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
- Implications for MICE
- How to study these effects
- Conclusion
Fracture Model

- E Field: Stress ~ 300 MPa
- Power density: \(10^{21}\) W/m³
- 10-100 J Energy

Graph:
- Local Field / \(\alpha\) (GV/m)
- Strength MPa
- Vac 11 GHz WG

- Au
- Cu
- SS
Melting Model

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

\[ j \propto \mathcal{E}_{\text{local}}^{10} \]

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

Local field / \( \alpha \) (GV/m)

Vac 11 GHz WG

Au

Cu

SS

0.0 0.5 1.0 1.5 2.0

\((T_m K/\rho)^{1/18}\)
Frequency dependence

\[ E \propto \sqrt{f} \]

\[ E_{\text{local}} = E_{\text{ave}} \beta_{FN} \quad \text{approximately constant} \]

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 \( \beta_{FN} \)
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 eventual damage
Electron motion in the cavity

- $B=0$
- $B=0.1 \text{ T}$
- $B=1 \text{ T}$

805 MHz Pill-box 17 MV/m
blue=far side  red=near side

Field emission
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 $\delta$

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

where $D = \frac{K}{\rho C_s}$

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

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

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

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

$$B \propto \sqrt{\frac{1}{I^{(1-2j)} \mathcal{E}_e} \left( \frac{\delta \rho C_s T_m}{\tau Q} \right)}$$
Fit to data
Prediction assumed uniform magnetic field

But for 805 MHz asymmetric case is better than symmetric

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)
- Electrons from right arrive on iris at glancing angle
penetration depth vs incident angle

- At 10 GV/m electron $E \approx 1.3$ MeV
- At 0 deg penetration $\gg$ thermal diffusion
- At 70 deg they almost match which is much worse
If $\Theta = 70$ deg

- Incident angle set to 70 deg from vertical
- Asymmetric 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: similar 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