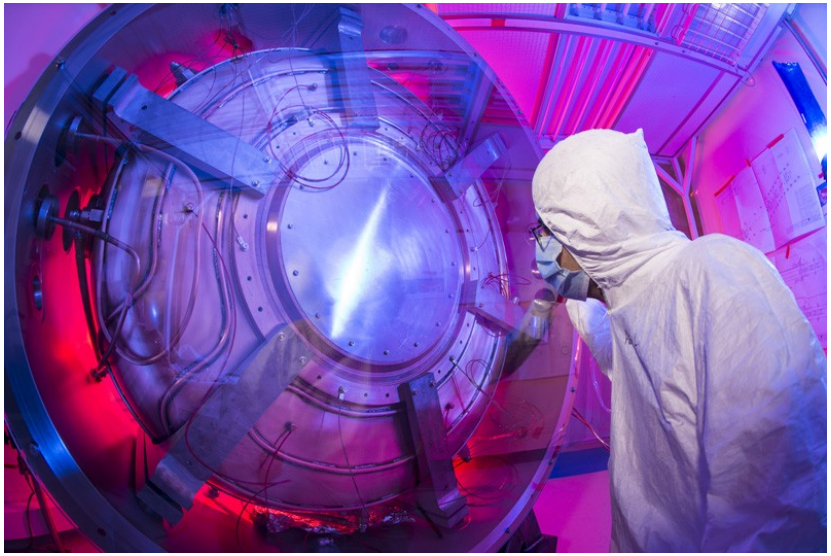
RF Technology Demonstrations For Future Cooled-Muon Accelerators



APT Seminar

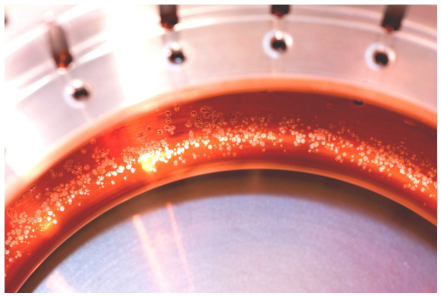
Daniel Bowring

FNAL

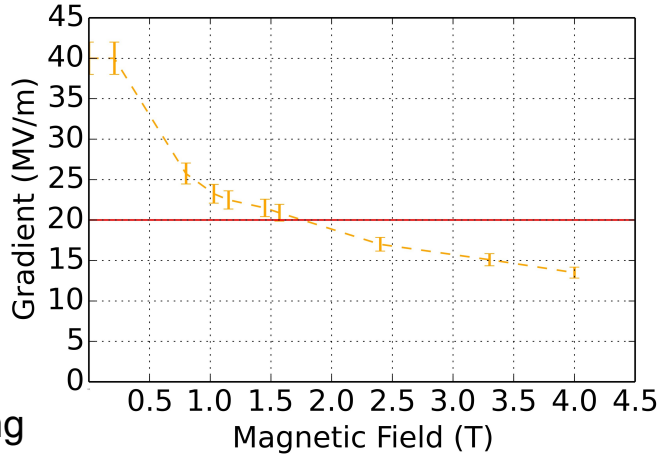
May 19, 2015

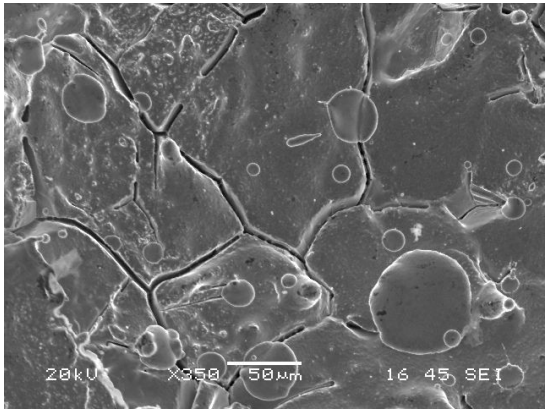
A statement of the problem

- RF breakdown limits the performance of accelerating cavities.
- Compounded when cavities operate in multi-Tesla magnetic fields.
  - Required for muon ionization cooling
  - Applies also to R&D for photoinjectors, klystrons, etc.
- For this talk, maximum "safe" gradients are defined by spark rates < 1e-5.

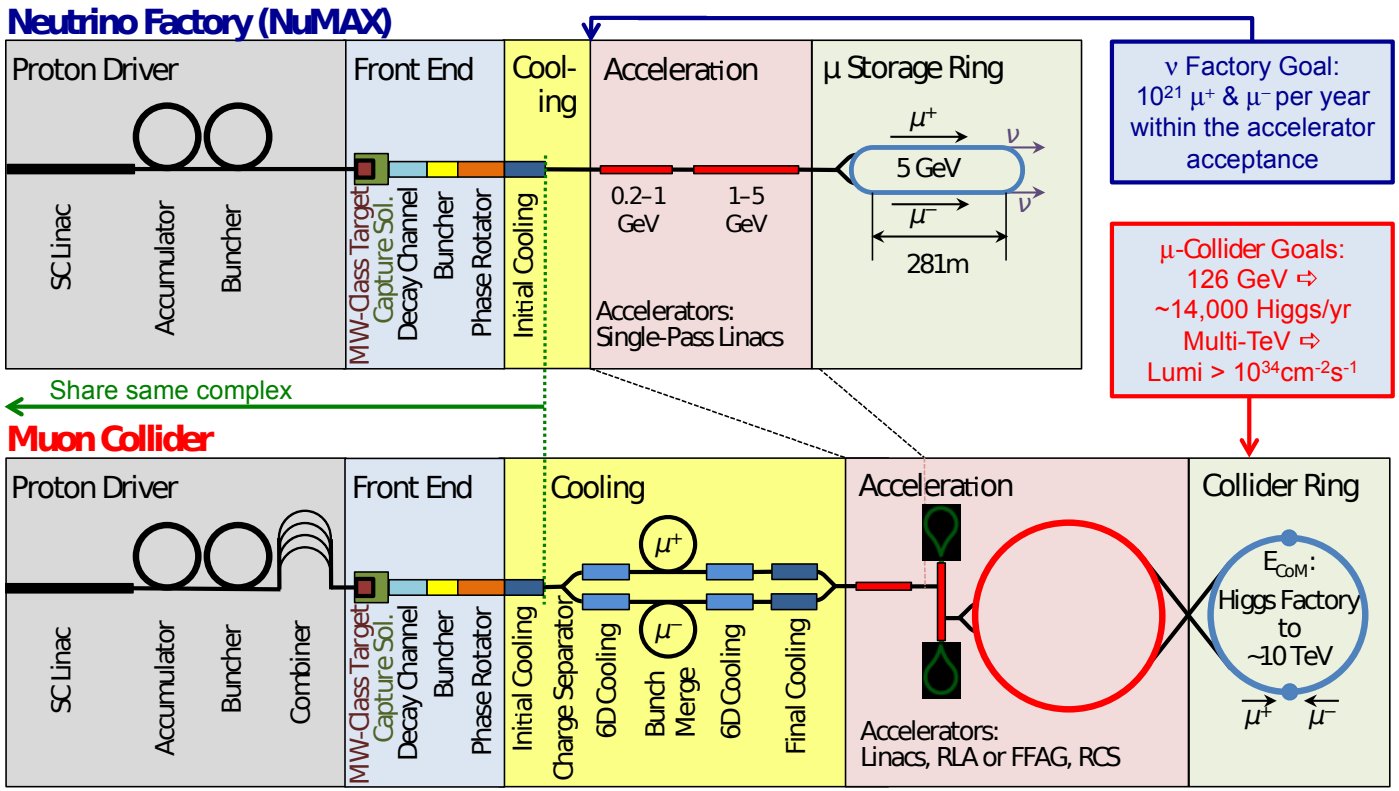


805 MHz pillbox cavity showing breakdown damage.



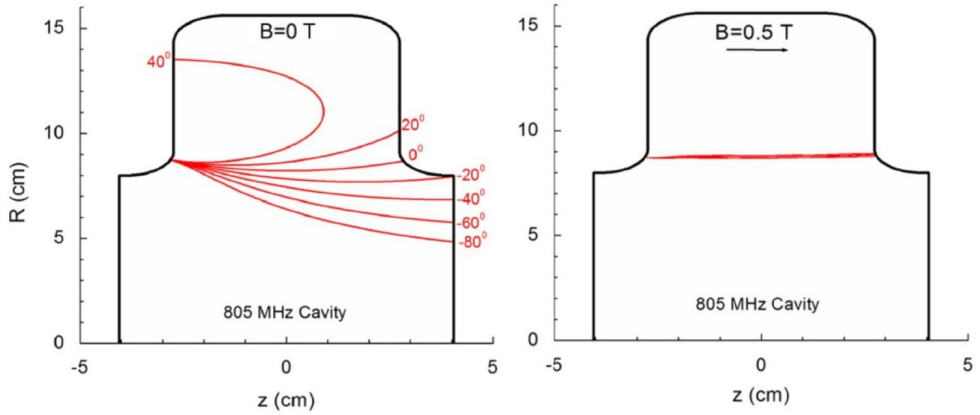


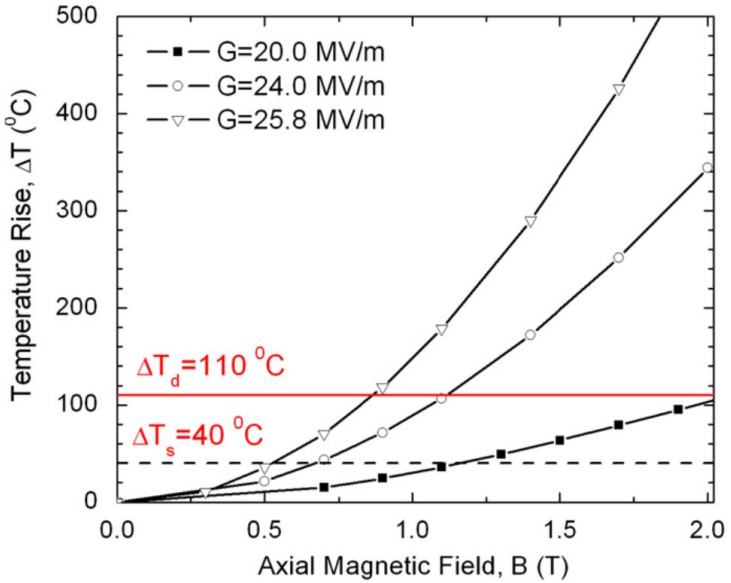
What gradients are required?



- Feasibility assessment documents specify 15 MV/m in buncher, 20 MV/m in phase rotator, and 25 MV/m in the cooler.

We have a model that describes the influence of multi-Tesla *B*-fields on breakdown rates.

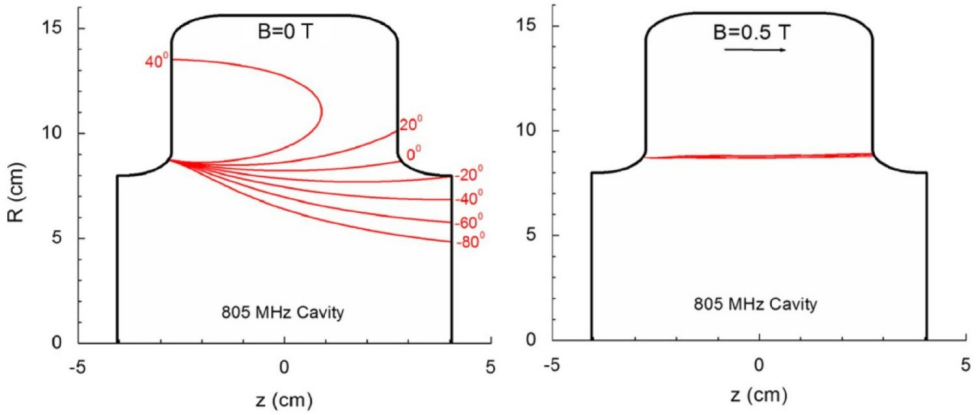




- D. Stratakis, *et al.*, NIMA **620**, 2010, pp147-154.
- Field emission from surface defect
- Solenoid focuses FE current into "beamlets".
- Beamlets persist for multiple cycles, causing pulsed heating, damage.

- ΔT_d = temperature rise threshold for plastic deformation of surface
- c.f. S.V. Kuzikov, M.E. Plotkin, Int. J. Infrared Milli. Waves **29** (2008) 298.

How can we operate cavities in these conditions?



(0) Circumvent problem: fill cavities with high-pressure gas.

(1) Polish and clean cavity surfaces using SRF best practices.

(2) Reduce impact energy of beamlets.

(3) Increase radiation length of cavity surfaces so less energy is deposited by beamlets.

Several RF R&D milestones for ionization cooling technology have been met recently.

(1) The 201 MHz MICE prototype cavity has been run above its design gradient with and without B-field.

- Zero breakdown in both cases.

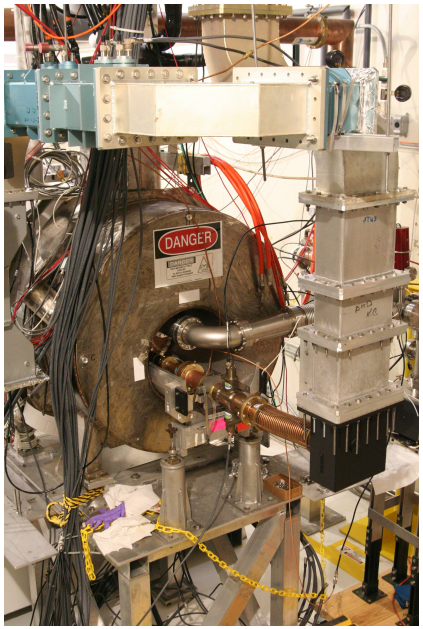
(2) We have demonstrated a solution to the problem of breakdown in B-fields.

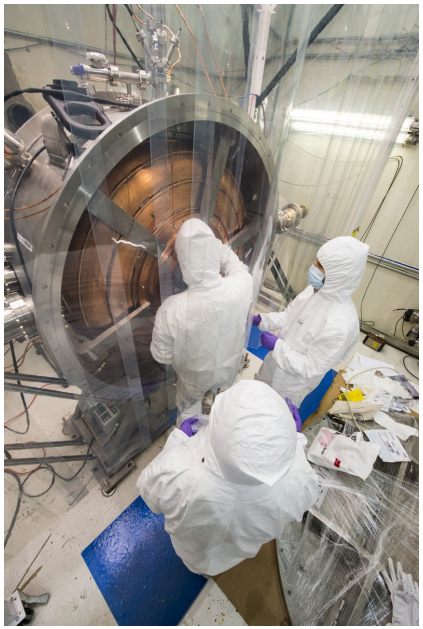
- A cavity filled with high pressure gas has operated at 65 MV/m with and without magnetic field.

(3) Significant progress has also been made with “traditional” vacuum RF cavities.

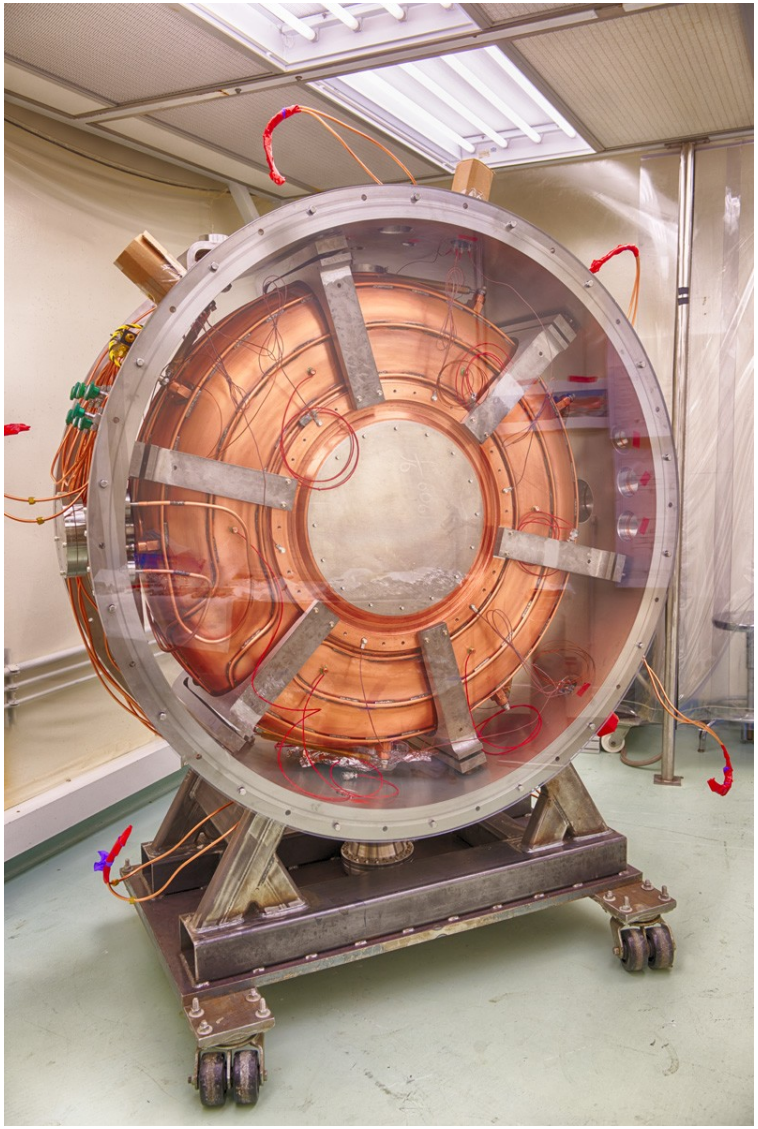
- Model of breakdown in B-fields supported by recent measurements.
- Several 805 MHz cavities demonstrate gradients in 5 T adequate for muon front end components.

The RF tests described here were conducted at Fermilab's MuCool Test Area (MTA).

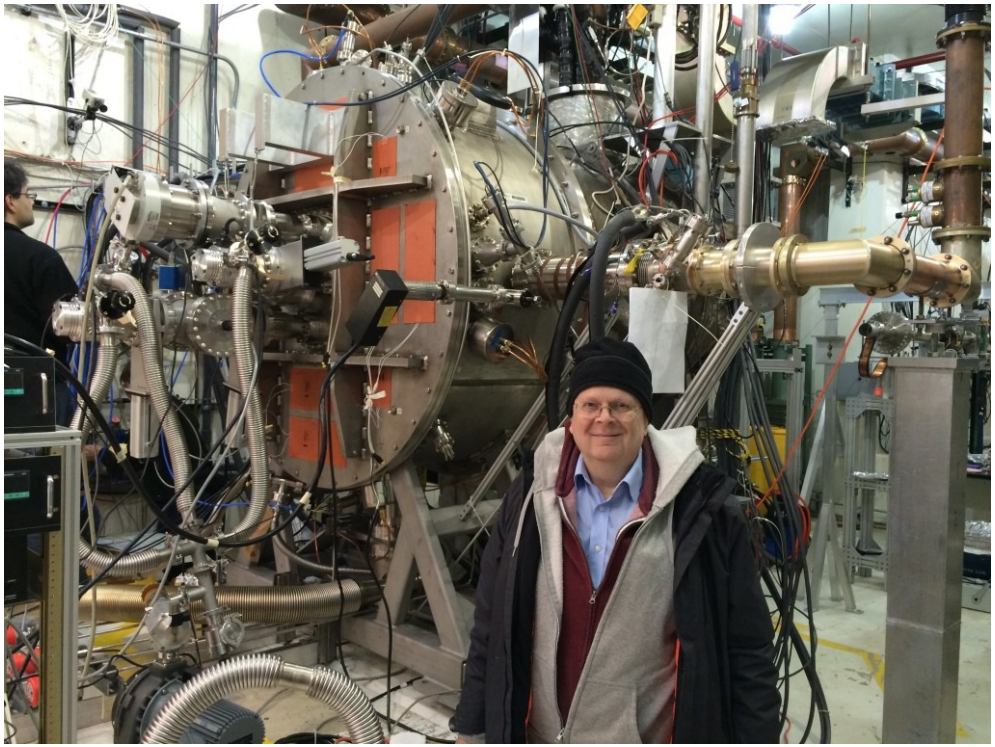




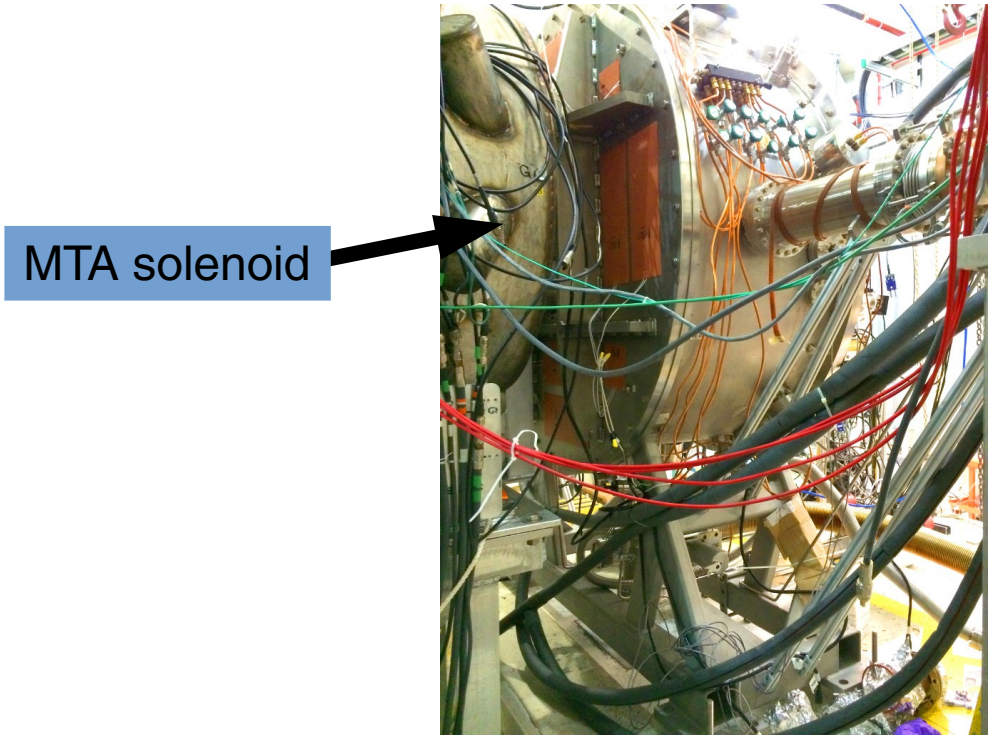
- 400 MeV H- beamline
- RF power at 201 MHz (4.5 MW) and 805 MHz (12 MW)
- 5 Tesla superconducting solenoid (& cryo plant) aligned with beamline
- Class 100 portable clean room
- Extensive instrumentation & detectors
- DAQ, control in Linac gallery
- Much more MTA news on Thursday afternoon, Friday.

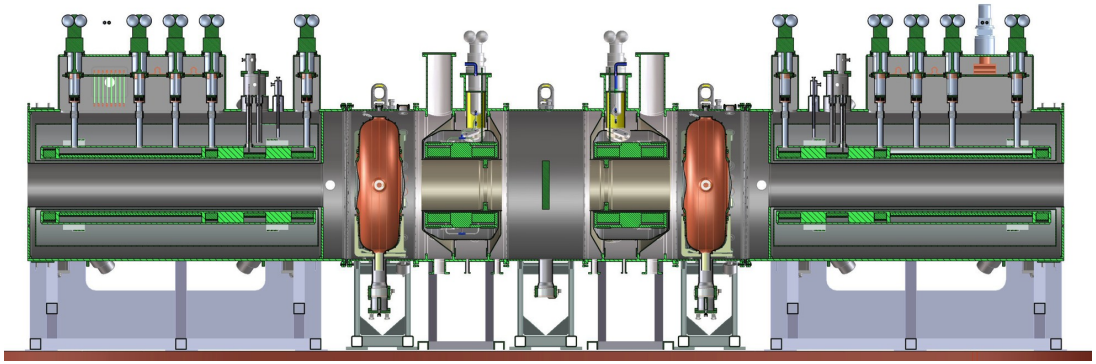


(1) The 201 MHz MICE prototype cavity has been run above its design gradient with and without B-field.



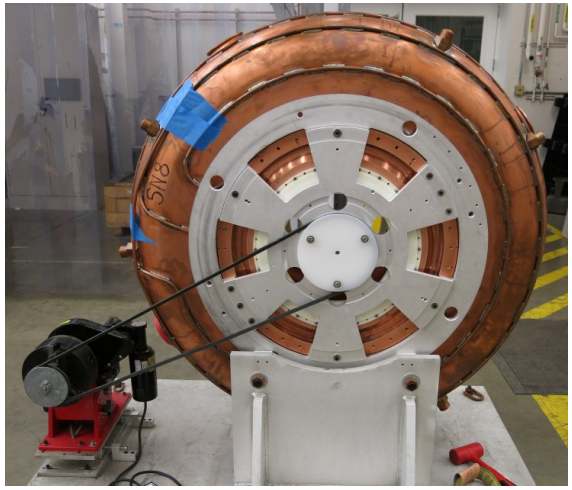
201 MHz prototype cavity operated in fringe field of MTA solenoid, similar to MICE configuration.

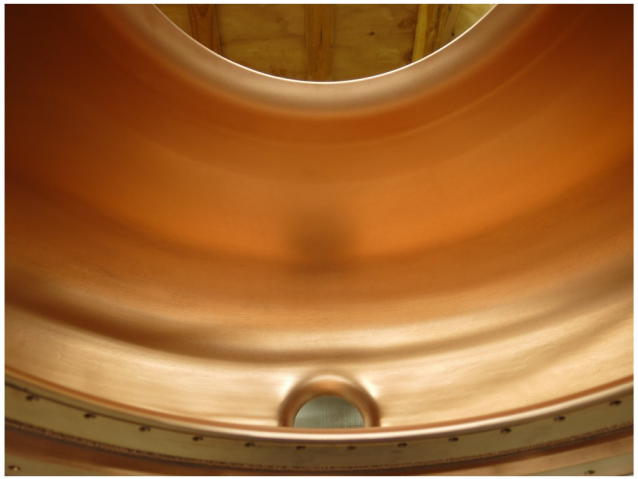


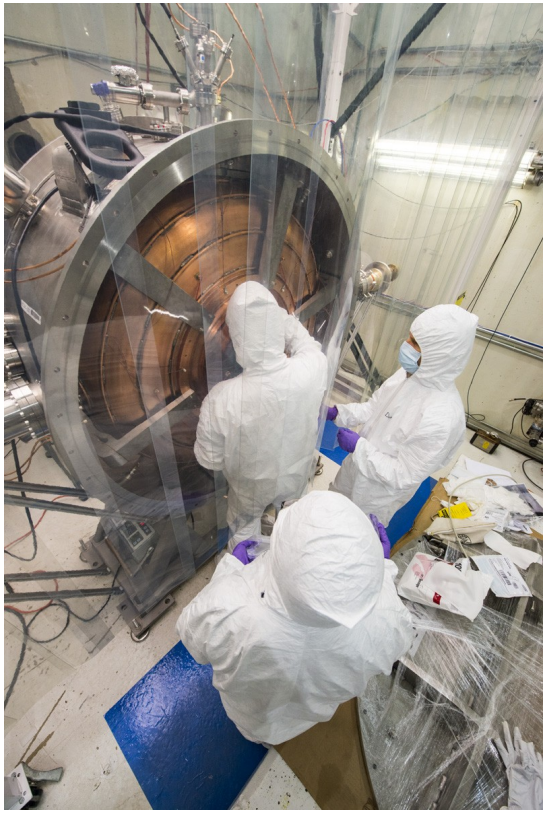


- MTA solenoid at 5 T:
  - 0.33 T @ upstream wall
  - 0.17 T @ midplane
  - 0.10 @ downstream wall
- Coupler simulated & optimized for operation in B-field.

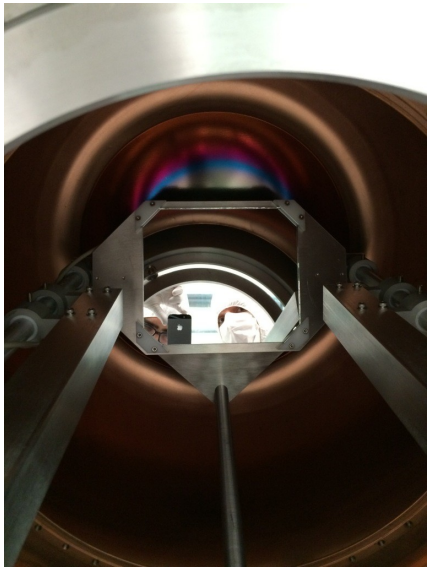
The cavity was electropolished & assembled in a clean room.







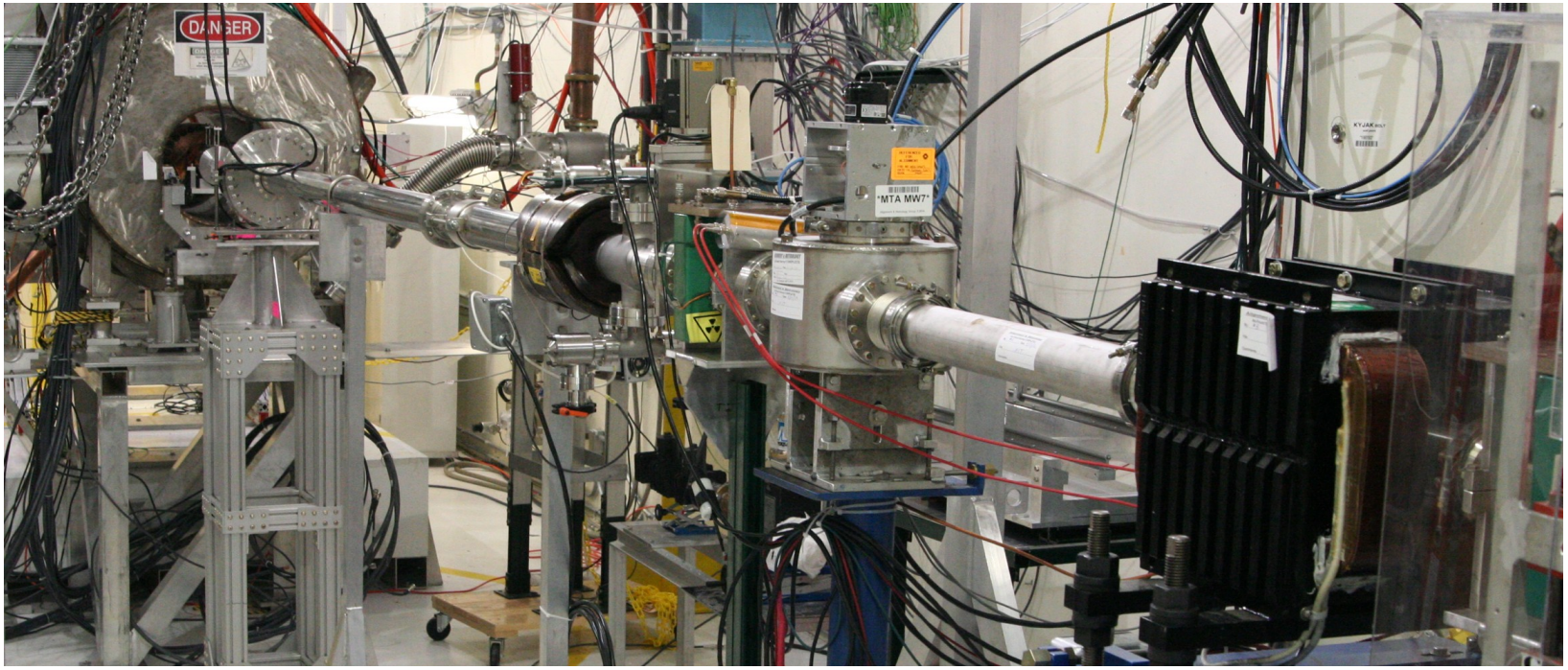
- EP reduces concentration of potential field emitter sites on cavity surface.
- **No evidence yet of breakdown on surfaces prepared in this way.**



Status and Ongoing Work

- ✔ B = 0 run complete (March 18 – April 6).
  - > 350 hours of continuous running, > 6M pulses
  - 0.5M+ pulses at 11 MV/m (MICE baseline is 10.3 MV/m).
  - **No breakdown events observed.**
- ✔ B > 0 run complete (April 24 – May 4).
  - 6M pulses total: 1M pulses at 1 MW (8 MV/m) and 3M pulses at 1.6 MW (10.7 – 11.2 MV/m).
  - **No breakdown events observed.**
- Get 3M pulses @ 3.1 MW, study high-power behavior. (1.5M+ as of this a.m.)
- Tuner systems tests: measure transfer function, etc.
- Alvin Tollestrup will present some interesting physics results on Friday morning.

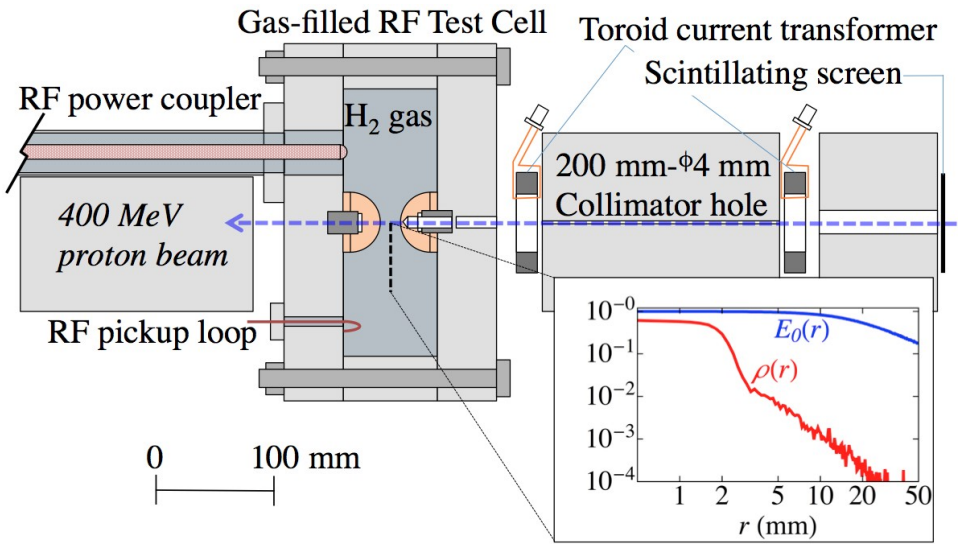
This is a very significant milestone for MICE!

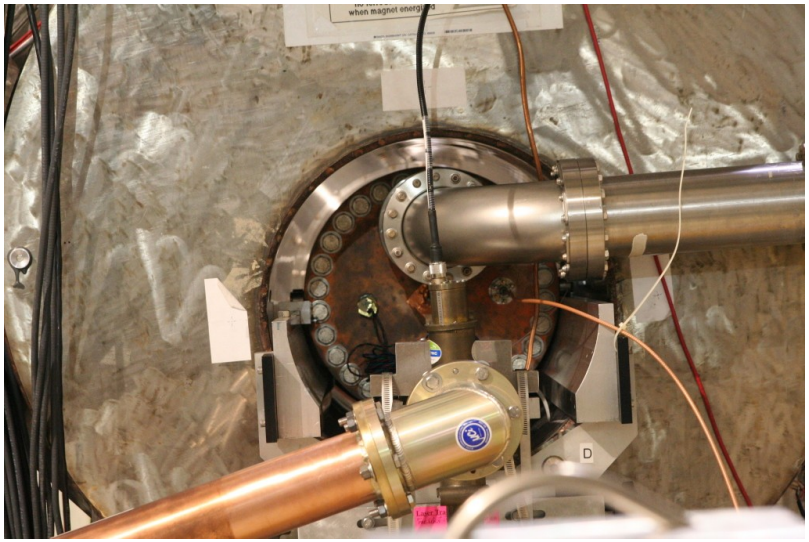


(2) We have demonstrated a solution to the problem of breakdown in B-fields.

- A cavity filled with high pressure gas has operated at 65 MV/m with and without magnetic field.

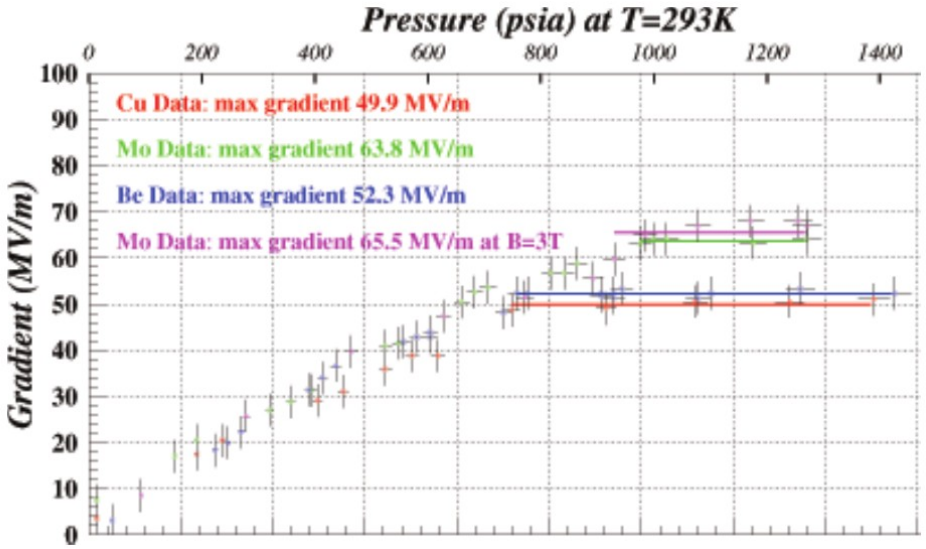
Fill cavity with H2 up to 100 atm: gas suppresses breakdown.

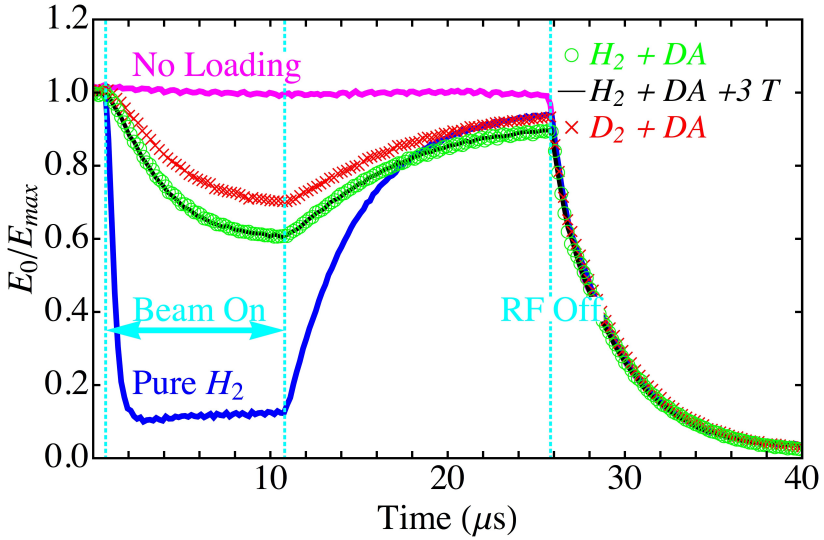




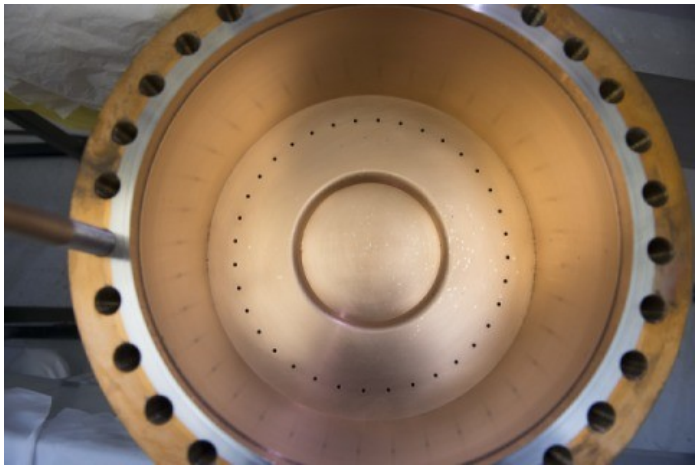
- c.f. Dave Neuffer's talk earlier today. Others will address this technology in depth on Wednesday and Friday.

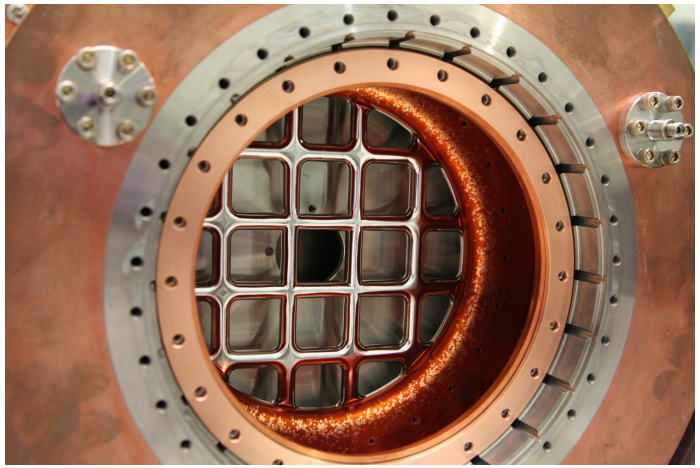
A demonstrated path to a solution: RF filled with high-pressure gas





- K. Yonehara *et al.,* Proc. IPAC'12. + M. Chung *et al.,* PRL **111** 2013, 184802.
- Up to 65 MV/m demonstrated in $B = 3$ Tesla.
- Gas suppresses breakdown, electronegative doping mitigates beam loading.

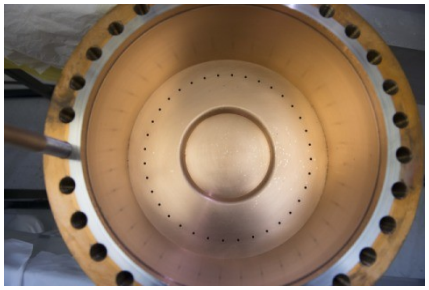


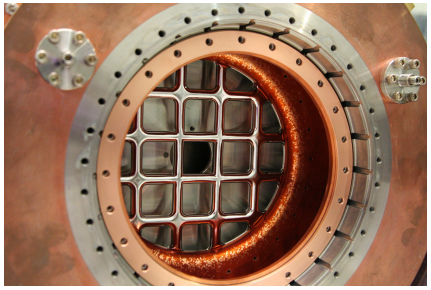


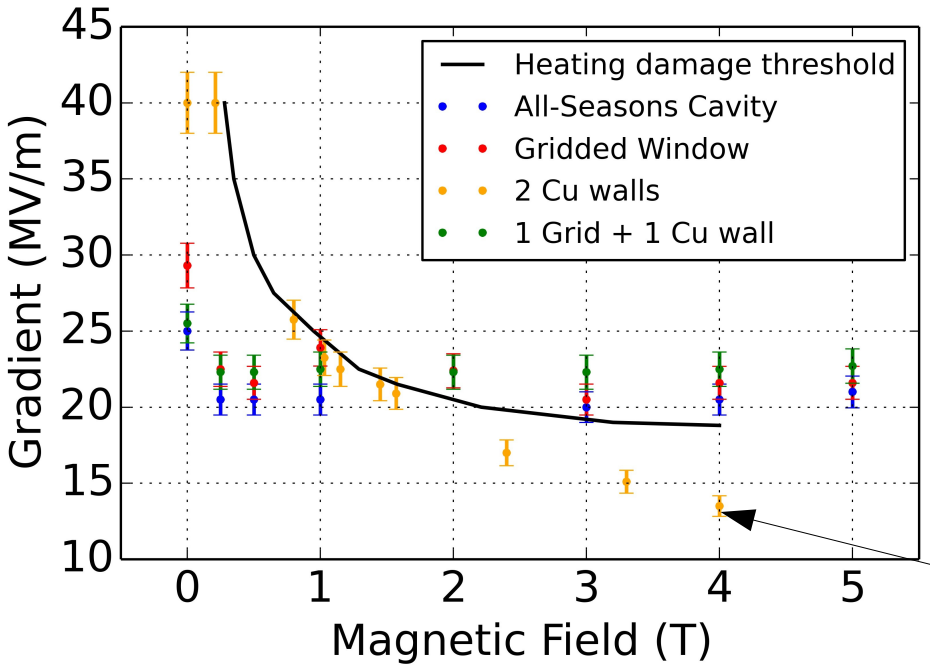
(3) Significant progress has also been made with "traditional" vacuum RF cavities.

- Model of breakdown in B-fields supported by recent measurements.
- Several 805 MHz cavities demonstrate gradients in 5 T adequate for muon front end components.

Measurements on several 805 MHz cavities support our model of RF breakdown in B-fields.







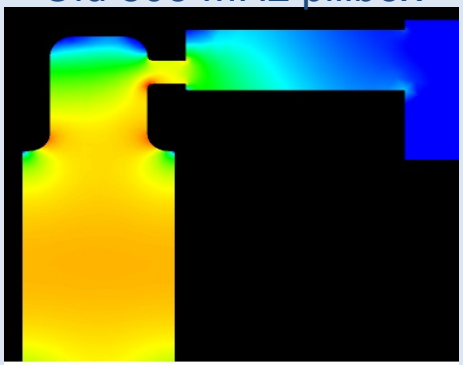
No surface prep for this cavity.

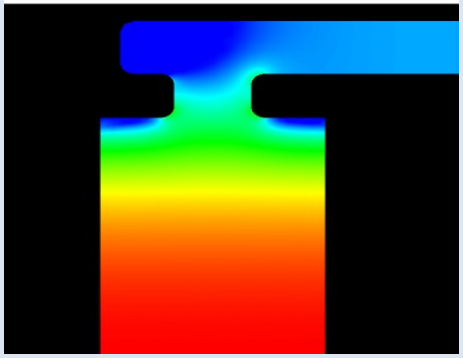
- **> 20 MV/m at 5 T for 2+1 cavities.**
- Black line indicates threshold for plastic deformation from cyclic beamlet heating.
- Fit quality affected by conditioning history, coupler effects.

The 805 MHz "Modular Cavity" directly addresses the issues of conditioning history & coupler effects.

Surface E-field at couplers is < 1/5 that at cavity axis.

Old 805 MHz pillbox

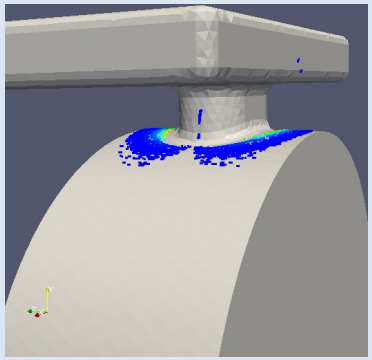


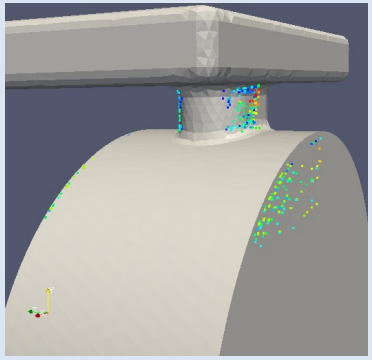


Modular cavity

Multipacting is optimized over a range of *B*-field values.

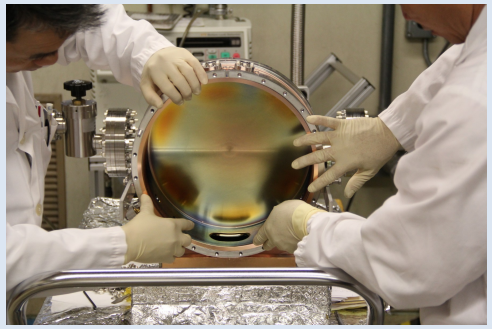
B = 0 Tesla





B = *3* Tesla

End walls easily removed for inspection, materials studies.



Chemically polished to minimize surface roughness.

Not shown: Extensive instrumentation (e.g. Faraday cup), cooling circuits. Improved DAQ.

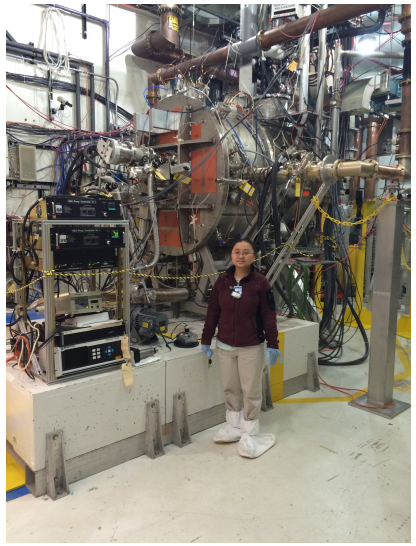
Status & future plans

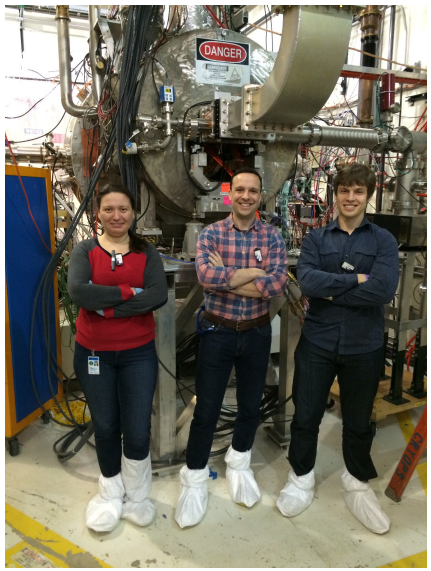
1) **Successful performance validation of 201 MHz prototype cavity in MTA.**

2) Modular cavity commissioned to 30 MV/m (B = 0) with ~10 sparks. Klystron maintenance underway. Will resume ASAP when MICE prototype finishes its current run.

3) Modular cavity tests include:

   - Determine maximum gradient for $0 < B < 5$ T with Cu and Be walls. (Be walls permit detailed x-ray, dark current measurements.)
   - Establish "lifetime" of Cu surface: observe spark rate over millions of pulses for $B > 0$.
   - Beam tests w/ Be walls.

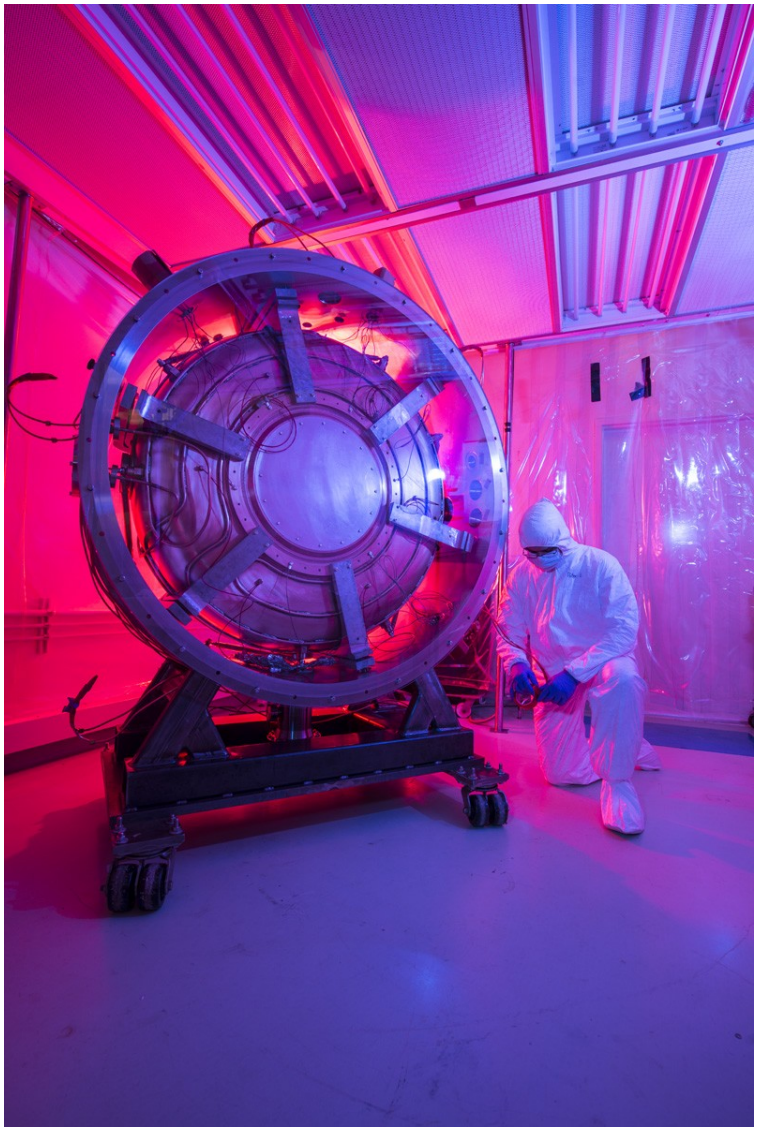




Conclusions

1) Observed behavior consistent with our model:
   - Careful surface preparation is crucial to controlling breakdown in B-fields.
   - Stable gradients in B-field when coupler & surface effects are eliminated.
2) SRF-style surface preparation techniques have enabled the 201 MHz MICE prototype to condition rapidly and spark-free, with and without B-field.
3) We have demonstrated > 20 MV/m operation of 805 MHz cavities at $B = 5$ T. This is sufficient for much of the front end in a high-intensity muon accelerator. The modular cavity will give clear guidance on gradient w/ low systematics.
4) Using RF cavities with high-pressure gas, we have demonstrated a general solution to the cooling problem.

Thanks for your attention!



- Many people have worked hard to deliver these results. Too many to list here!
- MTA shift heroes, March 18 – May 24 :

Michael Backfish
Ben Freemire
Terry Hart
Alexey Kochemirovskiy
Peter Lane
Maria Leonova
Tianhuan Luo
Al Moretti
Dave Neuffer
Dave Peterson
Milorad Popovic
Tim Stanley
Yagmur Torun
Colin Whyte

Thanks also to Fernanda Garcia and the Linac crew!