Breakdown from Asperities

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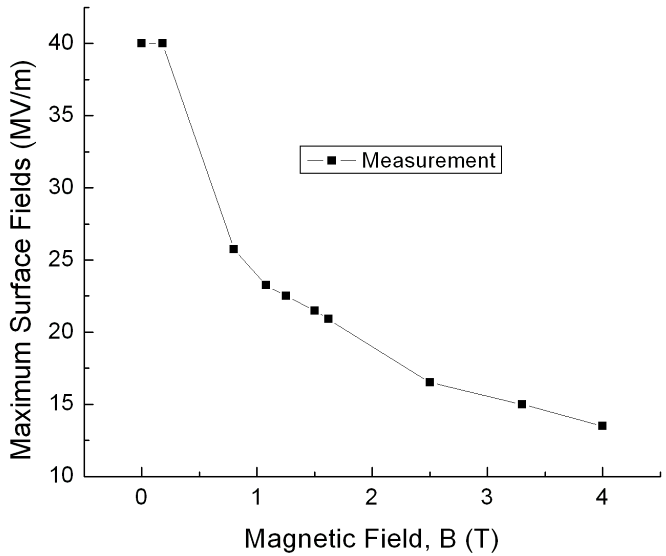
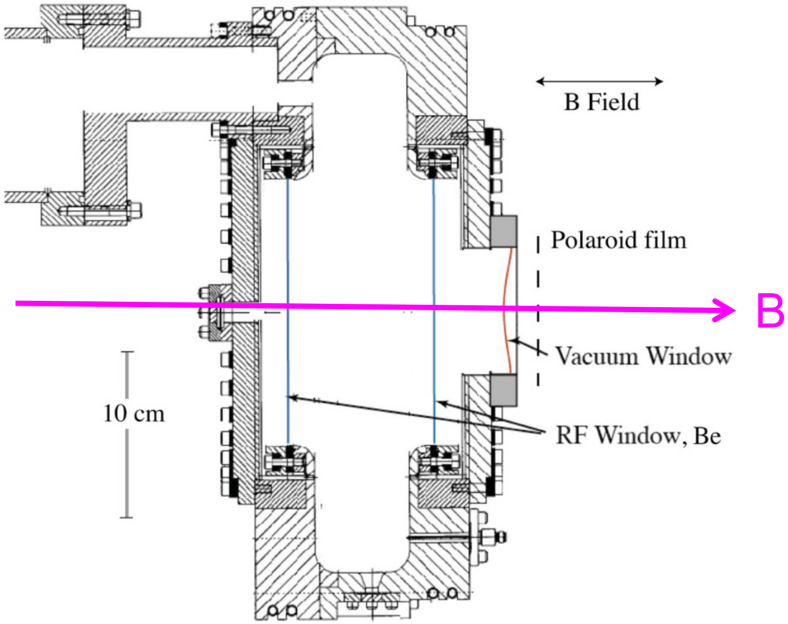
Motivation



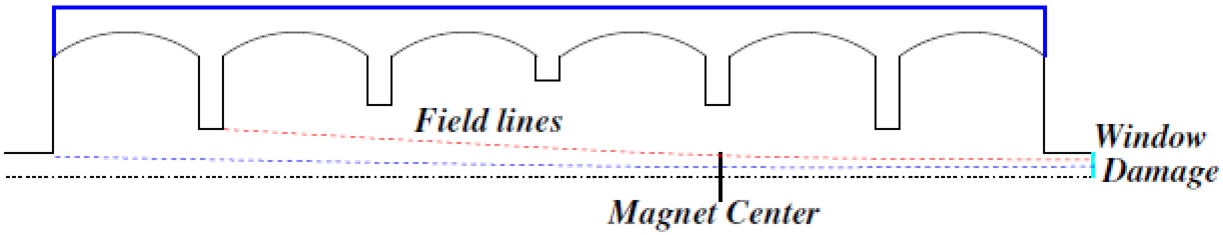


Moretti et al. PRST - AB (2005)

805 MHz

- Maximum gradients were found to depend strongly on the external magnetic field
- Consequently the efficiency of the RF cavity is reduced
- A solution to this problem requires the development of a model that describes well the effects of the external fields on cavity operation

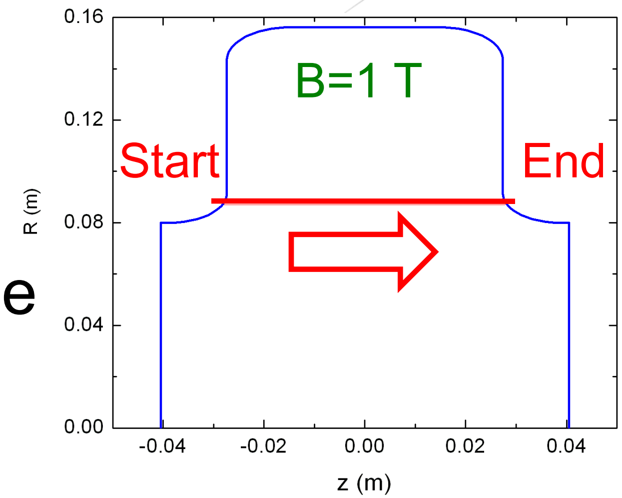
Introduction and Previous Work



- Dark currents electrons were observed in a multi-cell 805 MHz cavity.
- They arise most likely from local field enhanced regions ($\beta_e E_{surface}$) on the cavity iris. Currents scale as: $I \propto (\beta_e E_{surface})^n$
- Electron emitters are estimated to be around 1000, each with an average surface field enhancement β_e=184. The measured local field gradients where up to 10 GV/m.
- Enhancement is mainly due material imperfections

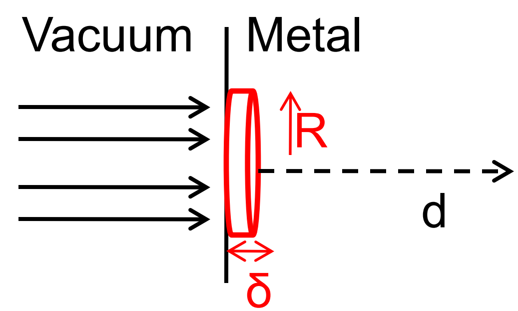
Norem et al. PRST - AB (2003)

Model Description



- Step 1: Emitted electrons are getting focused by the magnetic field and reach the far cavity side.
- Step 2: Those high power electrons strike the cavity surface and penetrate within the metal up to a distance d.
- Step 3: Surface temperature rises. The rise within the diffusion length δ is proportional to the power density g.

$$\Delta T \propto g(\delta,t) \quad \text{where} \quad g(\delta,t)=\frac{\chi P}{(\pi R^2)\delta}$$



P : Incident Power

χ : Fraction of net Power deposited within δ

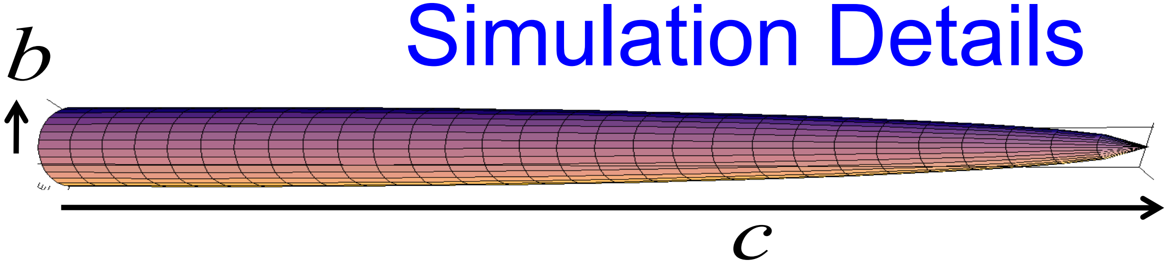
R : Beamlet Radius

- Step 4: At high fields, ΔT approaches melting temperature of metal. Breakdown.

Objectives of this Study

- Model the propagation of emitted electrons from field enhanced regions (asperities) through an RF cavity. In the simulation we include:
  - RF and externally applied magnetic fields
  - The field enhancement from those asperities
  - The self-field forces due space-charge
- Estimate the surface temperature rise after impact with the wall. See how it scales with magnetic fields and emission currents: both theoretically and through simulation
- Compare our findings with the experimental breakdown data.

Simulation Details



$$r = \frac{b^2}{c}$$

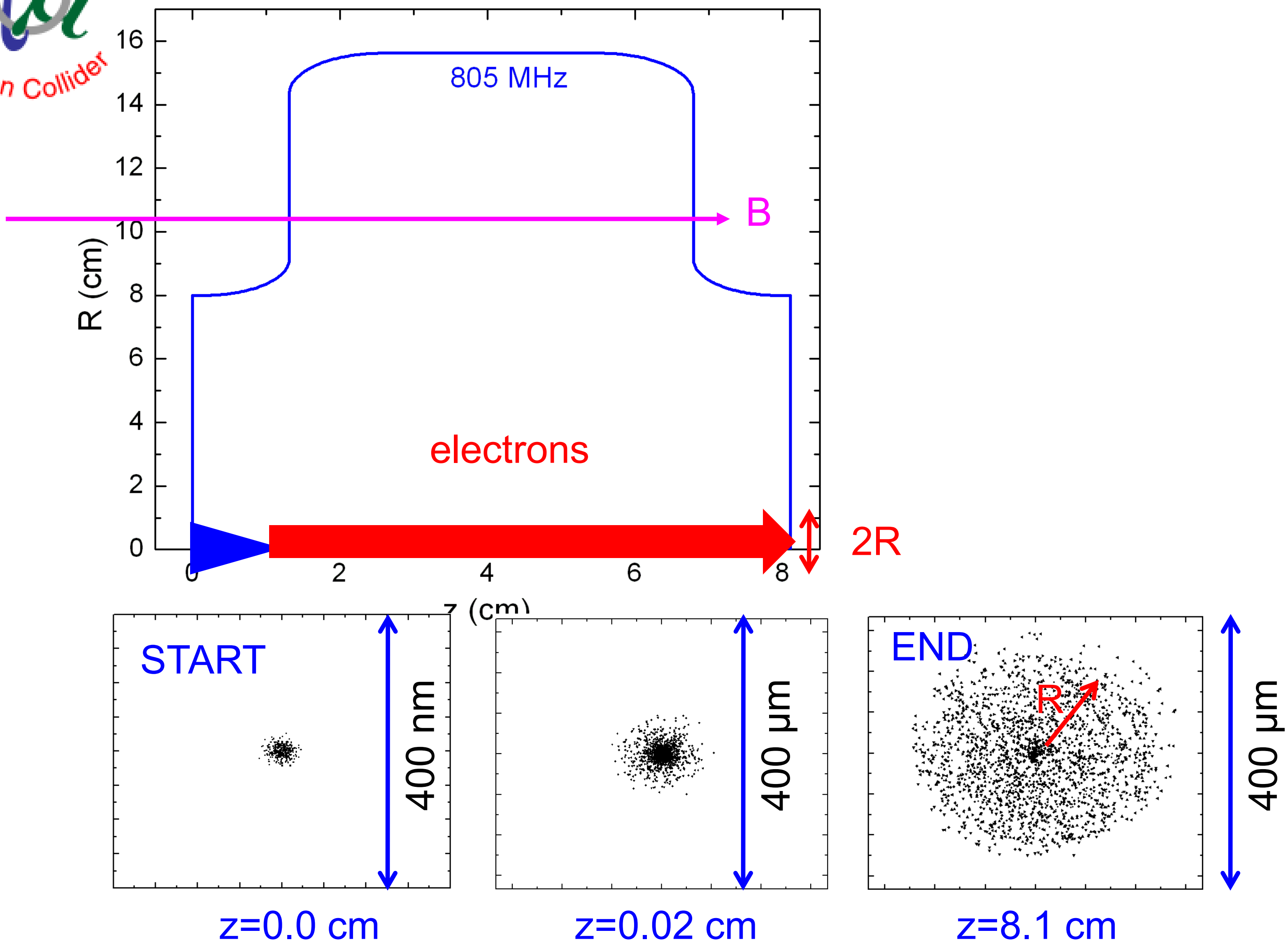
- Model each individual emitter (asperity) as a prolate spheroid. Then, field enhancement at the tip:

$$E_{TIP} = \left(\frac{\frac{c}{r}}{\ln 2\left(\frac{b}{r}\right) - 1} \right) E_{surf} = \beta_e E_{surf}$$

- Electron emission is described by Fowler-Nordheim model

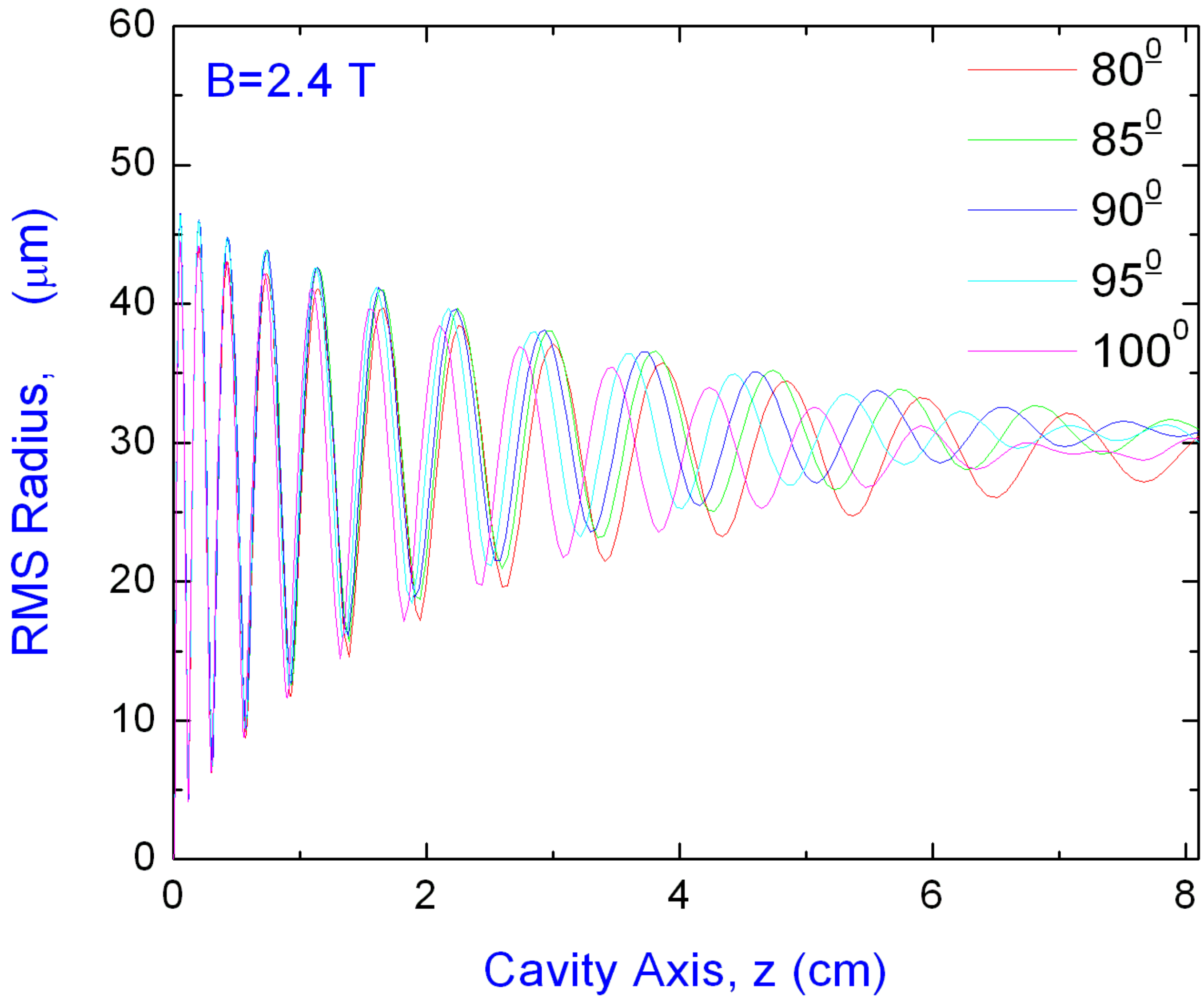
- What is similar to Norem/ Morretti experiment:
  - Average field enhancement: $c = 16\mu m, b = 0.7\mu m, \rightarrow \beta_e = 184$
  - Emission currents: I=0.1-1 mA
- What is not similar:
  - Asperity location and real geometry. We place asperity on cavity axis.
  - Asperity dimensions; real asperities are in sub-micron range.

Particle Tracking inside RF Cavity

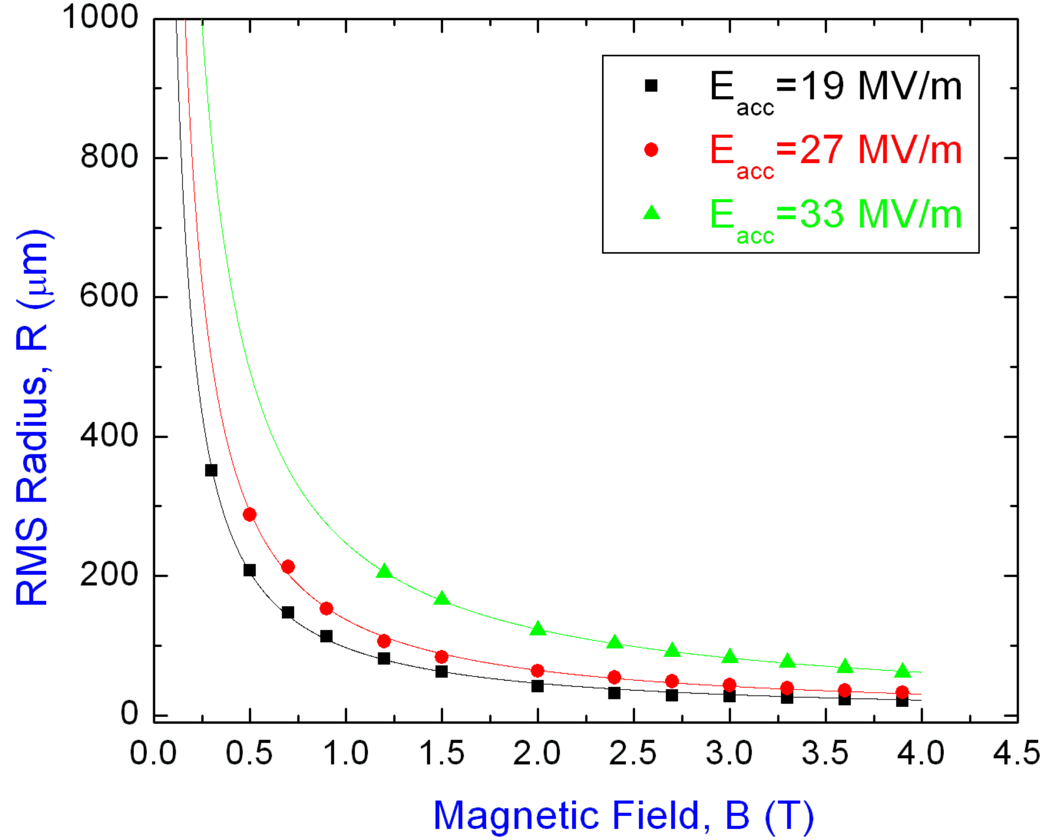


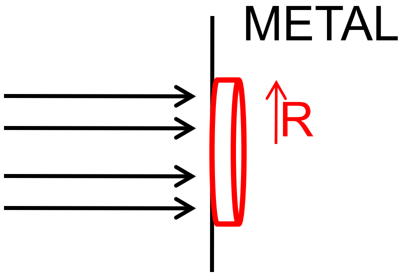
- Electrons will get focused by the magnetic field and move parallel to its direction.

Particle Tracking with the RF Cavity



Scale of Final Beamlet Size with B





- For any gradient, final beamlet radius at far side scales as:

$$R \propto \frac{1}{B}$$

Scale of Final Beamlet Radius with Current

- Beam Envelope Equation:

$$R'' + \frac{\gamma' R'}{\beta^2 \gamma} + \frac{\gamma'' R}{2\beta^2 \gamma} + \left(\frac{qB}{2mc\beta\gamma}\right)^2 - \left(\frac{p_\theta}{mc\beta\gamma}\right)^2 \frac{1}{R^3} - \frac{\varepsilon^2}{R^3} - \frac{K}{R} = 0$$

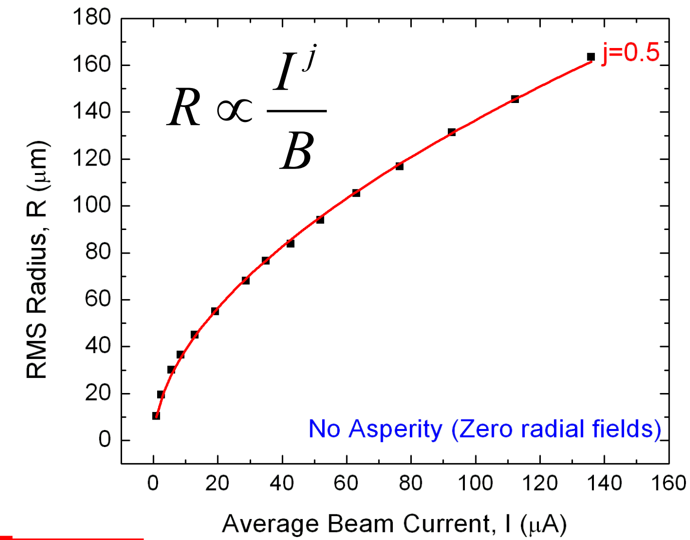
p_θ : Canonical angular momentum

ε : Beam emittance

K: Generalized perveance

R : RMS beamlet radius

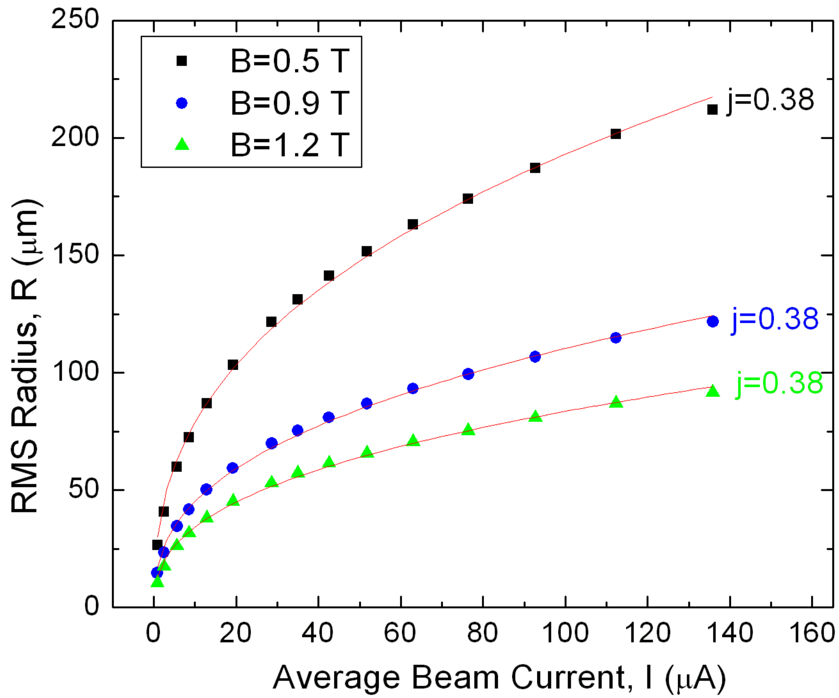
- Assume:
  - Conditions: $p_\theta = 0, \quad \varepsilon = 0$
  - "Matched Beam" $R' = 0, R'' = 0$
  - Flat emitter (No radial fields)



- Then:

$$R = \sqrt{\frac{2}{I_0} \frac{(\beta\gamma)^{-0.5}}{\left(\frac{q}{2mc}\right)B}} I^{0.5}$$

Scale of Final Beamlet Size with Current and B



- The final beamlet radius scales with the emitter current as:

$$R \propto \frac{I^{0.38}}{B}$$

- This result is independent from the magnetic field strength

Surface Temperature Rise and Magnetic Field

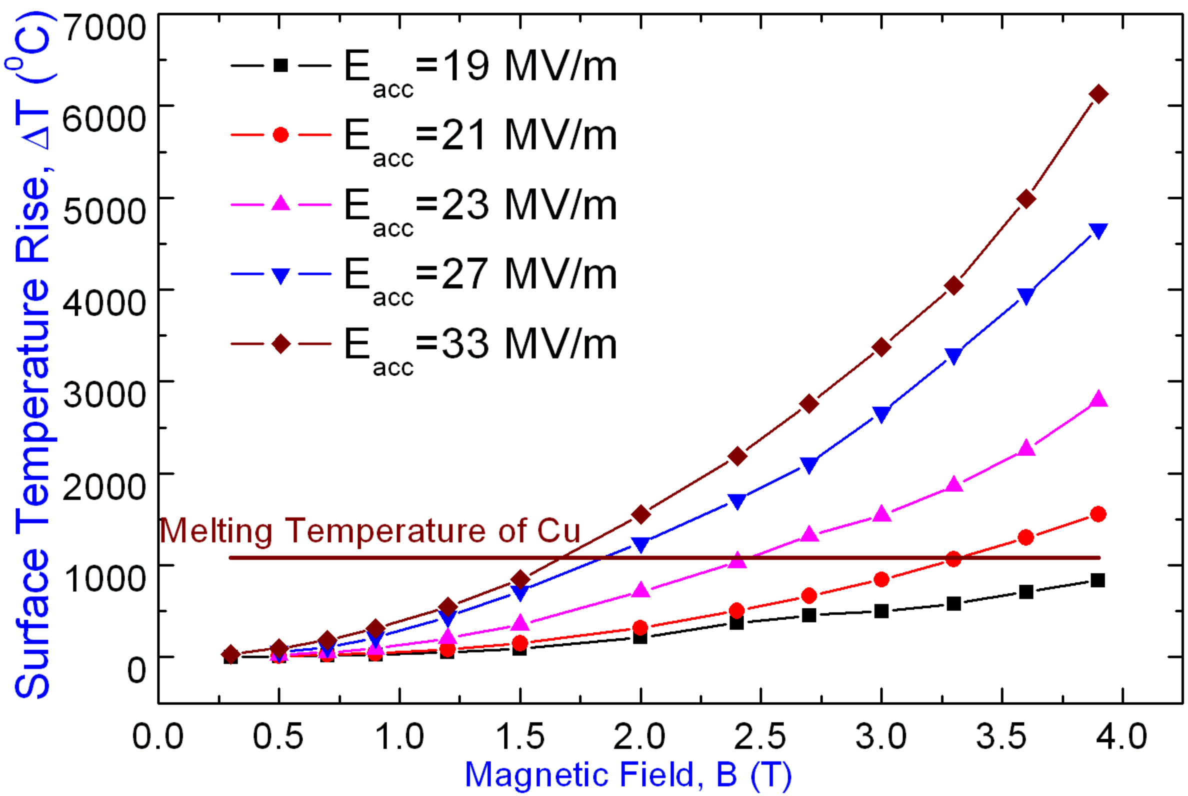
- Recall that: $\Delta T \propto g = \frac{\chi P}{\pi R^2 \delta}$ But: $R \propto \frac{I^{0.38}}{B}$ and $P = E_e I$
- Hence: $\Delta T \propto \frac{\chi E_e}{\pi I^{-0.24} \delta} B^2$

E_e : e Energy at Impact

I : Emission Current

δ : Diffusion Length

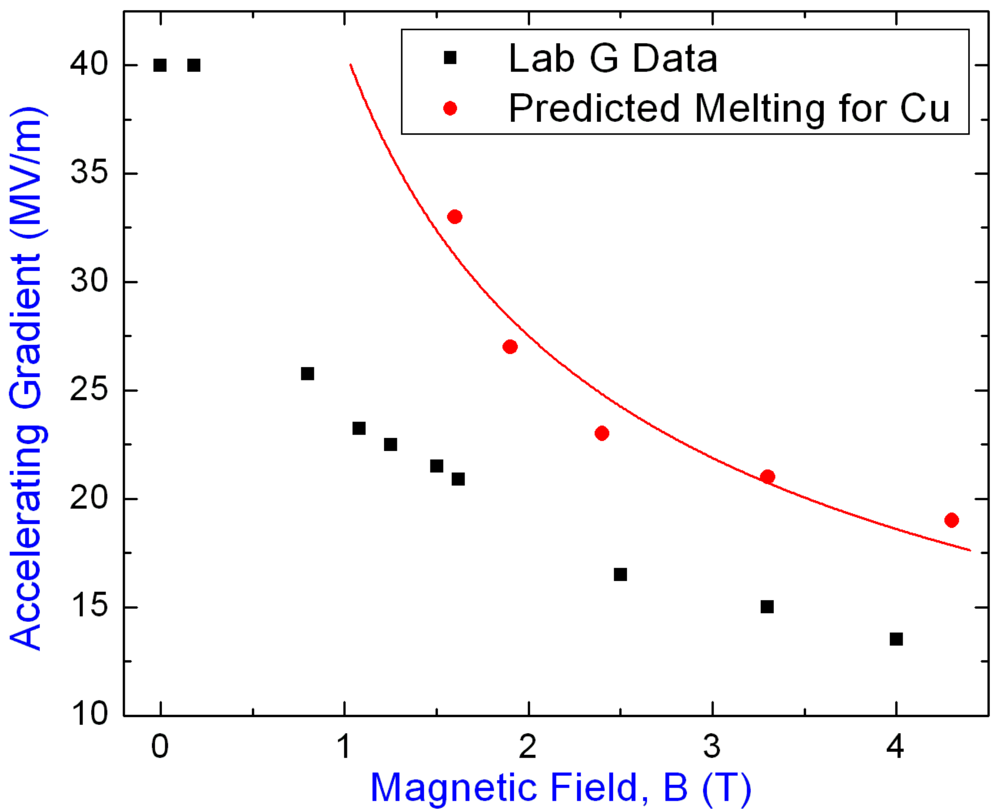
P : Power



Remember:

$I \propto E_{acc}^n$

Comparison Between Simulation and Experiment



- High gradients result to melting at lower magnetic fields

Summary

- Electrons were tracked inside an 805 MHz RF cavity with external magnetic fields
- Electrons, get focused by the external magnetic field and hit the cavity wall with large energies (1 MeV). Cause rise of surface temperature.
- Surface temperature scales with the external magnetic field as ~ B^2 and with the emission currents as $I^{0.24}$
- Therefore at high fields and high gradients melting can occur.
- Our model scales reasonably well with the experimental data however further studies are needed.