High gradient RF in strong magnetic fields status and plans

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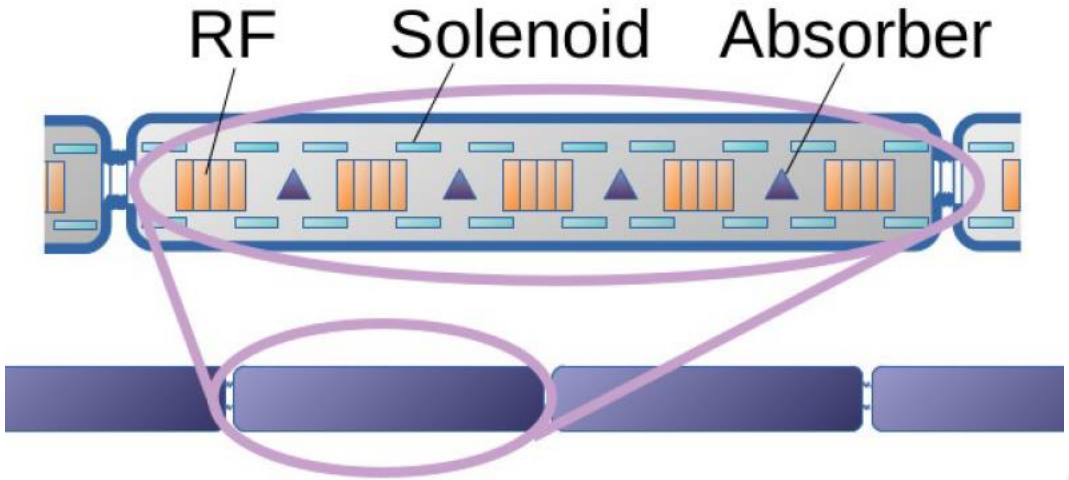
RF cavities for muon cooling cells

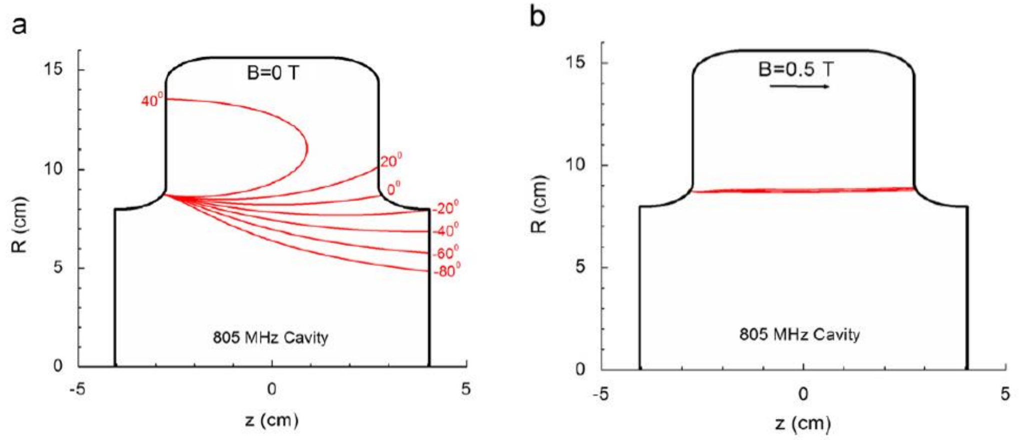


- Normal conducting cavities
- $f \sim 325\ MHz, 650\ MHz$
- Short RF pulses (~μs)
- High acceleration gradients (~30 MV/m)
- High magnetic solenoidal field (up to14 T)

Creates problematics of **break-down** that needs to be mitigated

What is the issue with strong magnetic fields?

- High acceleration gradients → Strong field emission.
- Strong magnetic field → Tends to focus the electron beam.
- Question: What is the consequence of the electron beam focusing on the cavity performances?

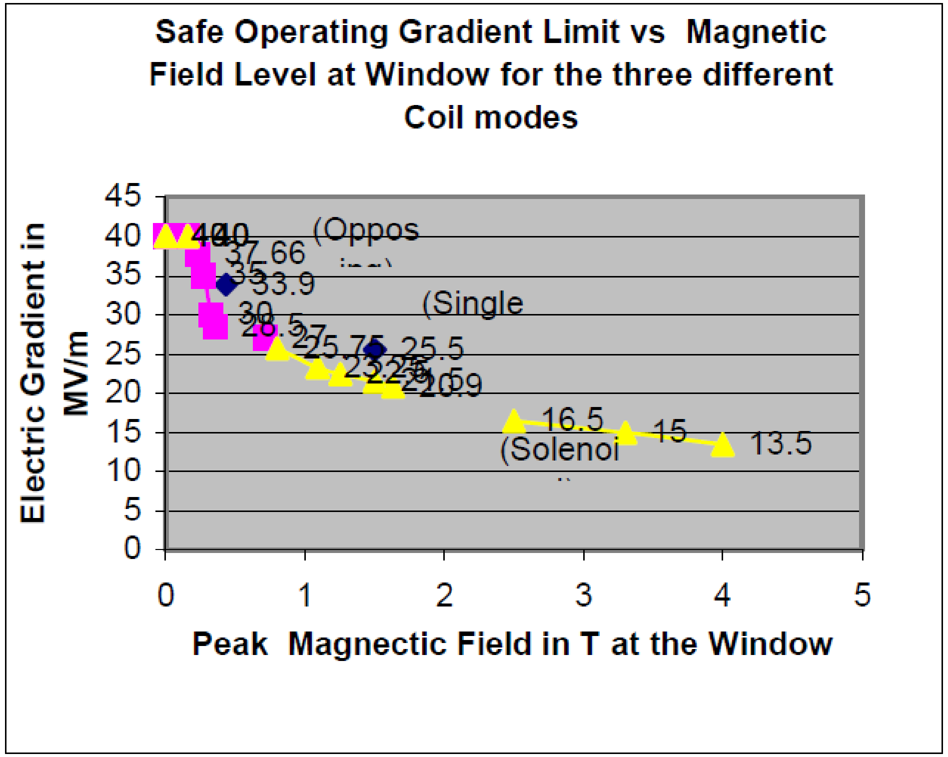


We can assume that this generates high temperature increase locally.

Does this limit the maximal achievable accelerating field?

A. Moretti, LINAC 2004.

- Effect of high solenoidal magnetic fields on breakdown voltages of high vacuum 805 mhz cavities, TU204, LINAC 2004, Lübeck, Germany.



Conclusion: « In general the breakdown limit is much lower when a solenoidal magnetic field is applied. In addition the dark current and x-ray emissions are much larger after the occurrence of sparking at very high electric and magnetic field levels […]. Even after long RF commissioning runs, the cavity does not return to the previous recorded low background level.

Figure from Moretti's paper.

Some models to explain it

- A thermal model was proposed by different laboratories:
  - RB Palmer et al. RF Breakdown with external magnetic fields in 201 and 805 MHz cavities. PRAB, 12, 031002 (2009).
  - D Stratakis et al. Effects of external magnetic fields on the operation of high-gradient accelerating structures, NIMA, 620, 147-154 (2010).

- General principle: the temperature rises at the focused point. If $\Delta T > T_s$, where T_s is a « safe » value, breakdown appears.

$$T_s = 2\frac{(1-\nu)\sigma_t}{E\alpha_{th}}$$

- Depends on the mechanical properties (Poisson ratio ν, elastic modulus E, yield stress σ_t).
- And the linear expansion of the material, α_{th}.

Experimental study: D. Bowring, PRAB 23, 2020

- Pillbox cavity at 805 MHz.
- Max available gradient: 50 MV/m.
- In a magnet field from 0 to 3.5 T. B-field parallel to Eacc.
- Two walls in copper or beryllium.
- Beryllium shows a higher « safe » Ts.

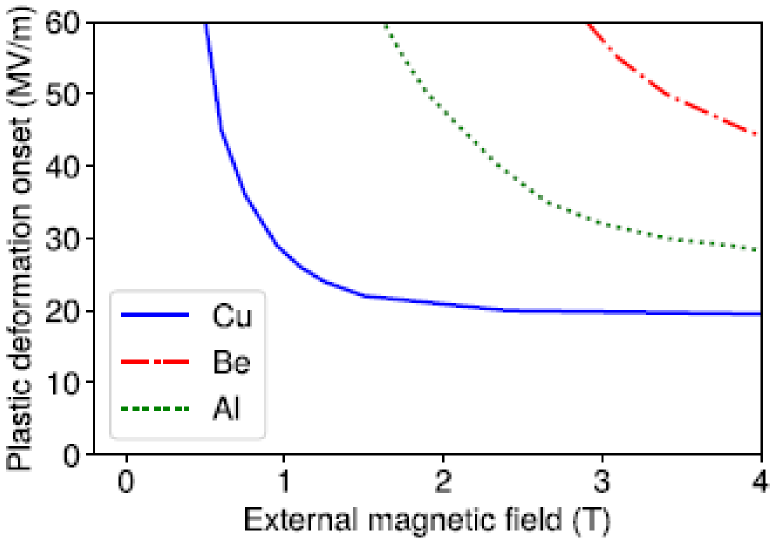
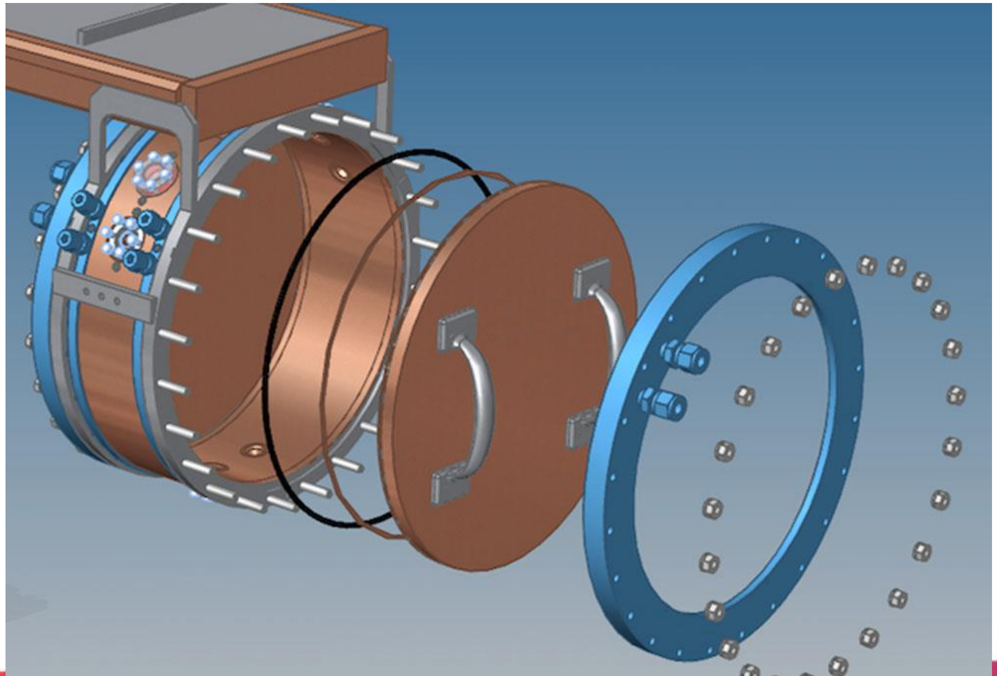


FIG. 3. Predicted cavity gradients vs external, solenoidal magnetic field strength, based on the beamlet pulsed heating model. Beryllium cavity walls should be less susceptible to fatigue from beamlet pulsed heating and should therefore operate at higher gradients relative to copper.



- On the left: diagram of the experimental device.
- On the right: predicted behaviour.

Conclusions

- Results from Bowring et al. PRAB 23, 072001, 2020.
- Magnetic field affects significantly the performances (breakdown probability) of the full copper cavity.

TABLE I. Demonstrated SOG for various cavity configurations and external magnetic field strengths. At each operating point, the breakdown probability (BDP, sparks per pulse) is also shown. “Be/Cu” indicates operation with one beryllium and one copper endplate.

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

- The beryllium cavity is significantly better than the copper cavity. And is not significantly affected by the magnetic field.
- Magnetic field affects the trajectory of the electrons, as we can expect.

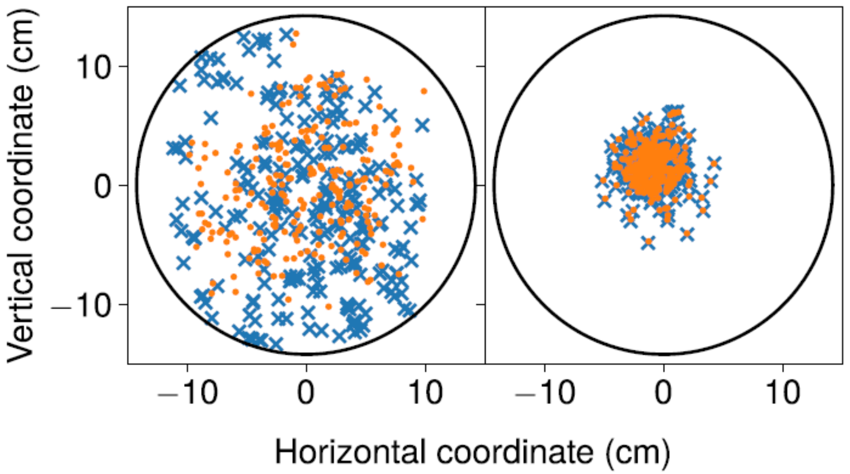
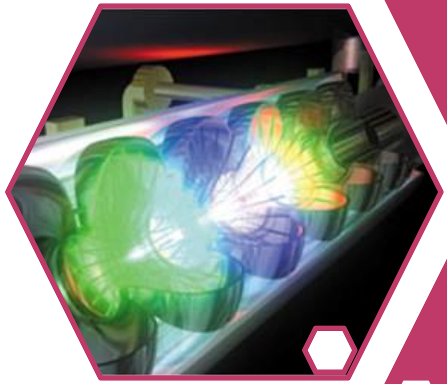


FIG. 6. Map of breakdown damage sites on copper cavity walls after high-power conditioning in zero-tesla external magnetic field (left) and three-tesla field (right). Damage locations are shown from the perspective of the “downstream” cavity wall in the foreground of Fig. 4; blue x’s denote damage on the upstream wall and orange dots denote damage on the downstream wall. Breakdown damage in a three-tesla magnetic field exhibits a one-to-one correspondence between opposite cavity walls.

A lot of questions



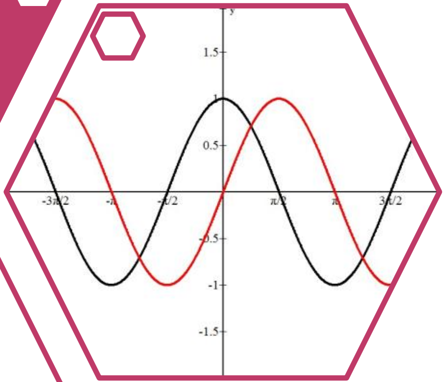
Pulse length?

Shape of the cavity?

Cooling temperature?

Other material?

Other frequencies?



First analyses – Short pulses

- Some first simulations at CEA. See "Break-down mitigation solutions and test plan for muon cooling cells RF cavities" presented by C. Marchand at previous IMCC meeting (2022).
- Analytic formula presented by Sergey Arsenyev in 2022 (CEA internal report):

$$B^2 = \rho C_s \frac{2(1-\nu)\sigma_t}{E\alpha_{th}} \times \frac{e\pi\xi^2}{I_{em}^{\frac{1}{3}}\left(\frac{dE}{dz}\right)} \times \frac{1}{\mathrm{t_{pulse}}}$$

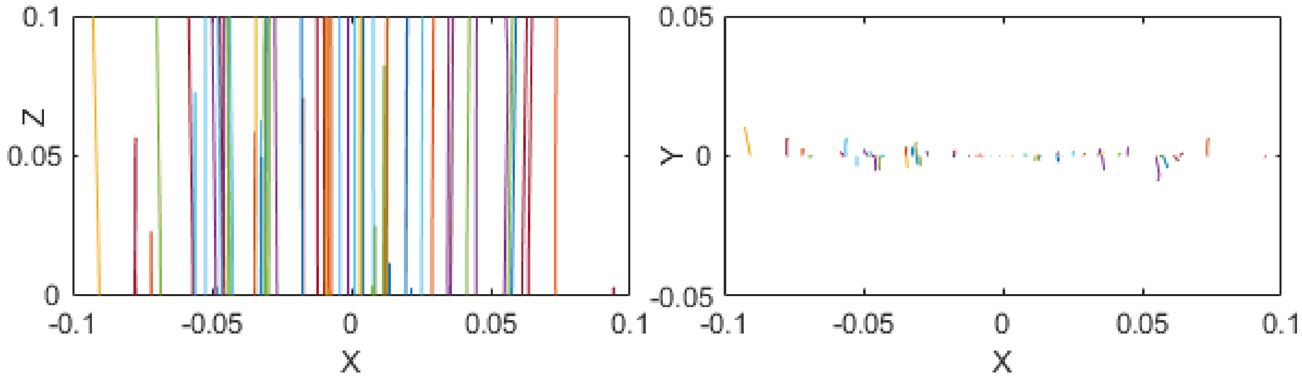
← Pulse length

- Analysis to be continued.

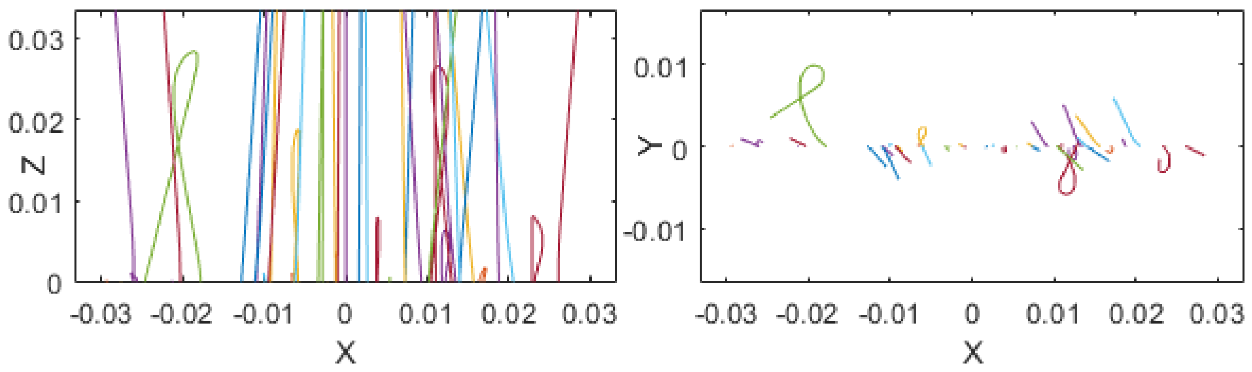
International MUON Collider Collaboration

First analyses – Effect of the RF frequency.

- A few simulations of particle in pillboxes with Matlab. Example at 0.2 T.
- Cylinder (pillbox) along the z-direction. Center: $x = 0, y = 0$. Length: 100 mm at 700 MHz and 33 mm at 2 100 MHz. All electrons start at different x-positions and $y = 0$.



Simulation at 700 MHz, 0.5 T, 30 MV/m



Simulation at 2 100 MHz, 0.5 T, 30 MV/m

A 2.1 GHz, it seems like the magnetic field must *be doubled* to focus the electron beam.

DC test bench

- Why would we need DC tests?
  - To test different materials. Generally, DC and RF performances are correlated.
  - To test different surface finishing. We are always far of the « optimal » performances as defined by the Fowler-Nordheim equation. Due to the fact that actual surfaces are not perfect. How to improve them?
  - Testing if the magnetic field could impact the breakdown limit in DC? (This would mean that the beamlet model does not fully explain the phenomenon, as there is no phase dependency in DC).

Contributions

- Simulations (RF, e- tracking, etc.): CEA, INFN, Strathclyde.
- DC test bench to study surfaces and materials: INFN, Strathclyde.
- Study of an RF test bench with a solenoid: CEA, INFN.

Questions

- Thank you for your attention.