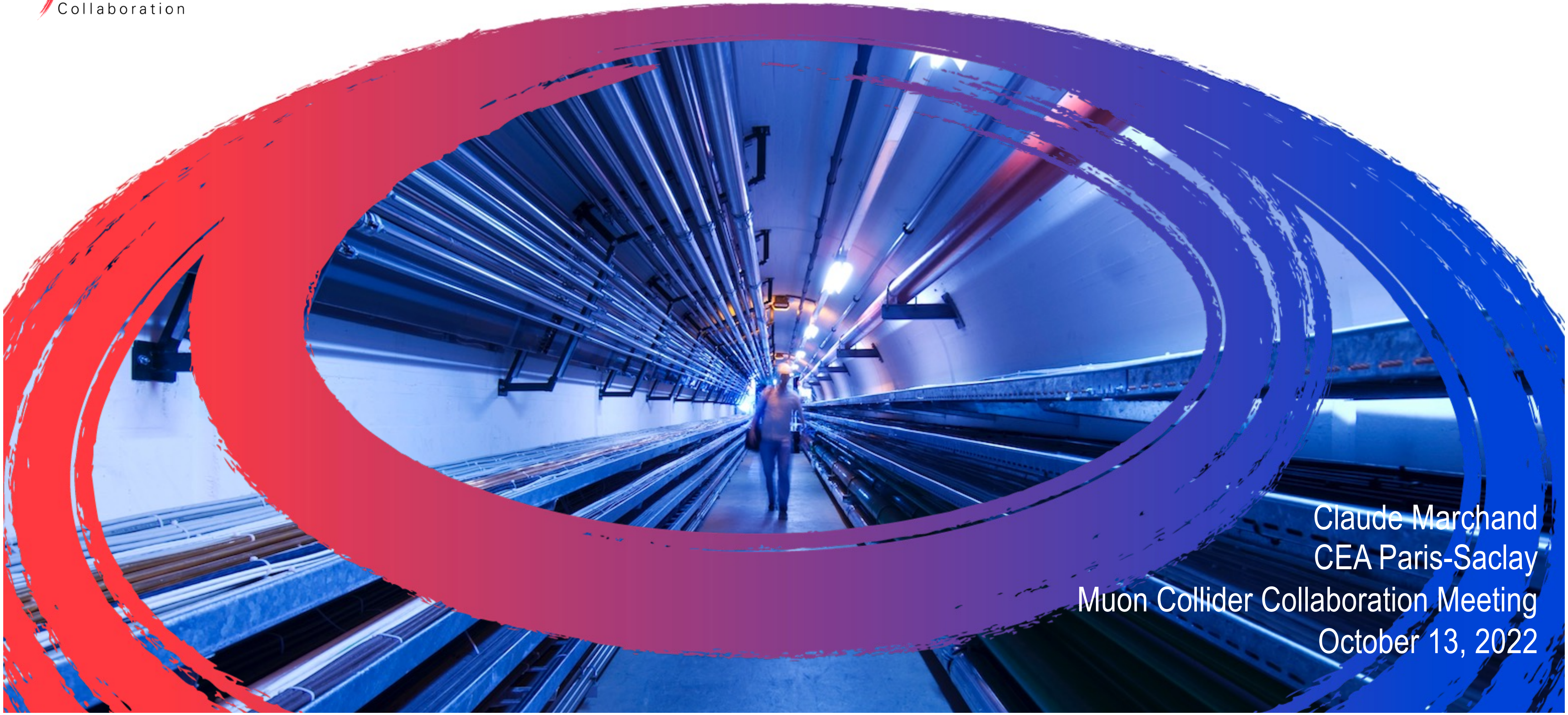
# Demands for RF testing in high magnetic fields



Claude Marchand
CEA Paris-Saclay
Muon Collider Collaboration Meeting
October 13, 2022

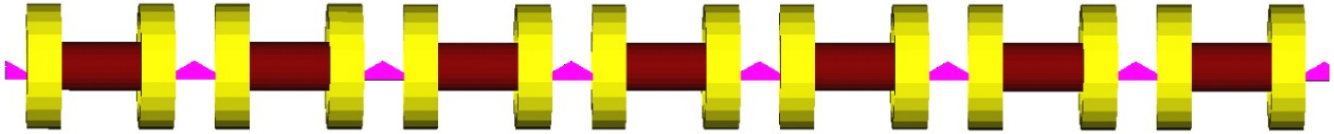
# Outline

- Problematic of NC RF cavities for the muon cooling complex in high magnetic fields:
  - Cavity parameters (f,… ) and magnetic field (MAP study)
  - Breakdown issues in magnetic field
  - Previous experimental tests of cavity prototypes in high B field: MICE, MUCOOL

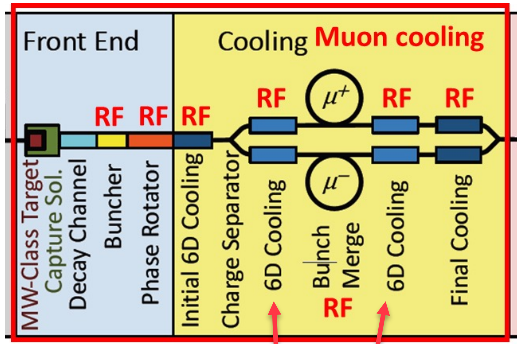
- Further tests are needed to test new/different BD mitigation solutions:
  - Choice of cavity (size, f), max RF power, magnet configuration and max B field

# 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)

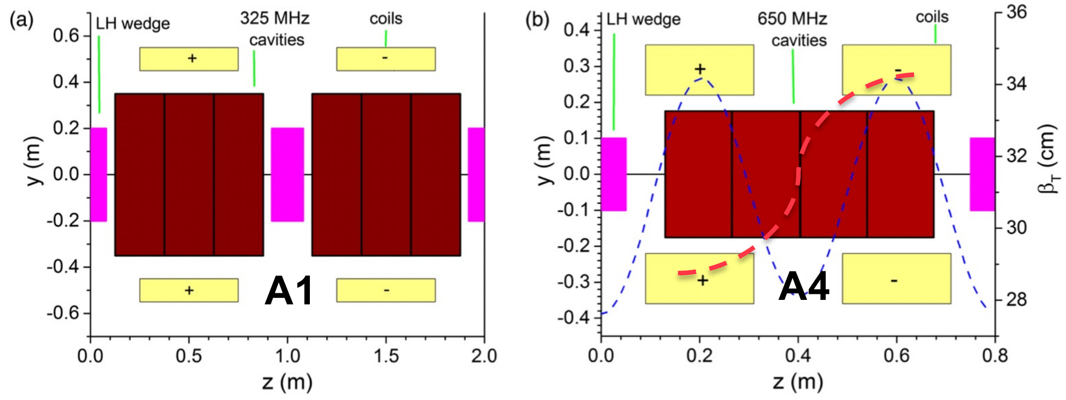


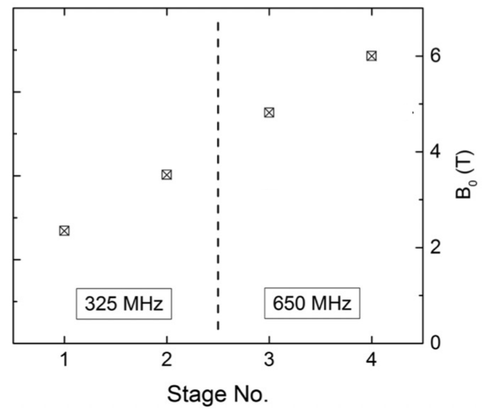

| Stage | Cell length [m] | Total length [m] | rf frequency [MHz] | rf gradient [MV/m] | rf # | rf length [cm] | Coil tilt [deg] | Pipe radius [cm] | B field [T] |
|---|---|---|---|---|---|---|---|---|---|
| A1 | 2.000 | 132.00 | 325 | 22.0 | 6 | 25.50 | 3.1 | 30.0 | 2.2 |
| A2 | 1.320 | 171.60 | 325 | 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

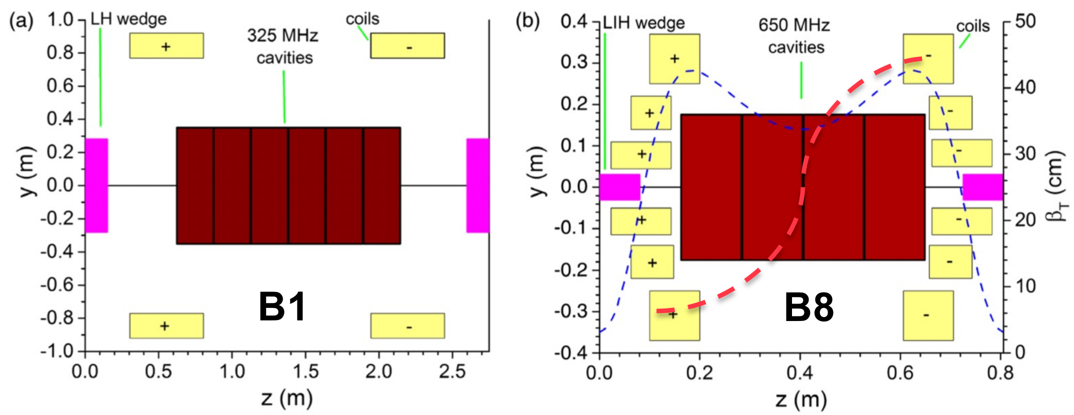
After bunch merge

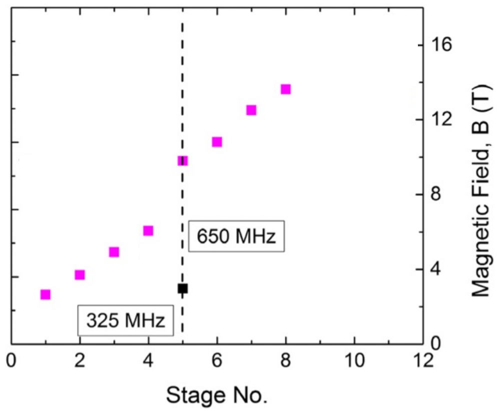
# RF system for 6D cooling (MAP study)



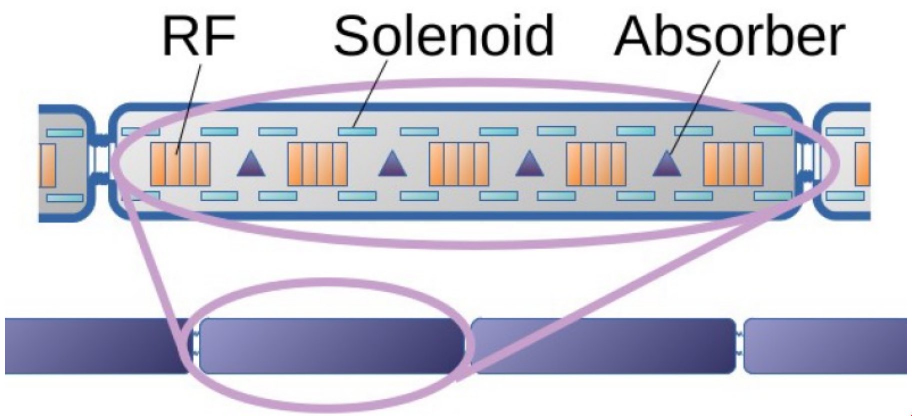

Before bunch merge




After bunch merge

# RF cavities for muon cooling cells

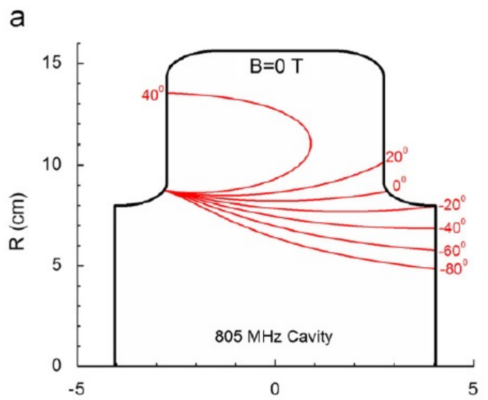


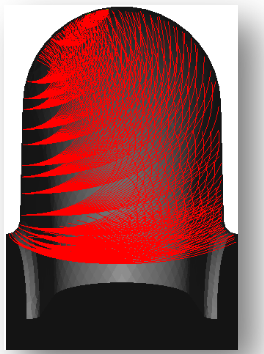

- Normal conducting cavities
- $f \sim 325\ MHz, 650\ MHz$
- Short RF pulses (~$\mu s$)
- High acceleration gradients (~30 MV/m)
- High magnetic solenoidal field (up to14 T)

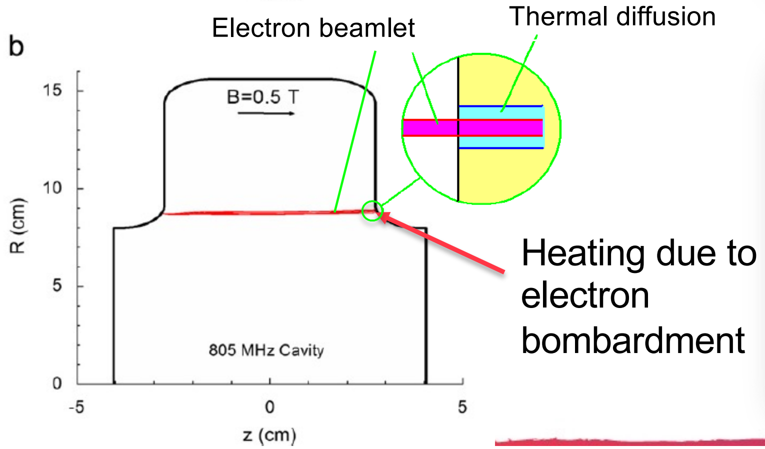
Creates problematics of **break-down** that needs to be mitigated

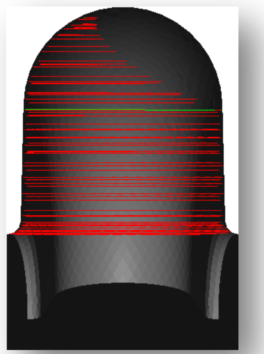
# Breakdown model: beamlet focused by magnetic field

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





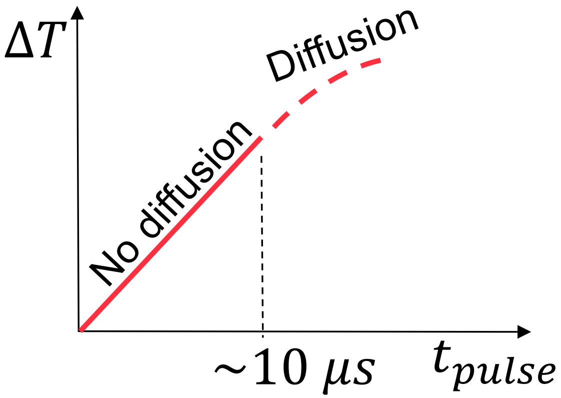



- Model developed by US labs, checked against measurements in high $B$. papers: Palmer et.al PRAB 2009, Stratakis et.al NIMPR 2010, Bowring et.al PRAB 2020
- Model predicts local temperature rise $\Delta T$ due to electron bombardment
- Breakdown occurs when $\Delta T > \Delta T_{plastic}$

$$\Delta T_{plastic} = \frac{2(1-\underbrace{\nu}_{\text{Poisson ratio}})\underbrace{\sigma_t}_{\text{Yield strength}}}{\underbrace{E}_{\text{Elastic modulus}}\,\underbrace{\alpha_{th}}_{\text{Linear expansion}}}$$

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

# 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:

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

Magnetic field at breakdown

Cavity-dependent constant

Pulse length

Emission current $I(E_{acc})$

Electron energy loss

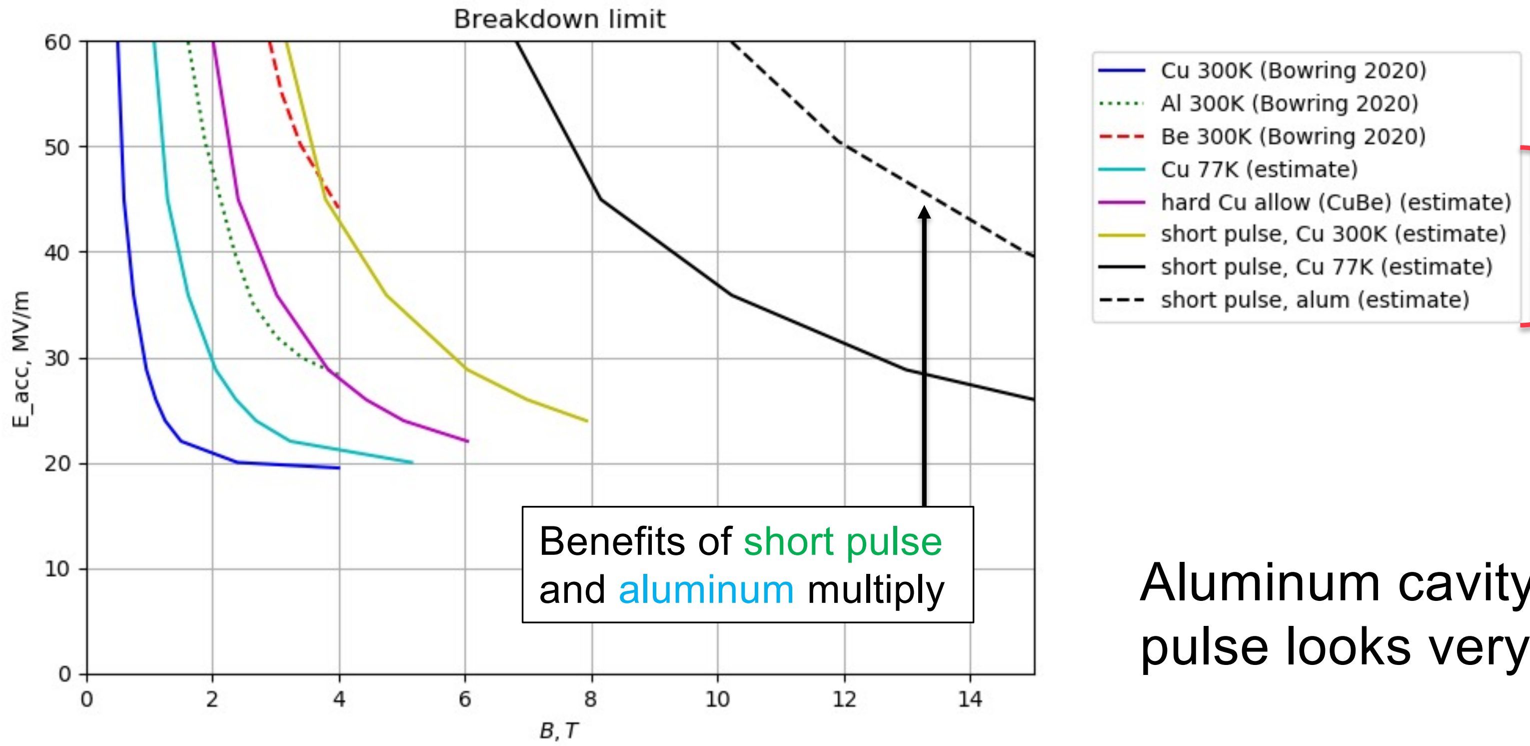
This equation provides scaling laws of $B(E_{acc})$ on different parameters. Mitigation solutions that follow from this equation:

When combined, benefits from different solutions would multiply

- Very short pulse (sub $\mu s$)
- Different wall materials (Al, hard copper alloys, 70 K copper)
- Cavity shape optimization

# 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)



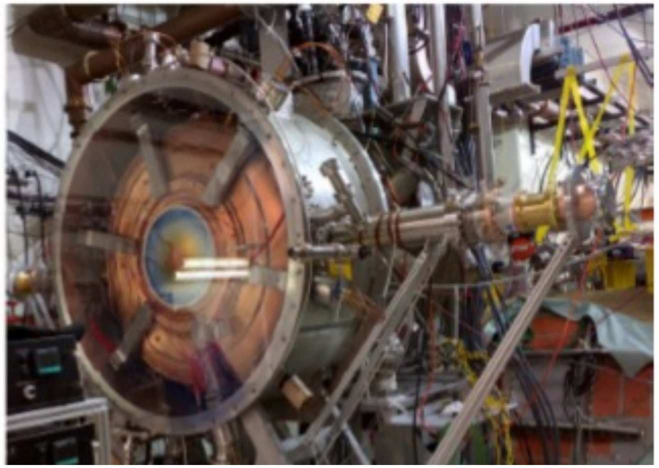

Scaled from the first 3 curves using the scaling model (slide 6)

Aluminum cavity with a short pulse looks very promising

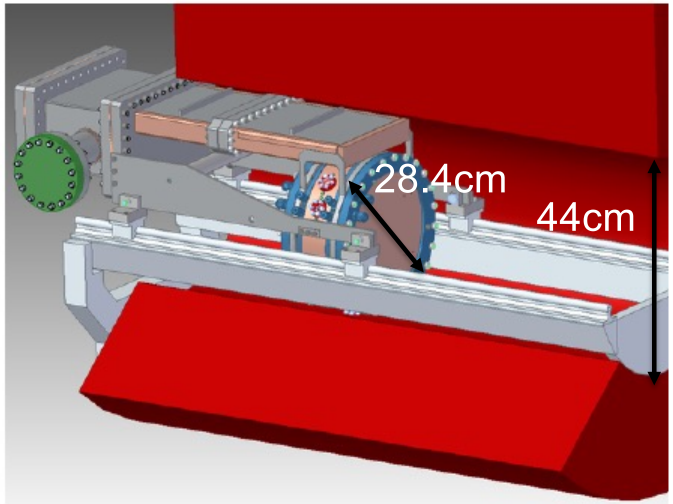
# Previous NC RF cavities tests in high B field

**State of the art (not complete):**

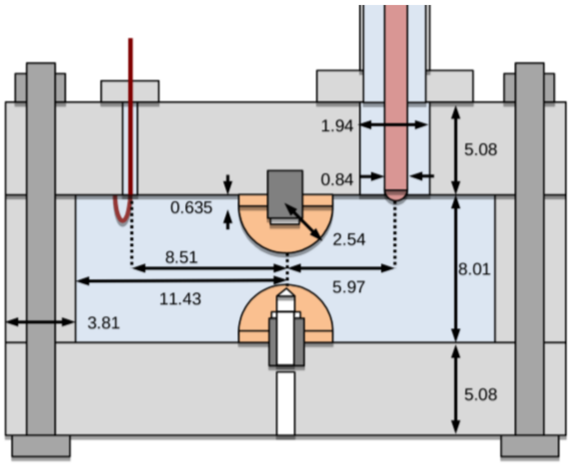
- MICE 200 MHz RF module prototype (beryllium windows): 4T, **10 MV/m**, 1ms@1Hz



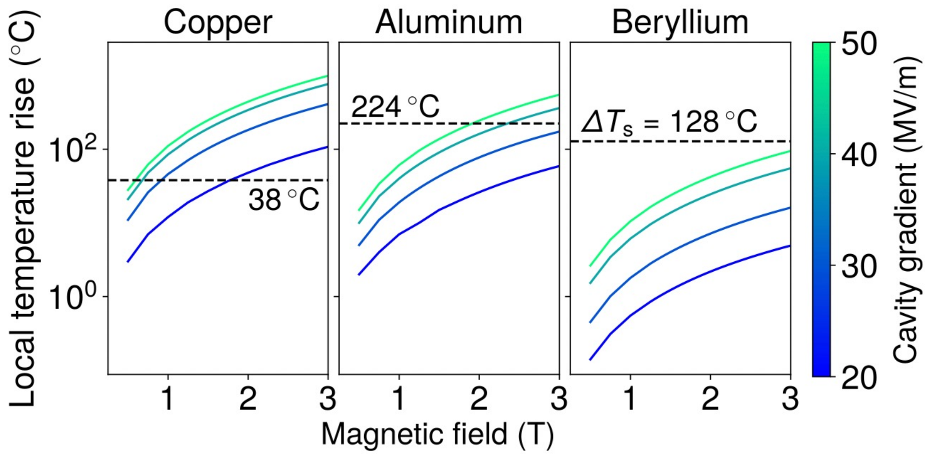
- MUCOOL 800 MHz **beryllium** cavity:
  3T, **50 MV/m**, 30us@10Hz




- MUCOOL **Gas** filled RF cavity:
  3 T, **65 MV/m** 800 MHz molybdenum cavity



# MuCool 800 MHz cavitiy test with modular plates

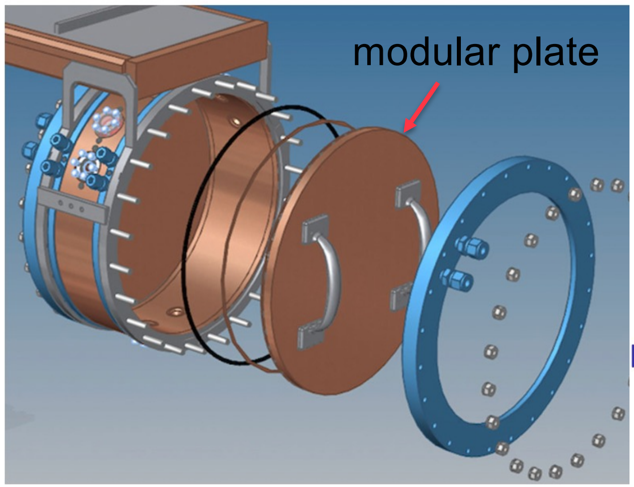



Operation of normal-conducting rf cavities in multi-Tesla magnetic fields for muon ionization cooling: A feasibility demonstration

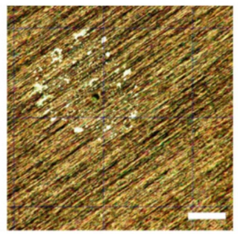
D. Bowring, A. Bross, P. Lane, M. Leonova, A. Moretti, D. Neuffer, R. Pasquinelli, D. Peterson, M. Popovic, D. Stratakis, K. Yonehara, A. Kochemirovskiy, Y. Torun, C. Adolphsen, L. Ge, A. Haase, Z. Li, D. Martin, M. Chung, D. Li, T. Luo, B. Freemire, A. Liu, and M. Palmer

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

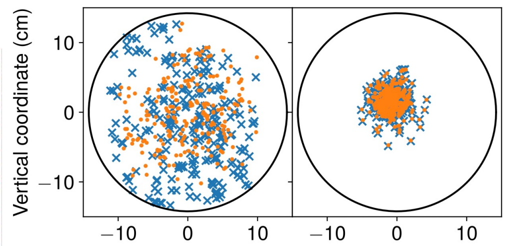
FIG. 2. Semi-log plot of local $\Delta T$ for Cu, Al, and Be cavities at various gradients and across a range of solenoidal magnetic field strengths. $\Delta T_s$ [Eq. (4)] is indicated in each plot by a horizontal, dashed line. Note that for Be, the local temperature rise is lower than $\Delta T_s$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



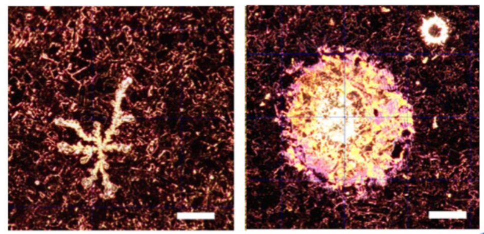

| Material | $B$-field (T) | SOG (MV/m) |
|---|---|---|
| Cu | 0 | $24.4 \pm 0.7$ |
| Cu | 3 | $12.9 \pm 0.4$ |
| Be | 0 | $41.1 \pm 2.1$ |
| Be | 3 | $> 49.8 \pm 2.5$ |
| Be/Cu | 0 | $43.9 \pm 0.5$ |
| Be/Cu | 3 | $10.1 \pm 0.1$ |



**Be: 0 & 3 T**




**Cu: 0 T** **Cu: 3 T**



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

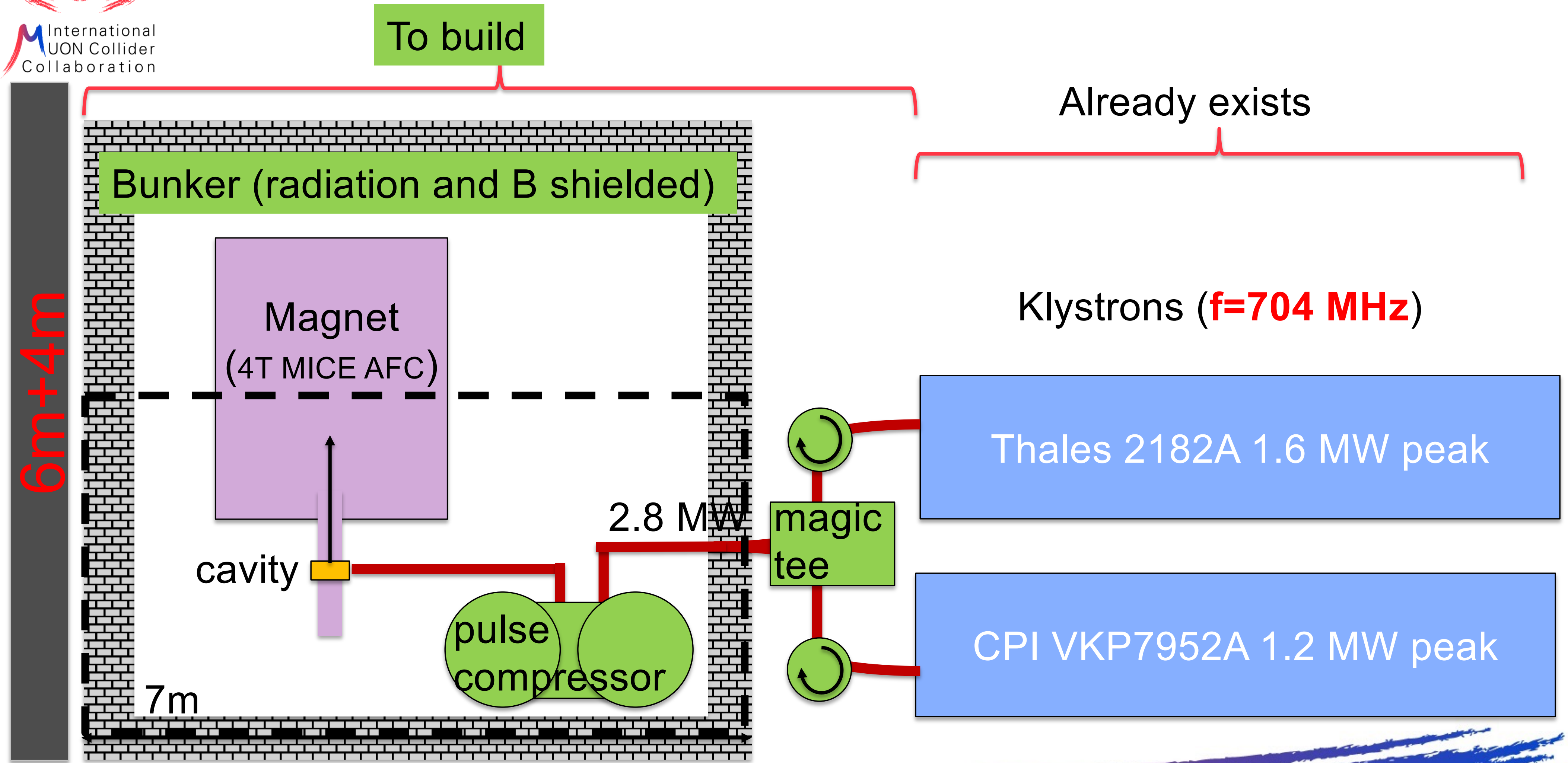
# R&D directions for NC RF cavities tests in high B field

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

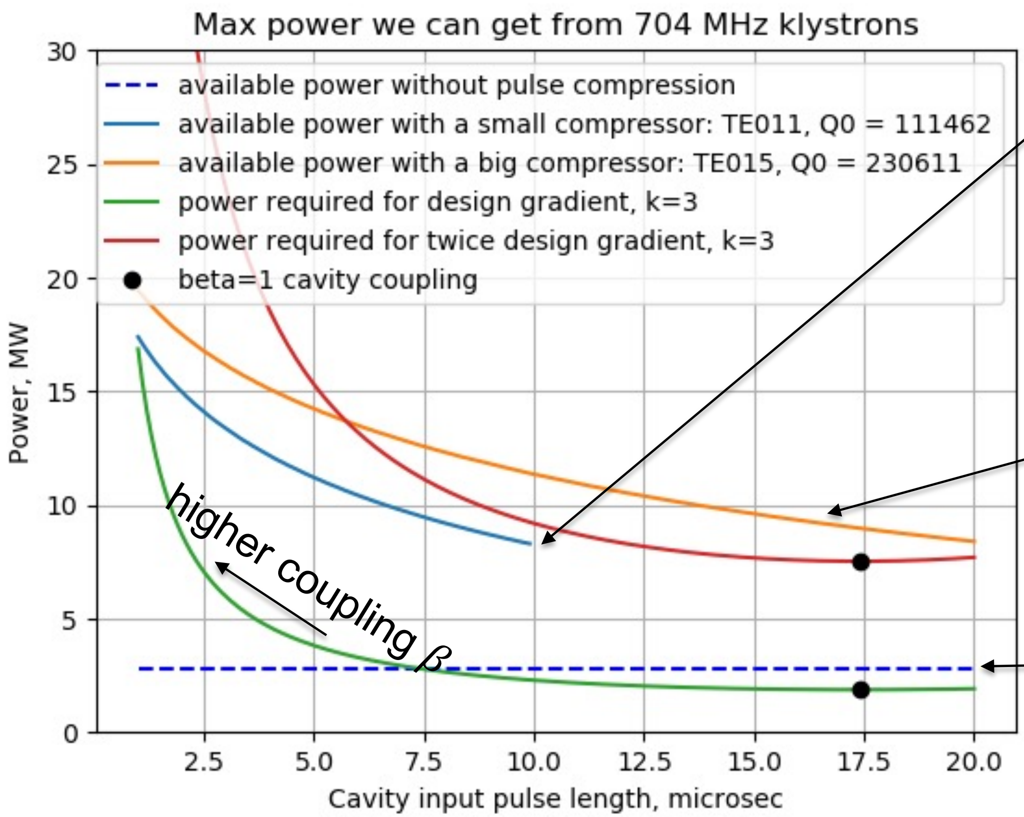
  Test cavities for technology development

  - Frequency: 300 to 700 MHz range, some usefull tests even in S-band
  - RF power to get gradients from 25 to 50 MV/m
  - Short RF pulses (~$\mu$s)
  - **Magnetic field: 0 - 14T, different field configurations**
  - Different materials: Cu, Be, **Al**, …
  - Different temperatures: 300K -> **70K** ->…

# Possible RF breakdown test stand at CEA Saclay



# Need for a pulse compressor




Small compressor ($Q_0 \sim 10^5$) can only produce short pulses ($\sim 10\ \mu s$ max), so an overcoupled cavity may be needed

Big compressor ($Q_0 \sim 2\times 10^5$) allows testing at twice the nominal gradient

No compressor - sufficient for tests at the nominal gradient

# Chosen test cavity

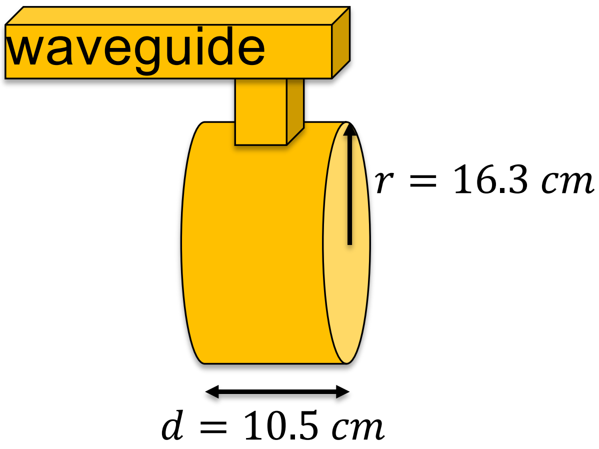
Cavity candidate for RF tests: B8 cavity adapted into a 704 MHz pillbox

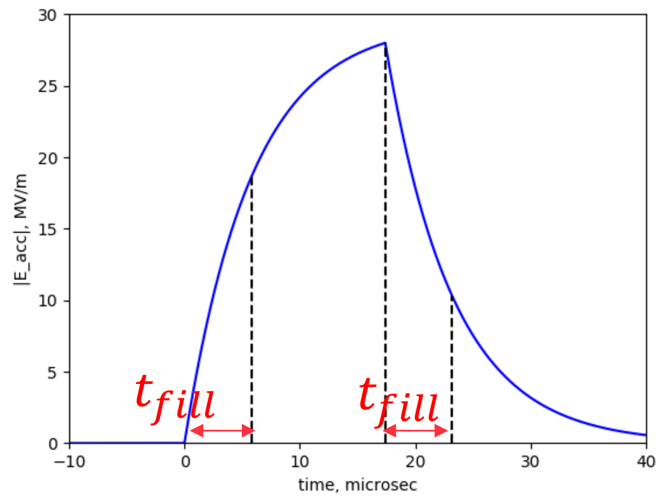
$$f = 704\ MHz$$
$$E_{grad} = 28\ MV/m$$
$$\left(\frac{R}{Q}\right)^{linac} = 194\ \Omega$$
$$G = 177\ \Omega$$
$$Q_0 = 25600$$
$$t_{fill} = \frac{Q_0}{\omega} = 5.8\ \mu s$$
$$P_{\beta=1,E=E_{grad}} = 1.7\ MW$$
$$P_{\beta=1,E=2E_{grad}} = 6.9\ MW$$

## 6D cooling channel RF cavities

| Stage | Cell length [m] | Total length [m] | rf frequency [MHz] | rf gradient [MV/m] | rf # | rf length [cm] | Coil tilt [deg] | Pipe radius [cm] | Dispersion [cm] | Wedge angle [deg] |
|---|---|---|---|---|---|---|---|---|---|---|
| A1 | 2.000 | 132.00 | 325 | 22.0 | 6 | 25.50 | 3.1 | 30.0 | 10.7 | 39 |
| A2 | 1.320 | 171.60 | 325 | 22.0 | 4 | 25.00 | 1.8 | 25.0 | 6.8 | 44 |
| A3 | 1.000 | 107.00 | 650 | 28.0 | 5 | 13.49 | 1.6 | 19.0 | 4.2 | 100 |
| A4 | 0.800 | 70.40 | 650 | 28.0 | 4 | 13.49 | 0.7 | 13.2 | 1.9 | 110 |
| B1 | 2.750 | 55.00 | 325 | 19.0 | 6 | 25.00 | 0.9 | 28.0 | 5.2 | 120 |
| B2 | 2.000 | 64.00 | 325 | 19.5 | 5 | 24.00 | 1.3 | 24.0 | 5.0 | 117 |
| B3 | 1.500 | 81.00 | 325 | 21.0 | 4 | 24.00 | 1.1 | 18.0 | 4.6 | 113 |
| B4 | 1.270 | 63.50 | 325 | 22.5 | 3 | 24.00 | 1.1 | 14.0 | 4.0 | 124 |
| B5 | 0.806 | 73.35 | 650 | 27.0 | 4 | 12.00 | 0.7 | 9.0 | 1.4 | 61 |
| B6 | 0.806 | 62.06 | 650 | 28.5 | 4 | 12.00 | 0.7 | 7.2 | 1.2 | 90 |
| B7 | 0.806 | 40.30 | 650 | 26.0 | 4 | 12.00 | 0.8 | 4.9 | 1.1 | 90 |
| B8 | 0.806 | 49.16 | 650 | 28.0 | 4 | 10.50 | 0.6 | 4.5 | 0.6 | 120 |

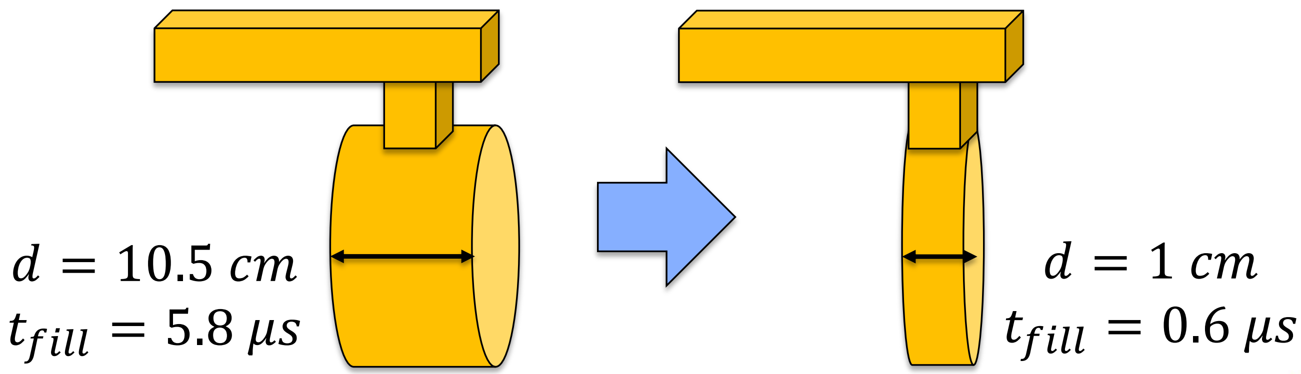
B=14 T needed!



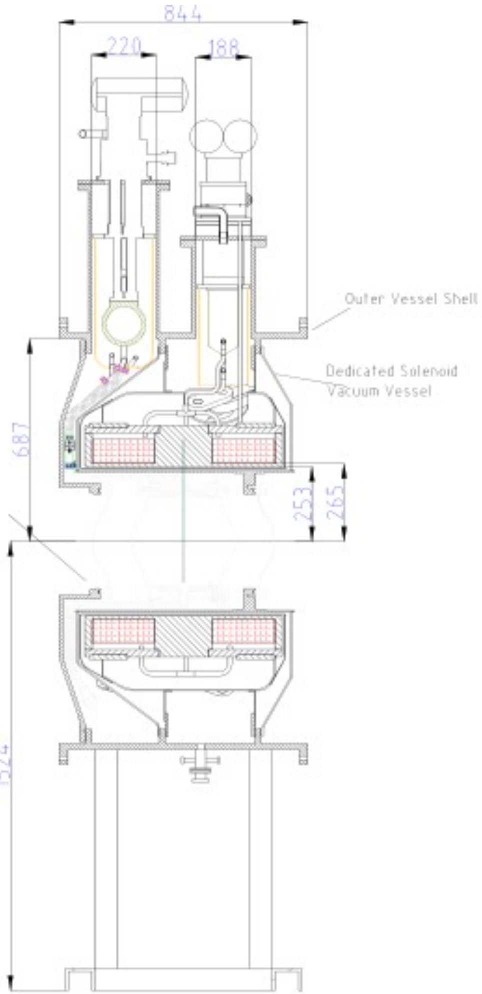



# Short cavity to test the effect of pulse length on breakdown

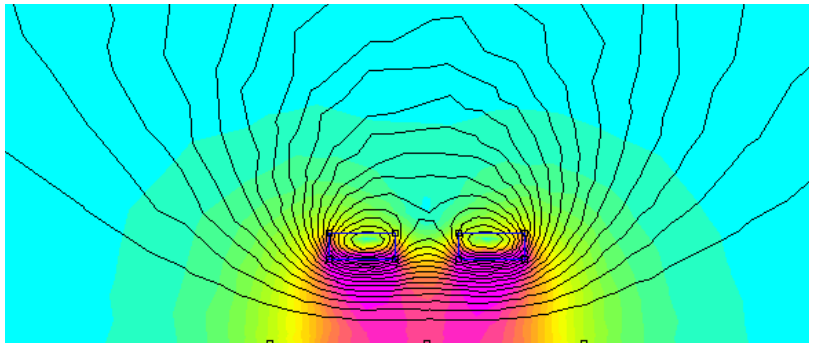
- We expect that a short RF pulse time will make cavity more breakdown-resistant, and we want to test it
- Testing this with the nominal-size cavity requires very high input power perhaps only reachable with a complex two-stage pulse compressor
- But testing it with a short cavity requires no additional input power. The hope is that a conclusion (e.g. "sub-$\mu$s pulse gives 3x boost in usable gradient") would translate to the nominal cavity.



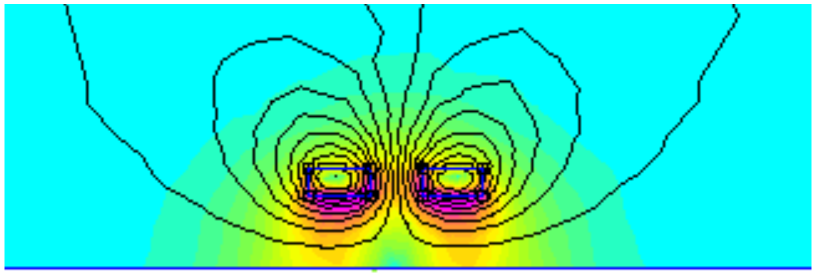
# 4T MICE AFC magnet




- Two internal coils, // or anti // operation
- Modes: solenoid / cusp
- In solenoid mode ~ 4T
- Bore diameter ~ 470mm



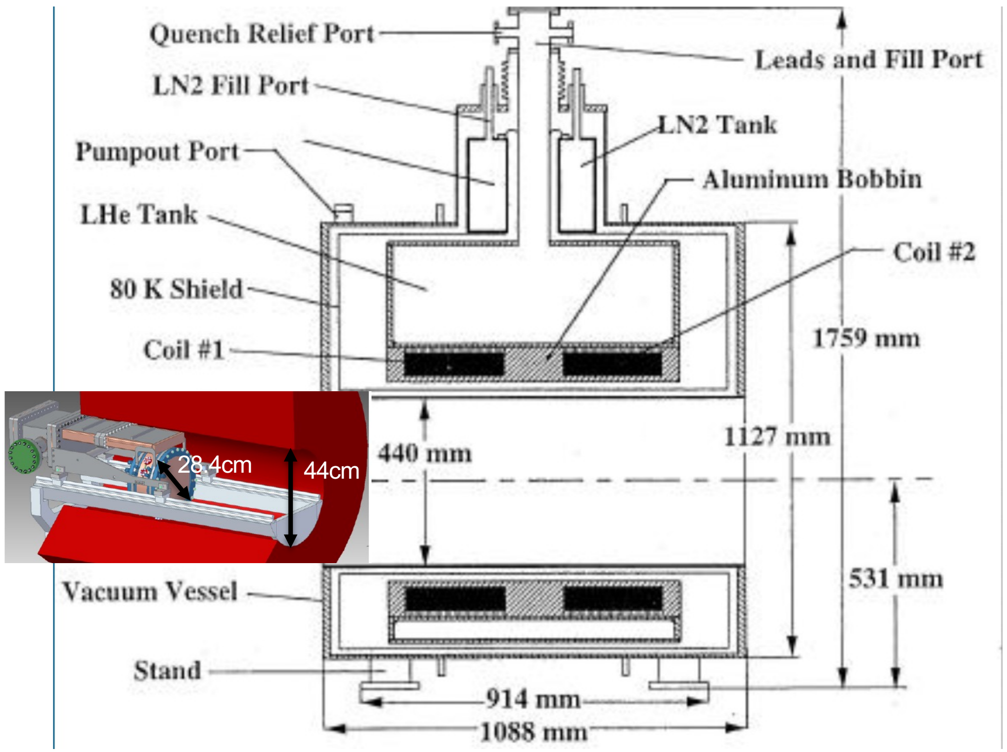
- Magnet in solenoid mode
- Centre flux density: 4T



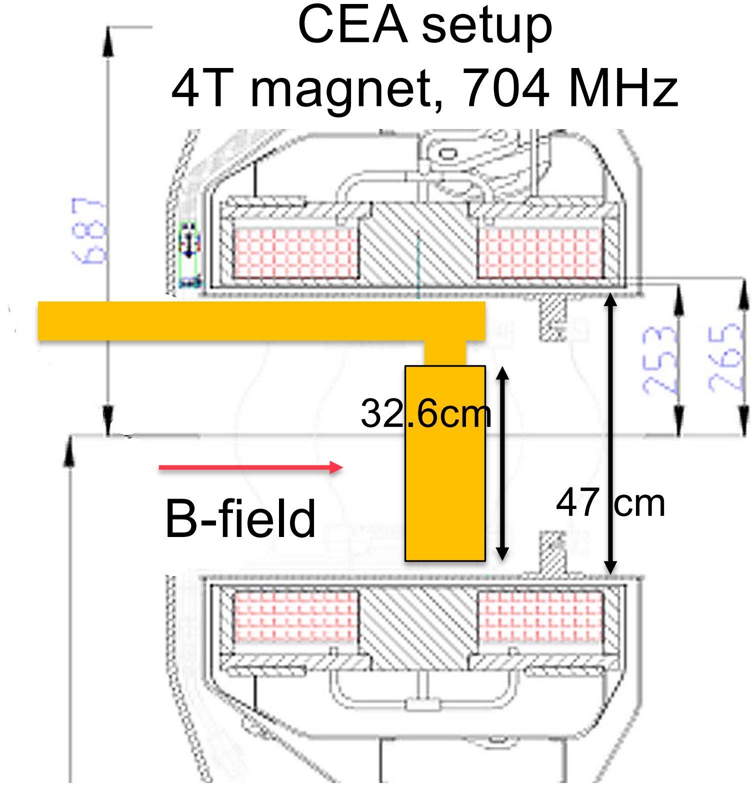
- Coils driven in cusp mod (anti //)
- Axial field lower (~2.5T)
- High radial gradient field

# 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

# Test plan for NC RF cavities in high B field (CEA)

1. Tests with existing 704 MHz klystrons, MICE 4T solenoid, gradients up to 28 MV/m
   - Ship the solenoid from UK and install at CEA Saclay
   - Build the magnetically and radiation shielded bunker
   - Build the waveguide lines
   - Design and fabricate the cavity (similar to modular cavity of MUCOOL)

2. Tests with a short cavity to probe into sub-$\mu$s pulses

3. Test different materials such as Al, CuBe, etc

4. Possibly 70K copper cavity. Requires cryostat design.

5. Adding a pulse compressor for testing at >28 MV/m (requires some compressor R&D as no compressors exist at <1 GHz)

6. Tests at B fields up to 14 T in different configurations

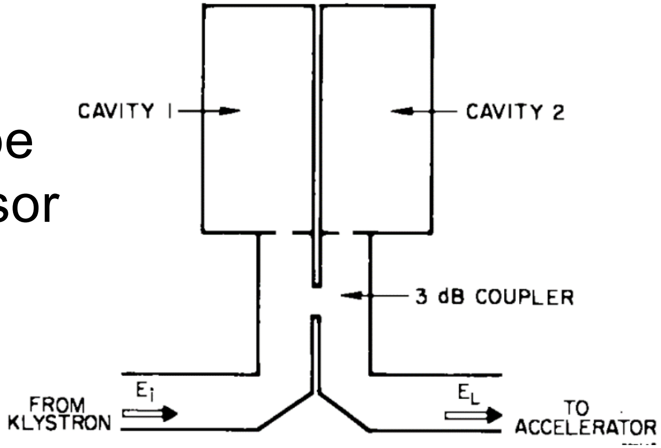
International
MUON Collider
Collaboration

***Thank you***
***for attention***

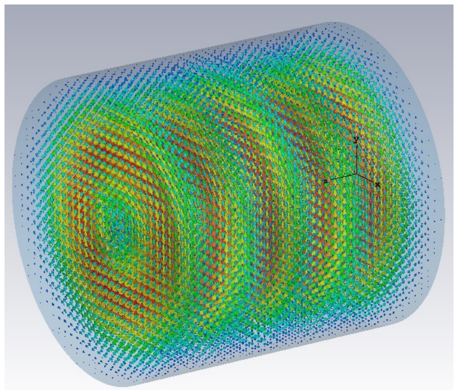
# Back-up slides

# Pulse compressor

SLED type compressor




Big compressor mode: TE015

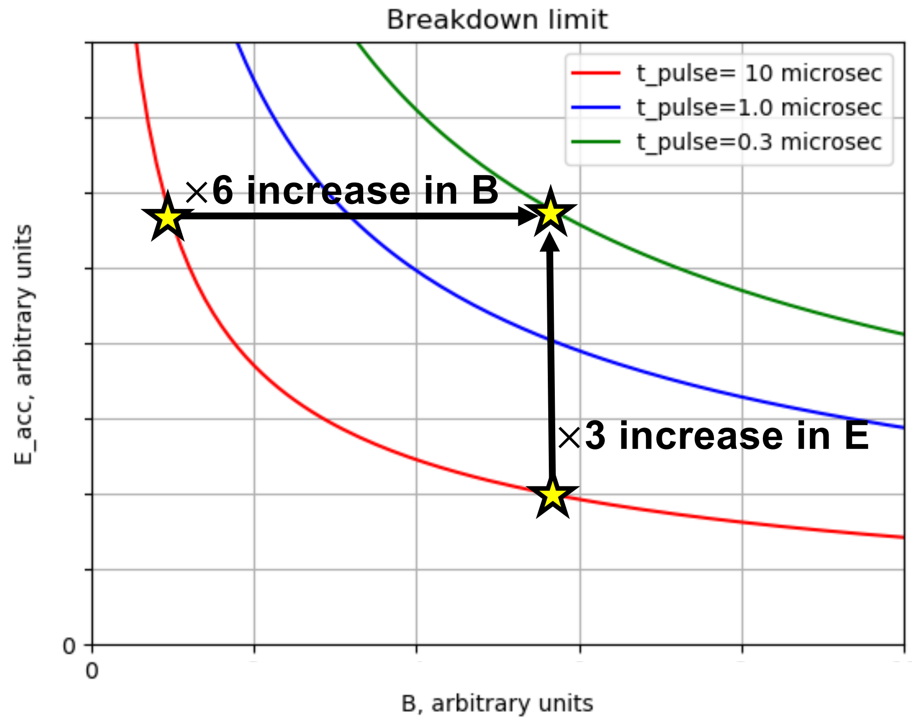


- Tests at the nominal gradient (28 MV/m) can be done without a pulse compressor
- Pulse compressor is needed to increase input power and test beyond nominal gradient
- We consider two options of a SLED type compressor:
  - Small compressor (60cm cavity diameter): power gain of 3 at output pulse length of $10\ \mu s$
  - Big compressor (1.3m cavity diameter): power gain of 4 at output pulse length of $10\ \mu s$ and possibility to go to $20\ \mu s$

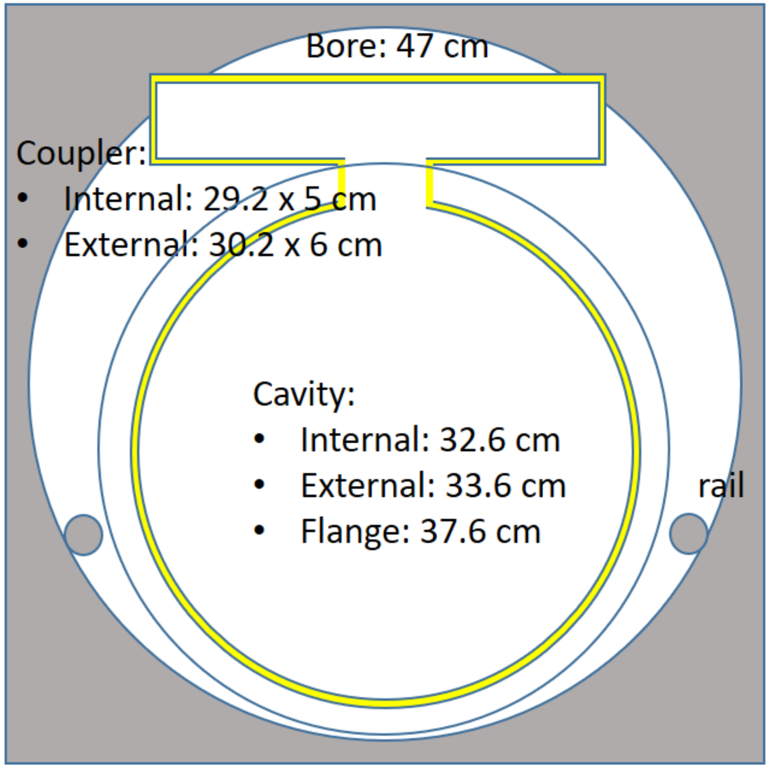
# Benefits of short sub-μs pulse

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

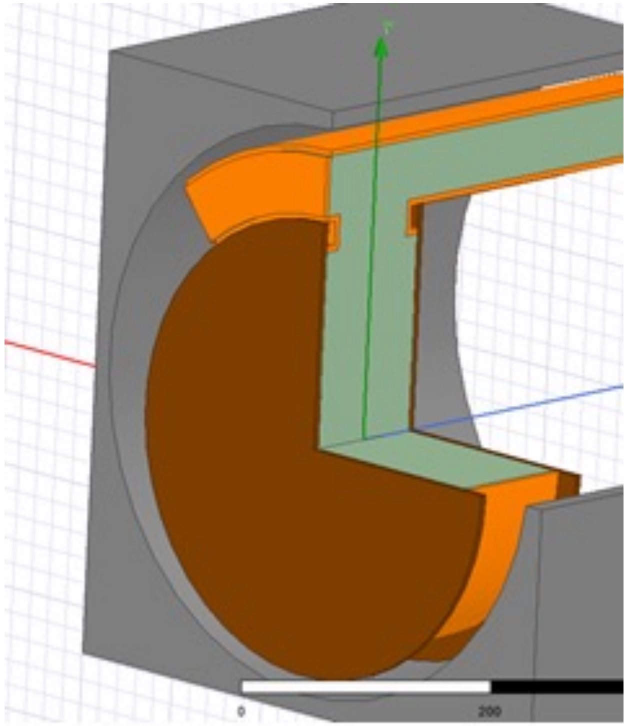
- 300 ns pulse length needs an overcoupled cavity and a 23 MW klystron (only a factor of 2 increase from Litton 805 MHz 12 MW klystron)



# Backup slide: cavity fit in MICE solenoid




Radial waveguide may not fit within the 47 cm bore



A custom curved waveguide can be a solution