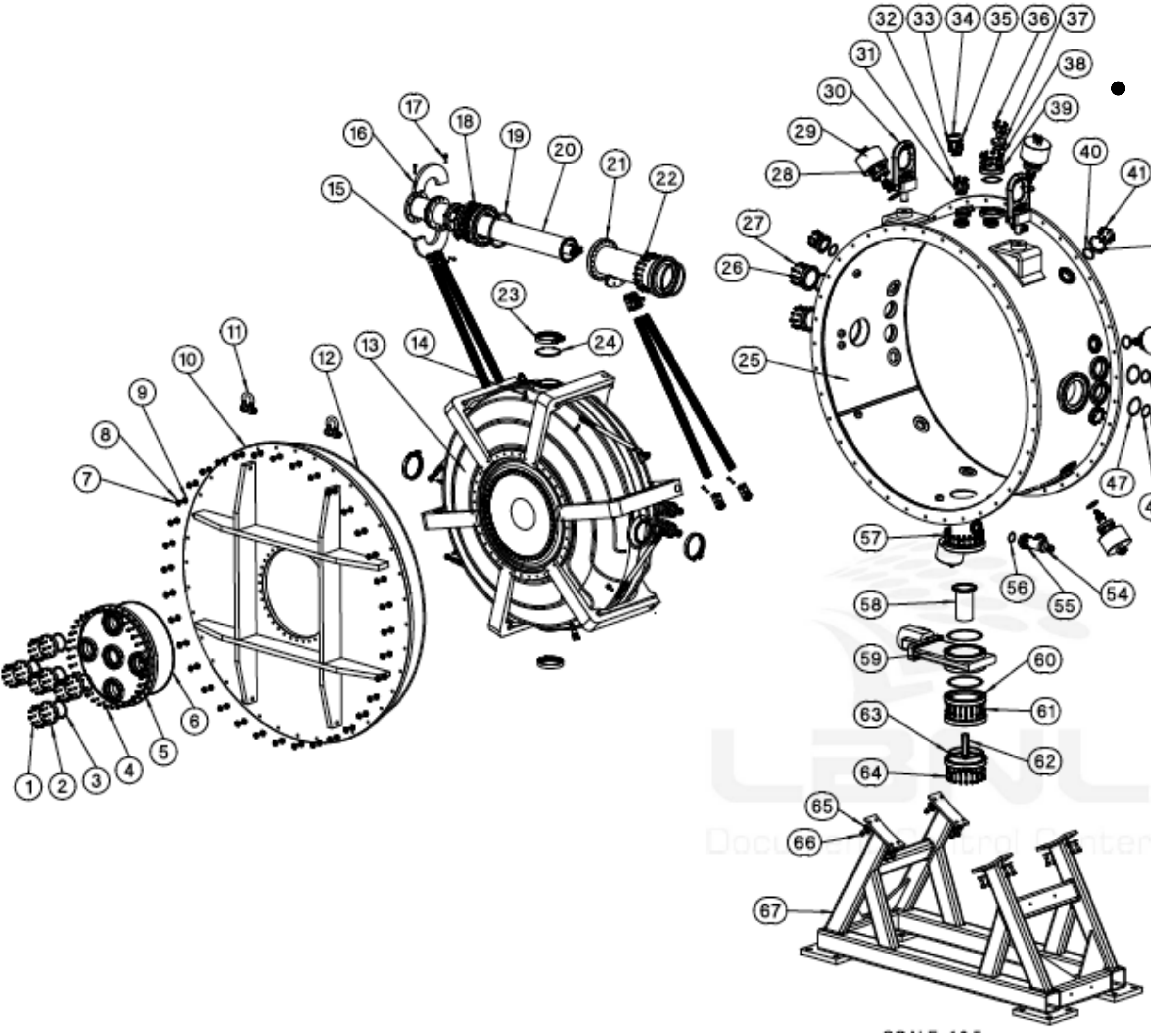
- 201-MHz MICE prototype cavity with SRF-like surface treatment (EP, HP rinse)
  - Conditioned to design gradient quickly
  - Demonstrated operation with large curved Be windows
  - Somewhat reduced performance in fringe field of solenoid
  - No surface damage seen on cavity interior
  - Some evidence for sparking in the coupler
    - Multi-pacting studied (T. Luo)
    - Design now modified
    - Also incorporated TiN coating
  - Radiation output measured (MICE detector backgrounds)
- Future
  - Commission/operate single-cavity vessel
  - Large diameter magnet (coupling coil) needed for field configuration closer to MICE/cooling channel



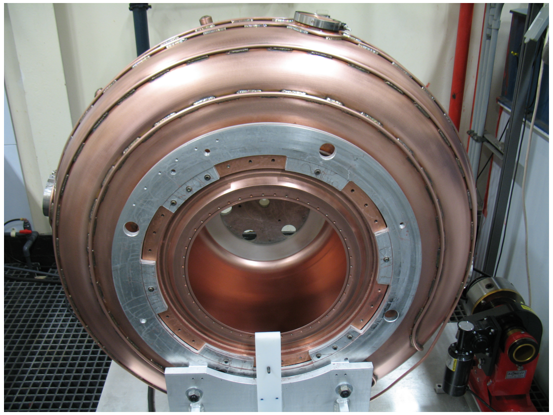




201-MHz Single-Cavity Module

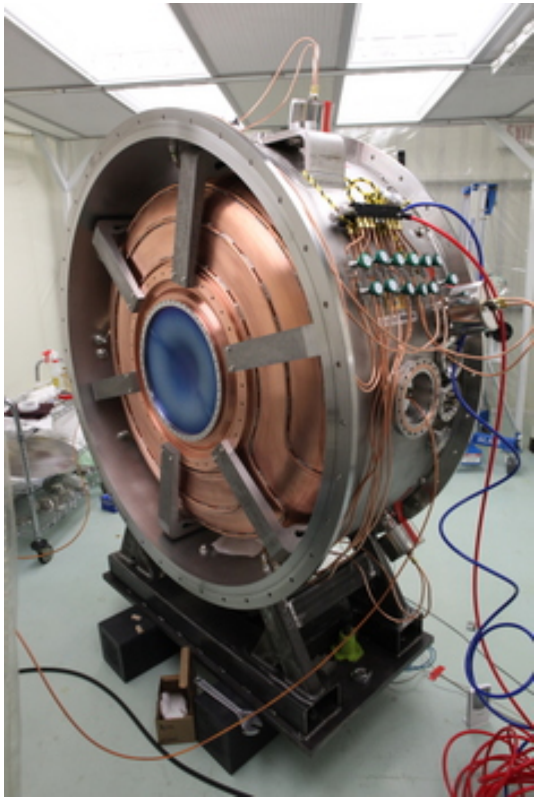


- MICE cavity in vacuum vessel for MTA test
- Components
  - 1st MICE cavity EP'ed at LBNL
  - Vacuum vessel built at Keller
  - Be windows to be reused
  - Actuators, couplers built at LBNL
  - Tuner forks built at FNAL

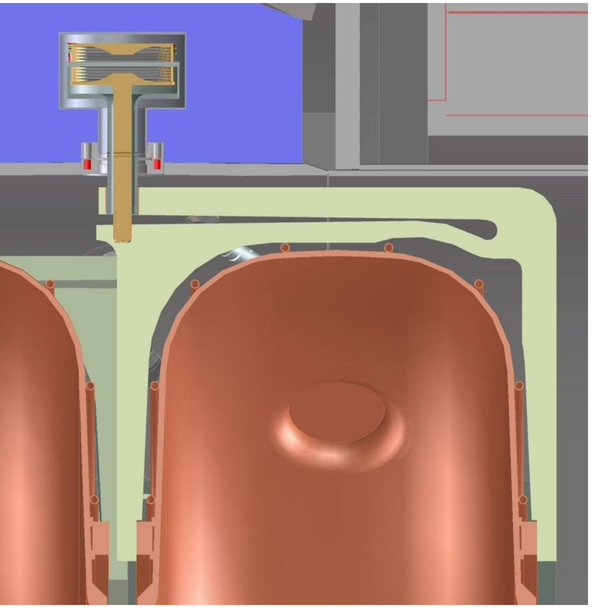


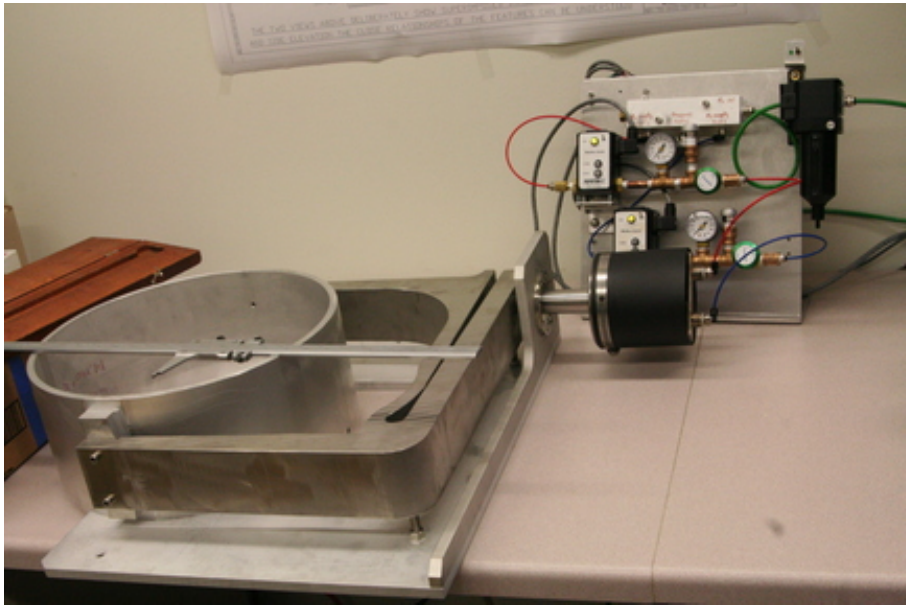
201-MHz Single-Cavity Module

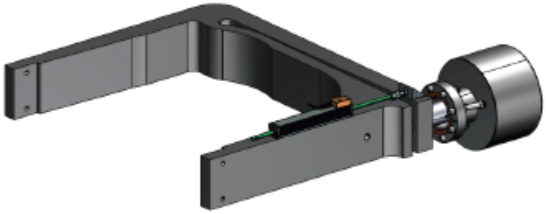
- Assembly/integration
  - Clean room prepared in Lab-6
  - Main assembly completed there
  - Transported to MTA
  - Tuner system tested
  - Hall infrastructure
    - Services mostly in place
    - Overhead crane installed
  - Expect operation Summer 2014
    - depends on RF source availability
  - beam test also under consideration
- Could be tested with the first Coupling Coil Magnet
  - Requires 6-month MTA shutdown

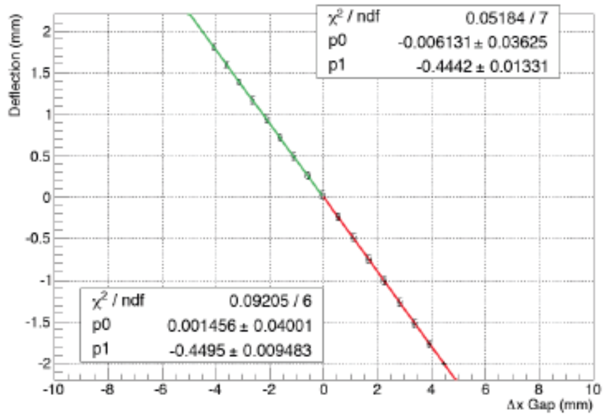


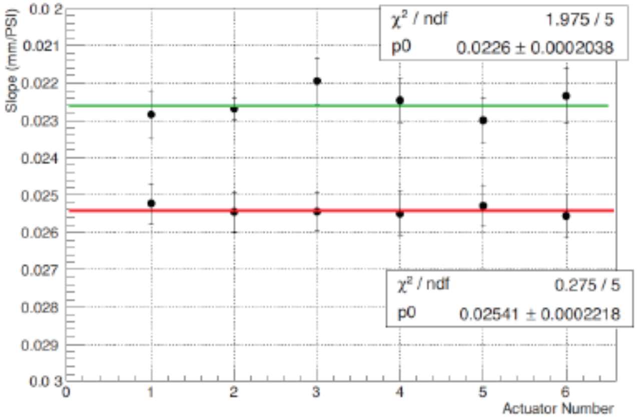
201-MHz Tuner System



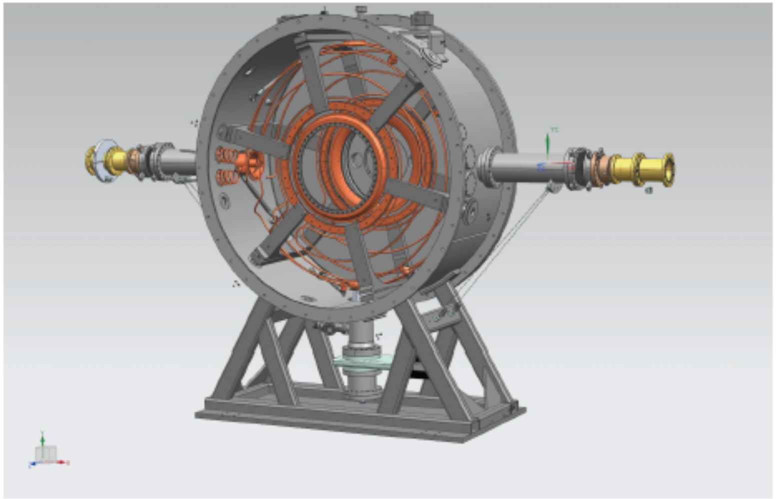


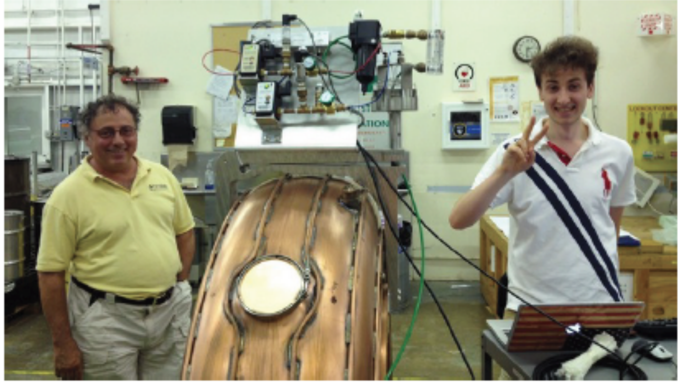


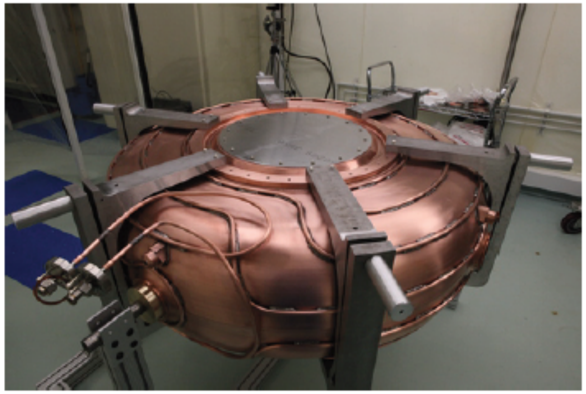




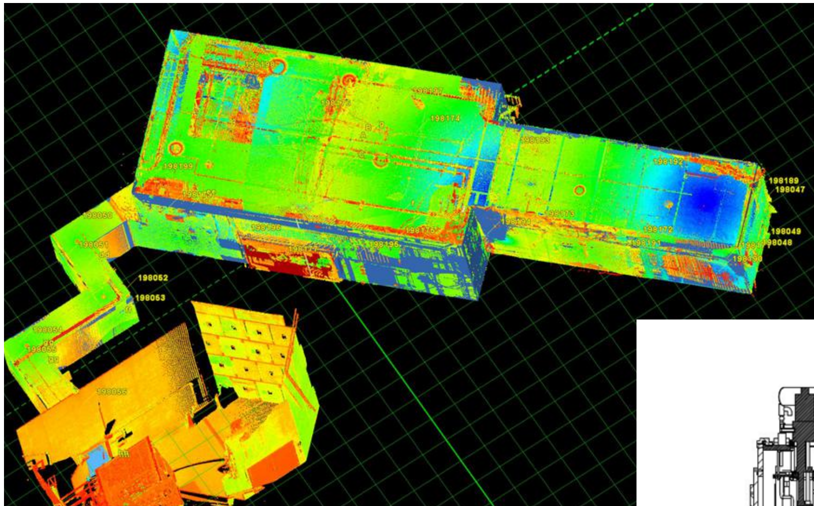
Assembly in Lab-6

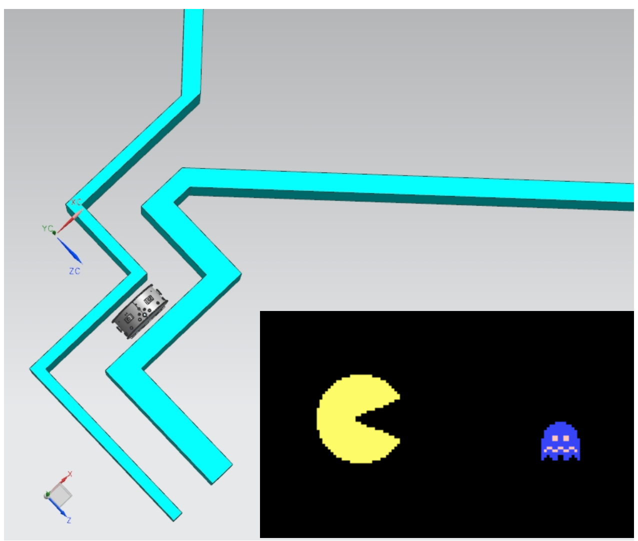


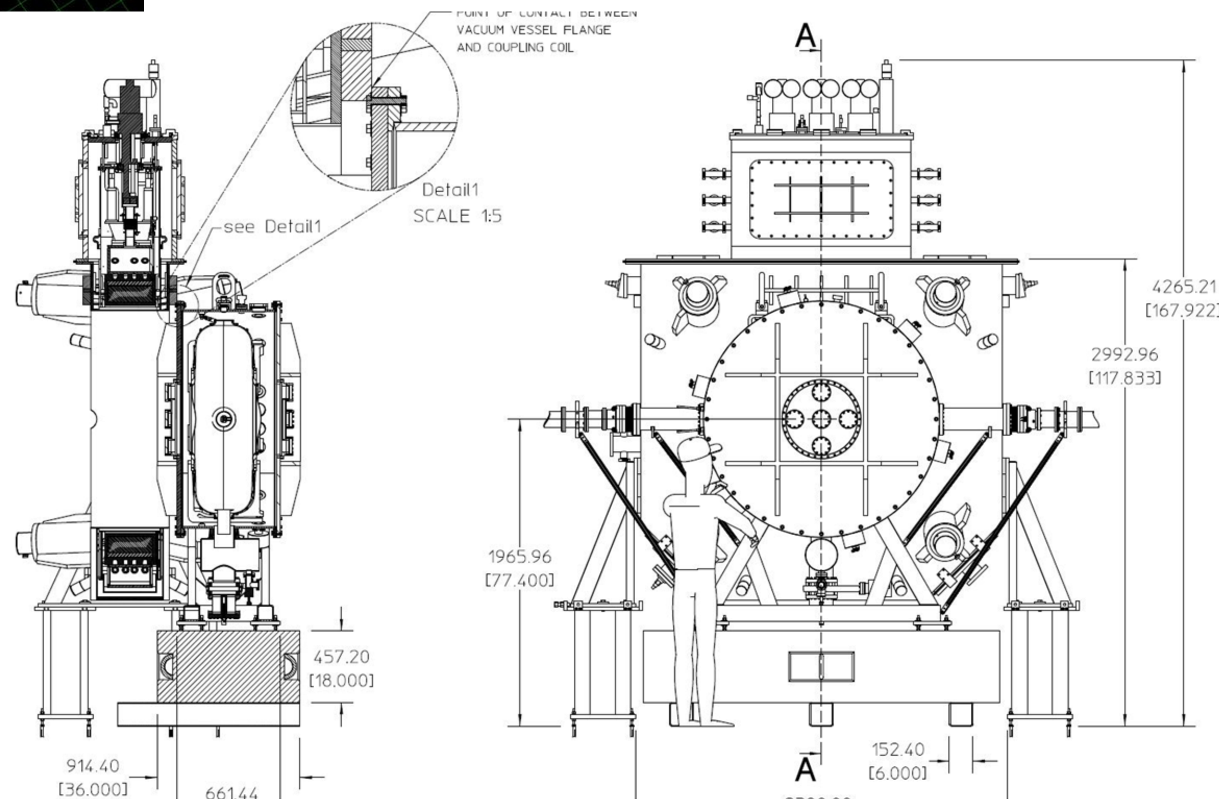




Transport to MTA

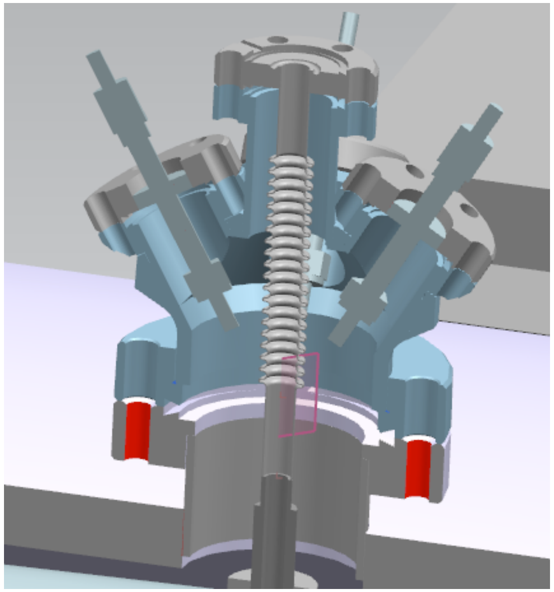


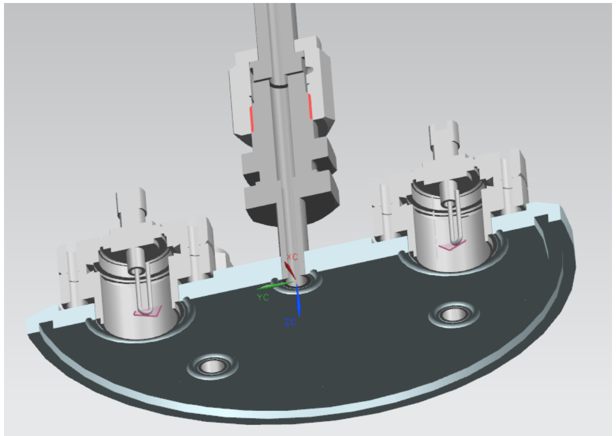


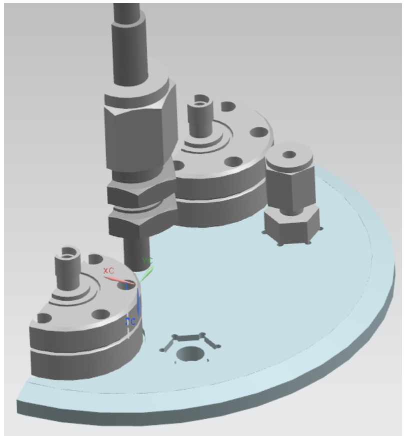


Diagnostics

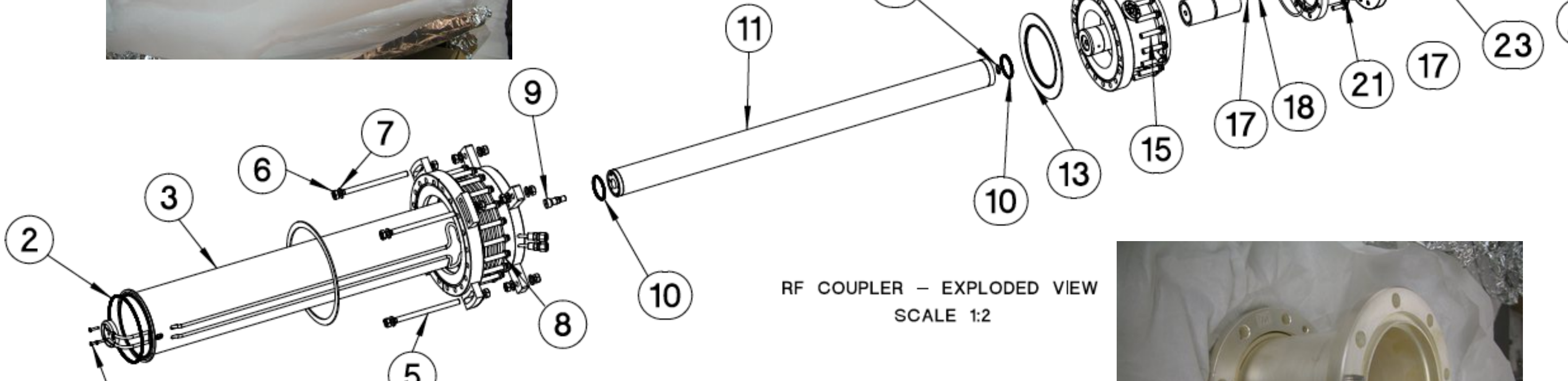
- Vessel
  - top plate for
    - RF pickups
    - cavity vacuum pickup
    - optical fibers
  - acoustic sensors tested on 805-MHz cavities
  - vacuum
  - Thermocouples
  - infrared sensor for window temperature
  - Faraday cup
- Couplers
  - directional couplers for forward/reverse power
  - vacuum
  - viewport/fibers
  - electron pickups
- External
  - air pressure (tuner control)
  - water temperature/pressure

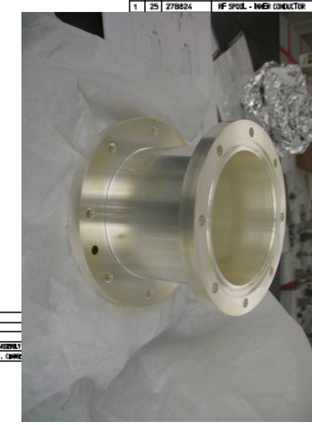






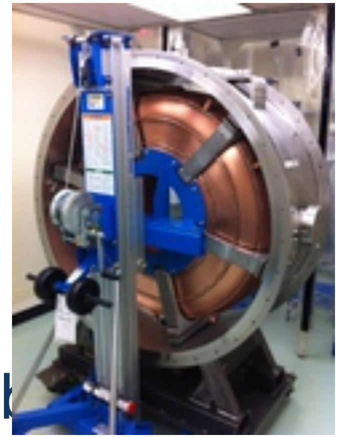
Coupler Fabrication at LBNL

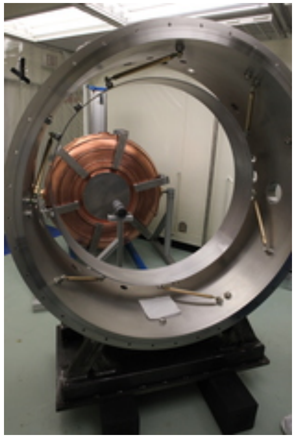




201-MHz MICE Single-Cavity Module Lessons learned

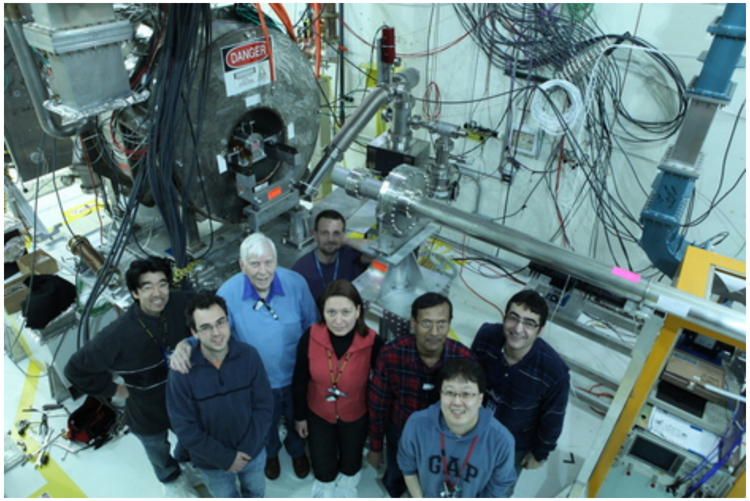
- Complete assembly sequence worked out
  - Modifications as needed
- Experience directly relevant to MICE RFCC module
  - Clean room practice
  - Assembly fixtures
  - Alignment tools
  - Tuner fork machining
  - Tuner transfer functions
  - Water feed-throughs, cooling tub
  - Support struts
  - Vacuum system
  - RF probes and other instrumentation
  - Possibly LLRF
- Reviewed at MICE RF Workshop (Jun 2-3, 2014)





805-MHz HPRF Cavity Program

- HPRF previously tested at the MTA
  - Dense H_2 gas buffers dark current while serving as ionization cooling medium
  - No B-field effect, 1 MV/m per atm H2
- 2 beam tests to evaluate response to high-intensity beam
  - Beam-induced plasma loads cavity
  - Mitigate with electronegative dopant
  - Wide range of parameters explored
  - Demonstrated operation with beam in 3T field
- Initial results published
  - Quantitative theory validated by measurement of energy loss in H2/D2+dopant
  - Dopants turn mobile ionization electrons into heavy ions, reducing RF losses by large factor
- Results extrapolate well to Neutrino Factory operation and a range of Muon Collider beam parameters
  - Plasma loading < beam loading
  - Bunch intensity limits being evaluated
- Also preparing for dielectric-loaded HPRF cavity test to enable smaller coils in HCC



PRL **111,** 184802 (2013) PHYSICAL REVIEW LETTERS week ending 1 NOVEMBER 2013

Pressurized H_2 rf Cavities in Ionizing Beams and Magnetic Fields

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(Received 12 July 2013; published 29 October 2013)

Measured (for H2/D2+dry air)

- Energy loss/e-ion pair/RF cycle
- e attachment time to oxygen
- Ion-ion recombination rates

Analysis of rest of the data close to completion

Plasma Loading in HPRF Beam Test