RF Breakdown of 805 MHz Cavities in Strong Magnetic Fields

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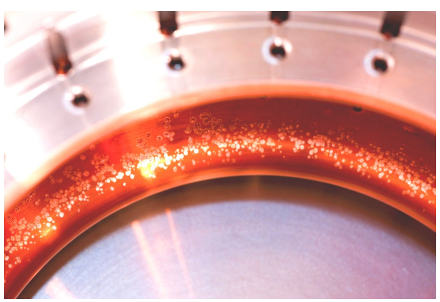
Thanks to those who contributed to this talk.

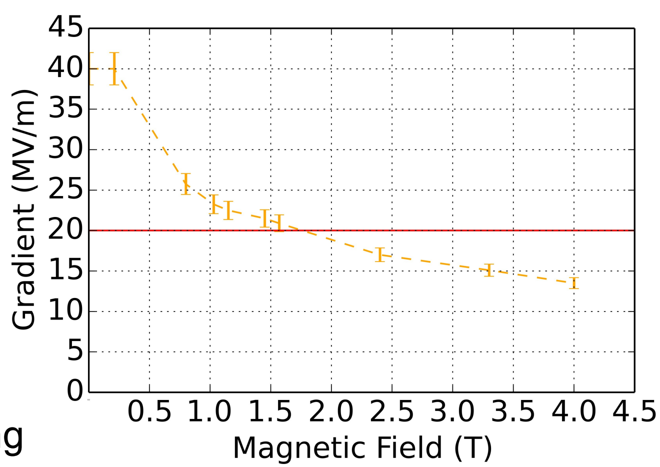
- At Fermilab:
  - A. Kochemirovskiy, M. Leonova, A. Moretti, M. Palmer, D. Peterson, K. Yonehara
- At IIT:
  - B. Freemire, P. Lane, Y. Torun
- At BNL:
  - D. Stratakis
- At SLAC:
  - A. Haase
- Plus the support and insight from many others in MAP!

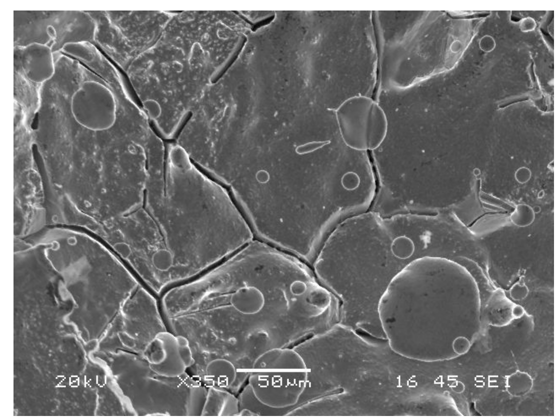
A statement of the problem

- 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.

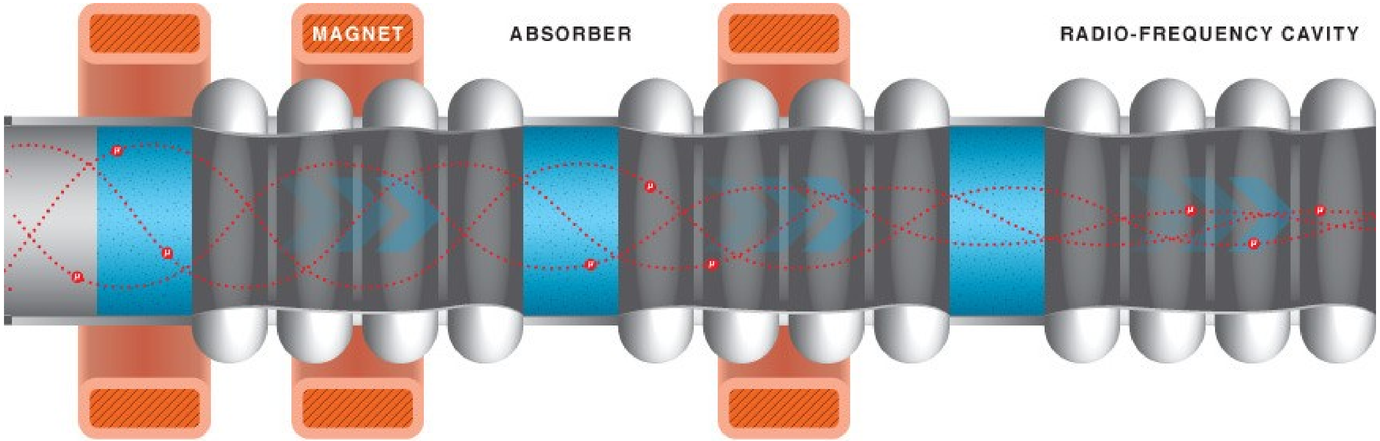




Talk overview

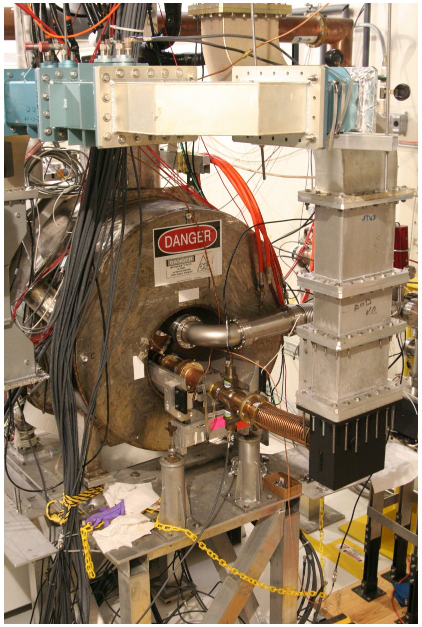
- We have a model that explains this behavior and experimental data that supports the model.
- Applying this model to cavity design:
  - MICE prototype cavity commissioned to its design gradient with essentially no breakdown. (Operating now in MICE-like *B*-fields with order-zero sparks.)
  - Multiple 805 MHz cavities have demonstrated > 20 MV/m in $B = 5$ Tesla.
    - Adequate for many of the accelerator components in the NF and MC that require RF operation in magnetic field. (D. Neuffer)

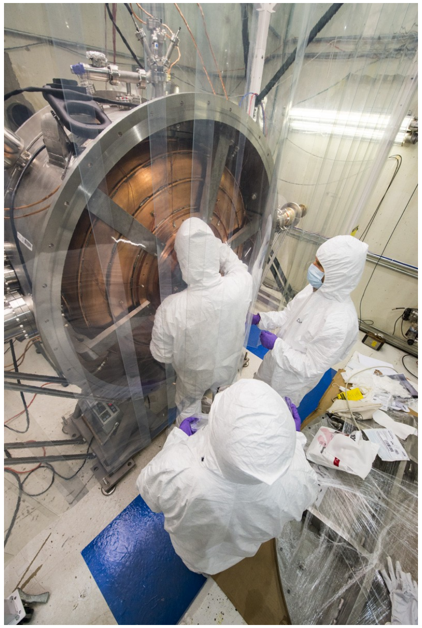
Ionization cooling in a nutshell



- Absorbers isotropically attenuate muon momenta.
- Longitudinal momentum replaced by RF cavities.
- Focusing via solenoids
- **Ionization cooling R&D at Fermilab indicates multi-Tesla magnetic fields increase the rate and extent of RF breakdown in Cu cavities.**

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

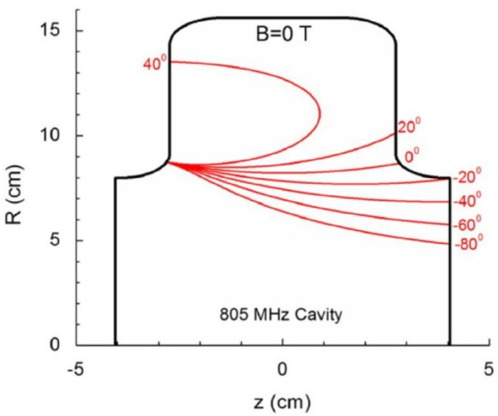




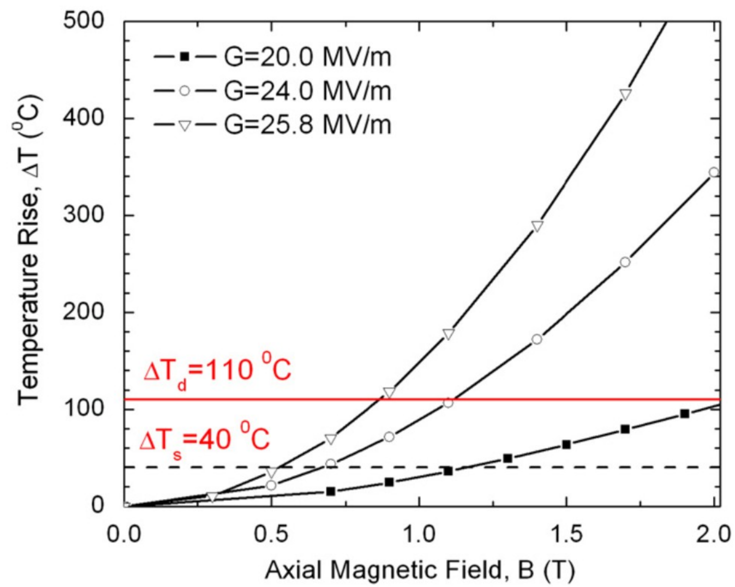
- 400 MeV H- beamline
- RF power at 201 MHz (4.5 MW) and 805 MHz (12 MW)
- 5 Tesla superconducting solenoid (& cryo plant) aligned with beamline
- Class 100 portable clean room
- Extensive instrumentation & detectors
- DAQ, control in Linac gallery

Y. Torun, WEPTY053

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



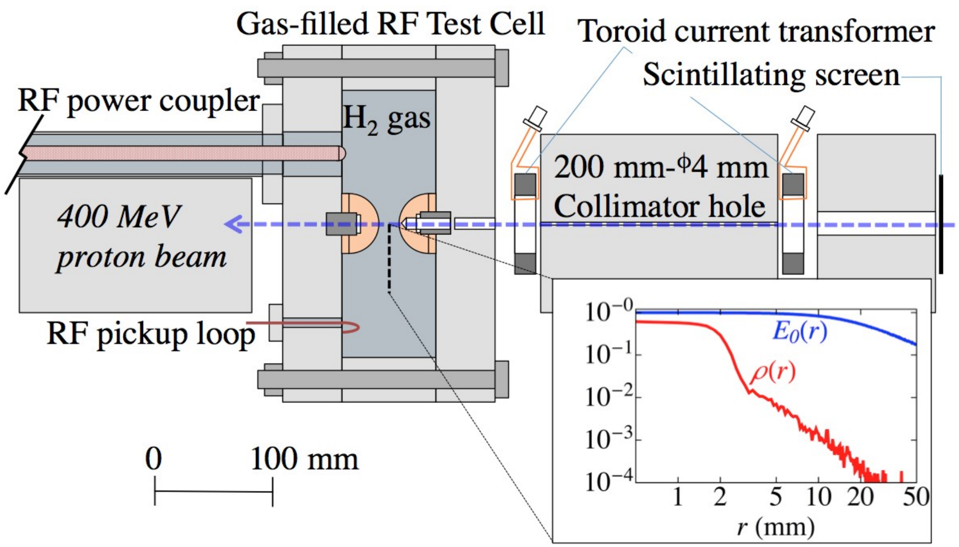
- D. Stratakis, *et al.*, NIMA **620**, 2010, pp147-154.

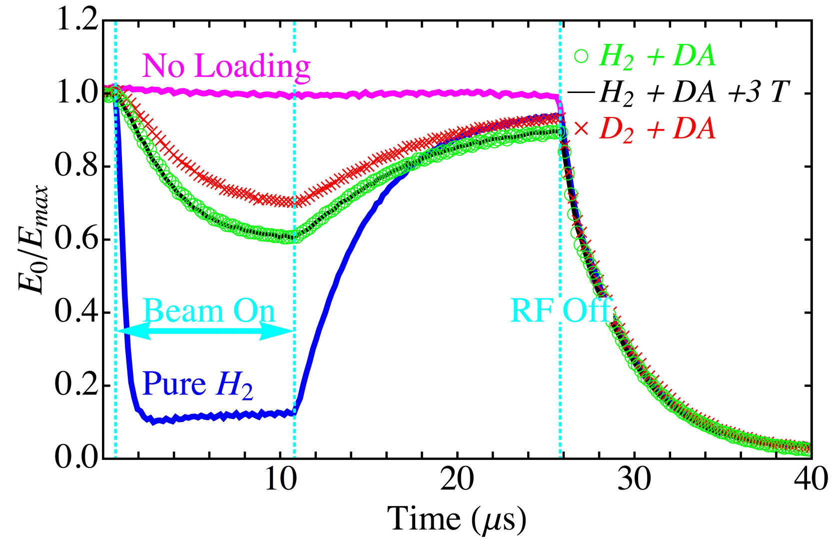


- Field emission from surface defect
- Solenoid focuses FE current into "beamlets".
- Beamlets persist for multiple cycles, causing pulsed heating, damage.

- 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.

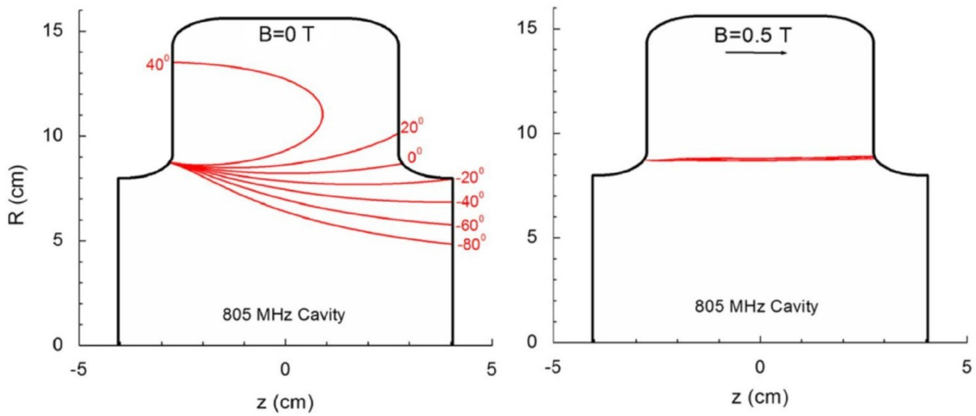
A demonstrated path to a solution: RF filled with high-pressure gas





- M. Chung *et al.*, PRL **111** 2013, 184802.
- Up to 65 MV/m demonstrated in $B = 3$ Tesla.
- Technology & applications to cooling presented by R. Johnson, WEPJE003.
- Gas suppresses breakdown, electronegative doping mitigates beam loading.

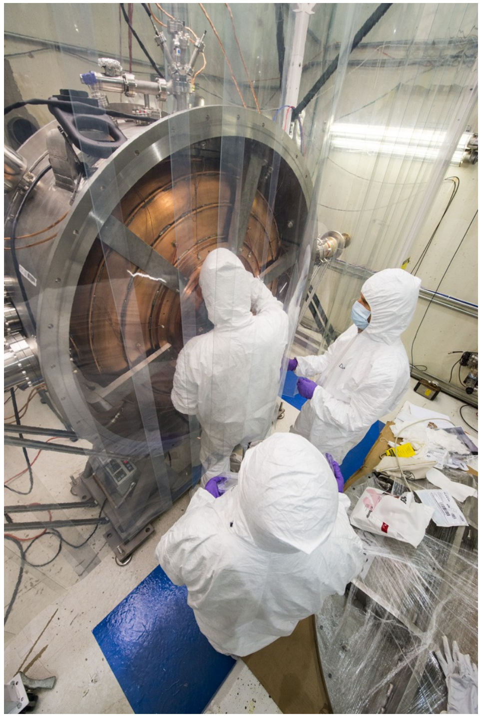
How can we prepare conventional cavities for these conditions?

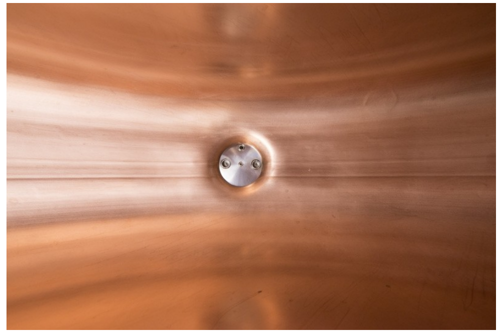


1) Polish and clean cavity surfaces using SRF best-practices.
2) Reduce impact energy of beamlets.
3) Increase radiation length of cavity surfaces so less energy is deposited by beamlets.

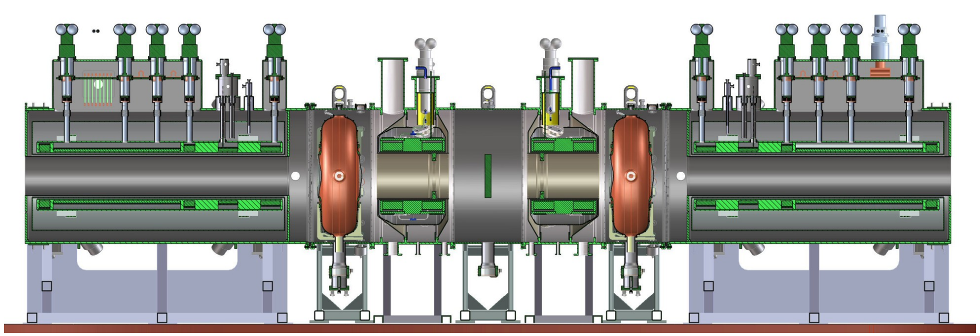
- Harder surfaces may be less susceptible to these effects.

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





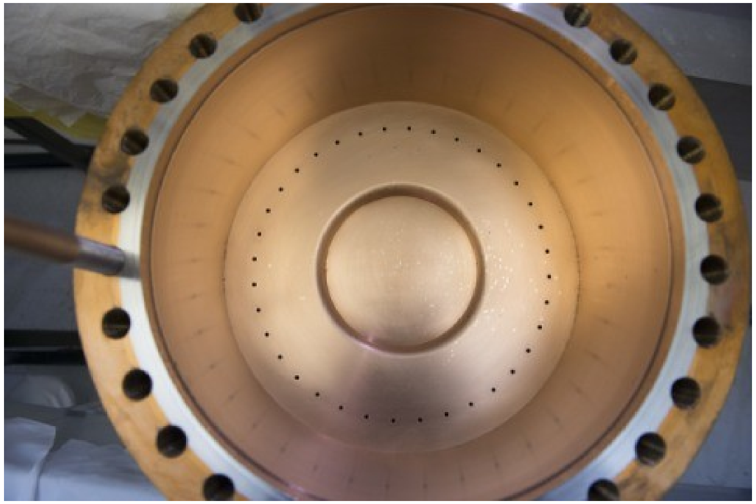
T. Luo, WEPTY046

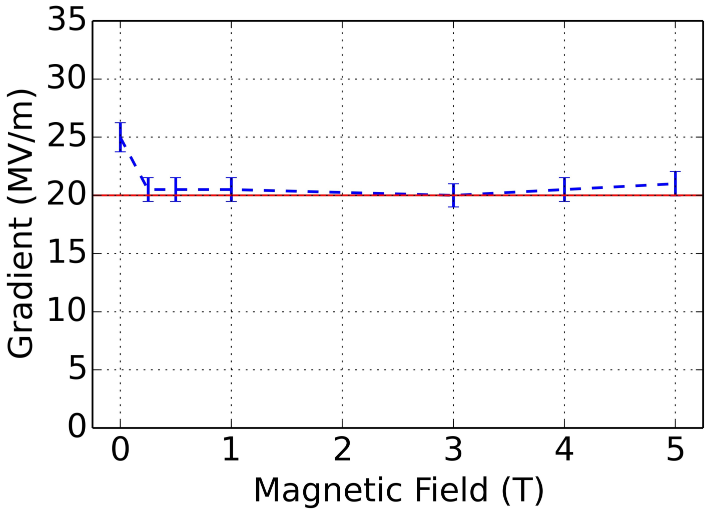


M. Palmer, FRXC3

- 201 MHz MICE prototype cavity electropolished, assembled in cleanroom conditions.
- Coupler simulated & optimized for operation in B-field.
- **Commissioned to design gradient in *B*=0 (no sparks)**
- **Now operating in B-field: < 1e-6 trip rate.**

(2) Reduce impact energy of beamlets.

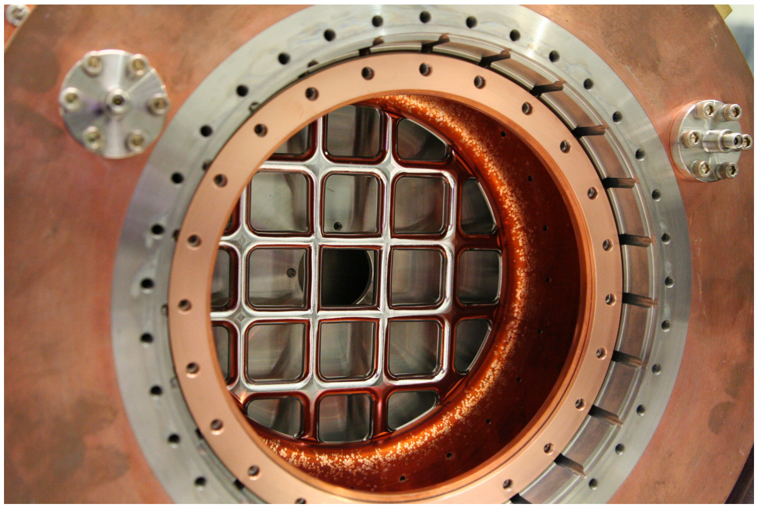




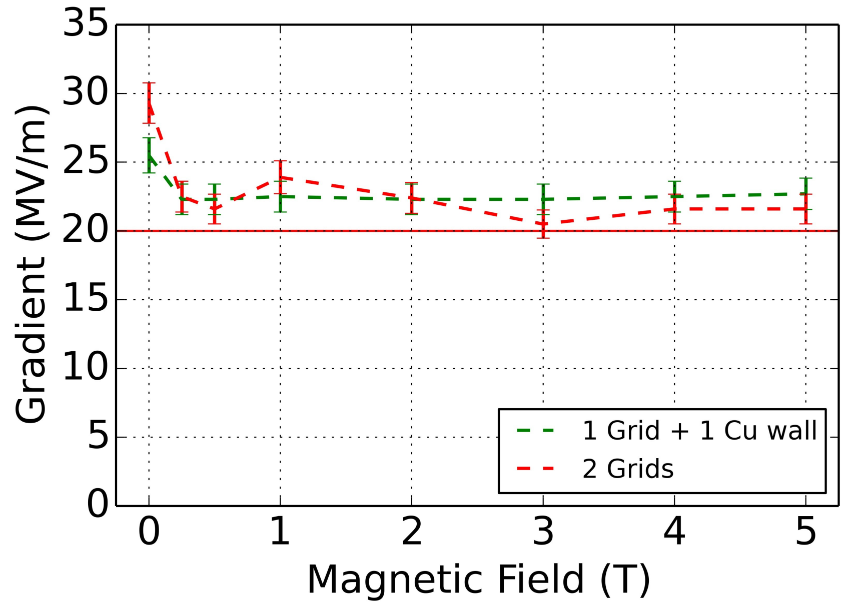
A. Kochemirovskiy, WEPTY030

- Designed, built by Muons, Inc. for high pressure and vacuum tests. “A cavity for all seasons”
- Inner surface is Cu-plated stainless steel, compared with bulk, machined Cu.
- 14.5 cm gap length reduces impact energy of field-emitted electrons.

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

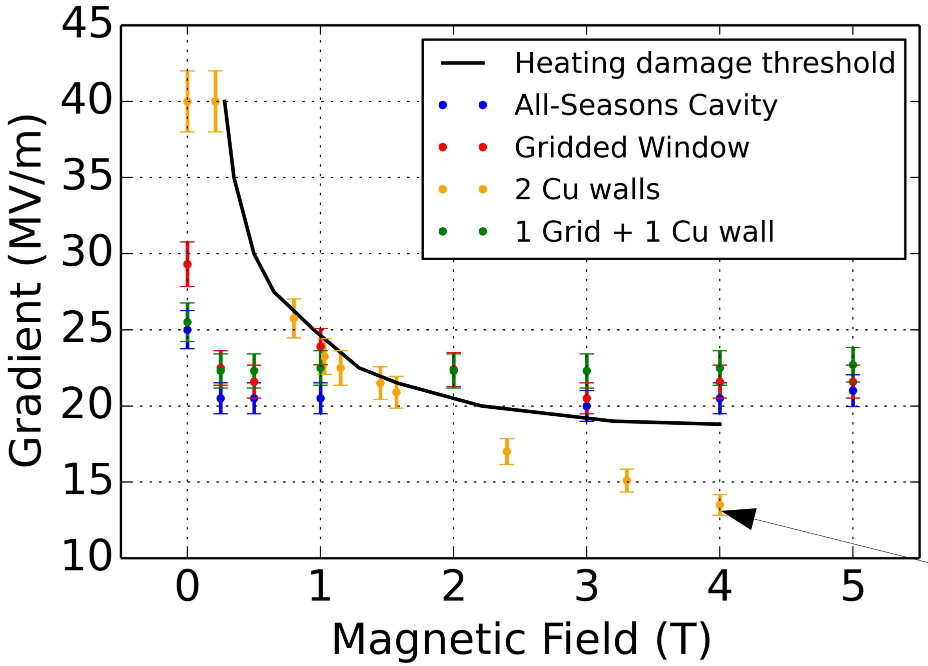


Y. Torun, WEPTY054



- c.f. M. Alsharo'a, *Electromagnetic and Mechanical Design of Gridded Radio-Frequency Cavity Windows*. PhD Thesis, Illinois Institute of Technology (2004).
- Grids raise shunt impedance, allow beamlets to exit active cavity volume.

Comparison of model with experimental results



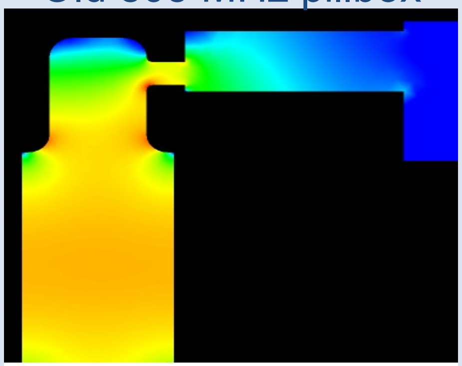
No surface prep for this cavity.

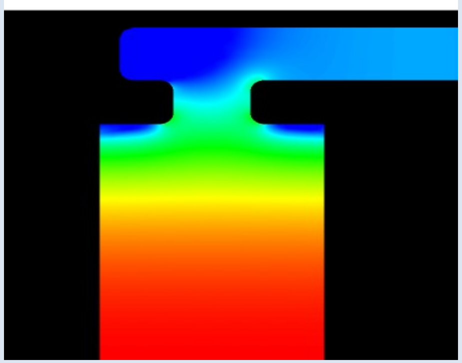
- Black line indicates threshold for plastic deformation from cyclic beamlet heating.
- Fit quality affected by conditioning history, coupler effects.

The 805 MHz “Modular Cavity” addresses these issues directly.

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

Old 805 MHz pillbox

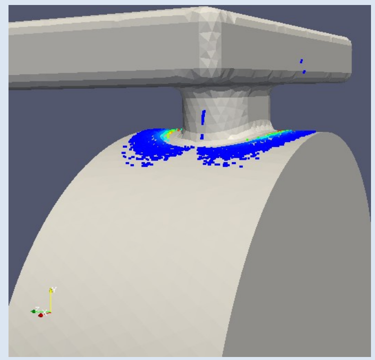


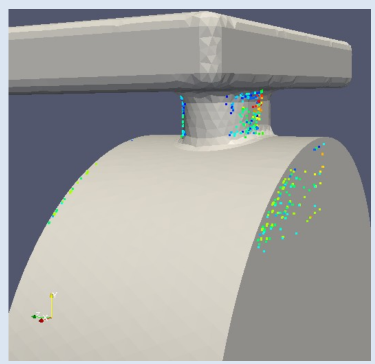


Modular cavity

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

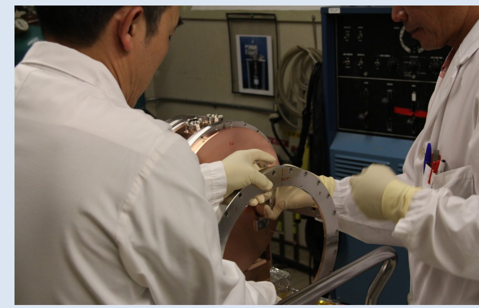
B = 0 Tesla

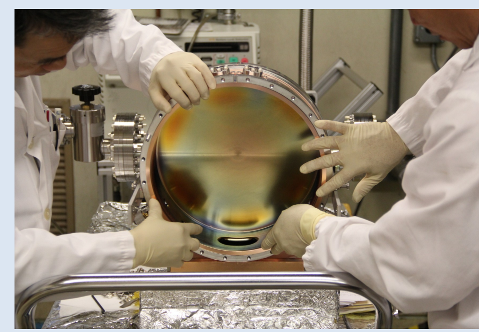




B = 3 Tesla

End walls easily removed for inspection, reconfiguration, materials studies.





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

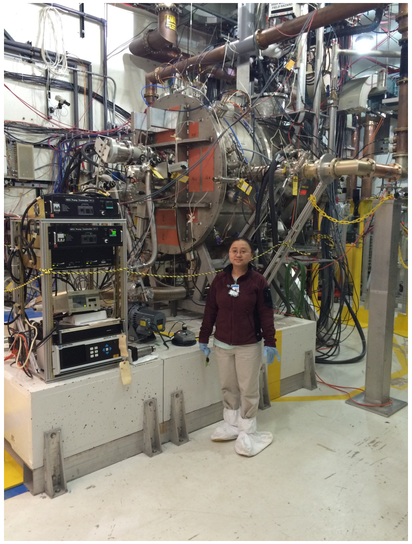
Status & future plans

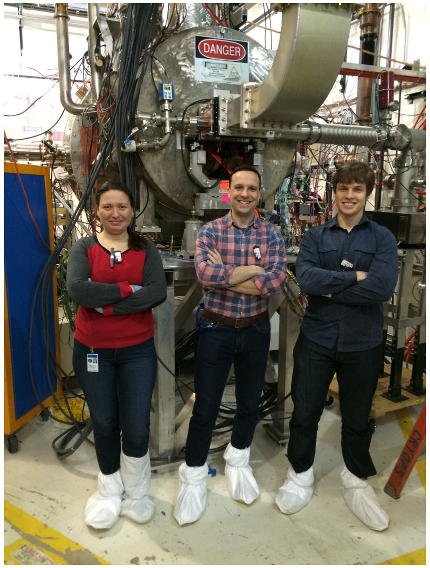
1) 201 MHz prototype cavity is running in the MTA in fields very similar to MICE conditions. Minimal breakdown events at design gradient.

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 virtually spark-free, with and without B-field.
3) We have demonstrated > 20 MV/m operation of 805 MHz cavities at $B = 5$ Tesla. This is sufficient for much of the front end in a high-intensity muon accelerator. (See D. Neuffer, TUBD2.)
4) Using RF cavities with high-pressure gas, we have demonstrated a general solution to the cooling problem.