RF Breakdown with and without external magnetic fields

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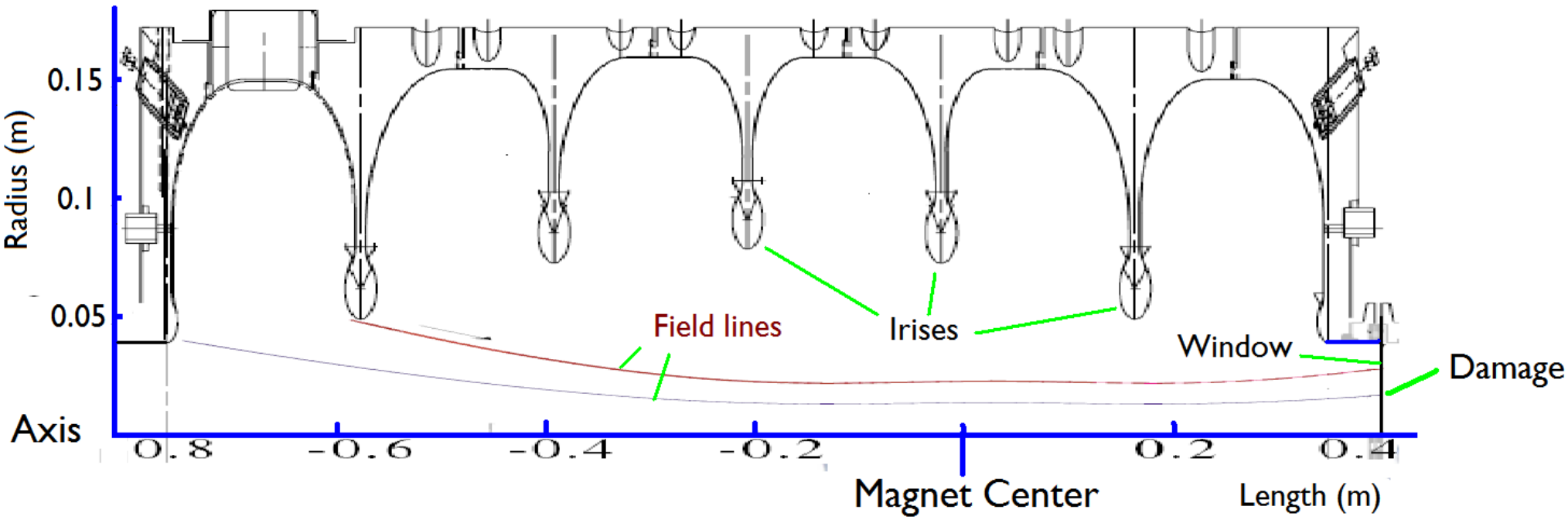
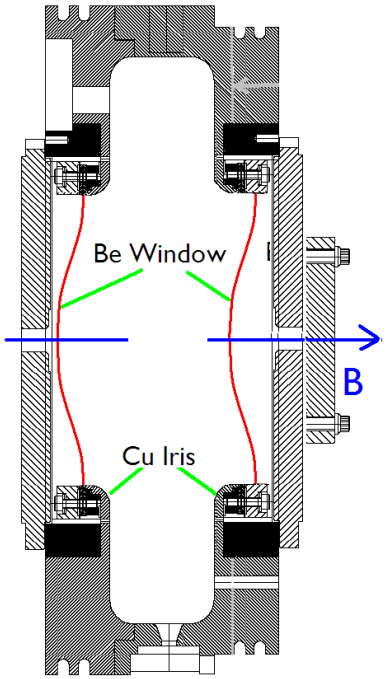
- Experiments
- Models for breakdown without magnetic fields
- Models with magnetic fields
- Implications for MICE
- How to study these effects
- Conclusion

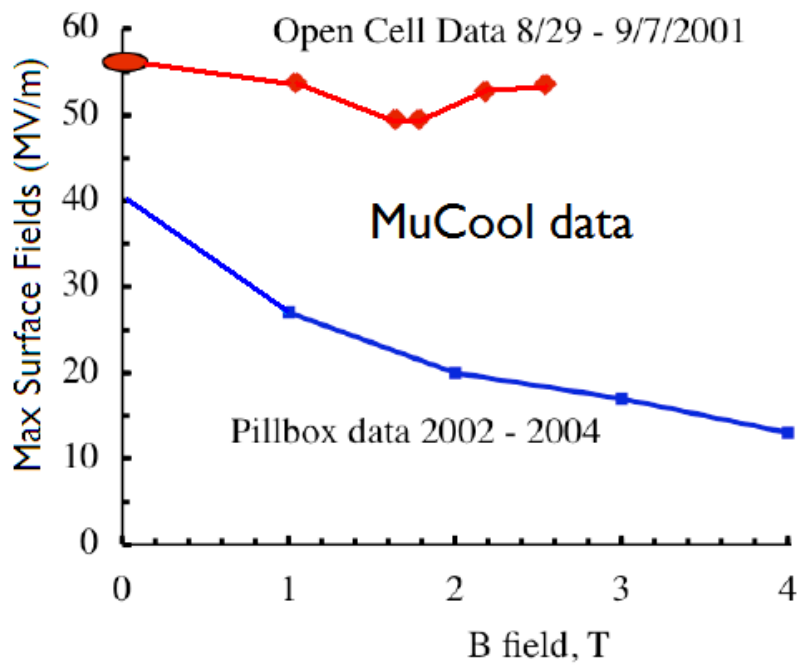
805 MHz multi cell cavity in 4.5 T solenoid



- We know a focus dark current can damage a 10 mill Ti window
- And, under some fields, there can be no effect on max gradient
- This field asymmetric & did not link high gradient to high gradient
- Maximum gradient $\approx$ 50 MV/m $\beta_{FN} \approx 180$

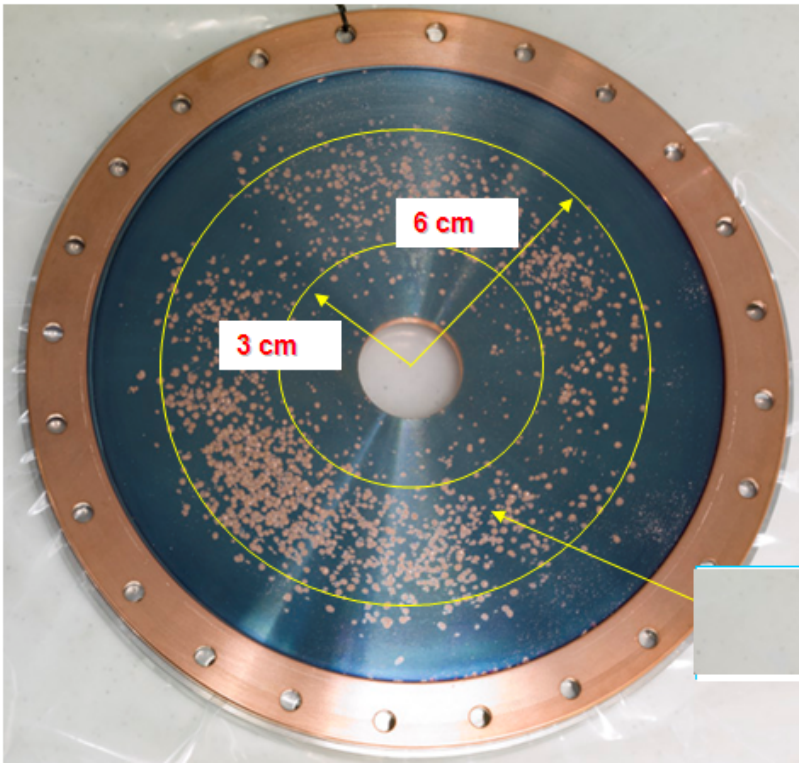
805 MHz Pillbox cavity in 4.5 T solenoid

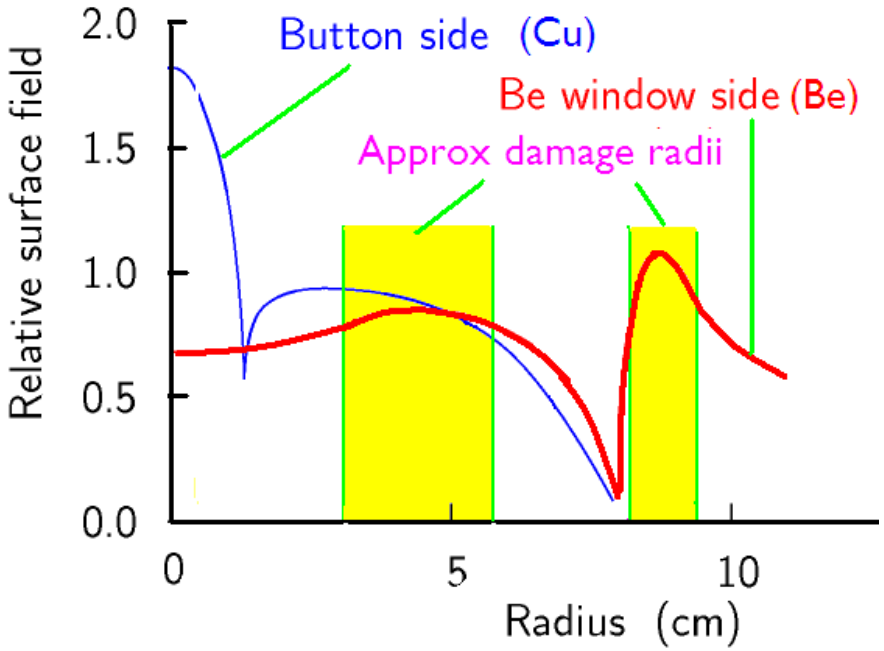




- We know, with field lines joining iris to iris, gradient are reduced
- Since there was no reduction with a different field geometry:
  this effect must be a function of the geometry
  NOT a local effect at an emitter

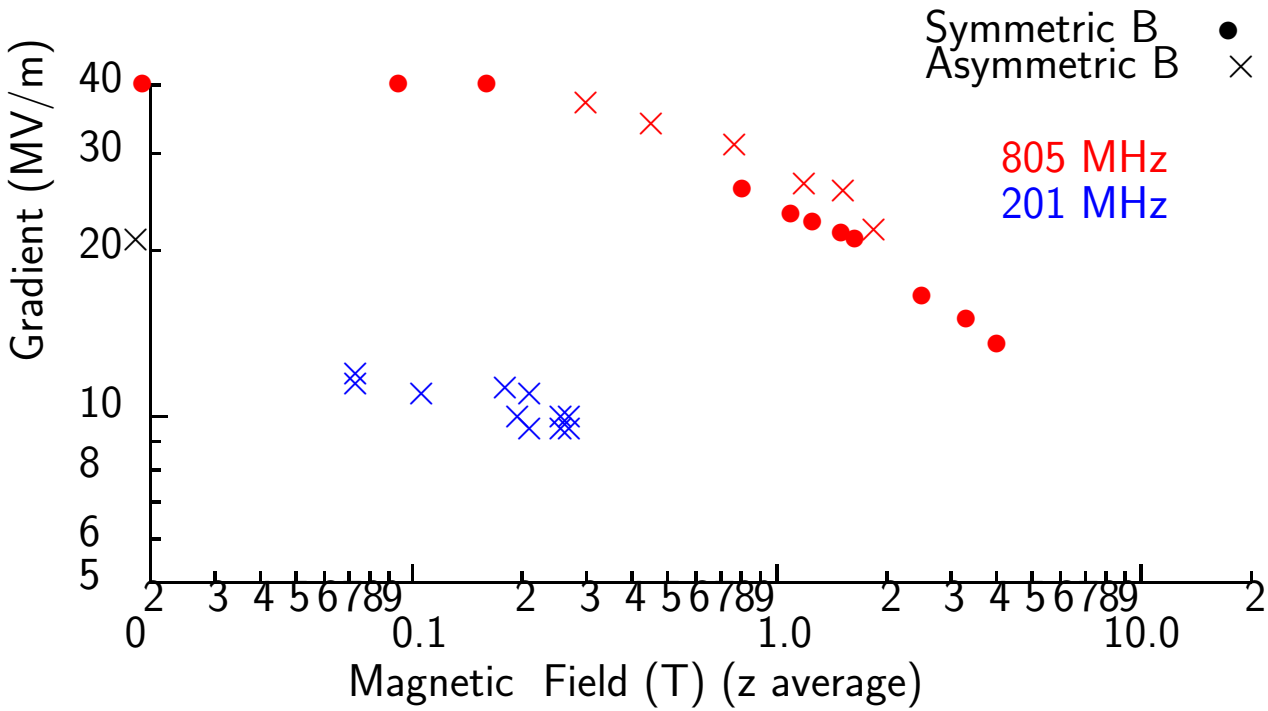
805 MHz button experiment





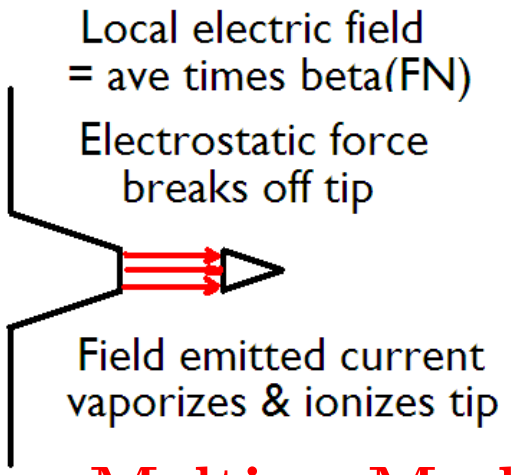
- Focused beams from an undamaged Be window can make visible damage on a Cu plate
- And this occurs opposite a maximum gradient on the Be
  NOT a maximum gradient on the Cu

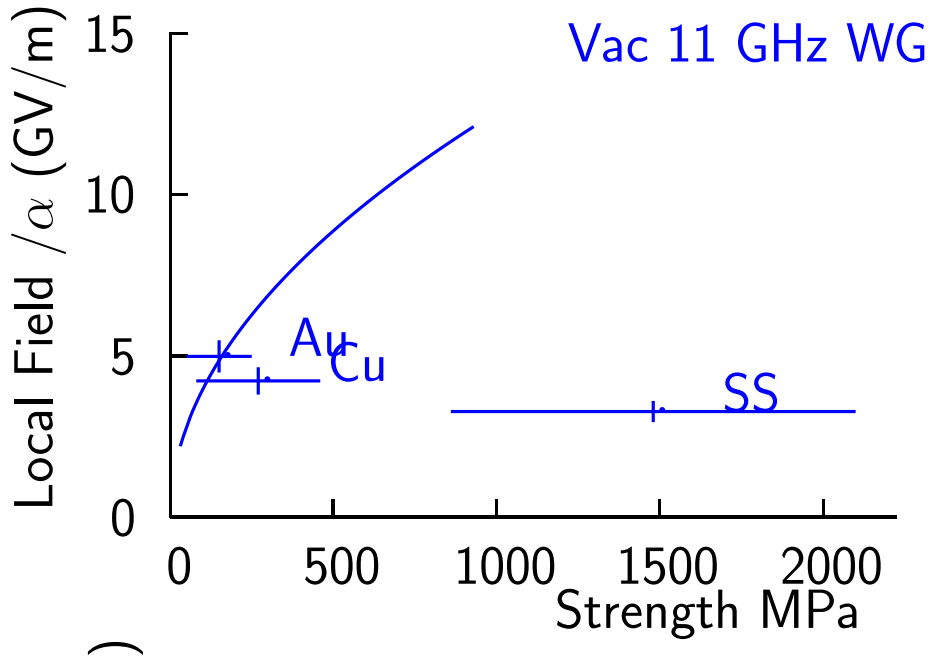
201 MHz near 4.5 T solenoid



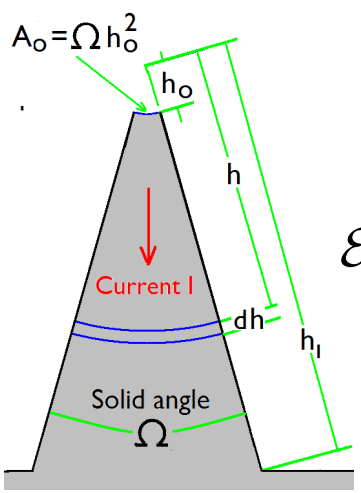
- Without magnetic field, initial gradients ($\geq$21 MV/m)
  Consistent with 805 data scaled $\propto \sqrt{f}$: β_{FN} 183 $\rightarrow$ 366
- With magnetic field, $\mathcal{E} \approx$ 10 MV/m: down another factor of 2
- Without field, after runs with B, max grad $\mathcal{E} \approx$ 15 MV/m (conditioned up to 18 MV/m)
- Presumably, runs with B raised β_{FN} 366 $\rightarrow$ 600

Fracture Model

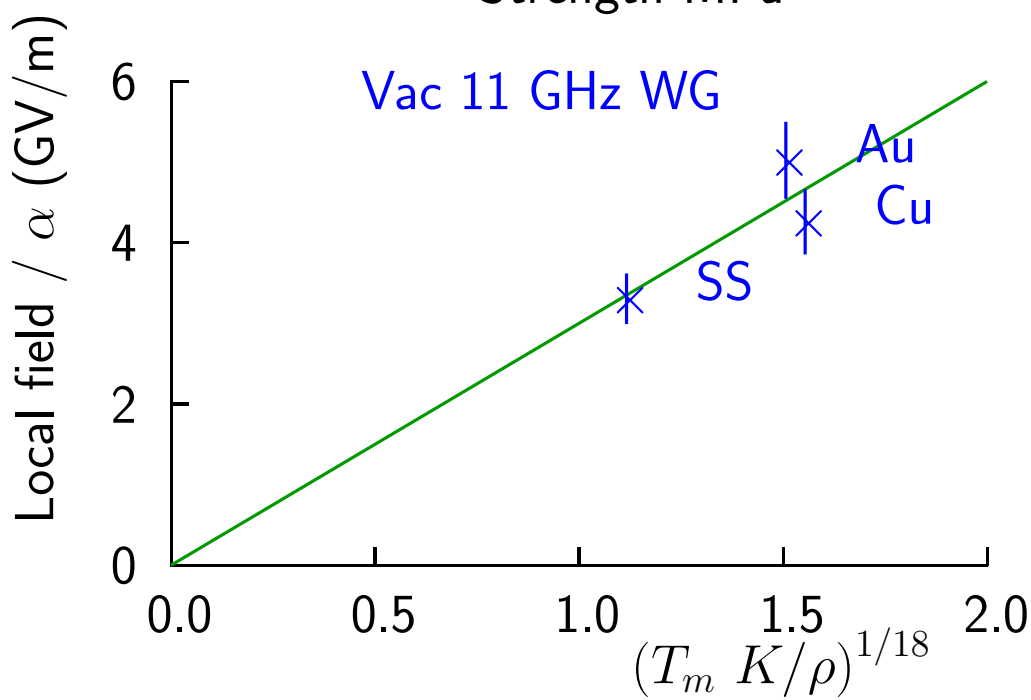




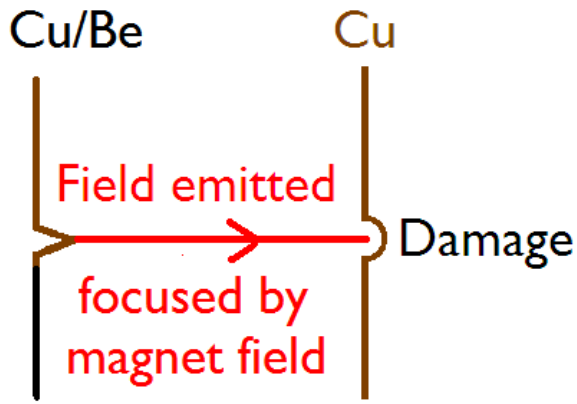
Melting Model



$$\mathcal{E}_{\rm local} \propto \left(\frac{\rm K\ T_m}{\rho}\right)^{1/20}$$



Proposed mechanism in magnetic fields

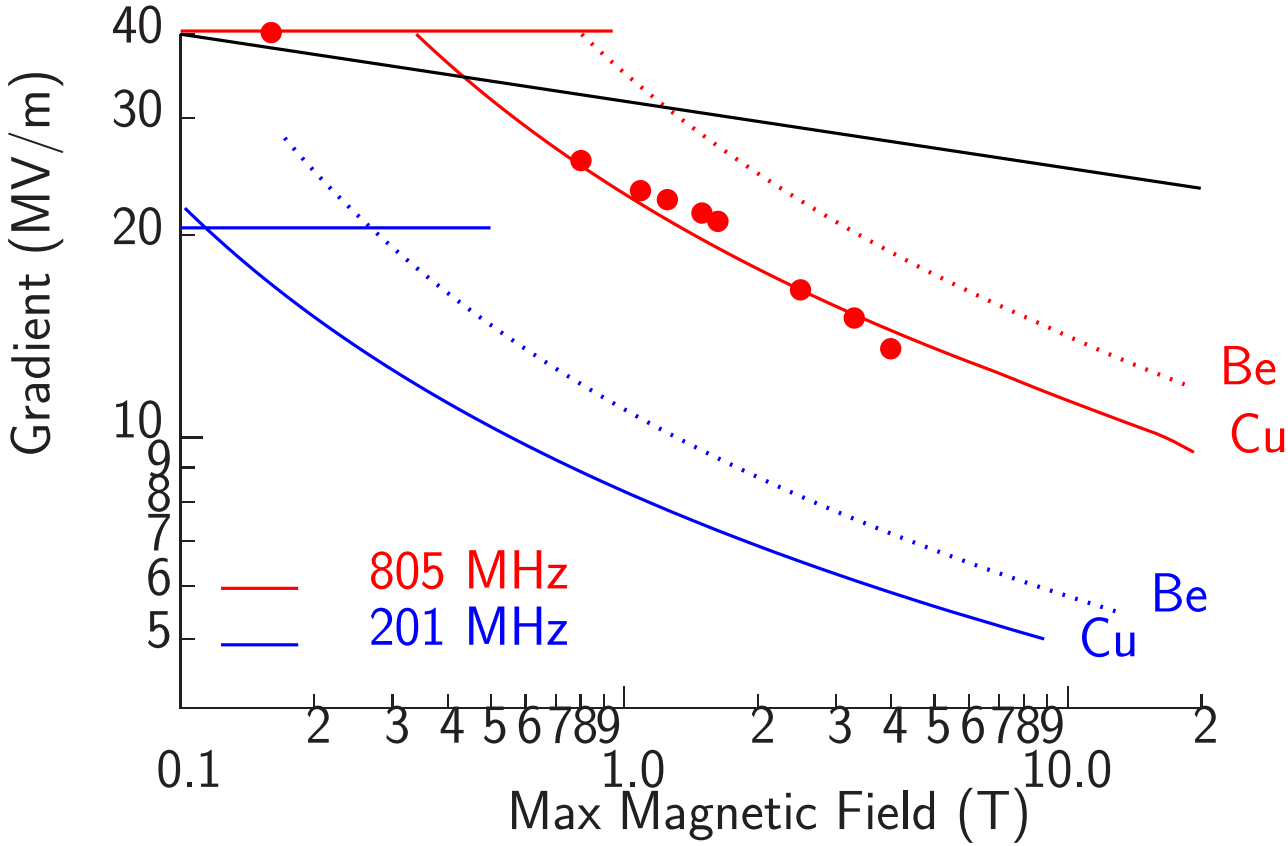


1. "Dark Current" electrons accelerated and focused by magnetic field
2. Beamlet radius from space charge and focus: $\propto I^j/B$
3. Fraction of energy deposited in diffusion length = Q
4. Calculate B that will melt on arrival
5. If on a location with high surface rf gradient: breakdown
6. If not, no breakdown, but damage

$$B \propto \sqrt{\frac{1}{I^{(1-2j)}\ \mathcal{E}_{\mathrm{e}}}\left(\frac{\delta\ \rho\ C_s\ T_m}{\tau\ Q}\right)}$$

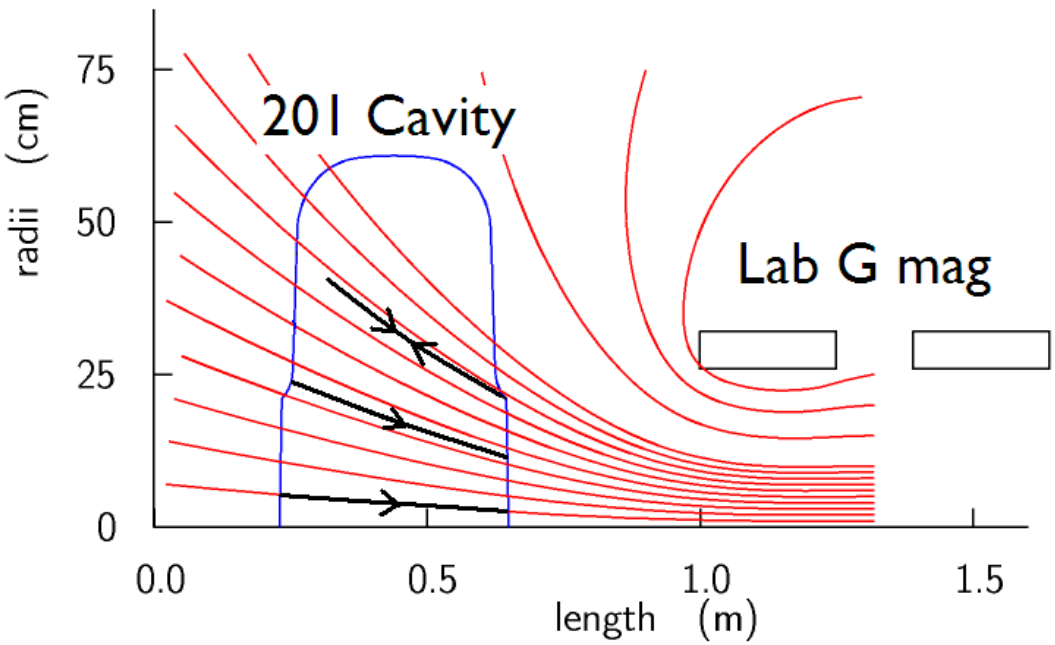
Fit to early pillbox data and prediction for 201 MHz

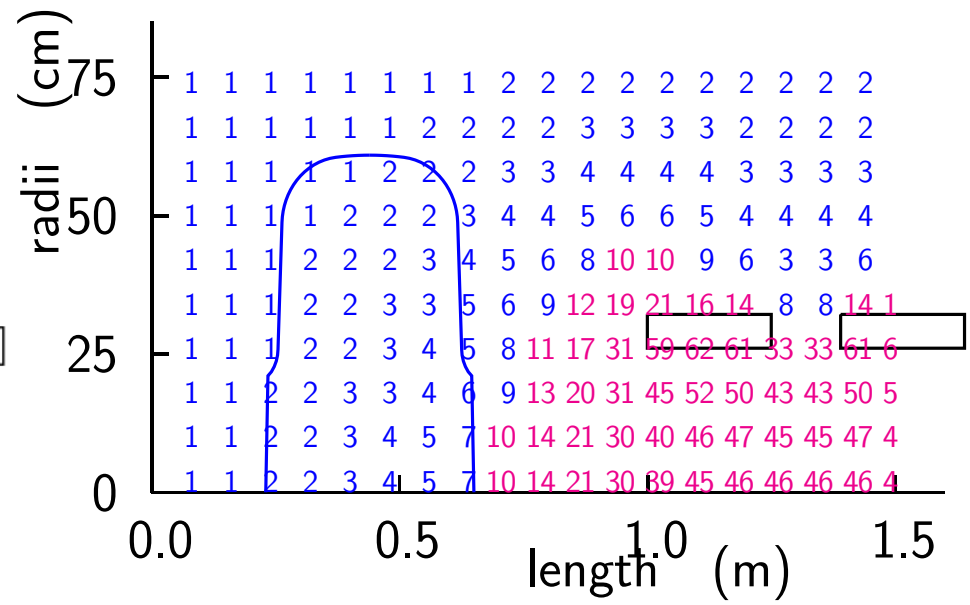
This is for symmetric cases



- Assumed β_{FN} =180 for 805 MHz
- Fit gave $j = 0.35$
- Assumed β_{FN} =360 for 201 MHz
  i.e. assume same local field of 7 GV/m

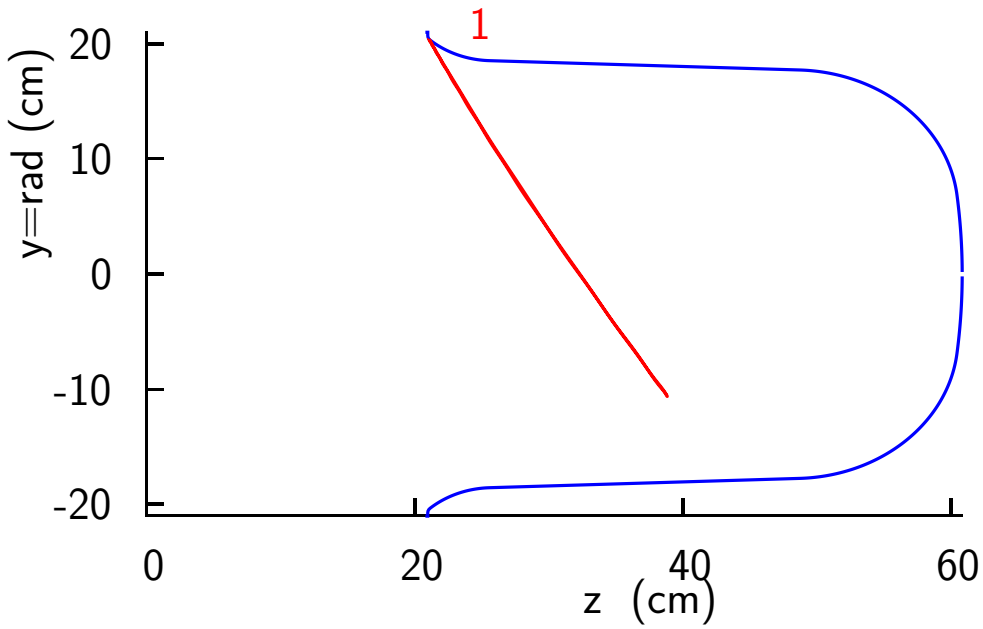
Simulation of current 201 MHz MTA exp

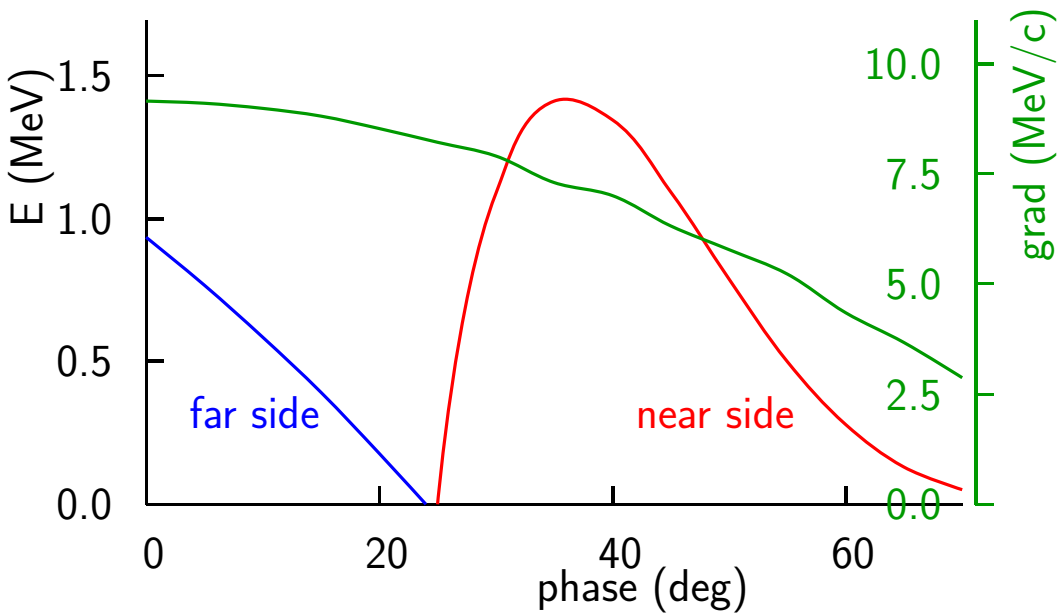




- Field lines do not link high gradient locations
- Fields very low: 0.3 T at center (0.15 to 0.65 T)
- Damage likely only on high field (right) side
- On Be window, from left iris or other window, or
- On right iris from returning electrons

Trajectories vs. phase



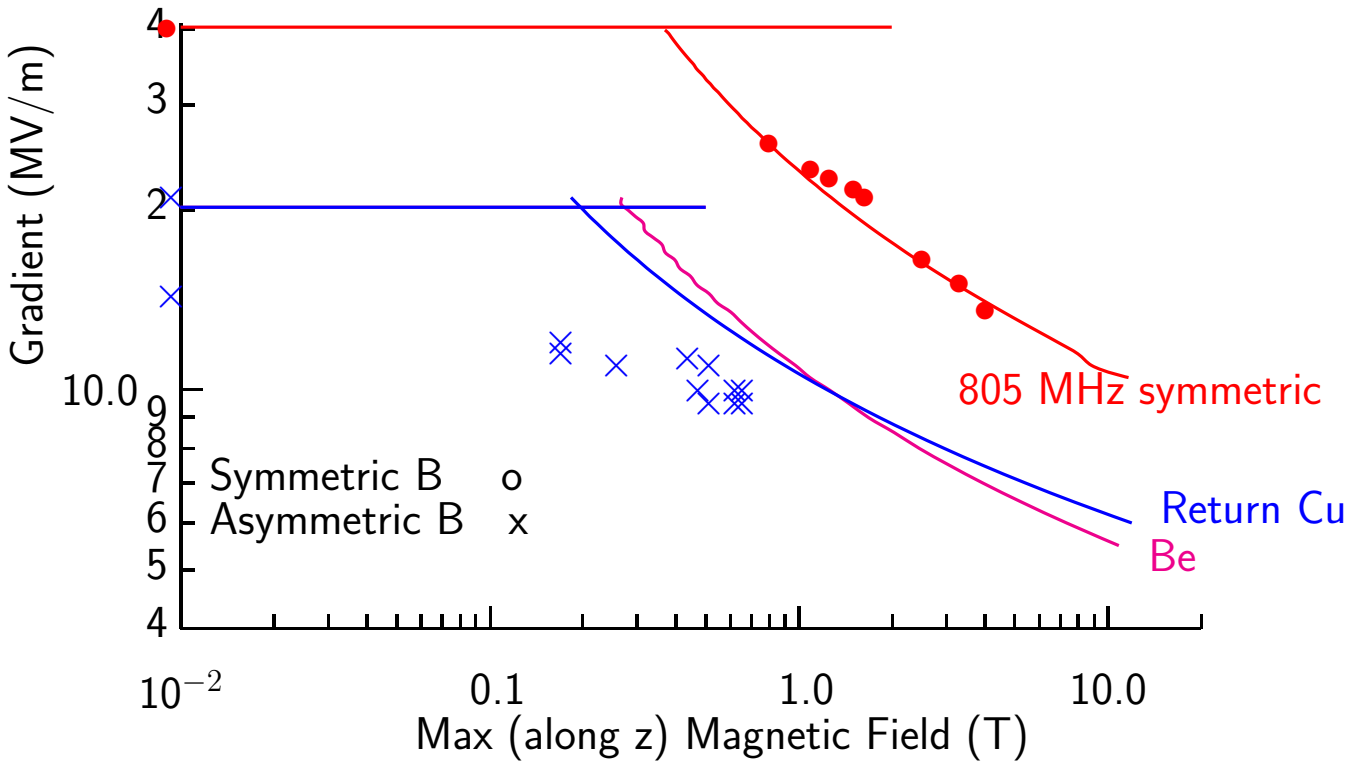


- Program now allows for angle of incidence
- Range energy of electrons corrected
- CAVEL study at B_o=4.5 T & $\mathcal{E}$ =10 MV/m
- Scaling to other gradients

- Relevant magnetic field is now the maximum along z, where the electrons hit a surface

Scaling from 201 MHz

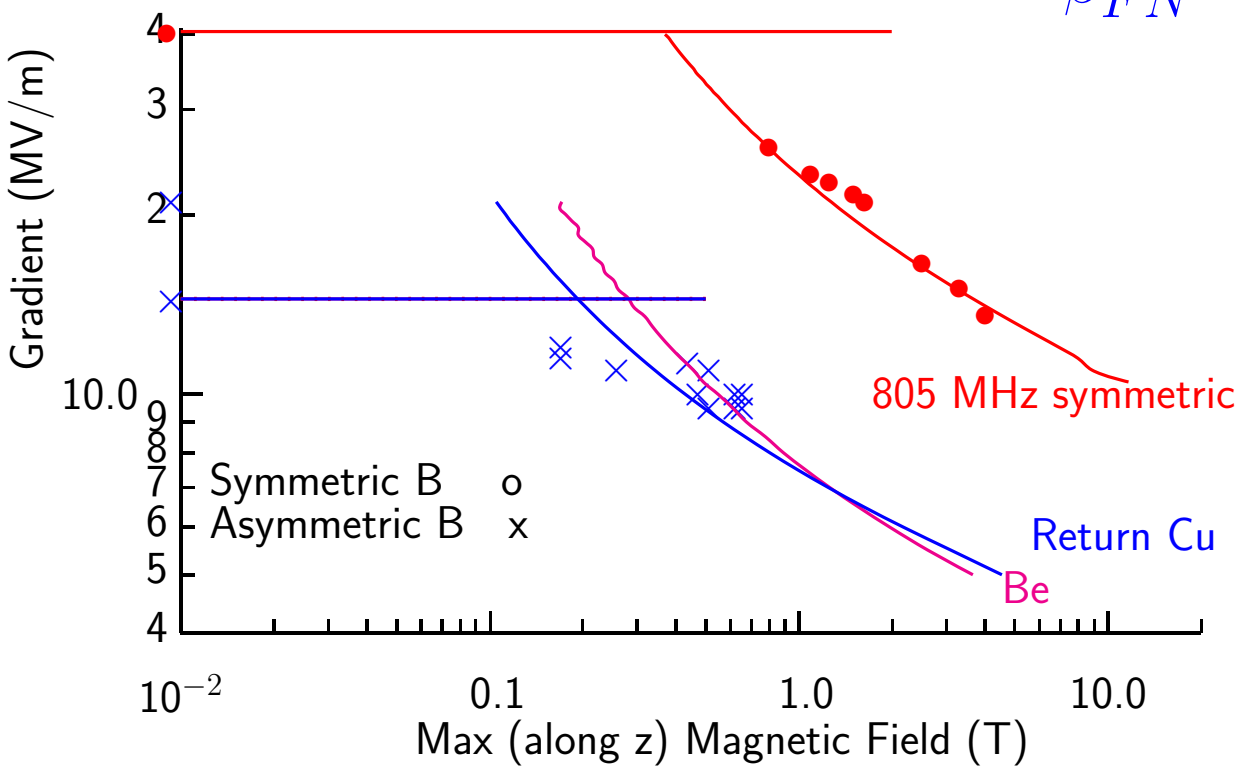
$$\beta_{FN} = 183 \times \sqrt{\frac{201}{805}} = 366$$



- Used $\beta_{FN} \propto 1/\sqrt{f}$ consistent with initial B=0 $\mathcal{E}$ =21 MV/m
- Does not explain data at 201 MHz with B
- But after running with 201 only $\mathcal{E}$ = 15 MV/m at B=0
- So damage had increased β_{FN} by 21/15

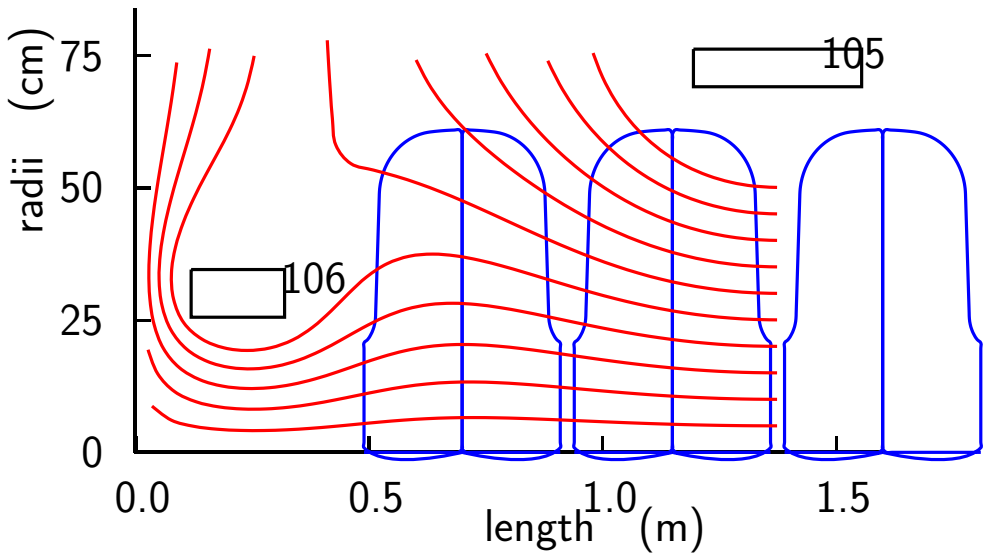
With increased β_{FN} from damage

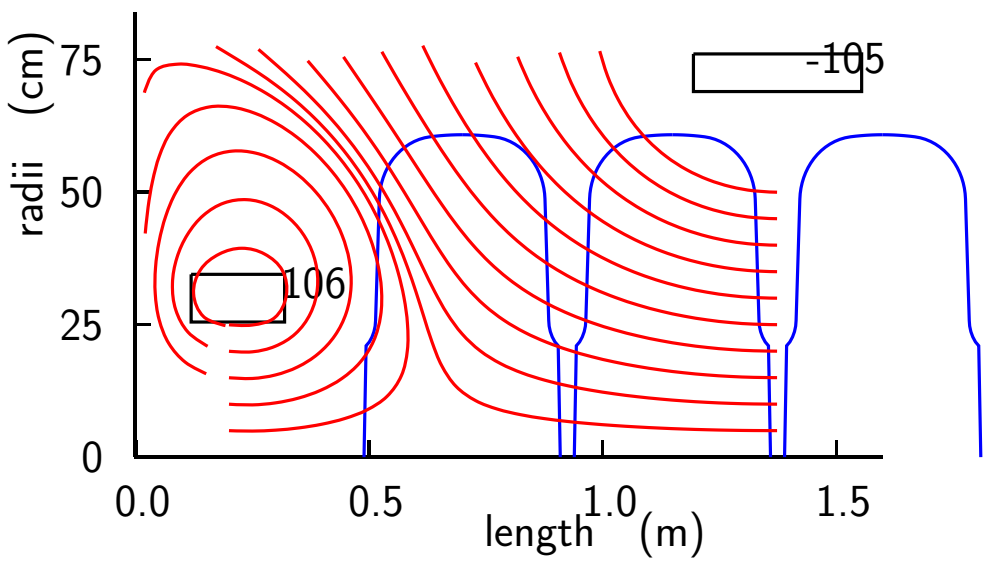
$$\beta_{FN} = \frac{21}{15}\,366 = 512$$



- Models now agrees with data within plausible errors
- Problem could be either
  - Returning electrons from an iris, or
  - Electrons from iris or window damaging the Be

Relevance to MICE

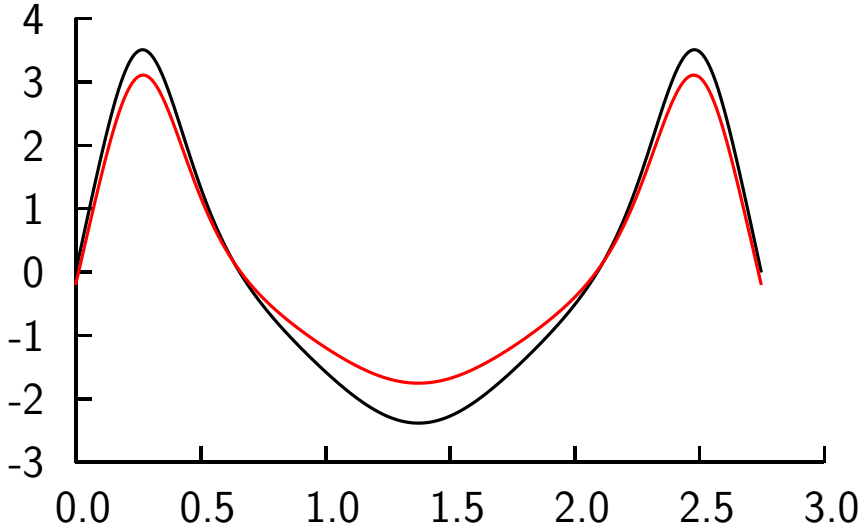


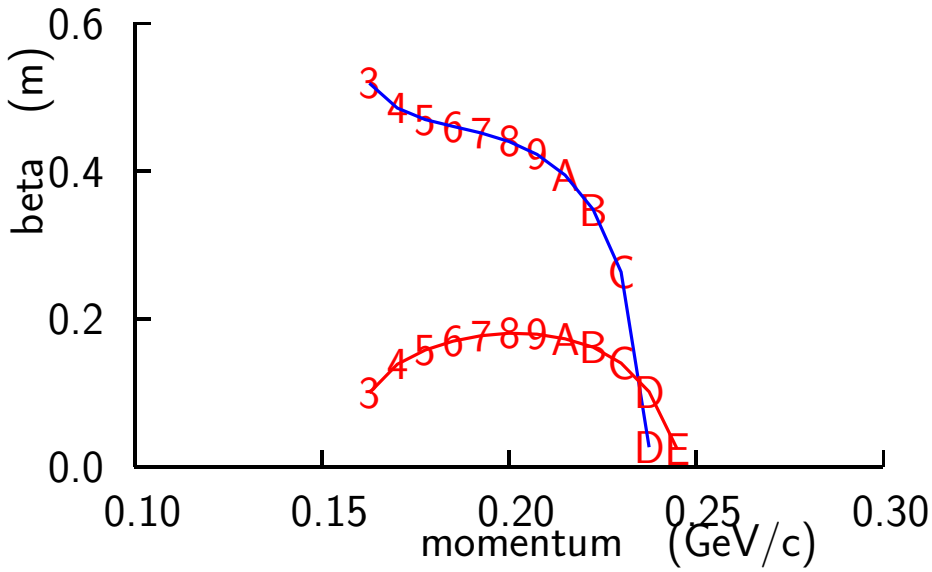


- Fields are NOT strongly divergent as in MTA
- Maximum gradients without damage from slide 8
  At B≈ 2 T: $\mathcal{E} \approx 7$ MV/m
- But with damage as in MTA: $\mathcal{E} \approx 5$ MV/m

- Possible saftey problem: beamlets passing through Be windows damage Al hydrogen saftey window
- Problem relieved if coupling coil sign reversed
- But beamlet at exactly r=0 may be a problem

Can one find lattice solutions with reversal?





- Yes, but momentum acceptance somewaht reduced
- Note: lattice studied here is a continuous one, as used to define MICE in the first place. If this solution were chosen, the matching would have to be modified.

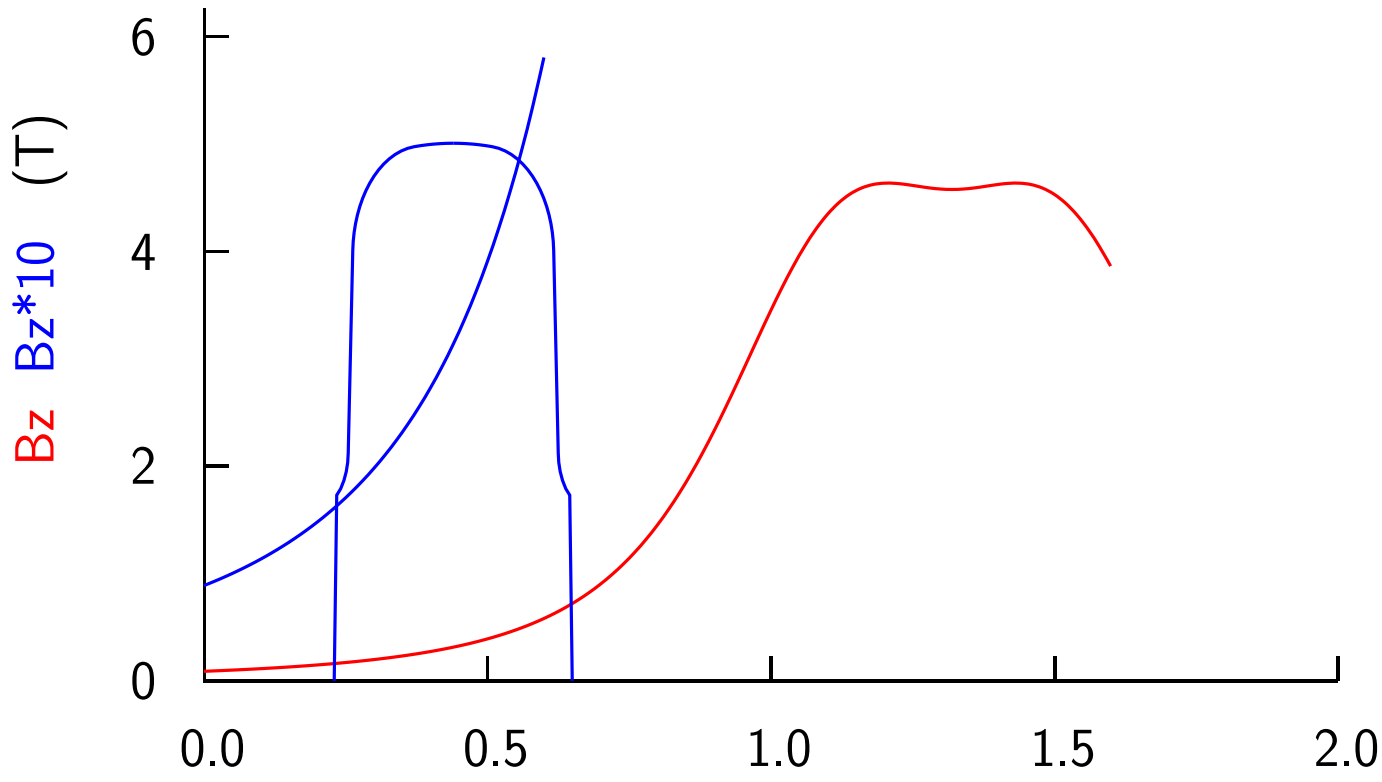
Conclusion

- Without magnetic field, melting model favored of fracture
- With magnetic field, damage by focused dark current can fit 805 MHz data

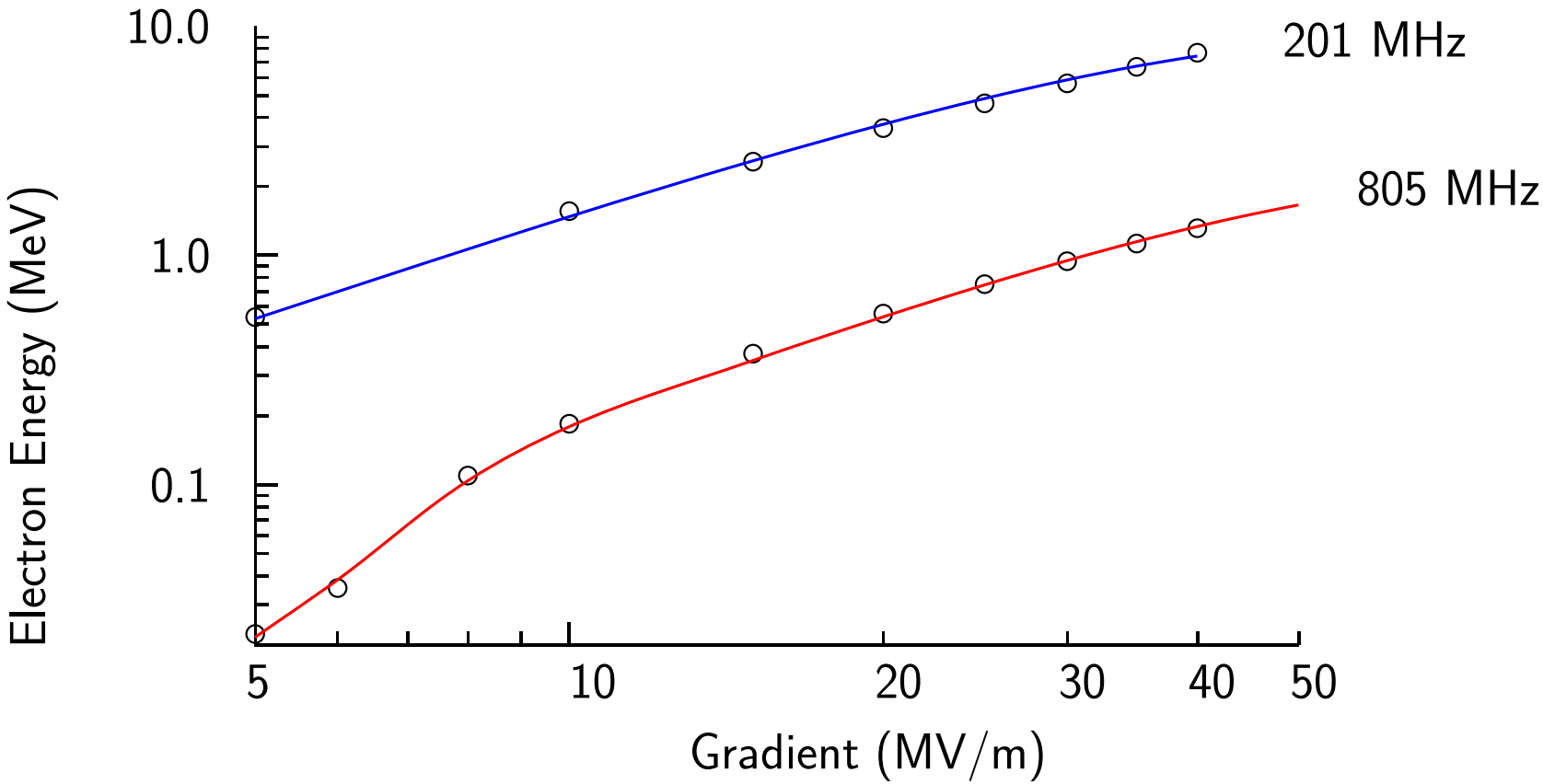
- 201 MHz without magnetic field $\mathcal{E}$=21 MV/m consitent with $\beta_{FN} \propto 1/\sqrt{f}$
- But with this beta the model does not fit data with magnetic fields

- If lower maximum gradient at B=0, after running with field, interpreted as increase in β_{FN} then reasonable agreement with finite B data is found

Appendix: Fields vs z



Appendix : Energy of electrons



Appendix 2: Range vs Energy

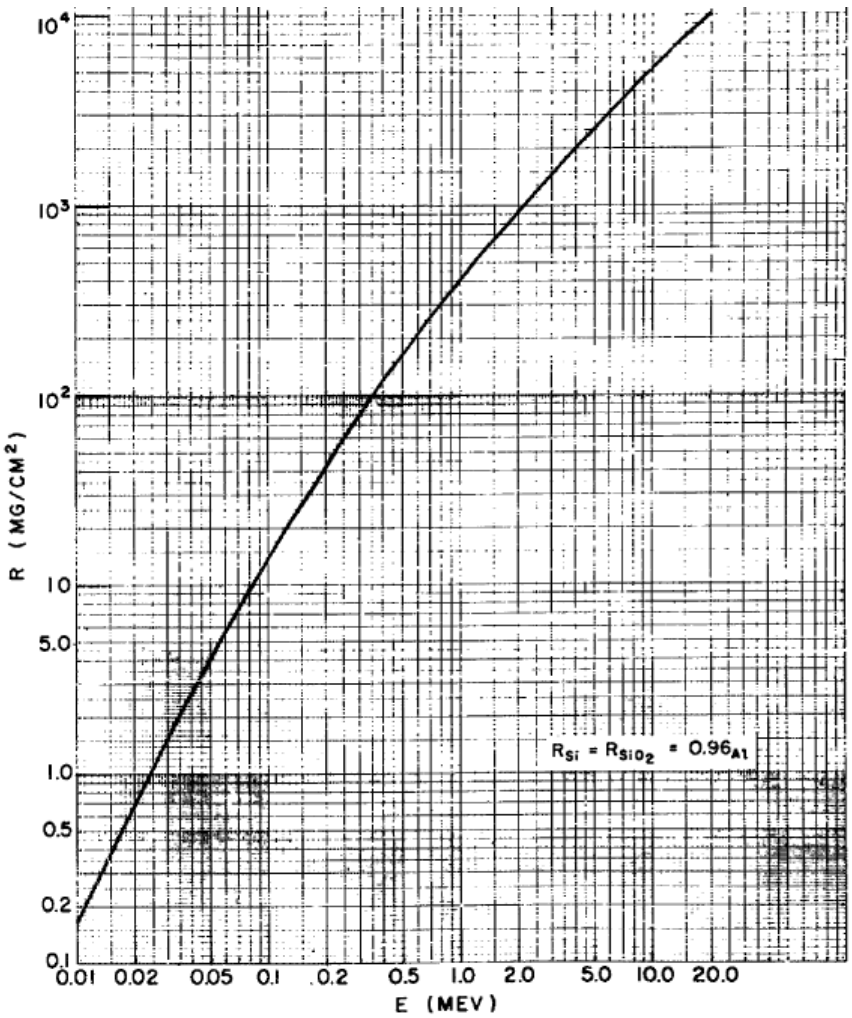


Fig. 5 - Range-energy relationship for electrons in aluminum (from Ref. 9)

Energy MeV	Cu range mm	Be range mm
.13	.02	.07
0.25	0.05	.2
.5	0.19	.76
1	0.44	1.76
4	2.2	8.8

Thermal diffusion depth

$$\tau_{201} = 200\mu\ sec \qquad \tau_{805} = 25\ \mu\ sec$$

$$\delta = \sqrt{\frac{2k\tau}{C_v}} = \sqrt{\frac{2\ 4.01\ \tau}{3.45}}$$

$$= 0.2\ \ (mm) \quad \text{for 201 MHz}$$

$$= 0.07\ \ (mm) \quad \text{for 805 MHz}$$

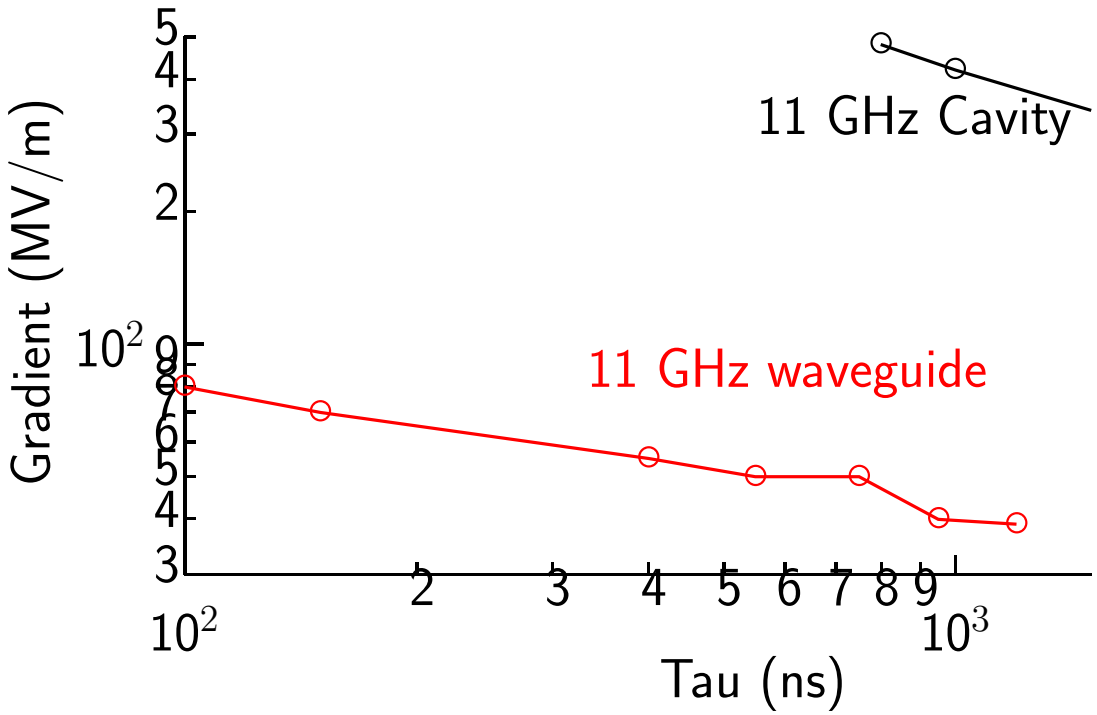
So $\approx$ .5 (.2) MeV bad at 201 MHz for Cu (Be)

So $\approx$ .3 (.13) MeV bad at 805 MHz for Cu (Be)

Be is better than Cu because the electrons go deep & dE/dx is less

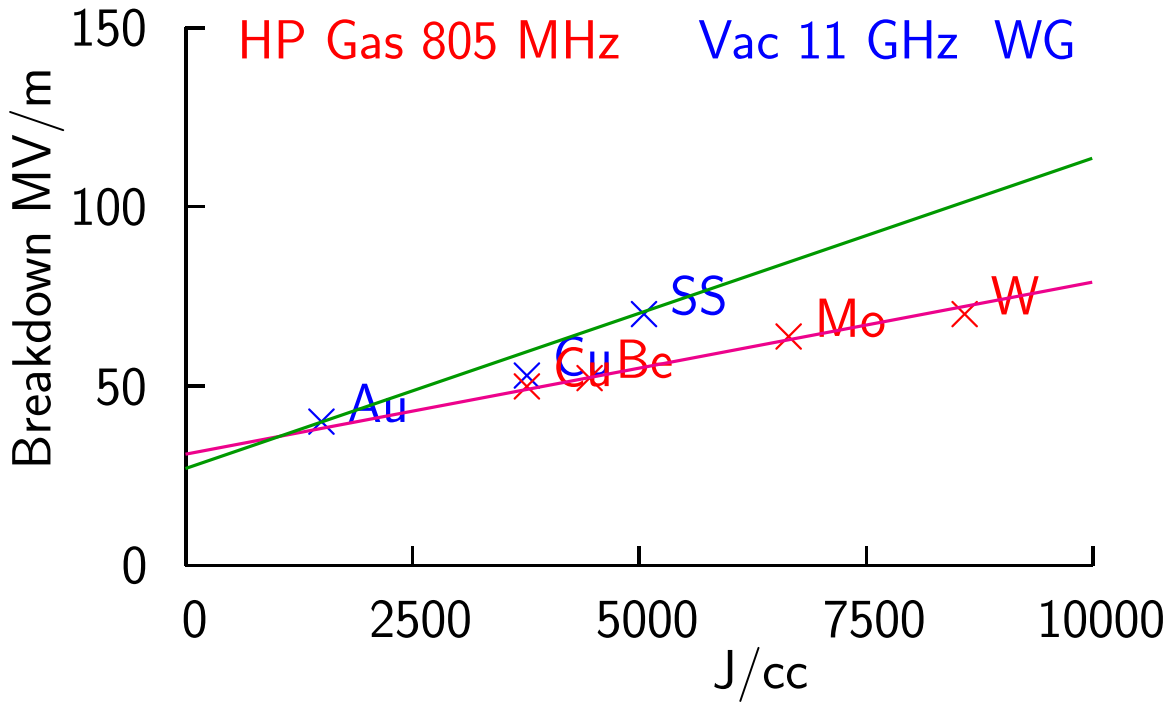
This needs a real simulation, the above is only a qualitative argument

Pulse length dependence



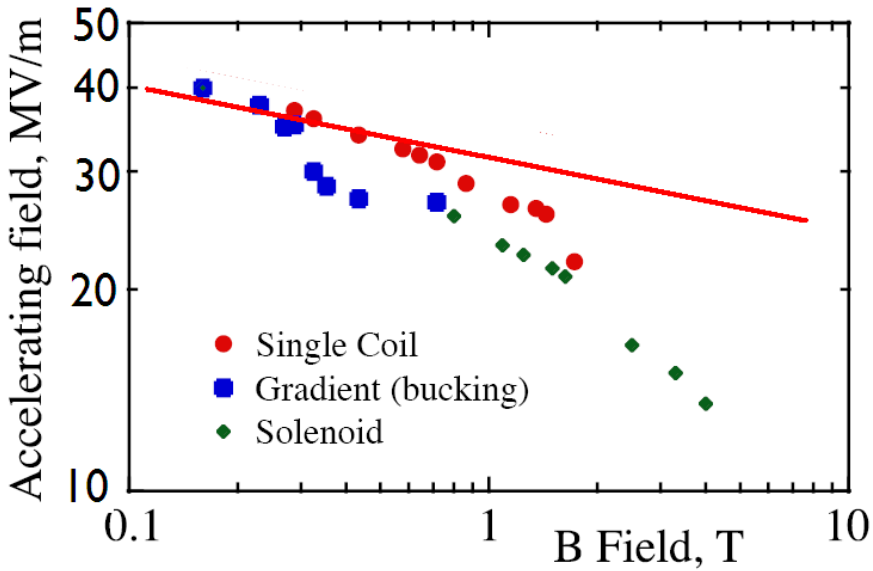
- more energy available with longer pulses
- do more damage on breakdown
- increasing β_{FN}

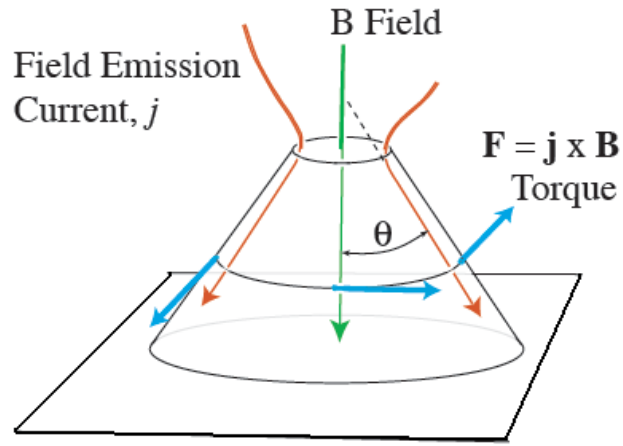
Material Dependence



- if less energy needed to melt
- more will be melted at breakdown
- doing more damage
- increasing β_{FN}

Twist model with external magnetic fields



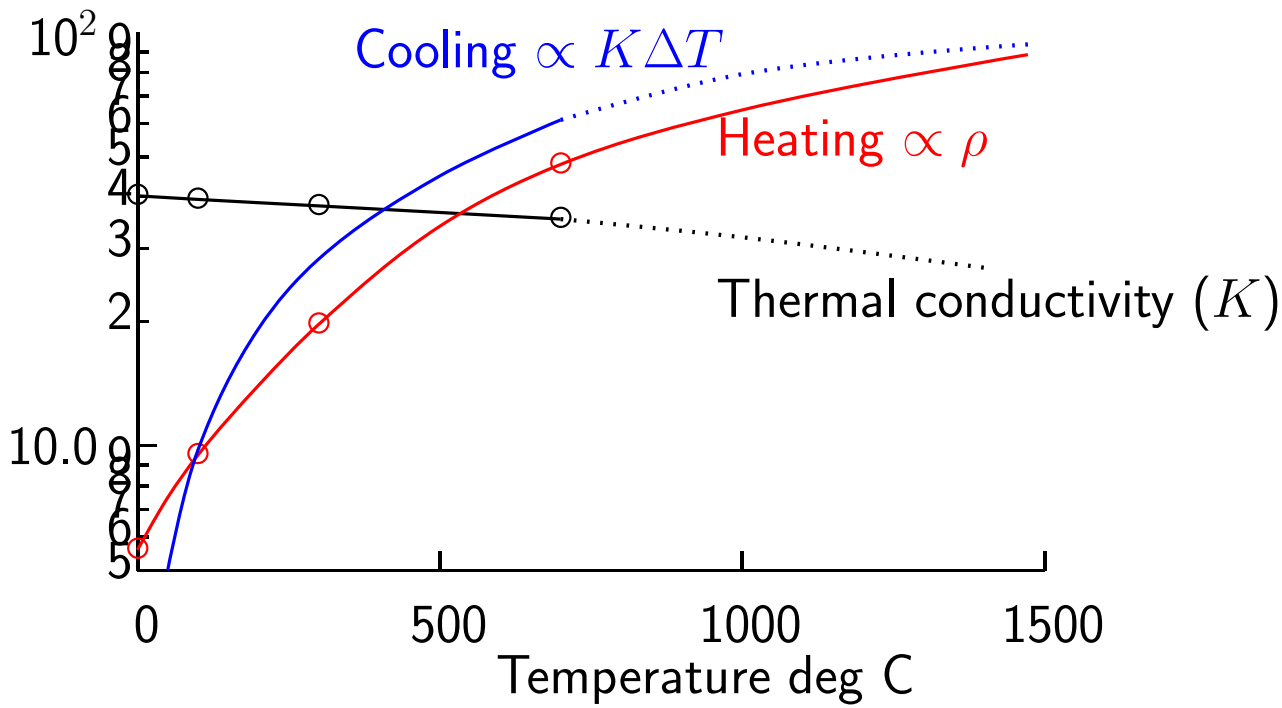


$$F \propto I \times B$$

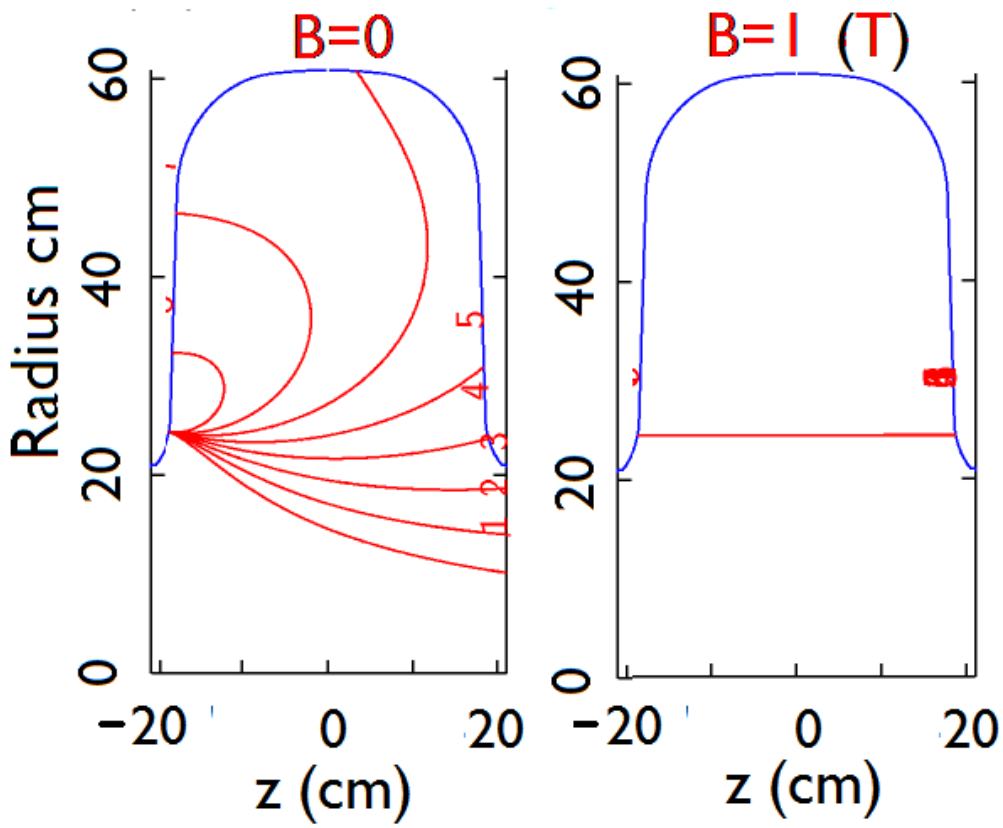
$$I \propto \mathcal{E}^{10}$$

$$\mathcal{E}_{\text{breakdown}} \propto \mathrm{B}^{-1/10}$$

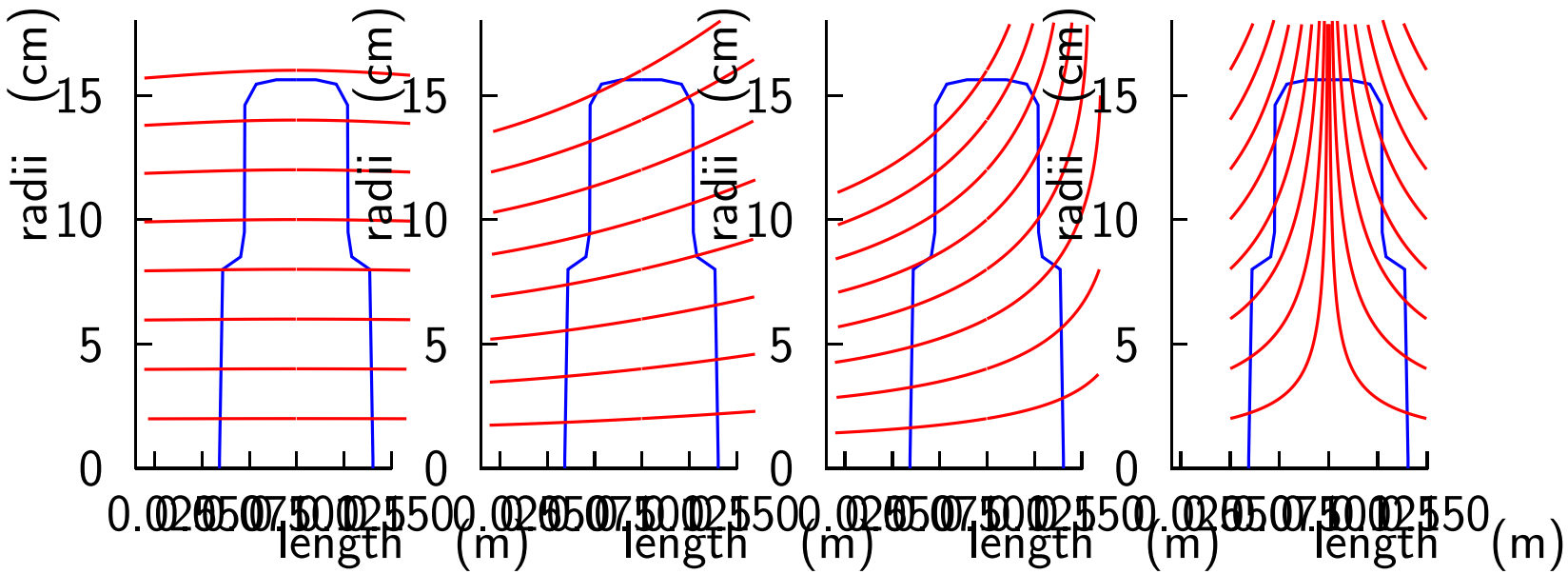
Thermal Runaway



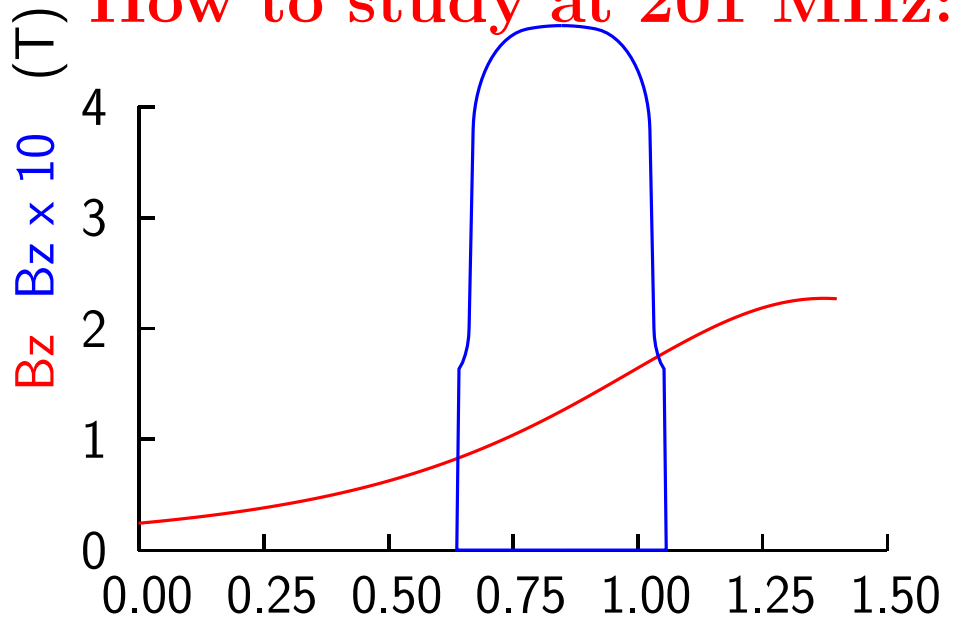
Returning electron model (Wilson)

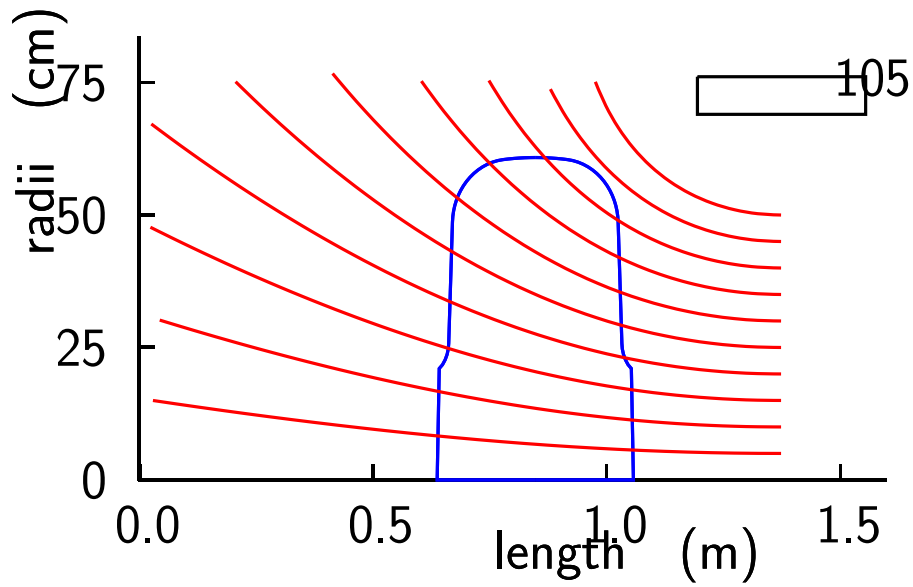


How to study at 805 MHz: MTA with Lab G magnet



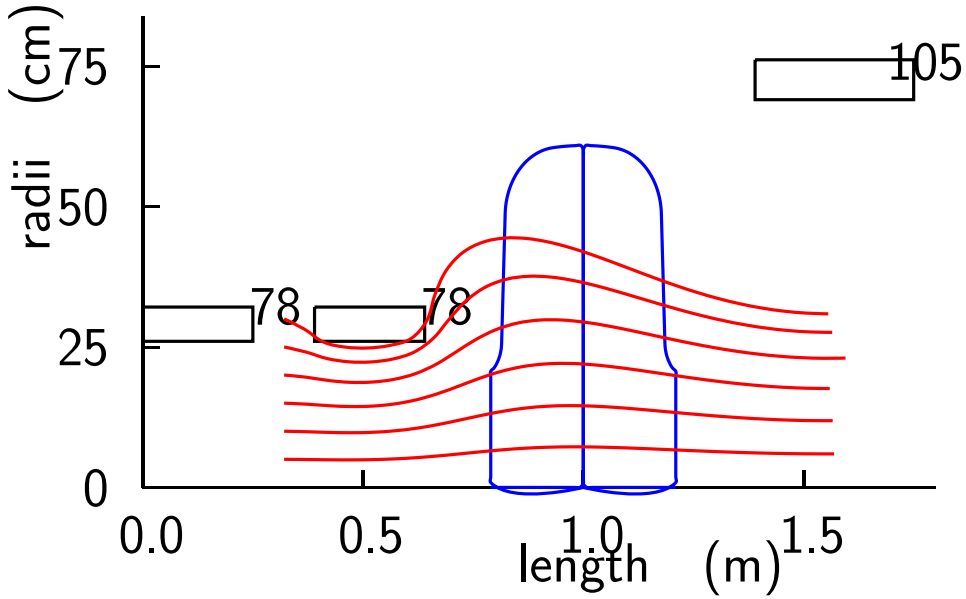
How to study at 201 MHz: MTA with coupling coil

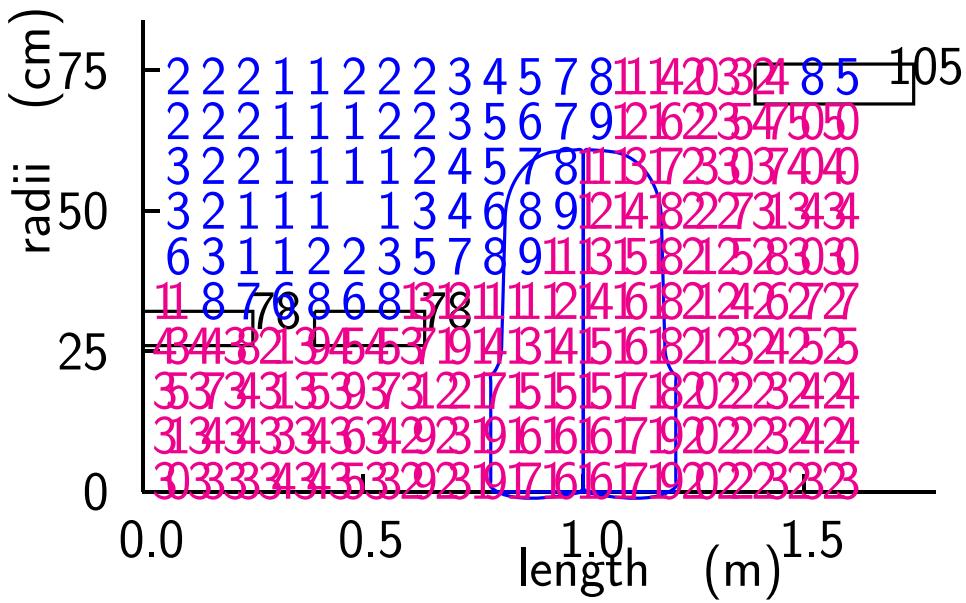




- Field lines do not link high gradient locations
- But fields now much higher: 1.6 T vs 0.3 T for Lab G magnet

MTA with both





- Now geometry similar to MICE: field lines link irises
- Fields at irises around 1.5 T at full current: similsr to MICE
- But excessive forces on coils
- But if 1/10th current:
  - Forces 1/100
  - Fields still 0.15 T
  - Where current experiment shows 1/2 gradient