RF Breakdown with and without external magnetic fields
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Highlights from MUC 528

• Muon Collider
• Models for breakdown without magnetic fields
• Experiments with magnetic fields
• Model of breakdown with magnetic fields
• Solution with high pressure gas
• Solution with magnetic insulation
• Needed experiments
• Conclusion
## MUON COLLIDER PARAMETERS

<table>
<thead>
<tr>
<th></th>
<th>1.5</th>
<th>4</th>
<th>TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>C of m Energy</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Luminosity</strong></td>
<td>1</td>
<td>4</td>
<td>$10^{34}$ cm$^2$·sec$^{-1}$</td>
</tr>
<tr>
<td><strong>Muons/bunch</strong></td>
<td>2</td>
<td>2</td>
<td>$10^{12}$</td>
</tr>
<tr>
<td><strong>Ring circumference</strong></td>
<td>3</td>
<td>8.1</td>
<td>km</td>
</tr>
<tr>
<td><strong>$\beta^*$ at IP = $\sigma_z$</strong></td>
<td>10</td>
<td>3</td>
<td>mm</td>
</tr>
<tr>
<td><strong>rms momentum spread</strong></td>
<td>0.1</td>
<td>0.12</td>
<td>%</td>
</tr>
<tr>
<td><strong>Required depth for $\nu$ rad</strong></td>
<td>13</td>
<td>135</td>
<td>m</td>
</tr>
<tr>
<td><strong>Repetition Rate</strong></td>
<td>12</td>
<td>6</td>
<td>Hz</td>
</tr>
<tr>
<td><strong>Proton Driver power</strong></td>
<td>$\approx 4$</td>
<td>$\approx 1.8$</td>
<td>MW</td>
</tr>
<tr>
<td><strong>Muon Trans Emittance</strong></td>
<td>25</td>
<td>25</td>
<td>pi mm mrad</td>
</tr>
<tr>
<td><strong>Muon Long Emittance</strong></td>
<td>72,000</td>
<td>72,000</td>
<td>pi mm mrad</td>
</tr>
</tbody>
</table>

- Based on real Collider Ring designs, though both have problems
- Emittance and bunch intensity requirement same for both examples
- 4 TeV luminosity comparable to CLIC’s
- Depth for $\nu$ radiation keeps off site dose < 1 mrem/year
Emittances vs. Stage

- Every stage simulated at some level,
- But with many caveats
6D Ionization Cooling for a Muon Collider

• Lattice arranged as 'Guggenheim' upward helix. Bending gives dispersion.
• Higher momenta pass through longer paths in wedge absorbers giving momentum cooling (emittance exchange).
• Starting at 201 MHz and 3 T, ending at 805 MHz and 10 T.
  e.g., 805 MHz 10 T cooling to 400 mm mrad.

• At all stages, simulated RF is in significant external magnetic fields.
• But experiments have shown severely reduced gradients in specified fields.
• Explanation and solutions are subject of seminar.
• But first a digression on breakdown models without magnetic fields.
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)

![Graph showing Local Field / $\alpha$ (GV/m) vs. Strength (MPa)]

- Vac 11 GHz WG
Melting Model  

(Greg Loew et al)

\[ \Delta T \propto \left( \frac{j_0^2 A \rho}{2 K \Omega} \right) \]

\[ j \propto E_{\text{local}}^{10} \]

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

Breakdown in waveguides at 11 GHz  

(Valery Dolgashev & Sami Tantawi)
Returning electrons model  (Perry Wilson)

- Perry proposed that electrons from a plasma spot return to their source, further heating it, and causing the breakdown

**40 MV/m without external magnetic field**

\[\phi_0 = 100^\circ\]  \[\phi_0 = 115^\circ\]  \[\phi_0 = 80^\circ\]  \[\phi_0 = 45^\circ\]  \[\phi_0 = 0^\circ\]  \[\phi_0 = 135^\circ\]

Trajectories of electrons with different initial phases relative to RF field

- In Romanov (and our) simulation of 805 MHz without magnetic field: no electrons return to their source
Breakdown with Magnetic Fields

805 MHz multi cell cavity in 4.5 T solenoid

- Cavity was asymmetric in magnet & field lines did not link high gradient to high gradient
- There was no effect on max gradient \( \approx 50 \text{ MV/m} \)
- 10 mill Ti window was damaged where electrons were focused, and vacuum lost
805 MHz Pillbox cavity in 4.5 T solenoid

- 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 (≥21 MV/m)
  Consistent with 805 data scaled $\propto \sqrt{f}$: $\beta_{FN} 183 \rightarrow 366$
- With magnetic field, $E \approx 10$ MV/m: down another factor of 2
- Without field, after runs with B, max grad $E \approx 15$ 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

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

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

Field emission

$E$ (MeV)

phase (deg)
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 $D = K/\rho C_s$

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

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

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

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

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

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.
• The highest currents must be somewhat above this: say 2 mA
• Could only 2 mA be enough to do damage

• The energies involved are of order 1 MeV giving powers of 2000 W
• For 20 micro-seconds this deposits \(0.04\, \text{J}\)

• The penetration depth in Cu is 0.4 mm
• The transverse thermal diffusion length is 0.08 mm
• So the minimum volume that a focused beamlet must melt is \(0.4 \pi \times 0.08^2 = 0.008\, (mm^3)\)
• And the energy to melt this volume is \(0.016\, \text{J} < 0.04\, \text{J}\)

• Which seems ok
Caveats

• Tracks only simulated from single maximum gradient location
• Thermal diffusion calculation ignored rise time shape and used an approximate calculation
• Both current scale, and space charge strength, normalized to fit data
• Multi-pacter studies only starting now

• Cavel studies will look at more locations
• SBIR proposal with Tech-X to study thermal diffusion and material damage
• Multi-pacter studies at SLAC
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
- 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 \( B=0 \): \( \mathcal{E} = 21 \) 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 to \( \beta_{FN} = \frac{21}{15} \times 366 = 512 \)
201 MHz prediction with $\beta = \times \frac{21}{15}$

- 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
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 → 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
PROPOSED EXPERIMENTS

1) Simple pillbox in two orientations in magnet

- Simplest Experiment
- SLAC study indicates no Multipacter for angles less than 7 deg
2) True Magnetically Insulated 805 MHz Cavity Experiment

- Poor cavity shape
- But ok for first experiment
Wind coils on cavity structure

- Initially, coils would be pulsed copper for $B=1\ T$
- Later HTS at 65 degrees for $B=3\ T$
- SBIR proposal with Muons Inc
3) Three cell experiment with bucking coils

- Face real technical challenges
  - Establish thin vacuum insulation between coils (4 deg) and cavity (77 deg)
  - Support coils with little prestress: argues for use of HTS
  - Establish cavity to cavity joint (although vac both sides
  - Establish realistic power coupler
Design real lattice for final 6D cooling
805 MHz & 12 T compare with simulated version

- Upper figure is from slide 2
- Lower figure shows current magnetically insulated design
- Design SBIR proposal with PBL
CONCLUSION

• Muon colliders need rf in magnetic fields for ionization cooling
• 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)

• Needed experiments
  – Gas filled cavity in ionizing beam
  – Simple pillbox in 2 orientations
  – Simple magnetically insulated cavity
  – 3 cell magnetic insulation test