RF Breakdown Theory
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Highlights from MUC 528

• Models for breakdown without magnetic fields
• Experiments with magnetic fields
• Model of breakdown with magnetic fields
• Solution with magnetic insulation
• Conclusion
BREAKDOWN WITHOUT MAGNETIC FIELDS

\[ E_{\text{ave}} \approx \alpha \sqrt{f} \]
\[ E_{\text{local}} = E_{\text{ave}} \beta_{FN} \approx \text{const} \]
\[ \beta_{FN} \propto 1/\sqrt{f} \]

- \( \beta \) from equilibrium between burning off asperities and new damage
  - low frequency cavities are larger
  - have more stored energy at fixed gradient
  - do more damage on breakdown
  - increasing \( \beta_{FN} \)

- But what is the mechanism for breakdown at a specific \( E_{\text{local}} \)?
  - Asperity fracture
  - Ohmic heating
  - Returning electrons
Asperity Fracture Model  (Jim Norem et al)

Breakdown in waveguides at 11 GHz  (Valery Dolgashev & Sami Tantawi)

Local Field / $\alpha$ (GV/m)

<table>
<thead>
<tr>
<th>Strength MPa</th>
<th>Vac 11 GHz WG</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>500</td>
<td>5</td>
</tr>
<tr>
<td>1000</td>
<td>10</td>
</tr>
<tr>
<td>1500</td>
<td>15</td>
</tr>
<tr>
<td>2000</td>
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Materials:
- Au
- Cu
- SS
Melting Model (Greg Loew et al)

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

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

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

Breakdown in waveguides at 11 GHz (Valery Dolgashev & Sami Tantawi)

![Graph showing breakdown in waveguides at 11 GHz](image)
Perry proposed that electrons from a plasma spot return to their source, further heating it, and causing the breakdown.

In Romanov (and our) simulation of 805 MHz without magnetic field: no electrons return to their source.
• Cavity was asymmetric in magnet & field lines did not link high gradient to high gradient

• There was no effect on max gradient $\approx 50$ MV/m

• 10 mill Ti window was damaged where electrons were focused, and vacuum lost
Pillbox cavity was symmetrical in magnet
Field lines linked high gradient locations
Maximum gradients fell sharply with magnetic field
This effect must be a function of the geometry
NOT a local effect at an emitter
After more running with mag field, performance continued to deteriorate
805 MHz button experiment

- Damage on the Cu plate opposite to maximum fields on Be window
- Little damage on Cu button where fields were maximum, but opposite lower fields on Be
- No damage was seen on Be - Presumably because e's penetrate
**201 MHz near 4.5 T solenoid**

- Without magnetic field, initial gradients ($\geq 21$ MV/m) Consistent with 805 data scaled $\propto \sqrt{f}$: $\beta_{FN} 183 \rightarrow 366$
- 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
- Presumably, runs with B raised $\beta_{FN} 366 \rightarrow 366 \times 21/15 = 512$
- Without field cavity conditioned up to 18 MV/m (not 21 MV/m) as in pillbox, damage running with magnetic field is sometimes irreversible
Proposed mechanism with magnetic fields

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

- $B=0$
- $B=0.1 \, T$
- $B=1 \, T$

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

Field emission

E (MeV)
Space charge blows up beamlet

For a point source on a flat surface, space charge gives \( \sigma_{p\perp} \propto \sqrt{I} \)

But from an asperity, local transverse field will give significant initial \( p_{\perp} \) and \( \sigma_r \) reducing the space charge and thus the dependence of \( \sigma_{p\perp} \) on current \( I \)

Simple simulation could be fit with

\[
\sigma_{p\perp} \propto I^j
\]

with \( j < 0.5 \). So when focused by a field \( B \)

\[
\sigma_r \propto \frac{I^j}{B}
\]

Energy density hitting wall:

\[
W = \frac{I E_e}{\pi \sigma_r^2} \propto I^{(1-2j)} E_e B^2
\]
Energy deposited in thermal diffusion length

The thermal diffusion length $\delta$

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

where $D = K/\rho C_s$

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

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

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

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

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

A better calculation would solve the thermal conduction vs. time in the surface
Required dark currents

- Observations on dark currents observed in the multi-cell 805 MHz cavity found average dark currents of 1 mA.
- Is 1 mA enough to do damage?

- The worst case is when the penetration depth $d = \text{thermal diffusion length } \delta$ for 805 MHz: $\delta = 0.07 \text{ mm}$, and energy 0.3 MeV, lasting 20 $\mu$s
  (Or for 201 MHz $\delta = 0.2 \text{ mm}$, at energy 0.5 MeV, lasting 200 $\mu$s)

- For 805 the energy deposited is $1 \times 10^{-3} \times 0.3 \times 10^6 \times 20 \times 10^{-6} = 6 \times 10^{-3} \text{ J}$
  (Or for 201 $1 \times 10^{-3} \times 0.5 \times 10^6 \times 200 \times 10^{-6} = 0.1 \text{ J}$)

- The minimum volume of deposition is $\pi \delta^2 d = 1 \times 10^{-3} \text{ mm}^3$
  (or for 805, $\pi \delta^2 d = 24 \times 10^{-3} \text{ mm}^3$)

- The energy to melt this volume is $1.8 \times 1 \times 10^{-3} = \boxed{1.8 \times 10^{-3} < 6 \times 10^{-3} \text{ J}}$
  (or for 201 MHz $1.8 \times 24 \times 10^{-3} = \boxed{0.043 < 0.1 \text{ J}}$)

And if 1 mA is the average, there will be some with significantly more
But there is still a problem

• Breakdown in magnetic fields is observed at gradients less than half that without fields and dark currents $\propto \mathcal{E}^{10}$

• So the dark currents causing the damage should be $< 1 \text{ mA} \times 0.5^{10} = 1 \mu\text{A}$

• How can such a small current do damage?

• One explanation would be if the highest current emitters are space charge limited with $I \approx \propto \mathcal{E}^{2}$ (see Laurent et al SLAC-PUB-8409)

• Another explanation would be if the electron impacts do not melt the surface, but damage it over many cycles by fatigue from thermal shocks

• Discussions with people at SLAC revealed their disbelief that asperities with high $\beta$s really exist, but they have no better explanations.
Fit to data with prediction and data for 201 MHz

Fit (with j=0.35) and predictions are for symmetric fields

- Prediction assumed uniform magnetic field
- In 805 MHz asymmetric case is better than symmetric
- But in this experiment the field was far more asymmetric
Geometry of 201 Experiment

- Field on magnet side was 4 times that on far side
- So no damage expected from impacts on far side
- Damage possible from returning electrons from Cu iris, or
- Damage on Be window from iris or other window
Scaling from 201 MHz

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

- Used \( \beta_{FN} \propto \frac{1}{\sqrt{f}} \) consistent with initial \( B=0 \): \( \mathcal{E} = 21 \text{ MV/m} \)
- Does not explain data at 201 MHz with \( B \)
- But after running with 201 only \( \mathcal{E} = 15 \text{ MV/m} \) at \( B=0 \)
- So damage had increased to \( \beta_{FN} = \frac{21}{15} \times 366 = 512 \)
Now there is good agreement with either hypothesis

Only inspection can decide whether returning electrons from the Cu iris, or those on Be are the cause
Relevance to MICE

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

- Possible safety problem: beamlets passing through Be windows damage Al hydrogen safety 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 somewhat 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 might have to be modified.
- solutions also found for a lower beta

<table>
<thead>
<tr>
<th></th>
<th>base</th>
<th>rev 1</th>
<th>rev 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_{\perp}(200)$</td>
<td>42 cm</td>
<td>44 cm</td>
<td>19 cm</td>
</tr>
<tr>
<td>Focus</td>
<td>1.0</td>
<td>1.21</td>
<td>1.60</td>
</tr>
<tr>
<td>Coupling</td>
<td>1.0</td>
<td>-1.15</td>
<td>-1.09</td>
</tr>
</tbody>
</table>
Simulation of cooling with/without CC reversal

- Performance is about $6\pm3\%$ worse for reverse case
SOLUTION #1 Gas Filled cavities

- Gas would stop electrons, so this is consistent

- So can we use high pressure gas?
  - Helical Cooling Channel uses high pressure gas
    Simulates well with 'ideal' fields, but no integration with rf yet
  - 'Guggenheim' lattices have been simulated with gas and LiH wedges
    Work reasonably well in early, high emittance, stages

- But gas may breakdown or absorb rf with ionizing beam

- Experiment planned with p beam at FNAL
SOLUTION #2  MAGNETIC INSULATION
Form cavity surface to follow magnetic field lines

- All tracks return to the surface
- Energies are very low
- No dark current, No X-Rays!
- No danger of melting surfaces
- But secondary emission $\rightarrow$ problems?
- Grateful to SLAC for help

- This cavity is inefficient $E_{\text{surface}} > 3 \times E_{\text{acc}}$
More efficient cavity shape

- Adding outer bucking coils improves cavity efficiency
CONCLUSION

- Experiments have shown damage and reduced gradients in required fields
- Proposed explanation is focused dark current beamlets damaging surfaces
- Model can fit data reasonably
- Possible solutions
  - High pressure hydrogen gas filled cavities
  - Magnetically insulated cavities
- Needed simulation and theory
  - Cooling simulation with new lattices
  - Multi-pacter study of mag insulation lattices (SLAC)
  - Beam impact studies (Tech-X)
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 $E=21$ MV/m consistent 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 $\beta_{FN}$ then reasonable agreement with finite $B$ data is found
Appendix: Estimate of worst electron energy

<table>
<thead>
<tr>
<th>Energy</th>
<th>Cu range</th>
<th>Be range</th>
</tr>
</thead>
<tbody>
<tr>
<td>MeV</td>
<td>mm</td>
<td>mm</td>
</tr>
<tr>
<td>.13</td>
<td>.02</td>
<td>.07</td>
</tr>
<tr>
<td>0.25</td>
<td>0.05</td>
<td>.2</td>
</tr>
<tr>
<td>.5</td>
<td>0.19</td>
<td>.76</td>
</tr>
<tr>
<td>1</td>
<td>0.44</td>
<td>1.76</td>
</tr>
<tr>
<td>4</td>
<td>2.2</td>
<td>8.8</td>
</tr>
</tbody>
</table>

Thermal diffusion depth

\[
\tau_{201} = 200 \mu \text{sec} \quad \tau_{805} = 25 \mu \text{sec}
\]

\[
\delta = \sqrt{\frac{2k\tau}{C_v}} = \sqrt{\frac{2 \times 4.01 \tau}{3.45}}
\]

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

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

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