International
MUON Collider
Collaboration

RF in strong B-field test stand motivation and requirements

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CEA Paris-Saclay
IMCC Annual Meeting
June 20, 2023

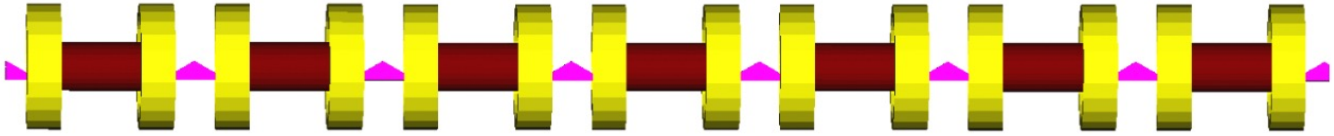
Outline

- Problematic of NC RF cavities for the muon cooling complex in high magnetic fields:
  - Overview of MTA (Mucool Test Area) experimental results:
    MICE 201 MHz and Mucool 805 MHz cavities in B field up to 4T
  - Model(s) that explain existing RF BD results in magnetic field

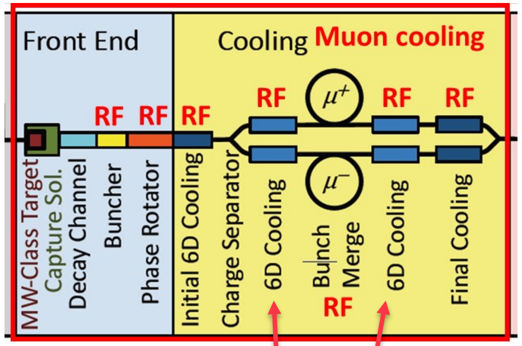
- Further tests are needed to consolidate models and test new BD mitigation solutions:
  - Different cavity materials, operating temperatures, frequencies, RF pulse length …
  - Calls for new RF test stand(s) à la MTA: cavity, RF power source, solenoid field …

RF system for 6D cooling (MAP study)

Rectilinear channel contains some of the most challenging NC cavity designs in terms of required RF gradient and B-field



(a)



Stage	Cell length [m]	Total length [m]	rf frequency [MHz]	rf gradient [MV/m]	rf #	rf length [cm]	Coil tilt [deg]	Pipe radius [cm]	B field [T]
A1	2.000	132.00	325	22.0	6	25.50	3.1	30.0	2.2
A2	1.320	171.60	325	22.0	4	25.00	1.8	25.0	3.4
A3	1.000	107.00	650	28.0	5	13.49	1.6	19.0	4.8
A4	0.800	70.40	650	28.0	4	13.49	0.7	13.2	6
B1	2.750	55.00	325	19.0	6	25.00	0.9	28.0	2.2
B2	2.000	64.00	325	19.5	5	24.00	1.3	24.0	3.4
B3	1.500	81.00	325	21.0	4	24.00	1.1	18.0	4.8
B4	1.270	63.50	325	22.5	3	24.00	1.1	14.0	6
B5	0.806	73.35	650	27.0	4	12.00	0.7	9.0	9.8
B6	0.806	62.06	650	28.5	4	12.00	0.7	7.2	10.5
B7	0.806	40.30	650	26.0	4	12.00	0.8	4.9	12.5
B8	0.806	49.16	650	28.0	4	10.50	0.6	4.5	13.6

Before bunch merge

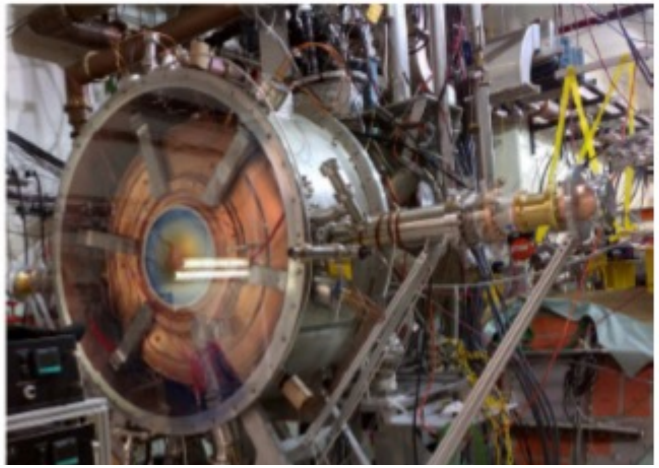
After bunch merge

Summary of NC RF cavities tests in high B field (MTA)

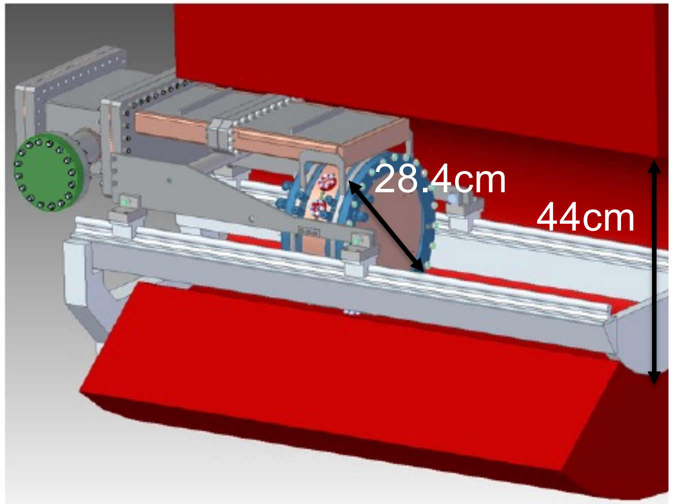
(comprehensive review by Derun Li, CERN LDG meeting 2021)

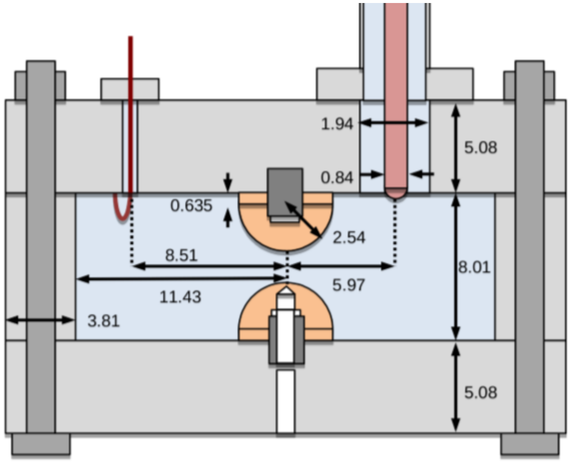
State of the art (not complete):

- MICE 201 MHz RF module prototype (beryllium windows):
  5T fringe field, **11 MV/m**, 1ms@1Hz



- MUCOOL 805 MHz pill box cavity,
  Cu & Be windows:
  Cu: 3T, 13 MV/m, 30μs@10Hz
  Be: 3T, **50 MV/m**





- MUCOOL **Gas** filled RF cavity:
  3 T, **65 MV/m** 805 MHz
  molybdenum cavity

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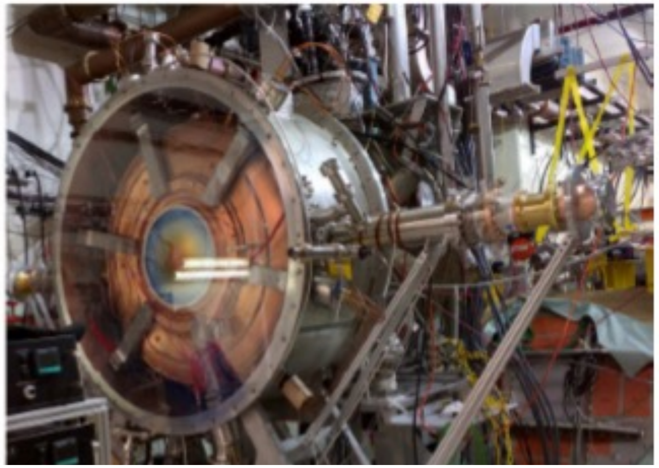

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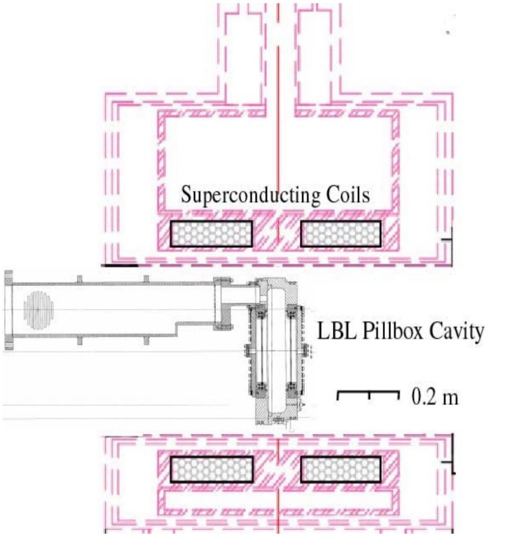

Figure 2: The single cell cavity in the superconducting 5 T solenoid.

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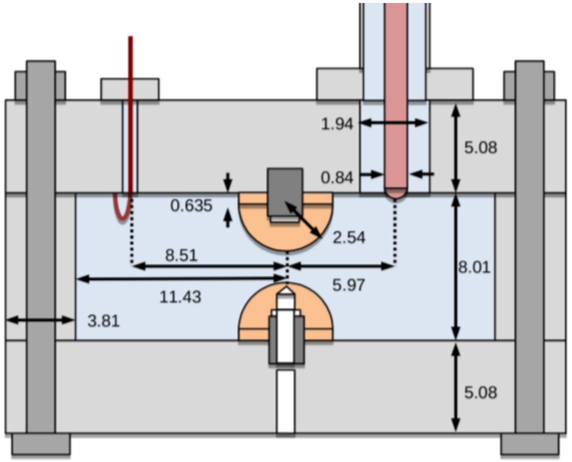
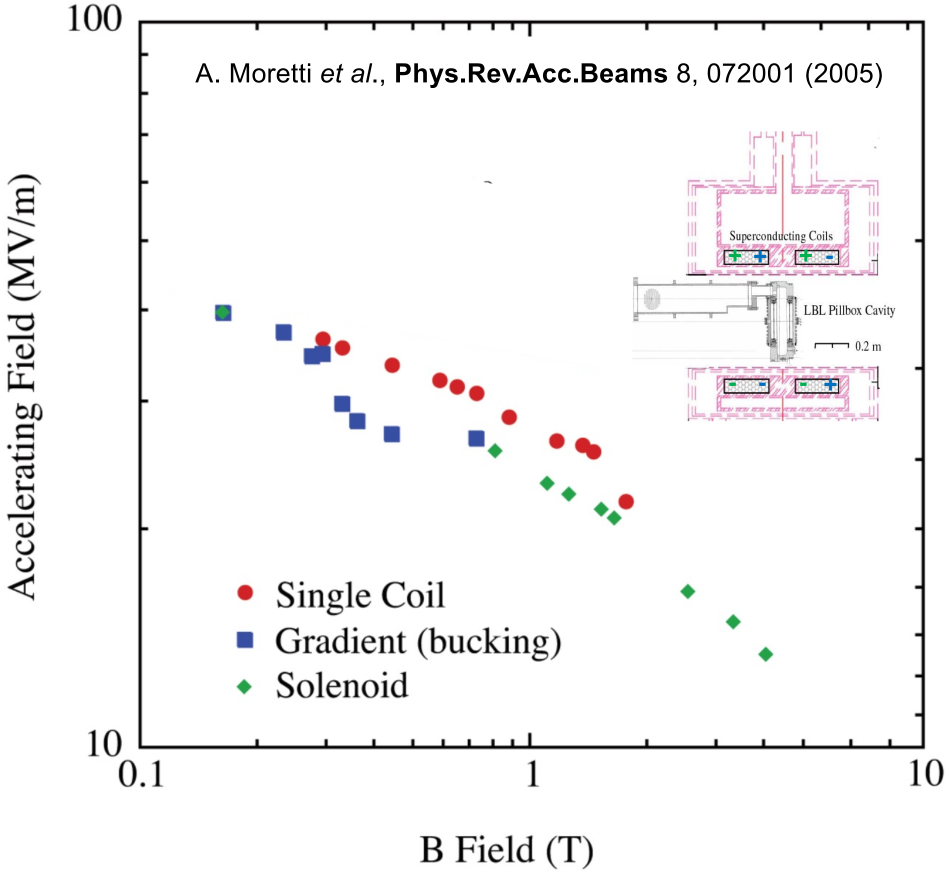
  molybdenum cavity



Some initial results on 805 MHz PB cavity with Cu

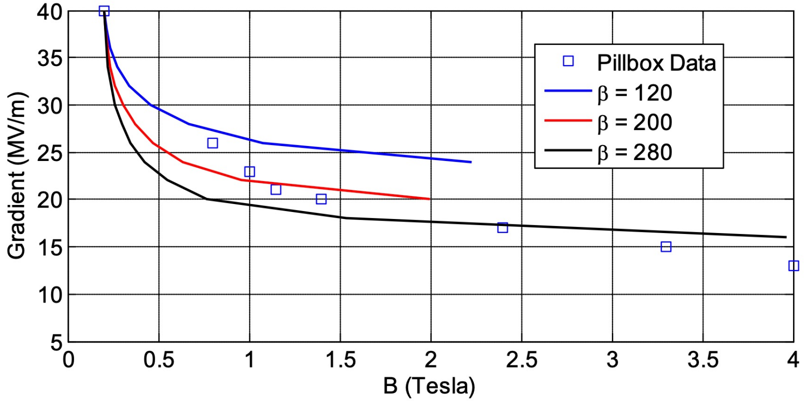

A. Moretti *et al.*, **Phys.Rev.Acc.Beams** 8, 072001 (2005)

Fowler-Nordheim Enhanced Field Emission current:

$$I_F = \frac{1.54\times 10^{-6}\times 10^{4.52\phi^{-0.5}} A_e \beta^2 E^2}{\phi} \exp\left(-\frac{6.53\times 10^{9}\phi^{1.5}}{\beta E}\right) \quad \text{A}$$

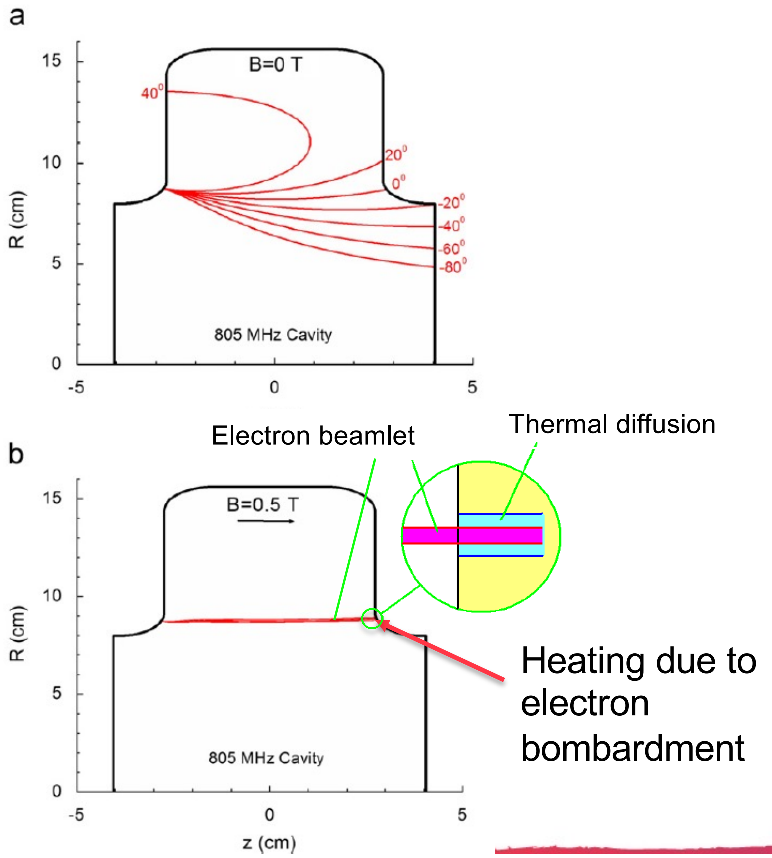
where $\beta = E_m / E_{surf}$ is the enhancement factor due to microscopic emmiter sites

(a) Metallic surface roughness due to imperfect machining, scratches, microprotrusions, "tip-on-tip" protrusions
(b) Metallic dust, microparticles
(c) Grain boundaries
(d) Molten craters after breakdown
(e) Dielectric impurities and layers
(f) Absorbed gas
(g) Metal-insulator-vacuum (MIV) or metal-insulator-metal (MIM) layers.



Breakdown model: beamlet focused by magnetic field

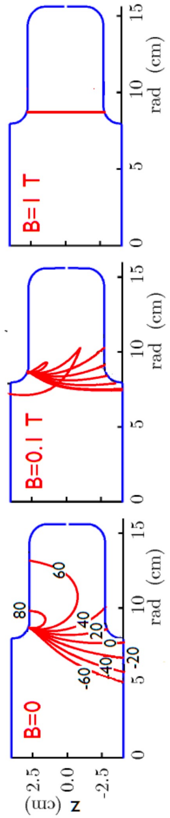
Numerical simulations conducted by SLAC collaborators showed trajectories of beamlets in the presence of the 805 MHz pillbox cavity



Electron beamlet

Thermal diffusion

Heating due to electron bombardment



- Model developed by US labs, checked against measurements in high B. papers:
  Palmer et.al PRAB 2009, Stratakis et.al NIMPR 2010, Bowring et.al PRAB 2020
- Model predicts local temperature rise ΔT due to electron bombardment
- Breakdown occurs when $\Delta T > \Delta T_{plastic}$

Poisson ratio

Yield strength

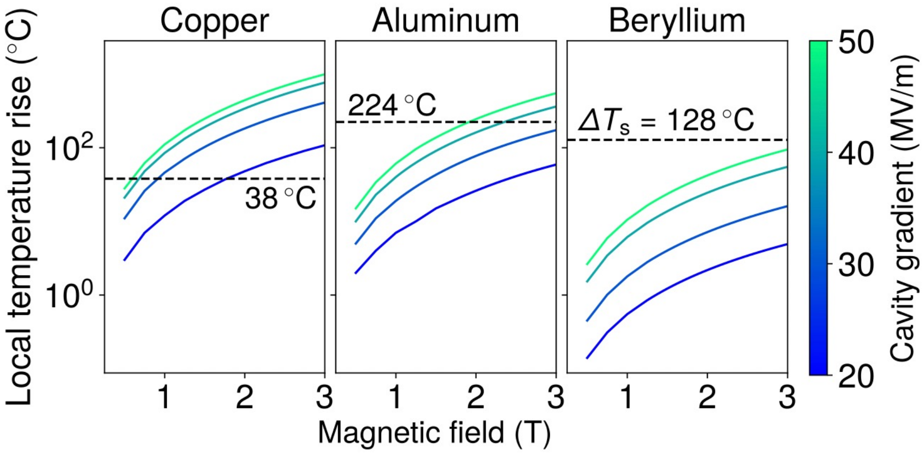
$$\Delta T_{plastic} = \frac{2(1-\nu)\sigma_t}{E\alpha_{th}}$$

Elastic modulus

Linear expansion

$\Delta T_{plastic}$: 38 °C for Cu, 129 °C for Be, 224 °C for Al

MuCool 805 MHz cavitiy test with modular plates



Operation of normal-conducting rf cavities in multi-Tesla magnetic fields for muon ionization cooling: A feasibility demonstration

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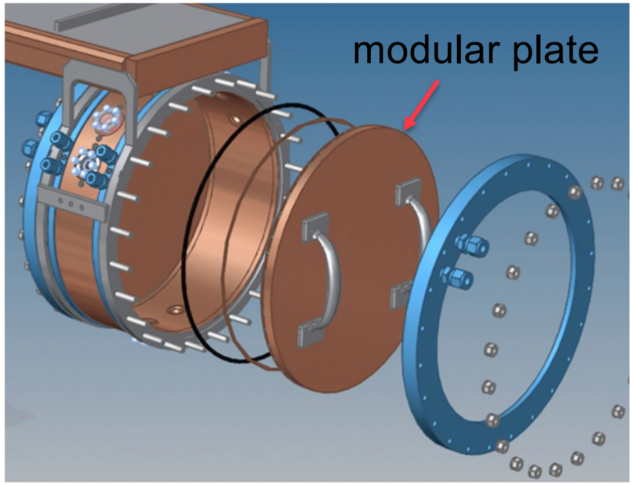
Phys. Rev. Accel. Beams **23**, 072001 – Published 2 July 2020

FIG. 2. Semi-log plot of local ΔT for Cu, Al, and Be cavities at various gradients and across a range of solenoidal magnetic field strengths. ΔT_s [Eq. (4)] is indicated in each plot by a horizontal, dashed line. Note that for Be, the local temperature rise is lower than ΔT_s for a broad range of gradients and magnetic fields.



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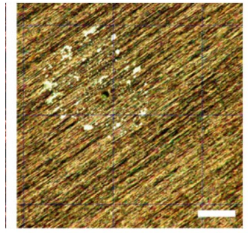
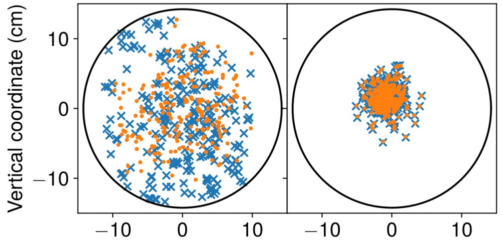
Cu	0	24.4 ± 0.7
Cu	3	12.9 ± 0.4
Be	0	41.1 ± 2.1
Be	3	$> 49.8 \pm 2.5$
Be/Cu	0	43.9 ± 0.5
Be/Cu	3	10.1 ± 0.1



Be: 0 & 3 T



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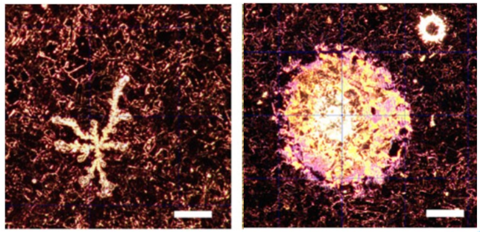
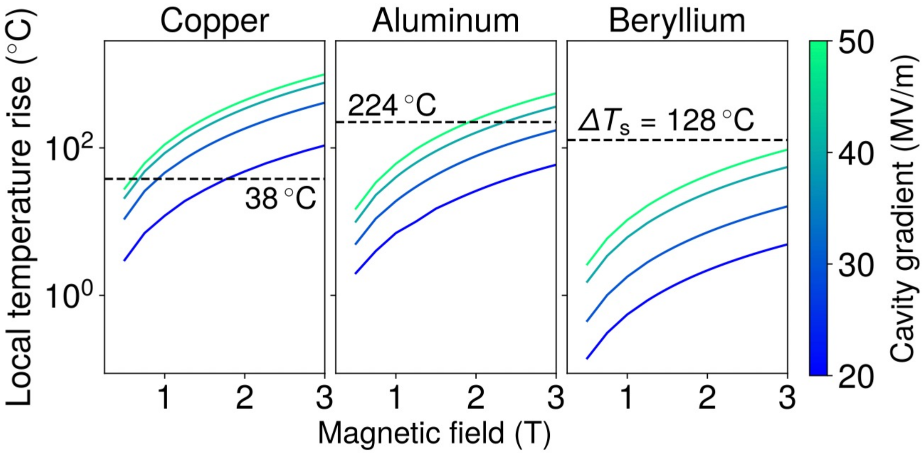


MuCool 805 MHz cavitiy test with modular plates



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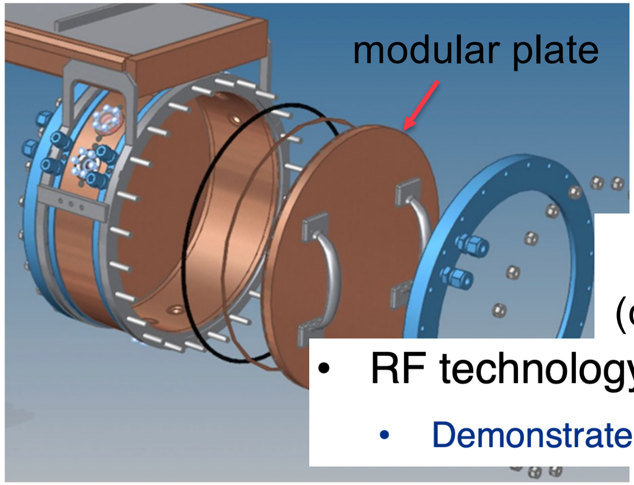

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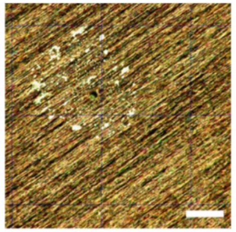

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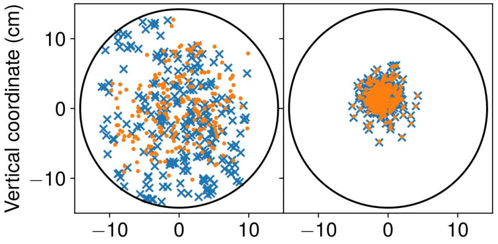

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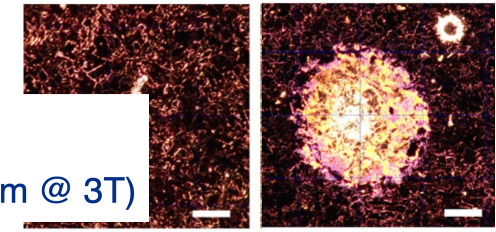
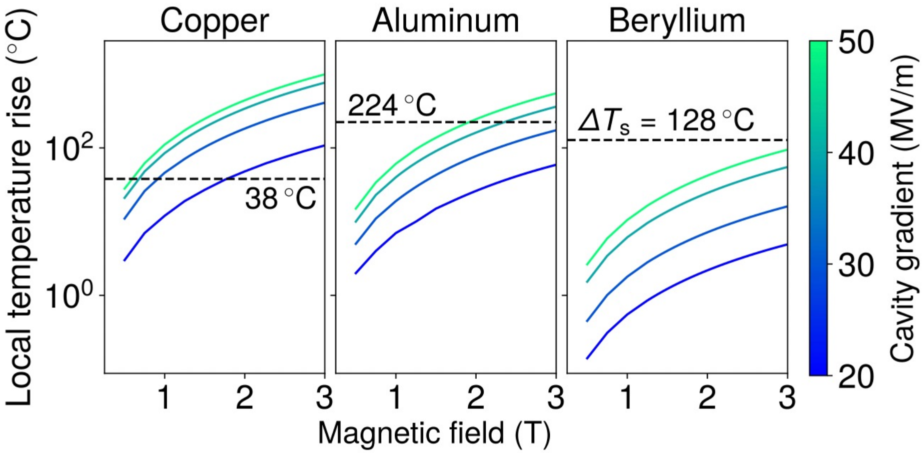


End of the game ?

(cf. Stratakis statement yesterday):

- RF technology
    - Demonstrated high-gradient operation of NC cavities in B-fields (50 MV/m @ 3T)

MuCool 805 MHz cavitiy test with modular plates



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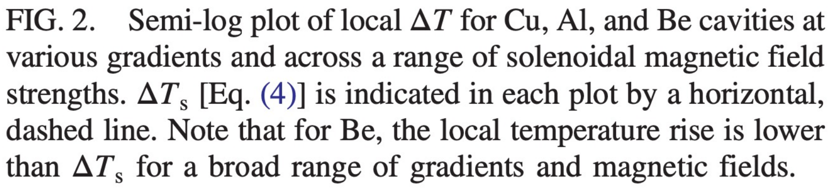

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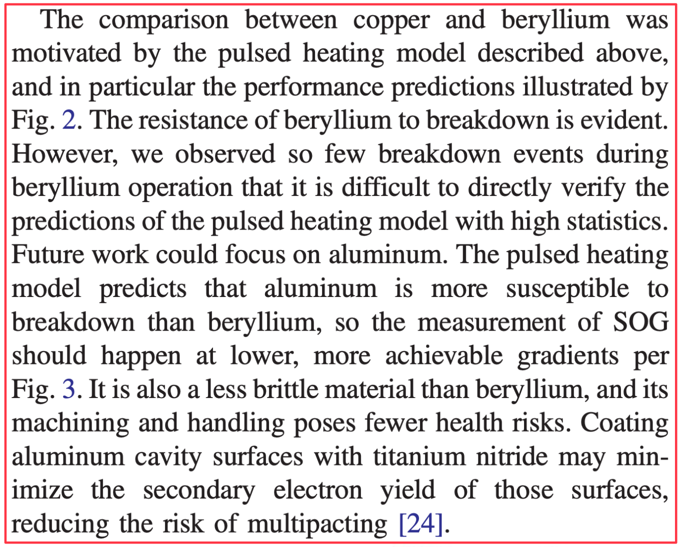
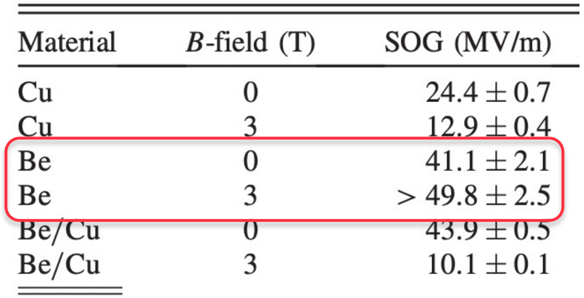


The comparison between copper and beryllium was motivated by the pulsed heating model described above, and in particular the performance predictions illustrated by Fig. 2. The resistance of beryllium to breakdown is evident. However, we observed so few breakdown events during beryllium operation that it is difficult to directly verify the predictions of the pulsed heating model with high statistics. Future work could focus on aluminum. The pulsed heating model predicts that aluminum is more susceptible to breakdown than beryllium, so the measurement of SOG should happen at lower, more achievable gradients per Fig. 3. It is also a less brittle material than beryllium, and its machining and handling poses fewer health risks. Coating aluminum cavity surfaces with titanium nitride may minimize the secondary electron yield of those surfaces, reducing the risk of multipacting [24].



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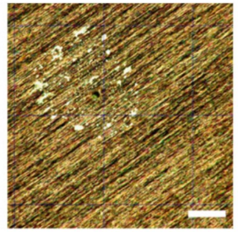

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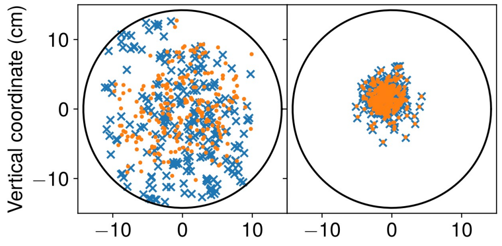

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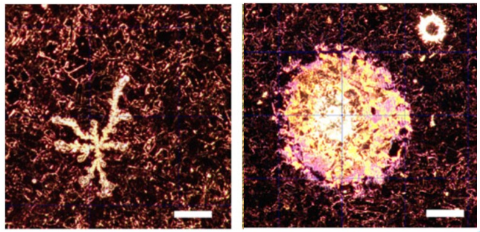
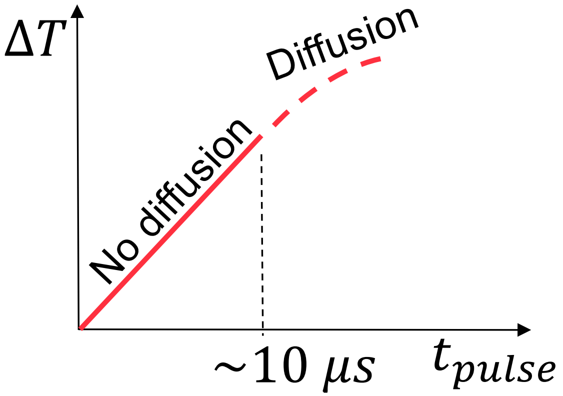


Or need for more ?

(Bowring 2020 paper left)

- Strong indication that Al could be a good middle ground between safety of Cu and performance of Be.

Scaling using no-diffusion beamlet model



The breakdown model can be simplified: for short pulses $(t_{pulse} < 10\ \mu s)$ we can neglect heat diffusion in the wall.

Then the breakdown condition $B(E_{acc})$ is given by (S. Arsenyev, 2021):

$$B^2 = \underbrace{\rho C_s \frac{\overbrace{2(1-\nu)\sigma_t}^{\Delta T_{plastic}}}{E\alpha_{th}}}_{\text{Wall material properties}} \times \frac{e\pi\xi^2}{I_{em}^{\frac{1}{3}}\left(\frac{dE}{dz}\right)} \times \frac{1}{t_{pulse}}$$

Cavity-dependent constant

Pulse length

Magnetic field at breakdown

Electron energy loss

Field Emission current $I(E_{acc})$

This equation provides scaling laws of $B(E_{acc})$ on different parameters. Mitigation solutions that follow from this equation:

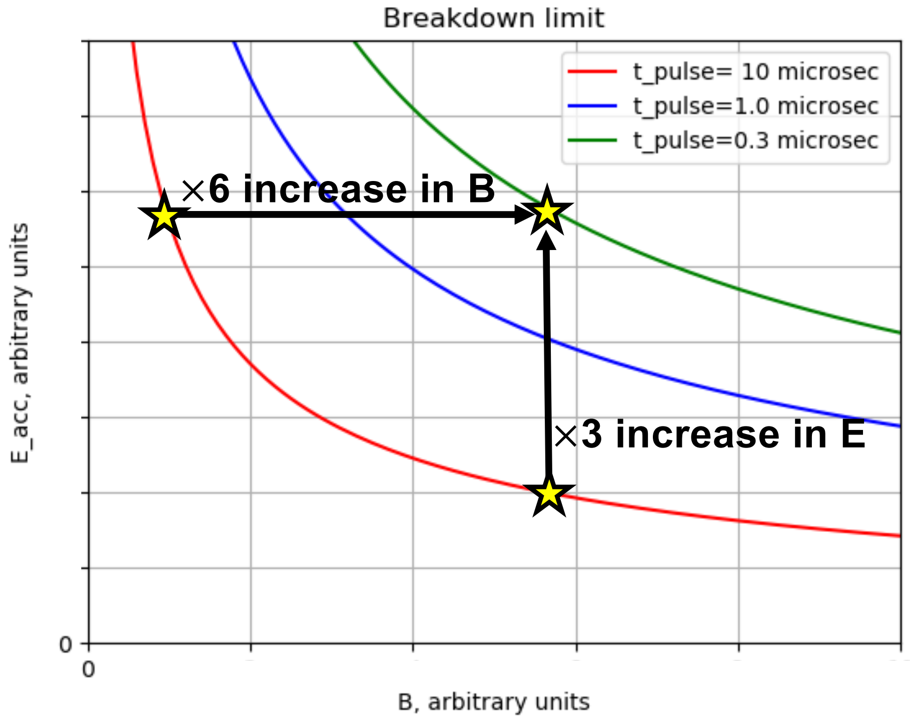
- Very short pulse (sub μs)
- Different wall materials (Al, hard copper alloys)
- Low temperature (nitrogen cooling 70 K)
- Cavity shape optimization

When combined, benefits from different solutions would multiply

Benefits of short sub-µs pulse

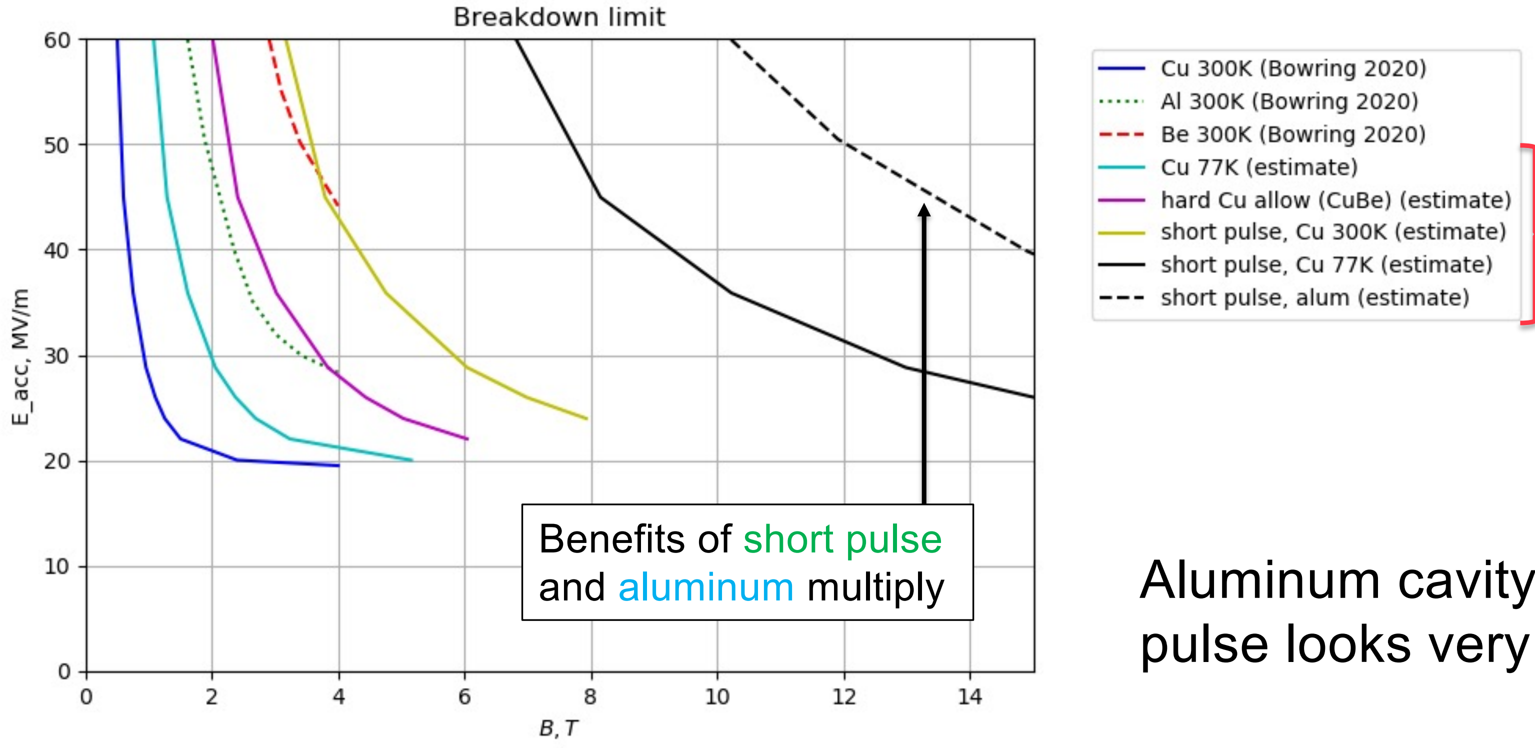
- Going down from 10 µs to 300 ns pulse would dramatically improve cavity breakdown performance

- 300 ns pulse length needs an over coupled cavity and a 23 MW klystron (only a factor of 2 increase from Litton 805 MHz 12 MW klystron)



Comparing breakdown mitigation ideas

This plot is not intended to give absolute values for breakdown threshold, but only a feeling of which solutions can be more promising. We scale curves from MUCOOL cavity study ($t_{pulse} = 20\ \mu s > 10\ \mu s$ so the no-diffusion model applies only approximately)



Benefits of short pulse and aluminum multiply

Scaled from the first 3 curves using the scaling model (slide 7)

Aluminum cavity with a short pulse looks very promising

R&D directions for NC RF cavities tests in high B field

- **Need high gradient RF test stand(s) with B field up to ~10T**

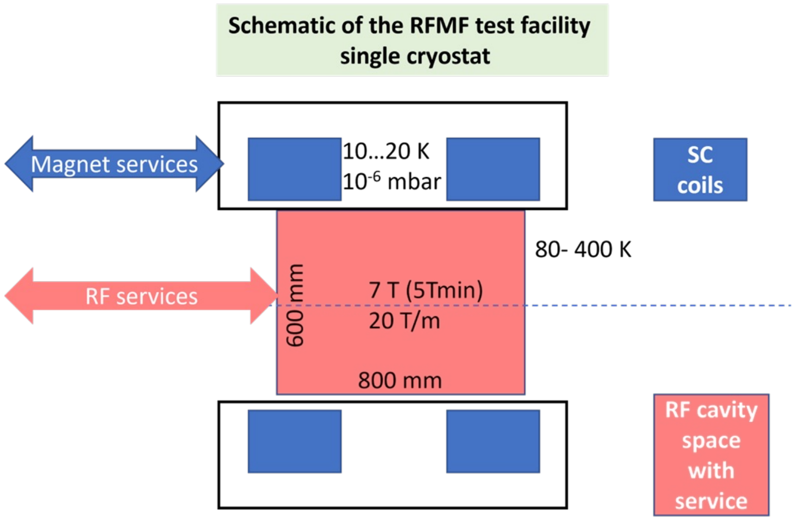
  Test cavities for technology development

  - Frequency: ideally 300 to 700 MHz range
    - tests at higher frequencies useful, but need some rescaling to MCC f range
  - Gradients from 25 to 50 MV/m
  - **Short RF pulses** (~μs)
  - **Magnetic field: 0 – ~10T, different field configurations**
  - Different materials: Cu, Be, **Al**, …
  - Different temperatures: 300K -> **70K** ->…
  - Different cavity shapes ?

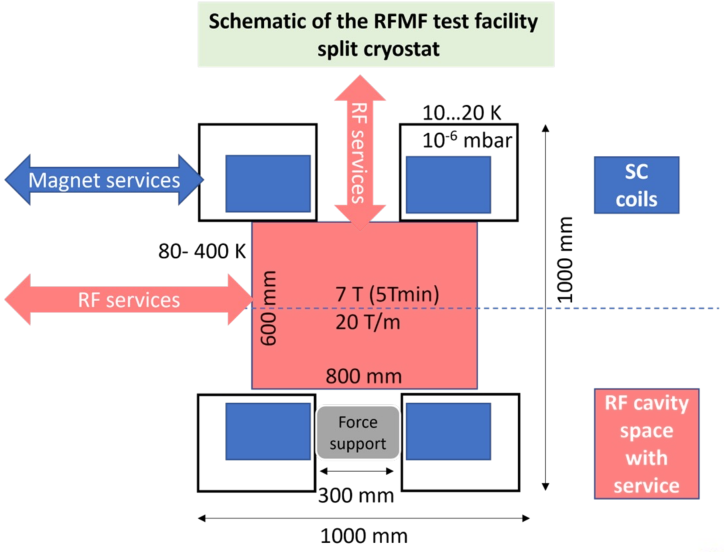
General layout of the RFMF test station

- Preliminary design is aimed at fitting a cavity of the size up **to a 700 MHz system**
- Minimum bore of the split coil
  - → ∅600 RT free bore for RF → **∅700 mm minimum SC coil diameter**

Scheme 1: single cryostat



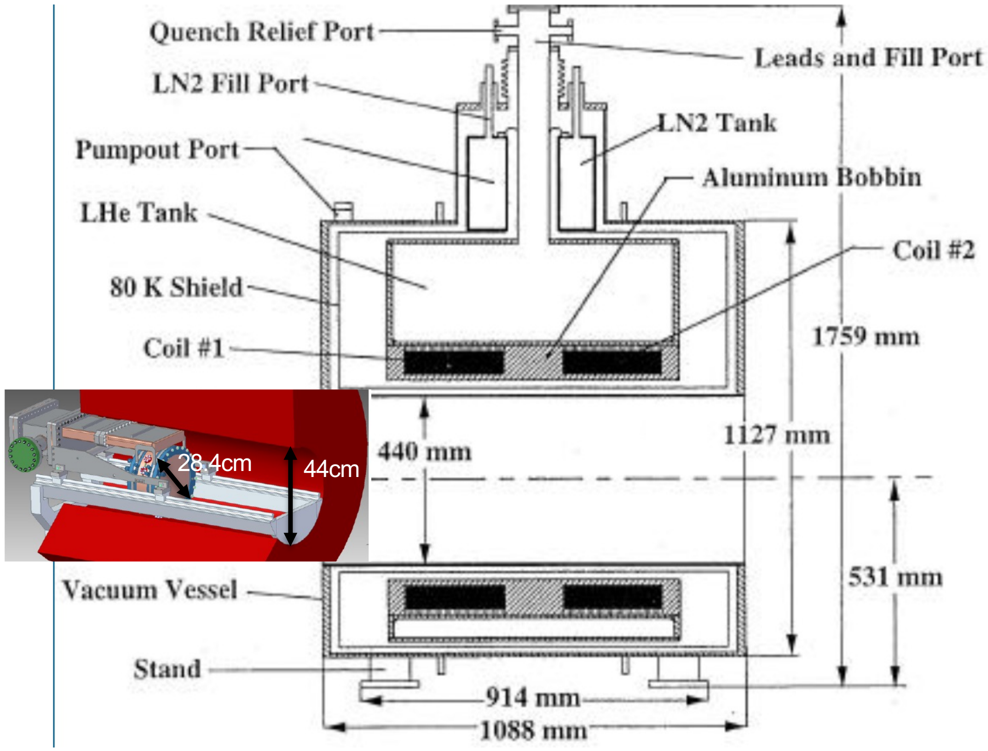
Scheme 2: split cryostat



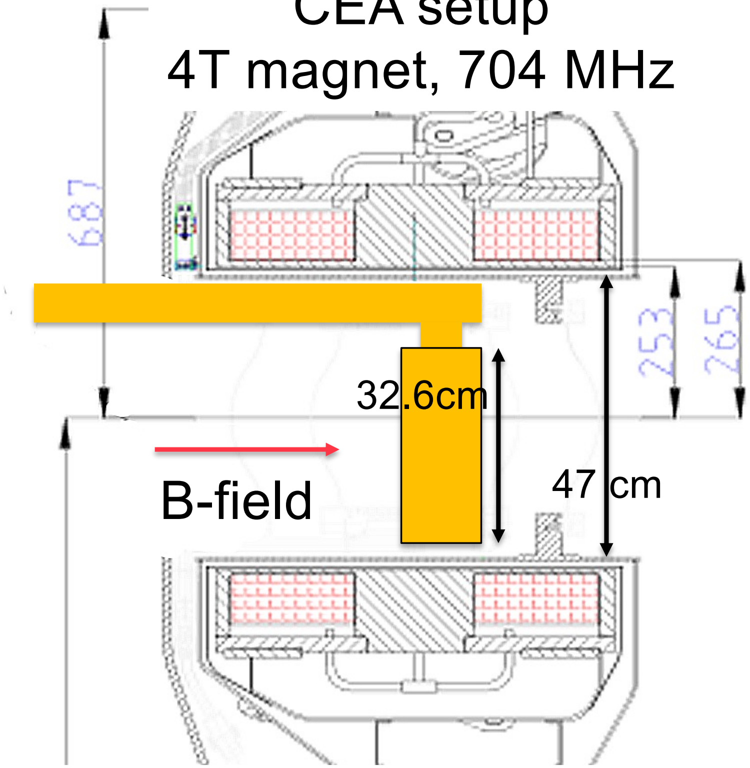
WP8 - RFMF test station - L. Rossi et al. UMIL&INFN

CEA setup with the 4T MICE AFC magnet

MUCOOL setup
5T magnet, 805 MHz

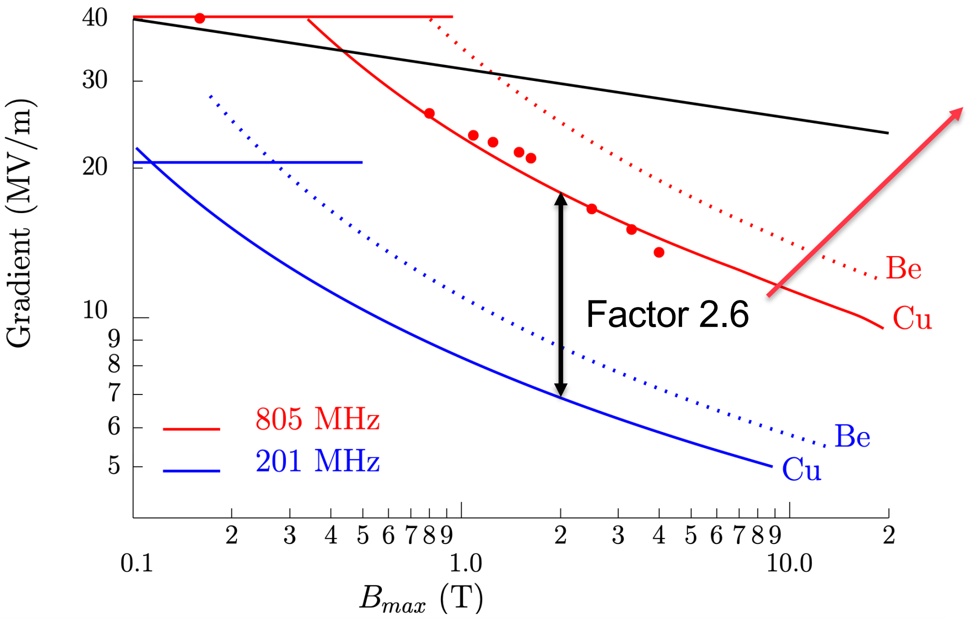


CEA setup
4T magnet, 704 MHz



47 cm bore of the MICE AFC magnet will tightly fit the cavity

Effect of the RF frequency in beamlet model (Stratakis)



While classical RF BD (Wang&Loew 1997) predicts less frequency dependence:

$$E = 220\,[f(\mathrm{GHz})]^{1/3}$$

-> E_{805}/E_{201}=1.58

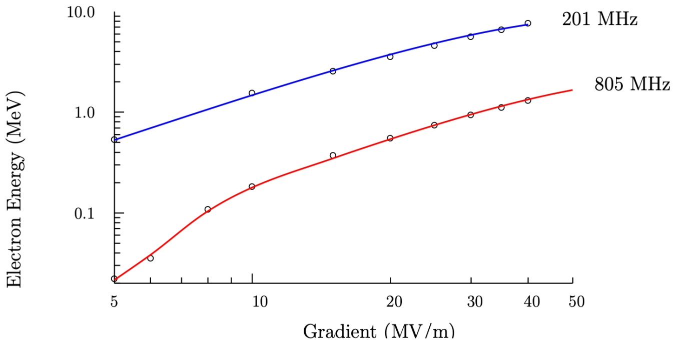
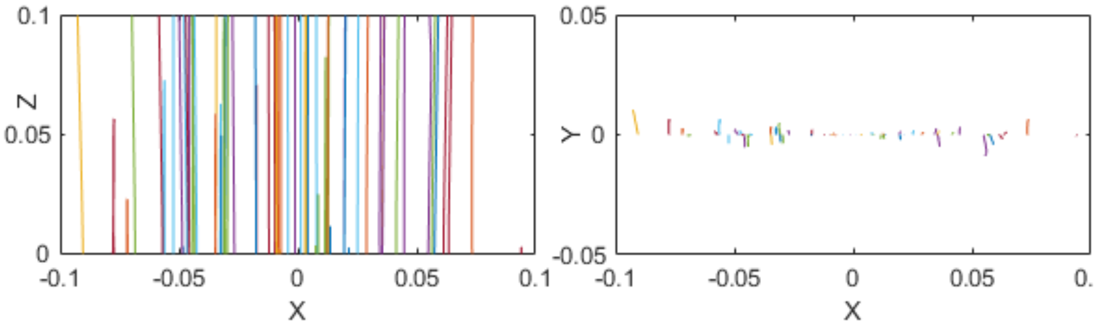


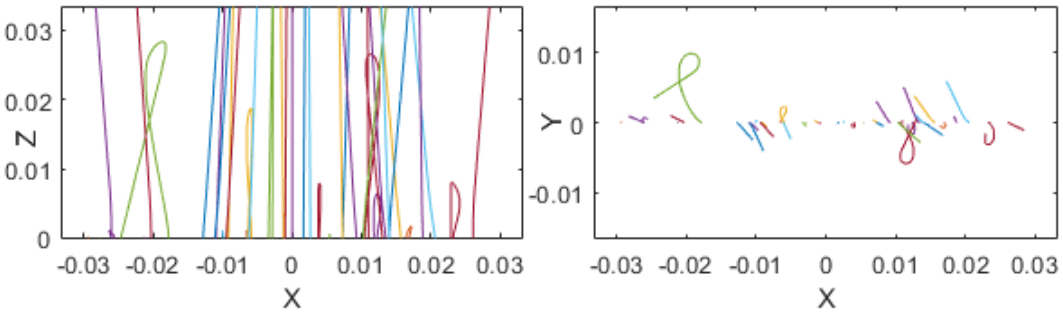
FIG. 13: (Color) The simulated final electron energy $\mathcal{E}_e$ as a function of axial rf gradient for (red) a 805 MHz pillbox cavity, and (blue) a 201 MHz cavity.

Effect of the RF frequency (G. Ferrand).

- A few simulations of particle in pillboxes with Matlab. Example at 0.5 T.



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



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

At 2.1 GHz, an identical focusing of the electron beam than at 700 MHz occurs at 2xB.

RF test stand requirements

- Frequency:
  - Ideally the ones chosen for the 6D cooling (325-352/650-704 MHz)
  - But the lower the frequency, the bigger the solenoid bore diameter and $$$
    -> tempting to perform BD tests at higher f (3 GHz), but have to rely on models to rescale to MCC frequencies

- Magnetic configuration:
  - two coils SC solenoid, B up to 5T min, ideally 10T, same and opposite polarization (~20T/m)
  - Bore diameter depends on frequency and exact cavity design (w/wo 70 K cooling)
    -> e.g. for 704 MHz, 60 cm free RF bore desired

- RF power sources:
  - ~10's MW range: depends on cavity Q factor and highest needed RF gradient
    -> e.g. for a PB cavity at 704 MHz (Cu) and 50 MV/m : ~7 MW peak
  - Pulses from sub μs to ~0.1 ms, the higher the rep. rate, the faster the cavity conditioning

- Test stand shielding:
  - Radiation shielding against high FE at highest RF gradients
  - May also need magnetic shielding due to extended solenoid stray field

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Thank you
for attention