Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Muon ionization cooling technology

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Muon Cooling working group meeting

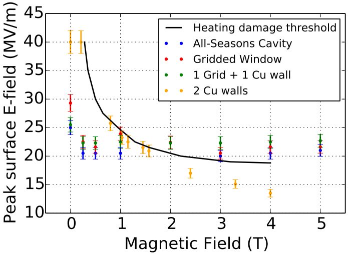
24 September 2020

One-slide summary

This is intended as a very general overview for a very general audience.

1. Problem statement: RF breakdown limits the performance of ionization cooling channels.
2. The US Muon Accelerator Program conducted extensive R&D on this topic.
3. The specific physical causes of RF breakdown are not well understood, generally, but we can offer some suggestions of contributing factors.
4. US MAP developed two potential solutions to this problem and I will review them both.

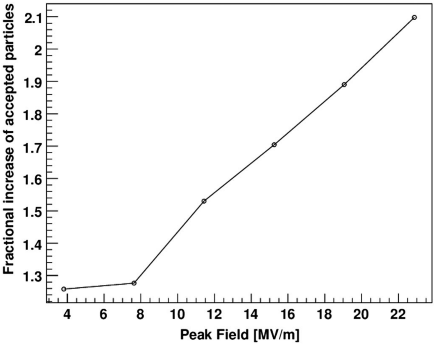
RF breakdown limits cooling channel performance.



D. Bowring *et al.*, Proc. IPAC 2015

- Ionization cooling requires high-power RF structures to operate within multi-tesla B-fields.
- We reproducibly observe a significant degradation in the max. achievable E_{acc} for these structures.

Why is this a problem?

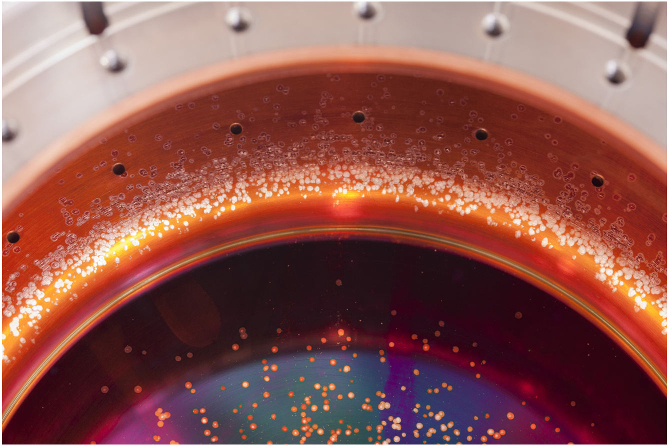


One example: CT Rogers et al., PRAB 16, 040104 (2013) simulates linear degradation in performance wrt peak accelerating field.

- Low gradients depress muon yield through channels.
- This is an undesirable contstraint on channel designs.

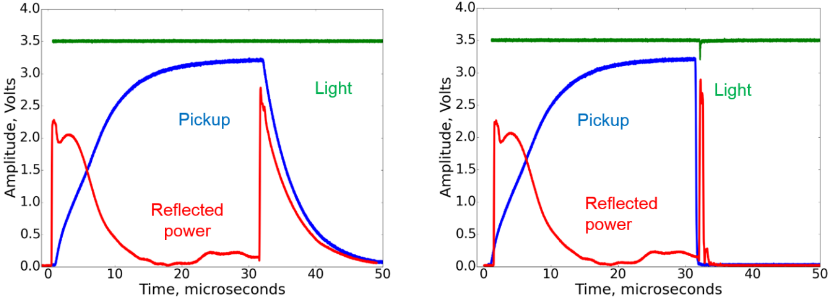
How does RF breakdown manifest in cavities?

1. Damage



How does RF breakdown manifest in cavities?

2. Vacuum arc shorts cavity.



How does RF breakdown manifest in cavities?

3. Other physical symptoms

- Spike in vacuum pressure
- Dark current
- Radiation
- Light

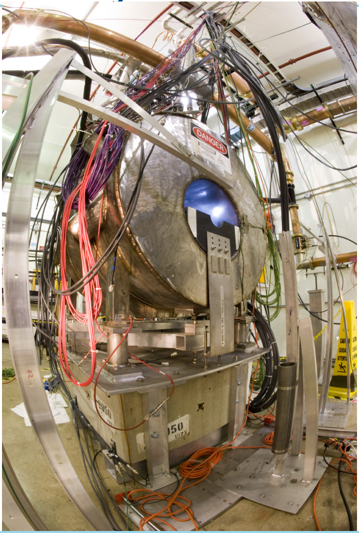
There is not broad agreement about what causes RF breakdown.

Some useful models and theories include:

- Electron and ion interactions with cavity surfaces
  - J. Norem *et al.*, PRAB 6, 072001, 2003.
  - W. Wuensch, Proc. Symposium on High-Gradient Accelerating Structures, 2013.
- Intensity and distribution of cavity fields and surface currents
  - V. Dolgashev *et al.*, Appl. Phys. Lett. 97, 171501 (2010).
  - A. Grudiev, PRAB 12, 102001 (2011).
- Pulsed heating and cyclyic fatigue of metal lattice
  - L. Laurent, PRAB 14, 041001 (2011).
  - Nordlund and Djurabekova, PRAB 15, 071002 (2012).

But why should a magnetic field make a difference? (q.v. the second half of this talk.)

FNAL built and operated an experimental facility to study these issues.



Features of FNAL's MuCool Test Area (MTA):

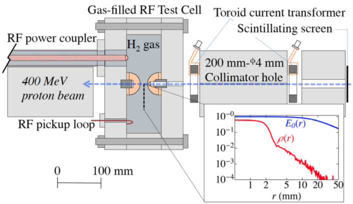
- High-power pulsed RF at 805 MHz and 201 MHz
- $B \leq 5$ tesla superconducting solenoid with 44-cm warm bore
- cryoplant for LHe and LN
- class-100 movable clean room
- 400-MeV H^-/p beam capability
- Extensive control and instrumentation infrastructure

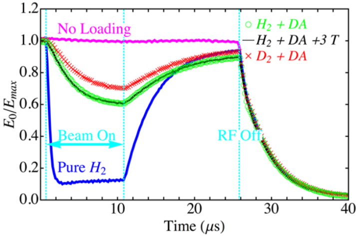
Plan for the remainder of this talk:

1. Remedy: loading cavities with high-pressure gas
2. Pulsed heating model of breakdown in B-fields
3. Remedy: alternate cavity materials

Before we continue: Questions?

Loading cavities with high-pressure gas circumvents the breakdown problem.





- PRL 111, 184802 (2013)
- PRAB 19, 062004 (2016)
- Gas serves as cooling medium.
- e^-/gas collision frequency $\gg$ e^- cyclotron frequency
- Doping with electronegative gas reduces loading from beam-induced plasma.
- $B \leq 3$ T shows no effect on cavity gradient.

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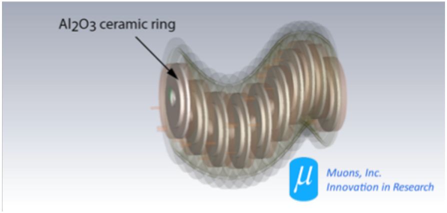
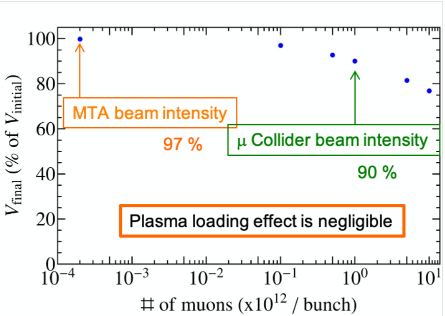
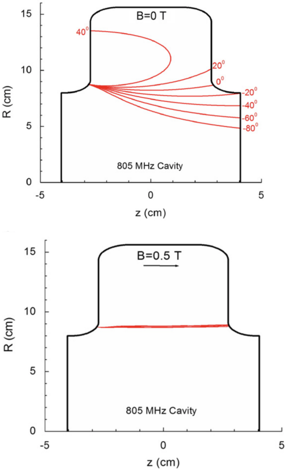
“HPRF” approach has been used in several channel design/simulation efforts.





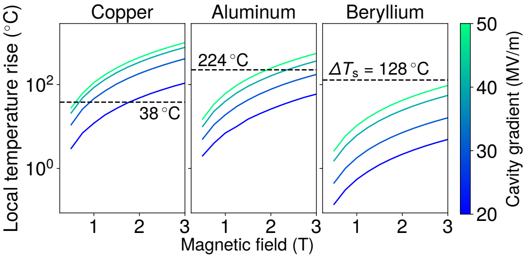
- (above) Helical cooling channel: K. Yonehara, arxiv:1806.00129
- Rectilinear FOFO: D. Stratakis, arxiv:1709.02331
- Helical FOFO “snake”: Y. Alexahin, MAP-doc-4377

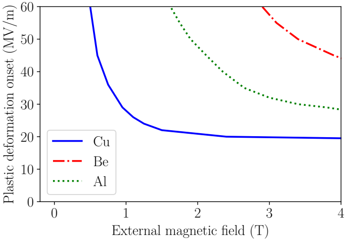
How can we explain the effect of the B-field?



- D. Stratakis *et al.* NIMA (2010).
- Field emission sources electrons in cavity volume
- e^- trajectory phase dependence varies with B-field.
- For $B > 0$, "beamlets" can cause pulsed heating, cyclic fatigue of cavity surfaces.

Pulsed heating model gives the following predictions:





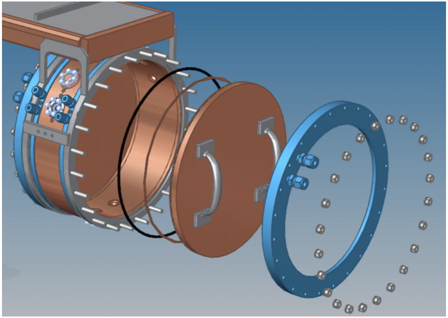
Beamlet current density varies with B-field. Heat deposition rises above plastic deformation threshold at different points depending on material.

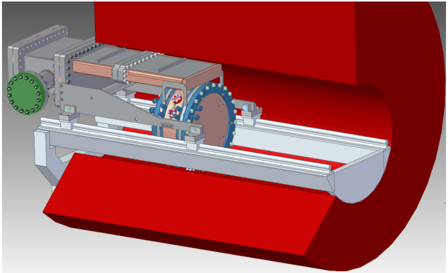
Predicted maximum achievable gradient vs B for Cu, Be, and Al.

D. Bowring, PRAB 23, 072001 (2020)

Pulsed heating model motivates systematic cavity material studies.

- We built a "modular cavity" with removable walls.
- Be performance directly, experimentally compared with Cu. Al included for reference.



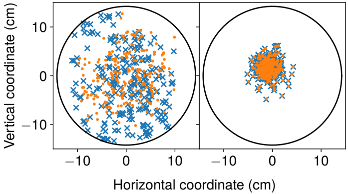


Results of modular cavity studies:

Material	B-field (T)	SOG (MV/m)	BDP ($\times 10^{-5}$)
Cu	0	24.4 ± 0.7	1.8 ± 0.4
Cu	3	12.9 ± 0.4	0.8 ± 0.2
Be	0	41.1 ± 2.1	1.1 ± 0.3
Be	3	$> 49.8 \pm 2.5$	0.2 ± 0.07
Be / Cu	0	43.9 ± 0.5	1.18 ± 1.18
Be / Cu	3	10.1 ± 0.1	0.48 ± 0.14

- SOG = "safe operating gradient", at which breakdown probability $< 10^{-5}$.
- For Be case, limiting factor was RF infrastructure and *not* cavity breakdown.
- Be/Cu = one Be and one Cu cavity wall.

Some Observations



- $\sim$ 50 MV/m achieved quite stably in 3 T.
- 56 MV/m observed in 3 T, but with poor statistics limited by available run-time.
- No evidence of breakdown anywhere in the cavity system except on the flat walls.
- 1:1 damage sites on flat walls for $B > 0$ runs.
- No damage to Be surfaces during $B > 0$ runs.

Conclusions

- Good evidence that pulsed heating model works, but we would need more statistics to be sure.
- Beryllium walls enable record gradients in cooling channel conditions, for vacuum cavities.
- HPRF cavities achieve record gradients in cooling channel conditions, period.
- Strong indication that Al could be a good middle ground between safety of Cu and performance of Be.

Thanks for your attention!

Questions?