Theory of rf breakdown for normal conducting cavities in magnetic fields

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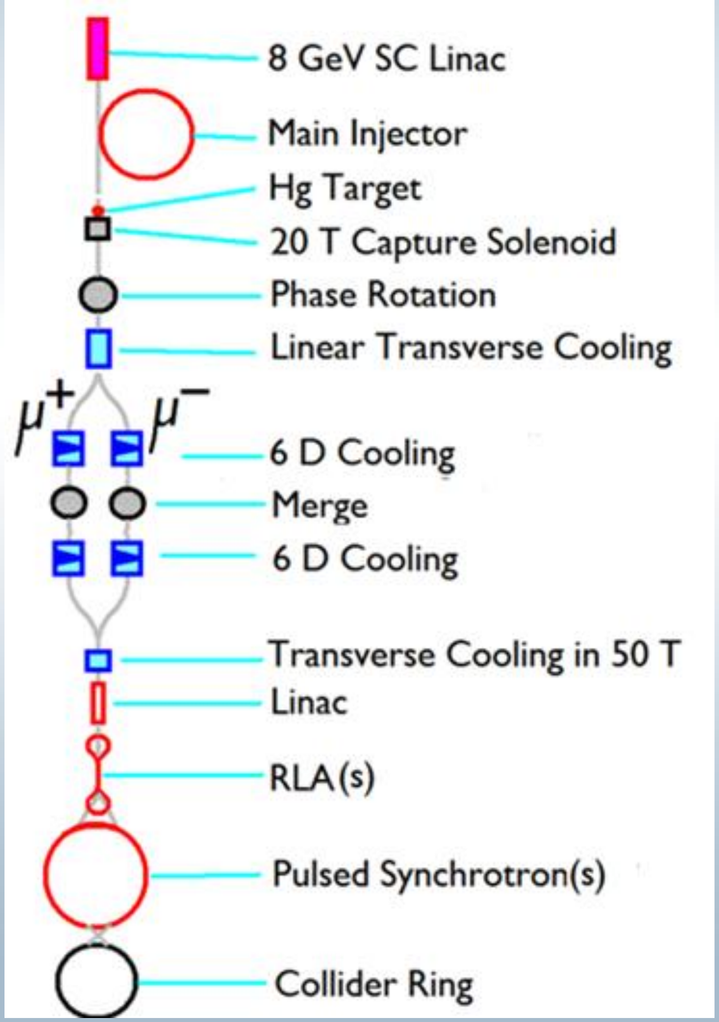
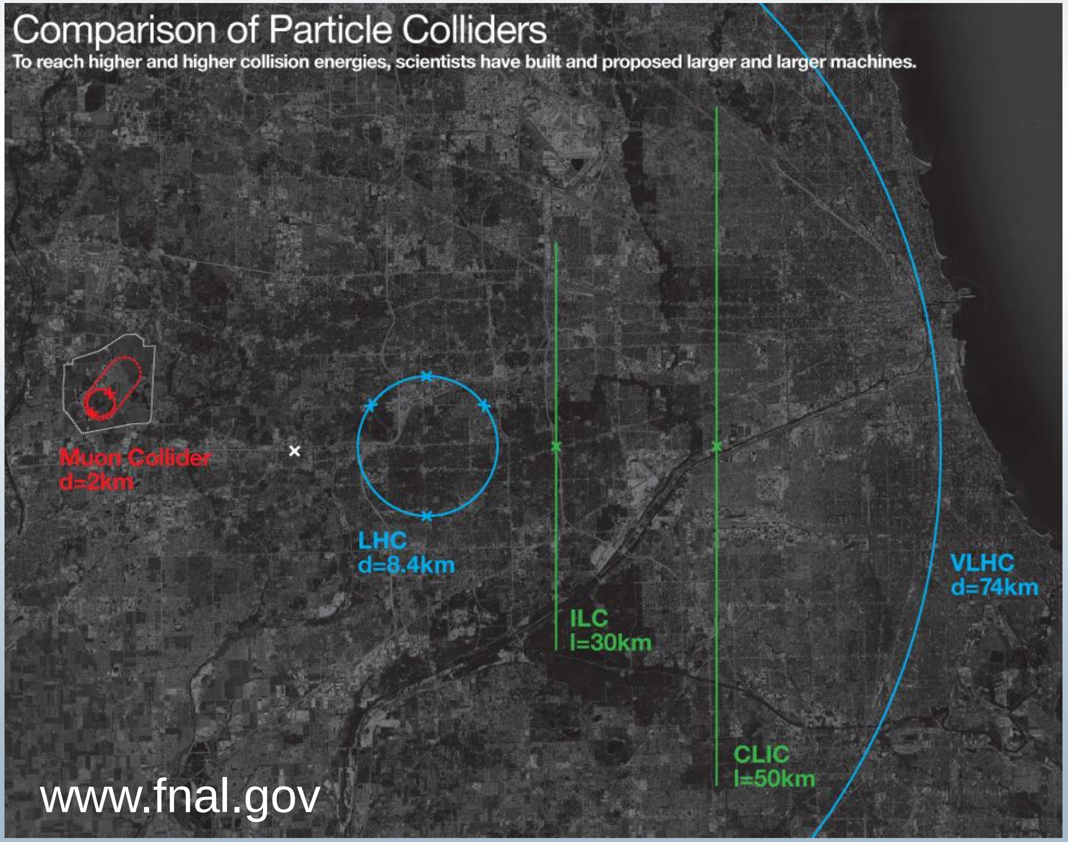
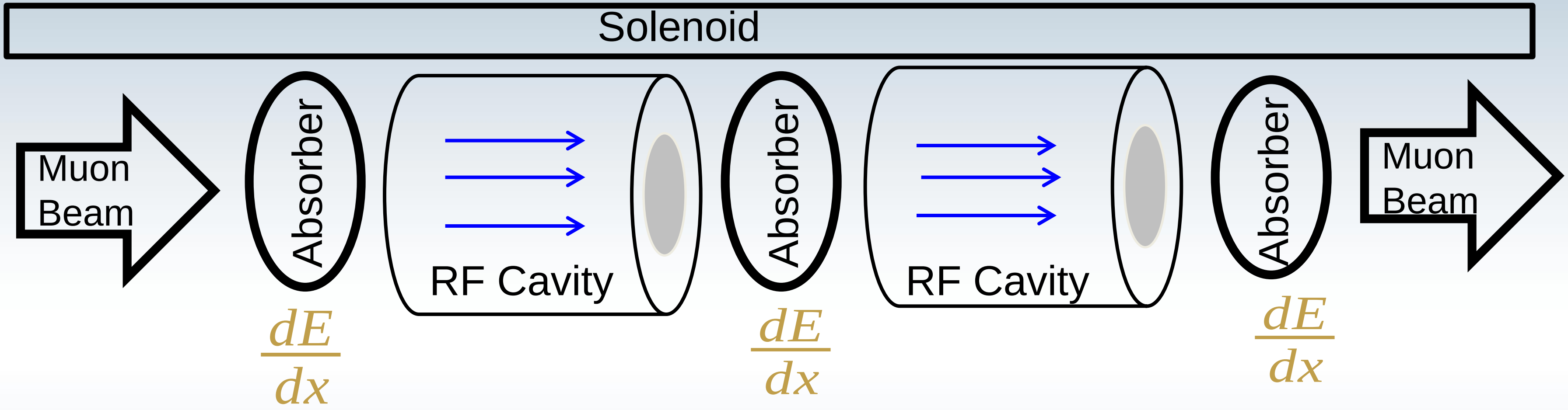
Muon Collider (MC)



- A MC offers high collision energy at a compact size



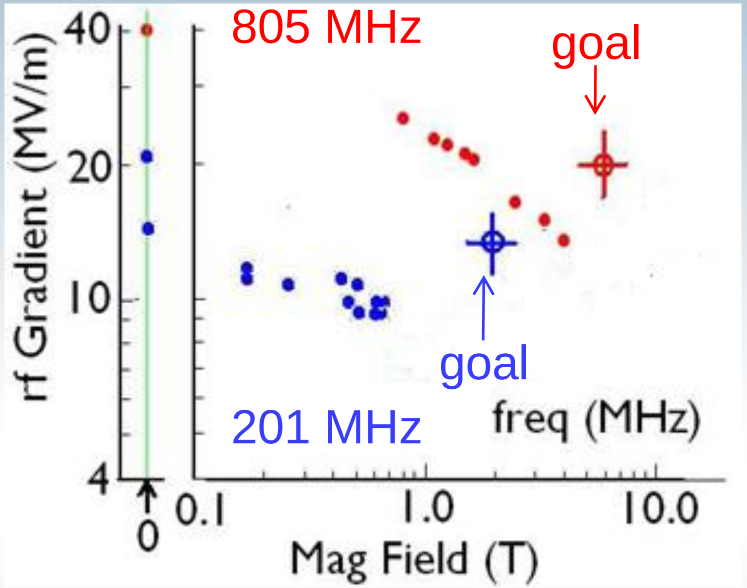
Ionization cooling

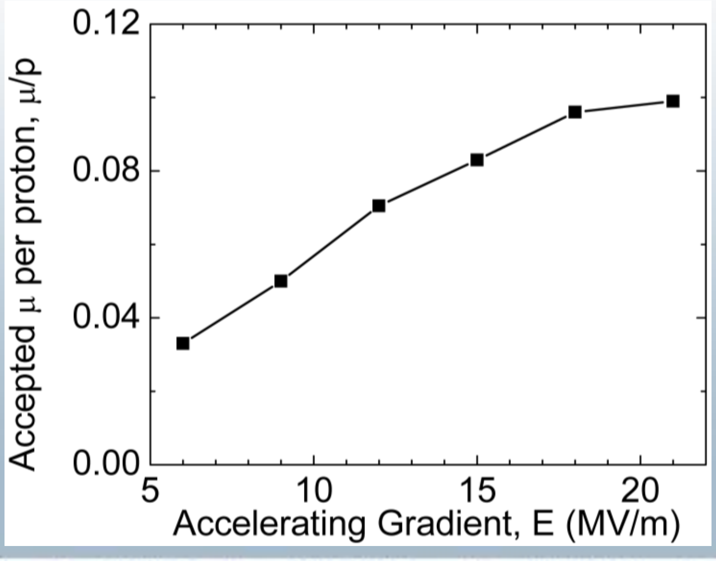


- Energy loss in absorbers
- rf cavities to compensate for lost longitudinal energy
- Strong magnetic field to confine muon beams
- Cooling with 201 MHz-805 MHz cavities operating in multi-Tesla magnetic fields

Motivation

- Goal:
  - 201 MHz rf at 15 MV/m in 2 T
  - 805 MHz rf at 25 MV/m in 5 T
- The data show that the rf gradient is strongly depended on the magnetic field
- If rf gradient drops, then this reduces the number of "surviving" muons, too.

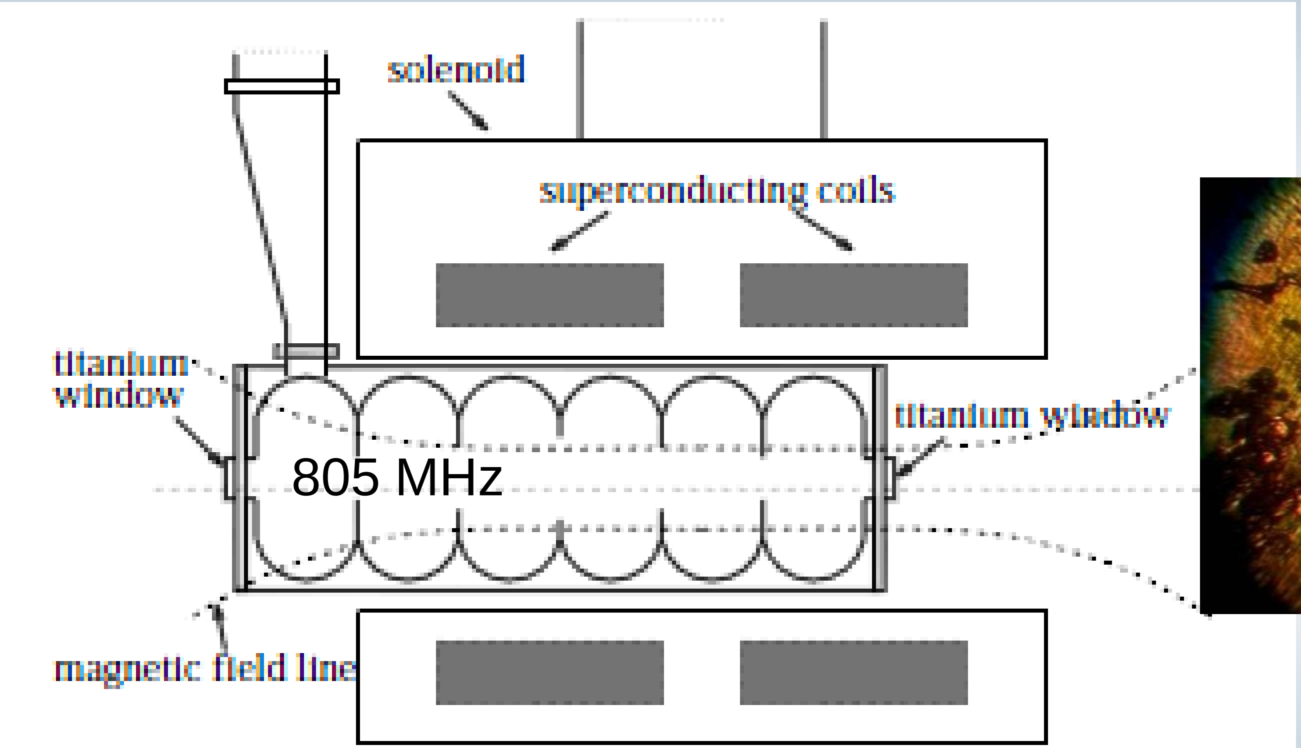




Scope of this work/ Outline

- Review results from experiments with rf in B-fields
- Describe a model for a potential trigger of rf breakdown in magnetic fields.
- Simulate it and compare to experimental data
- Offer solutions:
  - (1) More robust materials and (2) magnetic insulation
- Summary

Multi-cell cavity in magnetic field



Norem *et al.* PRST - AB 072001 (2003)

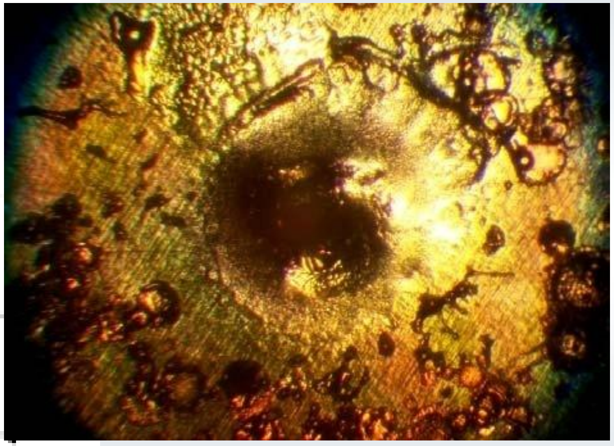
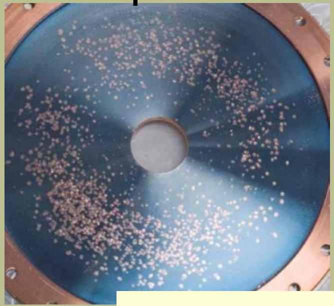


Photo credit: V. Wu

- When the magnetic was turned on, vacuum was lost and the right side window was severely damaged

Pillbox cavity in a magnetic field

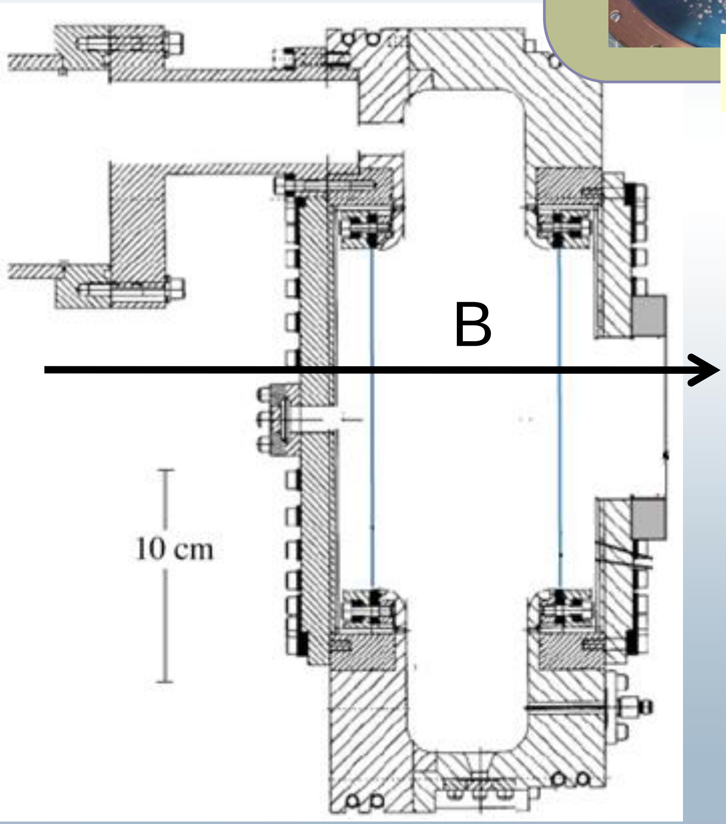
Cu plate



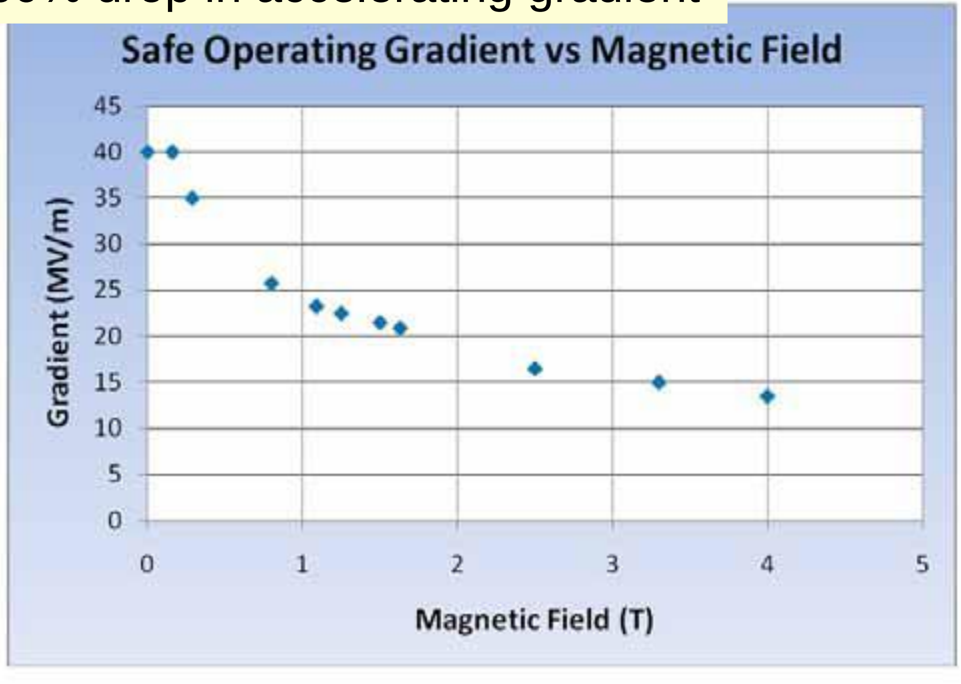
rf coupler

iris

805 MHz

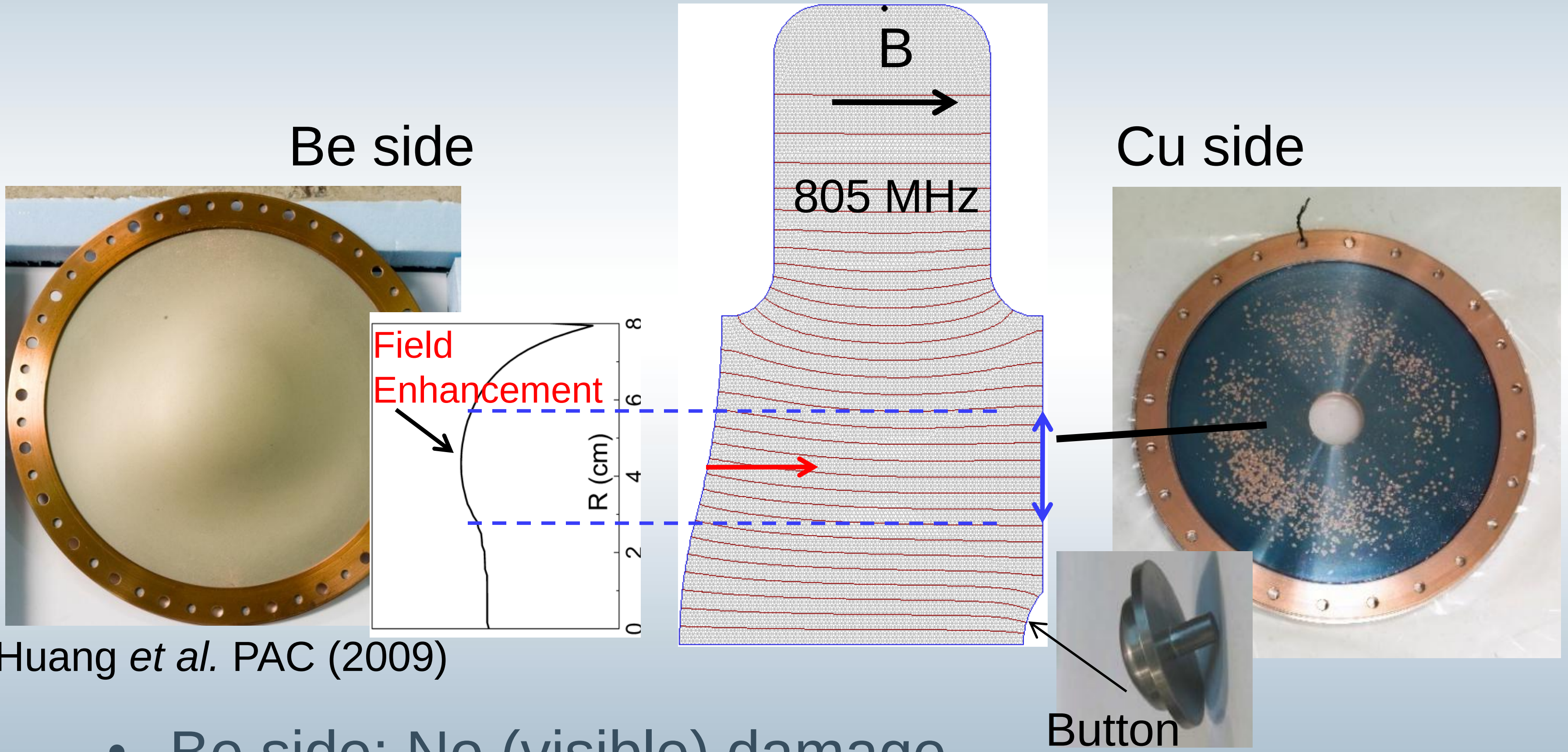


60% drop in accelerating gradient



Moretti *et al.* PRST-AB 072001 (2005)

Button experiment: Can Beryllium do better and why?



Huang *et al.* PAC (2009)

- Be side: No (visible) damage
- Cu side: Damage

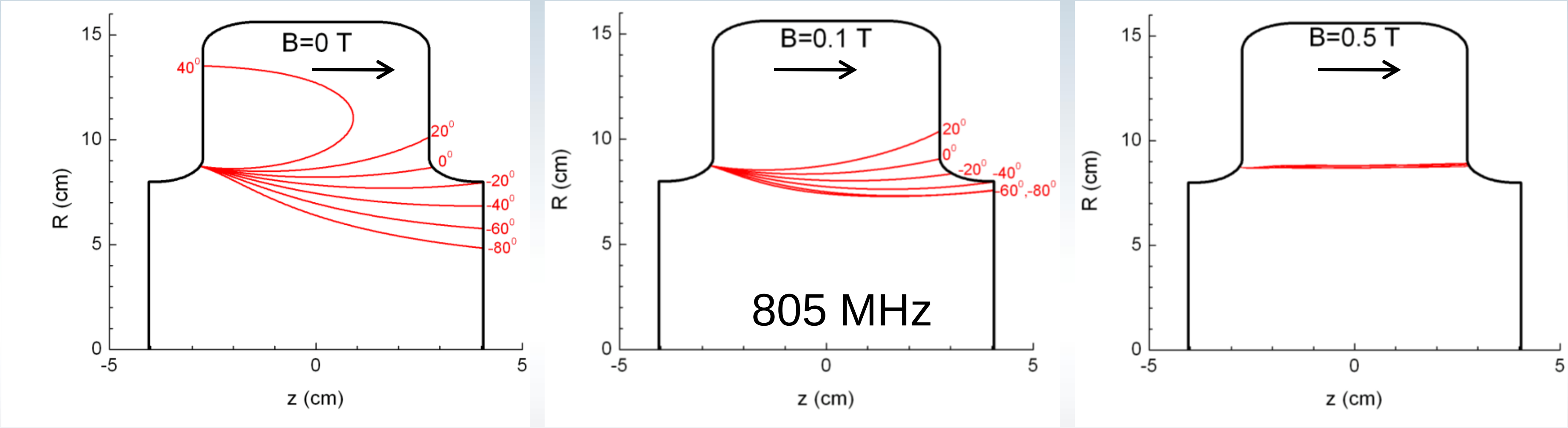
Proposed trigger of breakdown in B-fields

- Step 1: Field emitted electrons are accelerated and focused by the B-field to spots in the cavity
- Step 2: Penetrate inside the metal
- Step 3: Surface degradation from repetitively strains induced by local heating by these electrons
- Step 4: Fatigue failure of the metal at the surface that likely triggers breakdown

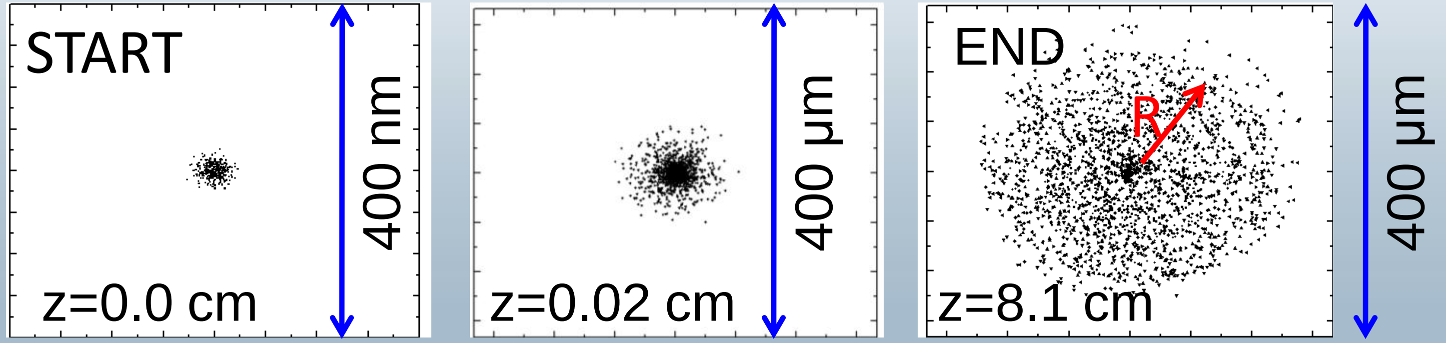
Simulation details

- Pillbox 805 MHz rf cavity
- The rf walls are made from Copper
- Fowler-Nordheim emission model (current: $I \sim E^n$)
- Track particles assuming uniform magnetic field
- Ignore temperature variation of material properties
- Codes: PARMELA, CAVEL

Step 1: Field-emission in B-fields (1)



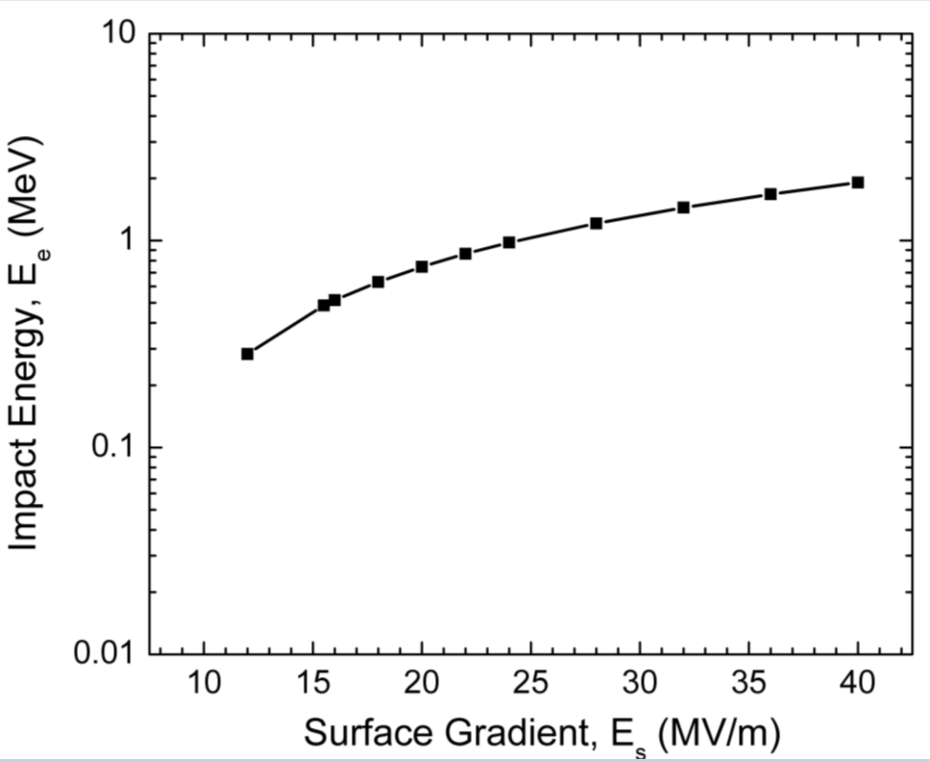
- Focusing effect of the magnetic field (B=0.5 T):



$$R \propto \frac{I^j}{B}$$

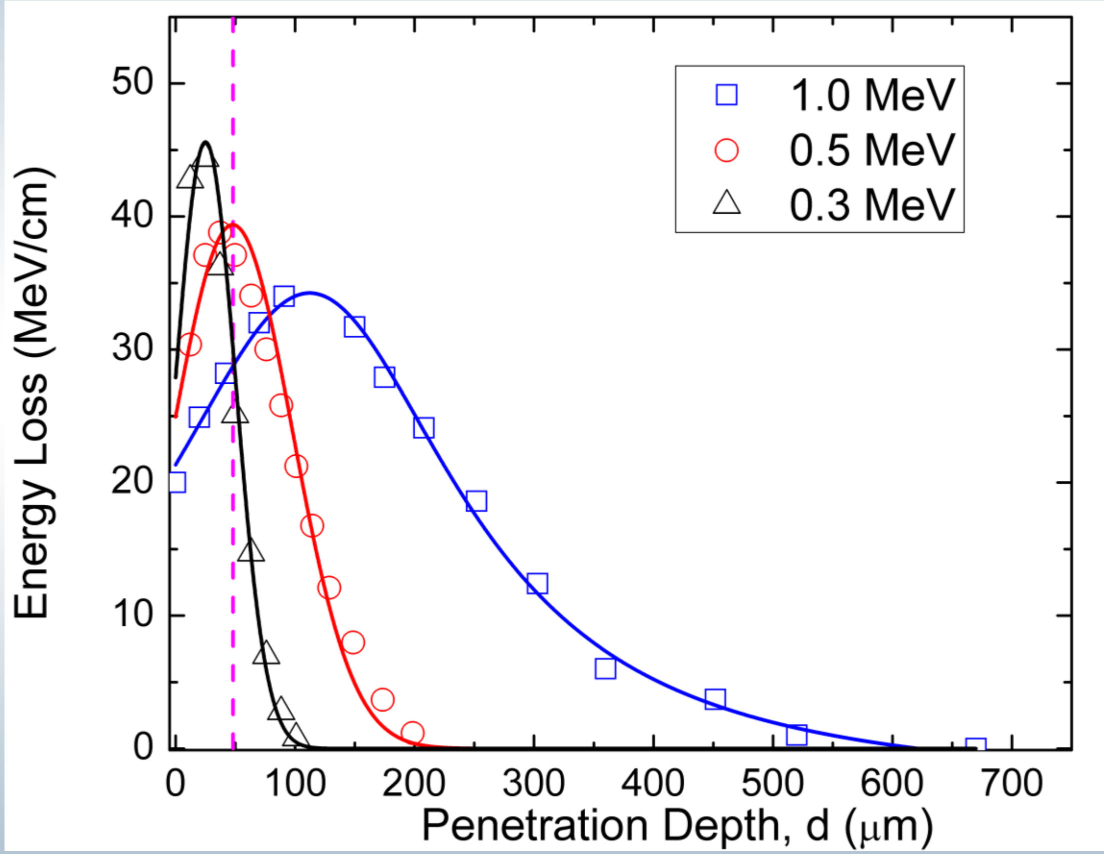
$$j \approx 0.3$$

Step 1: Field-emission in B-fields (2)



- Field-emitted electrons impact the rf surface with high energy (~ MeV range)

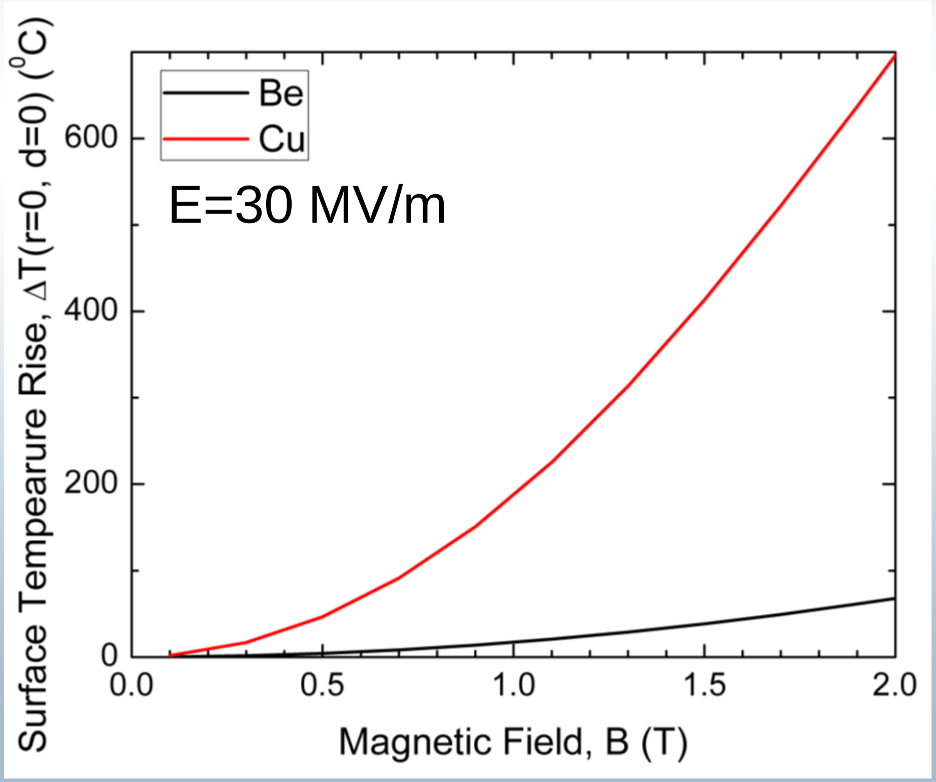
Step 2: Electron penetration in metal



Scatters: Sandia Report 79-0414 (1987)
Lines: Simulation with code Casino

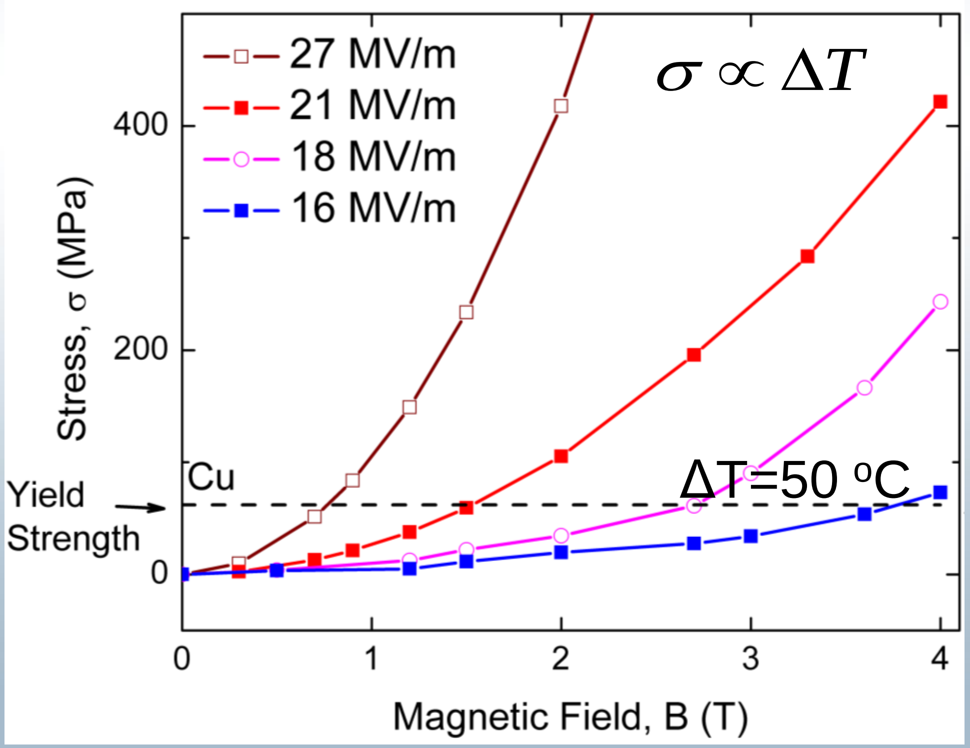
Step 3: Temperature rise at rf surface

- Temperature rise is a function of material properties, rf gradient and magnetic field



Step 4: Thermal stress from pulsed heating

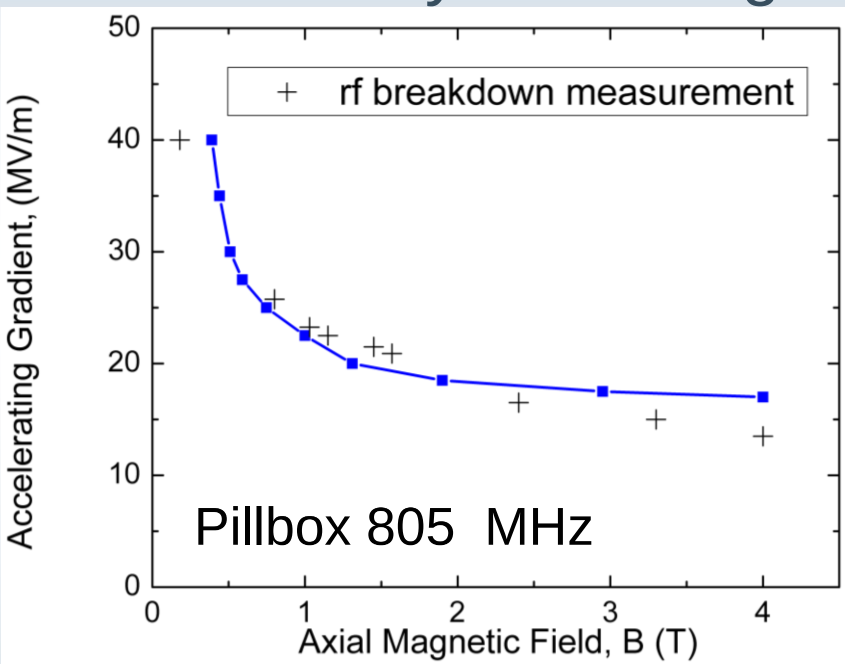
- Thermal expansion of the metal causes distortion in the near-surface region and induces stress (Musal, NBS 1979)



- If σ exceeds the yield strength irreversible strain will occur
- Can harm the material after a million or more rf pulses

Comparison with experimental data

- Blue line: B-field values for which the induced stress matches the yield strength of Cu



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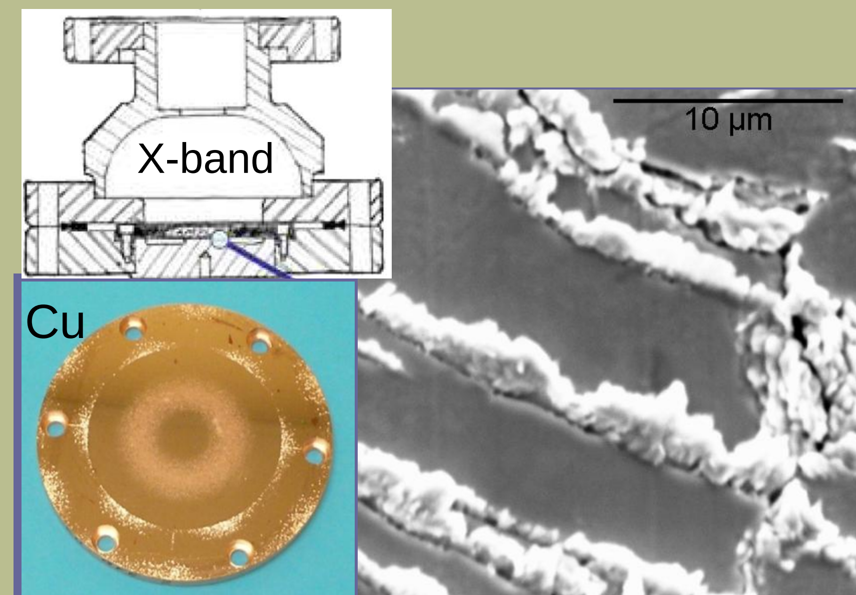
Diktys Stratakis *, Juan C. Gallardo, Robert B. Palmer

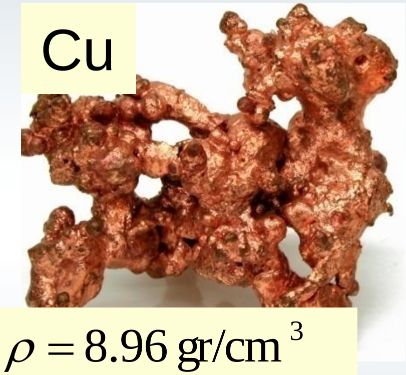
Laurent *et. al.*, PRST-AB 14 041001 (2011)



Magnified damage seen at SLAC by pulse heating at 110 ^{o}C

Solution I: Robust materials

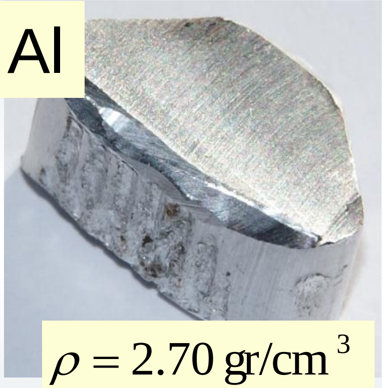
Cu



$\rho = 8.96\ \text{gr/cm}^3$

$a = 1.65 \times 10^{-5}\ /^{\text{o}}\text{C}$

Al



$\rho = 2.70\ \text{gr/cm}^3$

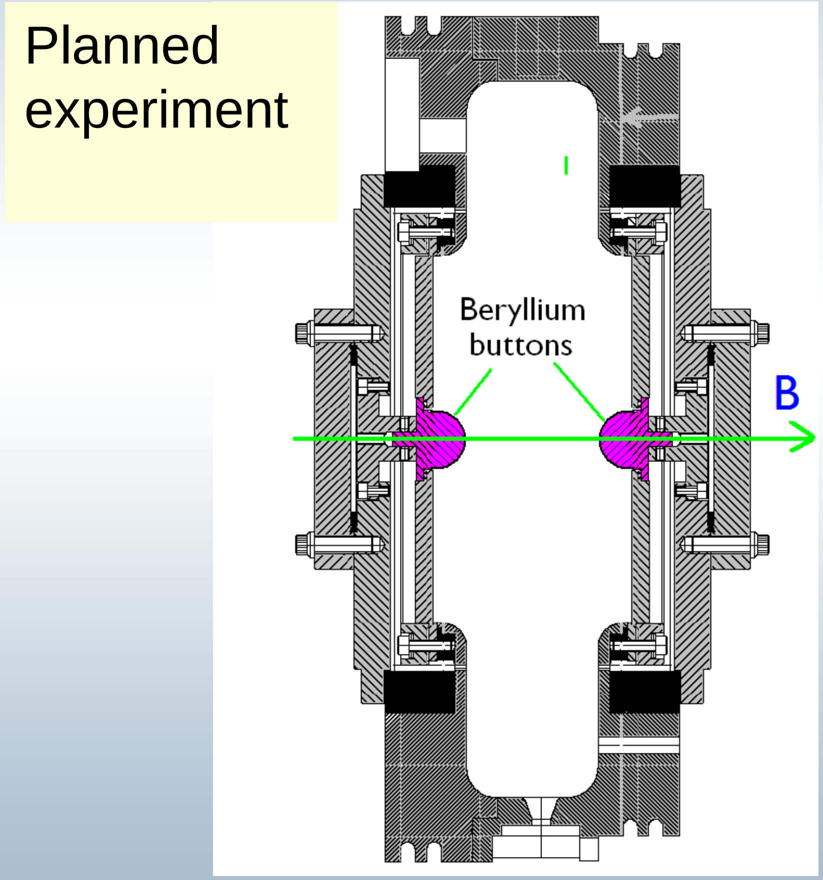
$a = 2.3 \times 10^{-5}\ /^{\text{o}}\text{C}$

Be

$\rho = 1.85\ \text{gr/cm}^3$

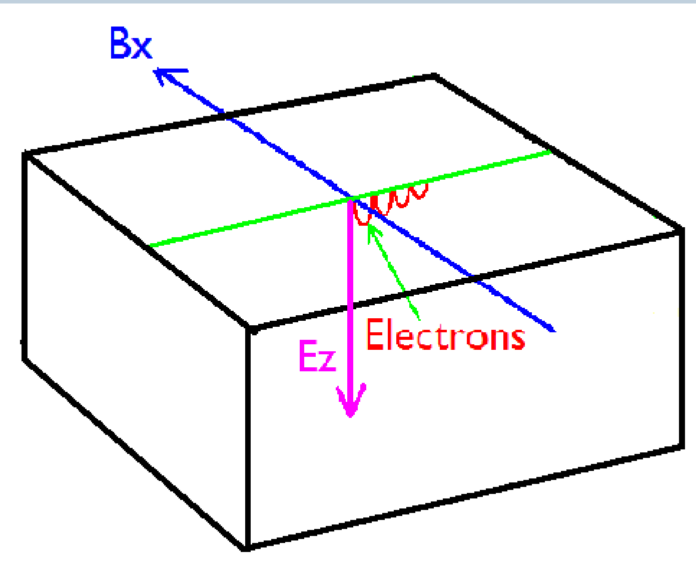
$a = 1.1 \times 10^{-5}\ /^{\text{o}}\text{C}$

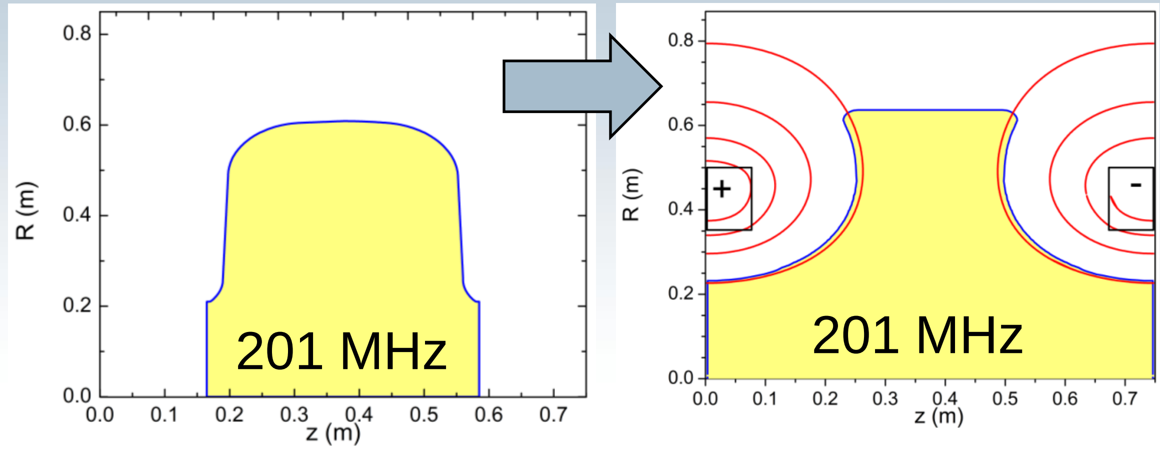
Experiment to test robust materials



- Removable buttons will allow the examination of different materials: Be, Al, Cu
- To be tested in the MTA in Fermilab

Solution II: Magnetic insulation





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ELSEVIER

Enhancement of accelerating field of microwave cavities by magnetic insulation

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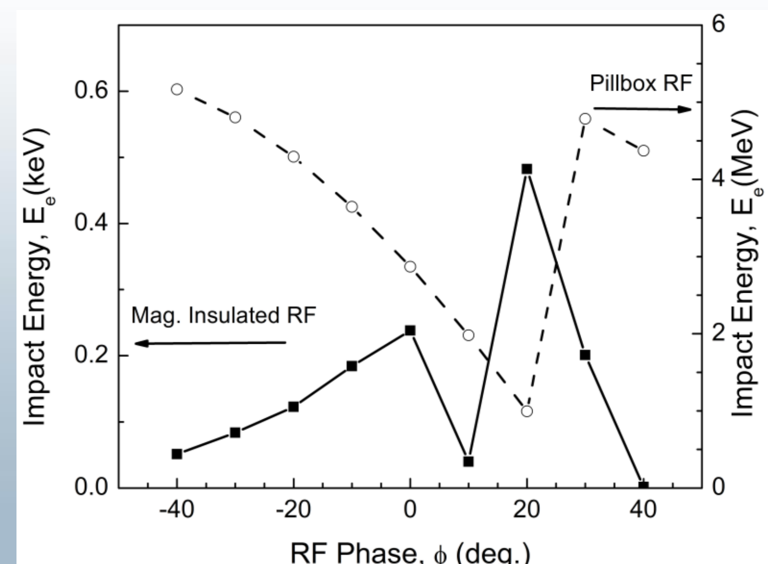
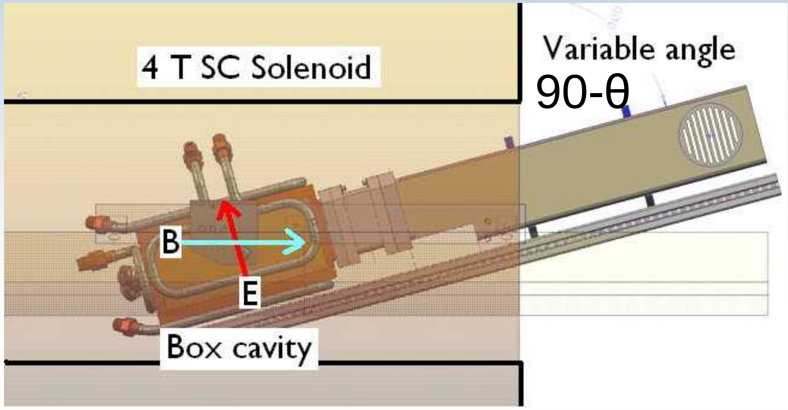
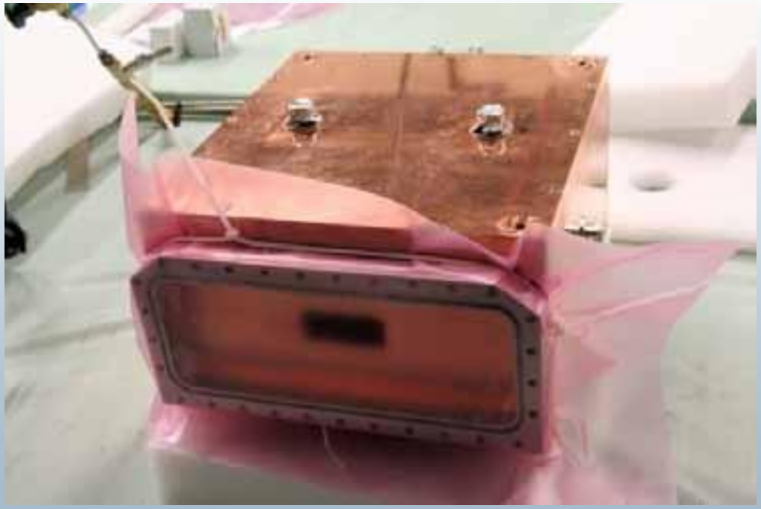


Experiment to test magnetic insulation (1)





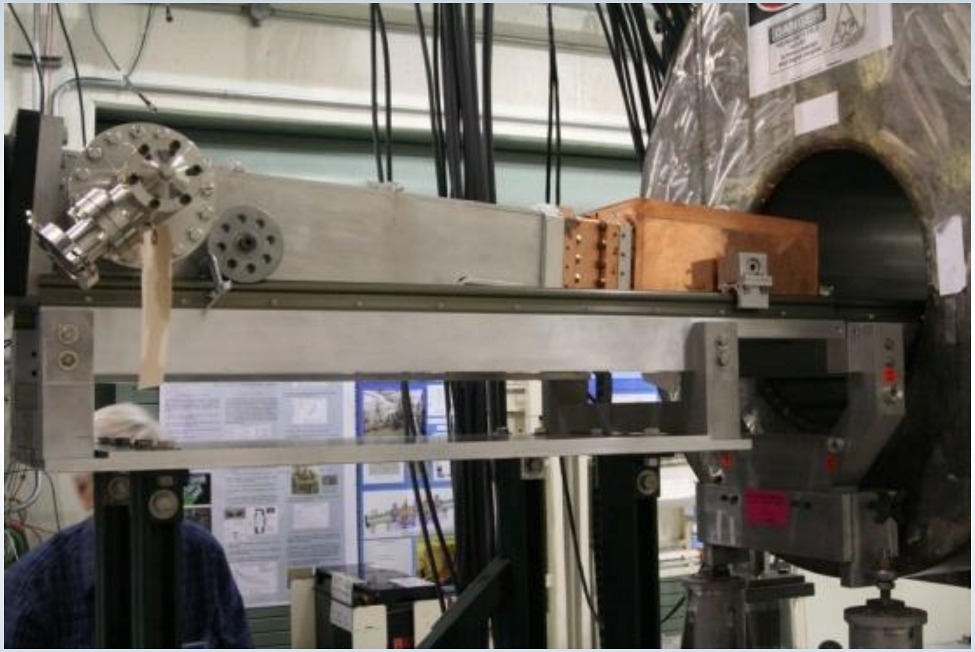


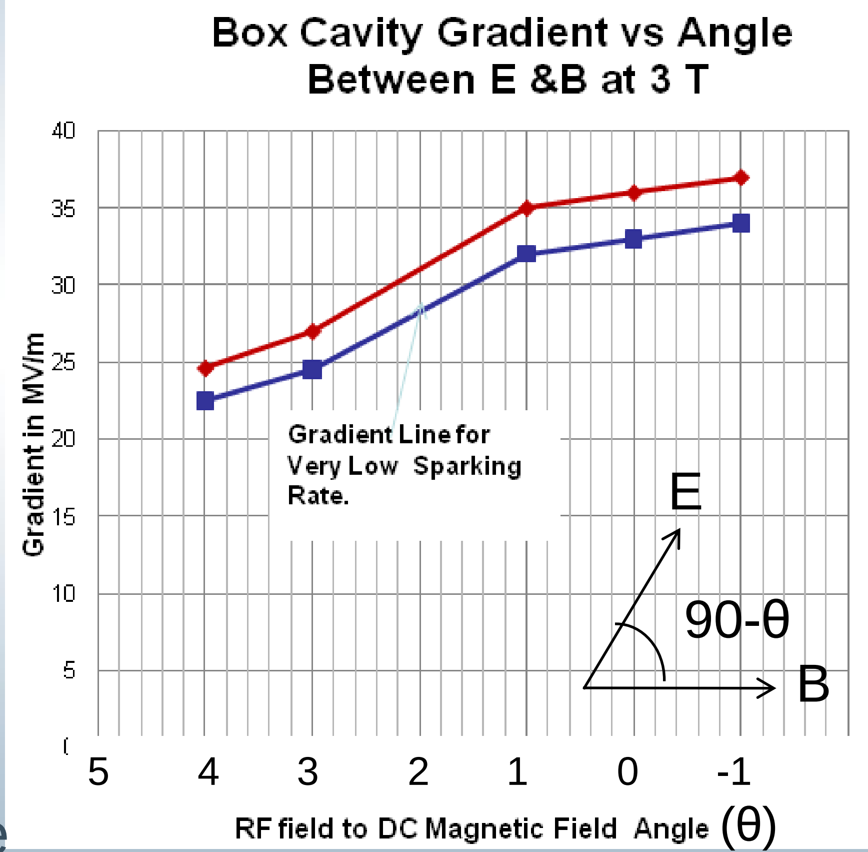
Photo credit: http://mice.iit.edu/mta/

- Cu-made box cavity at 805 MHz
- Rotation up to θ=12 deg.

Experiment to test magnetic insulation (2)

- Preliminary results & mysteries:
  - For B=3 T and θ=0^0 the gradient is ~35 MV/m
  - However, this is just 70% of the max. field reached when B=0 T
  - The max. achievable E-field depends on θ. Surprisingly it drops by 20% when θ=3^0.
  - Examination of the walls do not show severe damage like the one seen in the pillbox case

Moretti *et al.* MAP Meeting at JLAB (3/2011)



Future studies & Open problems

- The effect of magnetic field needs to be further studied by running the box cavity in the mode were E and B are parallel.
- Tests with more robust materials are needed. Be or Al seem to be good candidates
- In parallel, examine other options: High pressure gas cavities, atomic layer deposition
- **Importantly**, the consequences of those solutions to the muon lattices needs to be examined numerically , experimentally and financially

Summary

- rf experiments showed gradient limitations and damage when they operate within B-fields.
- It is likely that the trigger of the seen problems is field-emission from surface roughnesses.
- The rf damage is likely due fatigue from cycling heating from their impact on its surfaces.
- Important: Although the model takes into account the effect of the magnetic field we need more data to verify our proposed mechanism and its assumptions.