# 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

- **Critical Fields of Superconductors**
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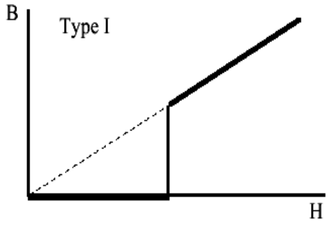
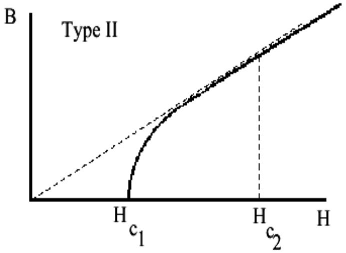
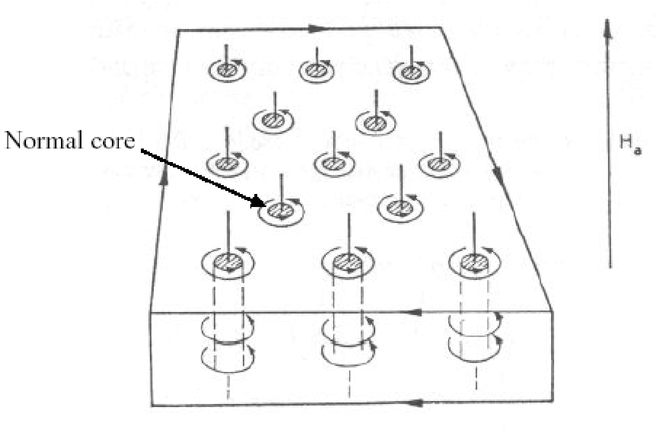
# Critical Fields of Superconductors

- Type-I: Meissner State below applied field Hc, normal above
- Type-II: Meissner State below Hc1. Energetically favorable to enter mixed state below Hc2. Normal above Hc2.
- Hc3 is a surface effect: bulk is normal, but surface layer (~ξ) superconducting.





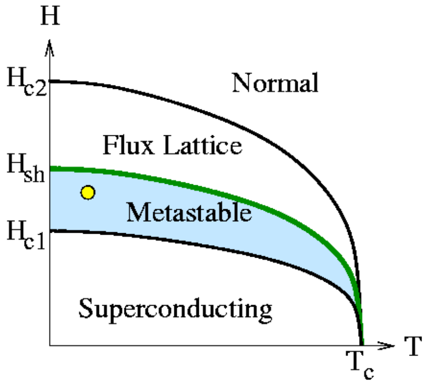


# Critical Fields of Superconductors

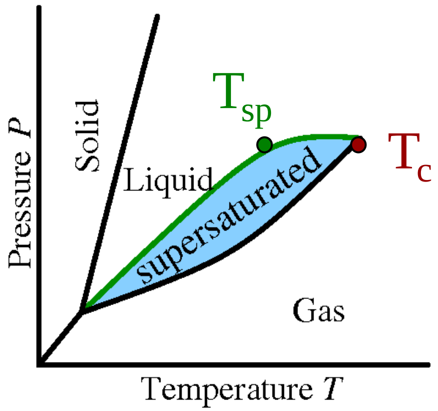
| Critical Field | Value at 0K (mT) | Reference |
|---|---|---|
| Bc | 200 | Finnemore; Casalbuoni |
| Bc1 | 174 | Finnemore |
| Bc1 | 190 | C. Vallet |
| Bc2 | 390 | Casalbuoni |
| Bc2 | 400 | Finnemore |
| Bc2 | 410 | Saito |
| Bc2 | 450 | C. Vallet |

# Superheating Field: Metastability and Nucleation

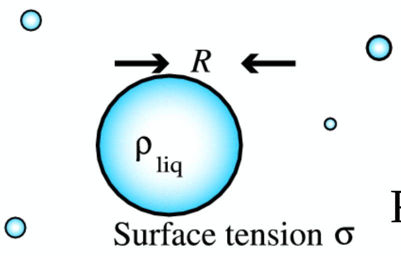
## Raindrops: the Liquid-Gas Transition



"Superheating" like
110% humidity

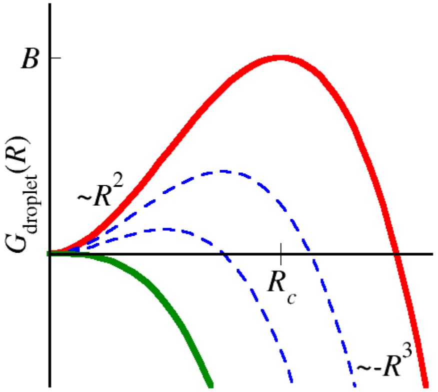


Gas phase metastable for
**$T_c$ > T > $T_{sp}$**, spinodal temperature



**Metastable**

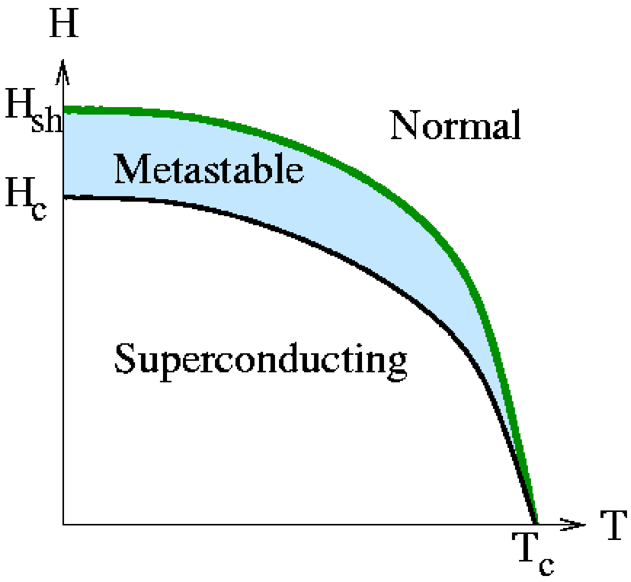
energy barrier B
droplet nucleation
$R^2$ surface tension cost
$R^3$ bulk energy gain



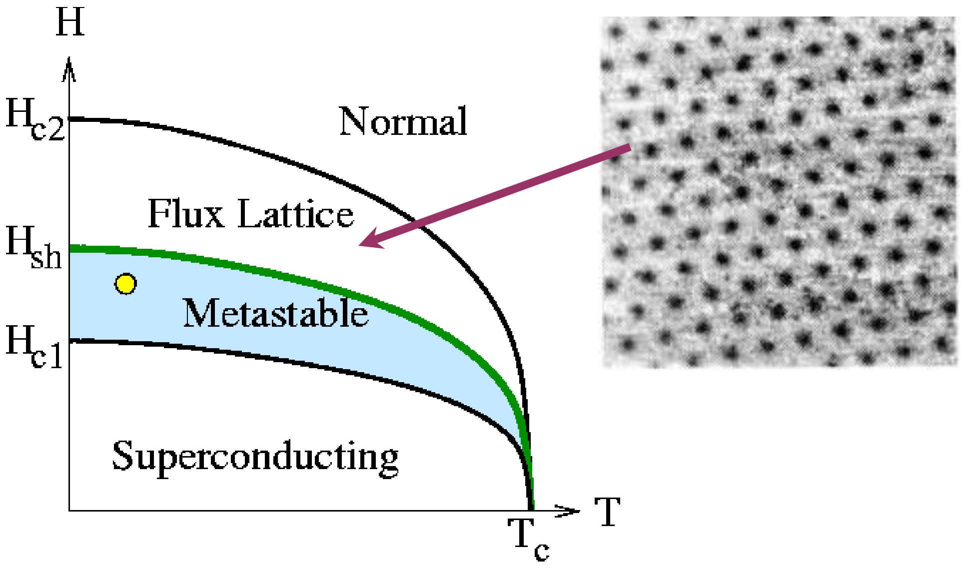
***J. Sethna, Cornell University***

# Superconductors & Magnetic Fields

## Type I (Pb)



## Type II (Nb and $Nb_3Sn$)



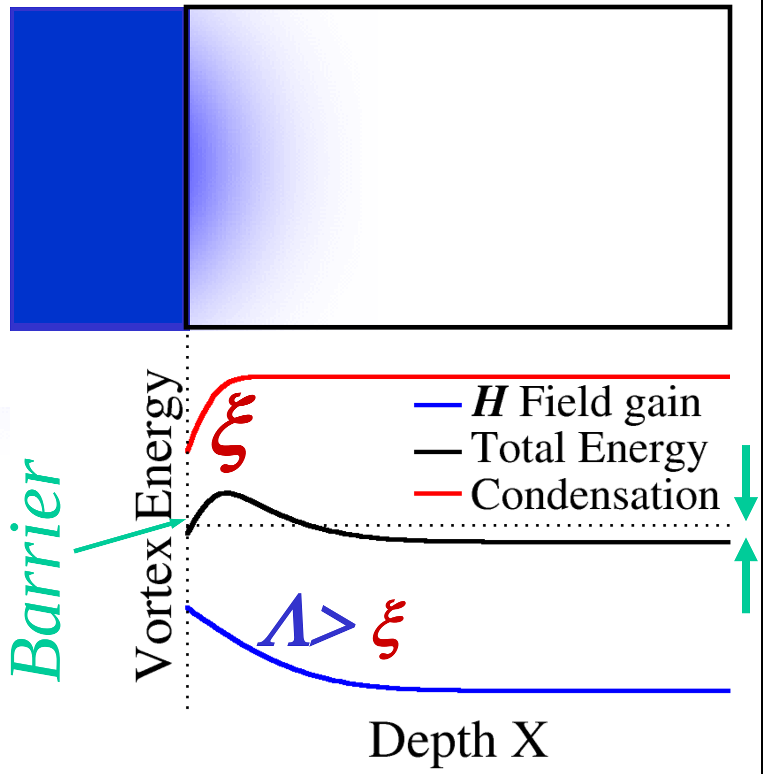
***J. Sethna, Cornell University***

Can we calculate the phase diagram for $H_{sh}$?

# Metastability Threshold and $H_{sh}$

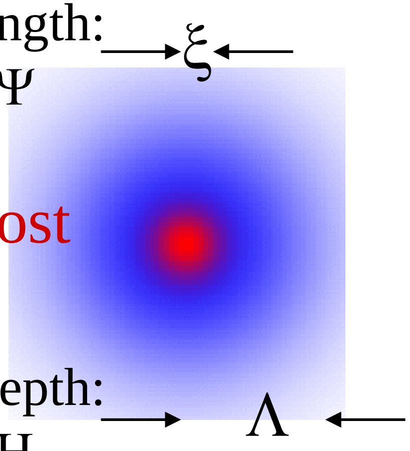
## Why is there a barrier to vortex penetration?

*Why a superheating field?*



Costly core *ξ* enters first;
gain from field *Λ* later

Coherence length:
Decay of Ψ



Energy cost

Penetration depth:
Decay of H

***J. Sethna, Cornell University***

# Motivation

- 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

# $H_{sh}$: Temperature Dependence

- Most $H_{sh}$ work based on Ginzburg-Landau Theory

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

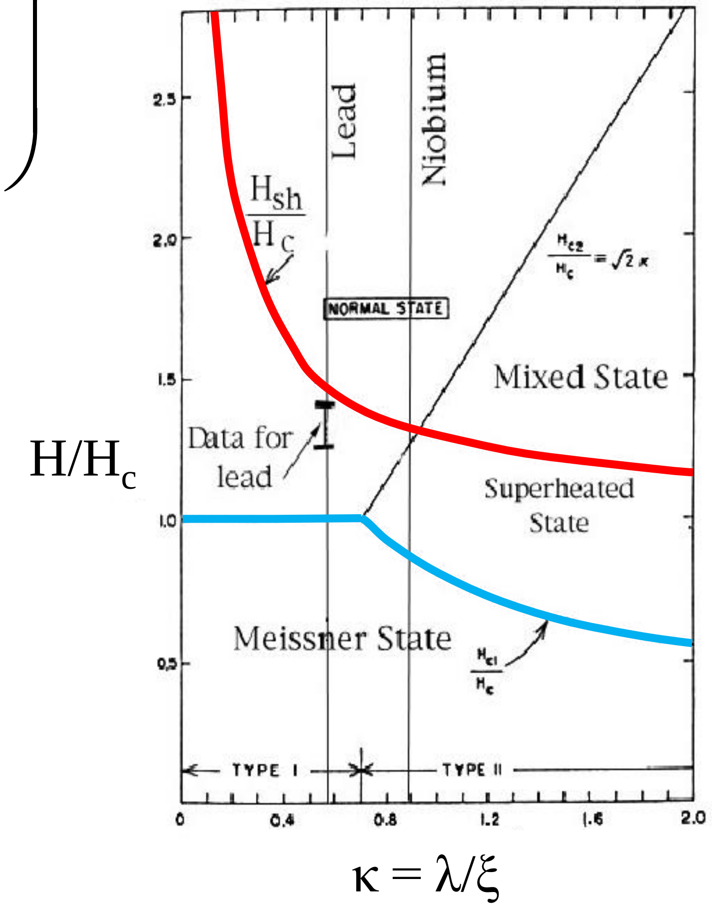
- GL solved in 1D case

$$H_{sh} \approx \frac{0.89}{\sqrt{\kappa_{GL}}} H_c \qquad \text{for } \kappa_{GL} \ll 1$$

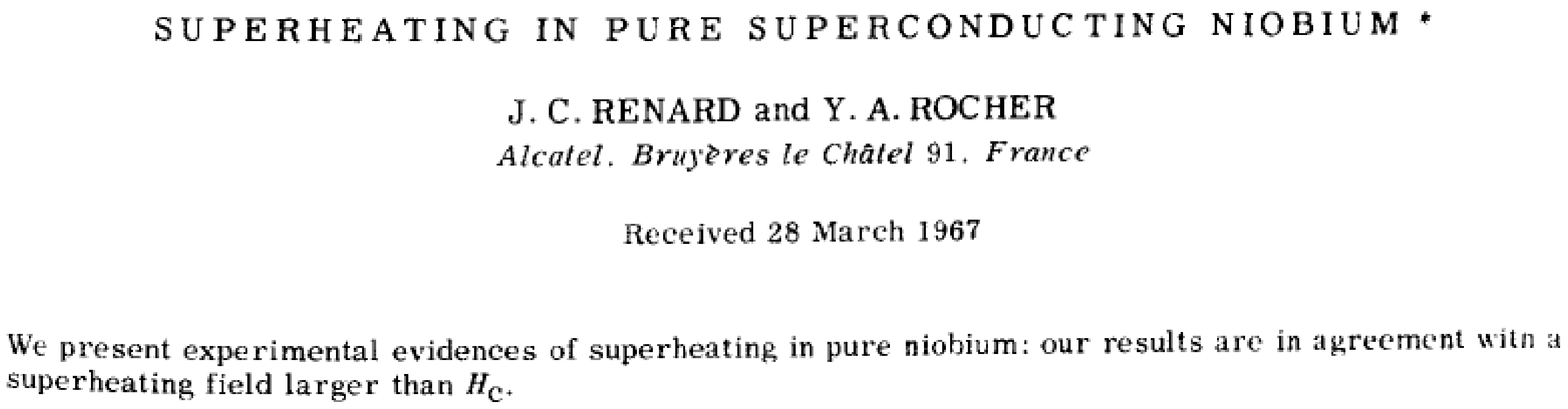
$$H_{sh} \approx 1.2 H_c \qquad \text{for } \kappa_{GL} \approx 1$$

$$H_{sh} \approx 0.75 H_c \qquad \text{for } \kappa_{GL} \gg 1.$$

  - Asymptotic expansion (Dolgert et. al.)



# First Evidence Hsh > Hc



SUPERHEATING IN PURE SUPERCONDUCTING NIOBIUM *

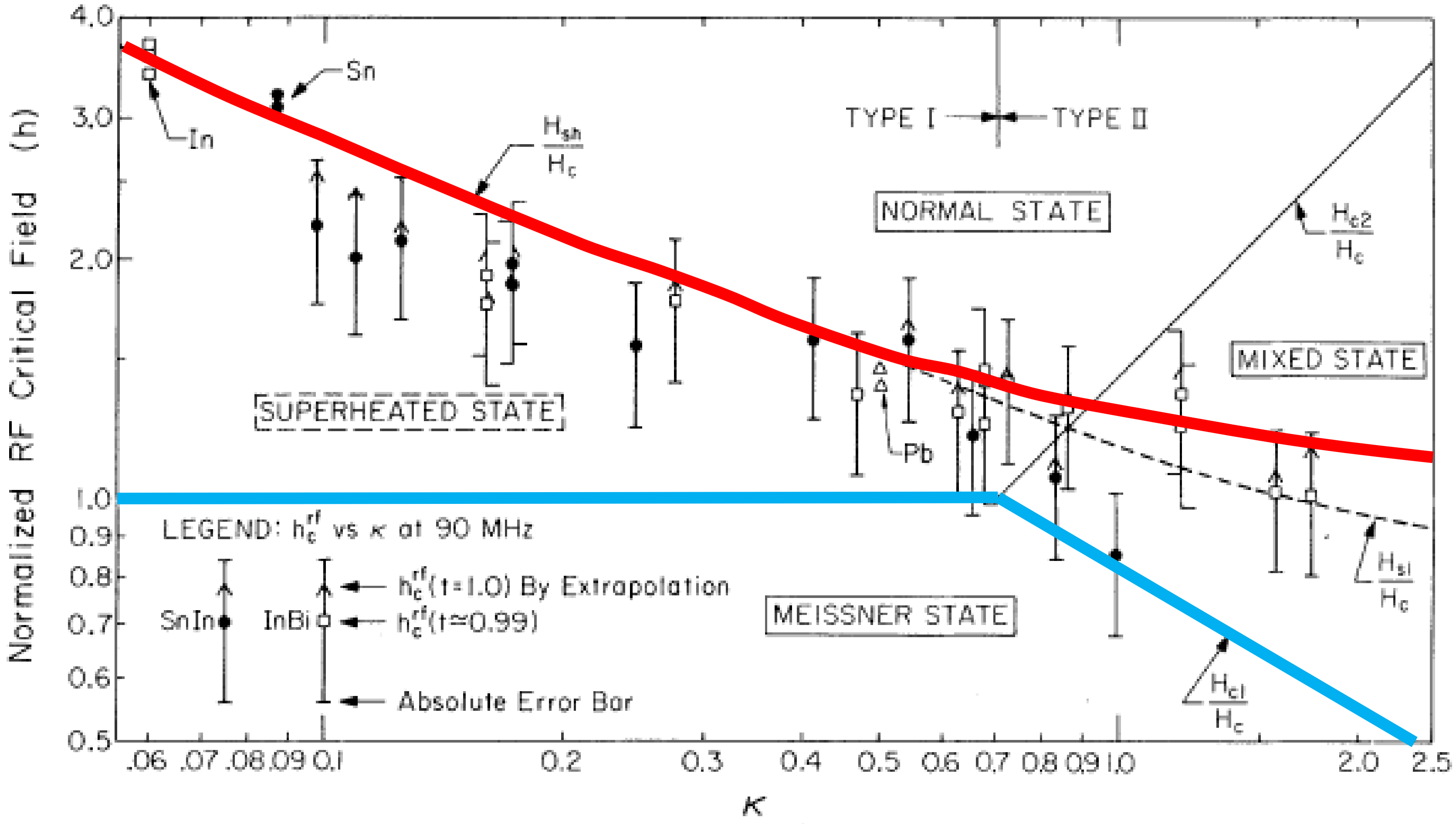
J. C. RENARD and Y. A. ROCHER
*Alcatel, Bruyères le Châtel 91, France*

Received 28 March 1967

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

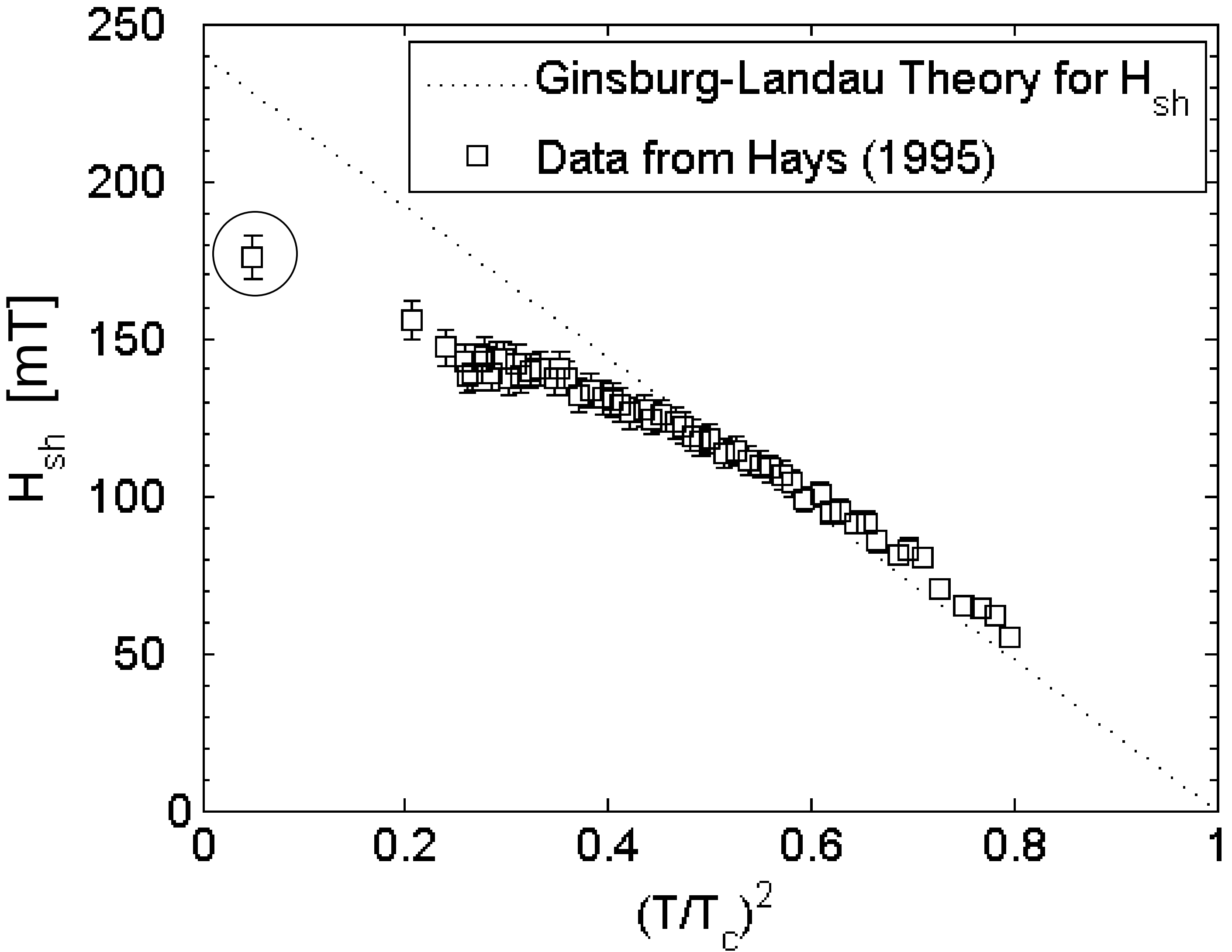
Magnetization curves of Nb cylinders at 4.2K showing Hsh > Hc

# Hsh Measurements: Midrange κ



Type-I and Type-II superconducting spheres near $T_c$. Yogi (1976)

# $H_{sh}$: First measurement of Temperature Dependence



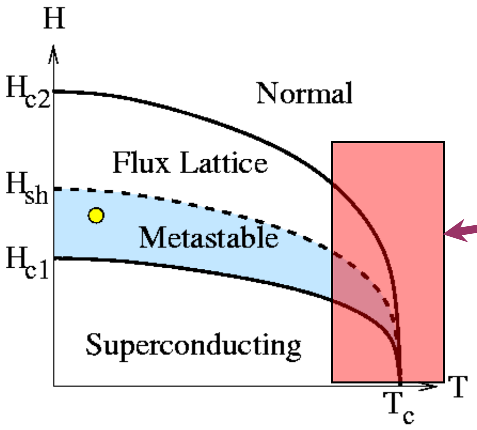
Hays Measurement of Hsh(T) for Nb (1995)

- Critical Fields of Superconductors
- Survey of Previous Work
- **New Results from Cornell on the Superheating Field**

# Validity versus complexity

## Ginzburg-Landau (GL)

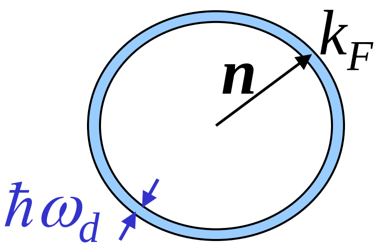
- ψ(r), H(r) order parameters
- Spatial dependence OK
- ***Valid only near $T_c$***



**Ginzburg-Landau valid**

## 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)



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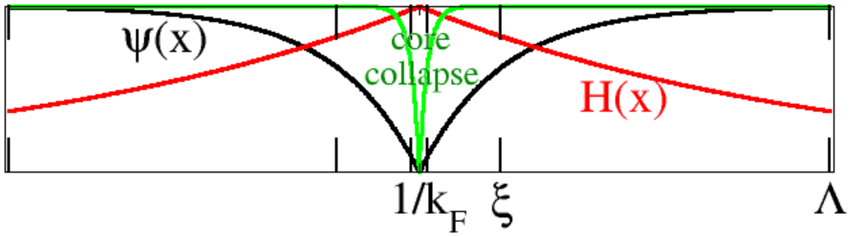
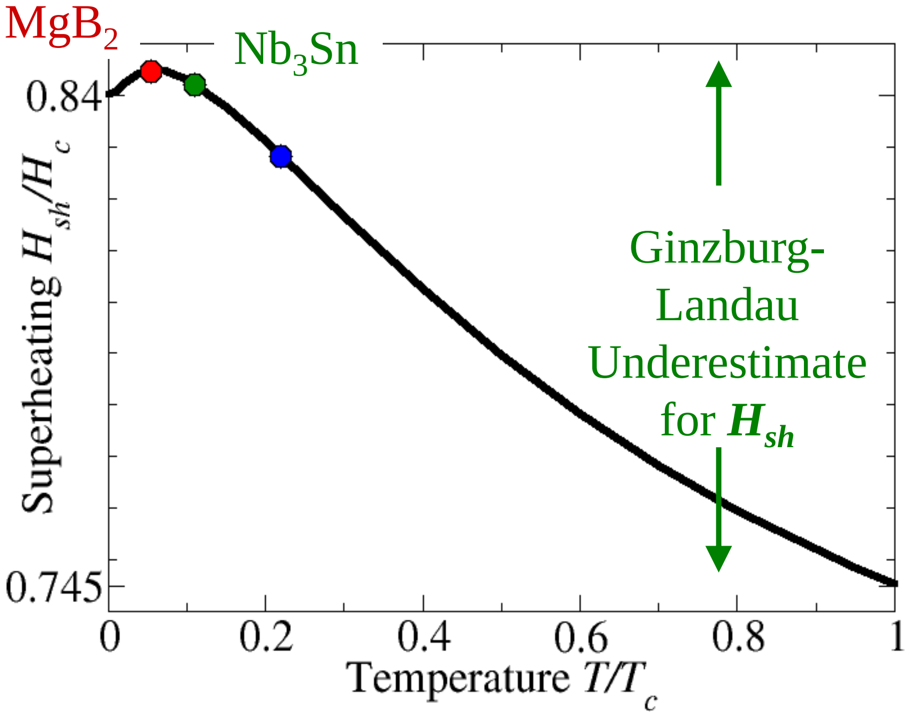
# Validity versus complexity

## Eilenberger Equations

- *Valid at all temperatures*
- Assumes Δ(r), H(r) vary slowly



Eilenberger equation results



Ginzburg-Landau Underestimate for $\boldsymbol{H_{sh}}$

## Eliashberg equations

- Needs electronic structure
- Never done before for $\boldsymbol{H_{sh}}$

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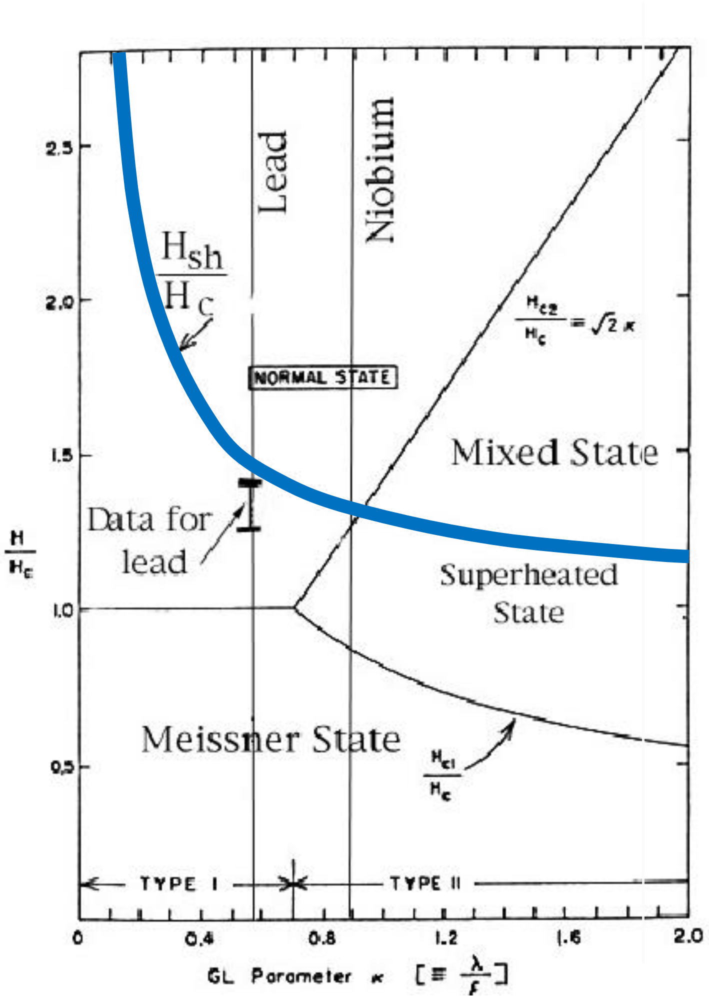
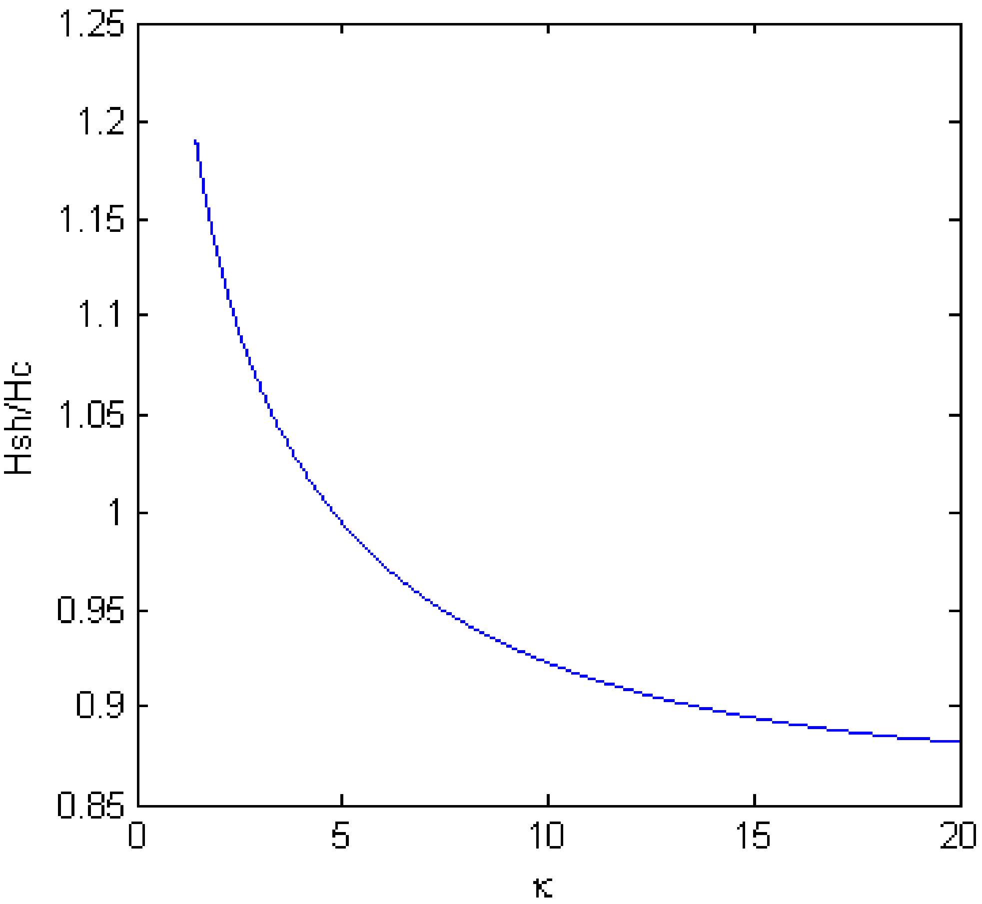
# Theoretical $H_{sh}$ Work

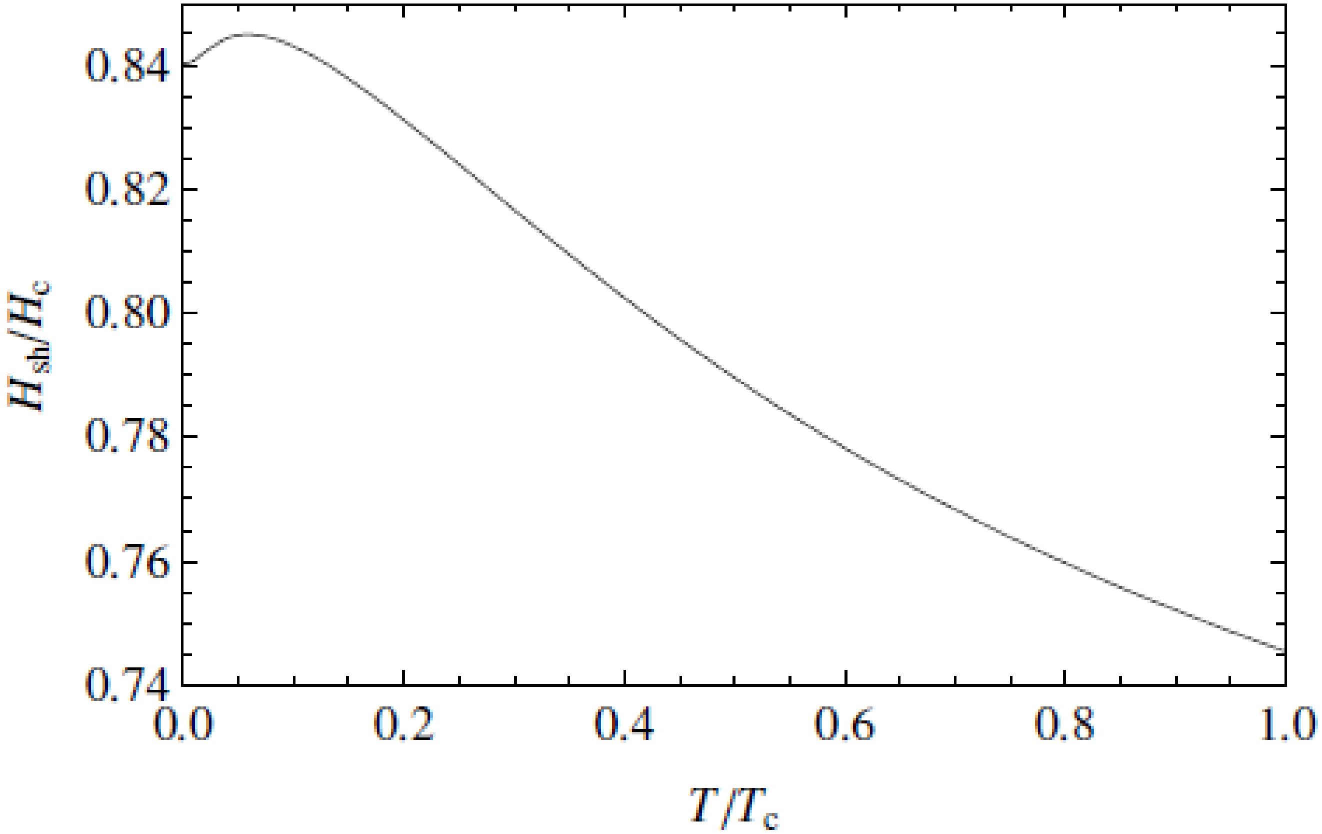
## Ginzburg-Landau



## Eilenberger near Tc – Mark Transtrum



# Hsh(T), Large κ



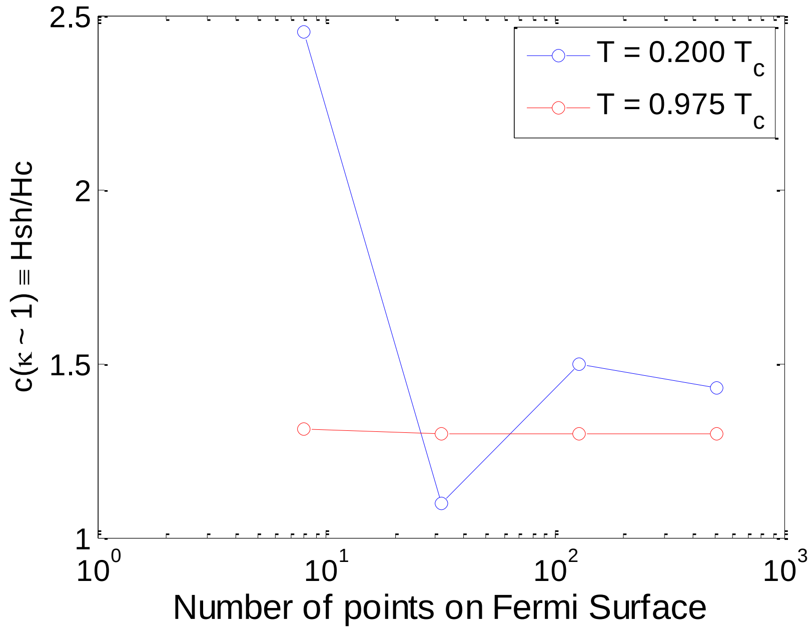
Eilenberger Eqns, κ >> 1.

Sethna , Catelani

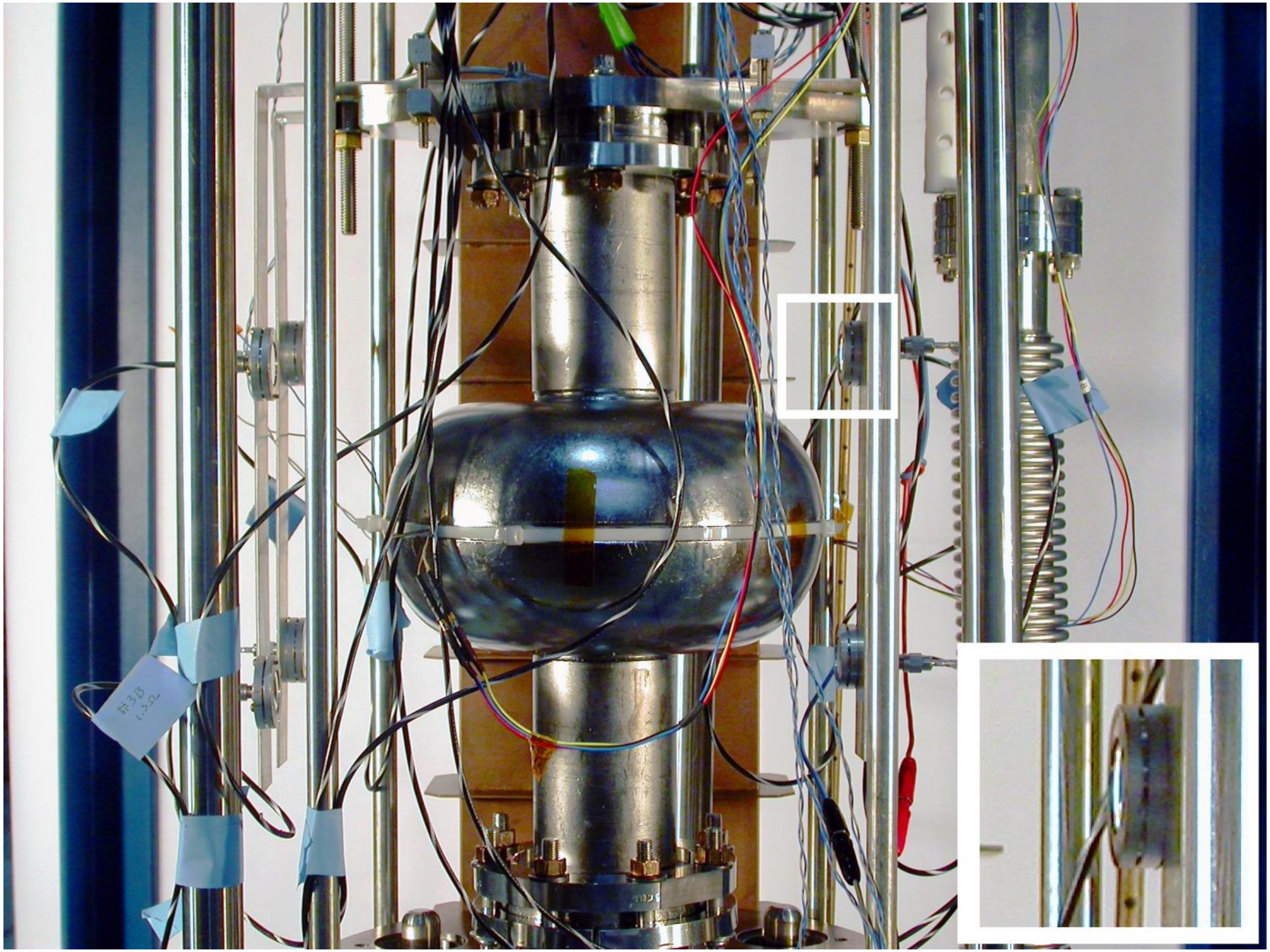
# Hsh(T), Intermediate κ

- Solving the Eilenberger equations are hard, especially for moderate or small κ
- Experimental measurements are necessary to help guide theory

## Hsh(κ ~ 1), convergence

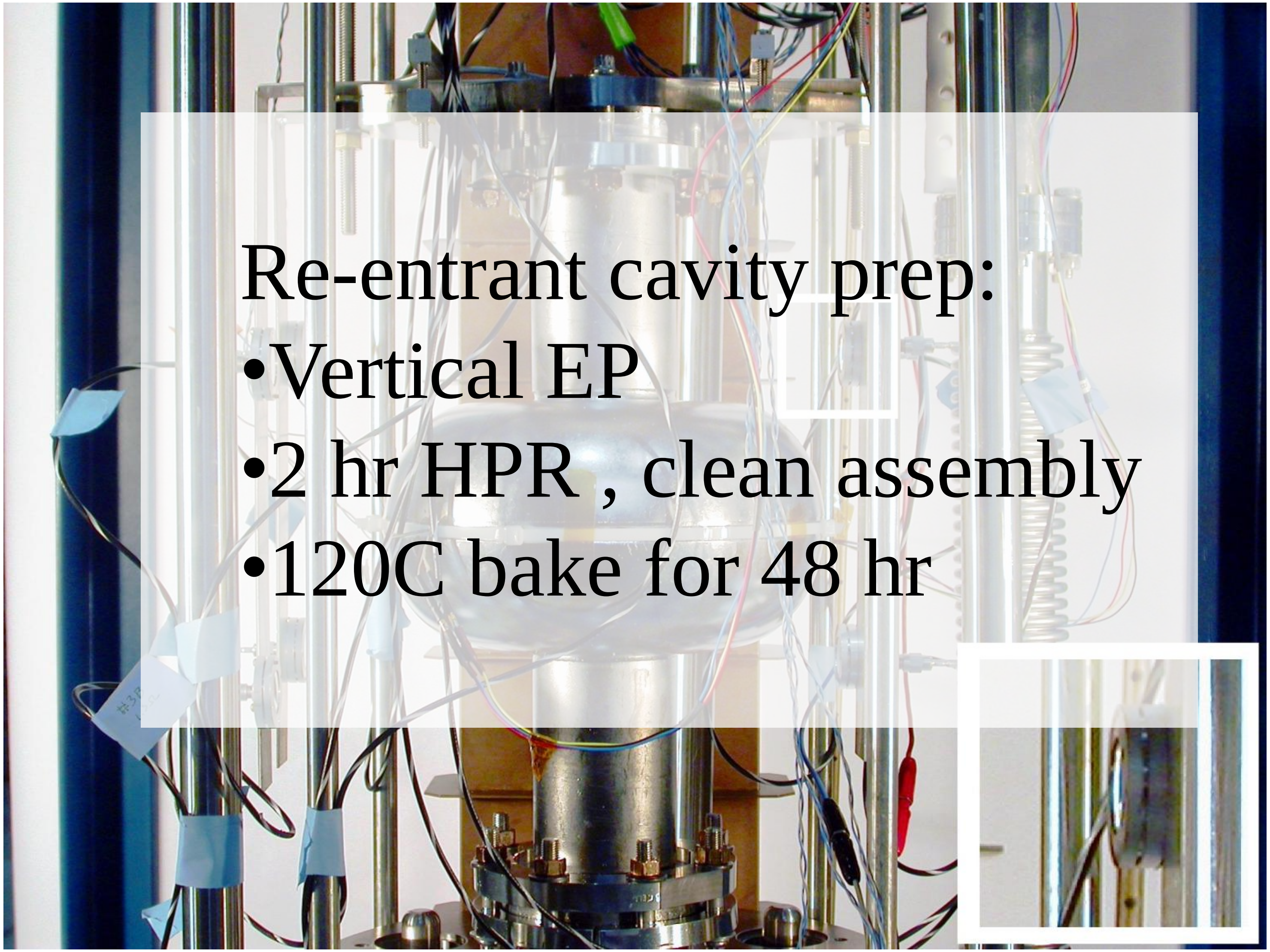


# Hsh(T) Measurement



LR1-3 to measure Superheating Field

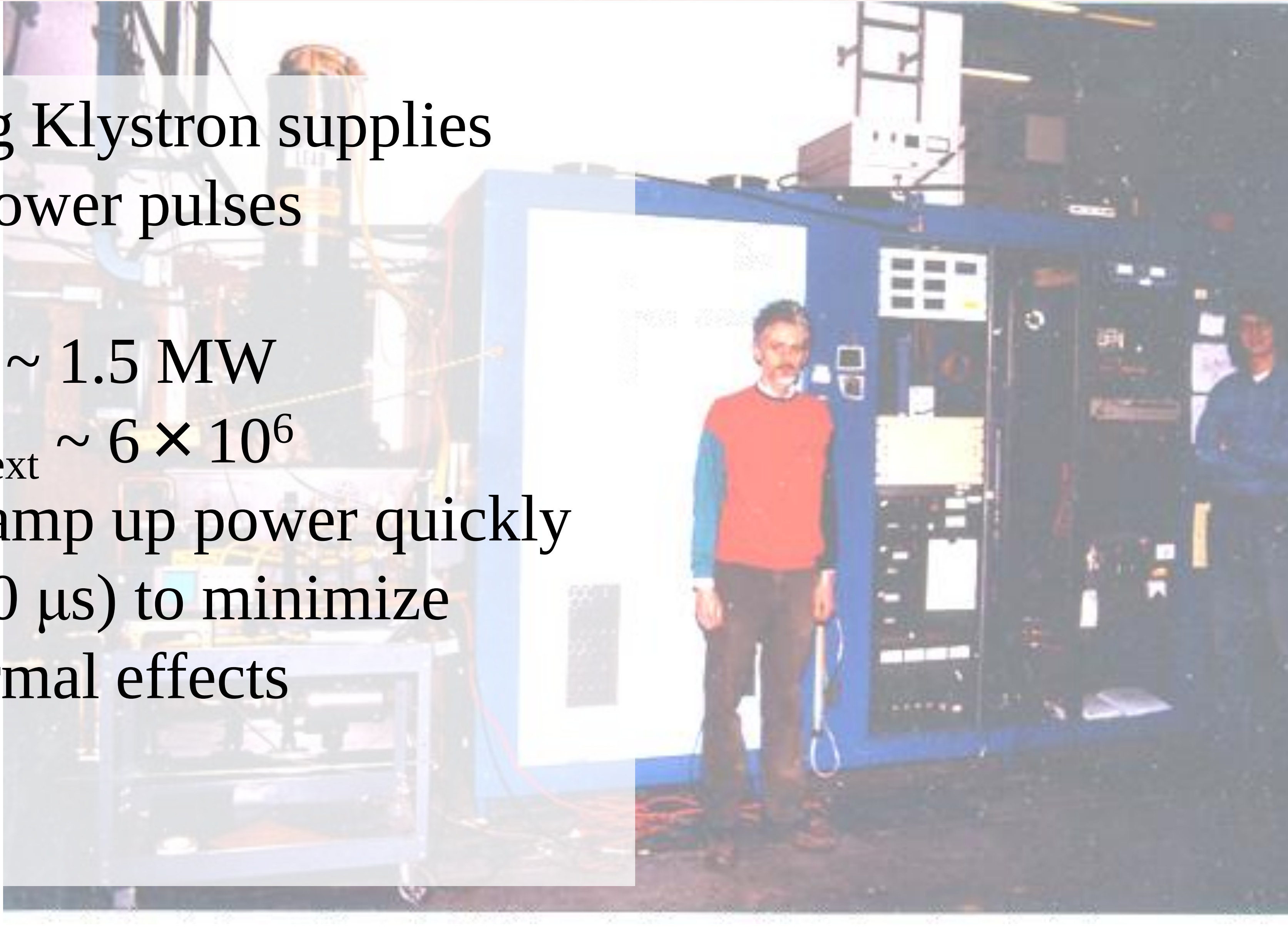
# Hsh(T) Measurement



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

LR1-3 to measure Superheating Field

# Pulsed Power Measurements



Boeing Klystron supplies high power pulses

- $P_f \sim 1.5$ MW
- $Q_{ext} \sim 6 \times 10^6$
- Ramp up power quickly (100 μs) to minimize thermal effects

# Calculating $Q_0$ vs Time

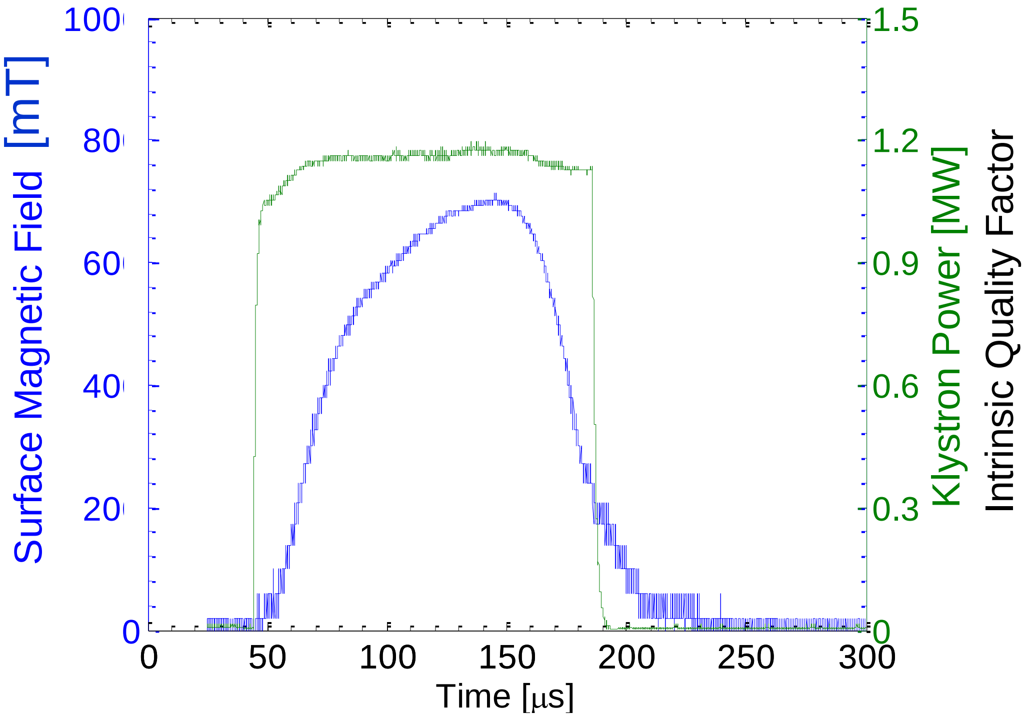
- Following Hays we can write:

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

which gives $\frac{\omega U}{Q_0} = 2\sqrt{\frac{\omega U P_f}{Q_{ext}}} - \frac{dU}{dt} - \frac{\omega U}{Q_{ext}}$ or

$$\boxed{\frac{1}{Q_0} = \frac{2}{\omega\sqrt{U}}\left(\sqrt{\frac{\omega P_f}{Q_{ext}}} - \frac{d\sqrt{U}}{dt}\right) - \frac{1}{Q_{ext}}}$$

# Measuring Hsh



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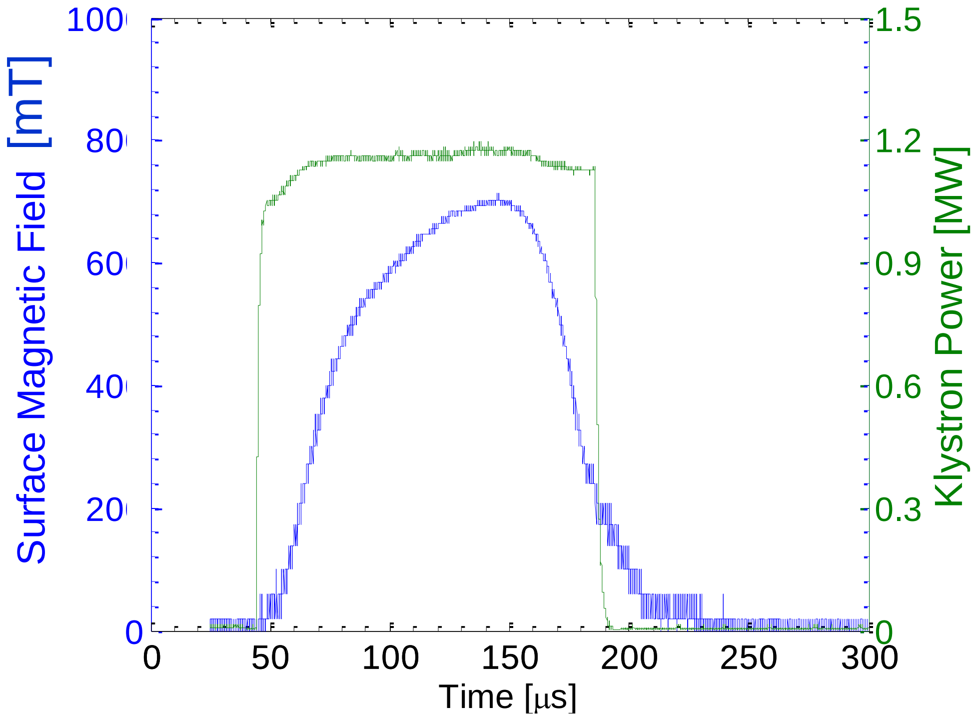
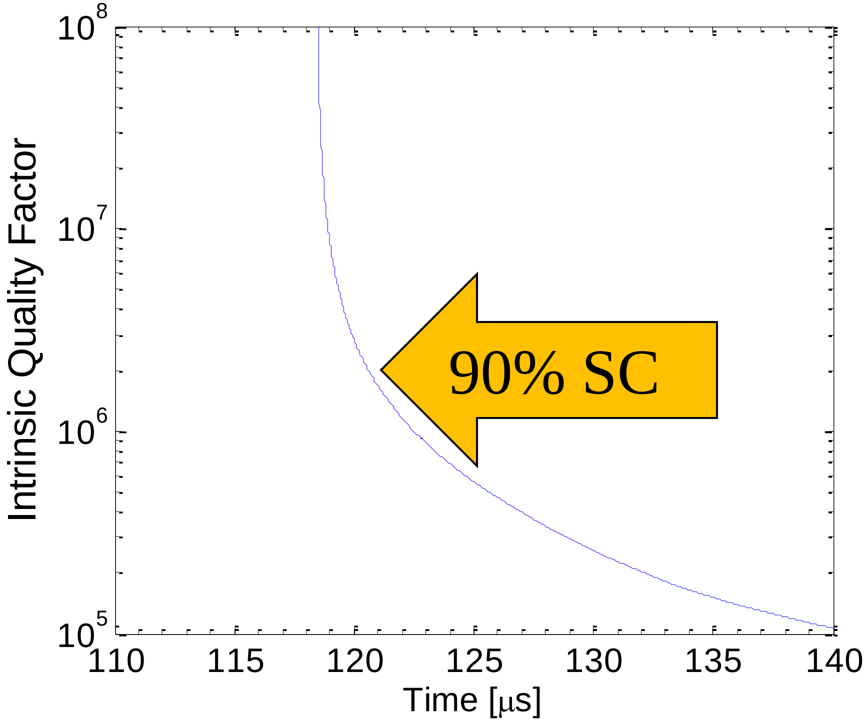
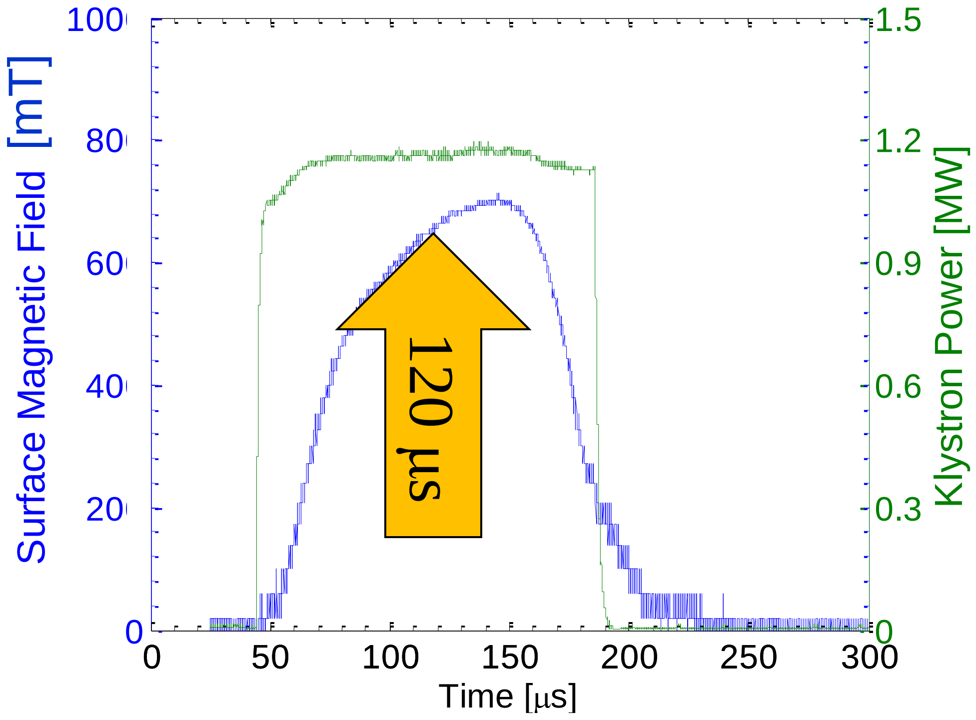
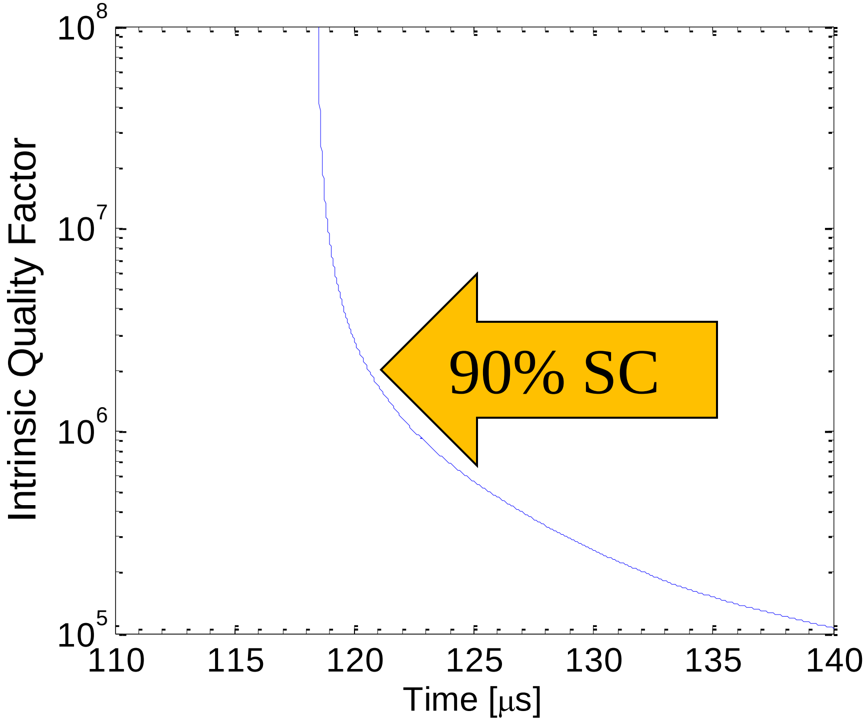


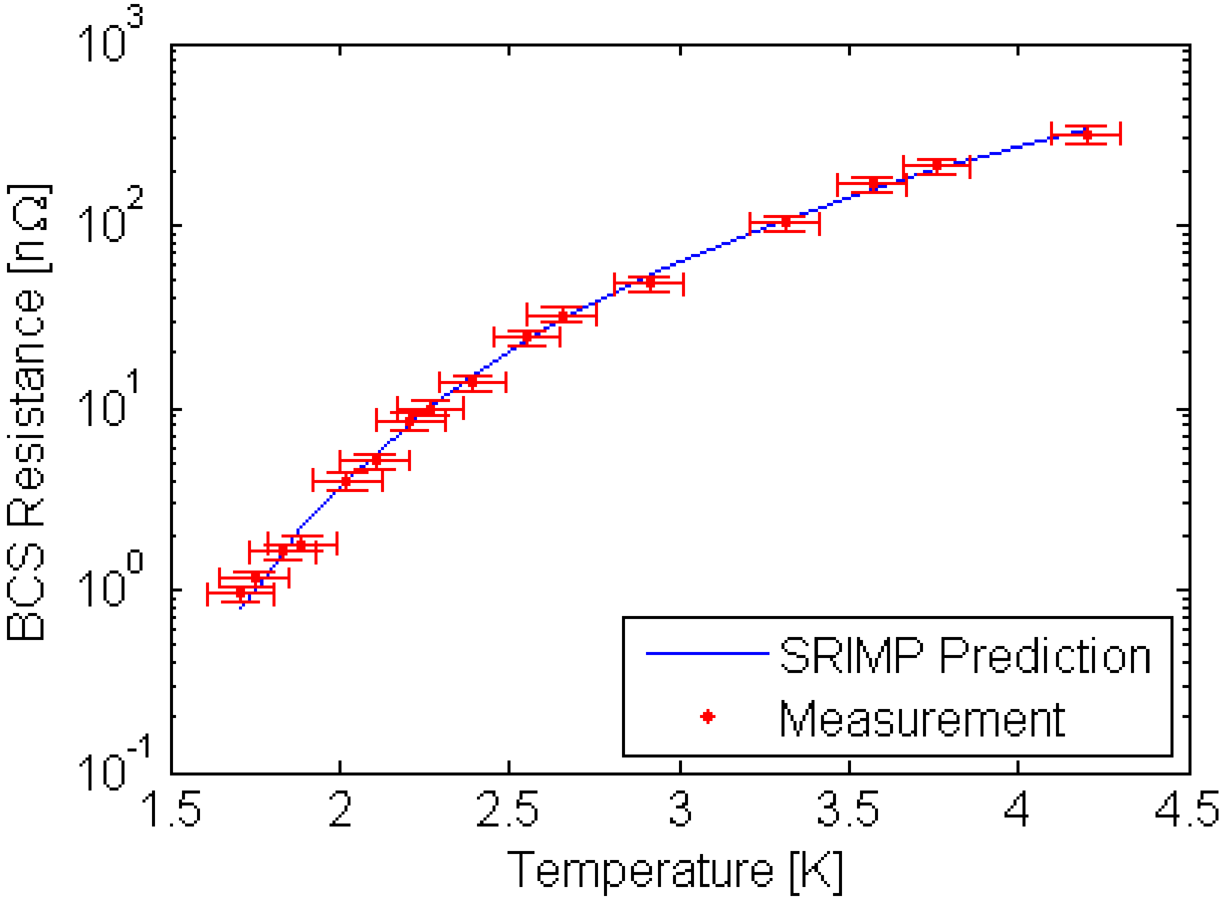


# Measuring Hsh



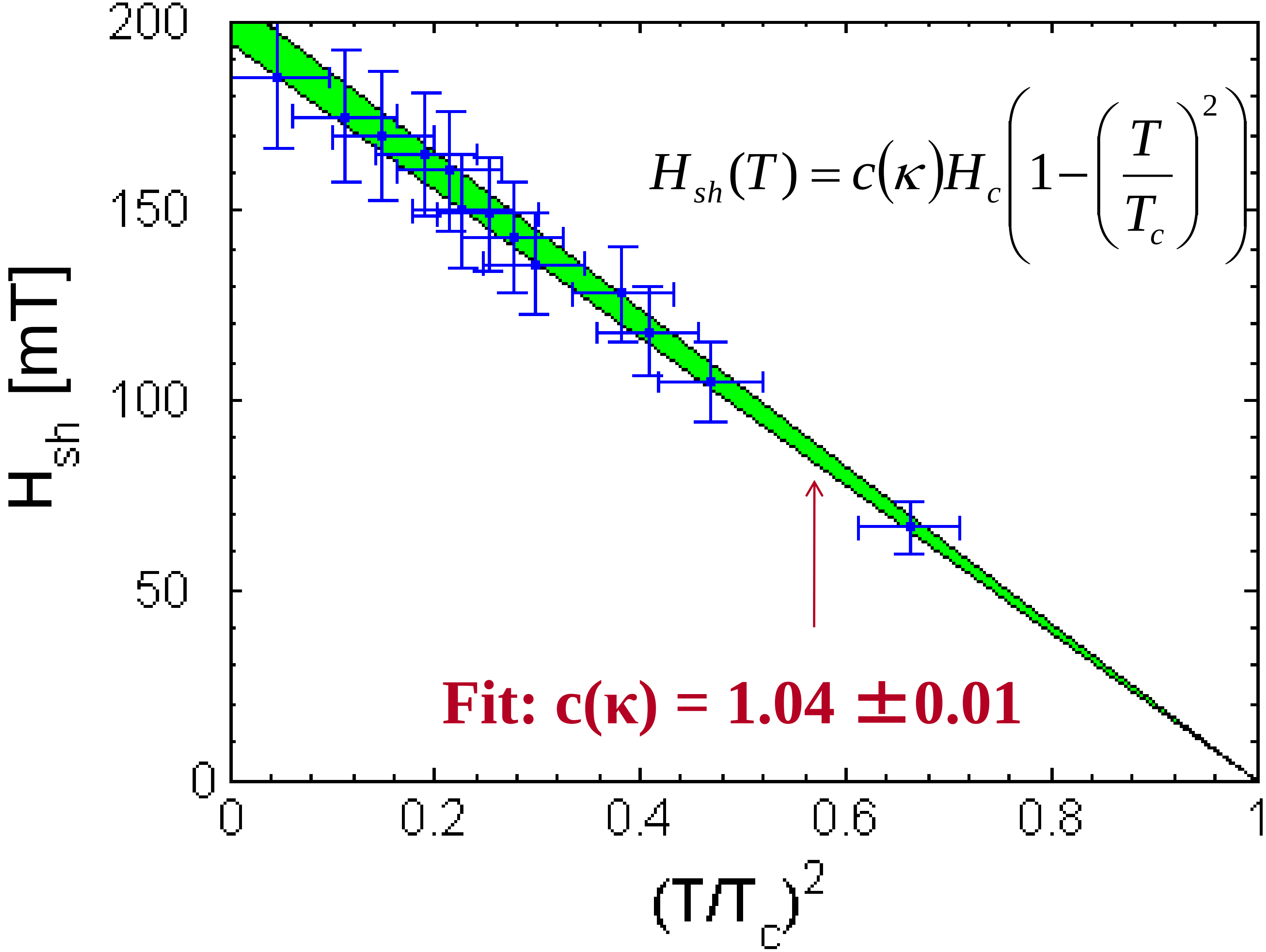


# Determining κ in CW



SRIMP Fit: MFP = 27 nm. κ = 3.5

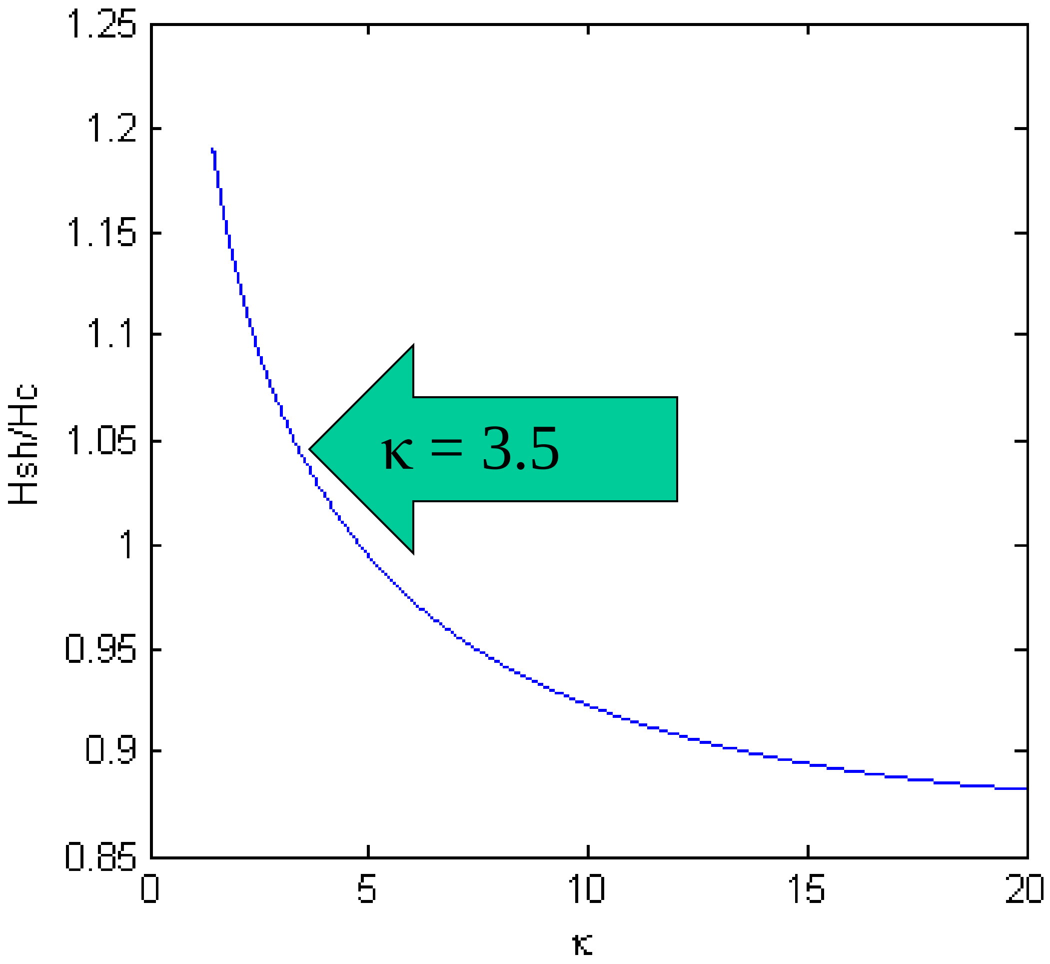
# Hsh(T) Measurement



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

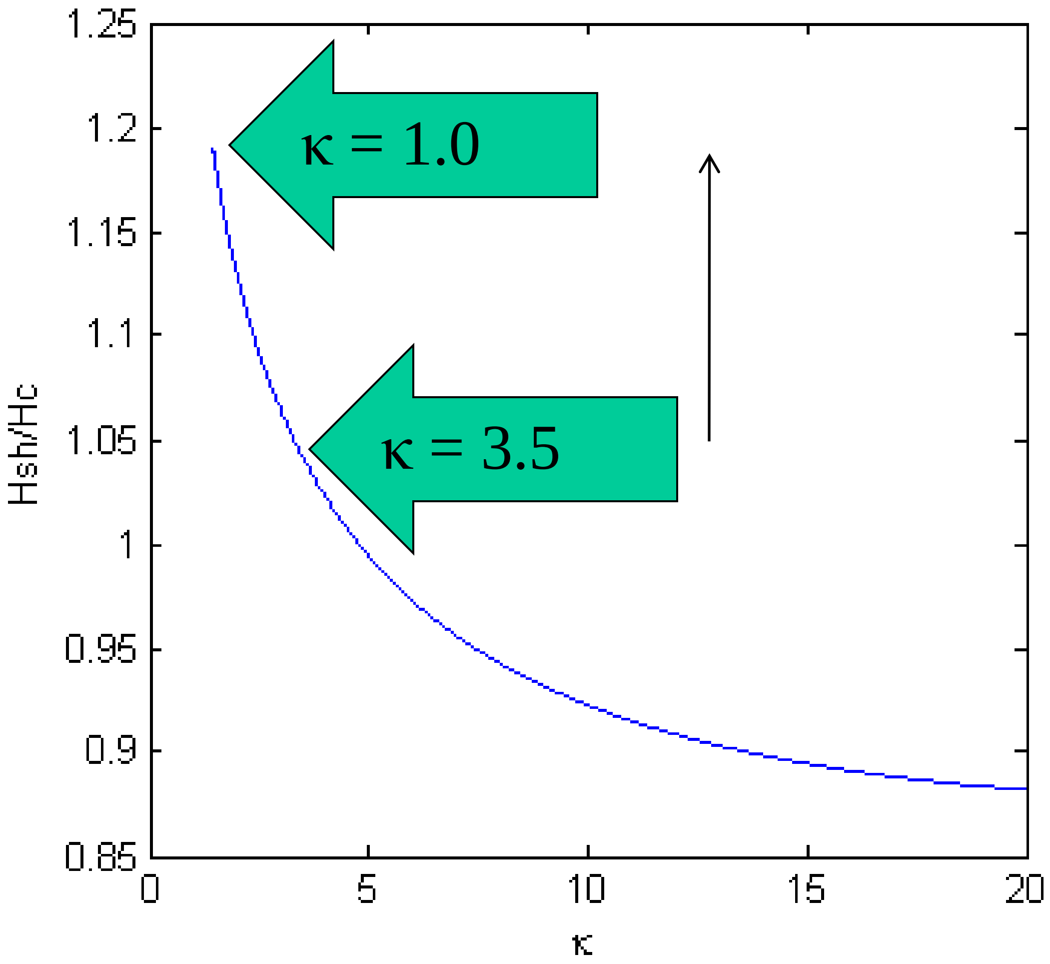
**Fit: c(κ) = 1.04 ±0.01**

# Transtrum: $H_{sh}(\kappa)$



$\kappa = 3.5$

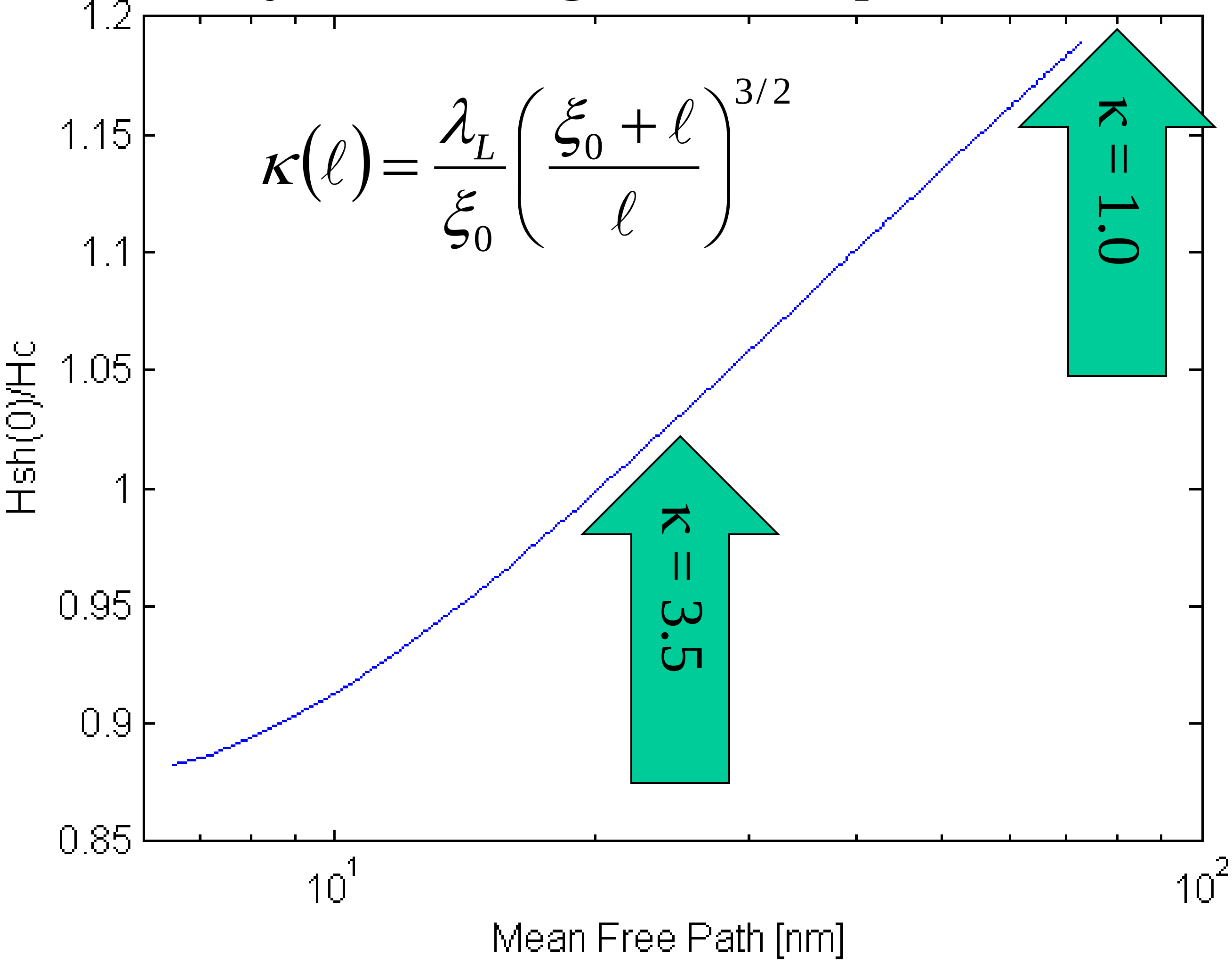
# Transtrum: $H_{sh}(\kappa)$



Possibility for 20% increase by changing κ

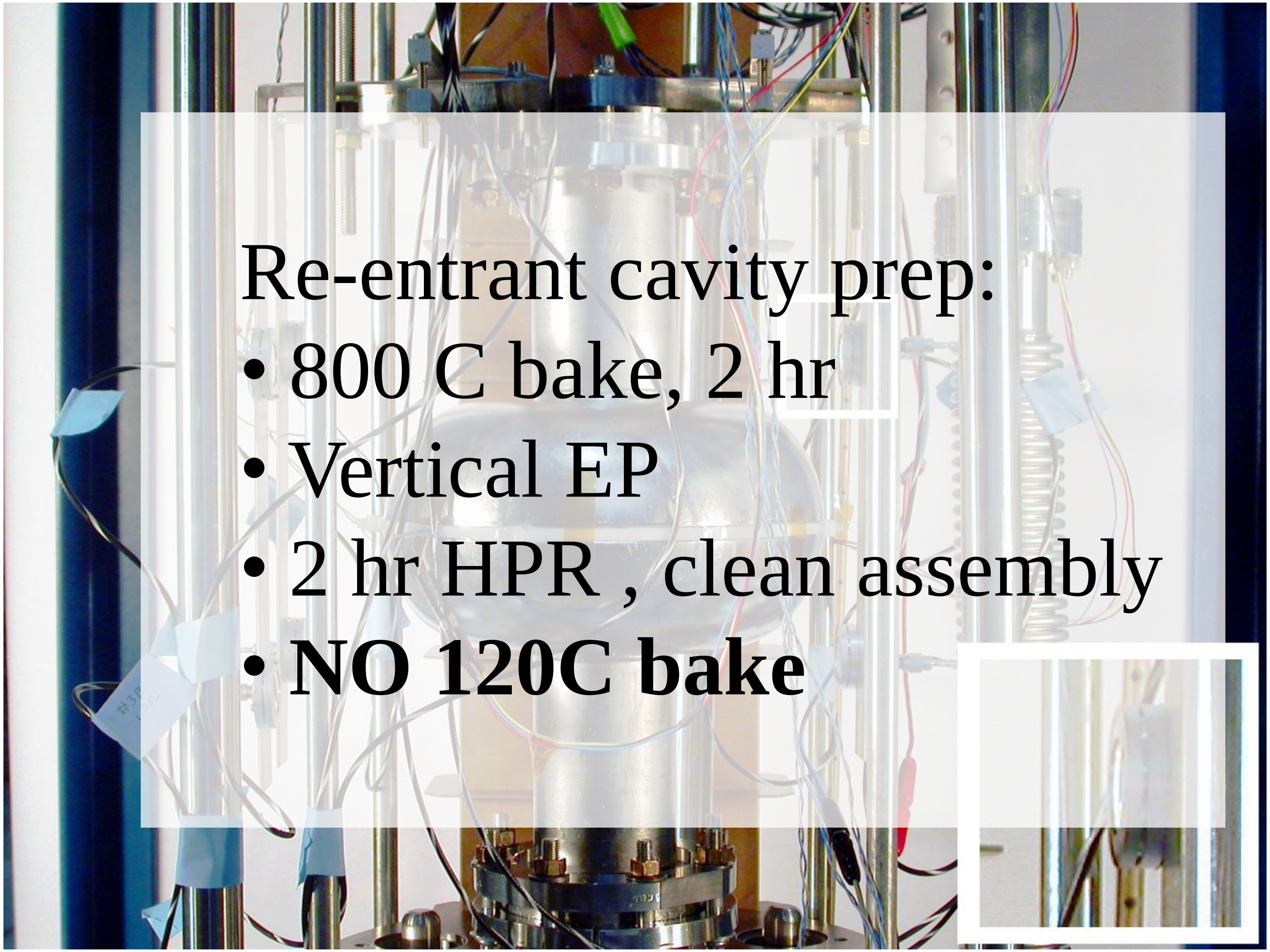
# c(κ) vs Mean Free Path

Baking lowers mean free path (and thus κ) by introducing surface impurities



$$\kappa(\ell) = \frac{\lambda_L}{\xi_0}\left(\frac{\xi_0 + \ell}{\ell}\right)^{3/2}$$

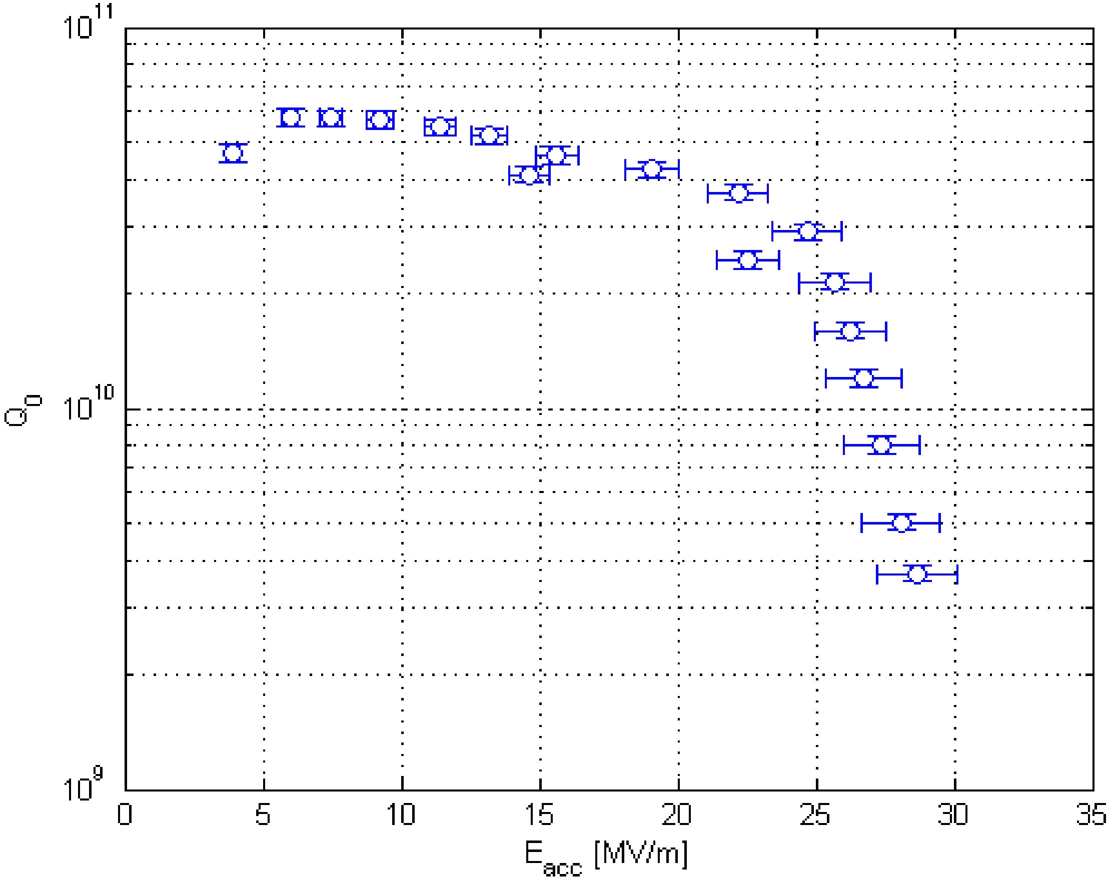
# $H_{sh}(T)$ Measurement



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

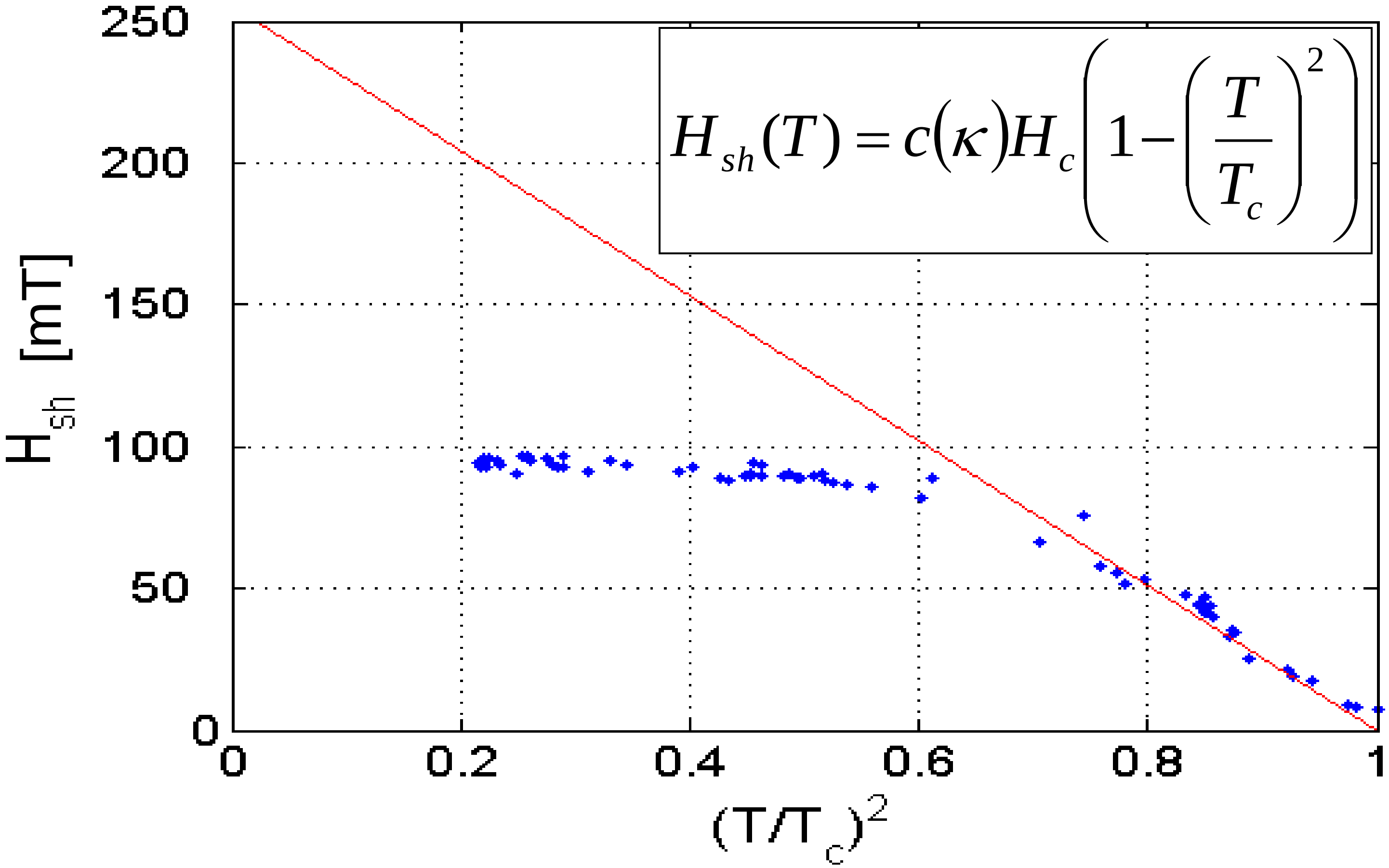
# Q vs E (CW), for LR1-3



Severe Q drop at low fields.

Small radiation, no quenches

# $H_{sh}(T)$ Measurement



c(κ) = 1.28±0.06

(Theory predicts 1.30) κ clearly changed!

# Conclusions

- We now have a measurement showing the full temperature dependence of Hsh
- GL theory is suprisingly accurate over the full temperature range
- Surface treatments strongly influence Hsh
- There appears to be a trade-off between removing high field Q-slope and high superheating field
  - Alternative to 120C bake?

# The Future of $H_{sh}$

- 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 $Nb_3Sn$ or $MgB_2$?

# The Future of $H_{sh}$

- Eilenberger theory appears to give a small increase to $H_{sh}$ at low temperatures
- $H_{sh}$ measurements are a place where experiment can
- Mor
conv $< T_c$
- Can we reproduce these results for new materials such as $Nb_3Sn$ or $MgB_2$?

Sam Posen at Cornell is currently making Nb3Sn. **THPO066**
$H_{sh}$ measurements to follow

# Thanks

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

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