High gradient RF in strong magnetic fields status and plans

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International MUON Collider Collaboration

Introduction

- The first slides come from the presentation of the IMCC in June 2023.
- They sum up the issue.

RF cavities for muon cooling cells

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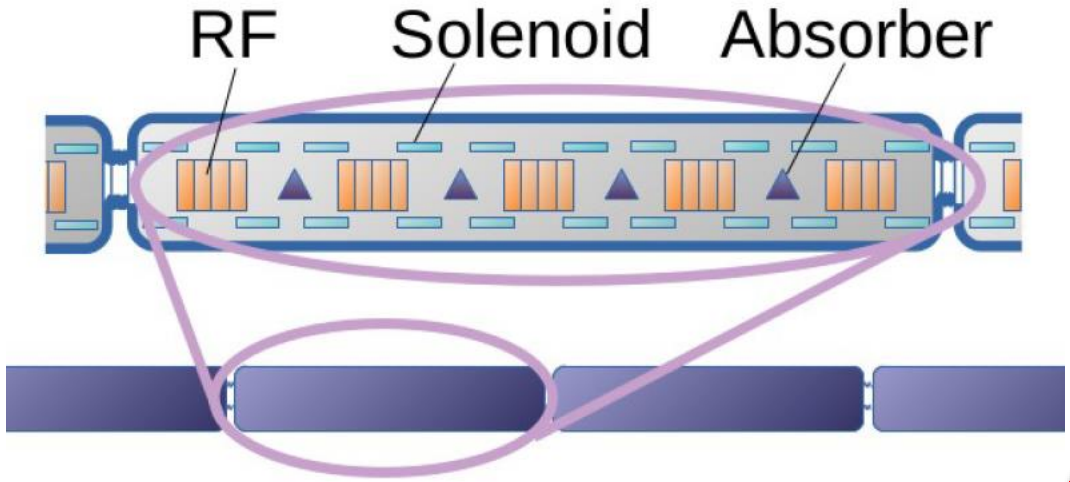
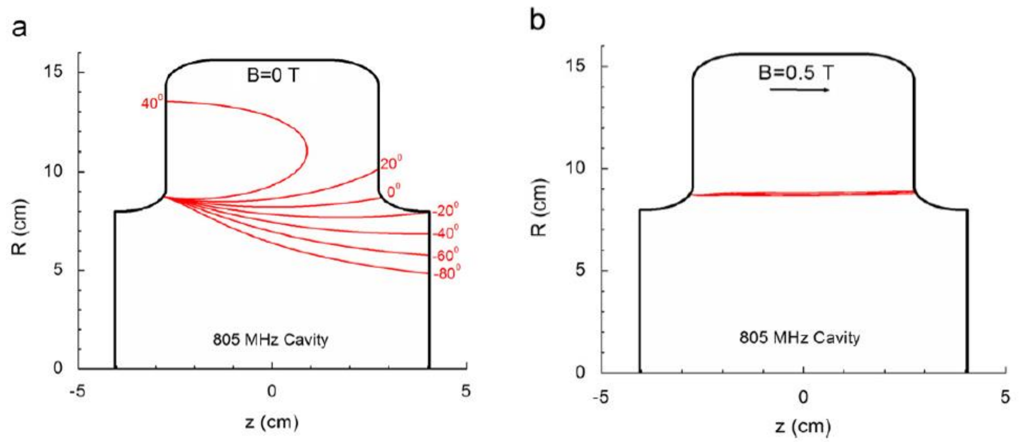


- Normal conducting cavities
- $f \sim 325\ MHz, 650\ MHz$
- Short RF pulses (~μs)
- High acceleration gradients (~30 MV/m)
- High magnetic solenoidal field (up to14 T)

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?

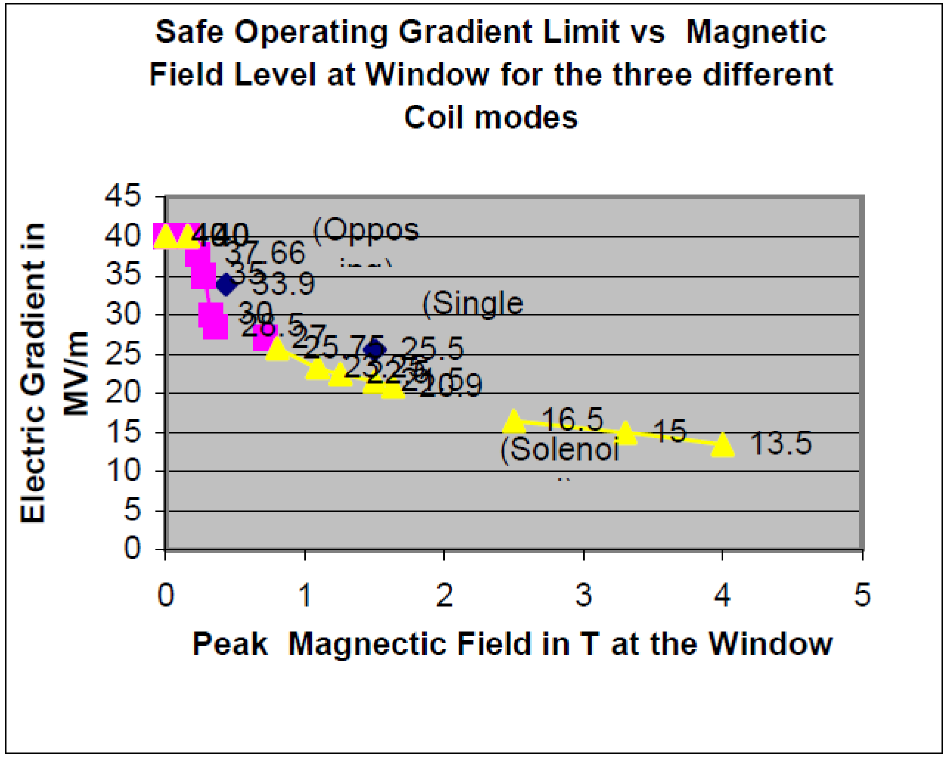


We can assume that this generates high temperature increase locally.

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.

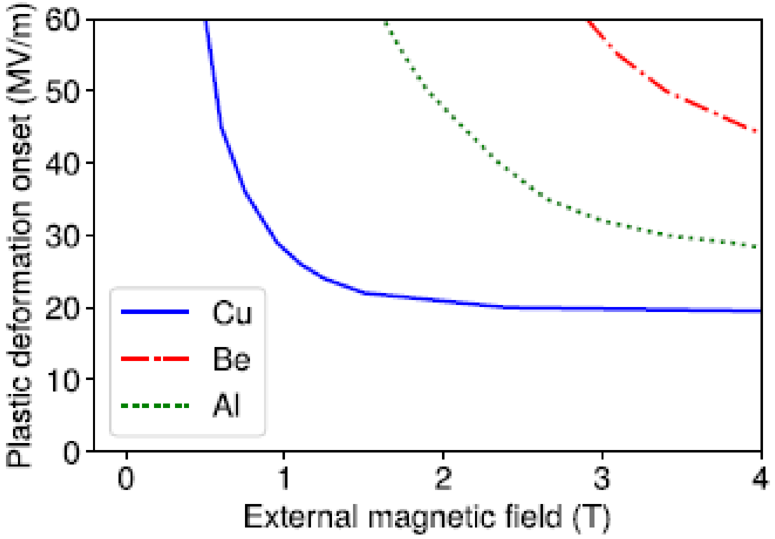
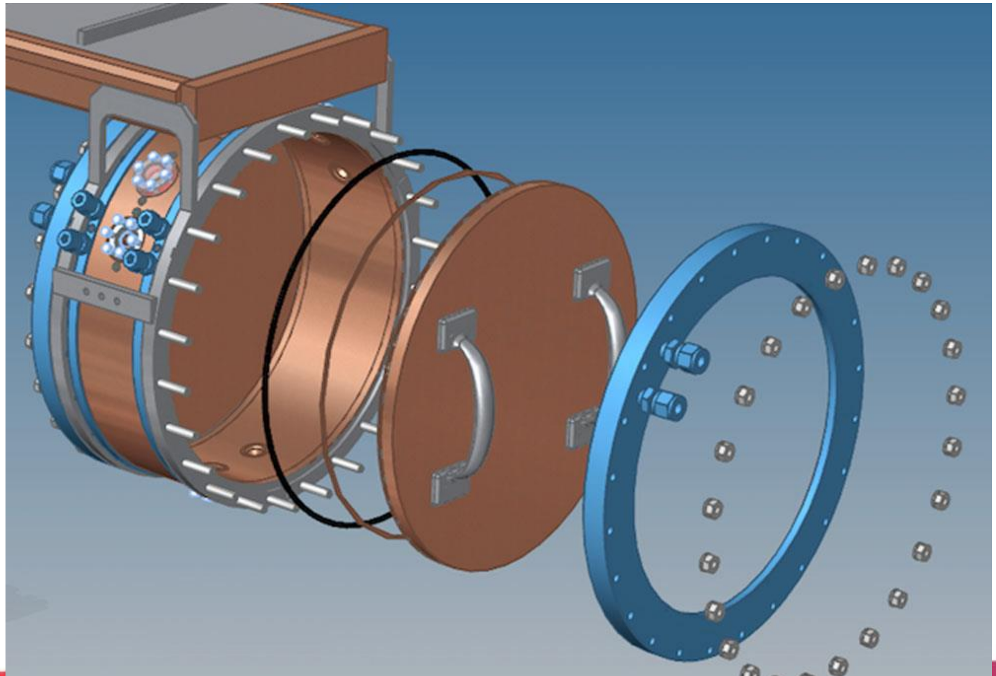


FIG. 3. Predicted cavity gradients vs external, solenoidal magnetic field strength, based on the beamlet pulsed heating model. Beryllium cavity walls should be less susceptible to fatigue from beamlet pulsed heating and should therefore operate at higher gradients relative to copper.



- 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.

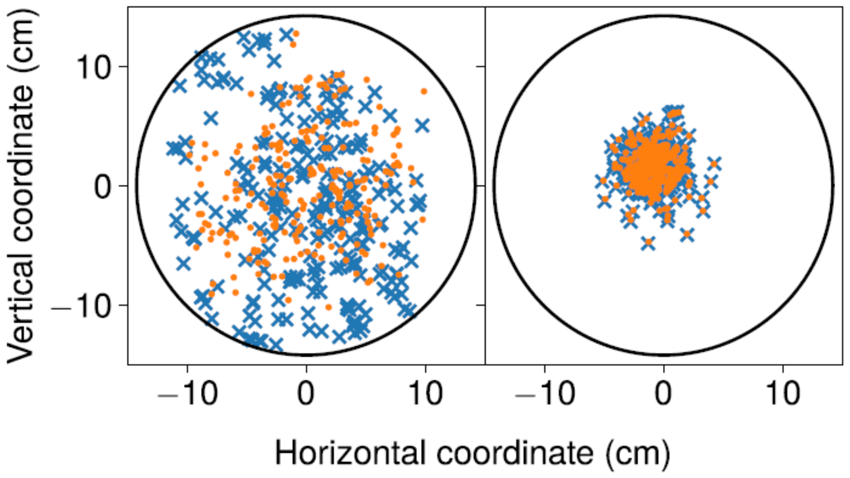
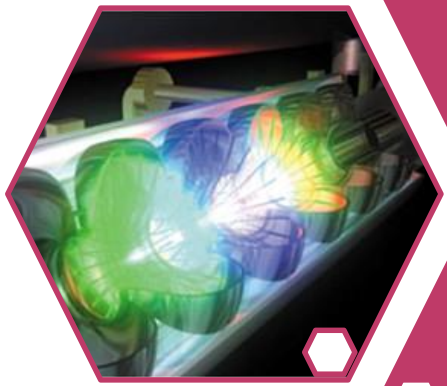


FIG. 6. Map of breakdown damage sites on copper cavity walls after high-power conditioning in zero-tesla external magnetic field (left) and three-tesla field (right). Damage locations are shown from the perspective of the "downstream" cavity wall in the foreground of Fig. 4; blue x's denote damage on 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



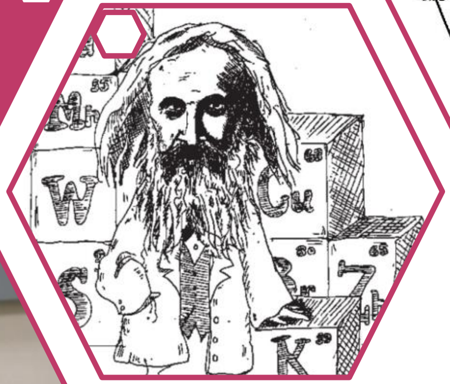
Pulse length?

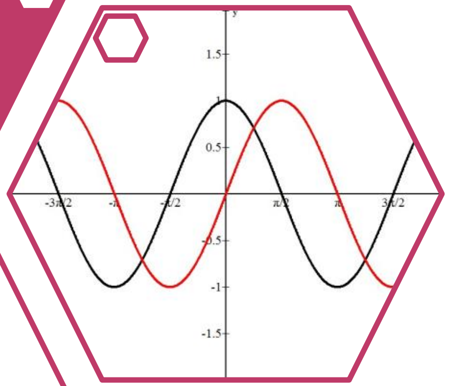
Shape of the cavity?

Cooling temperature?

Other material?

Other frequencies?





Discussion about these results

- Discussion about the pulse length
- Discussion about the material
- Discussion about the geometry of the cavity
- Pulse compressor ?
- RF test stand at Saclay ?

Pulse length

- In a very general way, it was demonstrated that, the lower the pulse length, the better the gradient.
- On the right, SLAC report (ref SLAC-PUB-10463), by Steffen Döbert, RF Breakdown in High-Frequency Accelerators, May 2004.
- X-band : 10 GHz.

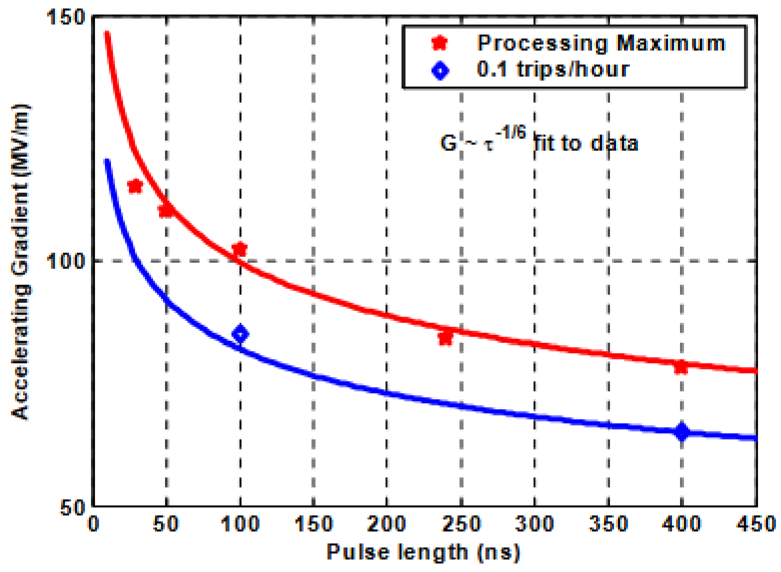
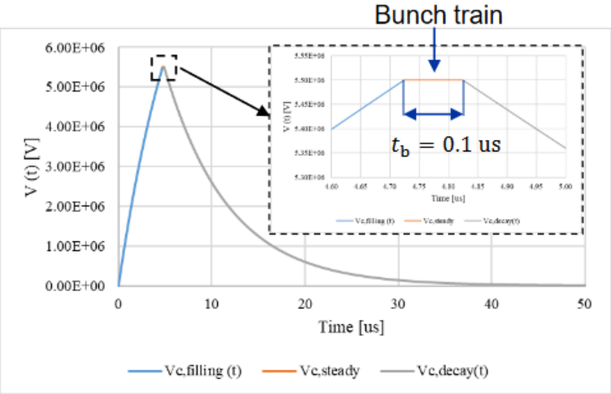
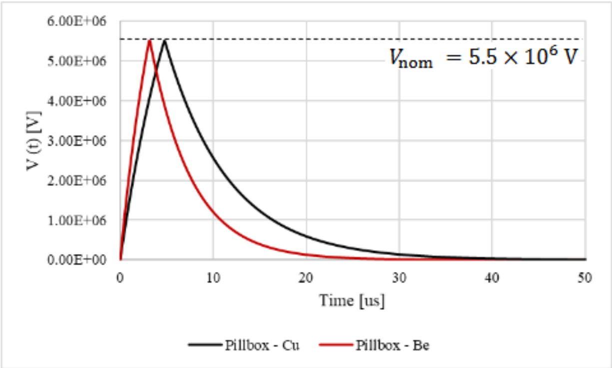


Figure 2: Pulse length dependence of the achievable gradient in X-band structures.

C. Barbagallo presentation for WP8

704 MHz Pillbox cavity – Cu vs. Be





Parameter	Unit	Pillbox - Cu	Pillbox - Be	Description
f_0	[MHz]	704	704	Operating frequency
Q_0	[-]	2.84e+04	1.86e+04	Intrinsic quality factor
**R/Q*	[Ω]	194.73	194.73	Geometric shunt impedance
$R/Q \cdot Q_0$	[Ω]	5.53e+06	3.63e+06	Shunt impedance
P_{diss}	[MW]	3.75	5.72	Peak power dissipated on the cavity walls
τ_l	[us]	3.41	2.24	Filling time constant
$t_{filling}$	[us]	4.70	3.10	Total filling time**
DF	[-]	7.00e-05	3.03e-05	Beam duty factor
P_{ave}	[W]	262.4	173.3	Average power

*(σ_{Cu} = 5.8e+07 S/m, σ_{Be} = 2.50e+07 S/m).

**(f_{rep} = 5 Hz)

- Useful definitions:

Filling voltage

$$V_{c,\text{filling}}(t) = 2V_0\left(1 - e^{-\frac{t}{2\tau_l}}\right)$$

Voltage decay

$$V_{c,\text{decay}}(t) = V_0 \cdot e^{-\frac{t}{2\tau_l}}$$

Filling time

$$t_{\text{filling}} = \tau_l \ln(4) = \frac{Q_0}{\omega_0(1+\beta_{\text{coupling}})}\ln(4)$$

Duty factor

$$\text{DF} = \frac{P_{ave}}{P_{diss}} = \frac{\int V(t)dt}{V_{acc}^2/(R/Q \cdot Q_0)}$$

- **Lower power dissipation for Cu cavity because of higher Q_0.**
- **Lower average power for Be cavity because of lower filling time and duty factor.**

Requirement:

- Very short pulses.
- High gradients.
- High magnetic field.

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:

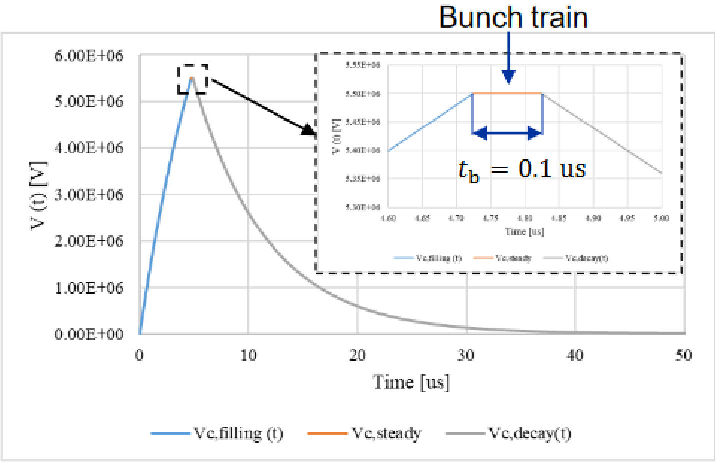
$$B^2 = \rho C_s \frac{2(1-\nu)\sigma_t}{E\alpha_{th}} \times \frac{e\pi\xi^2}{I_{em}^{\frac{1}{3}}\left(\frac{dE}{dz}\right)} \times \frac{1}{\mathrm{t}_{\mathrm{pulse}}}$$

← Pulse length

- It seems like, if t_{pulse} is « low enough », the effect of the « beamlet » phenomenon would be negligible. The acceptable B becomes far higher than the requirement for the cooling cell.
- In the Bowring study, the pulse length was 20 µs. + 12 µs of filling/decay time.

How to define the pulse length?

- RF breakdown will occur during the « RF step » (bunch train), but also during the filling time and decay time.
- To reduce the filling time, we must increase the input power.
- To reduce the decay time, we must decrease the Q0 of the cavity.
- Reducing the bunch train has no effect on the breakdown risk (as its duration is negligible).



After pulse RF breakdown

Example of study of breakdown during the decay of the field. (> GHz).

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ANALYSIS AND SIMULATION OF THE "AFTER-PULSE" RF BREAKDOWN

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Abstract

During the high power experiment of a single-cell standing-wave accelerating structure, it was observed that many RF breakdowns happen when the field inside cavity is decaying after the input rf pulse is off. The distribution of breakdown timing shows a peak at the moment of RF power switches off. A series of simulation was performed to study the after-pulse breakdown effect in such a standing-wave structure. A method of calculating poynting vector over time is proposed in this article to study the modified poynting vector at critical points in the cavity. Field simulation and thermal calculation were also carried out to analyze possible reasons for the after-pulse breakdown effect.

INTRODUCTION

RF breakdown is one of the main limitation to achieve high gradient accelerating structures [1], however, its mechanism still haven't been fully understood over decades of research. During this period, several physical parameters that affect breakdown rate (BDR) have been studied and proposed as a guidance for the design and optimization of high gradient structures, such as frequency, electric field, pulse heating, rf power and modified Poynting vector [2] .

Recent years, a series of accelerator structures fabricated at Tsinghua University were high gradient tested at the New

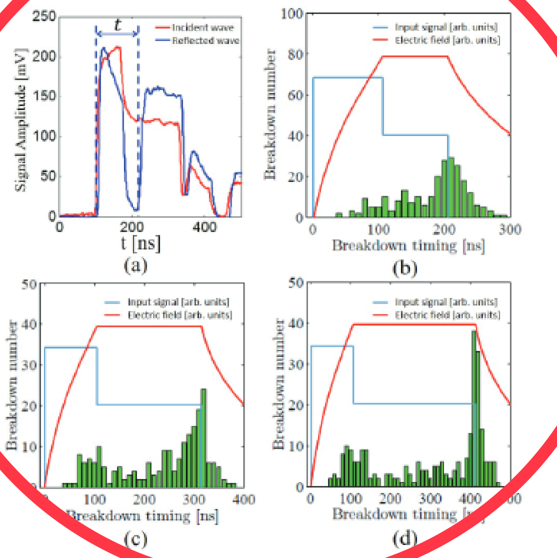


Figure 1: Detected signal and breakdown timing distribution. (a) Typical breakdown signal. *t* is the breakdown timing. (b-d) Breakdown timing distribution in THU-REF with 200 ns, 300 ns and 400 ns pulse width.

Material

- It seems clear that some materials are better than other ones.
- Especially beryllium.
- See beamlet model:
- $T_s = 2\frac{(1-\nu)\sigma_t}{E\alpha_{th}}$
- We can try to find other materials that optimize the « Ts »

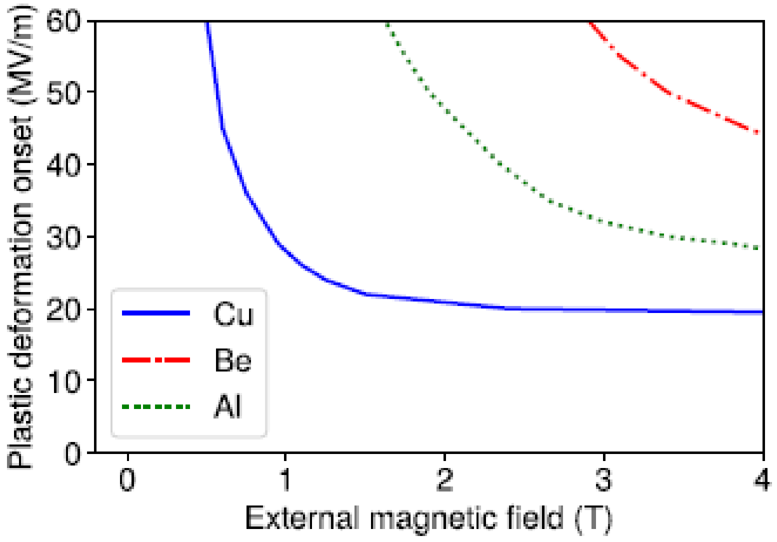


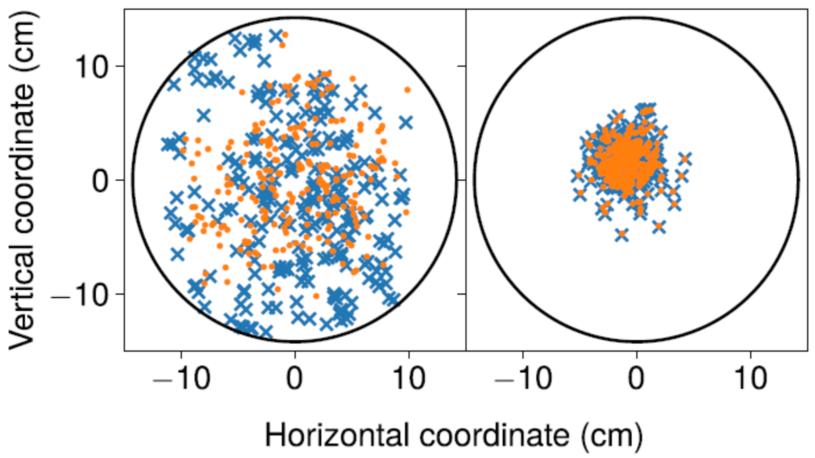
FIG. 3. Predicted cavity gradients vs external, solenoidal magnetic field strength, based on the beamlet pulsed heating model. Beryllium cavity walls should be less susceptible to fatigue from beamlet pulsed heating and should therefore operate at higher gradients relative to copper.

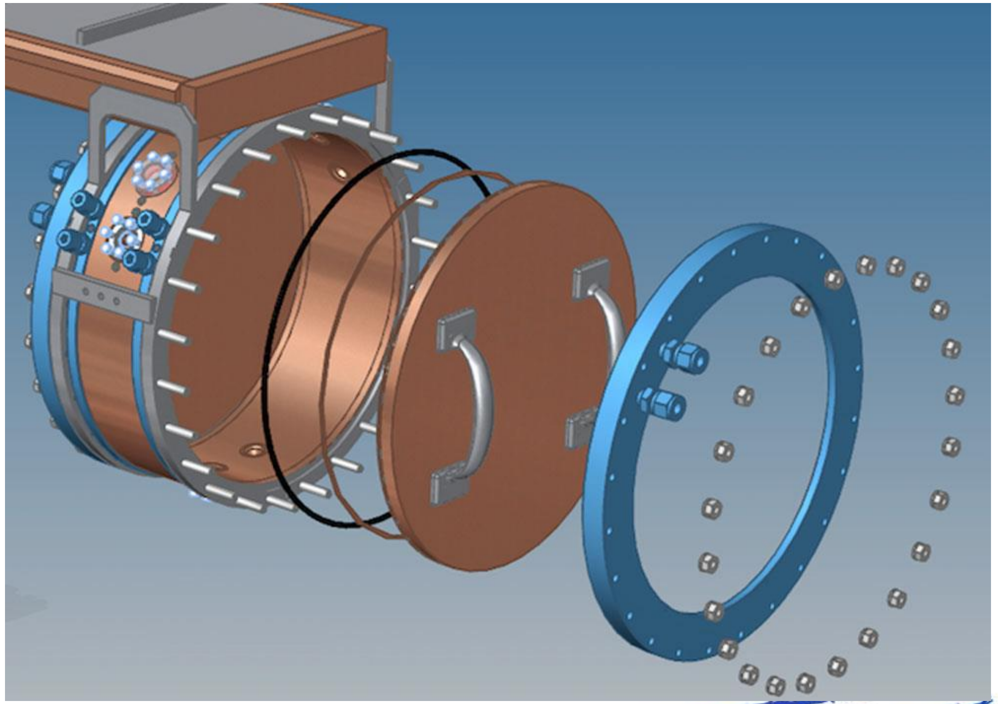
About Beryllium

- Electrical conductivity: $31.10^6\ \mathrm{S.m^{-1}}$. Half of copper. (Not critical).
- Toxicity: Very high. See Berylliosis. Chronic lung diseases due to beryllium poisoning. Well known carcinogen (CIRC 1).
- Mechanical properties: high young modulus ($\simeq 290\ \mathrm{Gpa}$), low yield stress ($\simeq 60\ \mathrm{Mpa}$). Rigid and fragile.
- Cost? I do not know.

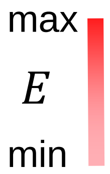
Geometry of the cavity

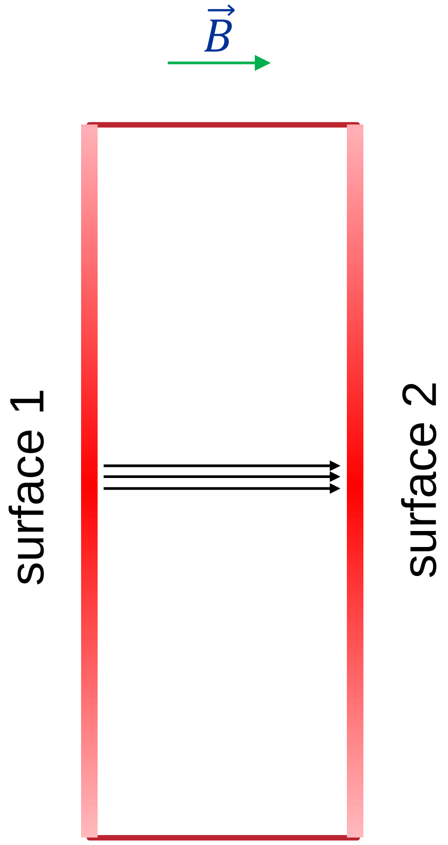
- In Bowring 2020, the cavity is a pillbox cavity.
- « Vicious circle » between the two flat surfaces.
- The area where the E-field is the higher, is the area where the electrons warm the surface.



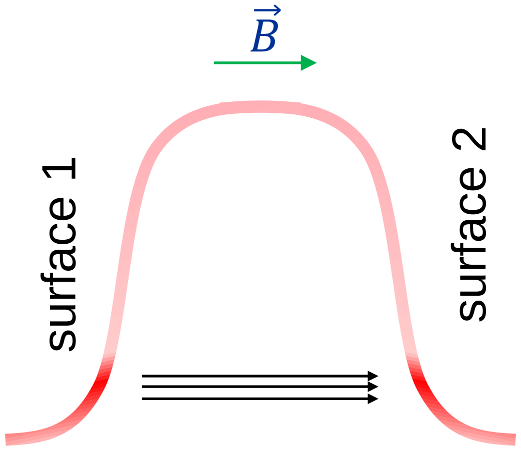


Geometry of the cavity

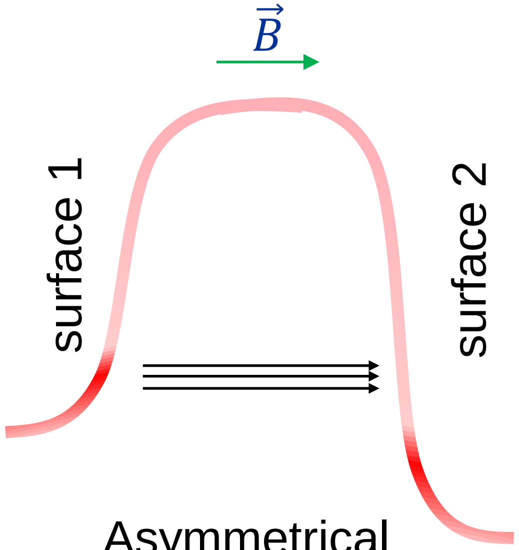




Pillbox. Large emitting area.



Elliptical.
Smaller emitting area.

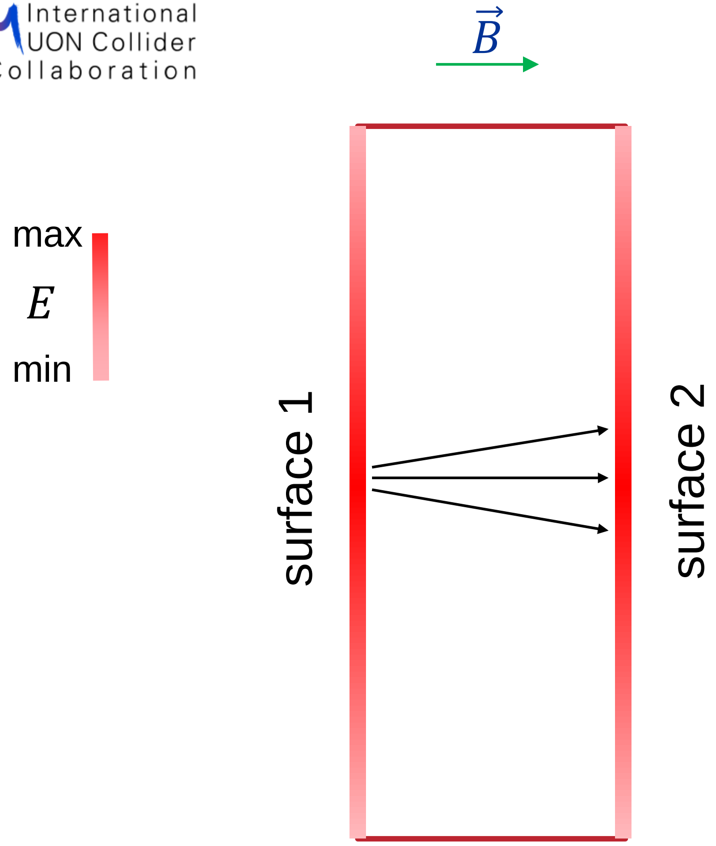


Asymmetrical

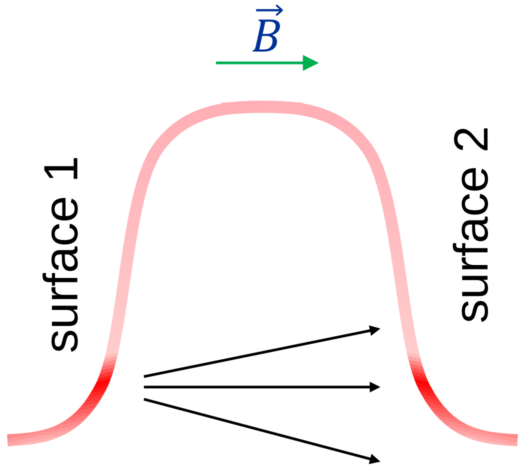
Electrons are emitted by the high E field area of surface 1… and **do not** hit the high E field area of surface 2.

Electrons are emitted by the high E field area of surface 1… and hit the high E field area of surface 2.

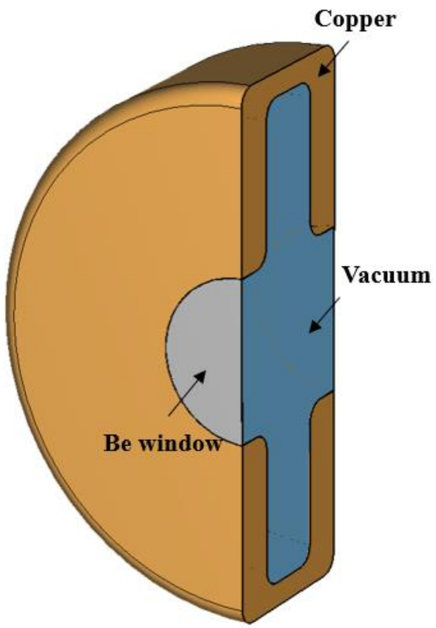
Direction of the B field



Perfect pillbox with no beam tube.
A small B field angle does not really solve the issue.



Cavity with a beam tube.
A small B field angle can reduce the beamlet effect.



Cavity design for a cooling cell by C. Barbagallo.

If the B field is not perfectly parallel to the beam axis, the problem is maybe less critical for « real cavities ».

Multicell cavities

- For multicell cavities, the B field shape can be different for each cell.
- If the breakdown rate increase is highly dependent of the B field shape, maybe some cells will be affected, and some cells will not.

- We are working, at CEA, on a simulation models with CST. (on-going)
- It would be interesting to have an idea of the cavity shape, and on the final B field shape, to do simulations of the electron trajectory.

Pulse compressor

- We need very high power with very short pulses.
- This is typically an application for pulse compressors.
- Illustrations: SLAC, Z. D. Farkas, 1974, SLED : A method of doubling SLAC's energy.

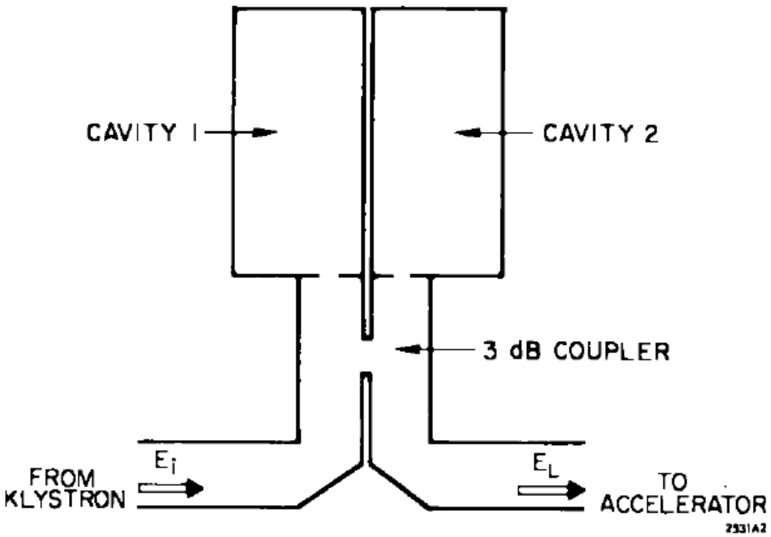


FIG. 1--Schematic drawing of the SLED microwave network.

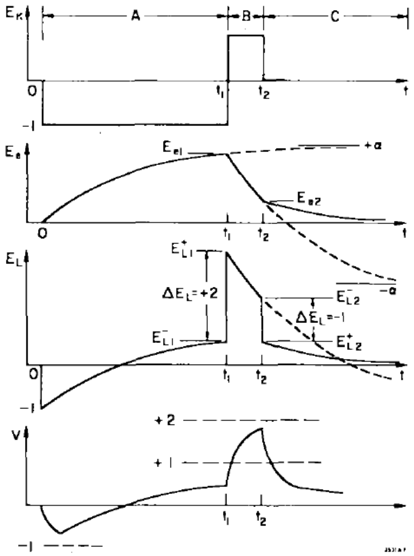


FIG. 3--Direct wave E_K, emitted wave E_e, and net load wave E_L for SLED.

Pulse compressor

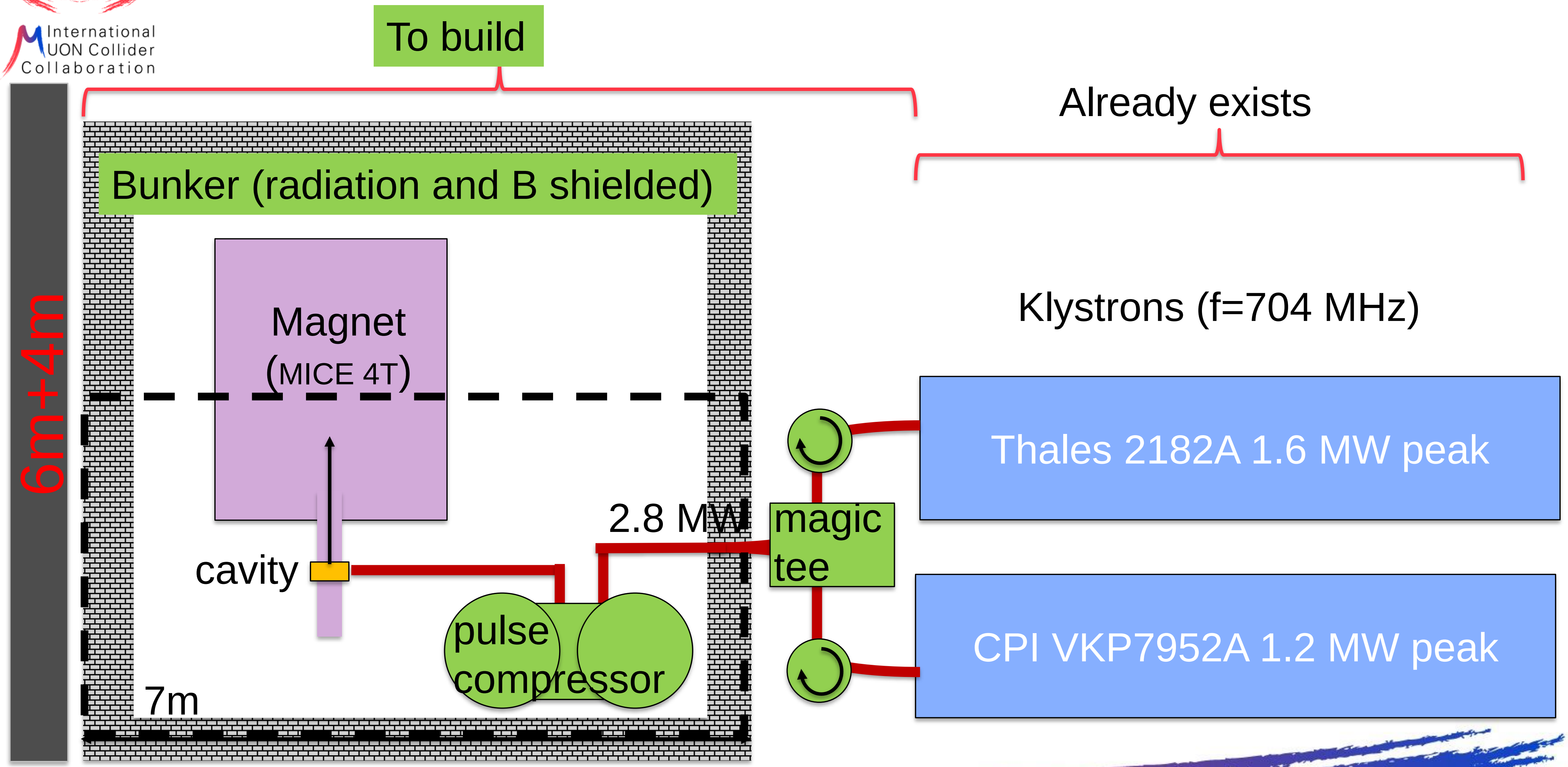
- Generally developped for far higher frequencies (> 1 GHz).
- New developments required for lower frequencies.

- Seems to be an interesting topic to work on.

Last point: Filling the cavity with a gas

- RF breakdown in a gas is very different of RF breakdown under vacuum.
- In a gas, the « dynamic » of the breakdown is described by the plasma physics.
- For now, we did not work about this topic but:
  - On one hand, it seems that the magnetic field should not affect the breakdown limit.
  - On the other hand, it makes the design of the system far more complicated and has certainly a lot of other impacts on the beam dynamics, etc.

Possible RF breakdown test stand at CEA



Questions ?