Triggers and mitigation strategies of rf breakdown for muon accelerator cavities

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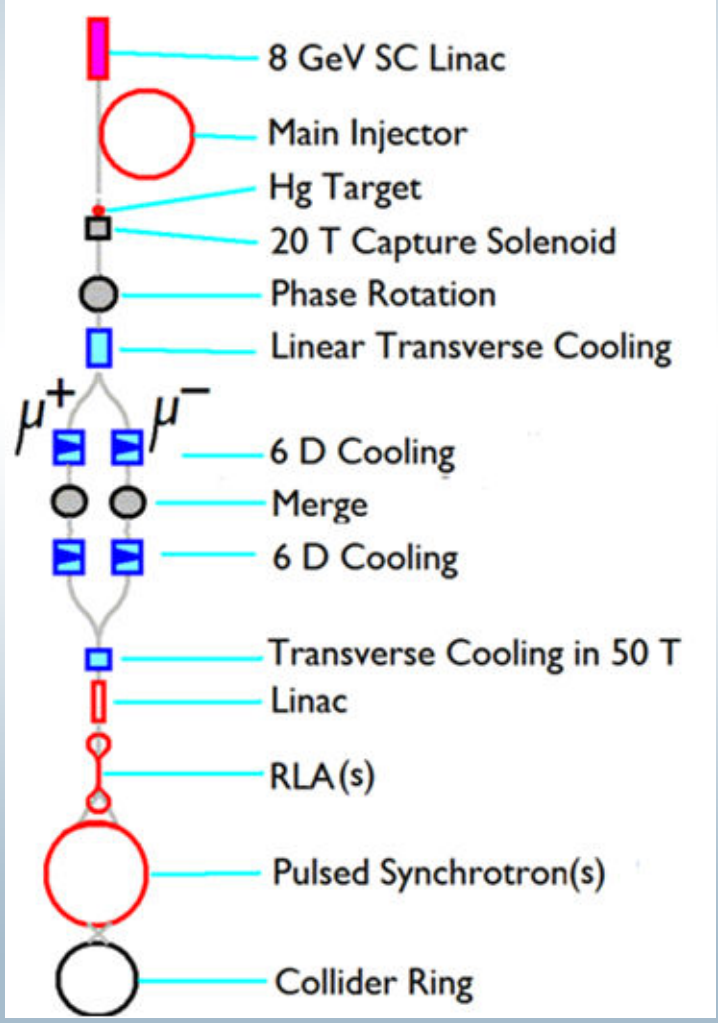
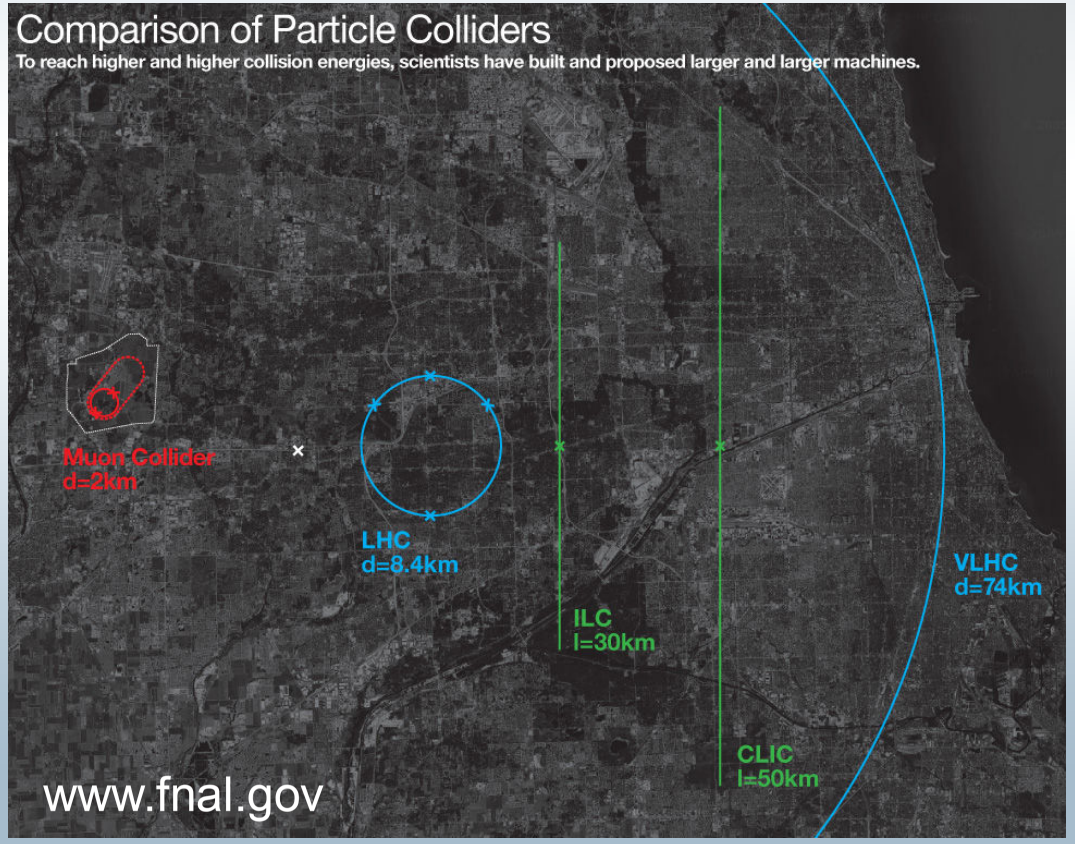
November 04, 2010

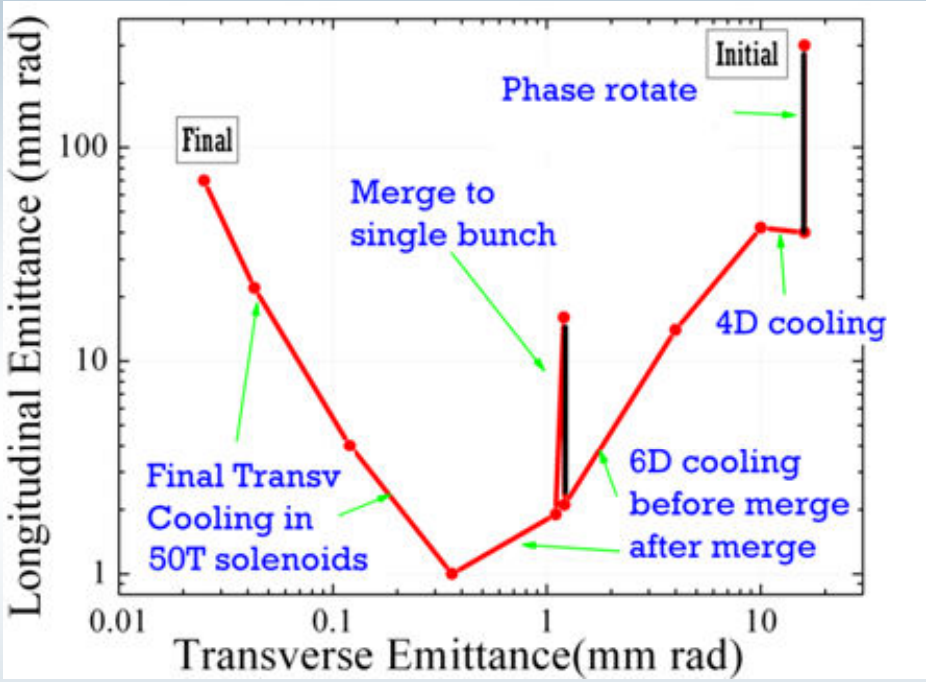
Muon Collider (MC)



- A MC offers high collision energy at a compact size

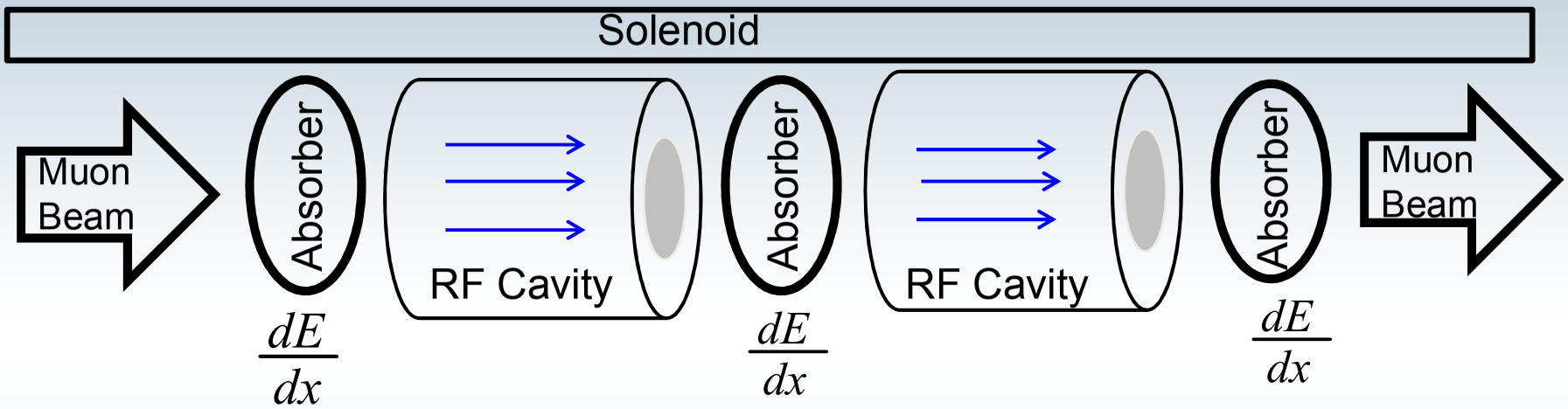


The challenge



- Muon beam is “born” with high emittance
- Muons decay fast (2 μs at rest) and thus beam manipulation has to be done quickly
- We consider ionization cooling

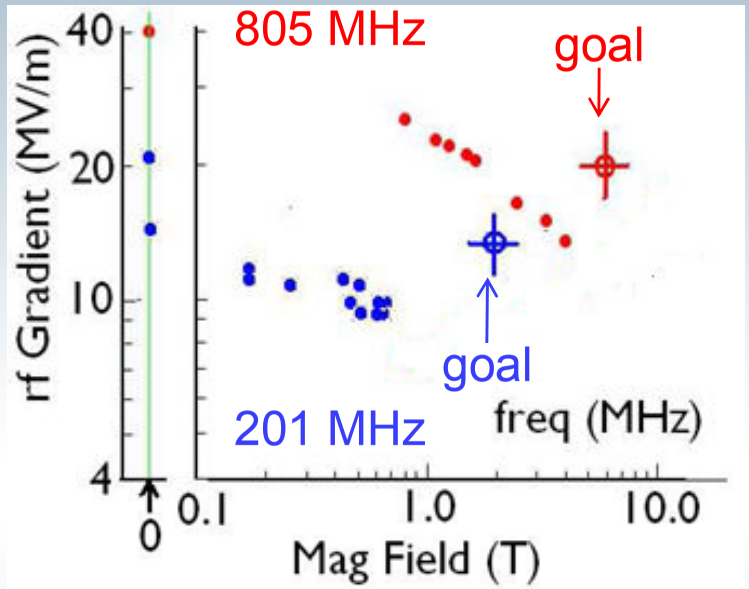
Ionization cooling

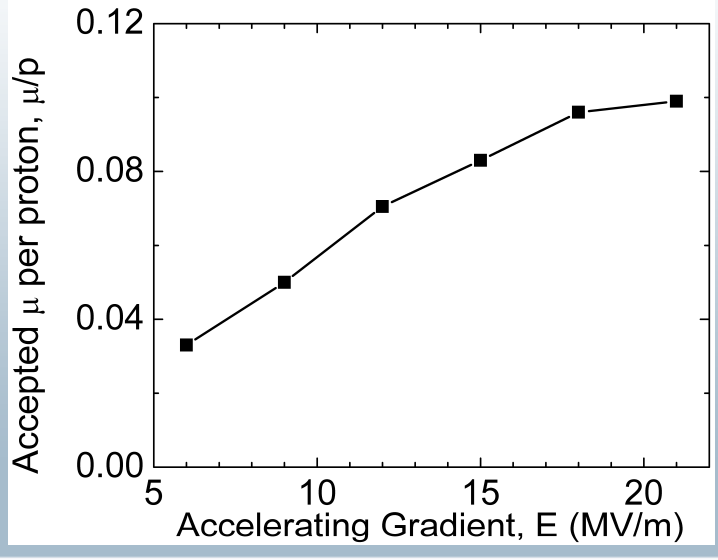


- Energy loss in absorbers
- rf cavities to compensate for lost longitudinal energy
- Strong magnetic field to confine muon beams
- Cooling with 201 MHz-805 MHz cavities operating in multi-Tesla magnetic fields

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.

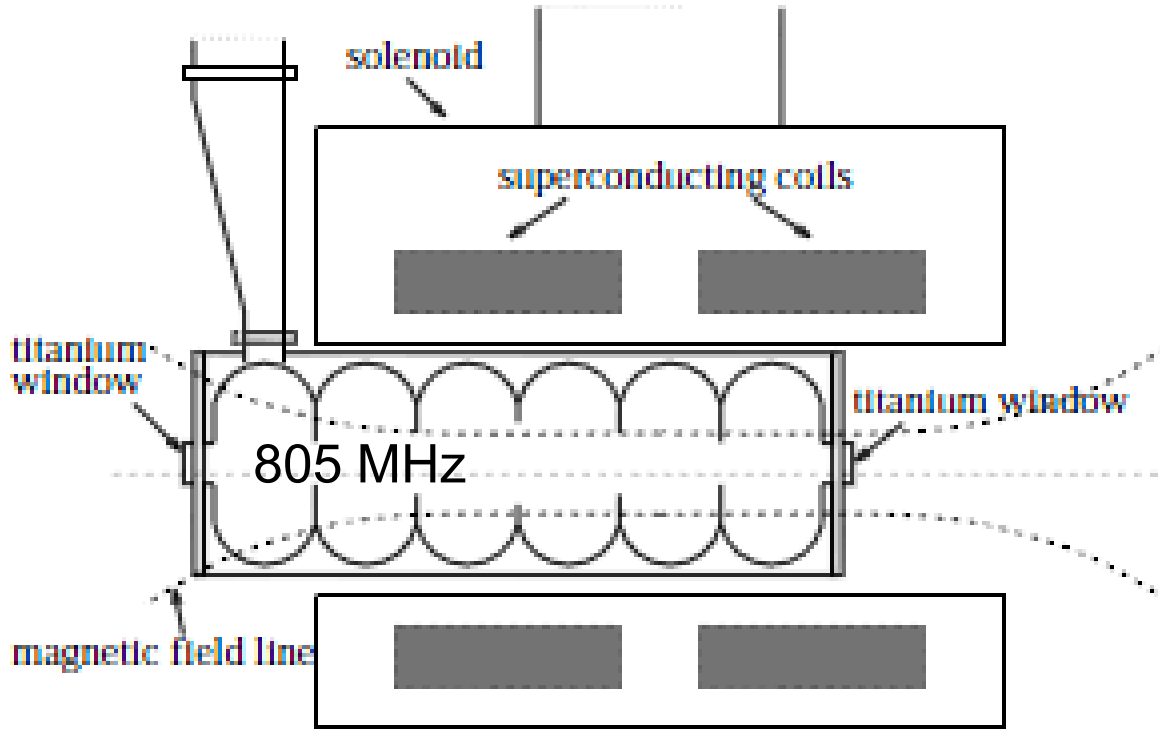


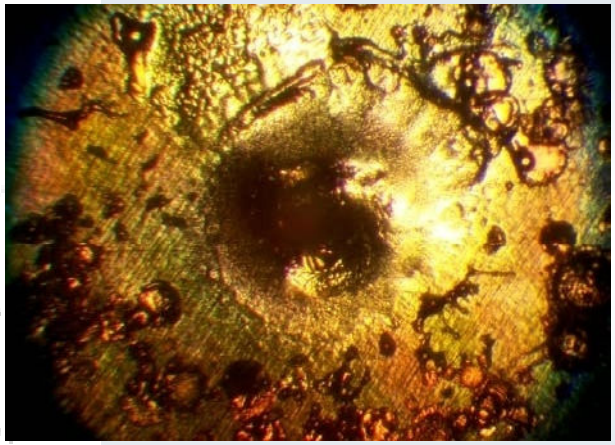


Scope of this work/ Outline

- 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
- Study the impact of those solutions on the muon transport and cooling (briefly)
- Summary

Multi-cell cavity in magnetic field

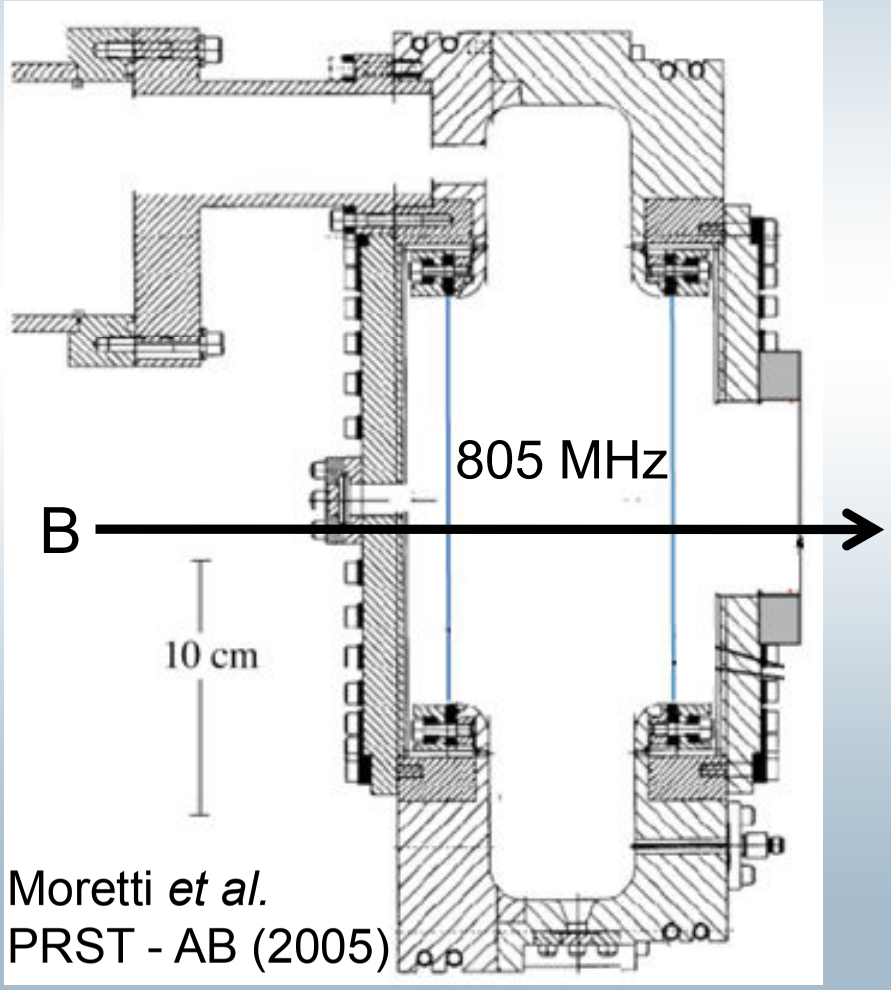




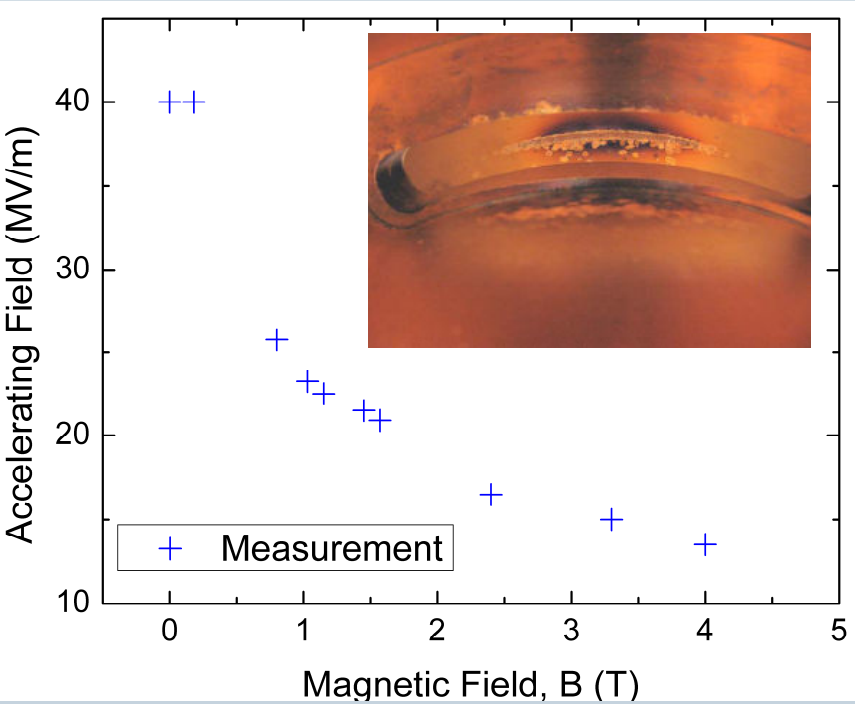
Norem *et al.* PRST - AB (2003)

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

Pillbox cavity in magnetic field



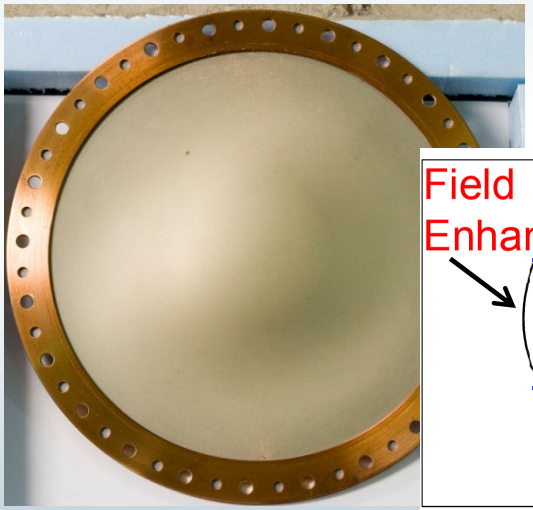
Moretti *et al.*
PRST - AB (2005)

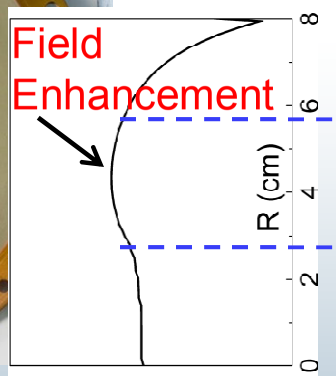


- rf gradient is B depended
- Surface damage

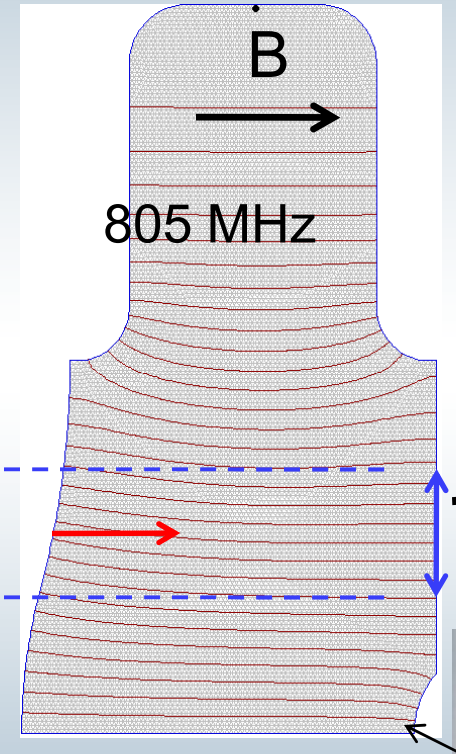
Button experiment: Can Beryllium do better and why?

Be side

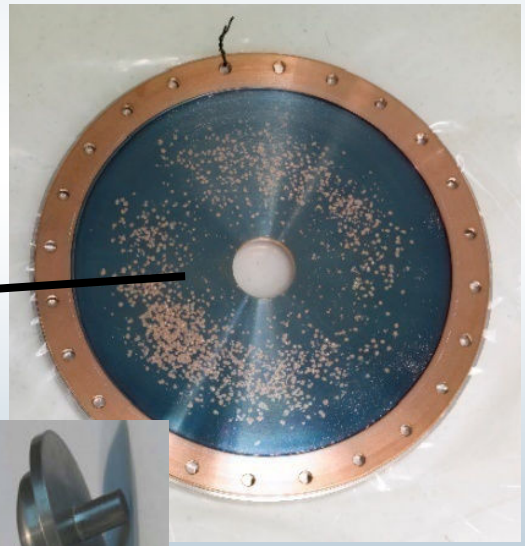




Huang *et al.* PAC (2009)



Cu side



Button

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

Proposed trigger of breakdown in magnetic 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

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **12**, 031002 (2009)

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

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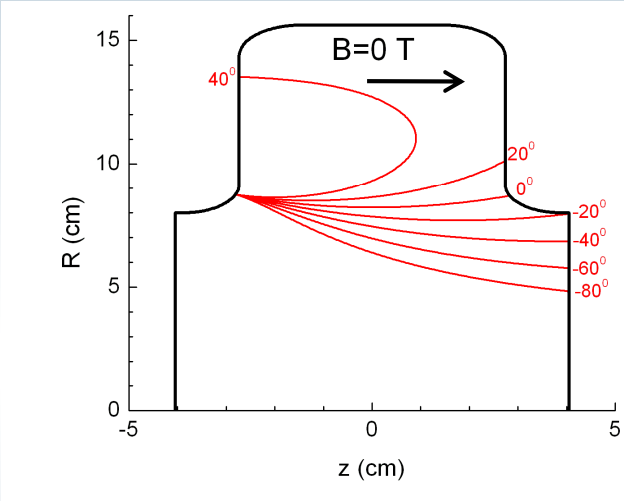
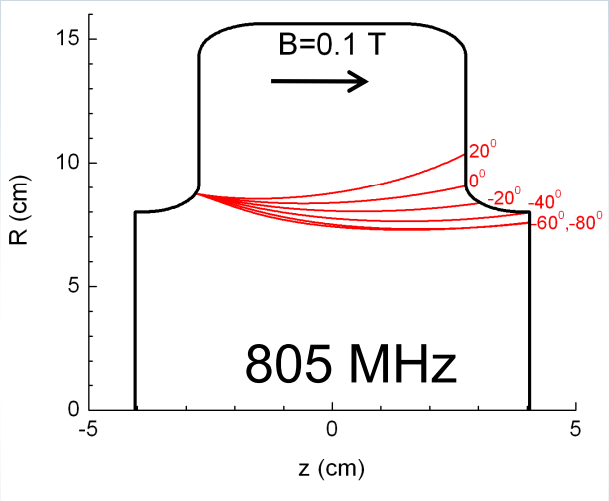
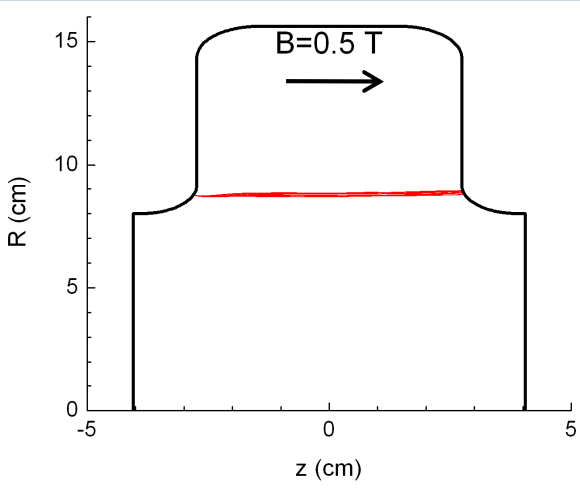
Simulation Details

- Pillbox cavity 805 MHz
- 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

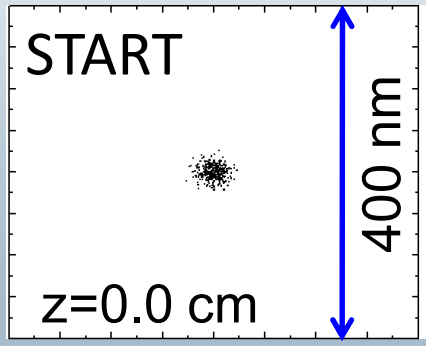
Step 1: Field-emission in B-fields (1)

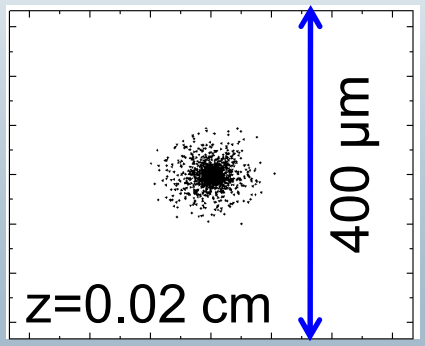


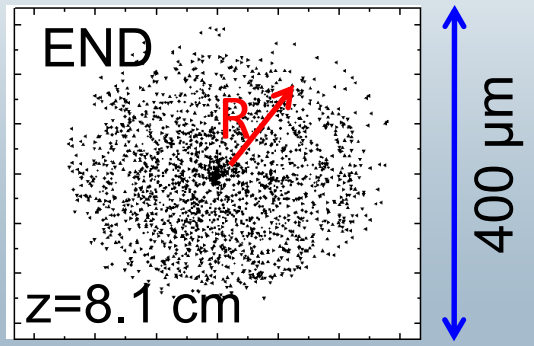




- Focusing effect of the magnetic field (B=0.5 T):

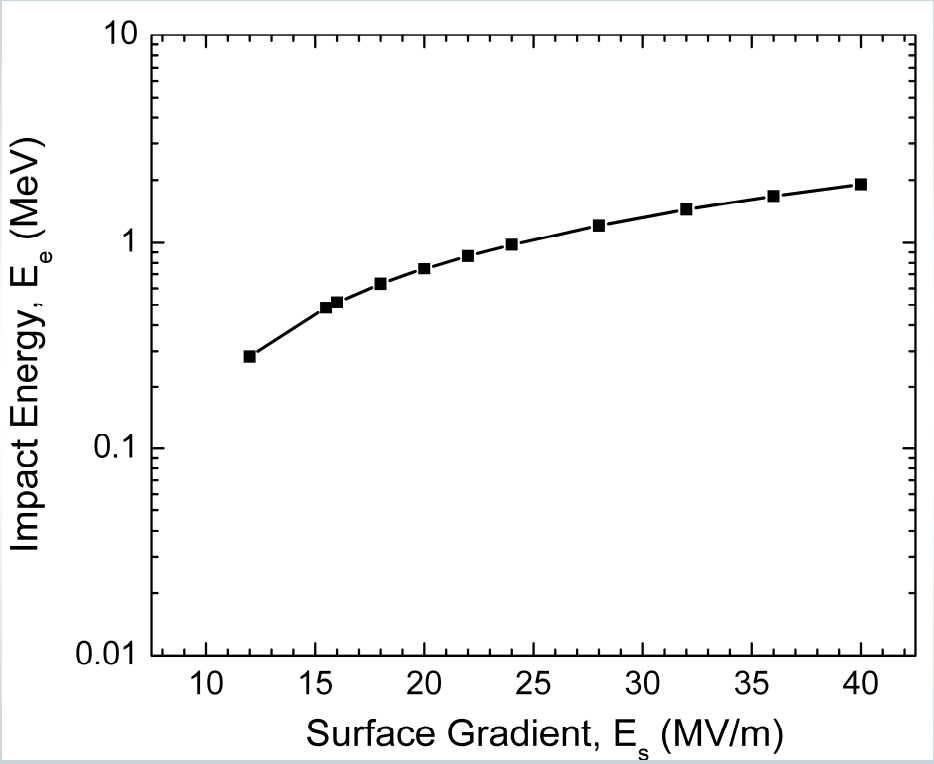






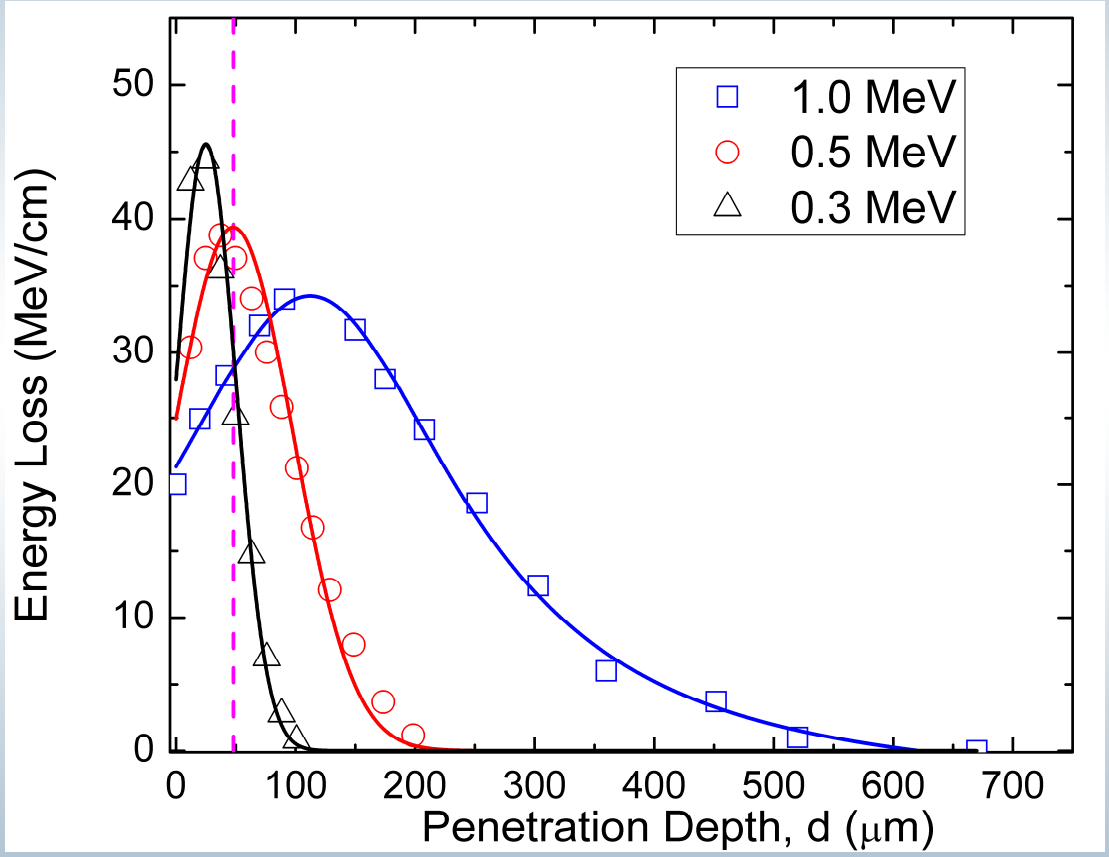
$$R \approx \frac{\sqrt{I}}{B}$$

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



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

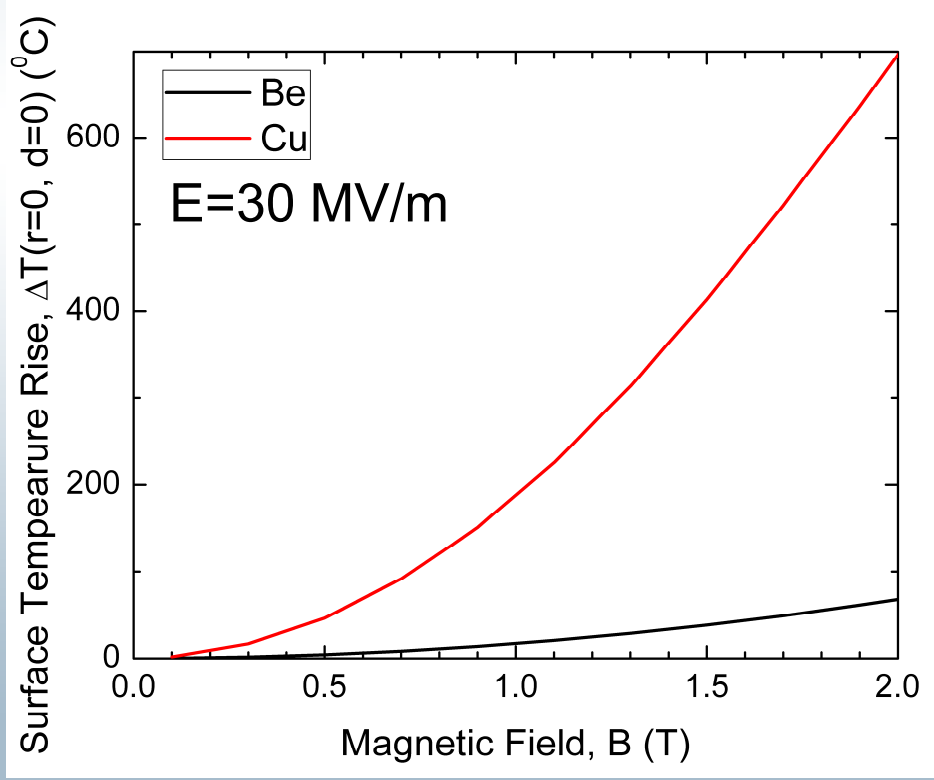
Step 2: Electron penetration in metal



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

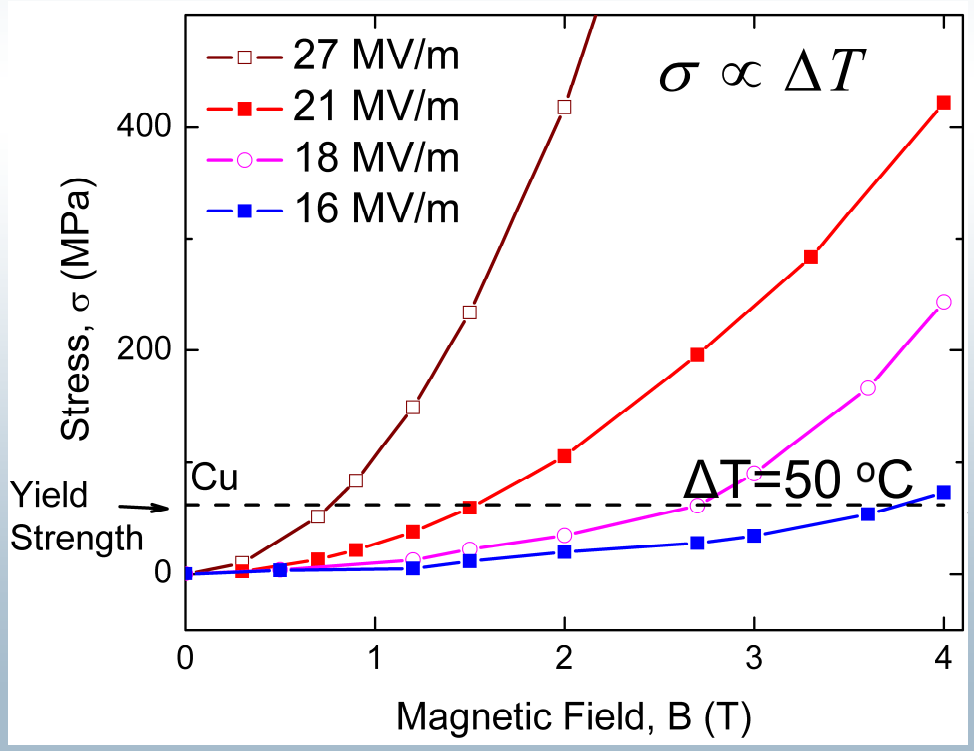
Step 3: Temperature rise at rf surface

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



Step 4: Thermal stress from pulsed heating

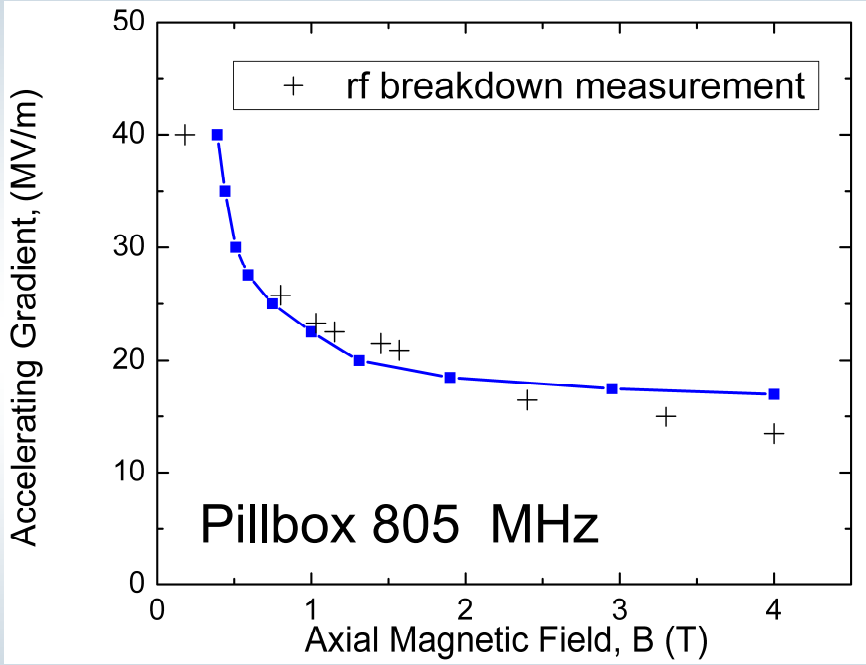
- Thermal expansion of the metal causes distortion in the near-surface region and induces stress (Musal, NBS 1979)



- 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: Mag. field values for which the induced stress matches the yield strength of Cu
- Important: We need more experimental data to verify our proposed mechanism and its (many) assumptions



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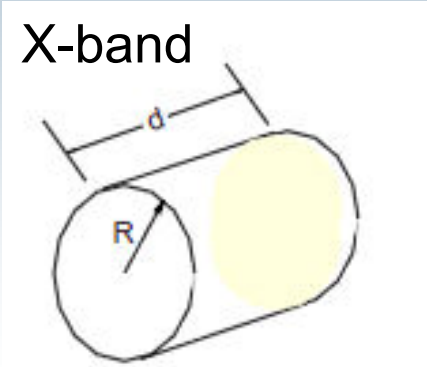
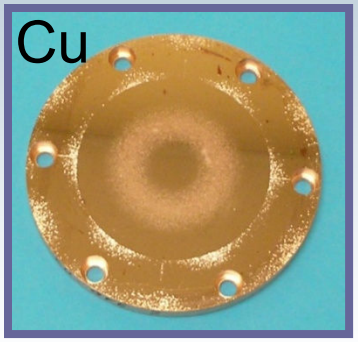
Effects of external magnetic fields on the operation of high-gradient accelerating structures

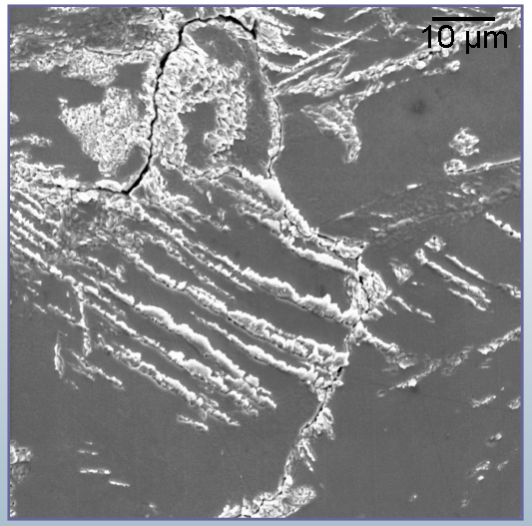
Diktys Stratakis *, Juan C. Gallardo, Robert B. Palmer

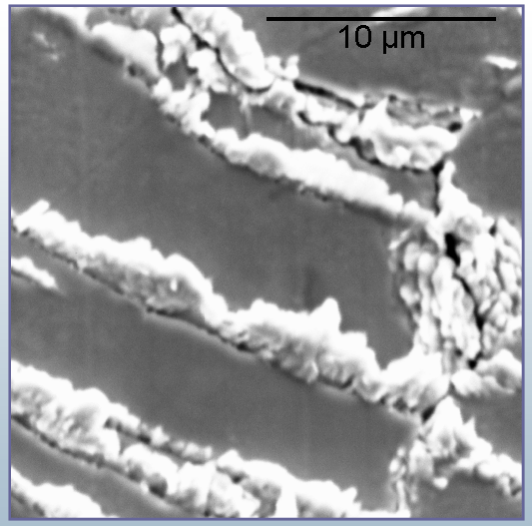
Pulse heating experiments at SLAC

- SLAC tested pulse heating in X-band cavities
- rf heating at 70-110 deg.
- Severe damage at >10^6 pulses





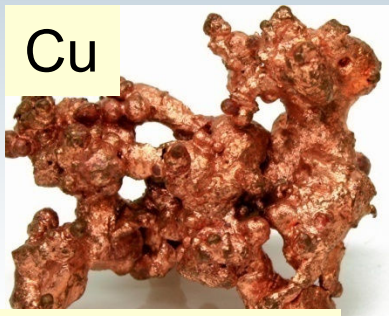




Pritzkau *et. al*, PRST-AB (2002)
Laurent *et. al.,* CLIC Workshop (2008)

Solution I: Alternate materials (1)

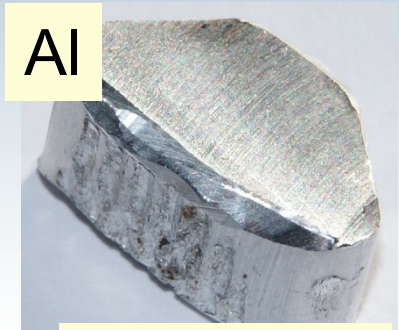
Cu



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

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

Al



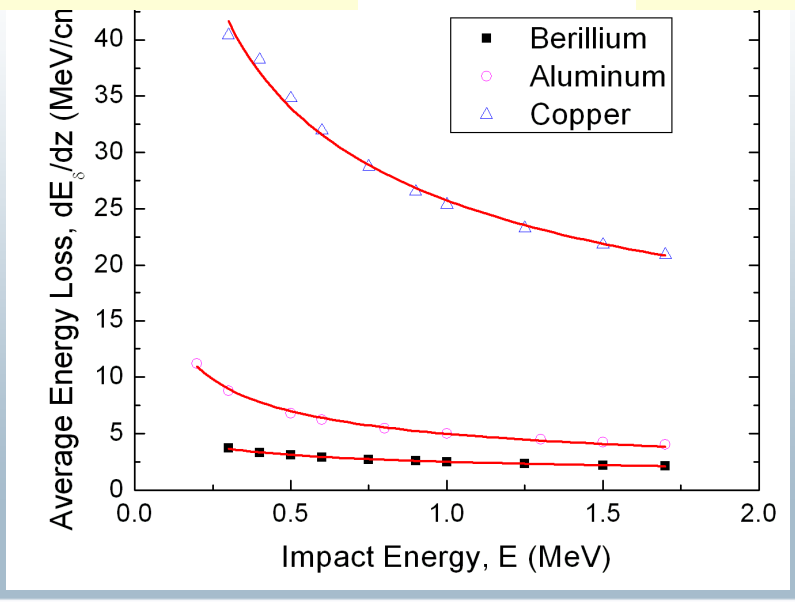
$\rho = 2.70\ \mathrm{gr/cm^3}$

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

Be

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

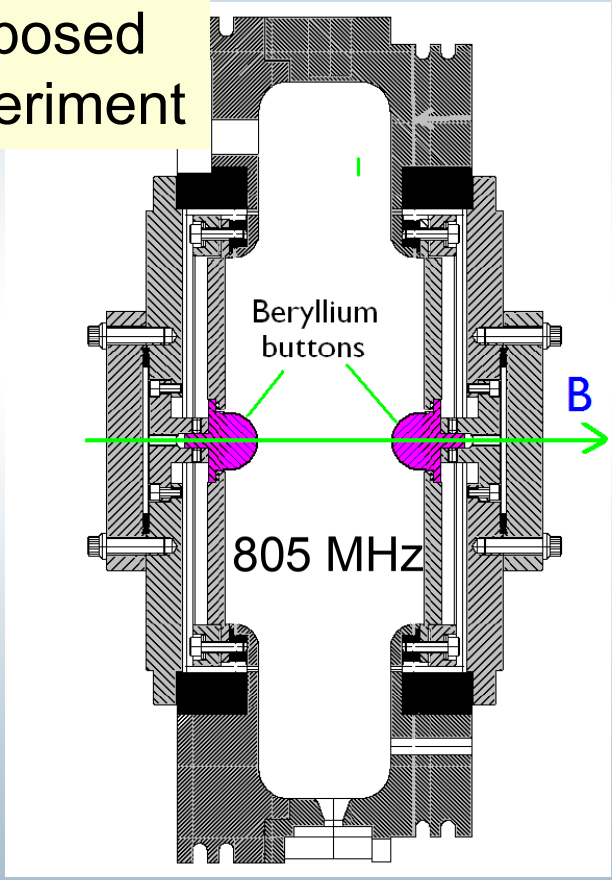
$a = 1.1 \times 10^{-5}\ /^{o}\mathrm{C}$



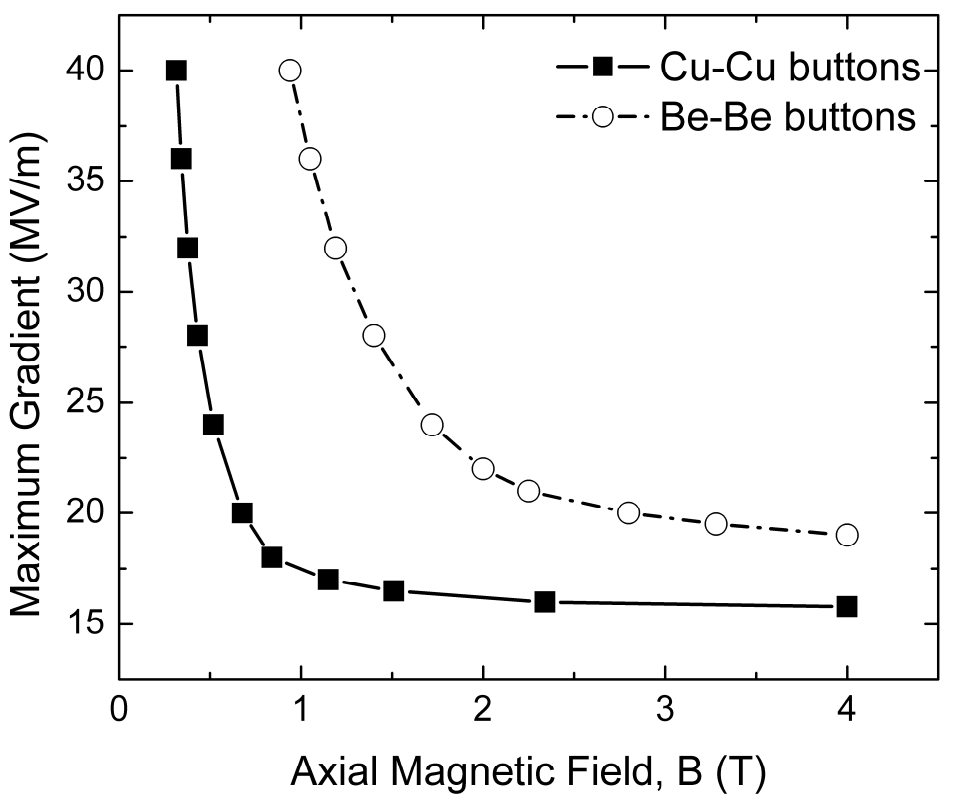
- The energy deposition at the Be surface is 7 times less than in Cu

Solution I: Alternate materials (2)

Proposed experiment

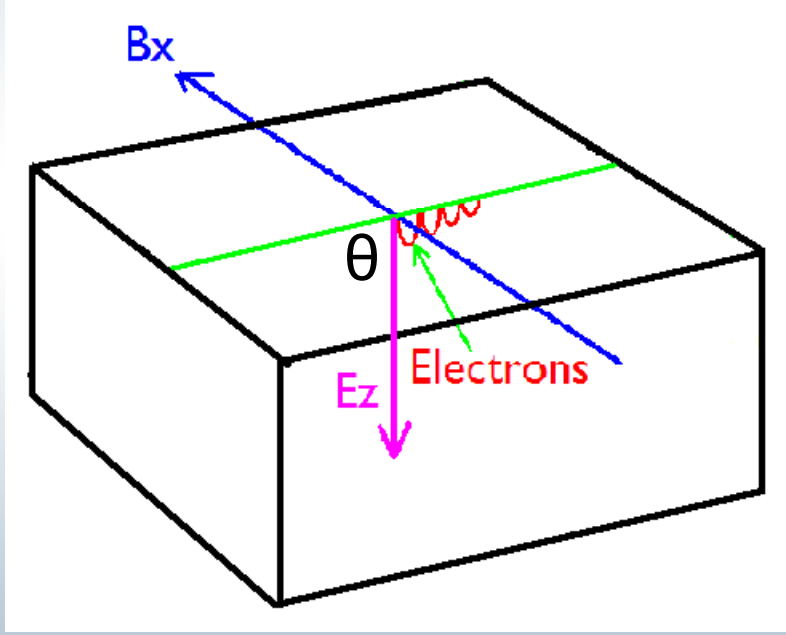


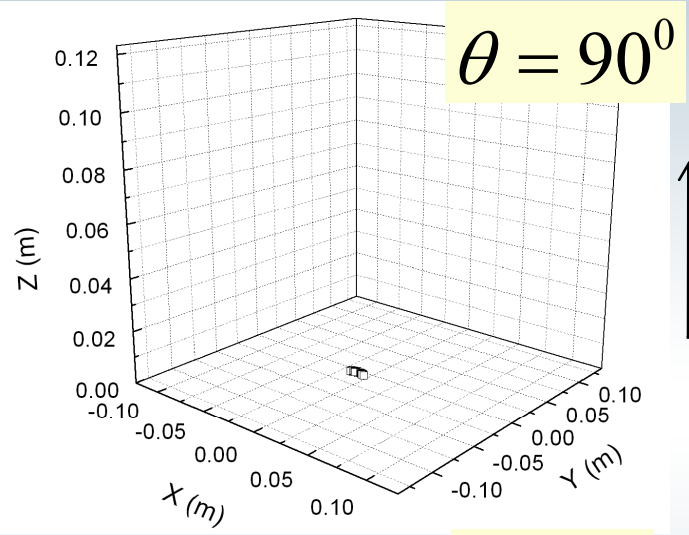
Prediction from simulation

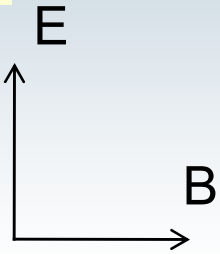


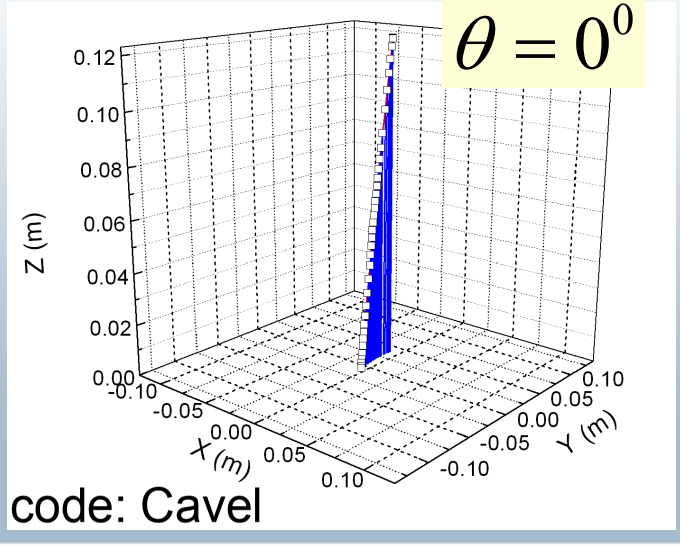
- If successful we can built and test a Be pillbox rf

Solution II: Magnetic insulation (1)



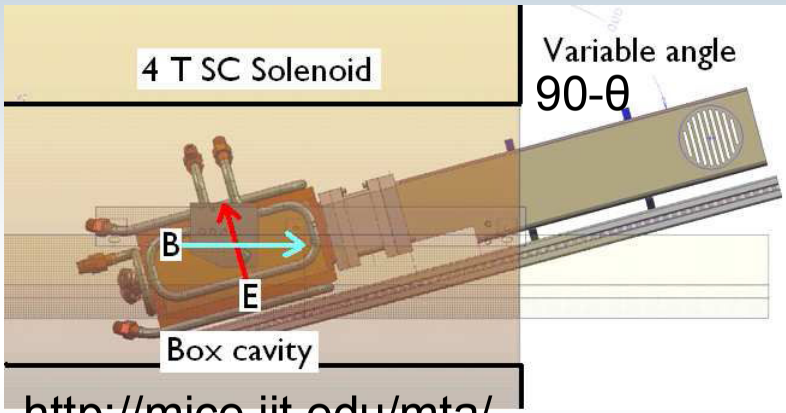




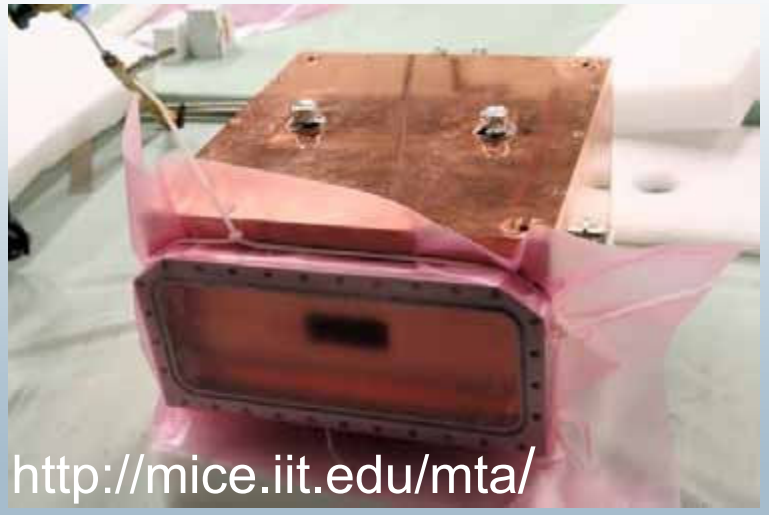


code: Cavel

Solution II: Magnetic insulation (2)

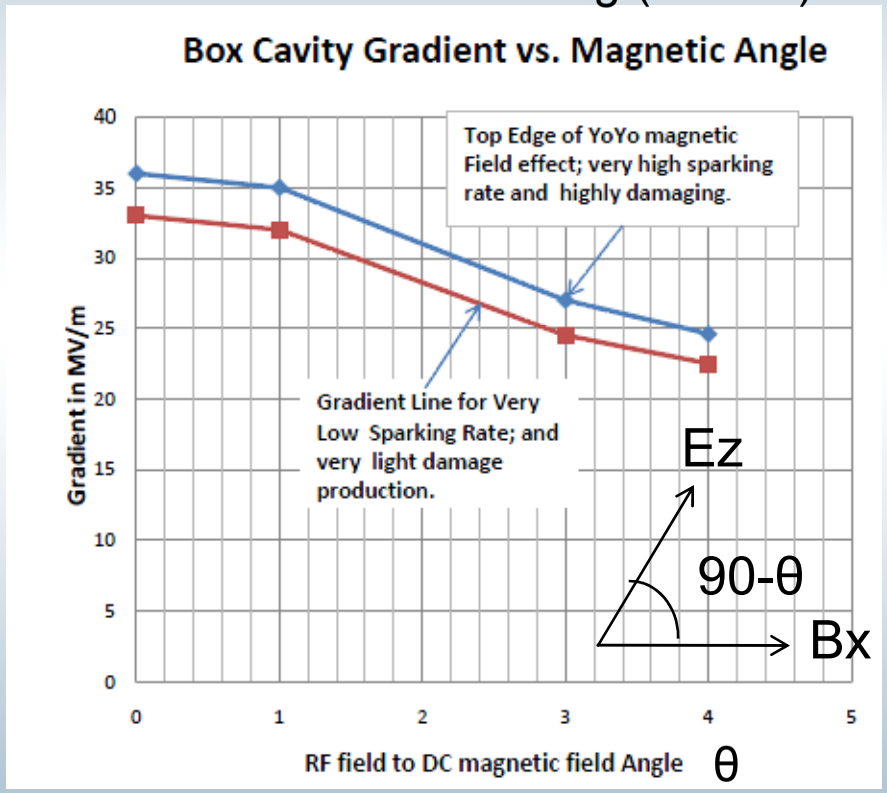


http://mice.iit.edu/mta/



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

Moretti *et al.* MAP Meeting (7/2010)

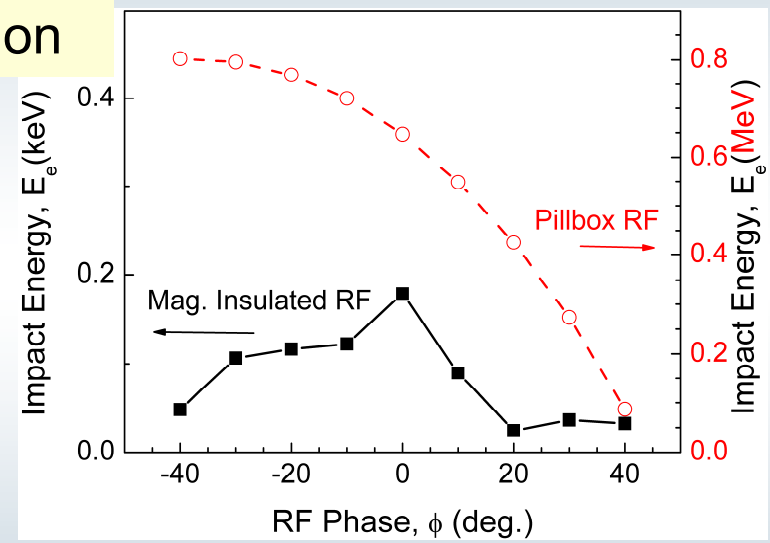


- When B, E are normal cavity performs better

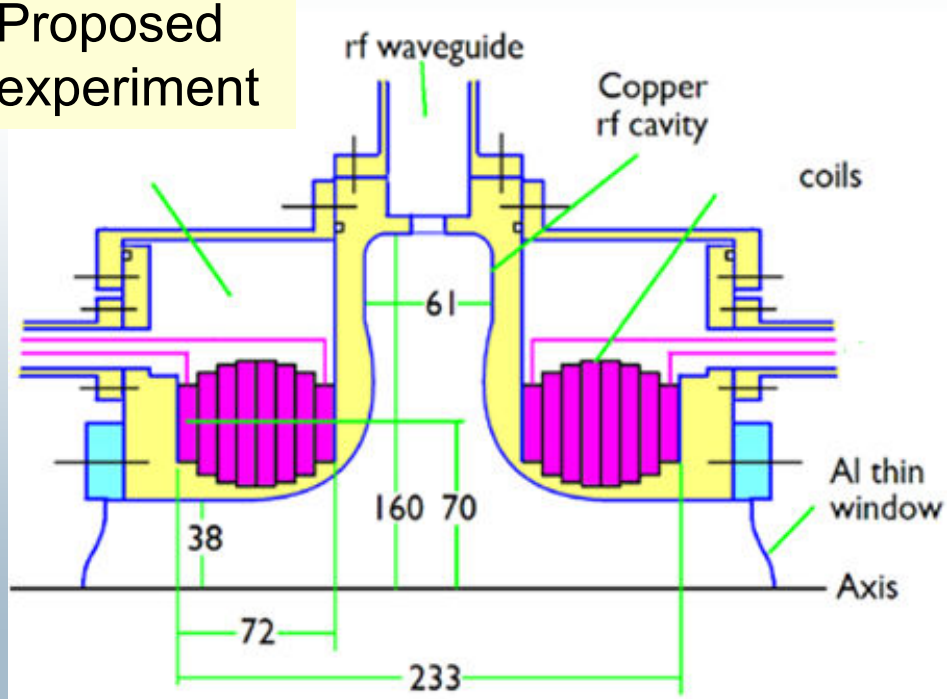
Solution II: Magnetic insulation (3)

- Test “a real” MI cavity, specifically shaped for muon accelerator lattices

Simulation



Proposed experiment



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Magnetically insulated high-gradient accelerating structures for muon accelerators

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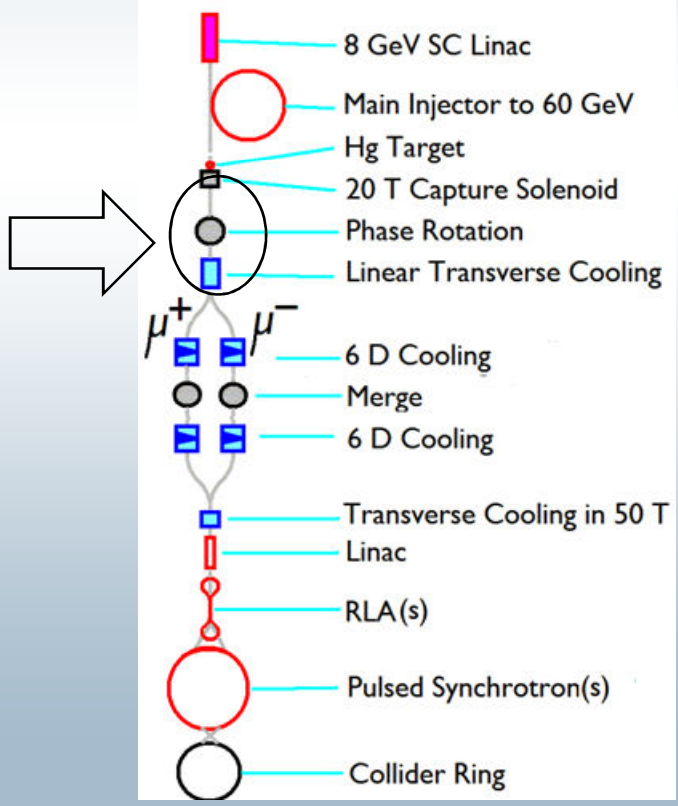
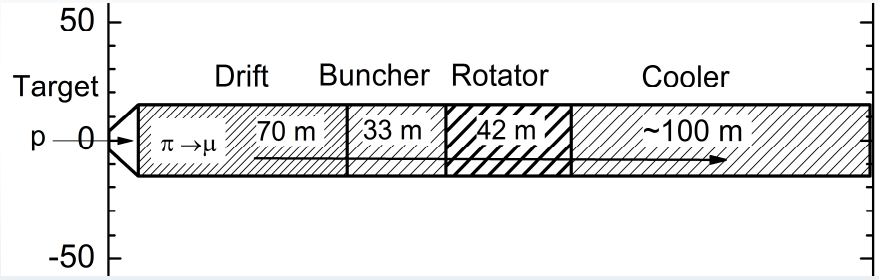
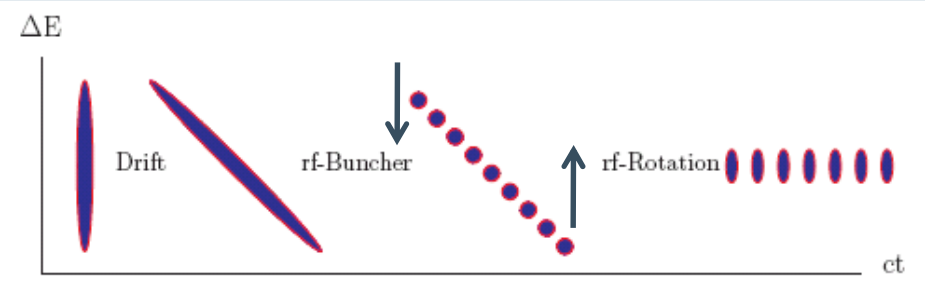
Application of magnetic insulation to muon accelerator lattices

Muon accelerator front-end (FE)

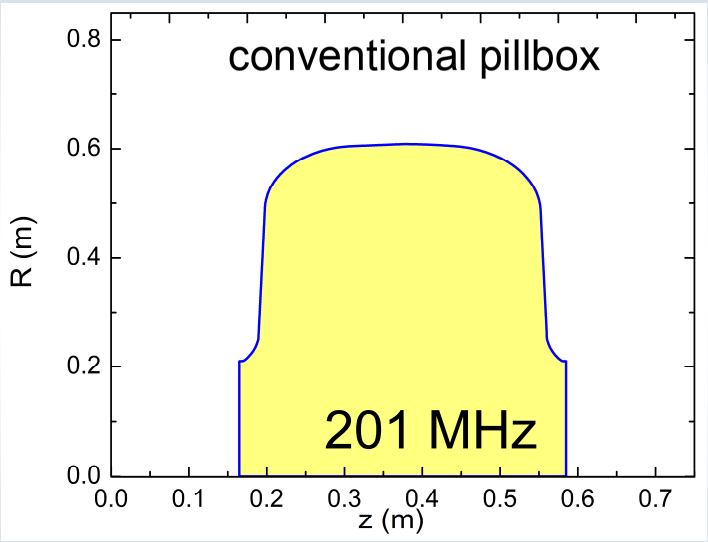
- Purpose of FE: Reduce beam phase-space volume to meet the acceptance criteria of downstream accelerators

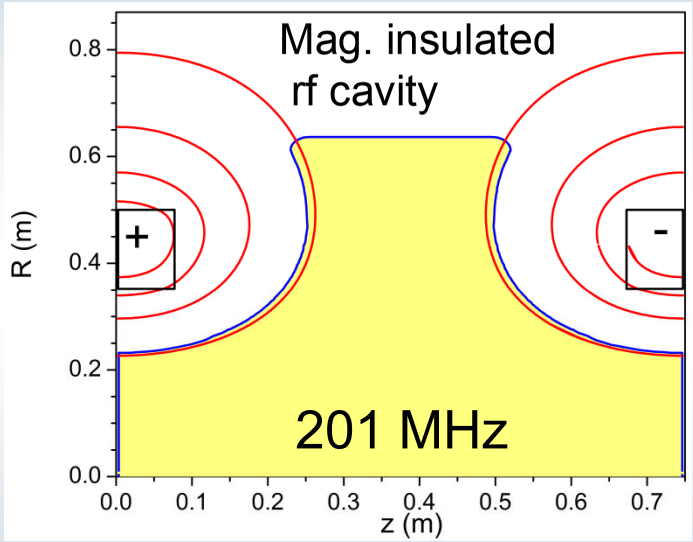






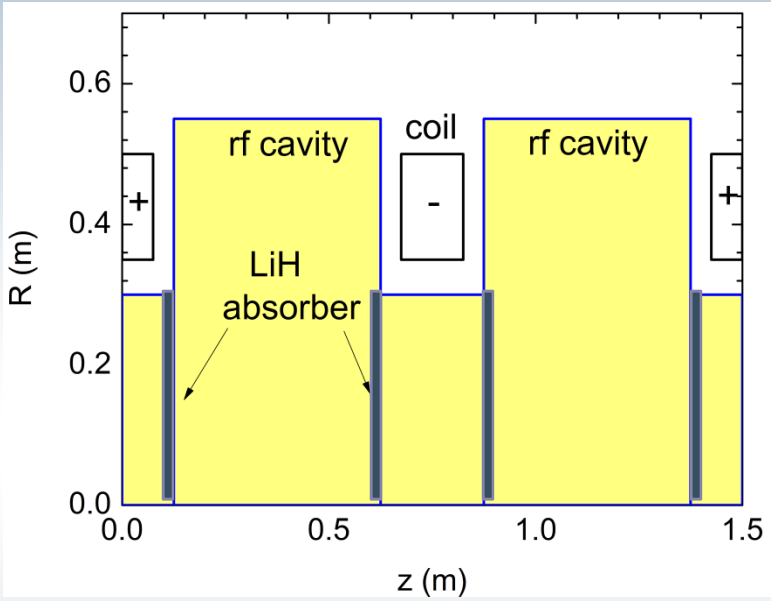
Application of magnetic insulation to the FE

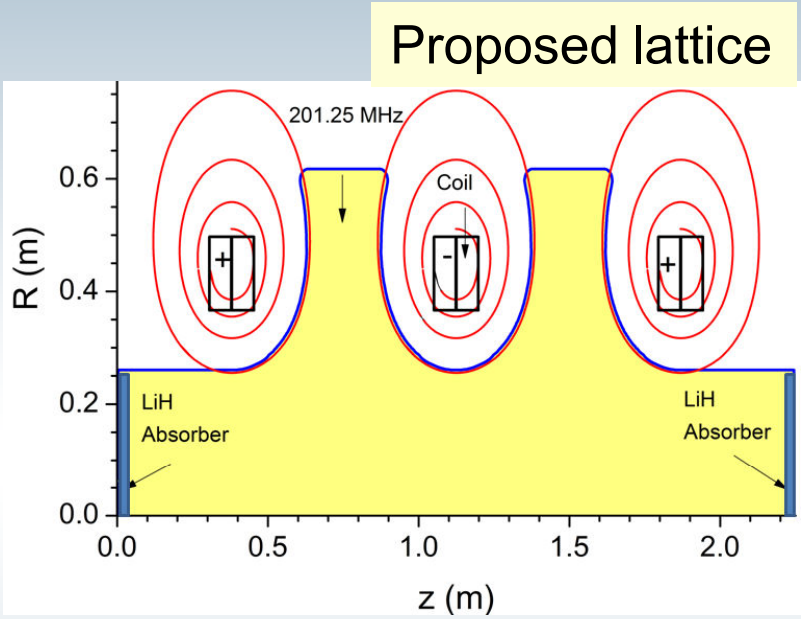




- The price to pay here is that the shunt impedance reduces by a factor of two

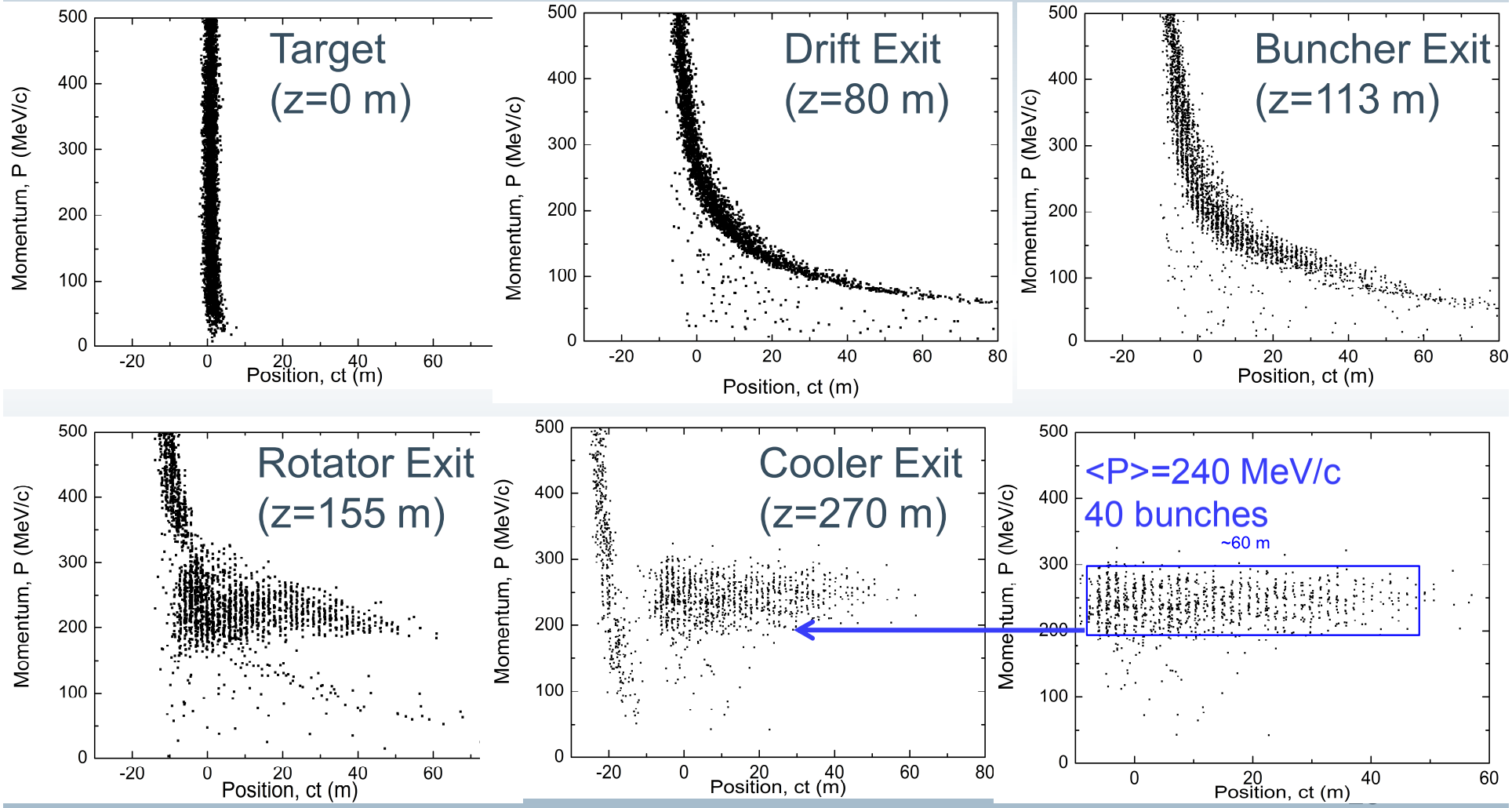
Front-end cooler section



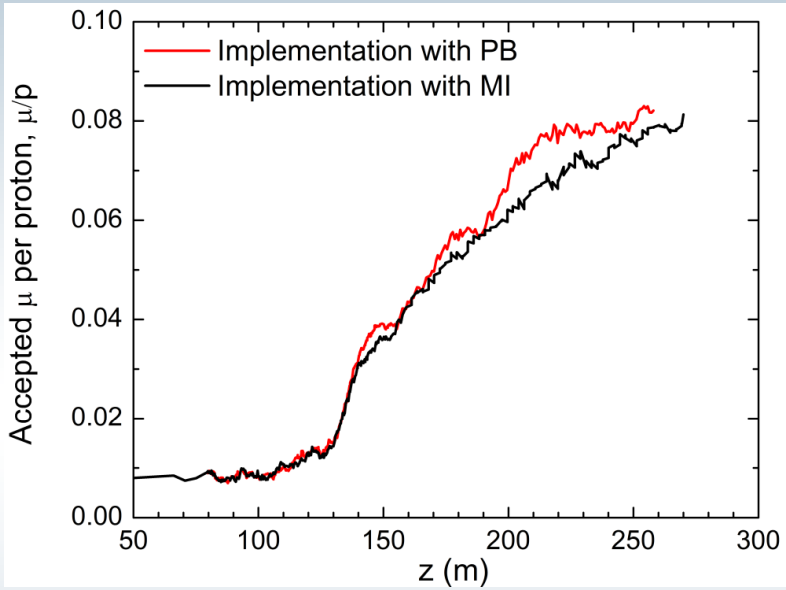


- Cooler length ~120 m
  - Alternating B ±2.8 T
  - LiH absorber, E=15 MV/m
- MI rf cavities are extended on sides, this:
  - Reduces fields on the cavity Be-window → less heating

Muon evolution in a magnetically insulated front-end channel (icool)



Overall performance (icool)



- Good news: The μ/p rate with MI (within acceptance A_T < 30 mm, A_L < 150 mm and cut in momentum 100<Pz<300 MeV/c) is only less than 5-10%
- Not so good news: MI cavities require at least twice the power of PB!

Stratakis et al. Phys. Rev. ST-AB, submitted (2010)

Future studies/ Open problems

- Box cavity data show higher gradients when the cavity is insulated. The effect of magnetic field needs to be further studied by running the cavity in the mode were E and B are parallel.
- Further tests with more robust materials are needed. Be, Al, and Mo are all good candidates
- Also examine alternative solutions: High pressure gas cavities, atomic layer deposition
- **Importantly**, the consequences of those solutions to the muon lattices needs to be examined <u>numerically</u> , <u>experimentally</u> and <u>financially</u>

Summary (1)

- 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.

Summary (2)

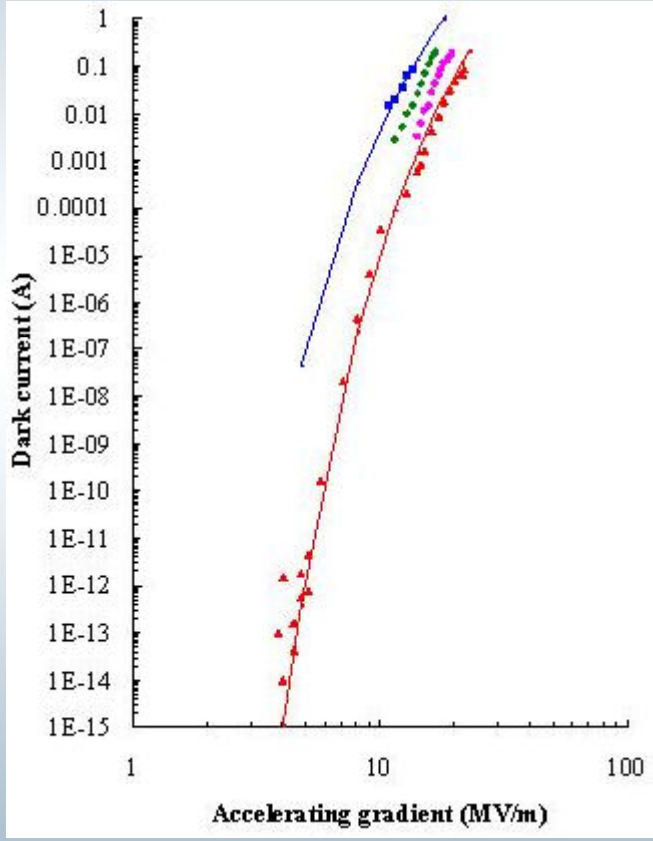
- Also it is interesting to examine more how surface fatigue causes breakdown (collaboration with SLAC, Univ. of MD)
- But likely the problem can be solved if:
  - Eliminate surface enhancements (ALD)
  - Mitigate the damaging effects to the cavity from the resulting emission (Insulation, materials, high pressure rf)
- Numerically studied a muon accelerator front-end lattice with magnetically insulated (MI) cavities. Although it is not the best option (twice power req.) the concept has been tested experimentally.

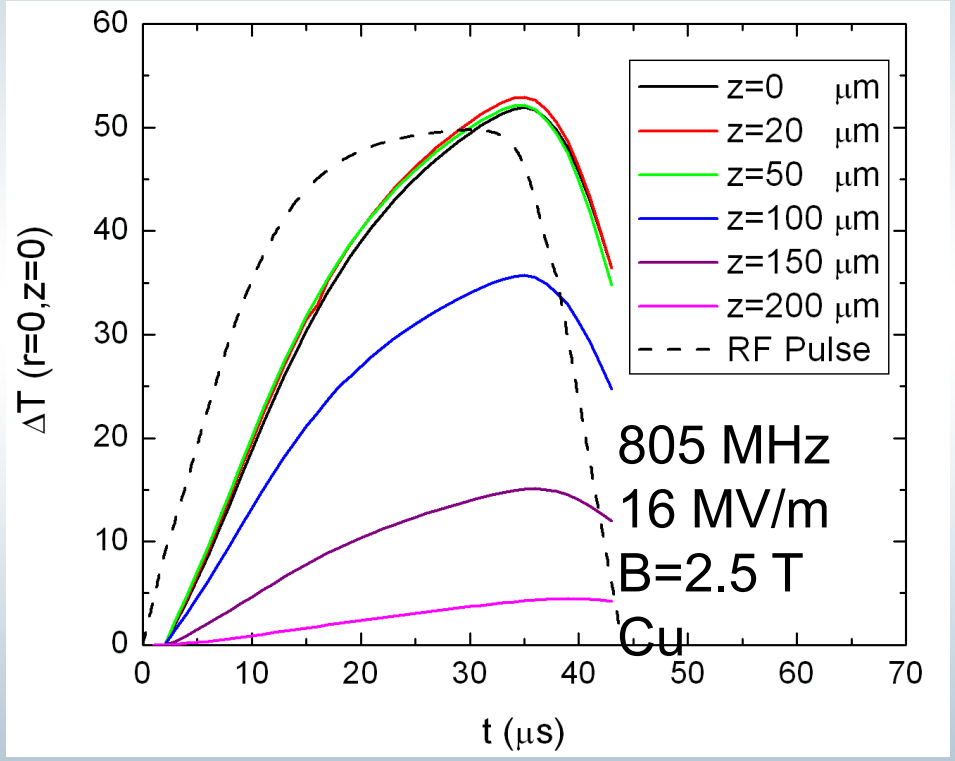
Acknowledgements

Advance Accelerator Group, BNL

But also **thanks** to: D. Neuffer, P. Snopok, A. Moretti, A. Bross, J. Norem, Y. Torun, D. Li, J. Keane, S. Tantawi, L. Laurent, G. Nusinovich, V. Dolgashev , Z. Li, Y. Y. Lau

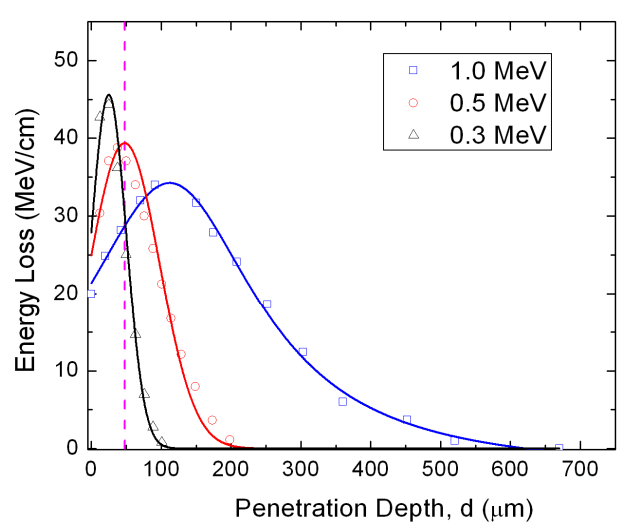
Appendix Slide 1



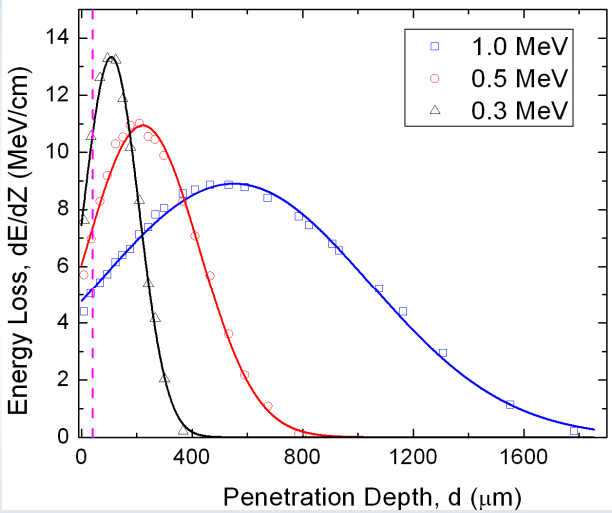


Energy Deposition on Wall

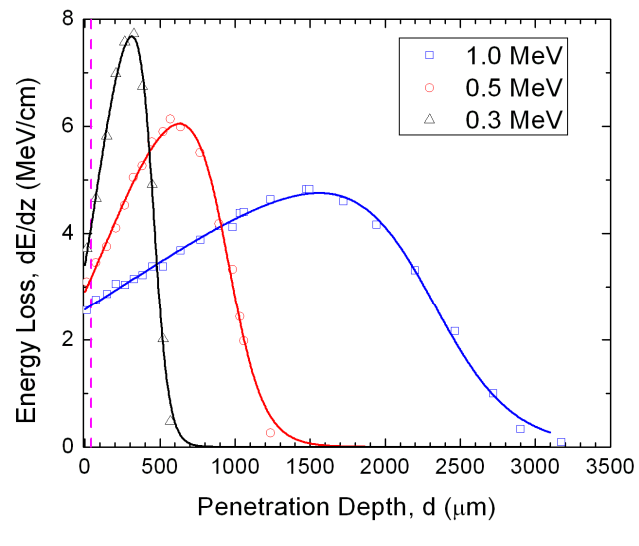
Copper, Cu



Aluminum, Al

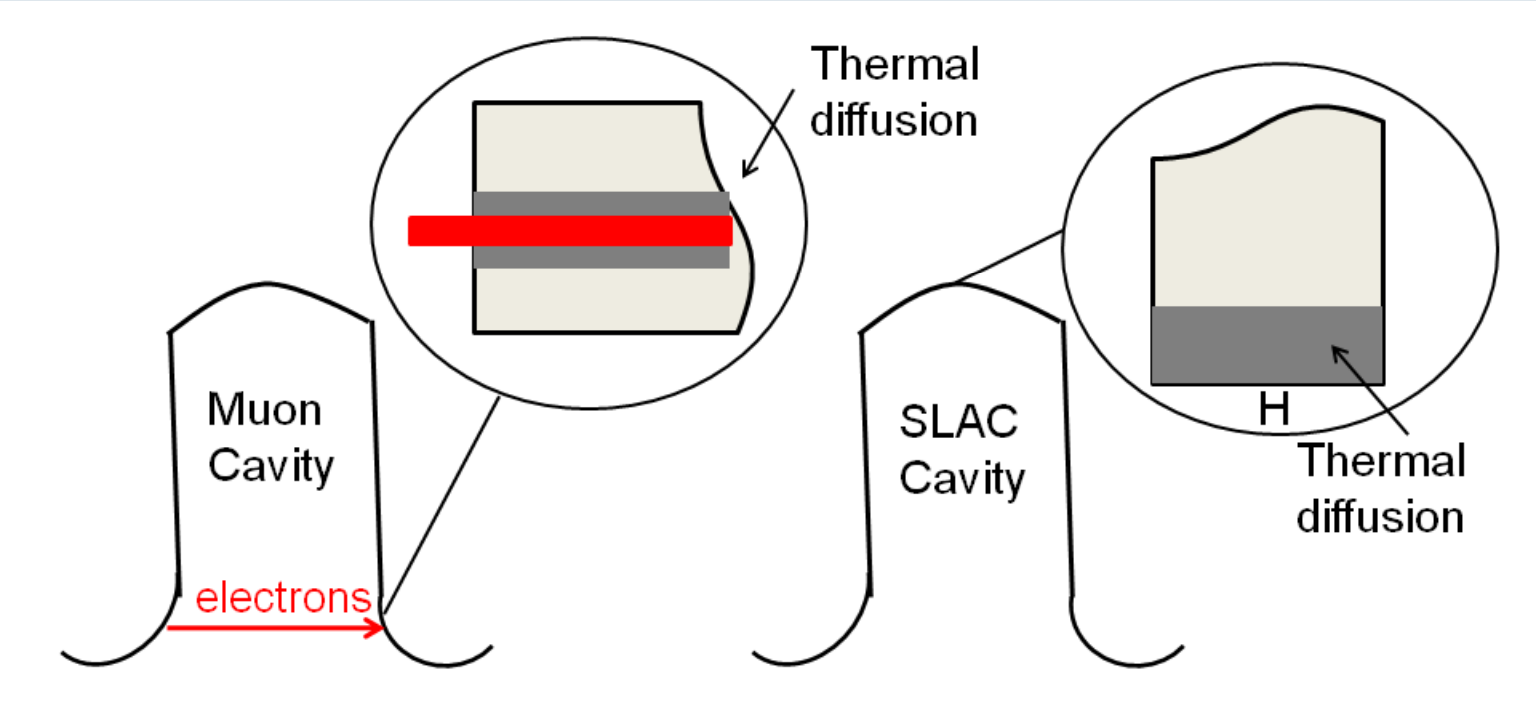


Beryllium, Be

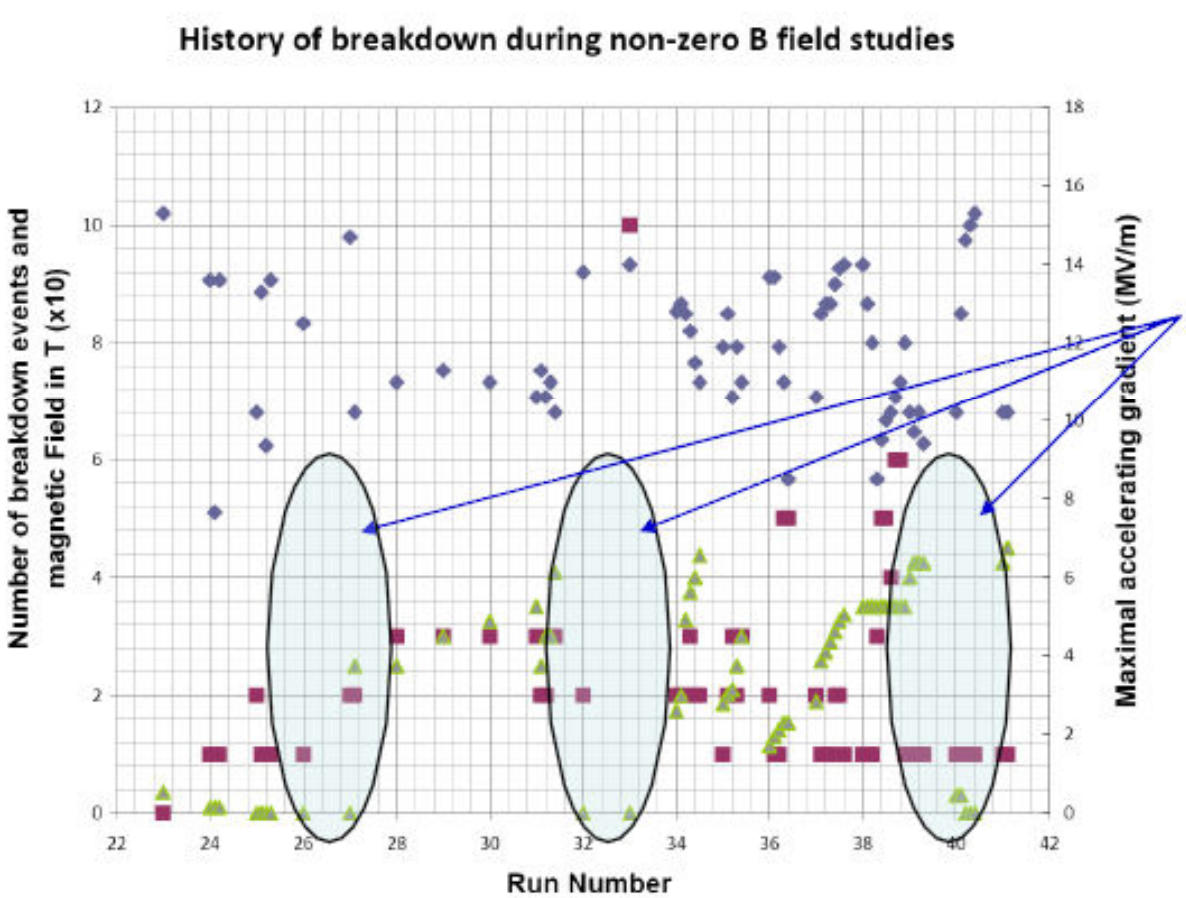


- Note that electrons penetrate deep in Beryllium
- Thus, less surface temperature rise would be expected.

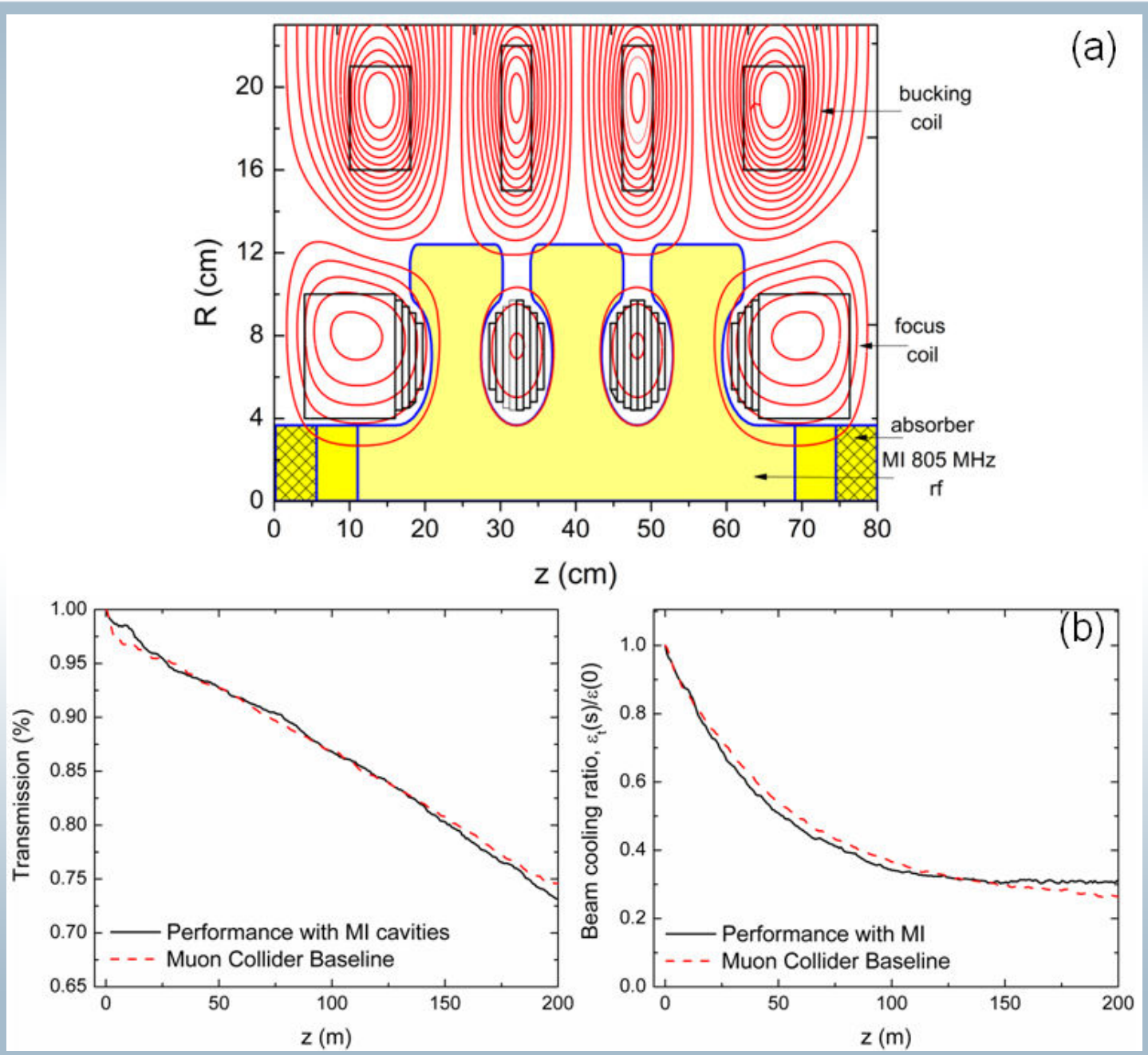
Common link between the two mechanisms

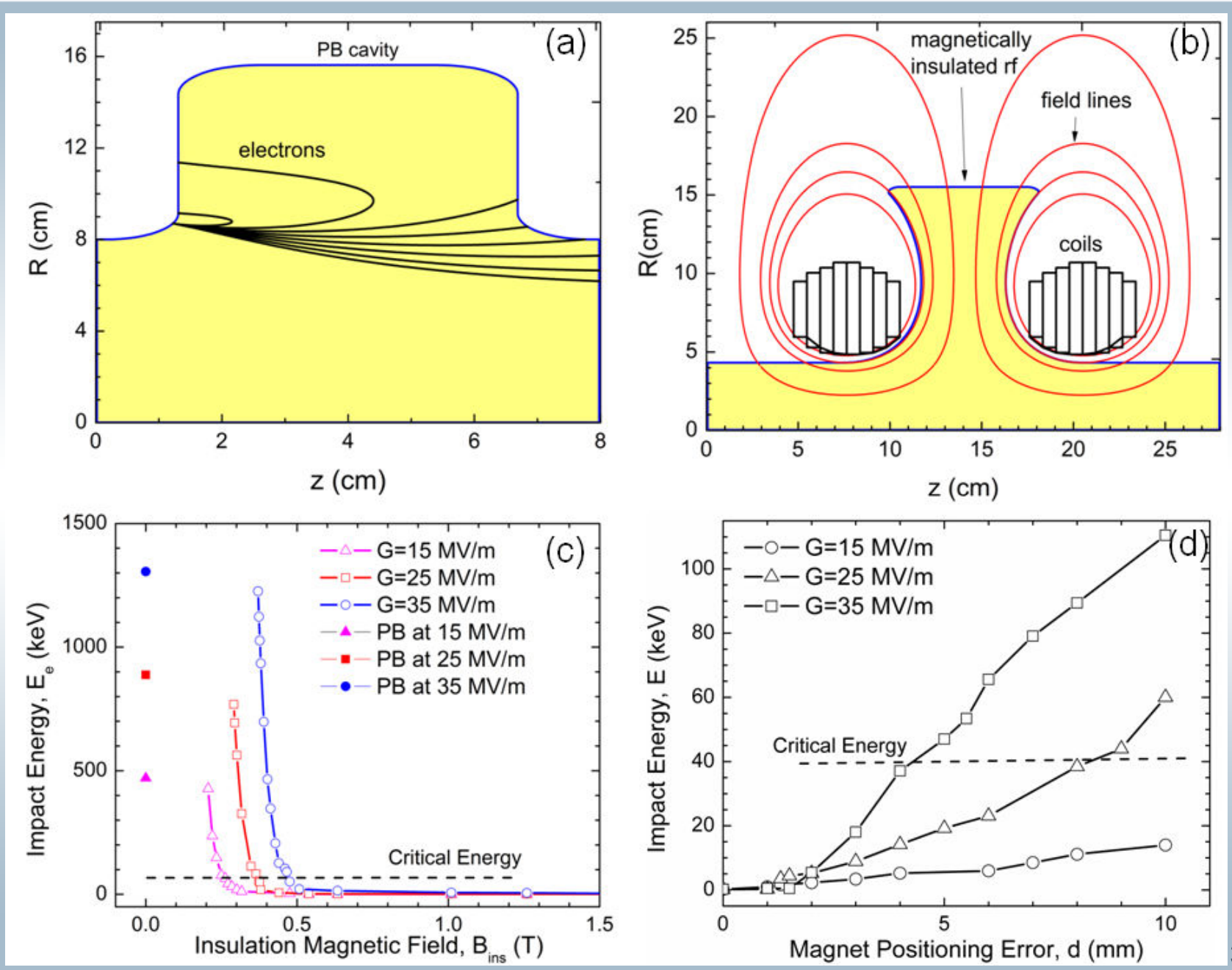


201 MHz: curved Be window test (B≠0)

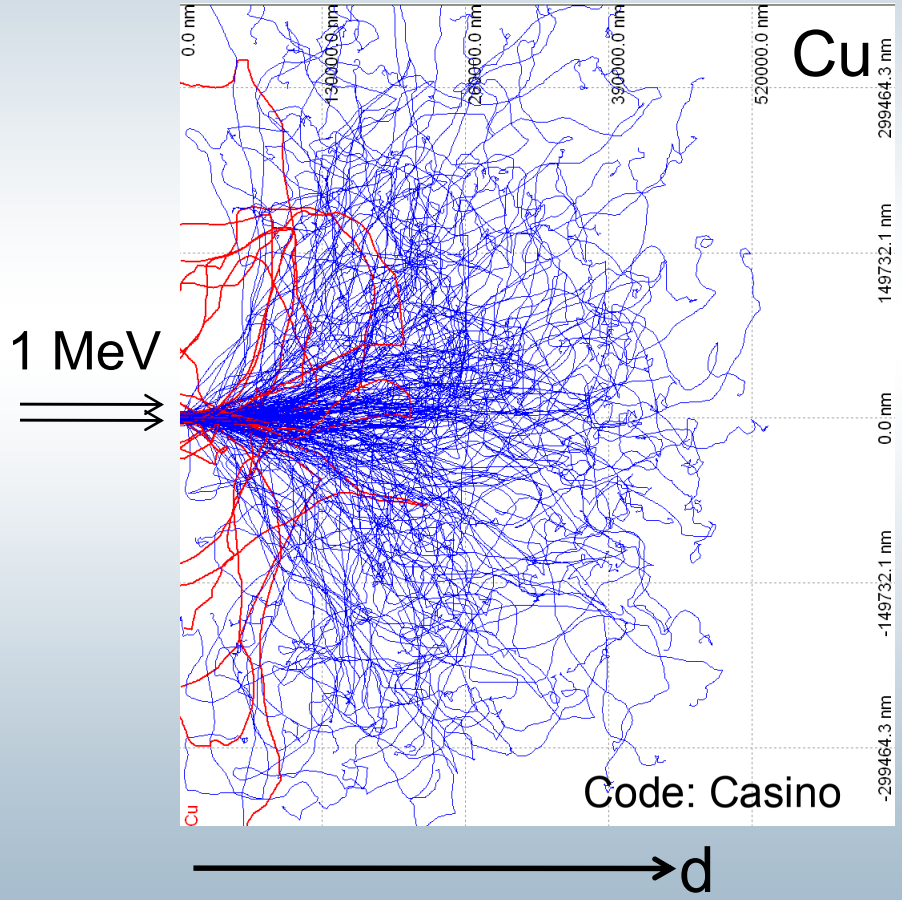


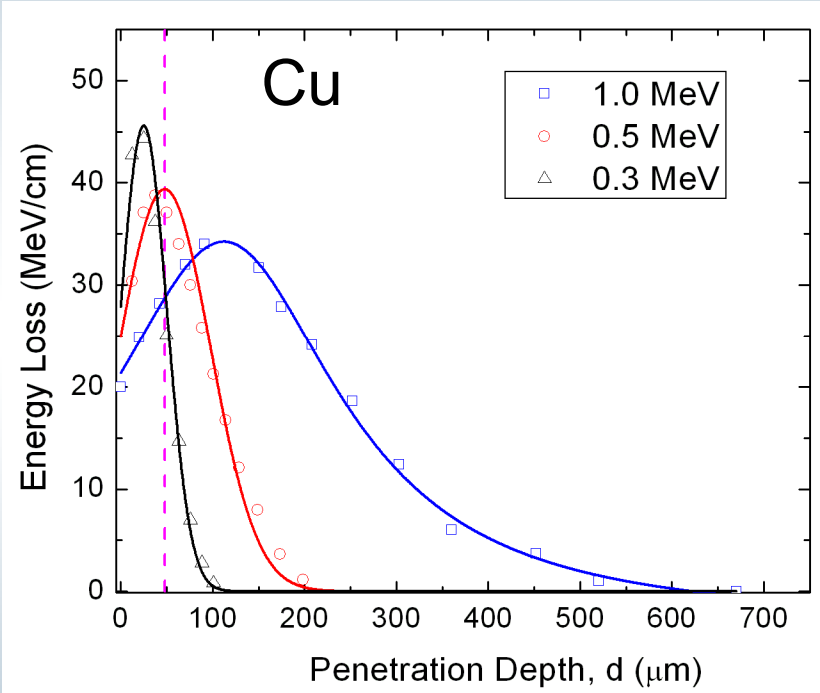
- Conditioning: a breakdown event may generate more field emitters and radiation level goes high. Thus we reduce magnetic field back to zero, and recondition the cavity to remove those field emitters in order to measure the accurate M.S.O.G. in magnetic field later on.


(a)
bucking coil
focus coil
absorber
MI 805 MHz rf
R (cm)
z (cm)
(b)
Transmission (%)
Performance with MI cavities
Muon Collider Baseline
z (m)
Beam cooling ratio, $\varepsilon_t(s)/\varepsilon(0)$
Performance with MI
Muon Collider Baseline
z (m)


(a)
PB cavity
electrons
R (cm)
z (cm)
(b)
magnetically insulated rf
field lines
coils
R(cm)
z (cm)
(c)
G=15 MV/m
G=25 MV/m
G=35 MV/m
PB at 15 MV/m
PB at 25 MV/m
PB at 35 MV/m
Critical Energy
Impact Energy, E_e (keV)
Insulation Magnetic Field, B_{ins} (T)
(d)
G=15 MV/m
G=25 MV/m
G=35 MV/m
Critical Energy
Impact Energy, E (keV)
Magnet Positioning Error, d (mm)

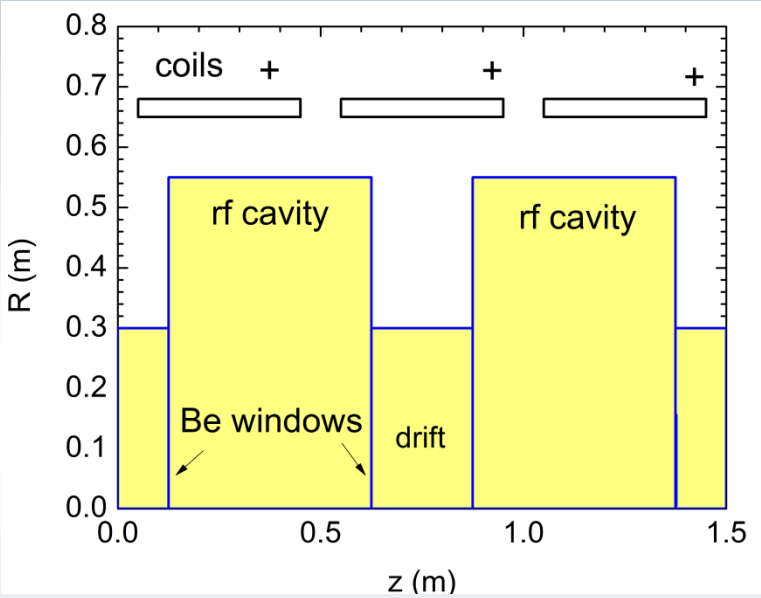
Step 2: Electron penetration in metal

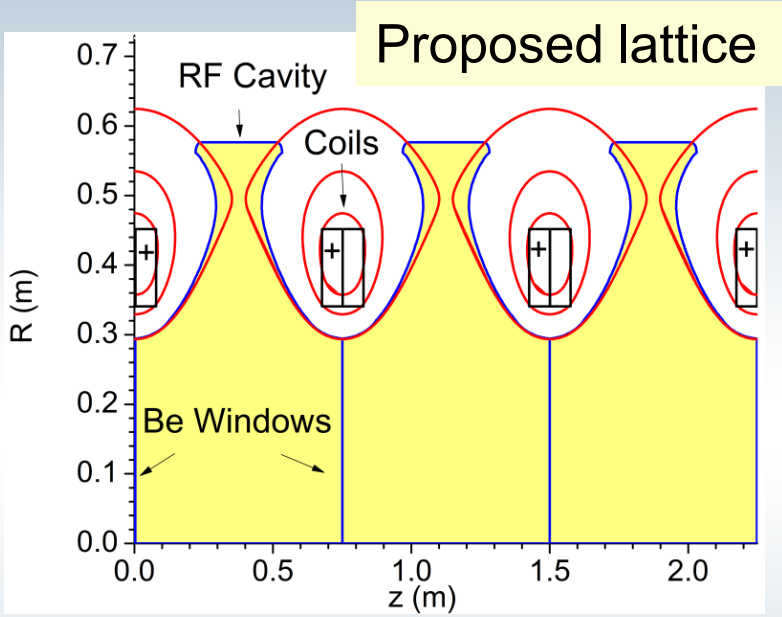




Scatters: Sandia Report 79-0414 (1987)

FE buncher and rotator sections





- Coils are brought closer to axis.
- Field lines become parallel to the cavity's surfaces at high-gradient locations
- Some concern about "unprotected" areas in Be-windows.