RF Breakdown with and without external magnetic fields

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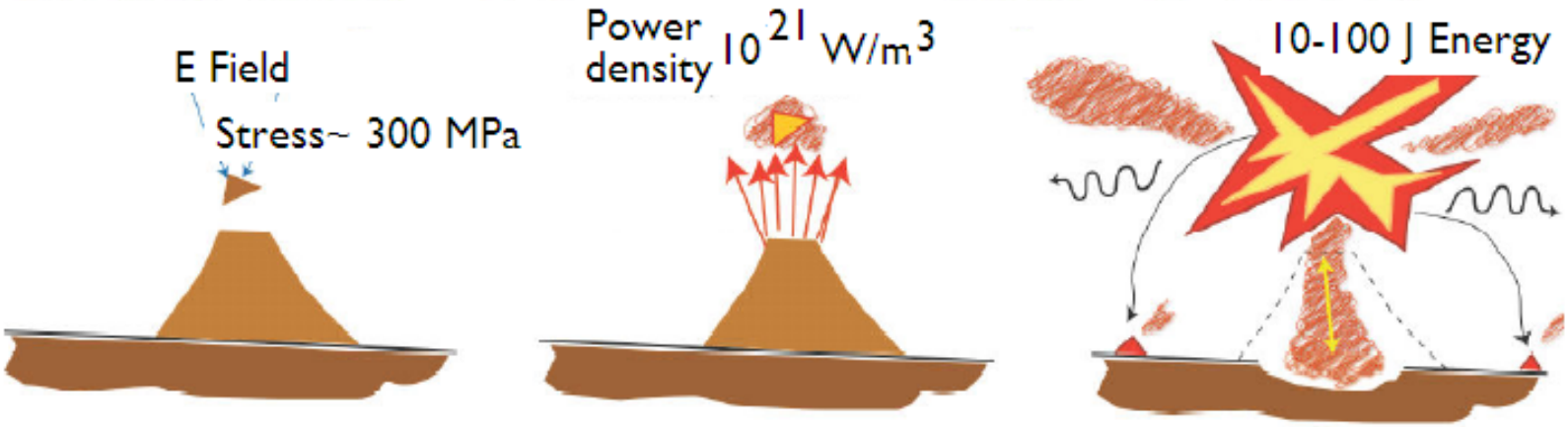
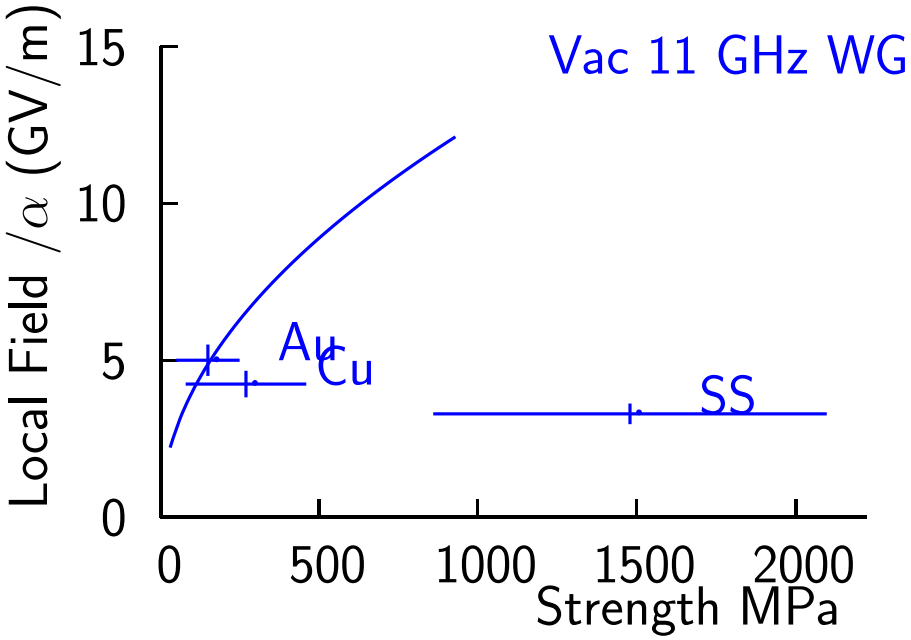
Highlights from MUC 528

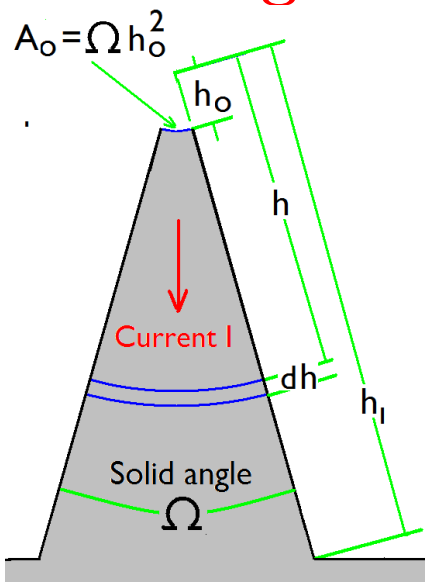
- Models for breakdown without magnetic fields
- Models with magnetic fields
- Impications for MICE
- How to study these effects
- Conclusion

Fracture Model





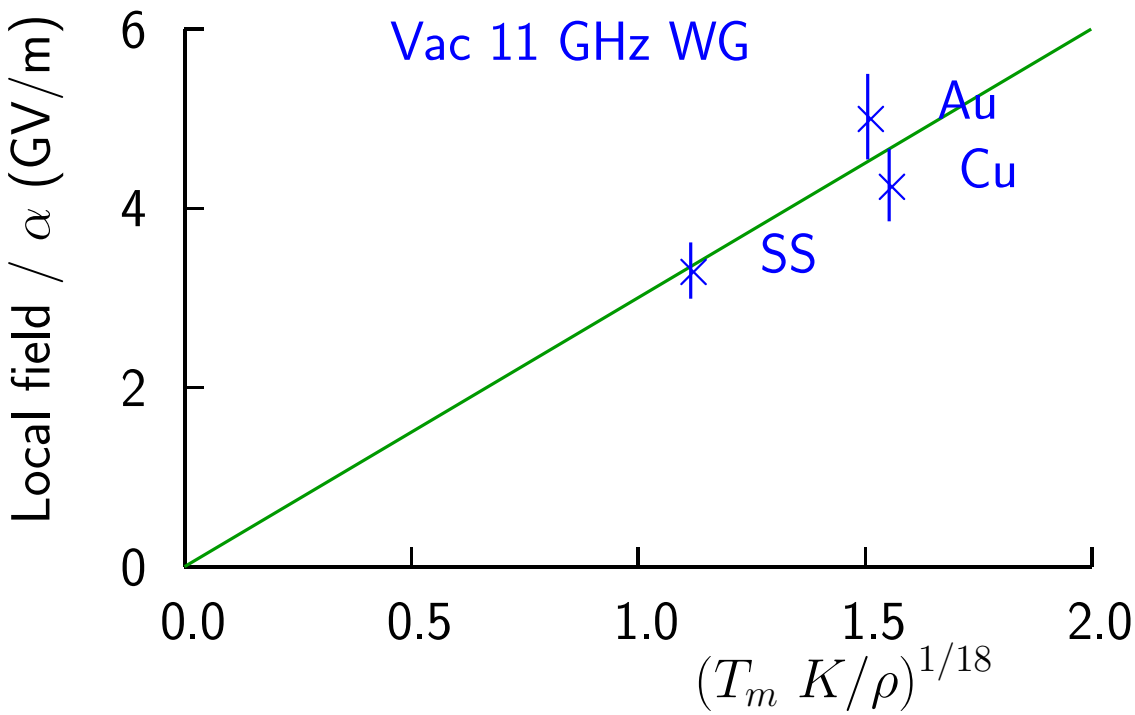
Melting Model



$$\Delta T \propto \left(\frac{j_o^2 \, A \, \rho}{2 \, K \, \Omega} \right)$$

$$j \propto \mathcal{E}_{\rm local}^{10}$$

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



Frequency dependence

$$\mathcal{E} \propto \sqrt{\mathrm{f}}$$

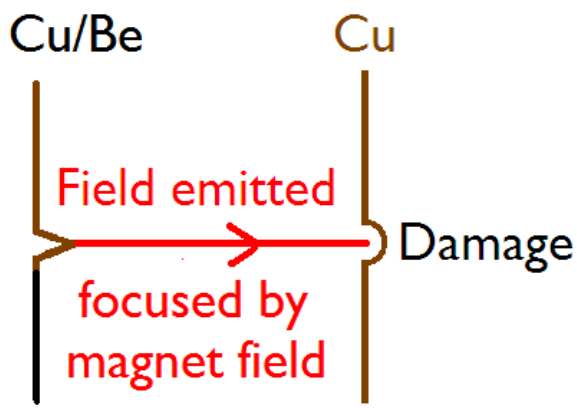
$$\mathcal{E}_{\mathrm{local}} = \mathcal{E}_{\mathrm{ave}}\, \beta_{\mathrm{FN}} \quad \mathrm{approximatelyconstant}$$

So

$$\beta_{FN} \propto 1/\sqrt{f}$$

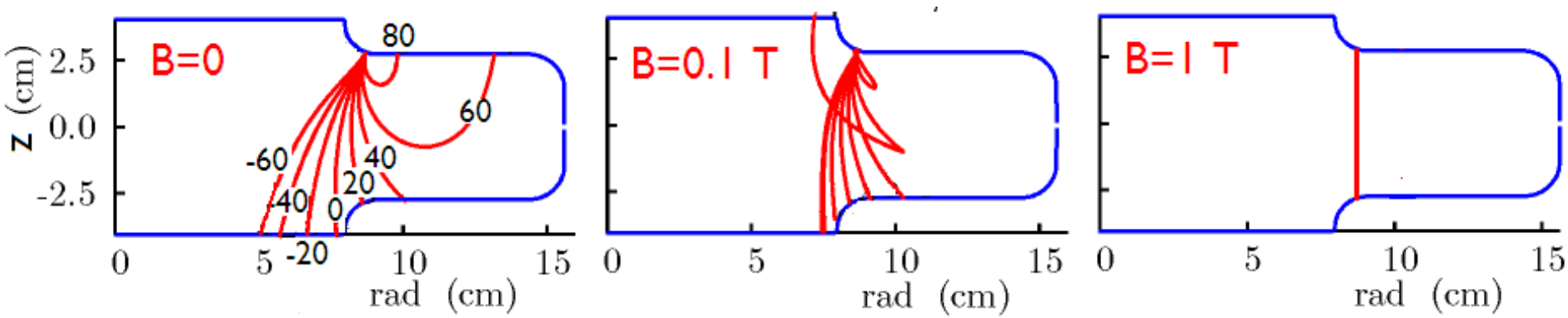
- low frequency cavities are larger
- have more stroed energy at fixed gradient
- do more damage on breakdown
- increasing β_{FN}

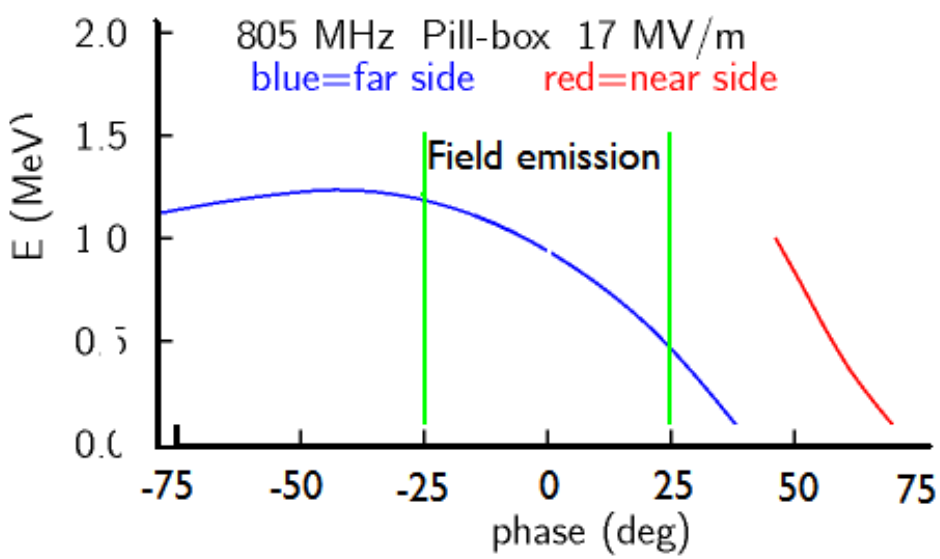
Proposed mechanism



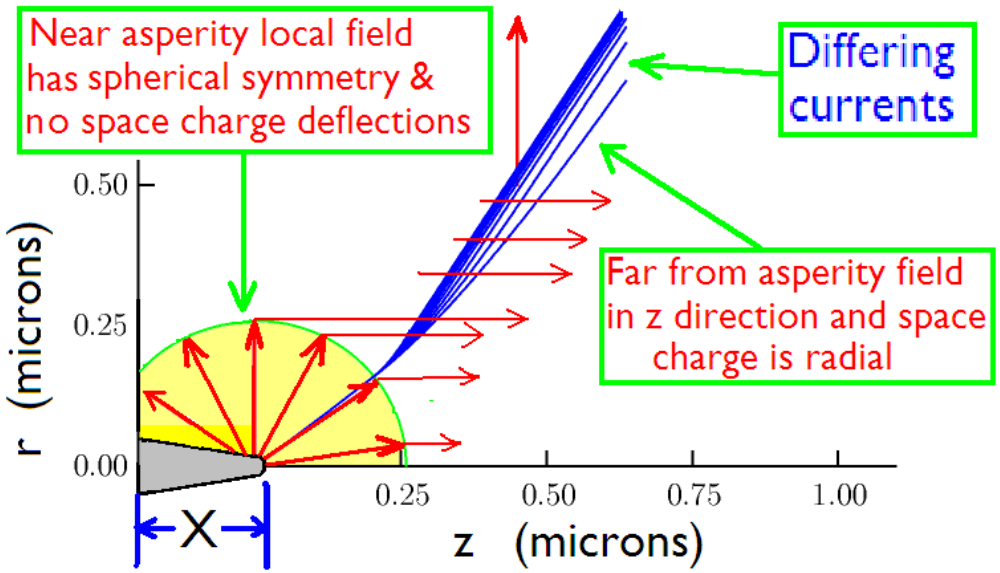
1. "Dark Current" electrons accelerated and focused by magnetic field
2. Melt small spots
3. If on a location with high surface rf gradient: breakdown
4. If not, no breakdown, but eventiual damage

Electron motion in the cavity





Space charge blows up beamlet



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

Energy density hitting wall:

$$W = \frac{I\ E_e}{\pi \sigma_r^2} \propto \frac{I^{(1-2j)}\ E_e\ B^2}{\pi}$$

Energy deposited in thermal diffusion length

The thermal diffusion length δ

$$\delta = 10^{-2}\sqrt{D\ \tau} \quad (\mathrm{m})$$

where $D = K/\rho C_s$

$$Q \ = \ \frac{Energy\ in\ \delta}{total\ energy}$$

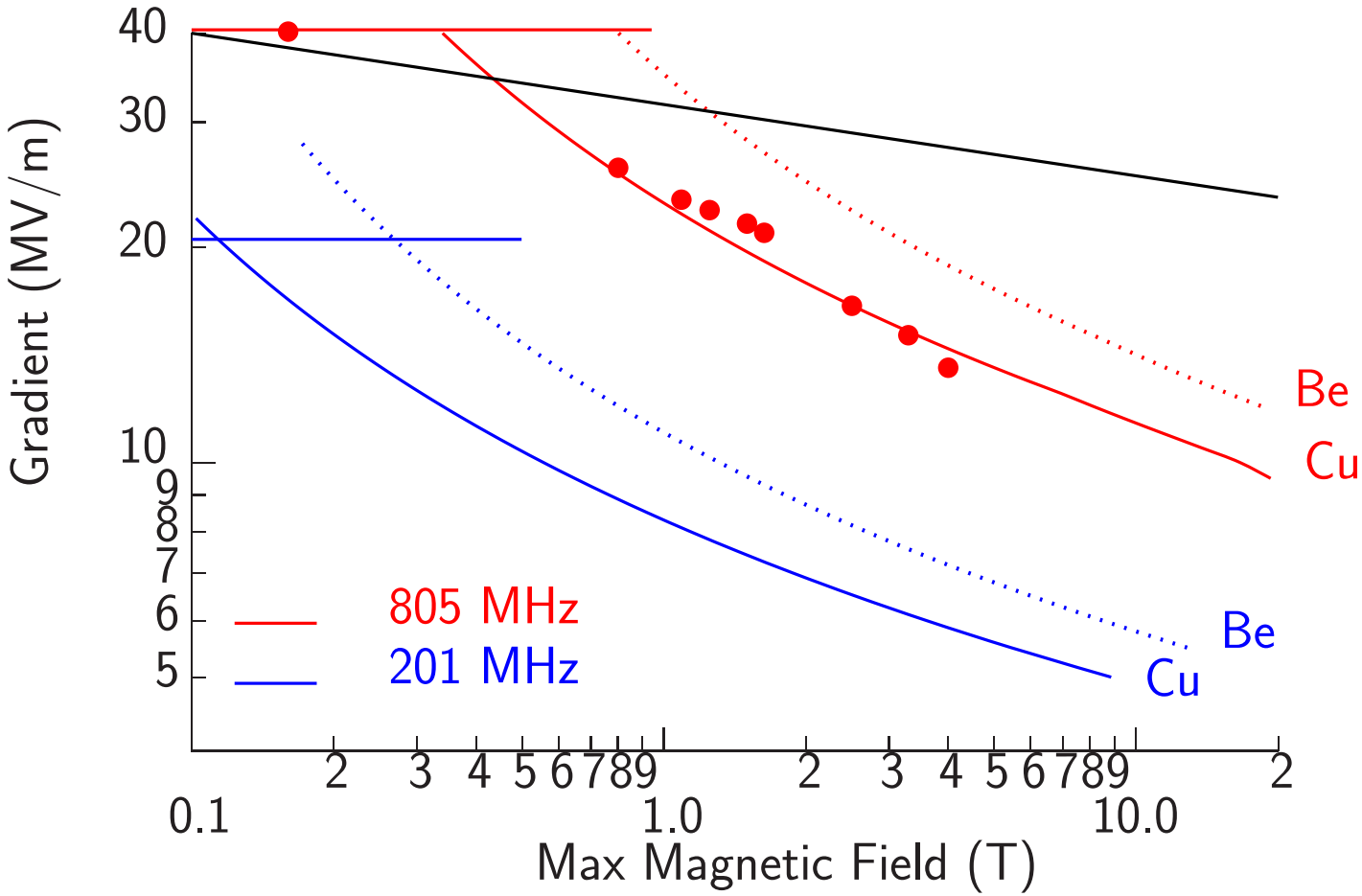
$$\Delta T \ \propto W \ \left(\frac{\tau\ Q}{\delta\ \rho\ C_s}\right)$$

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

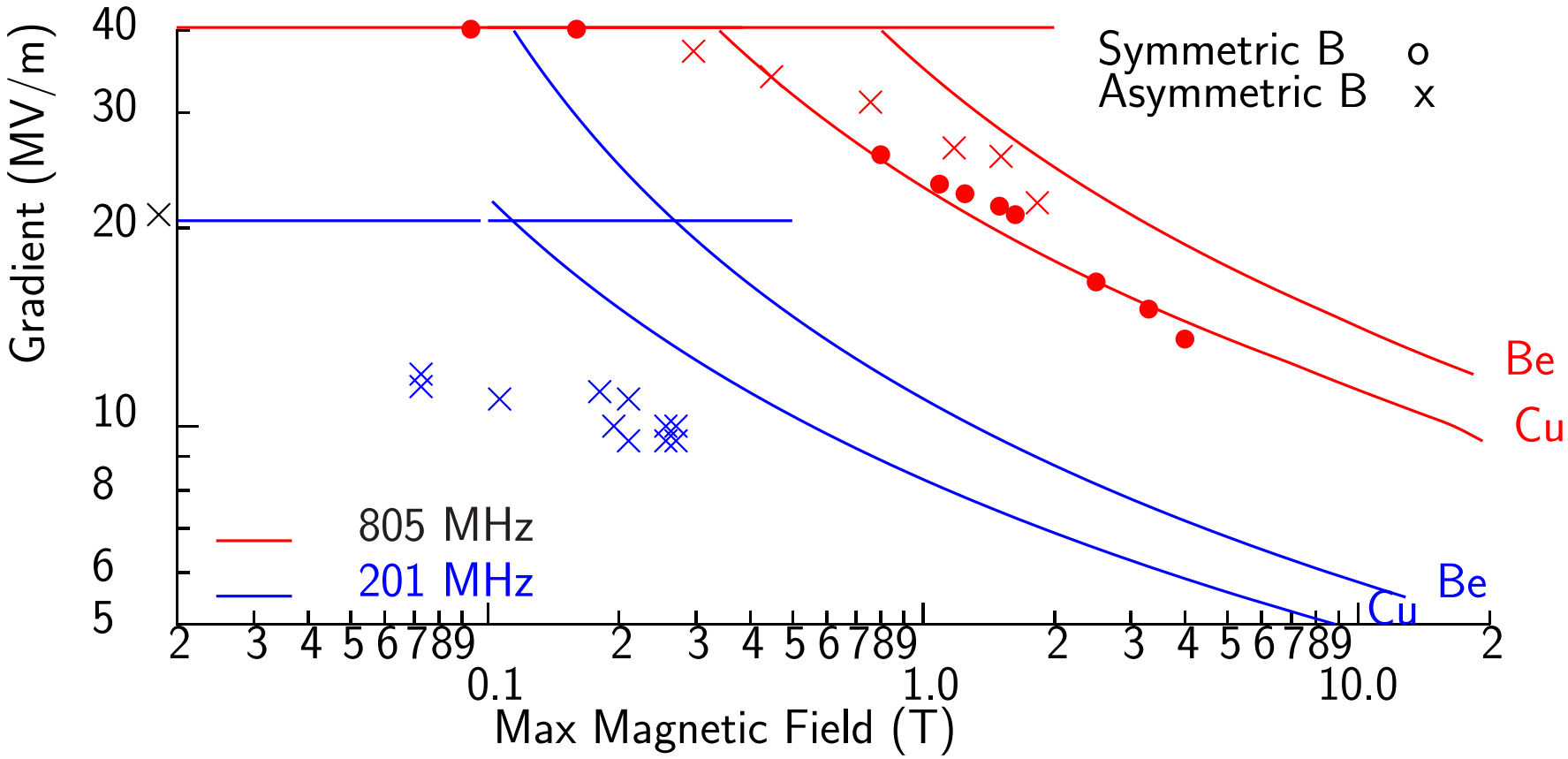
So for a temperature rise proportional to the melting temperature T_m:

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

Fit to data

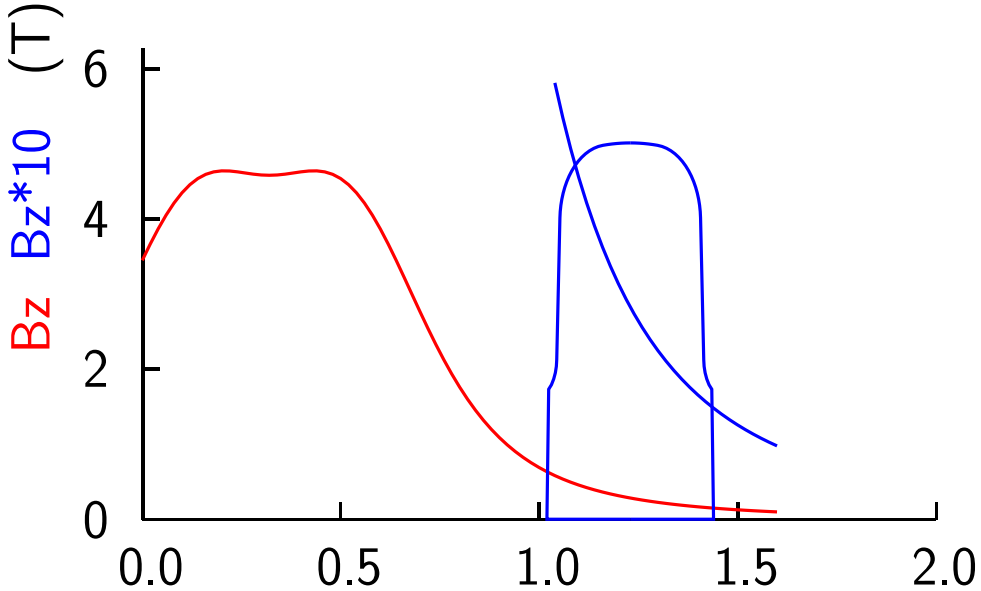

Gradient (MV/m)
40
30
20
10
9
8
7
6
5
805 MHz
201 MHz
Be
Cu
Be
Cu
0.1
1.0
10.0
Max Magnetic Field (T)

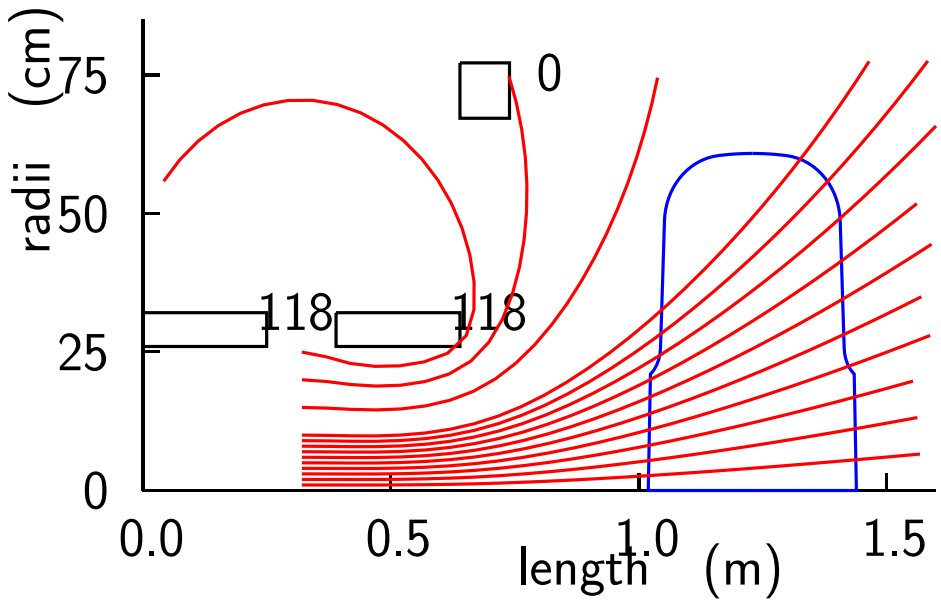
201 MHz data



- Prediction assumed uniform magnetic field
- But for 805 MHz assymetric case is better than symetric
- This is expected: when emission at high grad falls on another high gradient

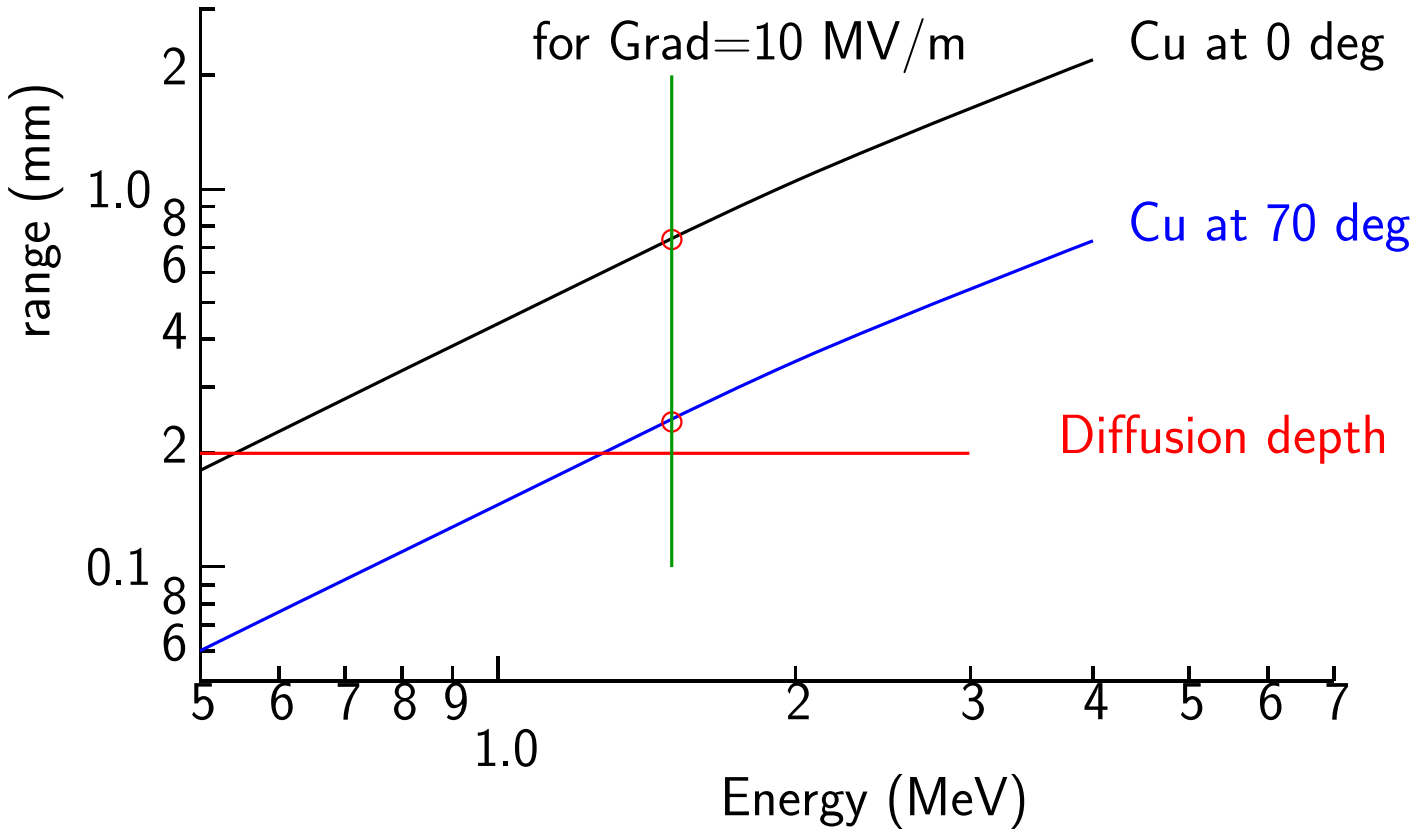
201 MHz MTA experiment





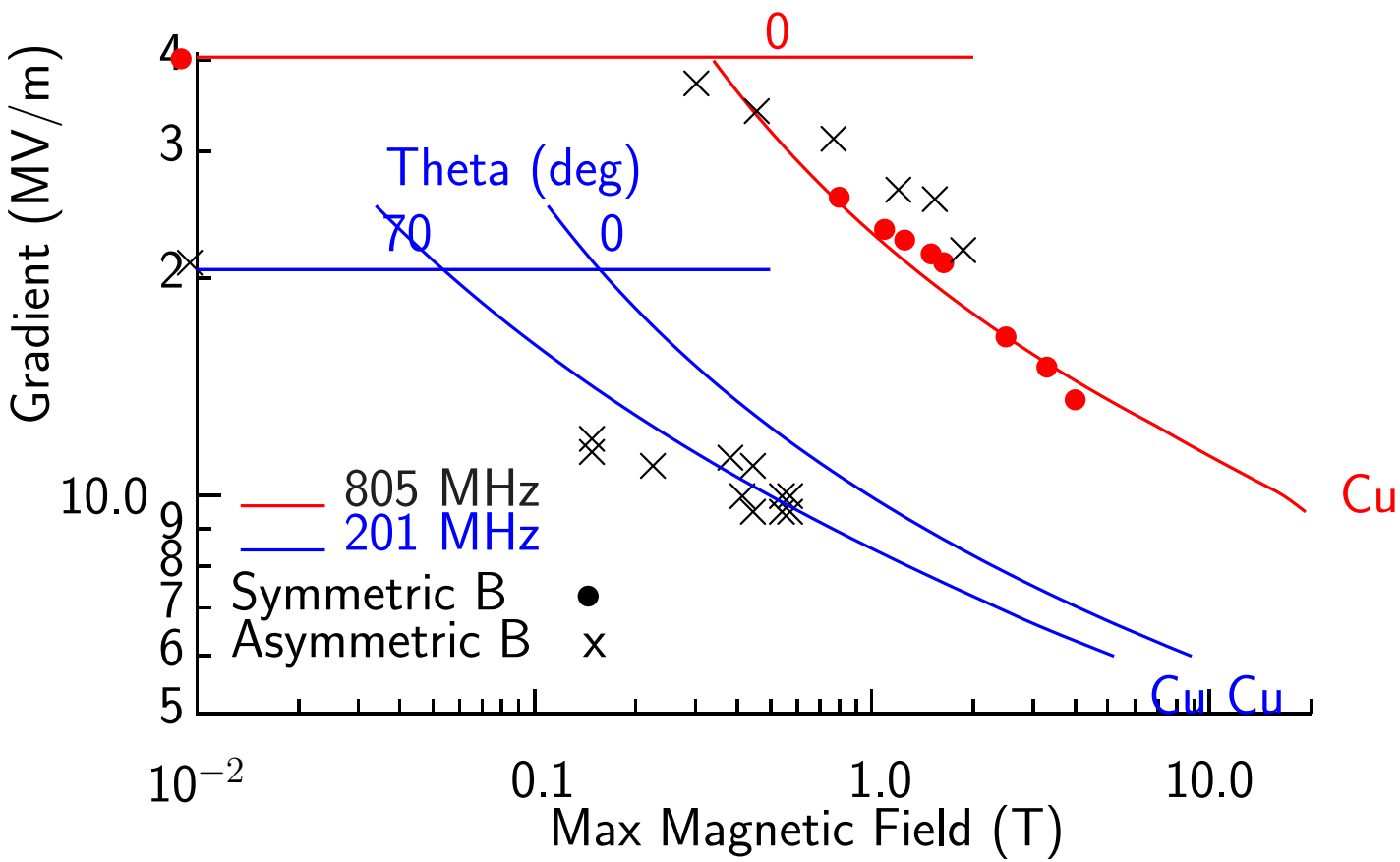
- Field lines do not link high gradient locations
- Fields very low: 0.3 T at center (0.6 to 0.1)
- Electons from right arrive on iris at glancing angle

penetration depth vs incident angle



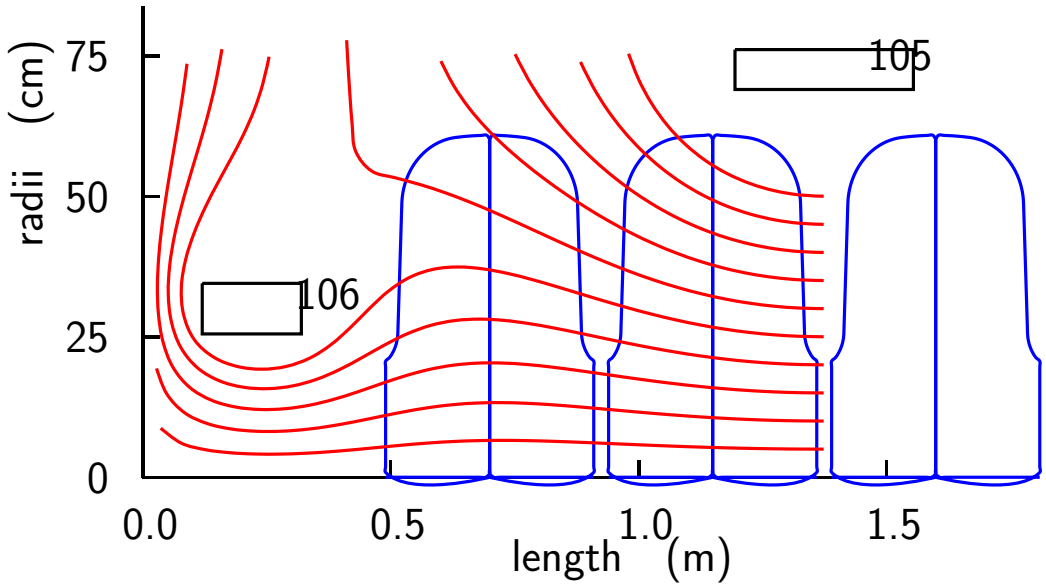
- At 10 GV/m electron E≈1.3 MeV
- At 0 deg penetration ≫ thermal diffusion
- At 70 deg they almost match which is mush worse

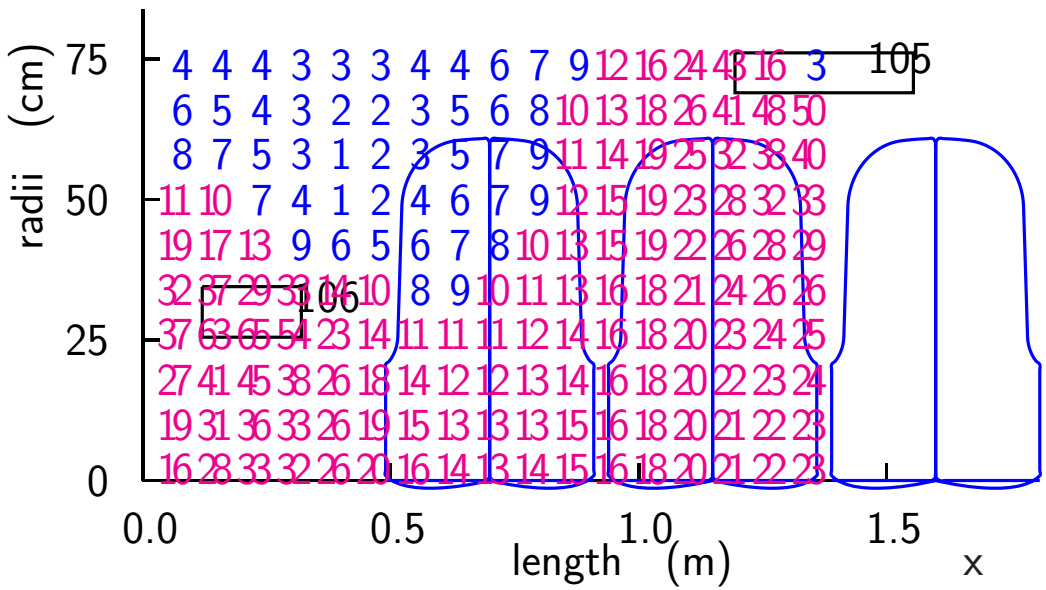
If Theta=70 deg



- Incident angle set to 70 deg from vertical
- Assymetric data plotted vs maximum B
- Surface gradient at source decreased by 20%
- These are NOT justified by analysis, but used to fit data

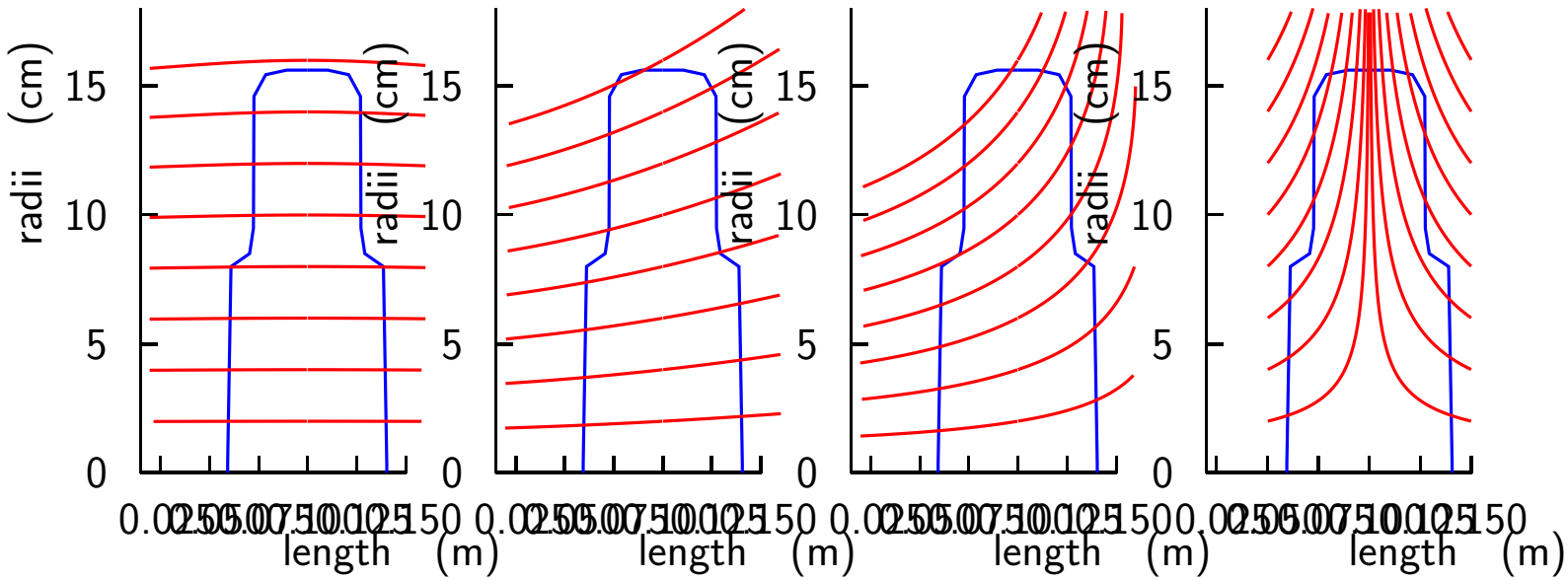
Implications for MICE



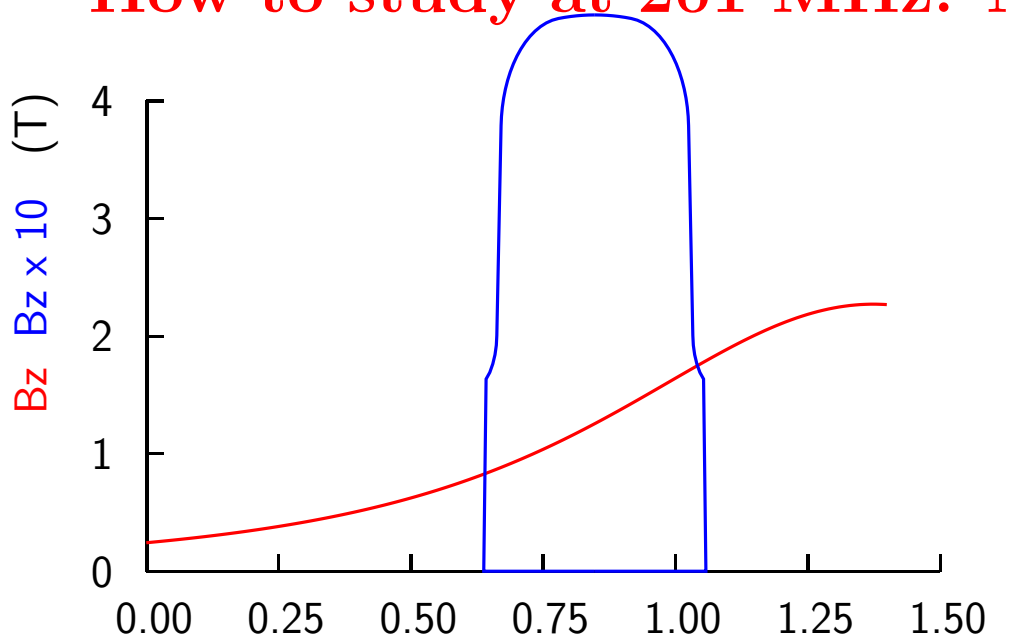


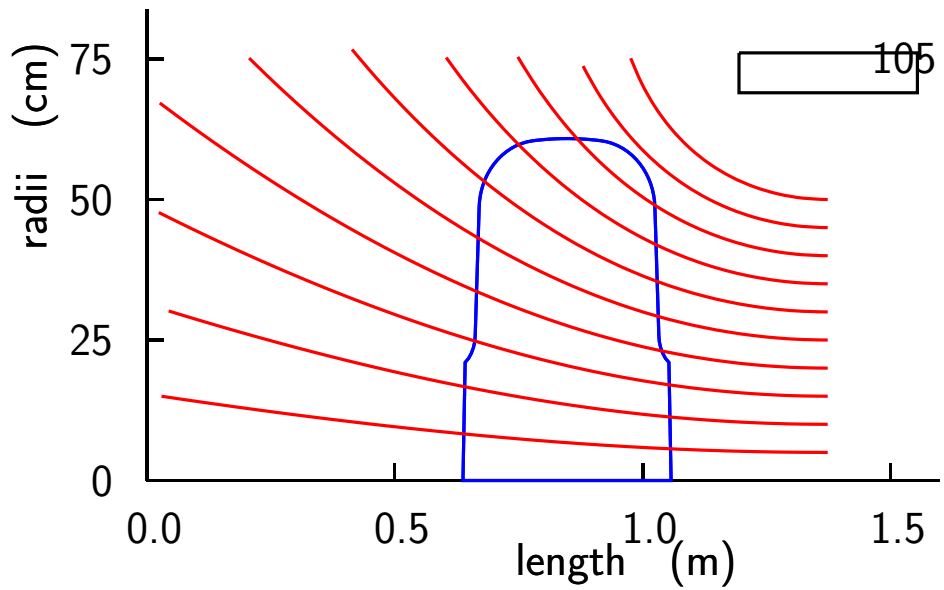
- If worst situation when field lines links two high gradient locations then cavities 1 and 4 have worst geometry
- But the lower arrival angles may make situation better
- But one should probably not assume gradients > 6 MV/m

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



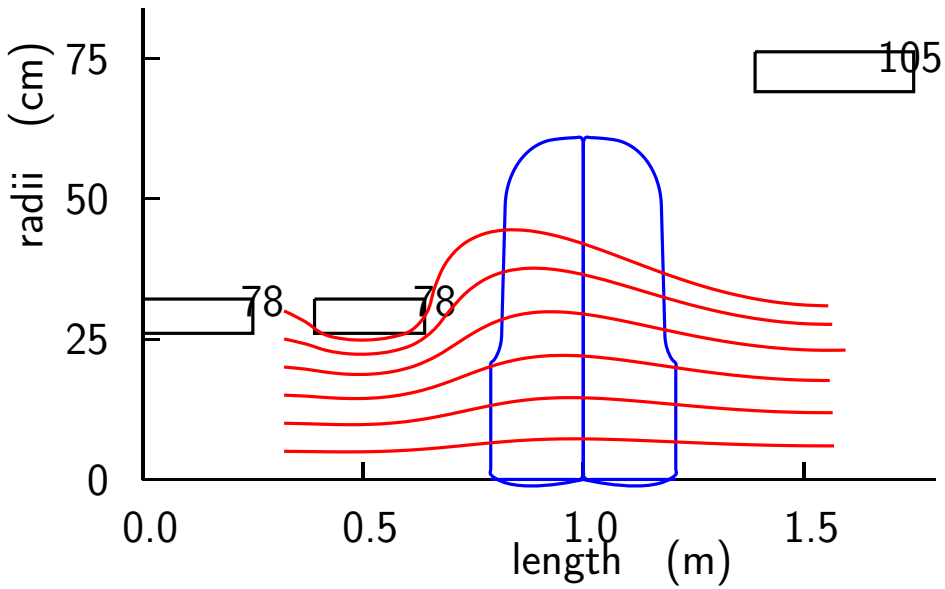
How to study at 201 MHz: MTA with coupling coil

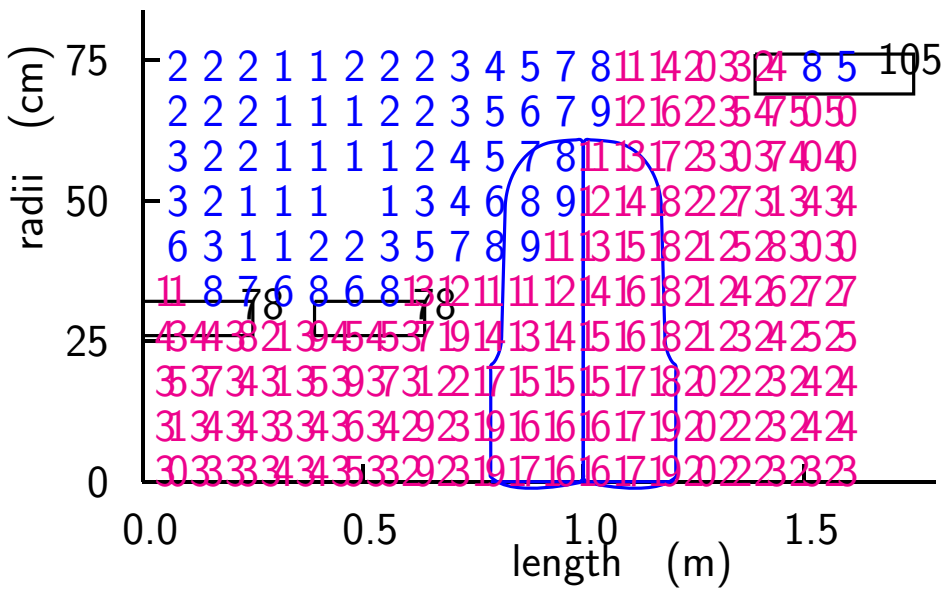




- Field lines do not link high gradient locations
- But fields now much higher: 1.6 T vs 0.3 T for Lab G magnet

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

Conclusion

- Without magnetic field, melting asperities model favored
- With magnetic field, damage by focused dark current fits 805 MHz data
- Breakdown expected worse if field lines link high gradient locations As observed in 805 MHz

- 201 MHz with assymetric fields worse than expected
- And MICE fields do link irises in cavities 1 and 4 which could make it even worse

- Neither the current tests at MTA, not those proposed with the coupling coil can test this case
- But if both magnets are used, even at 1/10th current, the MICE situation can be tested