Study of vacuum RF Breakdown in strong magnetic field

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Outline

• Statement of the problem

• Model explaining deterioration of gradient in strong B field

• Modular cavity program

• Experimental results

• Analysis
It was experimentally shown that presence of multi-Tesla magnetic increases the breakdown rate

\[ \text{Safe operating gradient} = \text{maximum gradient:} \quad \text{breakdown rate} < 10^{-5} \]
Model explaining deterioration of gradient in strong B fields

- Electron field emission from surface imperfections
- B field focuses dark current into beamlets
- Beamlets cause pulsed heating that leads to surface damage

Potential mitigations:

- Surface treatment
- Use higher radiation length materials (Be)
- Decrease impact energy of electrons
  - Longer RF gap
  - Change B || E configuration

Mechanical stress on the metal is induced due to temperature rise

\[ \Delta T_s \] - safe pulse heating temperature for copper

\[ \Delta T_d \] – required temperature for surface fracture

Temperature rise model for 805MHz copper pillbox


Model prediction of max safe gradient in external magnetic field \( G_s \)
Model of a breakdown in strong B field – prediction vs experiment

High power behavior of previous cavities

Factors that may affect the fit quality:
- Conditioning history
- Local field enhancement around coupler regions
- Surface treatment

Study of breakdown with better control over systematic error is required.
Modular cavity

- End walls can be un-mounted easily, allows for material swap
- The gap length can also be varied by replacing the cavity body
- Low E fields in the coupler region
- 805MHz, pillbox geometry
- Water cooling lines
Modular cavity: measurements

- Maximum safe operating gradient in zero and non-zero external B field
- Surface damage formation process dependence on the run conditions
- Effect of high power conditioning sequence on breakdown in strong magnetic fields
- Field emission study to verify the model of beamlet heating (Be endplate program)
- Surface evolution studies
Mucool Test Area (MTA)

Facility built specifically for muon cooling hardware R&D

- Capacity to test 201 and 805MHz cavities in fields up to 5T
- H-beamline can be commissioned through the center of the magnet bore
- Infrastructure for clean room assembly and inspection
- Extensive instrumentation for BD characterization
- Run control system to detect breakdown events and record relevant data streams

Recent experimental programs

- 805MHz: Modular cavity, high-pressure gas-filled cavity
- 201MHz: pillbox MICE cavity

MTA hall: solenoid magnet with inserted 805MHz modular cavity
Spark detection algorithm

Automated system for spark detection - logical OR between:

- Abrupt drop in pickup voltage
- Flash of light from optical ports
- Early spike in reflected power

![Graph showing normal and breakdown events](image-url)
# Figures of merit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range of values</th>
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<tbody>
<tr>
<td>Frequency</td>
<td>805MHz</td>
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<tr>
<td>Mode</td>
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<tr>
<td>Pulse length</td>
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<td>Repetition rate</td>
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<tr>
<td>Stored energy</td>
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<td>Quality factor</td>
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<td>Pillbox gap length</td>
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<td>Pillbox radius</td>
<td>15cm</td>
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<tr>
<td>Vacuum pressure</td>
<td>~10^{-8} Torr</td>
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</tbody>
</table>
Copper endplates experimental program
High-power runs with copper endplates: summary

• First B=0T run: Apr – Oct 2015
  – Maximum Safe Operating Gradient of 45 MV/m
  – Ran for ~13M pulses, 130 sparks detected

• First B=3T run: Dec 2015
  – Stable operation below 12 MV/m
  – Ran for ~5M pulses, 55 sparks detected

• “Conditioning” B=0T run: Jan – Feb 2016
  – Conditioned up to 22 MV/m
  – Ran for ~14M pulses, 460 sparks detected

• Second B=3T run: Apr 2016
  – Maximum Safe Operating Gradient of order of 10 MV/m
  – Ran for ~3M pulses, 81 sparks detected
Inspection after first $B=0T$ run

- Cavity ran up to ~50MV/m
- **130** breakdown events detected
- Documented ~400 damage features
- Damage is relatively “non-violent” and flat
- No correlation between damage on opposing endplates observed - asymmetry

Examples of most common types of damage

**Type 1**
- Count: > 250

**Type 2**
- Count: 92
First time inspections were carried out separately after run at zero magnetic field and run at high magnetic field.

All clearly visible damage was inflicted during B=3T run (!)
Typical BD pits

- Similar to BD damage we observed in other cavities
- Characteristic pit diameter ~1.5mm
- Traces of splashing
Inspection after $B=3T$ run: 3D imaging

- Damage is much more “violent” than after $B=0T$
- Melted bulk of copper
- Craters up to ~0.5mm in diameter and up to ~60um in depth
- SEM analysis will be possible in the future
Damage microstructure

Crater edges

Core center
Inspection after B=3T run: damage pattern

- Perfect 1-to-1 correspondence between 168 pits on each endplate
- Detected 55 sparks, but observed 168 damage sites
- Damage distribution is in agreement with E(R) dependence

Map of damage pits
Inspection after B=0T conditioning run

Processed up to 22MV/m in >10M pulses, inflicting ~460 sparks

No new damage sites observed
Some splashing traces disappeared

Microscopic image of splashing pattern after B=3T run
Closer look at splashing patterns

Melted copper “drops”

- Features that are being processed out during conditioning
- Splashes mostly lack directionality, often ~cm away from closest BD pit
- Characteristic time to solidify and cool down: 0.1 – 1s

300 µm
Common type of damage feature – splash with hollow center

(Units – microns)
We observed drastically different damage after $B = 0T$ and $B = 3T$ runs, which implies different energy deposition mechanisms. Does the data support it?

**Envelope of pickup signal during breakdown event**

**Decay time – exponential fit**

**Decay time**
Energy dissipation during breakdown events

• Decay time in B=3T is 30% smaller on average → Implies that energy deposition mechanism is more efficient in strong magnetic field

• That is what we have expected to see
  1. Based on “violent” type of damage we observed in B=3T
  2. Due to focusing of dark current beamlets: higher arc currents and hence lower impedance

Decay times for sparks in zero and 3T external magnetic field
Acoustic spark localization

- Goal: correlate location and time of each spark. That would help in understanding the surface evolution processes during operation.

- Microscopic surface inspection gives answers to the first one

- Spark detection system is responsible for the latter

- Acoustic system is aiming to bridge the gap between these two

Downstream endplate with microphones attached
Acoustic predictions

Recall: perfect one-to-one damage match

Acoustic predictions map: corresponding locations connected

- All predictions are within 7cm from the center of the endplate (R=14cm) – good agreement with damage distribution
- Error bar of measurement ~ 2cm
Be endplates experimental program
Be endplate program: motivation

Radiation length of Beryllium (~35cm) for electrons in MeV energy range is significantly higher than of copper (~1.4cm)

According to our model, that implies less effect of dark current electrons on a surface and hence, potentially lower breakdown rates per gradient.

Measurements enabled by Beryllium:

- Direct measurement of dark current (Faraday Cup)
- Dark current transverse emittance (film/glass)
- Study of surface evolution
First B=0T high-power run results

- Safe operating gradient of 37MV/m established
- 11M RF pulses accumulated
- Detected 160 breakdown events
- Observed ~ 135 damage spots (subjective counting)

Asymmetry between endplates’ damage

Damage distribution map

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Conclusion

• Cavity behaves as intended to:
  – Providing reproducible measurements
  – Allows for relatively fast inspection (turnaround of ~week)
  – Breakdown happens where we want it to happen

• Surface inspection revealed unique damage characteristic of operation in B=3T: violent nature of breakdown pits and perfect one-to-one correspondence between pits on opposing endplates

• Lower radiation length of Be will allow for more detailed field emission and surface evolution studies
Thank you for your attention