New fit to breakdown vs. mag field

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1. Introduction
2. Model
3. Fit to Cu pillbox data
4. Predictions for Be, Al and cold Al
5. A Be test cavity
6. Conclusion
Introduction

• Previous fits and predictions were made assuming:
  – guesses as to relative sizes of beamlet, phase spread and thermal diffusion
  – that the the $\beta_{FN}$ in the pillbox was the same as that determined in the open cavity
  – relative, rather than quantitative, heated temperatures of bombarded surface, & without defining the damage mechanism

• This analysis (a step forward, but needing further work):
  – Assumes damage arises from cyclical heating as observed by SLAC
  – Works backward from the damaging strains to determine beamlet currents
  – Includes PARMELA determination of beamlet size vs. current
  – Determines $\beta_{FN}$ from these currents, for assumed asperity source areas: better than using the FN $\beta = 183$ determined for the open cavity that operated at higher gradients
Data used for this study
Fit is not to guide the eye

\[ \mathcal{E} = B^{-0.42} \]

- Look at parameters for \( \mathcal{E} = 19 \) (MV/m) \( B = 1.7 \) (T)
Energy on arrival at other side
From CAVEL simulation

- For $\mathcal{E} = 19\,\text{MV/m}$ \hspace{1cm} $E_e = 0.5\,\text{MV}$
Note that the power \( n \) is not independent of \( \mathcal{E} \).

It is this that allows \( \beta_{FN} \) to be determined.
Beamlet radius

- Space charge blows the beam up near its source
- Magnetic field transports and focuses
- Beamlet radius from PARMELA: Diktys Talk

\[ R(\mu m) = 22.6 \times \frac{I^{0.33}(\mu A)}{B(T)} \]

For \( I=105 \ \mu m, \ B=1.7 \ T \): \( R=61.6 (\mu m) \)
Phase dependent rms sweep: dxy
From CAVEL simulations

- Shift in x comes from shift in B direction arising from vector sum of rf B(azimuth=x) and external Bz

rmsxy 299.6395 (microns)
\[ dxy = 0.031 \frac{\varepsilon}{B} \sqrt{\frac{10}{n}} \]

- For \( \varepsilon=19 \text{ MV/m} \) \( B=1.7 \text{ T} \) \( n=10.7 \): \( dx = 322 \text{ (\mu m)} \)
- With added diffusion length and spot size: \( dx = 331 \text{ (\mu m)} \)
• Diffusion plays little role at low $B$

• Only significant for $B > 2$ T
Material parameters used

- Pulse length $\tau = 20$ ($\mu$sec)

<table>
<thead>
<tr>
<th>Temp (K)</th>
<th>Cu</th>
<th>Be</th>
<th>Be</th>
<th>Al</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$ (gm/cc)</td>
<td>8.96</td>
<td>1.83</td>
<td>1.83</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>$C_p$ (J/gm)</td>
<td>0.385</td>
<td>1.83</td>
<td>0.10</td>
<td>0.871</td>
<td>0.367</td>
</tr>
<tr>
<td>$K$ (Watts/cm)</td>
<td>4.01</td>
<td>2.18</td>
<td>8.7</td>
<td>2.37</td>
<td>7.28</td>
</tr>
<tr>
<td>$\alpha$ ($10^{-5}$/deg)</td>
<td>1.65</td>
<td>1.03</td>
<td>0.06</td>
<td>2.21</td>
<td>0.92</td>
</tr>
<tr>
<td>$D=0.01\sqrt{K\tau/\rho C_p}$ ($\mu$ m)</td>
<td>48.2</td>
<td>35.9</td>
<td>309</td>
<td>44.8</td>
<td>119.8</td>
</tr>
</tbody>
</table>

E deposition vs. depth

c.f. Diktys talk

Preliminary treatment of thermal diffusion

- Heat deposits are Gaussian in x and y with $\sigma$s from sums in quadrature of:
  - beam dimensions from space charge simulation
  - ln x only: rms sweep from phases
  - Thermal diffusion = $D=0.01\sqrt{K\tau/\rho C_p}$ ($\mu$ m)

The later contribution may be a poor approximation
Current from local temperature rise

- $\tau = 20 \, \mu s \quad \frac{dE}{dx} = 35 \, \text{MV/cm} \quad D = 48.2 \, (\mu \text{m})$
- $R = 61.6 \, (\mu \text{m})$ With added diffusion length and spot size: $dy = 78 \, (\mu \text{m})$
- $dx = 325 \, (\mu \text{m})$ With added diffusion length and spot size: $dx = 335 \, (\mu \text{m})$

$$\Delta T = \left( \frac{2}{\pi} \right) \frac{\tau I \left( \frac{dE}{dx} \right) D}{\pi \, dxy \, R \, D \, C_p \, \rho} = \frac{50}{\text{deg}}$$

$$Strain = \alpha \Delta T = 8.24 \times 10^{-4}$$

- This ignores $T$ and position changes in $C_p$, ok at 273, poor at 80

- To obtain 50 deg we needed $I = 105 \, \mu\text{A}$
  implying $\beta = 398$ for source 30 nm, or 512 for 9 nm
  Are such high $\beta_{FNs}$ reasonable when 183 measured in the open cavity?

  – Correct for lower achieved gradients in pillbox: $52/40 \times 184 = 239$
  – Worst emitter cf. average emitter: $1.66 \times 236 = 398$
  – Or worst emitter cf. average emitter: $2.1 \times 236 = 512$
  – 1.66 seems not unreasonable
  – 2.1 a bit high, but could be true for the damaged cavity
$\mathcal{E}$ vs B for Cu and Be at iris

Having picked source radius and $\beta_{FN}$, we can now determine the $\mathcal{E}$ that will give the same damaging strains at other magnetic fields.

- Shape not strongly dependent on choice of areas and associated $\beta_{FN}$
- This fit, unlike earlier fits, uses observed fields at one B, but not the slope
- Worst fit at high B where crude treatment of thermal diffusion may be reason

\[
\text{strain} = 8.24 \times 10^{-4}
\]

line: $\beta = 398$, $r = 30$ nm
dots: $\beta = 512$, $r = 9$ nm
\( \mathcal{E} \) vs B for Cu and Be on axis

On axis there is no phase dependent sweep in x, and the beam is round and smaller requiring less \( \mathcal{E} \) for damage.

- But if Cu sides are tested in magnetic fields, breakdown should be worse.
- The gradients for Be are above the data, consistent with observed lack of breakdown on axis with Be windows.
Material and temperature effects on Beam sizes

- **B= 4 Cu**
  - Deposition
  - Diffusion
  - Beamlet
  - Diffusion plays modest role in Cu and warm Al

- **B= 4 Be**
  - Deposition
  - Beamlet
  - Diffusion
  - Diffusion plays little role for warm Be
  - But a strong role in cold Al

- **B= 4 Al**
  - Deposition
  - Beamlet
  - Diffusion

- **B= 4 Cold Al**
  - Deposition
  - Beamlet
  - Diffusion
Main effect of lowering temperature is to increase thermal diffusion
So its effect is only seen at high B
Cold Al is significantly better than Cu, but not nearly as good as Be
A Be test cavity design

Joined by tin gasket to allow TiNi coating and inspection. But can be braised if not good enough.

Pocket milled as in pillbox.

At least 6 mm radii.

Bolt pattern as in pill box to allow use of same transition to waveguide.

6 mm Be Plates braised to copper body.

Possible milled circles to 0.5 mm thickness for dark current measurements. These could be omitted initially.

Alternative design if Be plates require stabilizing when the cavity is cooled to nitrogen temperature.
Conclusion

• SLAC has shown that soft copper is damaged when thermally cycled to approximately 50 degrees, corresponding to strains of $0.824 \times 10^{-3}$.

• We assume that damage in cavities operating in a magnetic field are induced by space charge emitted electron beamlets that are focused by the field.

• PARMELA simulations have given space charge induced beamlet radii.

• Data from Los Alamos give quantitative energy depositions vs. depth.

• CAVEL simulations give spread of electron deposition location with initial phase for locations at finite radii.

• Using a crude model for thermal diffusion then gives energy deposition volume and the required currents to yield damage.

• Observed damage at one magnetic field give local field enhancement $\beta$ for a given source area.

• With no further assumptions, we can predict the field dependence of damage thresholds on axis and at finite radii for Cu, Be, Al and cold Al.
Conclusion (2)

- This analysis indicates $\beta_{FN}=398$ for a source radius of 30 nm, or higher for smaller source areas. This is higher than that measured in the open cavity, but is not unreasonable for a worst asperity in the damaged cavity.

- The beamlet radii for Cu and Al are relatively large, and greater than the diffusion length for fields less than 1.7 T.

- The beamlet radii for Be are even larger, and greater than the diffusion length for all fields.

- Be is much better than Cu because energy loss is low.

- Al and cold Al are better than Cu, but by much less than for Be.

- Remaining tasks are:
  - Gain access to a code to provide 3 dimensional energy depositions.
  - Develop a 3 dimensional thermal diffusion code to replace the current crude model.
  - Integrate temperature rise with changing $C_p(T)$.
  - Make predictions for 201 MHz.