Quench and high field q-slope studies using a single-cell cavity with artificial pits

Yi Xie
Superconducting RF group, Cornell University
Now at Euclid Techlabs LLC.
This talk is adapted from part of my PhD defense presentation at Cornell University
Development of Superconducting RF Sample Host Cavities and Study of Pit-induced Cavity Quench

Yi Xie

Department of Physics, Cornell University

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Outline

• Pit cavity experiment;
  ➢ Motivation and experiment setup;
  ➢ Experiment results and analysis;
  ➢ Key achievements:
    Proves that pit with sharp edge will cause quench;

• Conclusions;

• A general rf heating simulation code for SRF community.

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Why study pits

Pits are identified as sources of quench mostly below 25MV/m. Some pits will cause cavity to quench but some bigger pits don’t cause quench.

Open question: Why some pits cause quench, some are not? What are the relevant parameters?

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A possible explanation: Magnetic field enhancement (MFE) at pit edges
A possible explanation

Due to magnetic field enhancements at the pits edge, some of the smaller pits with sharp edges may reach Nb superheating field **earlier** than some bigger pits with shallow edges;

\[
\beta \propto \left(\frac{r}{R}\right)^{-1/3}
\]

Valery Shemelin and Hasan Padamsee’s initial idea and then I redid the pits simulation using ACE3P

New calculation see TUP008

500 um
Magnetic field enhancement factor calculation by ACE3P using a 3-d model. The fit equation is $\beta = 1.17 \times (r/R)^{-1/3}$. 
Current flow

Magnetic field enhancement near the pit edge.
To systematically study pits, we need statistics, so I made a cavity with lots of artificial pits with different sizes $R$. 
I artificially created pits with five sizes on a single cell Nb cavity, three of them on each half cup before welding, all together 30 pits;

Radius: 200 μm, 300 μm, 400 μm, 600 μm, 750 μm;
Depth: 1.5mm;

The cavity received 120um BCP and in-situ 120 C bake;
T-map

- For every pit, I used Cornell single-cell T-map system to record the temperature rise as a function of magnetic field;
- The cavity reached \( \sim 550 \) Oe (55 mT) on the quenched pits surface;

\[ \sim 650 \text{ sensors, n}\Omega \text{ sensitivity!} \]
A typical T-map at ~ 500 Oe (50 mT)
Note the bigger pits shows bigger heating
The quench locations were found by measuring the length of time that the resistors stayed warm after the quench of the cavity.
For two quenched pits, both show gradual heating until sudden jump to ~ 1K range, which may indicates pits go normal conducting;
Normal conducting region exists!

My ring-type defect model simulations show that **there is a thermally meta-stable state below quench field** for pit-like defects. At this state, only the edge of the pits will get normal conducting.

Normal conducting region, \( T = 5.76\text{K} \) > \( T_c = T_{c0} \cdot \sqrt{1 - H/H_0} = 5.4\text{K} \), Here \( H \) is slightly below quench field.
For the quenched pits, \( R \sim 750 \, \mu\text{m}, \ r \sim 10 \, \mu\text{m} \), using MFE formula we can get MFE factor \( \sim 4 \). Which is in good agreement with pits cavity quench field 55 mT (assuming Nb superheating field \( \sim 200 \, \text{mT} \))!
Laser confocal microscopy was used to obtain the precise Values of pit edge radius r.

Since magnetic field is parallel to cavity equator, so edges of pits perpendicular to the direction of the magnetic field show highest fields due to MFE effect. So we only sample area indicated above.
Range of pit edge radius $r$ of three pits with the biggest drill bit radius $R = 750 \, \mu m$
<table>
<thead>
<tr>
<th>Pit number</th>
<th>Pit drill radius ($\mu$m)</th>
<th>Range of pit edge radius $r$ ($\mu$m)</th>
<th>Range of pit radius $R$ ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#30</td>
<td>750</td>
<td>5~30</td>
<td>850~900</td>
</tr>
<tr>
<td>#27</td>
<td>750</td>
<td>20~55</td>
<td>880~900</td>
</tr>
<tr>
<td>#28</td>
<td>750</td>
<td>15~45</td>
<td>820~850</td>
</tr>
<tr>
<td>#23</td>
<td>600</td>
<td>30~60</td>
<td>520~550</td>
</tr>
<tr>
<td>#24</td>
<td>600</td>
<td>25~60</td>
<td>580~610</td>
</tr>
<tr>
<td>#22</td>
<td>600</td>
<td>5~45</td>
<td>570~610</td>
</tr>
<tr>
<td>#19</td>
<td>600</td>
<td>20~55</td>
<td>550~600</td>
</tr>
<tr>
<td>#20</td>
<td>600</td>
<td>35~60</td>
<td>570~600</td>
</tr>
<tr>
<td>#7</td>
<td>300</td>
<td>20~50</td>
<td>280~310</td>
</tr>
<tr>
<td>#6</td>
<td>200</td>
<td>25~55</td>
<td>180~210</td>
</tr>
<tr>
<td>#2</td>
<td>200</td>
<td>35~60</td>
<td>190~200</td>
</tr>
</tbody>
</table>

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How does magnetic enhancement model apply to those pits geometrical information
### MFE at pit edges

<table>
<thead>
<tr>
<th>Pit number</th>
<th>Pit drill radius ($\mu$m)</th>
<th>Range of pit edge radius $r$ ($\mu$m)</th>
<th>Range of pit radius $R$ ($\mu$m)</th>
<th>Range of magnetic field enhancement factor $\beta = 1.17*(r/R)^{-1/3}$</th>
<th>Range of local magnetic fields at $H_{pk}$ reached in the pit cavity (Oe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#30</td>
<td>750</td>
<td>5~30</td>
<td>850~900</td>
<td>3.6~6.6</td>
<td>1940~3560</td>
</tr>
<tr>
<td>#27</td>
<td>750</td>
<td>20~55</td>
<td>800~850</td>
<td>2.9~4.1</td>
<td>1560~2210</td>
</tr>
<tr>
<td>#28</td>
<td>750</td>
<td>15~45</td>
<td>790~810</td>
<td>3.0~4.4</td>
<td>1620~2370</td>
</tr>
<tr>
<td>#23</td>
<td>600</td>
<td>30~60</td>
<td>520~550</td>
<td>2.4~3.1</td>
<td>1290~1670</td>
</tr>
<tr>
<td>#24</td>
<td>600</td>
<td>25~60</td>
<td>580~610</td>
<td>2.5~3.4</td>
<td>1350~1830</td>
</tr>
<tr>
<td>#22</td>
<td>600</td>
<td>5~45</td>
<td>570~610</td>
<td>2.7~5.8</td>
<td>1460~3130</td>
</tr>
<tr>
<td>#19</td>
<td>600</td>
<td>20~55</td>
<td>550~600</td>
<td>2.5~3.6</td>
<td>1350~1940</td>
</tr>
<tr>
<td>#20</td>
<td>600</td>
<td>35~60</td>
<td>570~600</td>
<td>2.5~3.0</td>
<td>1350~1620</td>
</tr>
<tr>
<td>#7</td>
<td>300</td>
<td>20~50</td>
<td>280~310</td>
<td>2.1~2.9</td>
<td>1130~1560</td>
</tr>
<tr>
<td>#6</td>
<td>200</td>
<td>25~55</td>
<td>180~210</td>
<td>1.7~2.4</td>
<td>910~1290</td>
</tr>
<tr>
<td>#2</td>
<td>200</td>
<td>35~60</td>
<td>190~200</td>
<td>1.7~2.1</td>
<td>910~1130</td>
</tr>
</tbody>
</table>

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MFE theory suggests that the edge of pit #30, #28, #22 will go to normal conducting first, is it that true?
Heating vs magnetic field level for pit #30

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Heating vs magnetic field level for pit #28
Heating vs magnetic field level for pit #22
MFE theory suggests that the edge of pit \#27 will go normal conducting at higher fields compared with pit \#30, \#28, Is it that true?
Heating vs magnetic field level for pit #27
pit #30

pit #28

pit #27
For different size pits, it appears heating generally increases along with pit diameter \( R \) which is also consistent with MFE model since our bigger pits have bigger MFE factor.
Non-quench pits

Ohmic heating

Pit #2

Pit #6

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Non-quench pits

Field dependent BCS resistance

Ohmic heating

$R_s \sim H^{2}$

$R_s \sim H^{4\sim6}$

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Non-quench pits

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Non-quench pits

$\begin{align*}
\text{Fit 1} & : y = 8.497x - 54.34 \\
\text{Fit 2} & : y = 5.82x - 37.85
\end{align*}$

pit #24

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<table>
<thead>
<tr>
<th>Pit number</th>
<th>Slope of $\ln(\Delta T/K)$ vs $\ln(H_{pk}/Oe)$ in field region I ($H_{local} &lt; 800$ Oe)</th>
<th>Slope of $\ln(\Delta T/K)$ vs $\ln(H_{pk}/Oe)$ in field region II ($800 &lt; H_{local} &lt; 1300$ Oe)</th>
<th>Slope of $\ln(\Delta T/K)$ vs $\ln(H_{pk}/Oe)$ in field region III ($H_{local} &gt; 1300$ Oe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#27</td>
<td>~ 2</td>
<td>6.2</td>
<td>4.3</td>
</tr>
<tr>
<td>#28</td>
<td>~ 2</td>
<td>10.0</td>
<td>5.0</td>
</tr>
<tr>
<td>#23</td>
<td>~ 2</td>
<td>8.3</td>
<td>4.2</td>
</tr>
<tr>
<td>#24</td>
<td>~ 2</td>
<td>8.4</td>
<td>4.8</td>
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<tr>
<td>#19</td>
<td>~ 2</td>
<td>7.8</td>
<td>4.1</td>
</tr>
<tr>
<td>#20</td>
<td>~ 2</td>
<td>8.1</td>
<td>4.6</td>
</tr>
<tr>
<td>#7</td>
<td>~ 2</td>
<td>8.5</td>
<td>4.0</td>
</tr>
<tr>
<td>#6</td>
<td>1.92</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>#2</td>
<td>1.97</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Non-quench pits

- Low field: \( H^2 \) heating;
- Higher field: with the magnetic field to a power of 4 to 6 at medium fields, and with a power of \( \sim 2 \) of the high fields above 1300 Oe;
- The transition to field dependent surface resistance happens at fields similar to where the high field Q-slope starts in BCP cavities (\( \sim 900 \) Oe);
- The pit heating data shows that a BCP cavity surface can reach high fields close to the superheating field.
• Pit cavity experiments and simulations verify that MFE enhancement will cause pit edge nc first. Then the nc will spread and cause the whole cavity quench. Pit cavity is able to separate thermal effects from q-slope information.

• Pit cavity is a powerful tool to explore basic SRF niobium materials properties.

• Repeat what I did, just EP the cavity, see what the slope looks like.
Acknowledgement

• Thanks to my advisors Profs. Matthias Liepe, Hasan Padamsee and Georg Hoffstaetter;
• Thanks to my fellow graduate students Dan Gonnella, Sam Posen for the help of pit cavity test, thermometry system; Thanks Ge Mingqi, F. Barkov and A. Romenenko for help on laser confocal microscopy.
• Thanks to entire Cornell SRF group!

Thank you for your attention!

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Advertisement for a general rf heating simulation code
Welcome! Select a model and enjoy!

Simple Model 1-D
Disk Defect 2-D
Ring Defect 2-D
Multi-layer 2-D

Edit parameters

When running this sign will appear

I'm busy. Don't click!

After calculation results is shown in these tables
Disk defect temperature distribution
• Four running modes;
  - Simple defect free 1-D;
  - Defect case with disk-type and ring-type;
  - Multilayer cases: niobium on copper, Gurevich’s coating;

• User can define niobium/helium properties (modular);
  - Basic: $\text{RRR, R}_0, f, \text{PMFP} \Rightarrow \text{Rbcs, Kappa, Kapitza}$
  - Advanced: user can write their own $\text{Rbcs/Rres, Kappa and Kapitza resistance formula}$;

• User can define mesh configurations;
  - Flexible control mesh density near defects or the different layers;
Application examples

- Fermilab crab cavity version: wall thickness;
- Fermilab 650 MHz: RRR selection;
- Will nitrate coating affect niobium outside surface thermal properties?
- Material and thickness choices for niobium-copper and multilayer-coating;
- More important: defect and quench modeling;

You can download the whole code (include sources):
https://www.dropbox.com/sh/3qtzz4tpvq458hr/cNqY7UrLTc