The Superheating Field of Niobium: Theory and Experiment

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Outline

• Critical Fields of Superconductors
• Survey of Previous Work
• New Results from Cornell on the Superheating Field
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• Type-I: Meissner State below applied field $H_c$, normal above

• Type-II: Meissner State below $H_{c1}$. Energetically favorable to enter mixed state below $H_{c2}$. Normal above $H_{c2}$.

• $H_{c3}$ is a surface effect: bulk is normal, but surface layer ($\sim \xi$) superconducting.
## Critical Fields of Superconductors

<table>
<thead>
<tr>
<th>Critical Field</th>
<th>Value at 0K (mT)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bc</td>
<td>200</td>
<td>Finnemore; Casalbuoni</td>
</tr>
<tr>
<td>Bc1</td>
<td>174</td>
<td>Finnemore</td>
</tr>
<tr>
<td>Bc1</td>
<td>190</td>
<td>C. Vallet</td>
</tr>
<tr>
<td>Bc2</td>
<td>390</td>
<td>Casalbuoni</td>
</tr>
<tr>
<td>Bc2</td>
<td>400</td>
<td>Finnemore</td>
</tr>
<tr>
<td>Bc2</td>
<td>410</td>
<td>Saito</td>
</tr>
<tr>
<td>Bc2</td>
<td>450</td>
<td>C. Vallet</td>
</tr>
</tbody>
</table>
Raindrops: the Liquid-Gas Transition

“Superheating” like 110% humidity

Metastable

energy barrier B

droplet nucleation

$R^2$ surface tension cost

$R^3$ bulk energy gain

J. Sethna, Cornell University
Can we calculate the phase diagram for $H_{sh}$?
Why is there a barrier to vortex penetration?

Why a superheating field?

Costly core $\xi$ enters first; gain from field $\Lambda$ later

Coherence length: Decay of $\Psi$

Energy cost

Penetration depth: Decay of $H$

J. Sethna, Cornell University
• Why do we care?
  – $H_{sh}$ sets the ultimate physical limit for surface fields
  – $H_{sh}$ can be effected by surface treatments
  – Metastability is an interesting phenomenon to study
• Critical Fields of Superconductors
• Survey of Previous Work
• New Results from Cornell on the Superheating Field
Most $H_{sh}$ work based on Ginzburg-Landau Theory

$$H_{sh}(T) = c(\kappa)H_c \left(1 - \left(\frac{T}{T_c}\right)^2\right)$$

GL solved in 1D case

- $H_{sh} \approx \frac{0.89}{\sqrt{\kappa_{GL}}} H_c$ for $\kappa_{GL} \ll 1$
- $H_{sh} \approx 1.2H_c$ for $\kappa_{GL} \approx 1$
- $H_{sh} \approx 0.75H_c$ for $\kappa_{GL} \gg 1.$

- Asymptotic expansion (Dolgert et. al.)
Superheating in pure superconducting niobium *

J. C. RENARD and Y. A. ROCHE
Alcatel, Bruyères le Châtel 91, France

Received 28 March 1967

We present experimental evidences of superheating in pure niobium: our results are in agreement with a superheating field larger than $H_c$.

Magnetization curves of Nb cylinders at 4.2K showing $H_{sh} > H_c$.
Type-I and Type-II superconducting spheres near $T_c$. Yogi (1976)
H$_{sh}$: First measurement of Temperature Dependence

Hays Measurement of H$_{sh}(T)$ for Nb (1995)

Ginsburg-Landau Theory for H$_{sh}$

Data from Hays (1995)
• Critical Fields of Superconductors
• Survey of Previous Work
• New Results from Cornell on the Superheating Field
Validity versus complexity

### Ginzburg-Landau (GL)
- $\psi(r), H(r)$ order parameters
- Spatial dependence OK
- *Valid only near $T_c$*

### Bardeen Cooper Schrieffer (BCS) theory
- Pairing $k, -k$ within vibration energy
- Excellent for traditional superconductors
- $H_{c1}(T), H_{c2}(T)$ done
- $H_{sh}(T)$ hard (spatial dependence)

*J. Sethna, Cornell University*
Validity versus complexity

Eilenberger Equations
- Valid at all temperatures
- Assumes $\Delta(r), H(r)$ vary slowly

Eliashberg equations
- Needs electronic structure
- Never done before for $H_{sh}$

J. Sethna, Cornell University
Ginzburg-Landau

Eilenberger near Tc – Mark Transtrum

Theoretical $H_{sh}$ Work

February 20, 2012

N. Valles. 15th International Conference on RF Superconductivity (2011)
Hsh(T), Large $\kappa$

Eilenberger Eqns, $\kappa >> 1$. Sethna, Catelani
• Solving the Eilenberger equations are hard, especially for moderate or small $\kappa$
• Experimental measurements are necessary to help guide theory

$$H_{sh}(\kappa \sim 1), \text{ convergence}$$

![Graph showing $c(\kappa \sim 1) \equiv H_{sh}/H_c$ vs. number of points on Fermi Surface for different temperatures.](image)

- $T = 0.200 T_c$
- $T = 0.975 T_c$
LR1-3 to measure Superheating Field
Hsh(T) Measurement

Re-entrant cavity prep:
• Vertical EP
• 2 hr HPR, clean assembly
• 120C bake for 48 hr

LR1-3 to measure Superheating Field
Boeing Klystron supplies high power pulses

- $P_f \sim 1.5$ MW
- $Q_{\text{ext}} \sim 6 \times 10^6$
- Ramp up power quickly (100 $\mu$s) to minimize thermal effects
• Following Hays we can write:

\[
P_f = P_r + \frac{\omega U}{Q_0} + \frac{dU}{dt} \quad \text{and} \quad \sqrt{P_r} = \sqrt{P_f} - \frac{\omega U}{Q_{ext}}
\]

which gives

\[
\frac{\omega U}{Q_0} = 2 \sqrt{\frac{\omega U P_f}{Q_{ext}}} - \frac{dU}{dt} - \frac{\omega U}{Q_{ext}} \quad \text{or}
\]

\[
\frac{1}{Q_0} = \frac{2}{\omega \sqrt{U}} \left( \sqrt{\frac{\omega P_f}{Q_{ext}}} - \frac{d \sqrt{U}}{dt} \right) - \frac{1}{Q_{ext}}
\]
Measuring Hsh

[Graphs showing magnetic field and intrinsic quality factor over time, with axes labeled appropriately.]
Measuring Hsh

- **Surface Magnetic Field [mT]**
- **Klystron Power [MW]**
- **Intrinsic Quality Factor**

- **Time [µs]**

90% SC
Determining $\kappa$ in CW

SRIMP Fit: MFP = 27 nm. $\kappa = 3.5$
Fit: $c(\kappa) = 1.04 \pm 0.01$
Transtrum: $H_{sh}(\kappa)$

\[ \kappa = 3.5 \]
Possibility for 20% increase by changing $\kappa$
Baking lowers mean free path (and thus $\kappa$) by introducing surface impurities.

\[
\kappa(\ell) = \frac{\lambda_L}{\xi_0} \left( \frac{\xi_0 + \ell}{\ell} \right)^{3/2}
\]
Re-entrant cavity prep:
• 800 C bake, 2 hr
• Vertical EP
• 2 hr HPR, clean assembly
• NO 120C bake

LR1-3 to measure Superheating Field
Severe Q drop at low fields.
Small radiation, no quenches
$H_{sh}(T) = c(\kappa)H_c \left(1 - \left(\frac{T}{T_c}\right)^2\right)$

c(\kappa) = 1.28 \pm 0.06

(Theory predicts 1.30) $\kappa$ clearly changed!
Conclusions

• We now have a measurement showing the full temperature dependence of $H_{sh}$
• GL theory is surprisingly accurate over the full temperature range
• Surface treatments strongly influence $H_{sh}$
• There appears to be a trade-off between removing high field Q-slope and high superheating field
  – Alternative to 120C bake?
• Eilenberger theory appears to give a small increase to $H_{sh}$ at low temperatures
• $H_{sh}$ measurements are a place where experiment can really drive theory
• More work needs to be done to ensure the convergence of the Eilenberger eqns for $T << T_c$
• Can we reproduce these results for new materials such as Nb$_3$Sn or MgB$_2$?
The Future of $H_{sh}$

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- $H_{sh}$ measurements are a place where experiment can really drive theory.
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- Can we reproduce these results for new materials such as Nb$_3$Sn or MgB$_2$?

February 20, 2012

Sam Posen at Cornell is currently making Nb$_3$Sn. THPO066

$H_{sh}$ measurements to follow

N. Valles. 15$^{th}$ International Conference on RF Superconductivity (2011)
Thanks

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  - Matthias Liepe, Hasan Padamsee, and Zachary Conway for great help with experimental measurements
  - James Sethna and Mark Transtrum for temperature dependence from Eilenberger Theory
References

2 Boato, G., G. Gallinaro, and C. Rizzuto (1965), Solid State Communications 3 (8), 173.
4 Campisi, I. E., and Z. D. Farkas (1984), SLAC AP-16.
20 de Gennes, P. G. (1965), Solid State Communications 3 (6), 127.
22 Halbritter, J. (1970), KAROLA - OAVolltextserver des Forschungszentrums Karlsruhe (Germany).
26 J.A. Crittenden, e. a. (2009), in Particle Accelerator Conference.
33 Saito, K. (2004), in Pushing the Limits of RF Superconductivity Workshop.
34 Sethna, J., and M. Transtrum (2009), Personal Communication.
35 Shemelin, V. (2005), in The 2005 Particle Accelerator Conference.