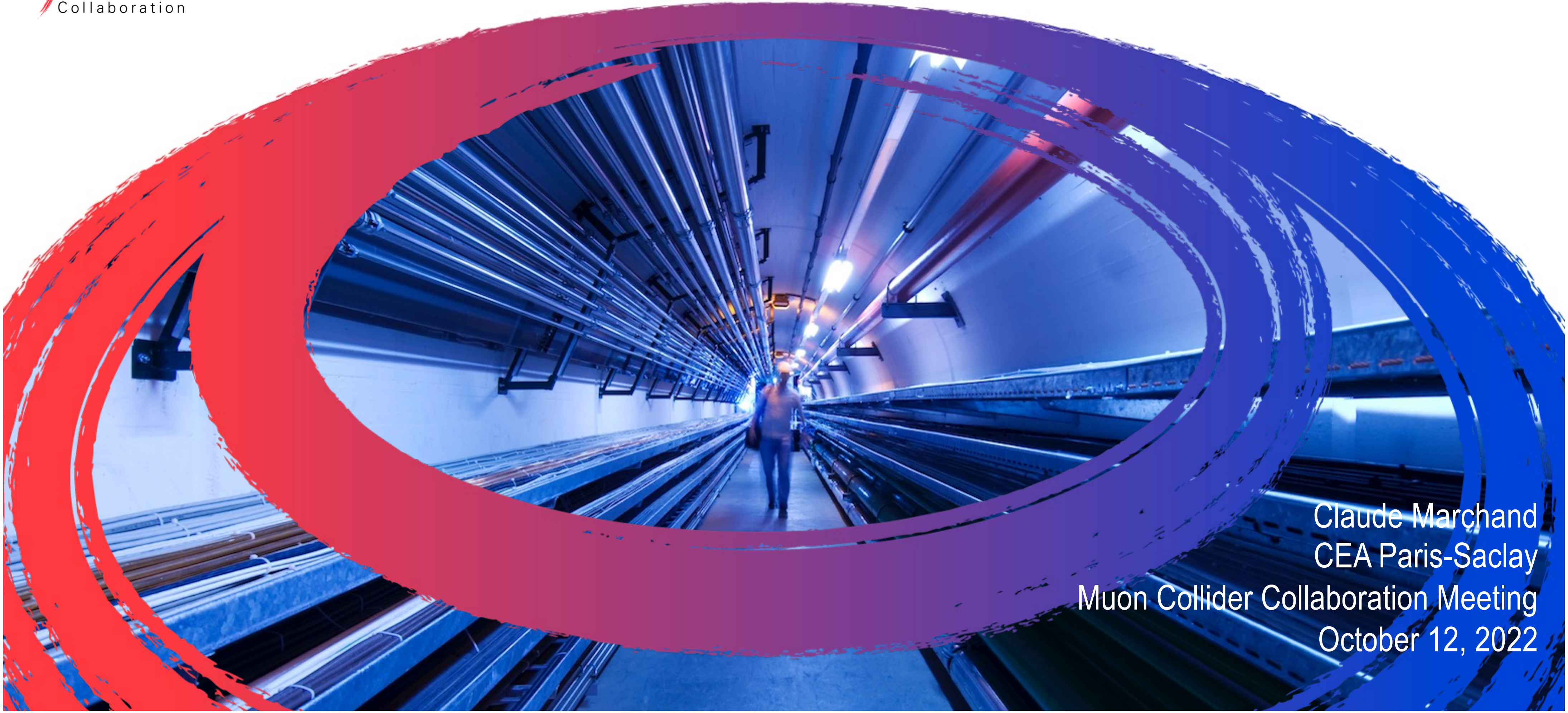
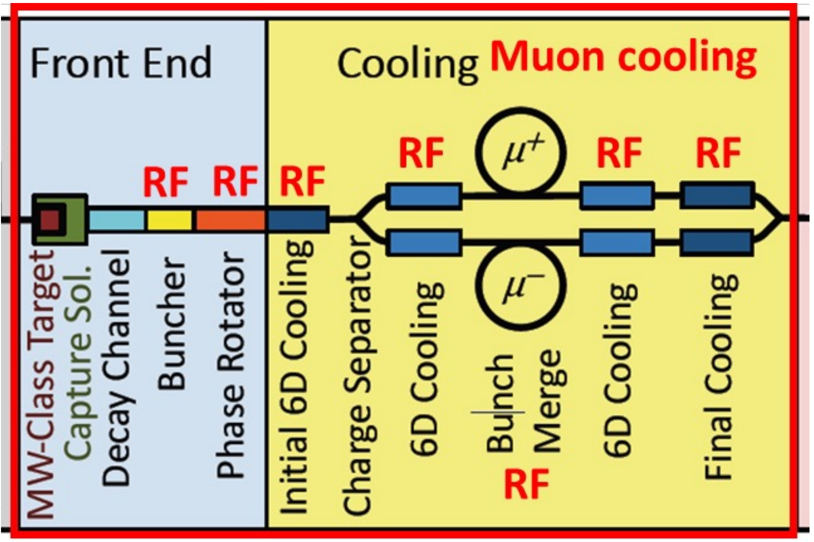
High gradient testing in magnetic field at CEA Saclay



Claude Marchand
CEA Paris-Saclay
Muon Collider Collaboration Meeting
October 12, 2022

RF system for muon capture and cooling

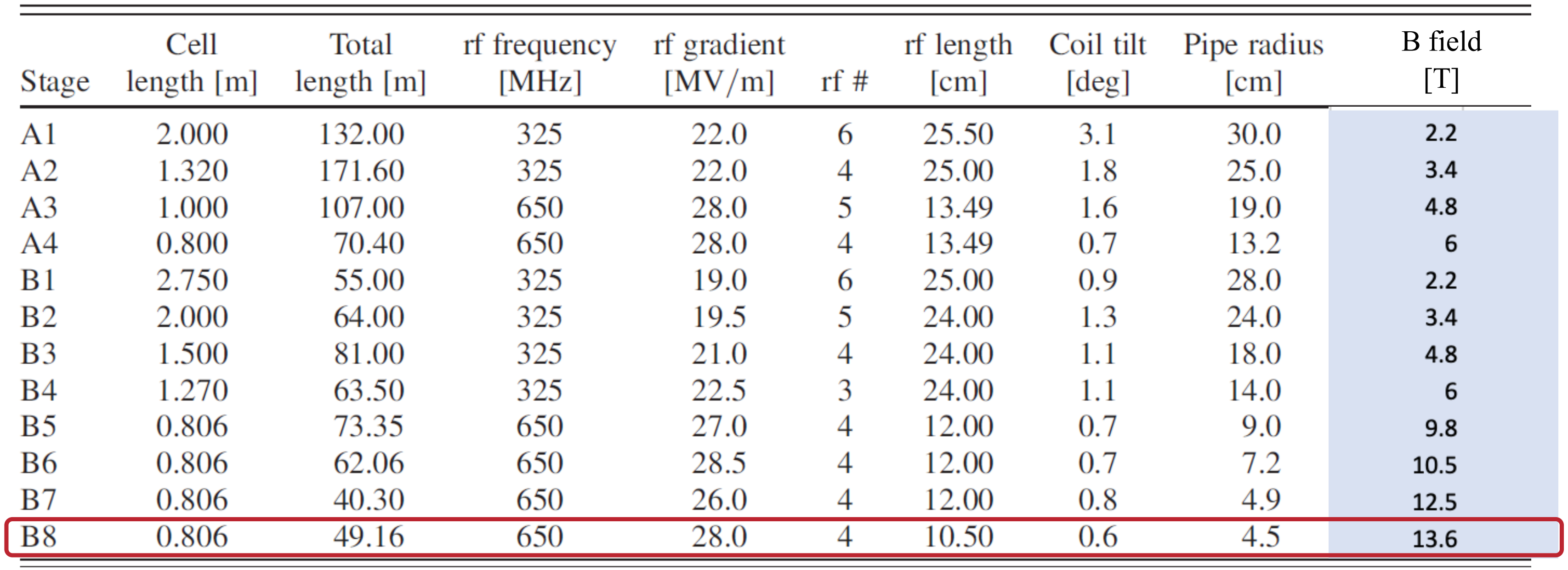
Region	Length [m]	N of cavities	Frequencies [MHz]	Peak Gradient [MV/m]	Peak RF power [MW/cav.]
Buncher	21	54	490 - 366	**0 - 15**	1.3
Rotator	24	64	366 – 326	**20**	2.4
Initial Cooler	126	360	325	**25**	**3.7**
Cooler 1	400	1605	325, 650	**22, 30**	
Bunch merge	130	26	108 - 1950	**~ 10**	
Cooler 2	420	1746	325, 650	**22, 30**	
Final Cooling	140	96	325 - 20		
Total	**~1300**	**3951**			**~12GW**



It is a very large and complex RF system with high peak power

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

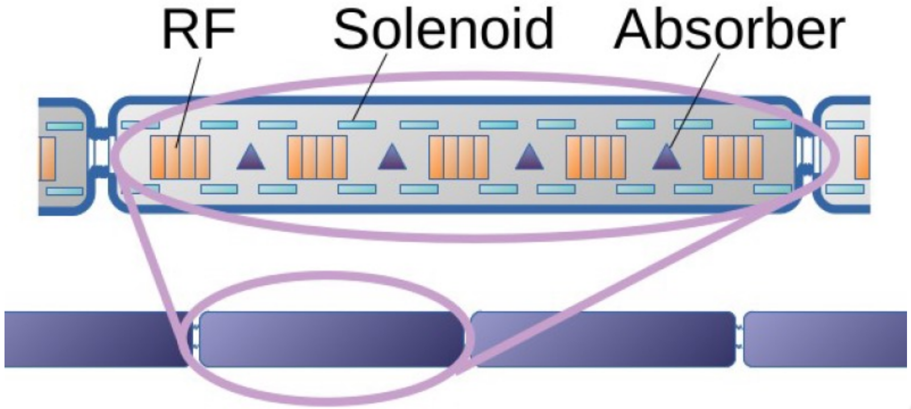


Stage	Cell length [m]	Total length [m]	rf frequency [MHz]	rf gradient [MV/m]	rf #	rf length [cm]	Coil tilt [deg]	Pipe radius [cm]	B field [T]
A1	2.000	132.00	325	22.0	6	25.50	3.1	30.0	2.2
A2	1.320	171.60	325	22.0	4	25.00	1.8	25.0	3.4
A3	1.000	107.00	650	28.0	5	13.49	1.6	19.0	4.8
A4	0.800	70.40	650	28.0	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 cavities for muon cooling cells



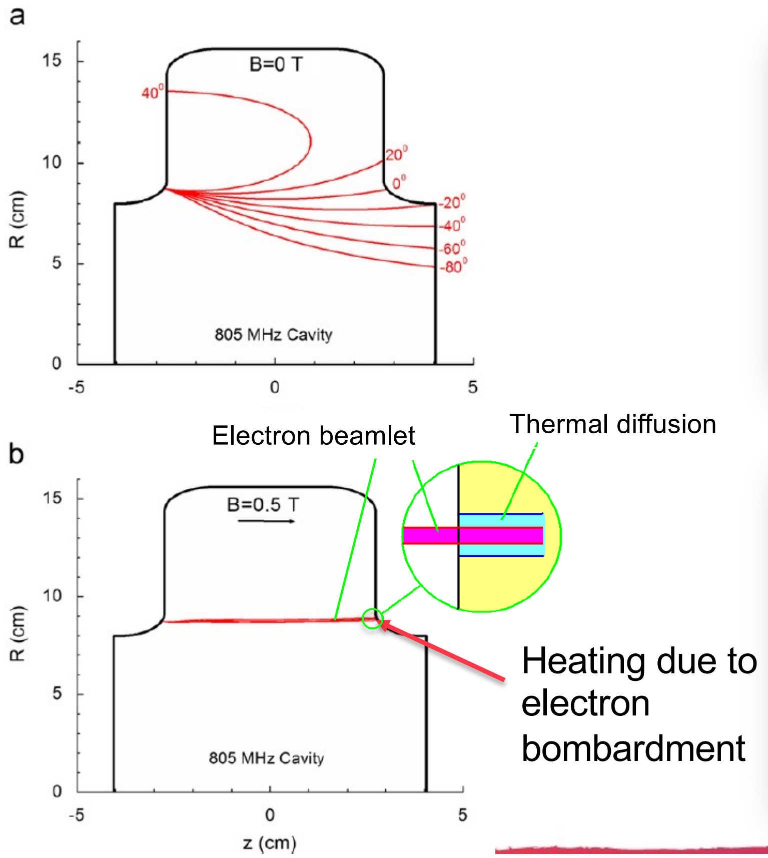
- Normal conducting cavities
- $f \sim 325\ MHz, 650\ MHz$
- Short RF pulses (~μs)
- High acceleration gradients (~30 MV/m)
- High magnetic solenoidal field (up to13 T)

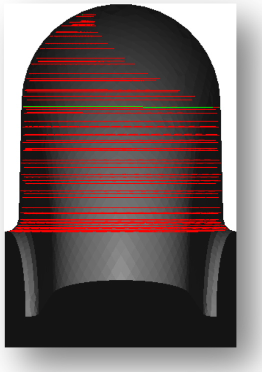
Creates problematics of **break-down** that needs to be mitigated

Part 1: ideas for breakdown mitigation in high B-fields

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





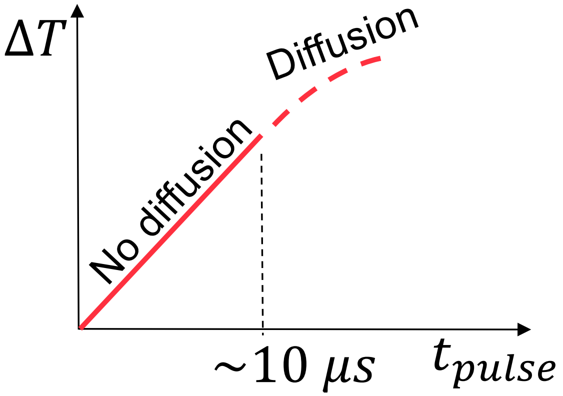
- Model developed by US labs, checked against measurements in high B. Papers: Palmer et.al PRAB 2009, Stratakis et.al NIMPR 2010, Bowring et.al PRAB 2020

rf breakdown with external magnetic fields in 201 and 805 MHz cavities

R. B. Palmer, R. C. Fernow, Juan C. Gallardo, Diktys Stratakis, and Derun Li
Phys. Rev. ST Accel. Beams **12**, 031002 – Published 12 March 2009

- Model predicts local temperature rise ΔT due to electron bombardment
- Breakdown occurs when $\Delta T > \Delta T_{plastic}$

Approximation for no-diffusion beamlet model

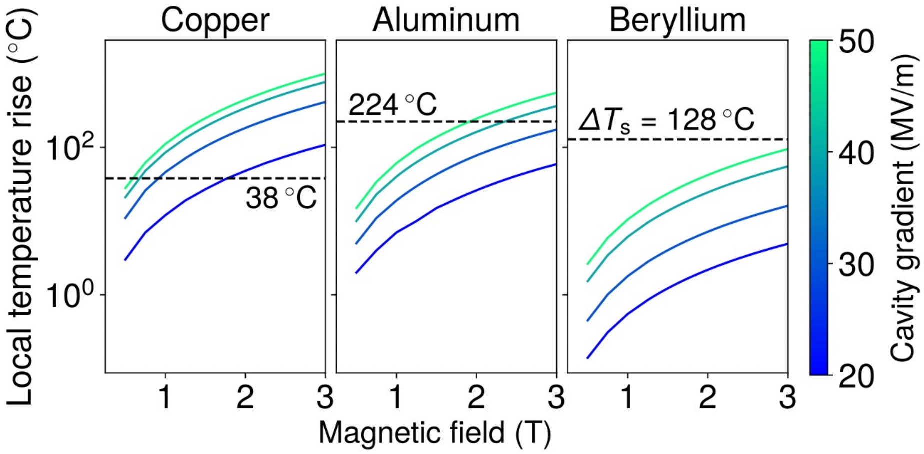


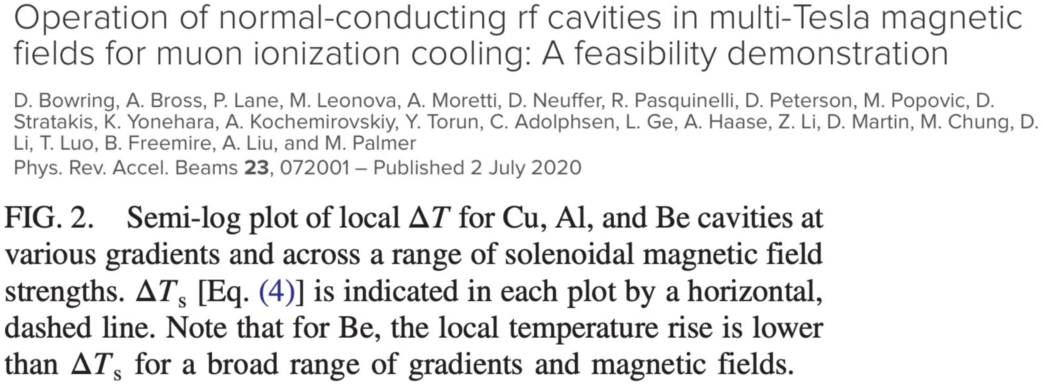
The breakdown model can be simplified: for short pulses ($t_{pulse} < 10\ \mu s$) we can neglect heat diffusion in the wall. Then the breakdown condition is given by:

Poisson ratio
Yield strength

$$\Delta T \approx \frac{1}{\rho C_s}\frac{B^2 I^{1/3}}{e\pi\xi^2}\frac{dE}{dz}\,\mathrm{t_{pulse}} = \Delta T_{plastic} = \frac{2(1-\nu)\sigma_t}{E\alpha_{th}}$$

Specific heat capacity
Elastic modulus
Linear expansion



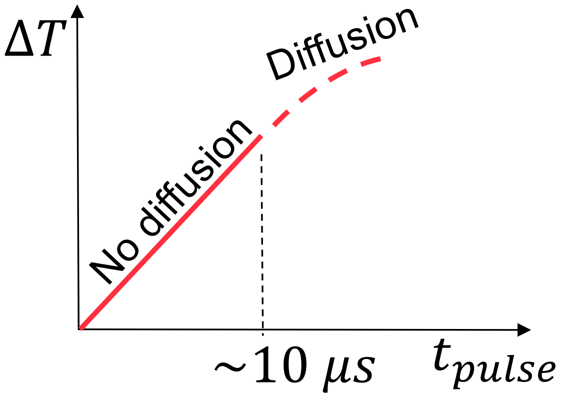

Operation of normal-conducting rf cavities in multi-Tesla magnetic fields for muon ionization cooling: A feasibility demonstration

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 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.

Scaling using no-diffusion beamlet model



The breakdown condition equation in the no-diffusion model (previous slide) can be reshuffled to express the breakdown frontier $B(E_{acc})$:

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

Cavity-dependent constant

Pulse length

Magnetic field at breakdown

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:

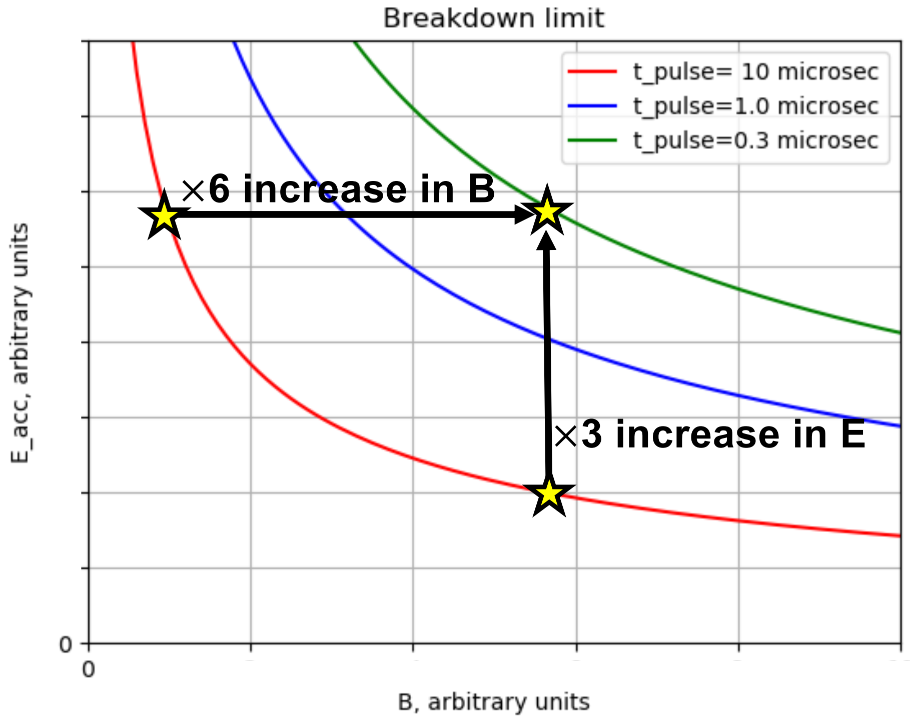
When combined, benefits from different solutions would multiply

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

Benefits of short sub-μs pulse

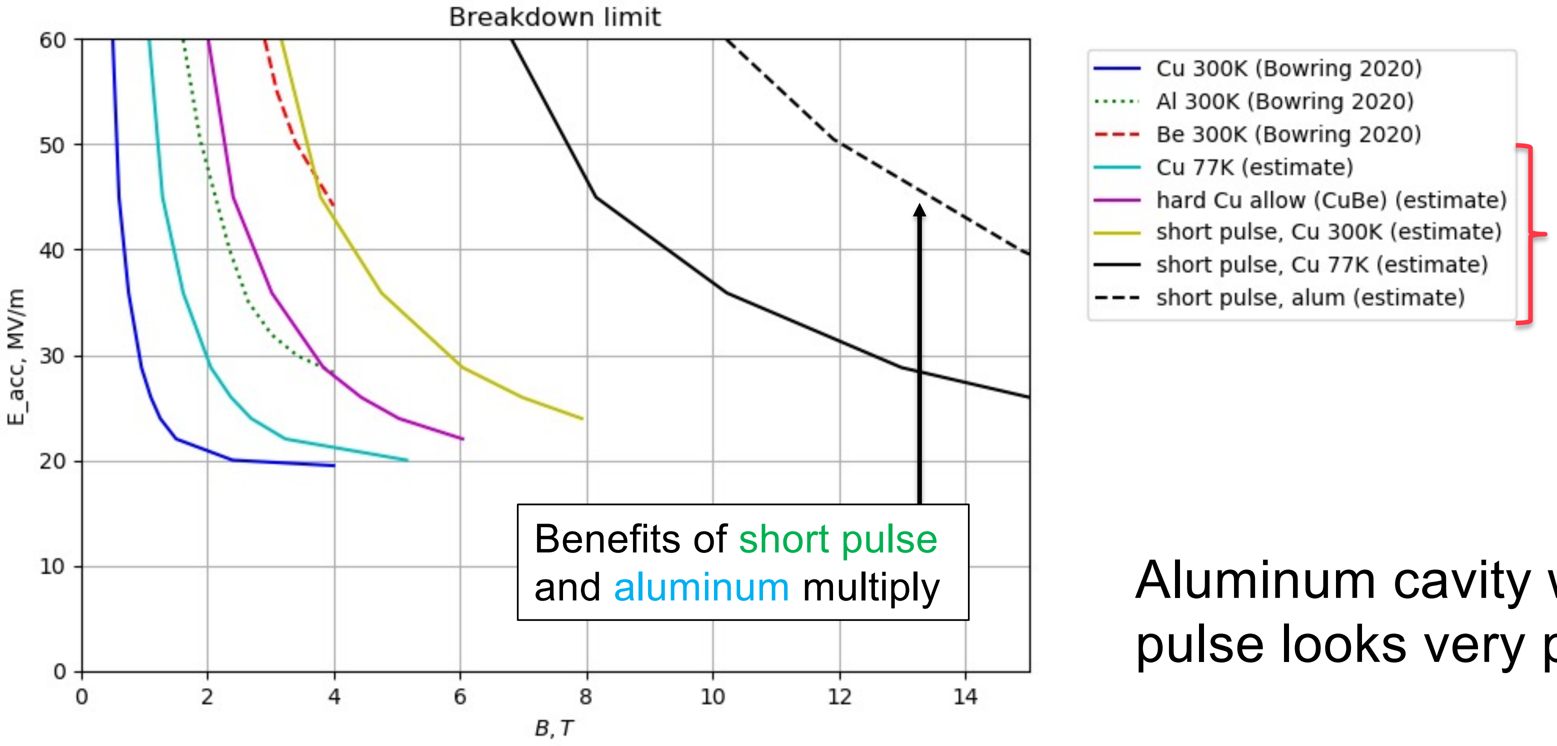
- Going down from 10 μs to 300 ns pulse would dramatically improve cavity breakdown performance

- 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)



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 6)

Aluminum cavity with a short pulse looks very promising

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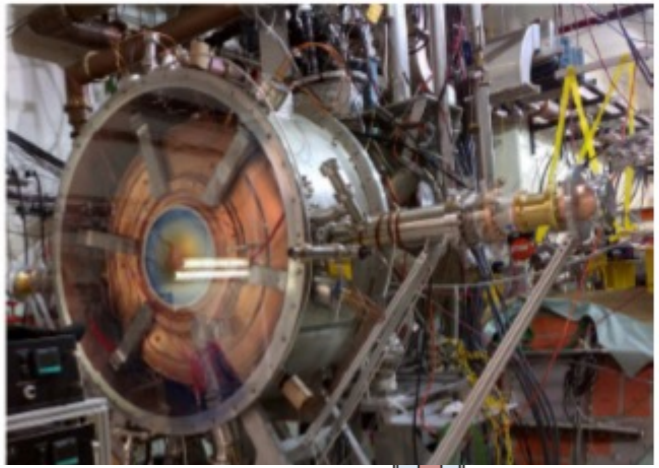
Part 2: proposal of a test plan

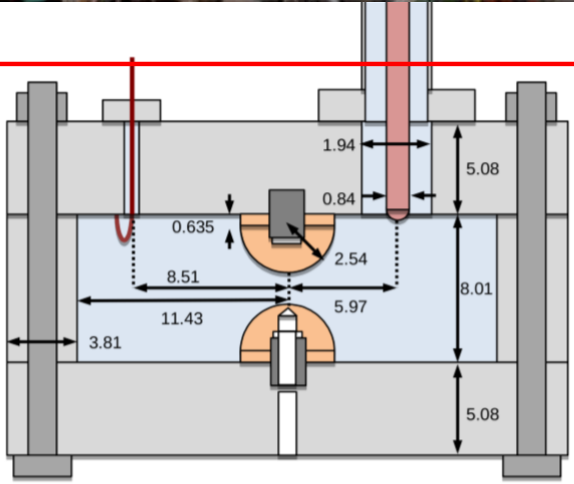
RF test cavities for MCC tested so far

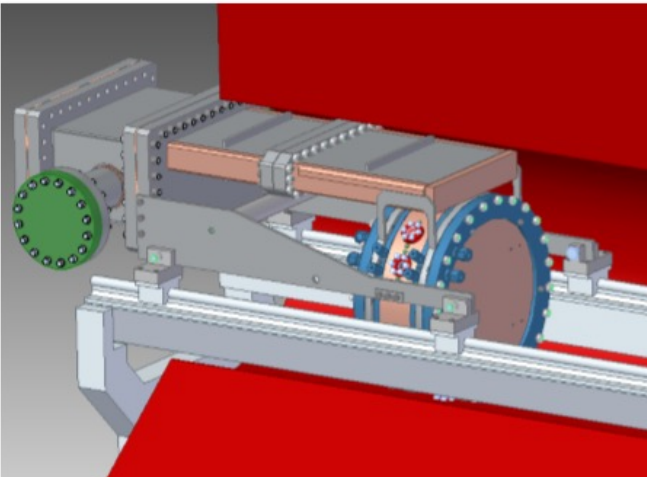
State of the art (not complete):

- 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

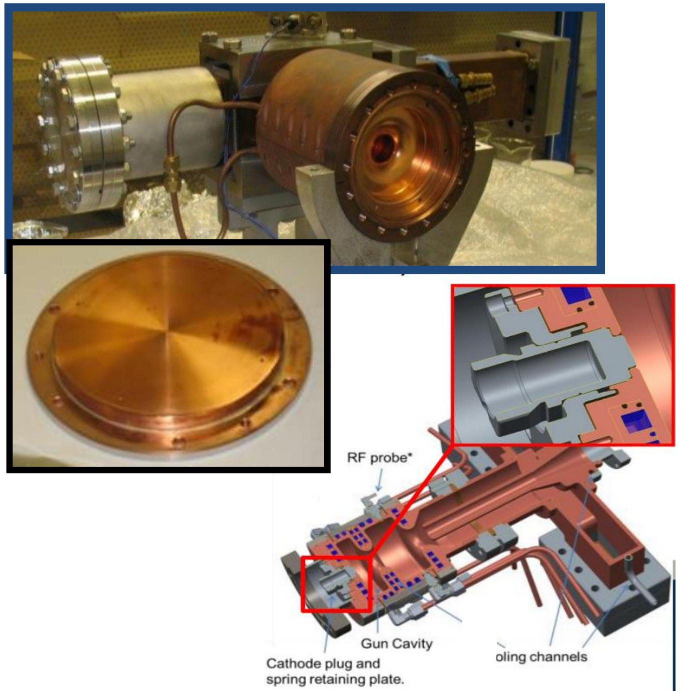
R&D directions for MCC RF cavities

- **High gradient RF test facility with magnetic field up to ~10T :** Test cavities for technology development
  - Frequency: 200 - 800 MHz, some initial tests even in S-band (UK)
  - RF power to get 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 ->…

RF test stand at the Cockcroft Institute

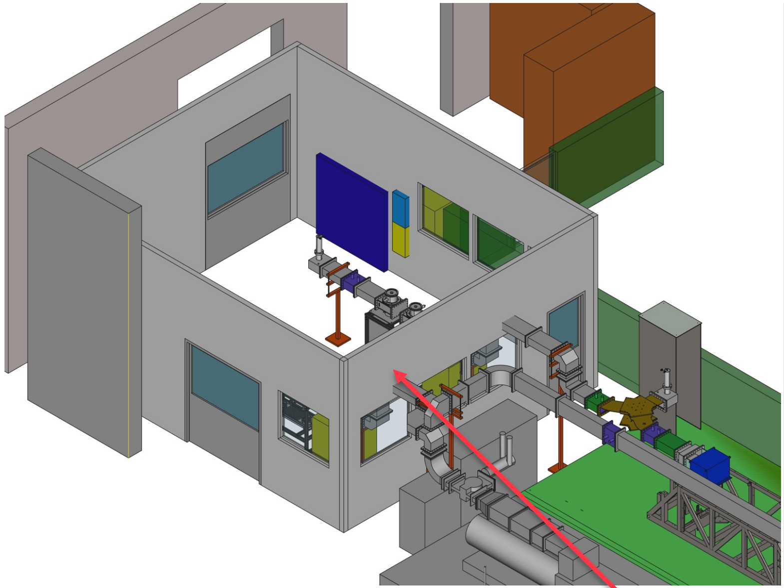
RF sample testing

- Plan to replicate something like our RF guns where we have removable back plates or plugs
- Can design to maximise peak fields on the removable part while keeping most of the cavity the same
- Can test different materials
- Possibility to test same sample with DC
- RF : 3 GHz, B up to 2 T

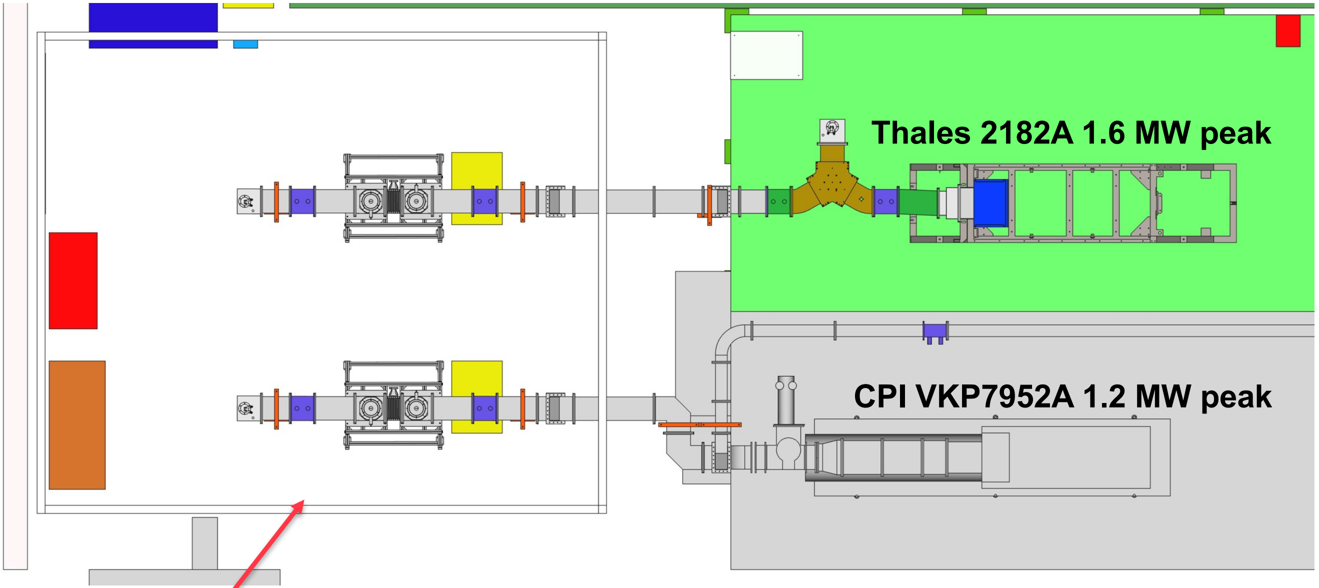


CEA 704 MHz test station for ESS FPC conditioning

3D view

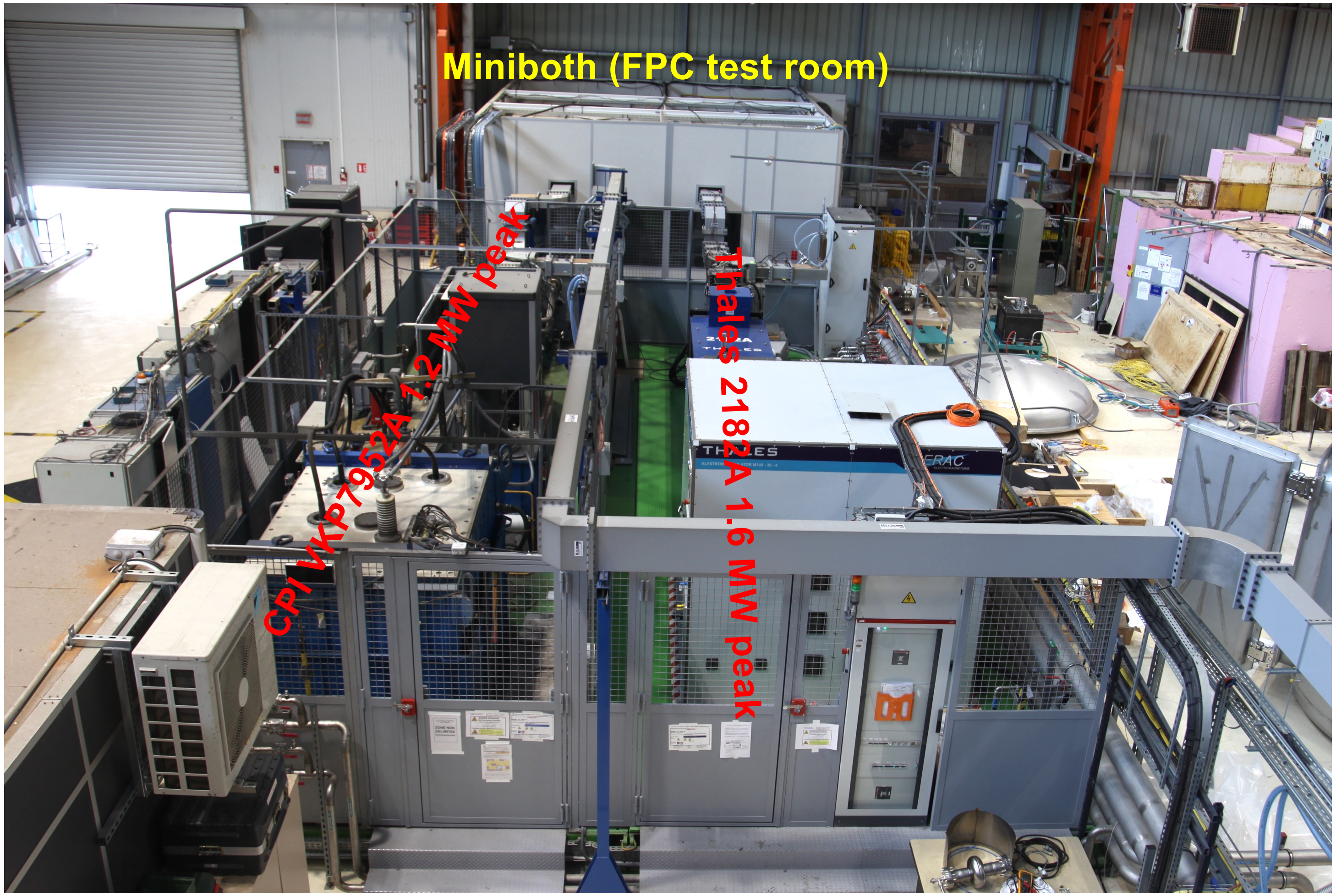


Top view

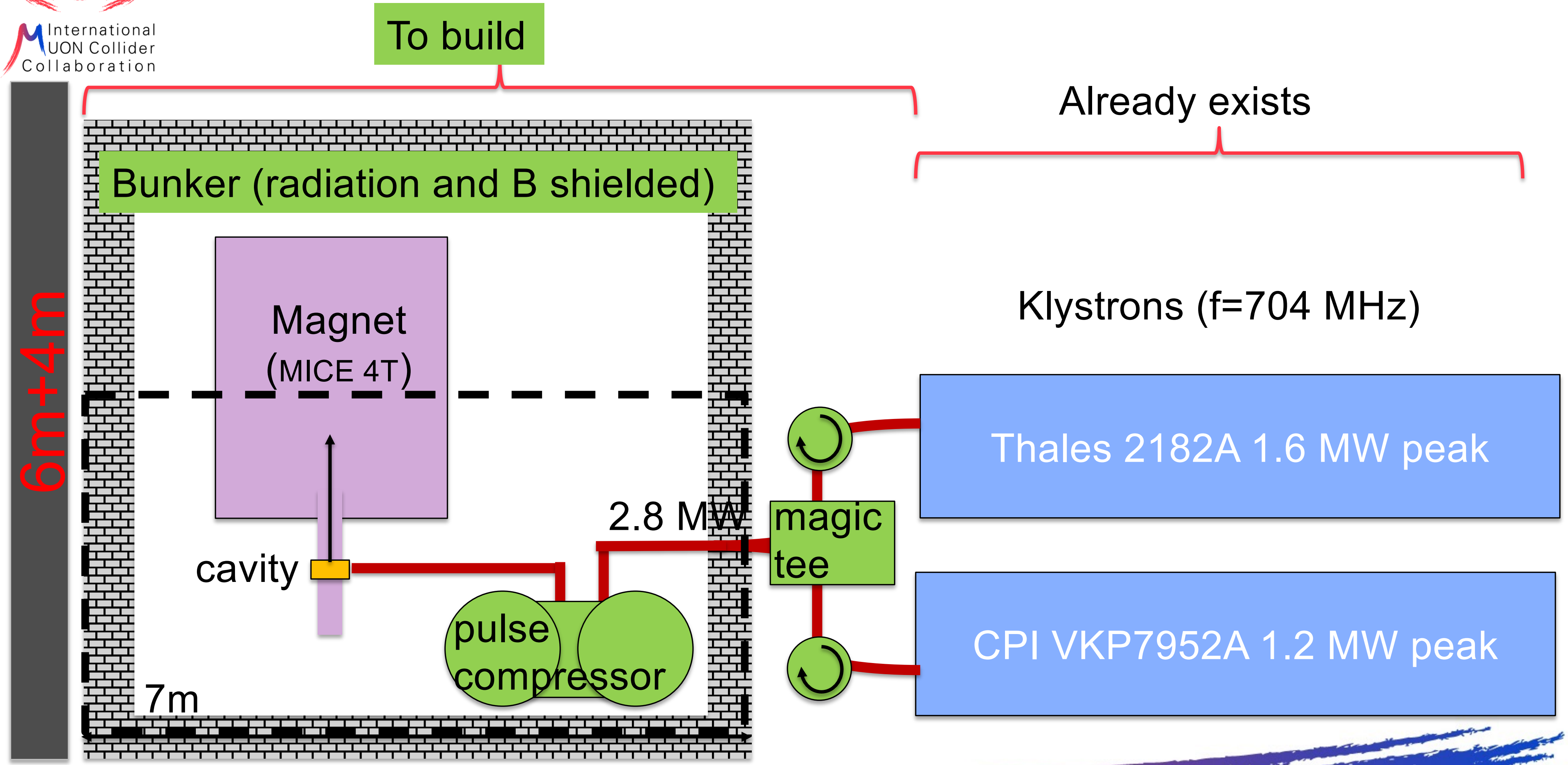


Miniboth (FPC test room)

CEA 704 MHz test station for ESS FPC conditioning



Possible upgrade for a RF breakdown test stand



To build

Already exists

Bunker (radiation and B shielded)

Magnet

(MICE 4T)

6m+4m

cavity

2.8 MW

magic tee

pulse compressor

7m

Klystrons (f=704 MHz)

Thales 2182A 1.6 MW peak

CPI VKP7952A 1.2 MW peak

Chosen test cavity

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

$$f = 704\ MHz$$

$$E_{grad} = 28\ MV/m$$

$$\left(\frac{R}{Q}\right)^{linac} = 194\ \Omega$$

$$G = 177\ \Omega$$

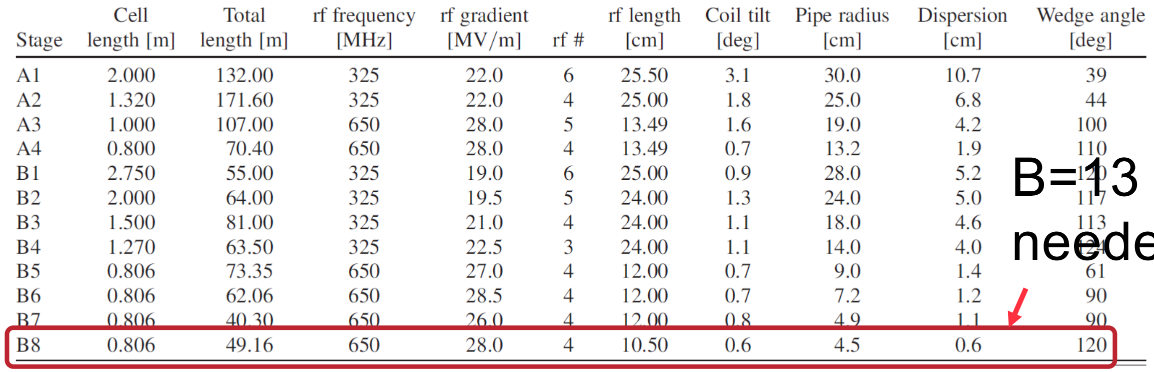
$$Q_0 = 25600$$

$$t_{fill} = \frac{Q_0}{\omega} = 5.8\ \mu s$$

$$P_{\beta=1,E=E_{grad}} = 1.7\ MW$$

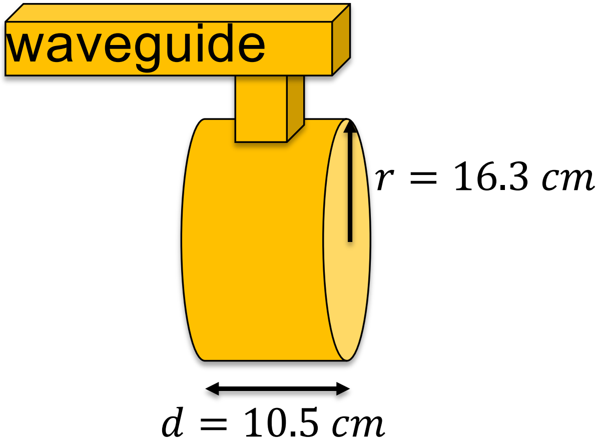
$$P_{\beta=1,E=2E_{grad}} = 6.9\ MW$$

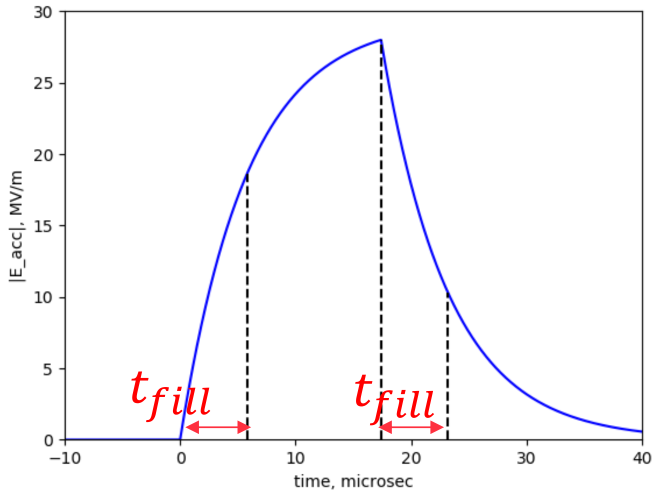
6D cooling channel RF cavities



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

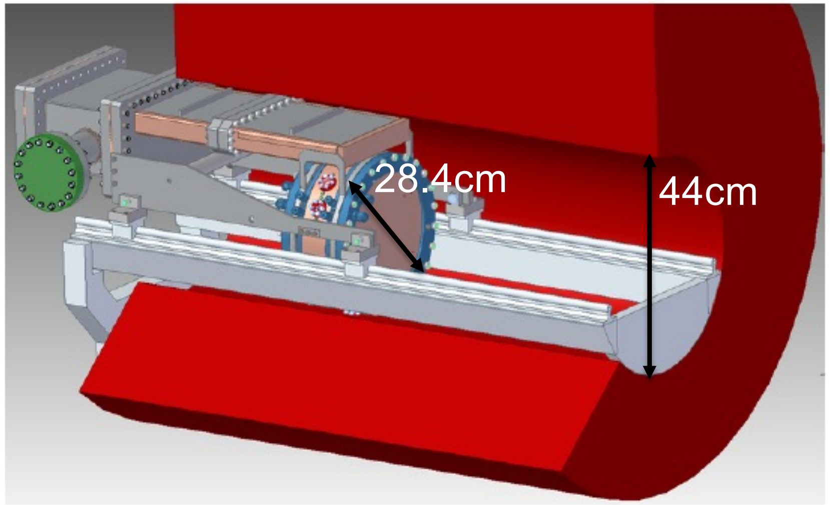
B=13 T needed!



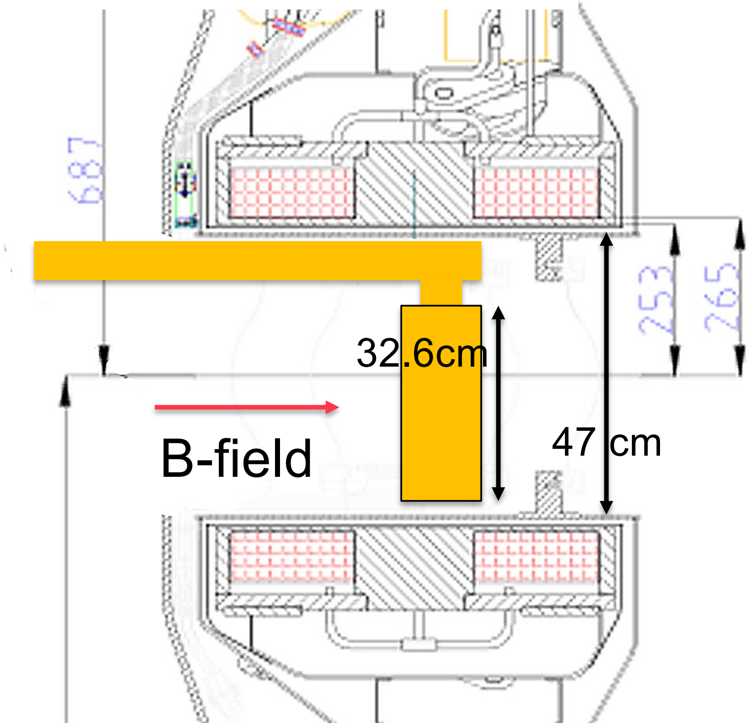


Cavity position in the magnet

MUCOOL setup, 805 MHz
(D. Bowring)



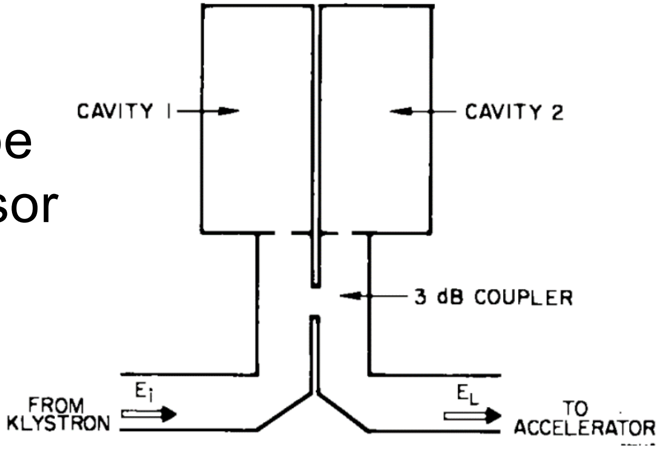
CEA setup, 704 MHz



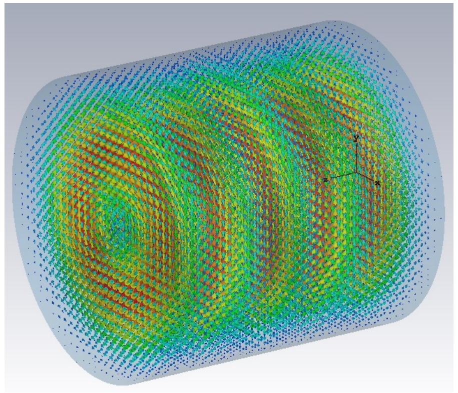
47 cm bore of the MICE magnet will tightly fit the cavity

Pulse compressor

SLED type compressor



Big compressor mode: TE015



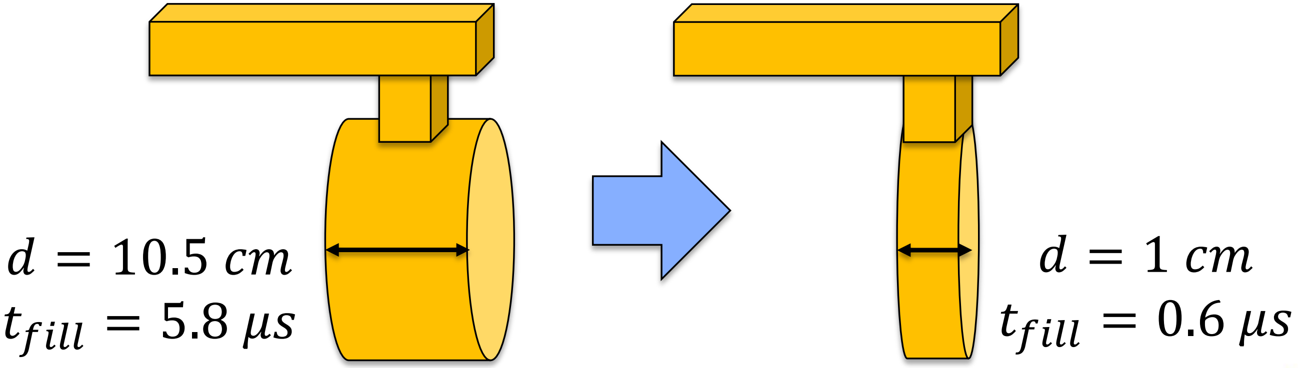
- Tests at the nominal gradient (28 MV/m) can be done without a pulse compressor
- Pulse compressor is needed to increase input power and test beyond nominal gradient
- We consider two options of a SLED type compressor:
  - Small compressor (60cm cavity diameter): power gain of 3 at output pulse length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

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-μs pulse gives 3x boost in usable gradient”) would translate to the nominal cavity.



$d = 10.5\ cm$

$t_{fill} = 5.8\ \mu s$

$d = 1\ cm$

$t_{fill} = 0.6\ \mu s$

Test plan for RF test cavities for MCC

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 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-μs 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. Test at B fields > 4T (10 to 14 T solenoid)

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Thank you for attention

Back-up slides

How to achieve shorter RF pulse

Method 1: lower $Q_0 \rightarrow Q_0/\alpha$

- t_{fill} decreases by factor α
- Required P_{source} increases by factor α

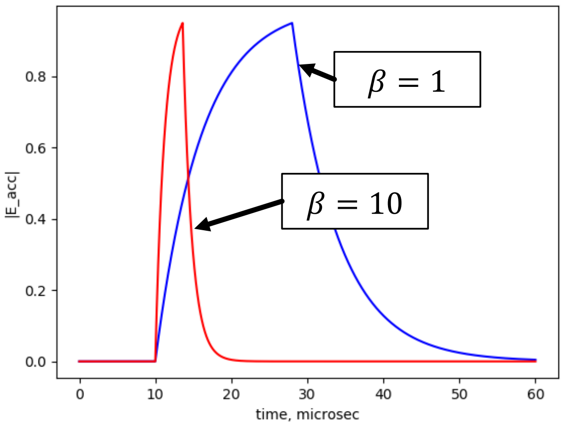
method 2 is more efficient

Method 2: over-coupled cavity with $\beta \gg 1$

- t_{fill} decreases by factor $\alpha = \frac{1+\beta}{2}$
- Required P_{source} increases by factor $\frac{(1+\beta)^2}{4\beta} \approx \alpha/2$

The energy consumption per pulse scales as $t_{pulse}P_{source} \propto \frac{1+\beta}{2\beta}$ - we save a factor of 2 in energy for $\beta \gg 1$

Over-coupled cavity:



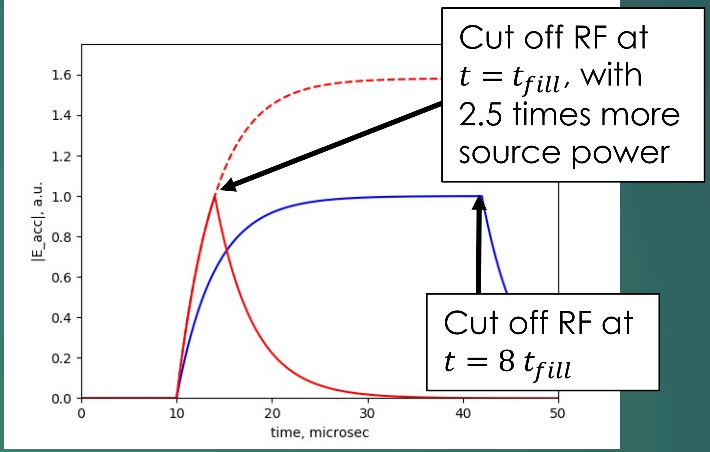
How to achieve shorter RF pulse

Method 3: triangular pulse

It is beneficial to cut off the input power at $t = kt_{fill}$ before the steady state is reached, resulting in a triangular pulse.

Required power scaling with the pulse time is more complicated (see Appendix 3)

Triangular pulse:



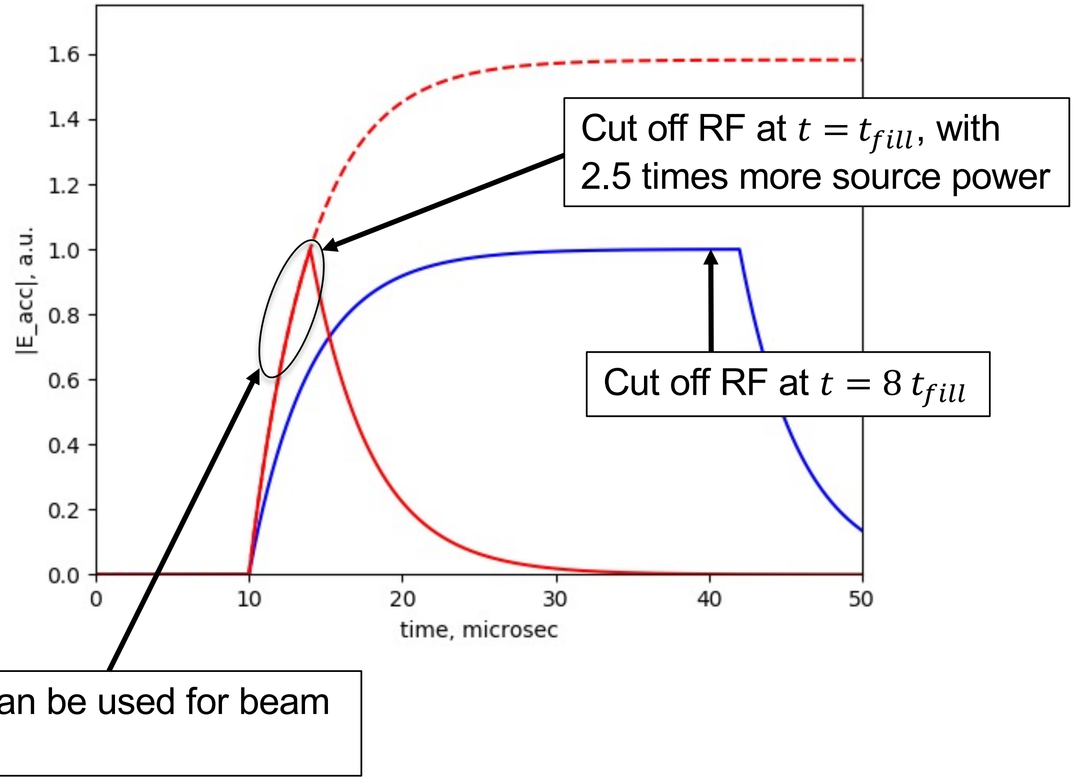
Cut off RF at $t = t_{fill}$, with 2.5 times more source power

Cut off RF at $t = 8\, t_{fill}$

For now, let's focus on methods 2 and 3

Back-up slide: triangular pulse

One way to shorten the pulse length is to not wait until saturation but cut off the RF before ("early stopping"):

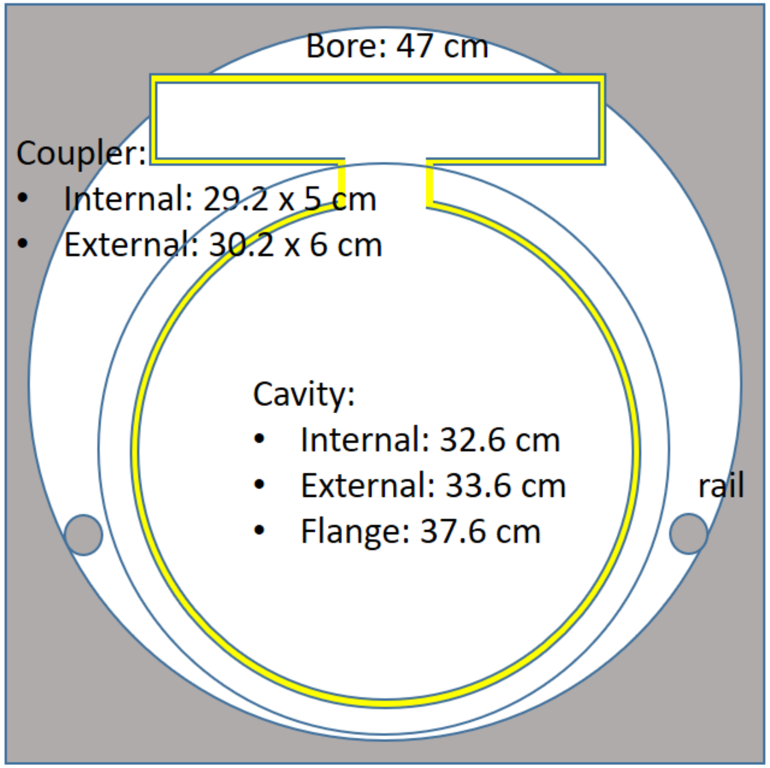


Cut off RF at $t = t_{fill}$, with 2.5 times more source power

Cut off RF at $t = 8\, t_{fill}$

Steep rise in cavity gradient can be used for beam loading compensation

Backup slide: cavity fit in MICE solenoid



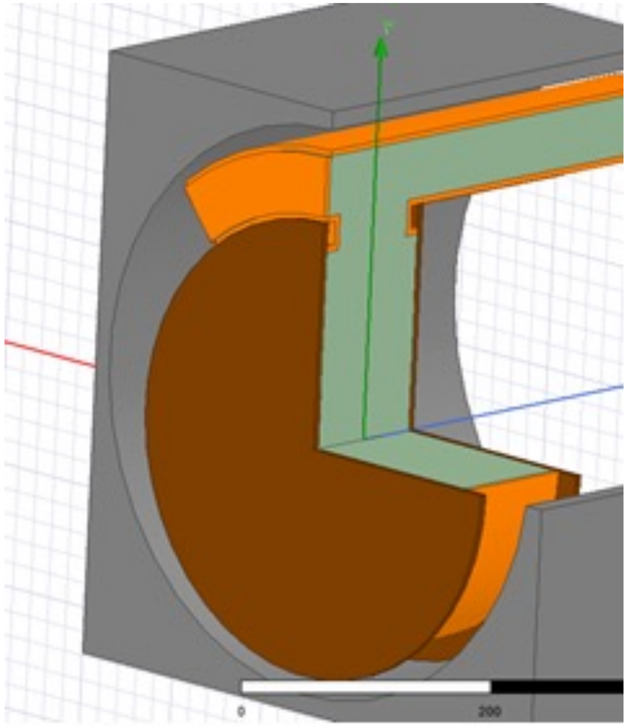
Bore: 47 cm

Coupler:
- Internal: 29.2 x 5 cm
- External: 30.2 x 6 cm

Cavity:
- Internal: 32.6 cm
- External: 33.6 cm
- Flange: 37.6 cm

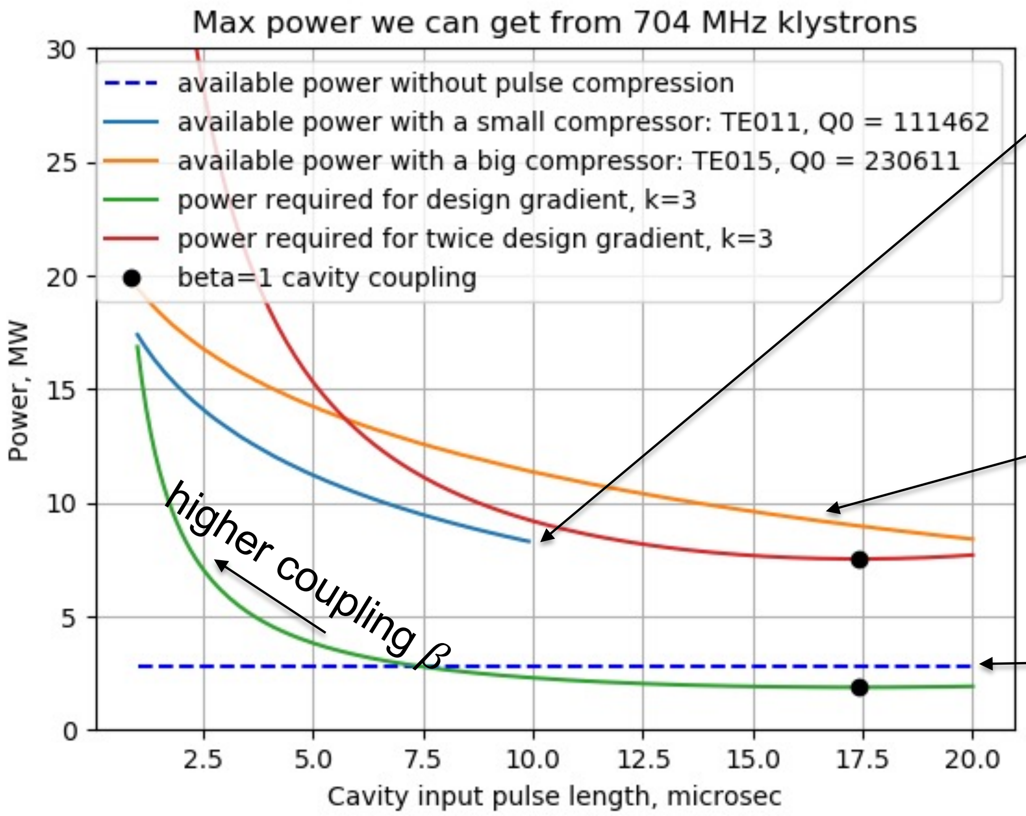
rail

Radial waveguide may not fit within the 47 cm bore



A custom curved waveguide can be a solution

Back-up slide: 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