The Superheating Field of Niobium: Theory and Experiment

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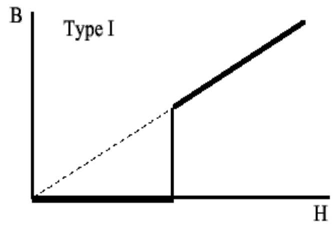
Outline

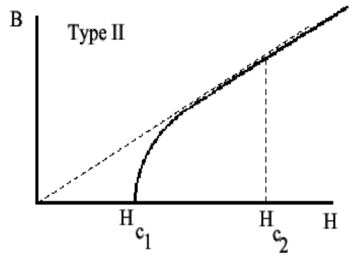
- Critical Fields of Superconductors
- Survey of Previous Work
- New Results from Cornell on the Superheating Field

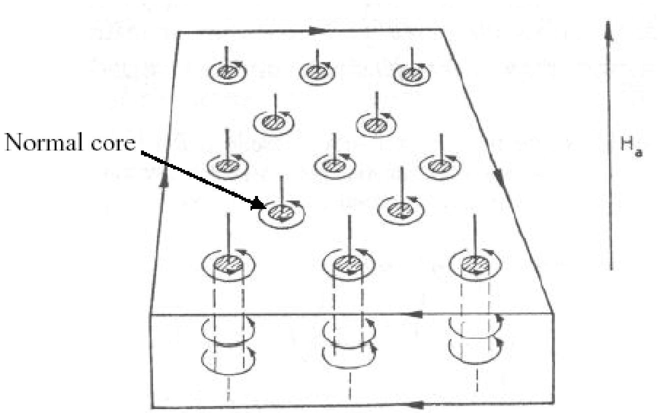
- **Critical Fields of Superconductors**
- Survey of Previous Work
- New Results from Cornell on the Superheating Field

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.



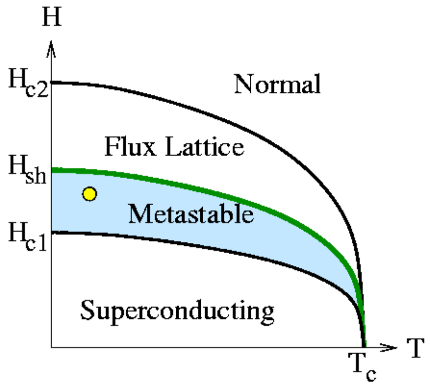




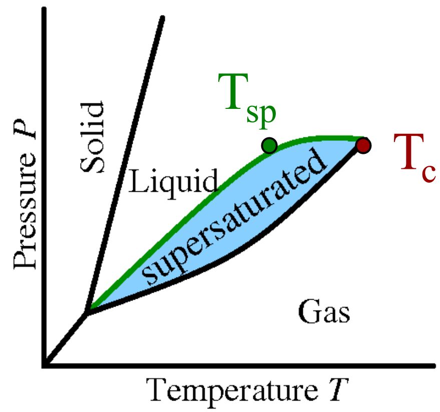
Critical Fields of Superconductors

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

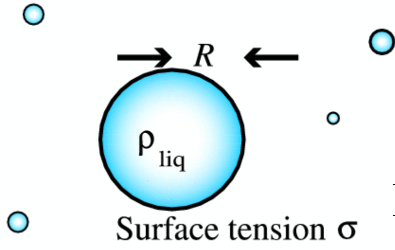
Raindrops: the Liquid-Gas Transition



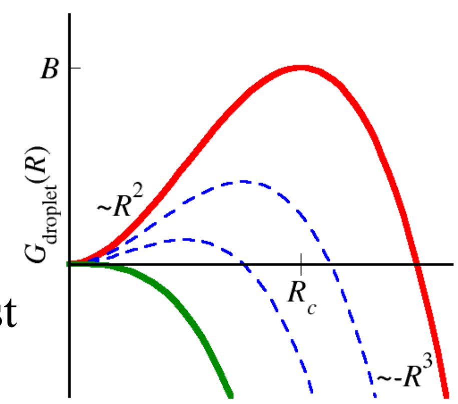
"Superheating" like
110% humidity



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



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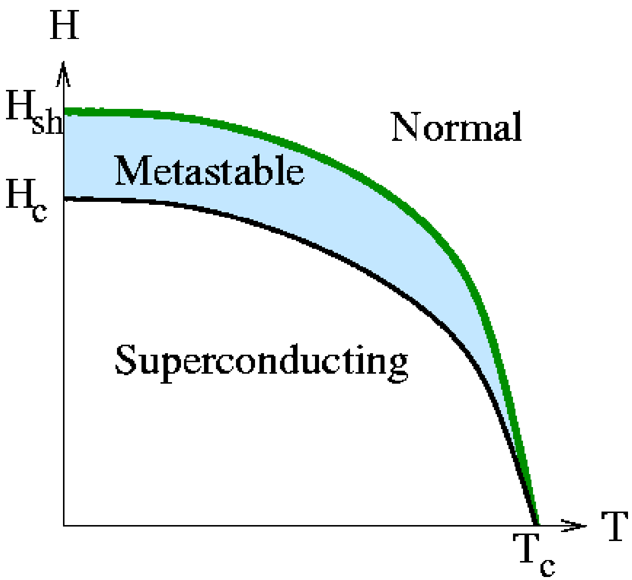
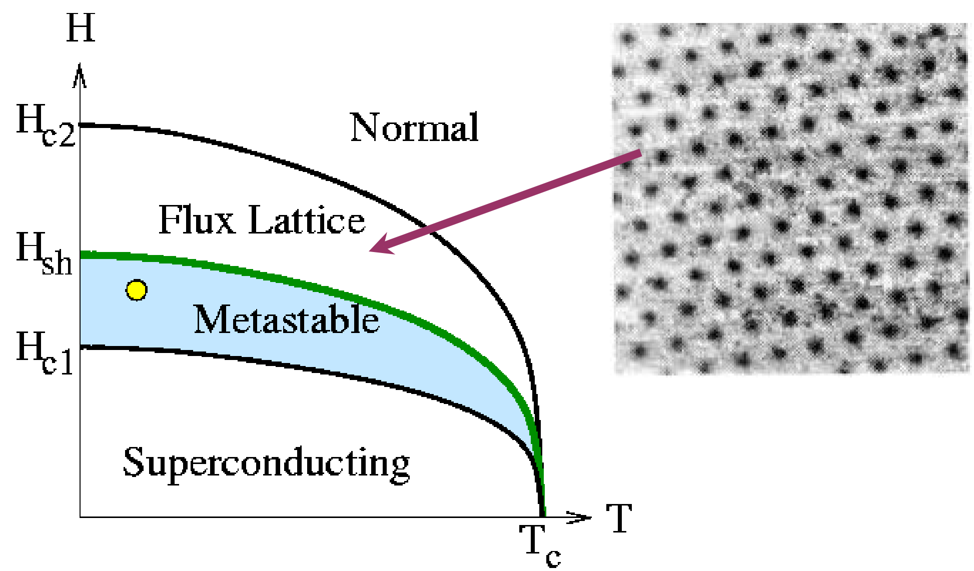
Superconductors & Magnetic Fields

Type I (Pb)



Type II (Nb and Nb_3Sn)



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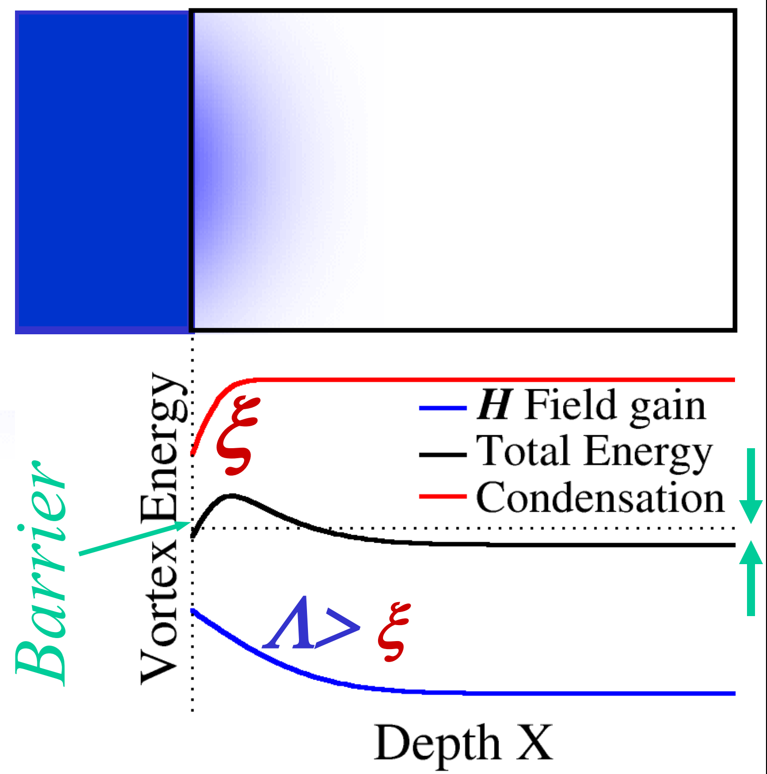
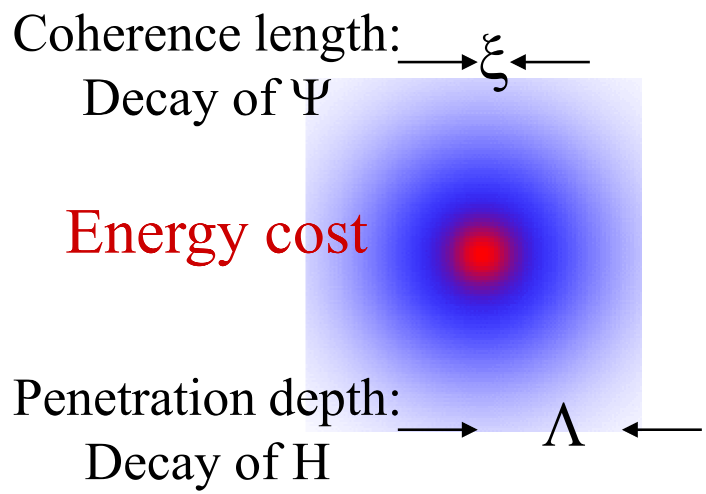
Can we calculate the phase diagram for H_{sh}?

Why is there a barrier to vortex penetration?

Why a superheating field?



Costly core ξ enters first;
gain from field Λ later



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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

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

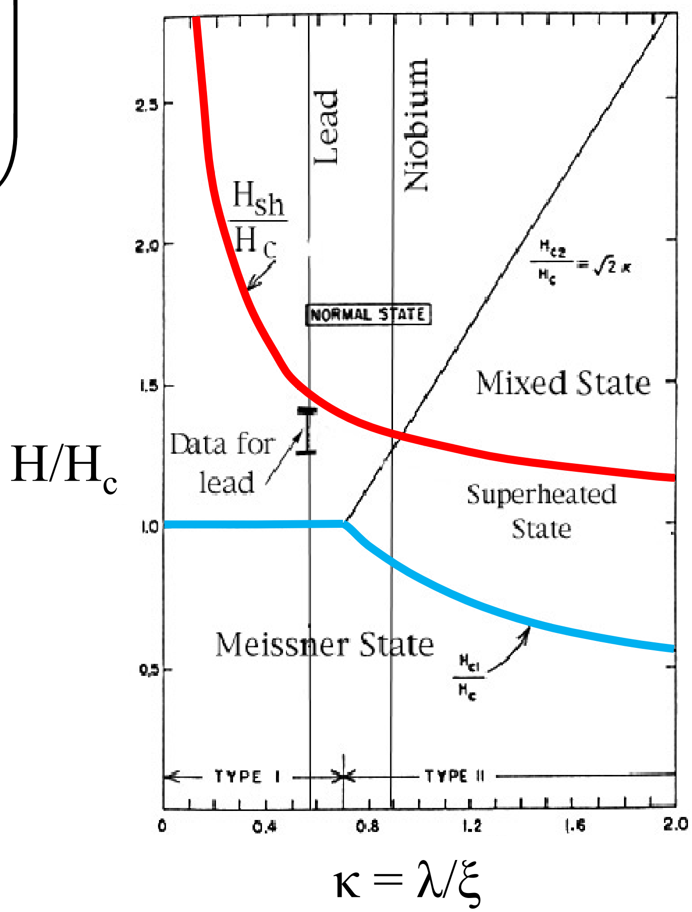
- GL solved in 1D case

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

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

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

  – Asymptotic expansion (Dolgert et. al.)



First Evidence Hsh > Hc

SUPERHEATING IN PURE SUPERCONDUCTING NIOBIUM *

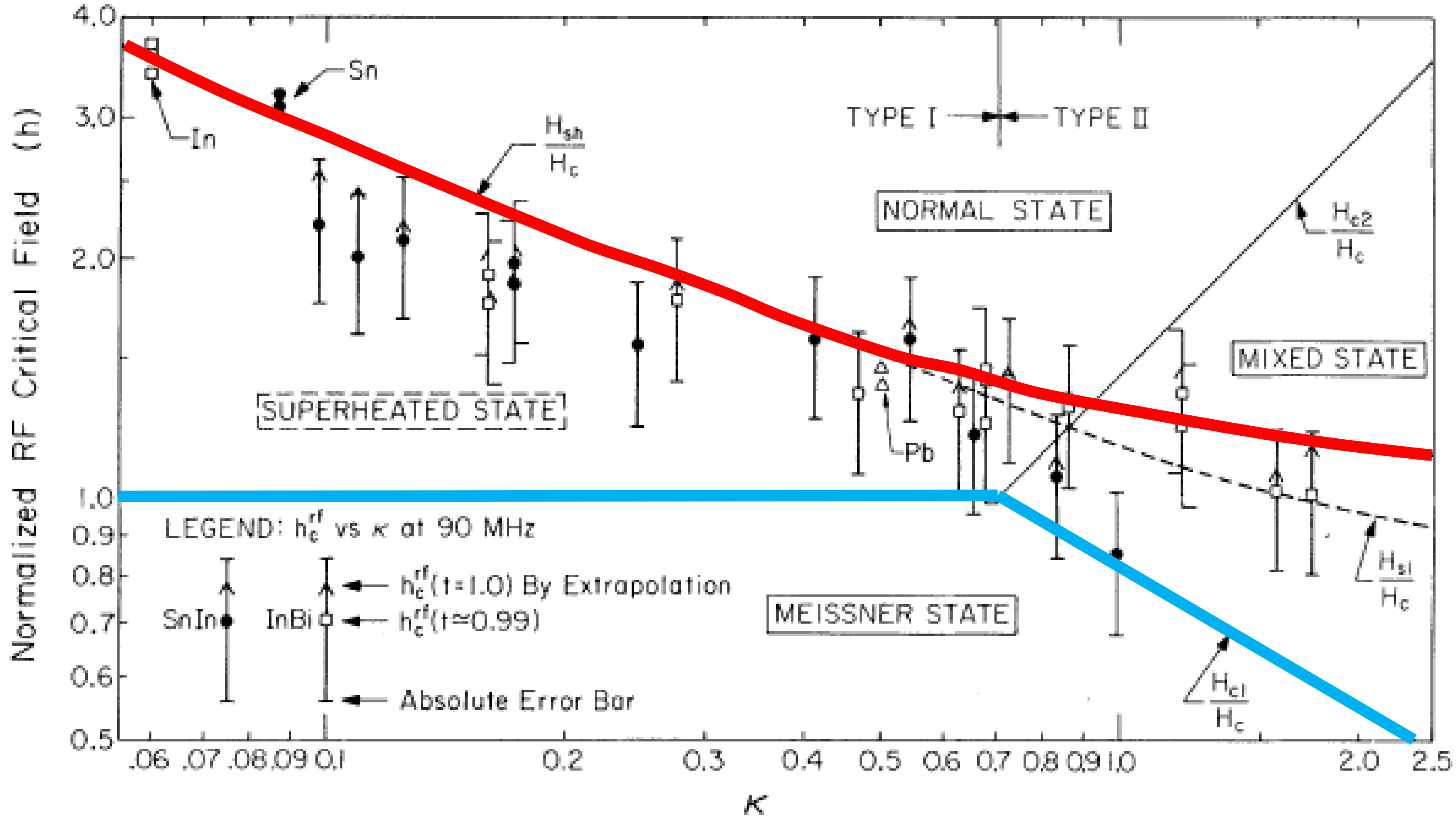
J. C. RENARD and Y. A. ROCHER
Alcatel, Bruyères le Châtel 91, France

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.

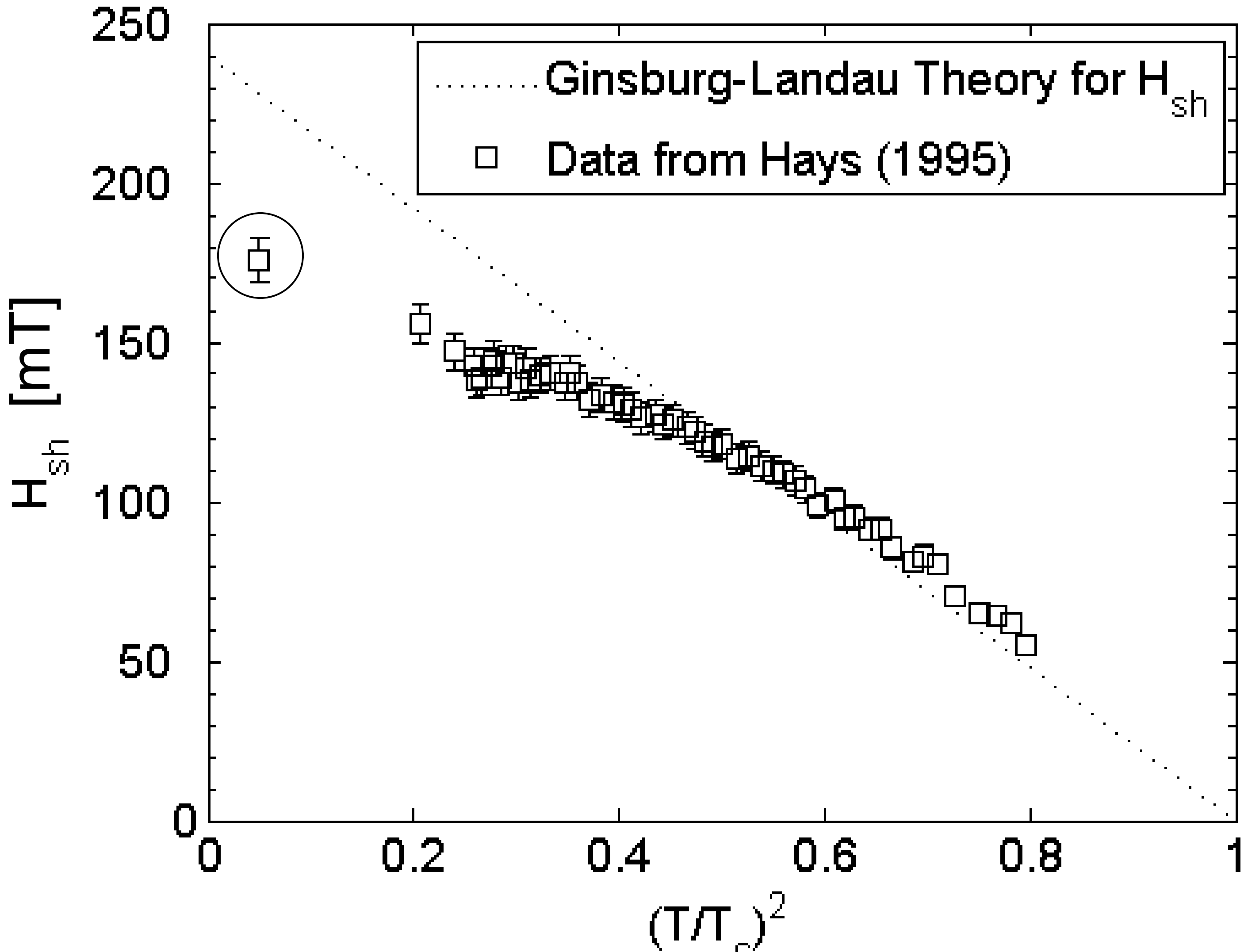
Magnetization curves of Nb cylinders at 4.2K showing Hsh > Hc

Hsh Measurements: Midrange κ



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

H_{sh}: First measurement of Temperature Dependence



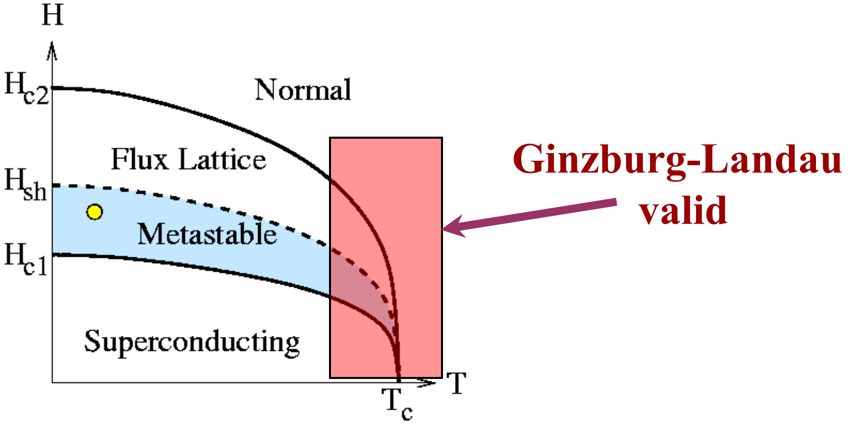
Hays Measurement of Hsh(T) for Nb (1995)

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

Validity versus complexity

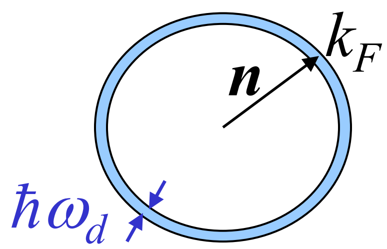
Ginzburg-Landau (GL)

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



Bardeen Cooper Schrieffer (BCS) theory

- Pairing *k, -k* within vibration energy
- Excellent for traditional superconductors
- $\boldsymbol{H_{c1}}(T)$, $\boldsymbol{H_{c2}}(T)$ done
- $\boldsymbol{H_{sh}}(T)$ hard (spatial dependence)



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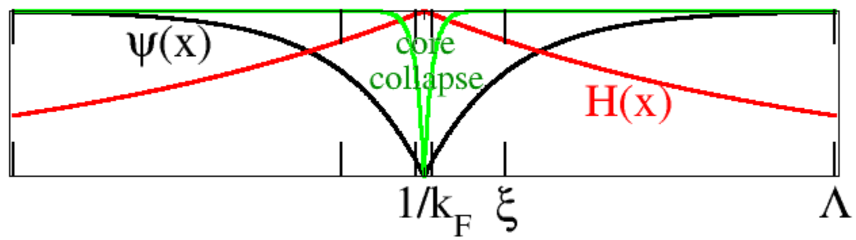
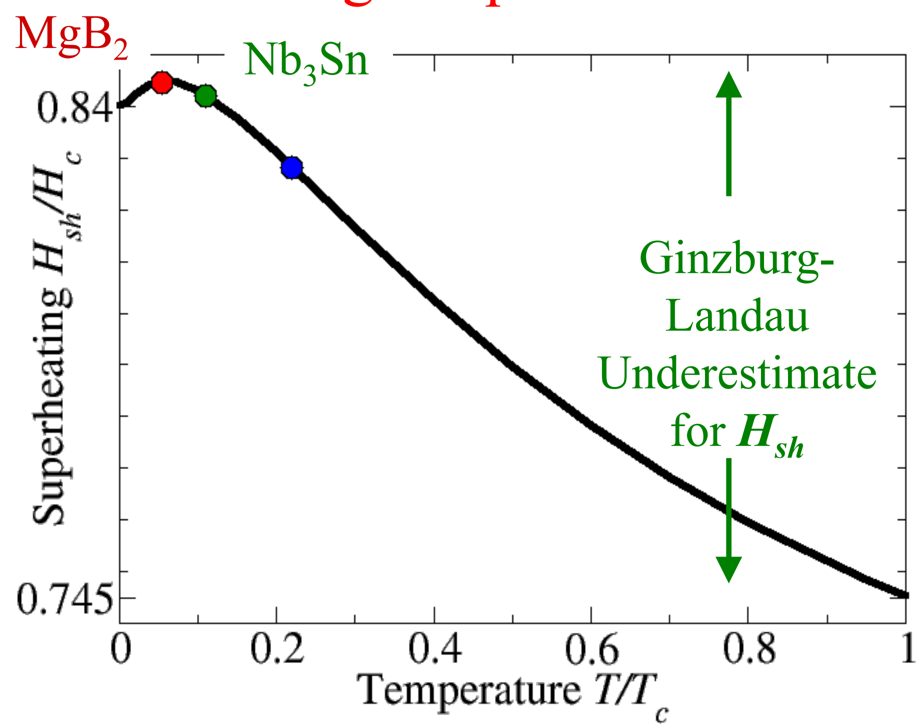
Validity versus complexity

Eilenberger Equations

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



Eilenberger equation results



Eliashberg equations

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

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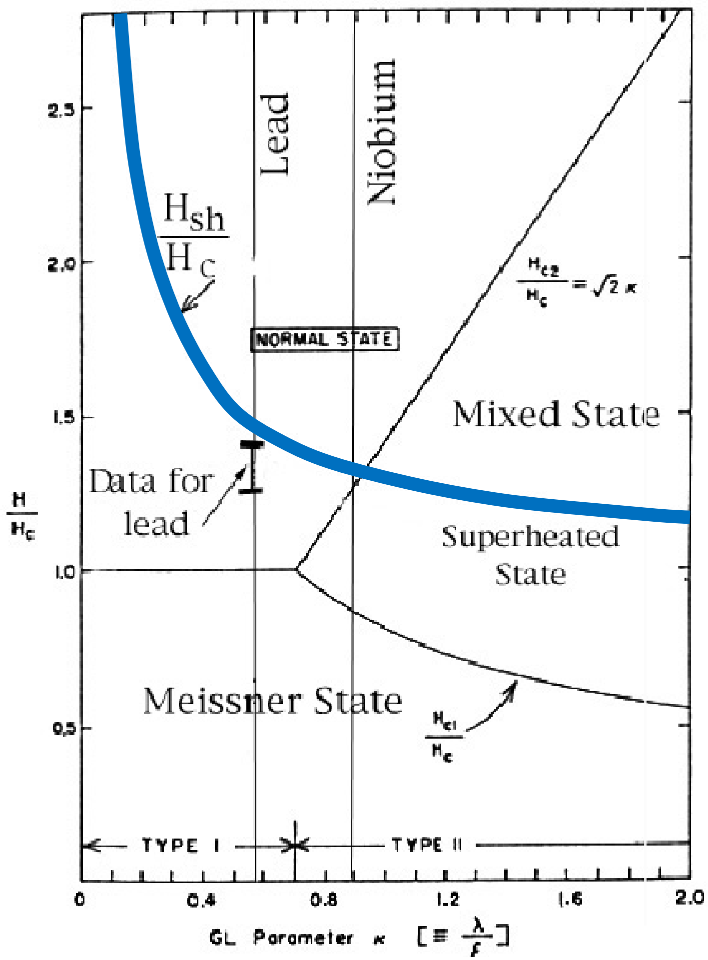
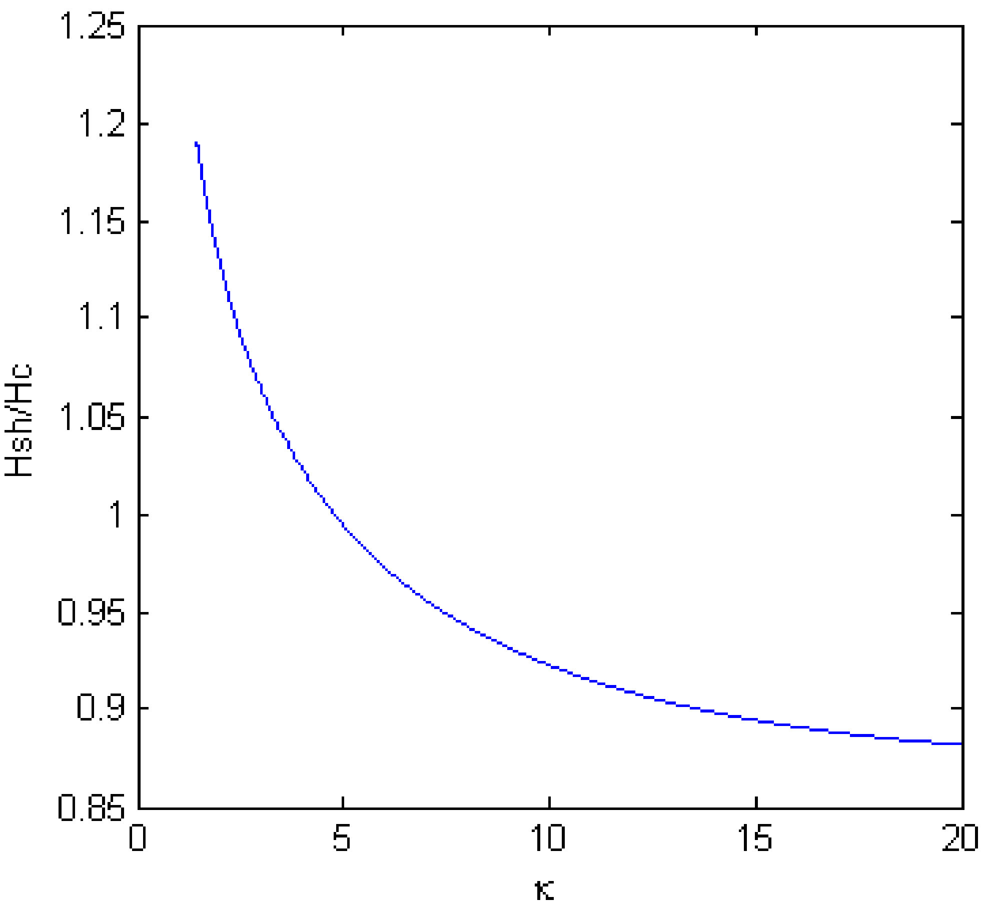
Theoretical H_{sh} Work

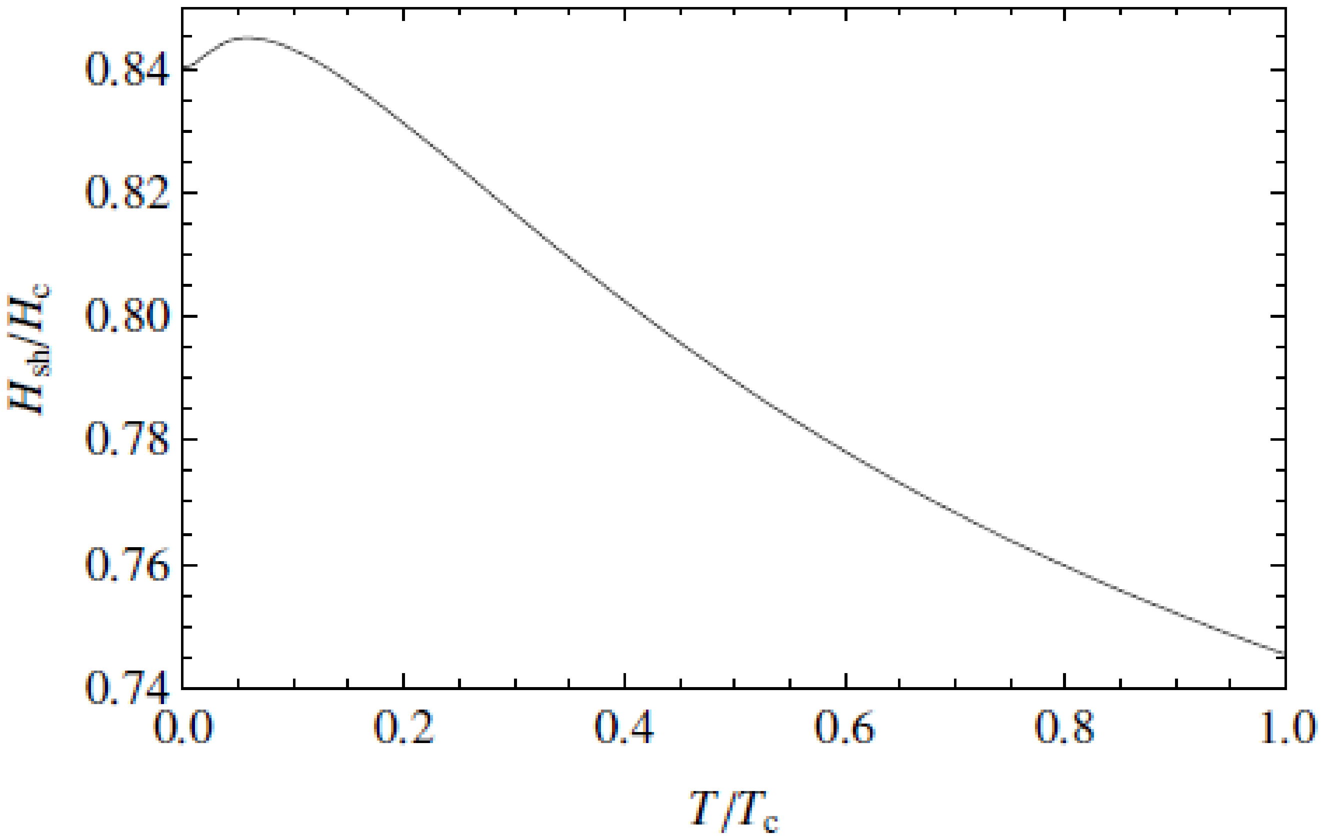
Ginzburg-Landau



Eilenberger near Tc – Mark Transtrum



Hsh(T), Large κ

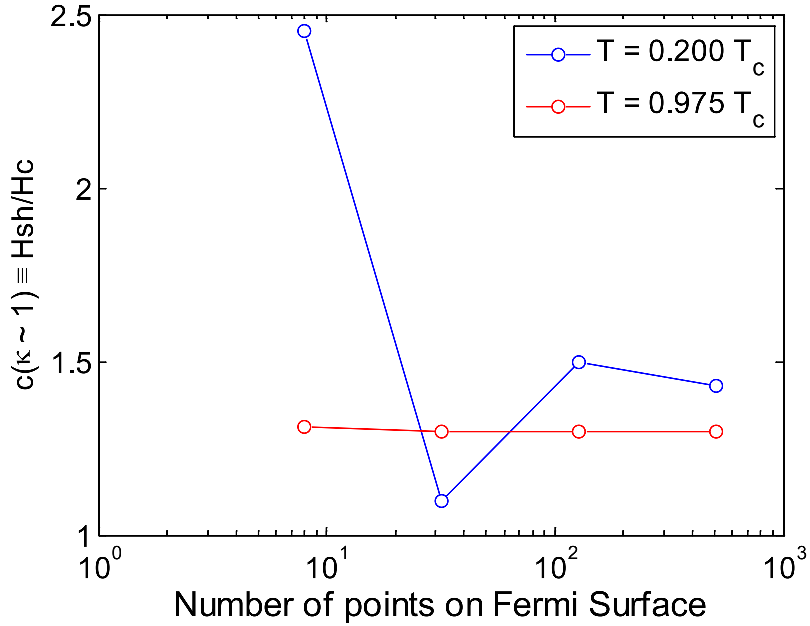


Eilenberger Eqns, κ >> 1.
Sethna , Catelani

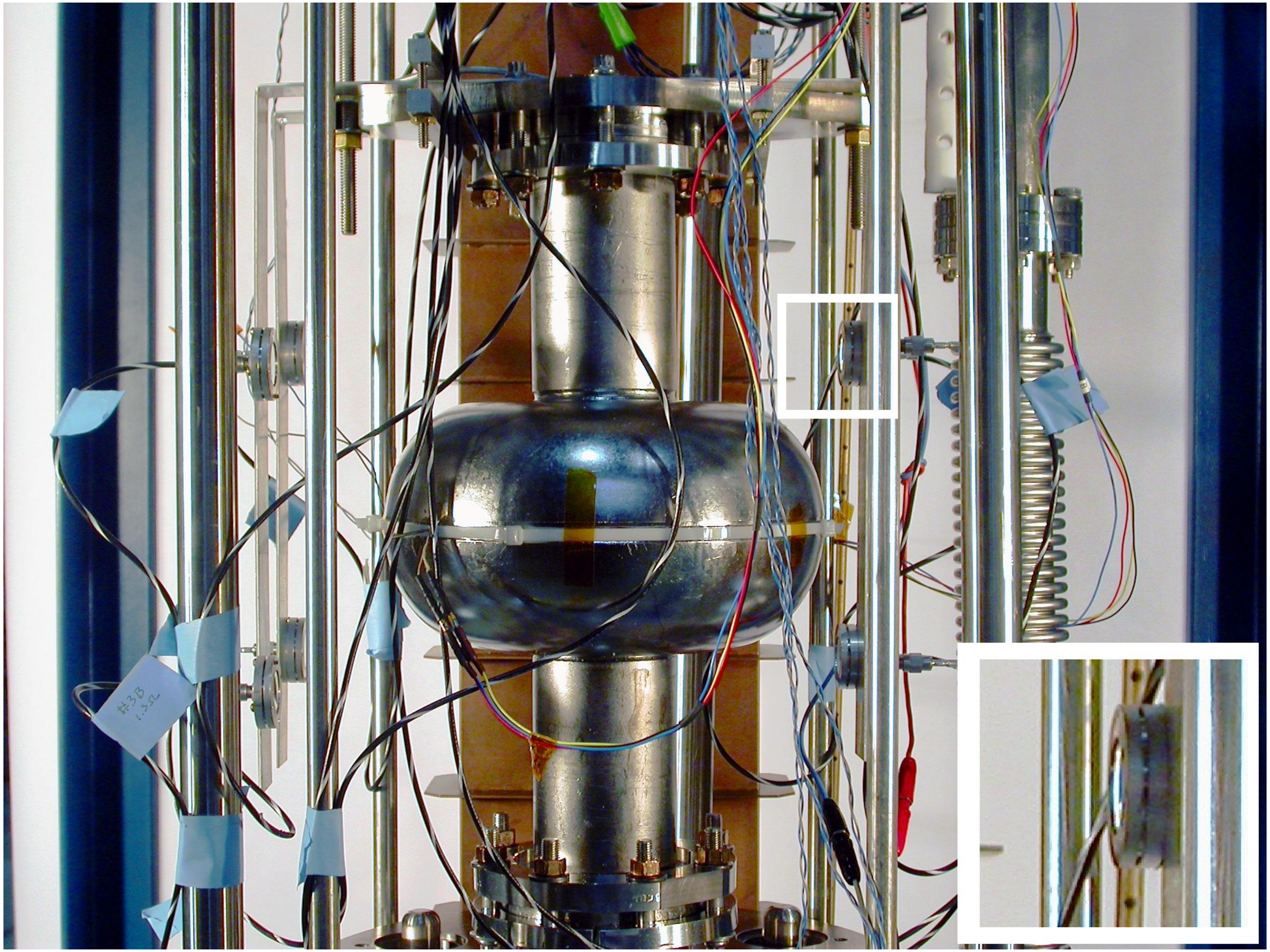
Hsh(T), Intermediate κ

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

Hsh(κ ~ 1), convergence

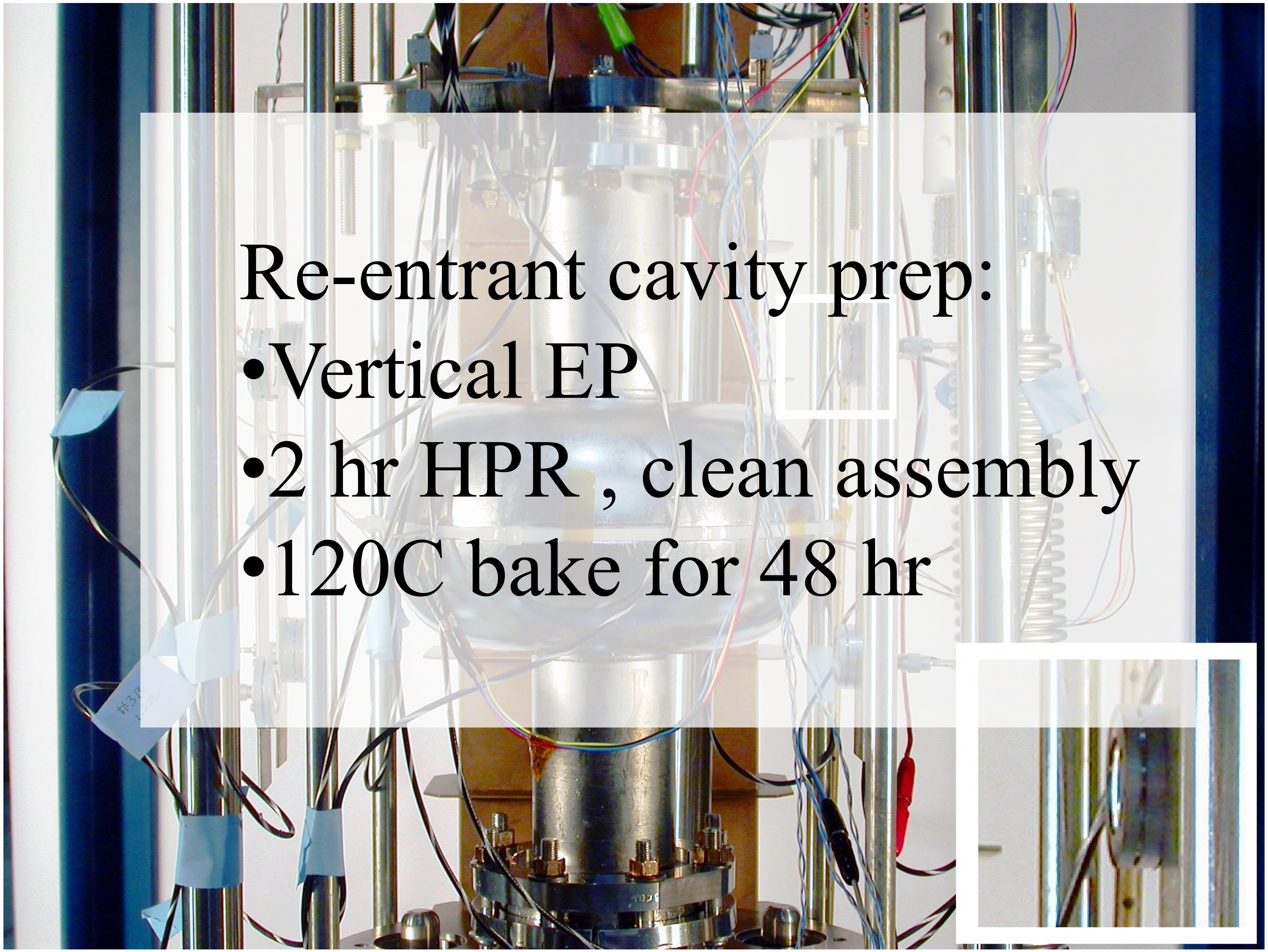


Hsh(T) Measurement



LR1-3 to measure Superheating Field

Hsh(T) Measurement

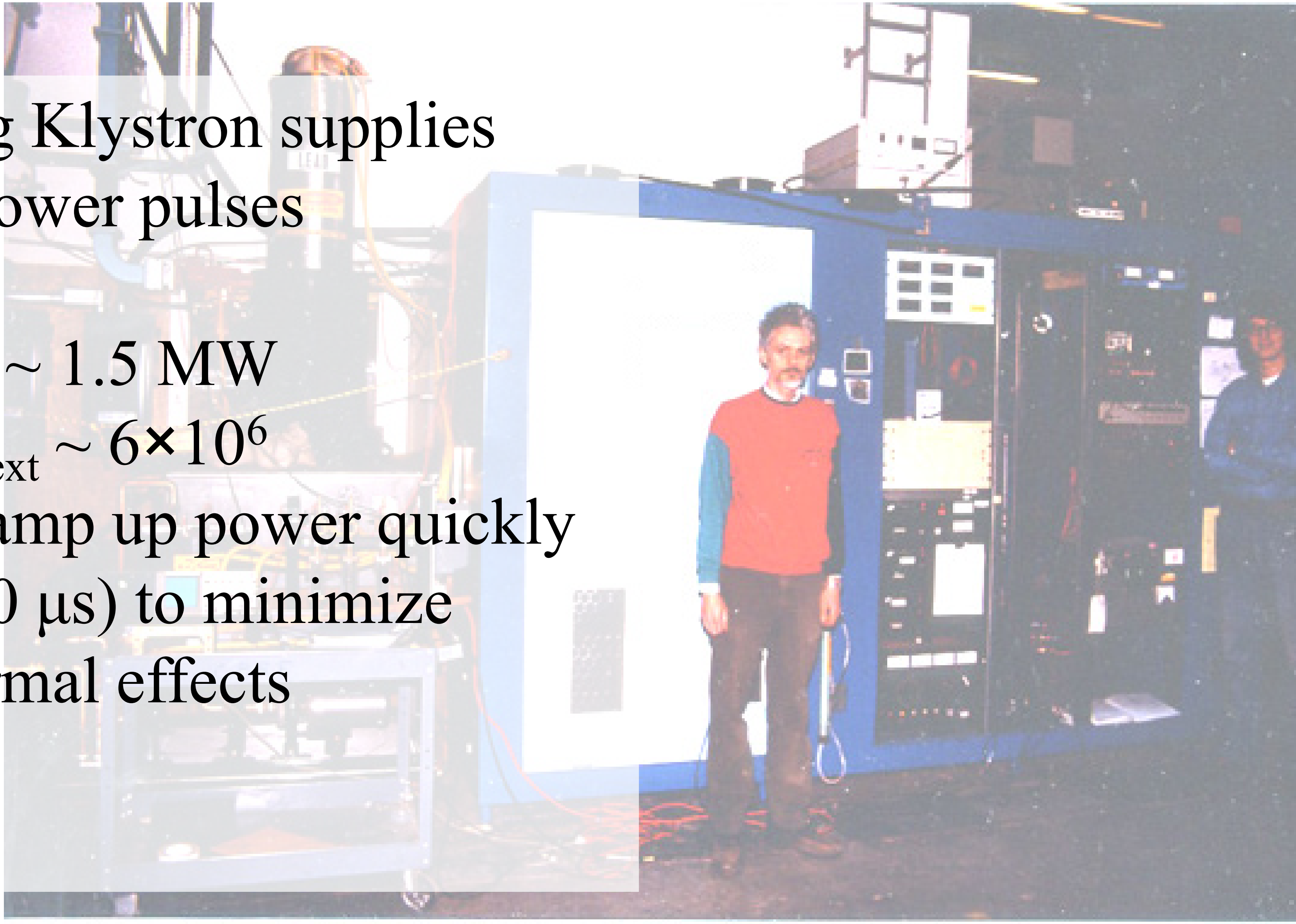


Re-entrant cavity prep:

- 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
- $Q_{ext} \sim 6\times10^6$
- Ramp up power quickly (100 μs) to minimize thermal effects

Calculating Q_0 vs Time

- Following Hays we can write:

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

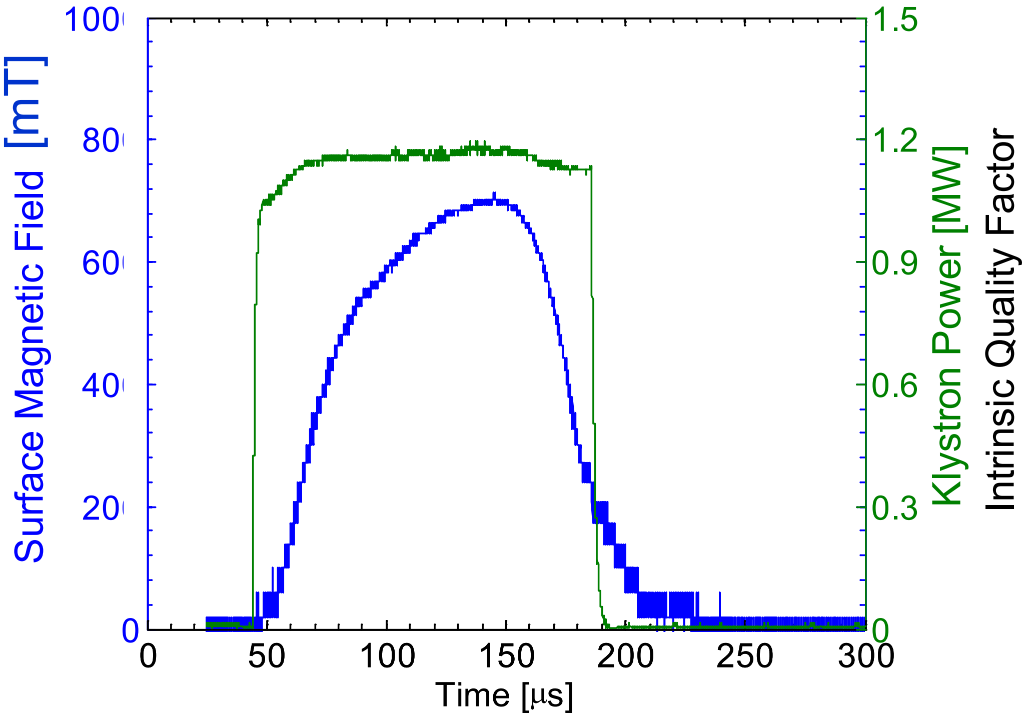
which gives

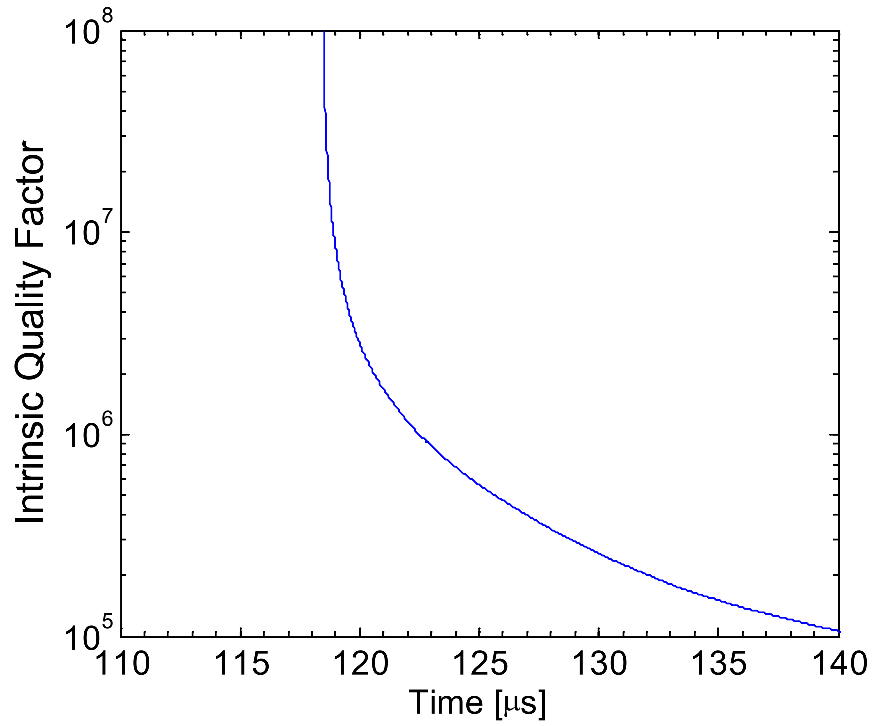
$$\frac{\omega U}{Q_0} = 2\sqrt{\frac{\omega U P_f}{Q_{ext}}} - \frac{dU}{dt} - \frac{\omega U}{Q_{ext}}$$

or

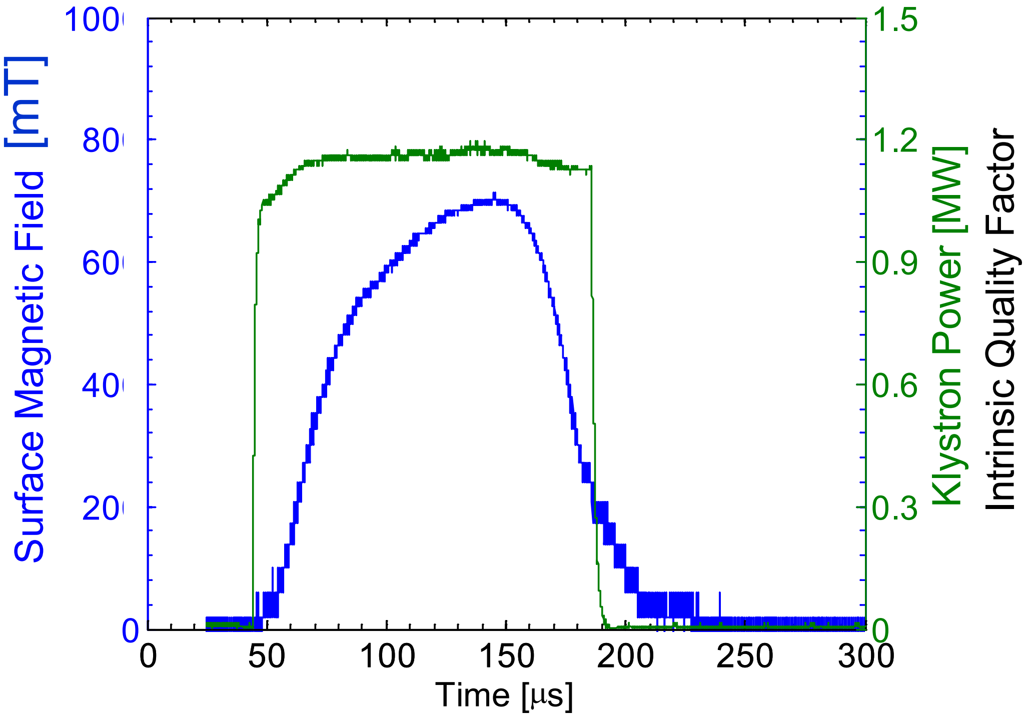
$$\frac{1}{Q_0} = \frac{2}{\omega\sqrt{U}}\left(\sqrt{\frac{\omega P_f}{Q_{ext}}} - \frac{d\sqrt{U}}{dt}\right) - \frac{1}{Q_{ext}}$$

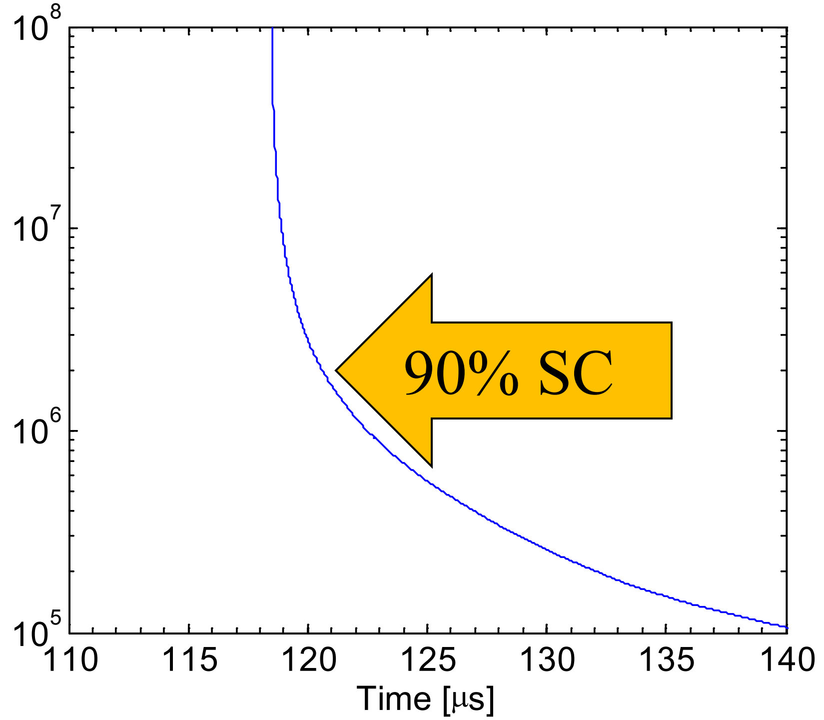
Measuring Hsh



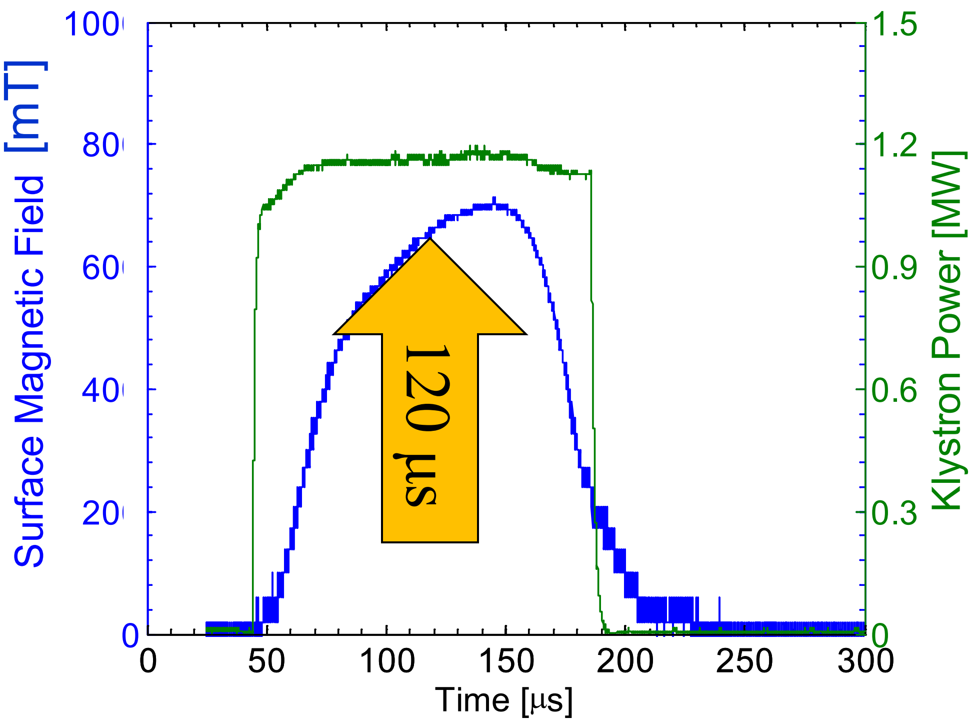


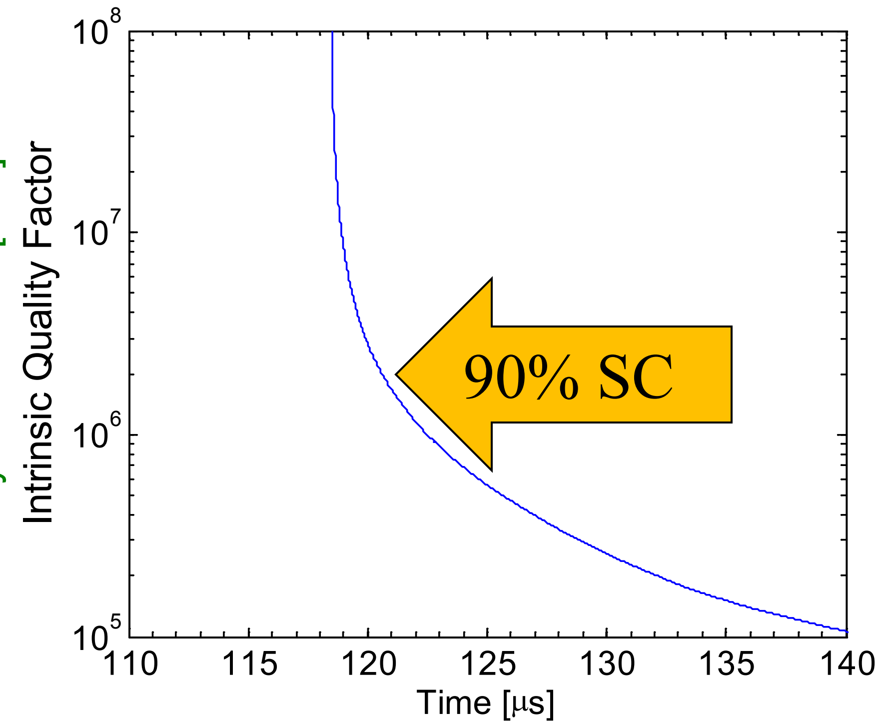
Measuring Hsh



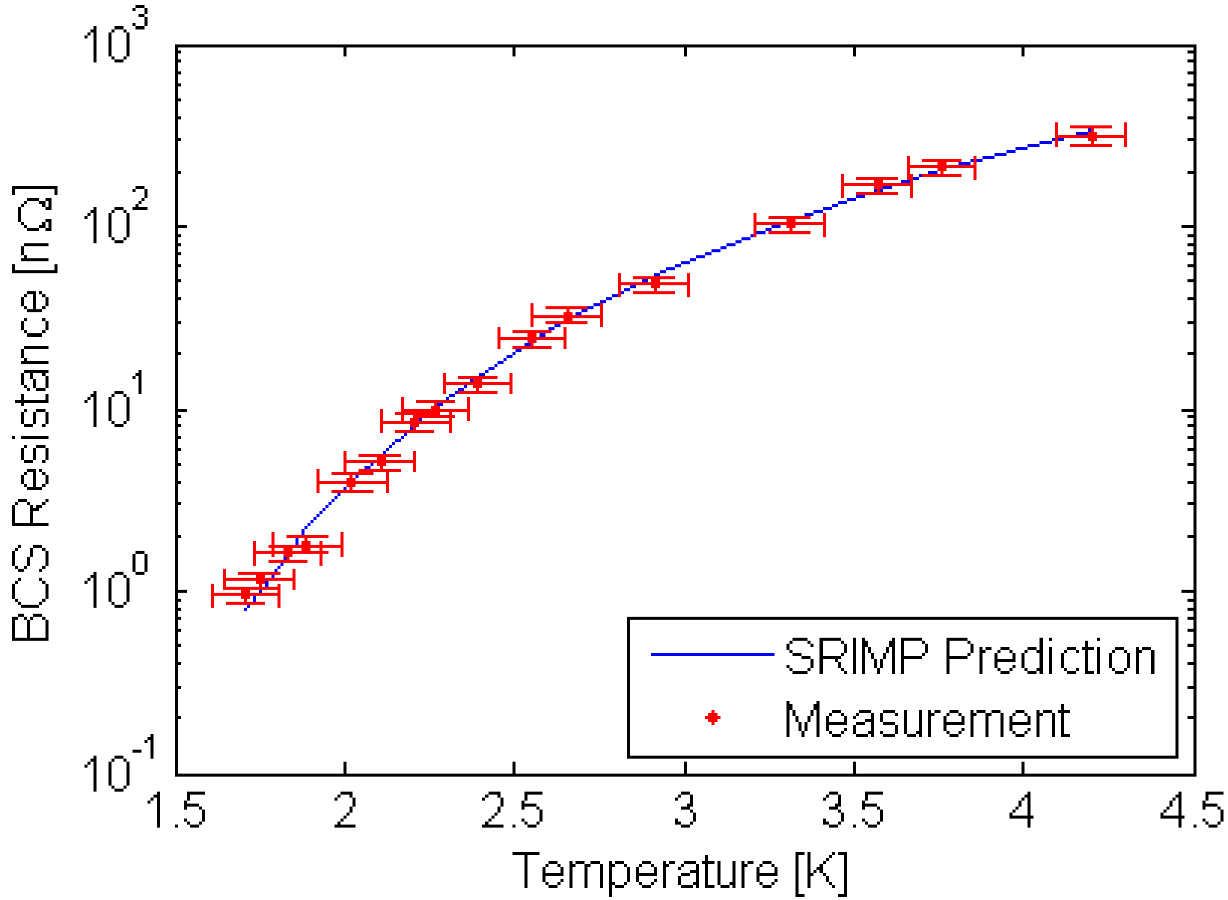


Measuring Hsh



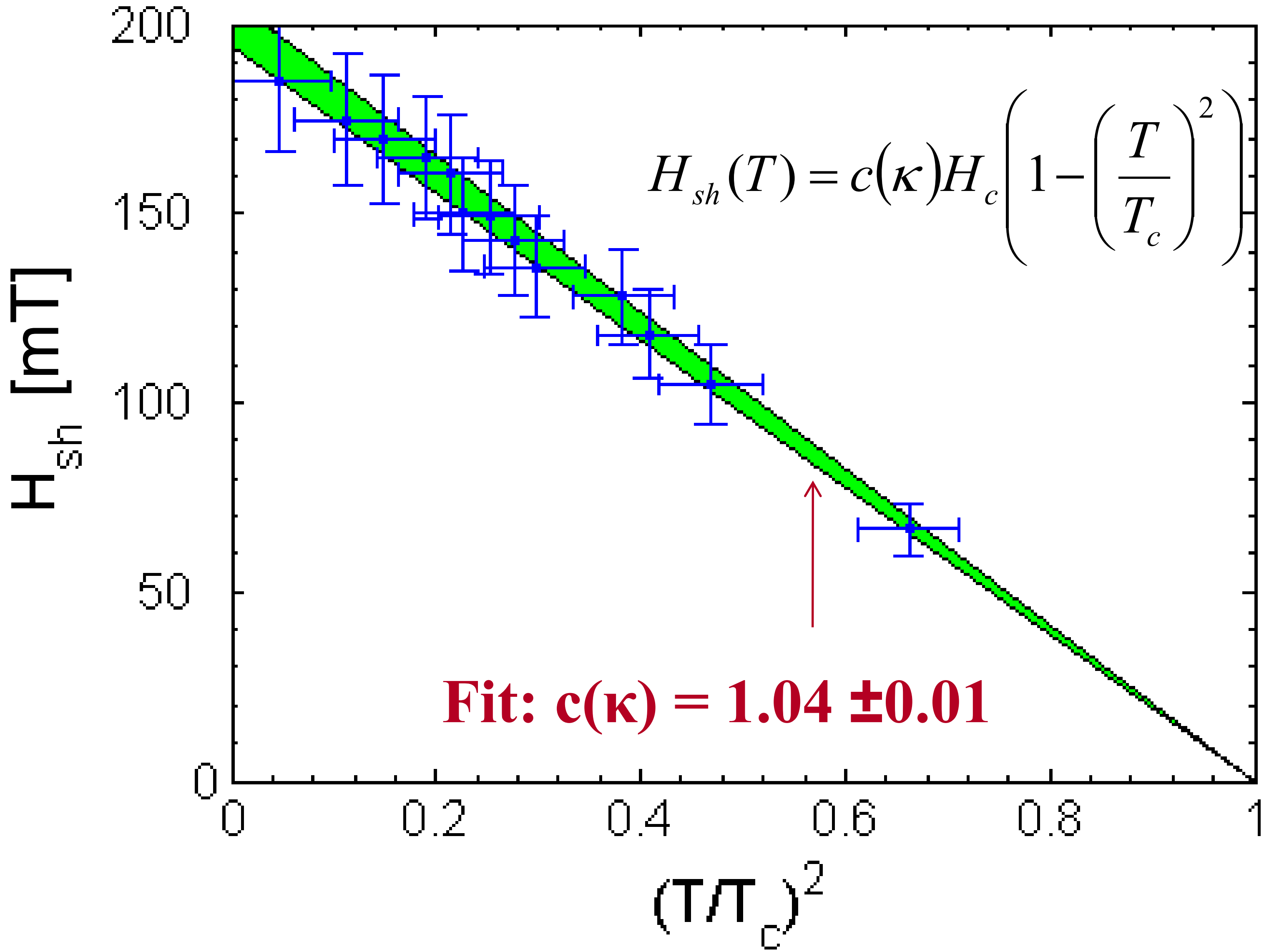


Determining κ in CW

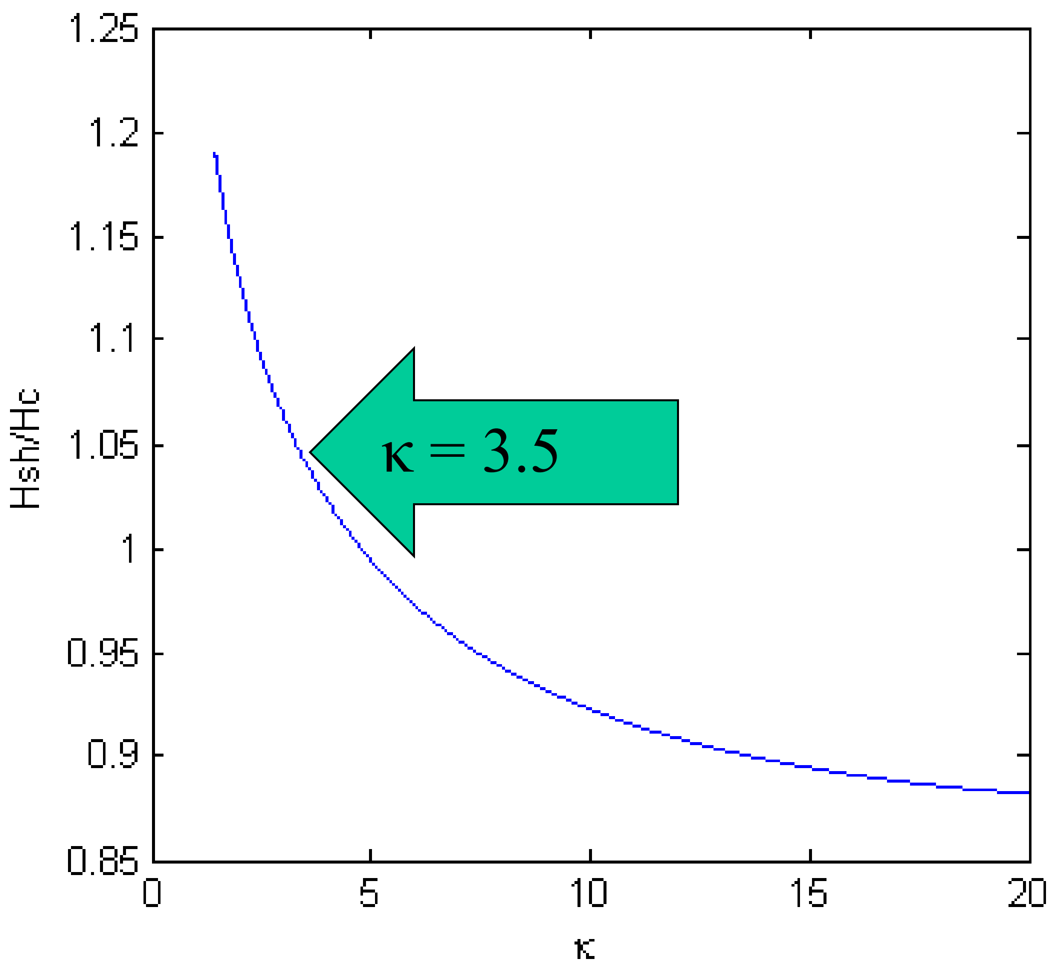


SRIMP Fit: MFP = 27 nm. κ = 3.5

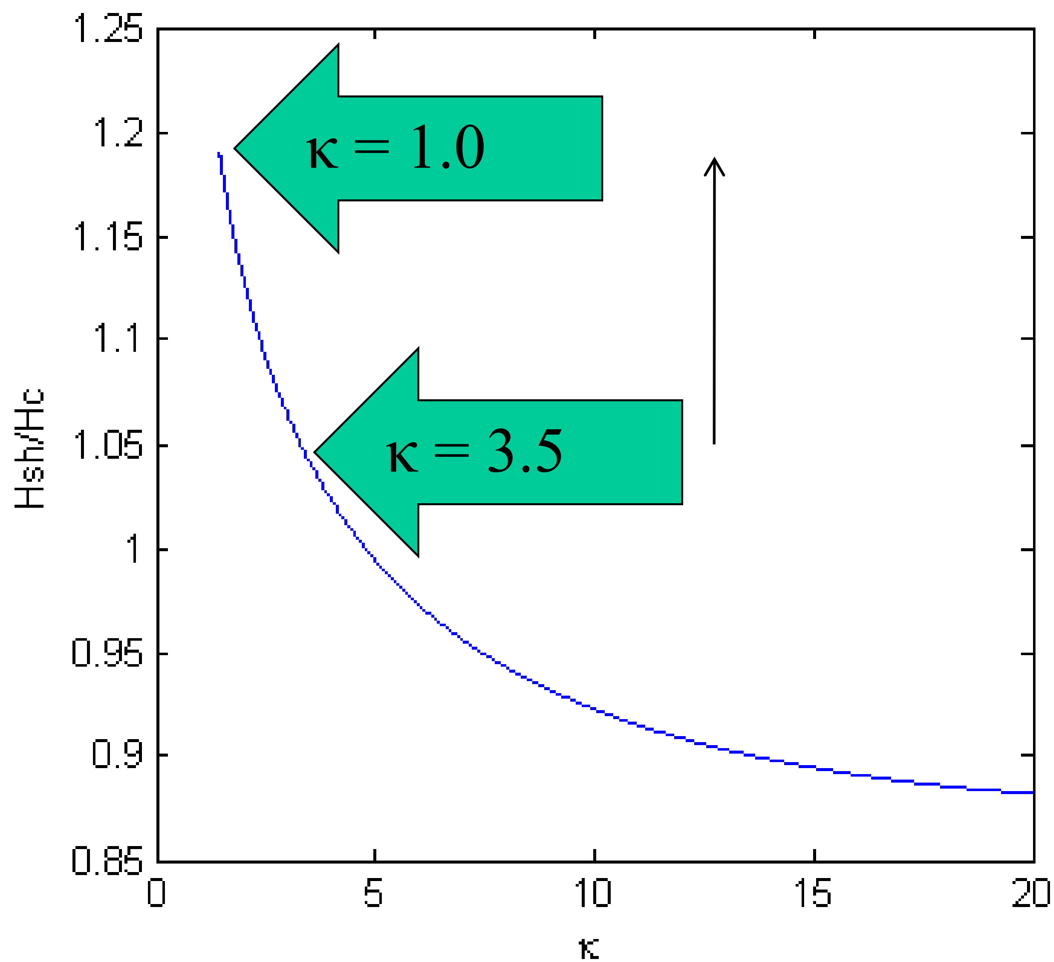
Hsh(T) Measurement



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



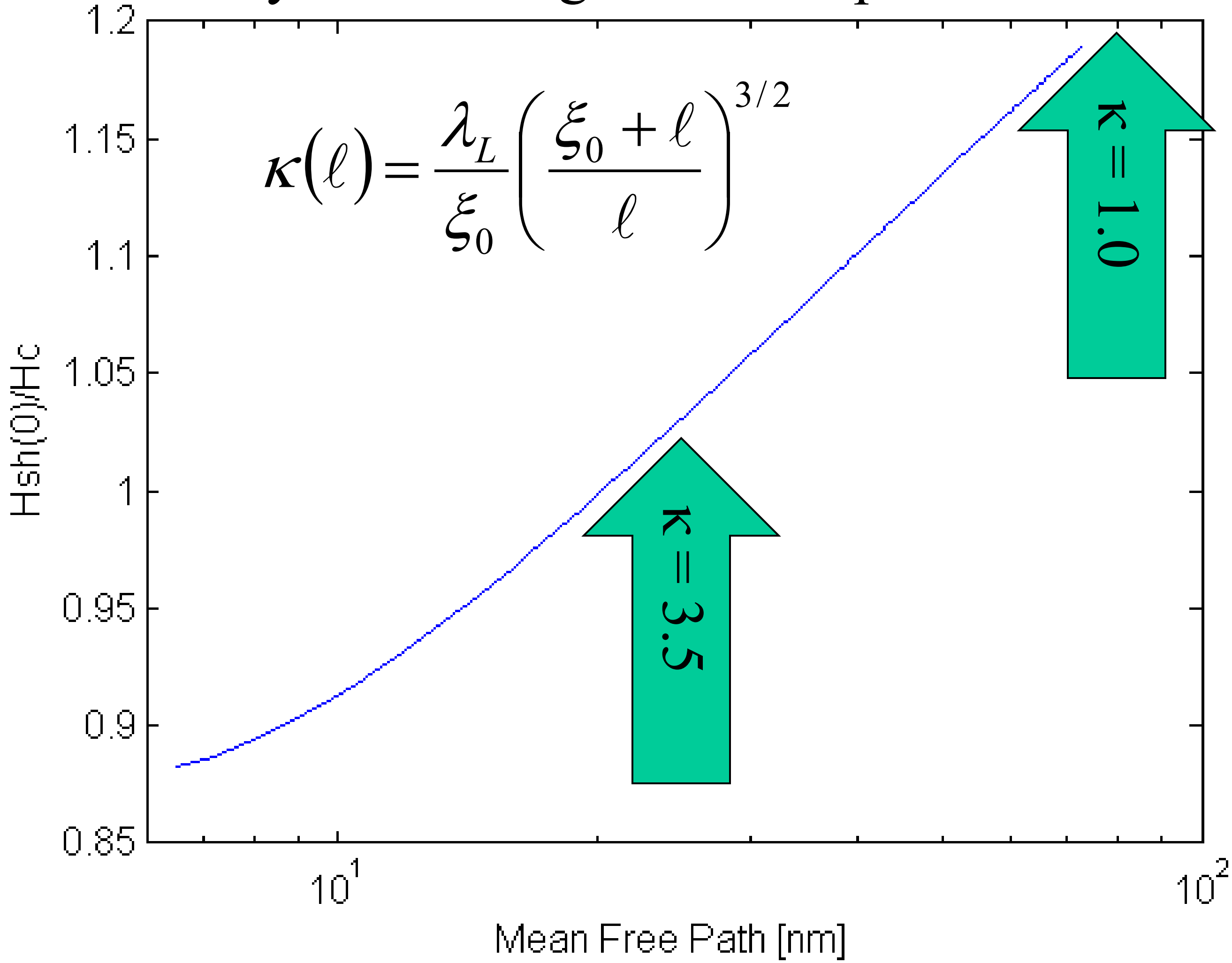
Transtrum: $H_{sh}(\kappa)$



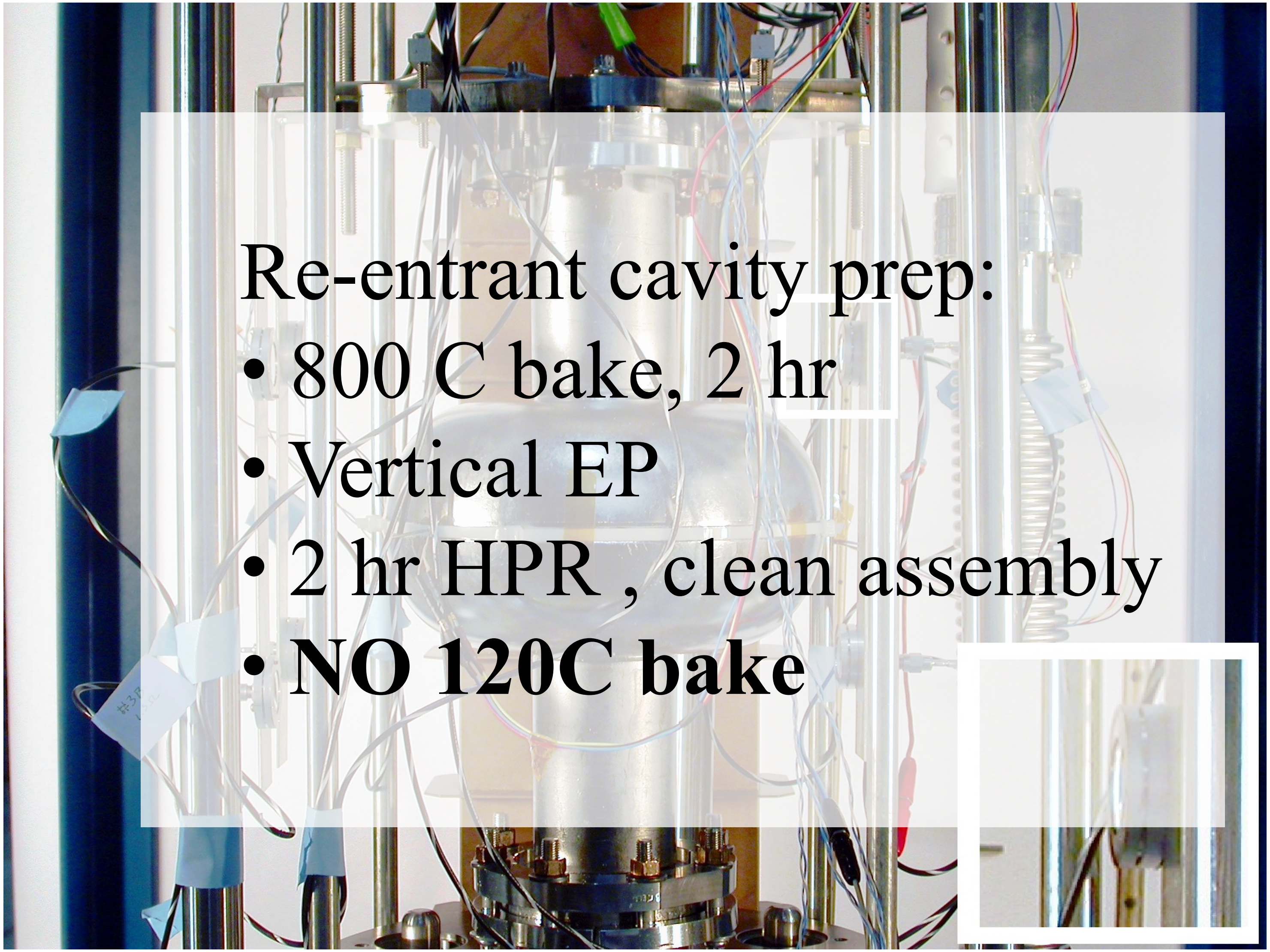
Possibility for 20% increase by changing κ

c(κ) vs Mean Free Path

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



$H_{sh}(T)$ Measurement

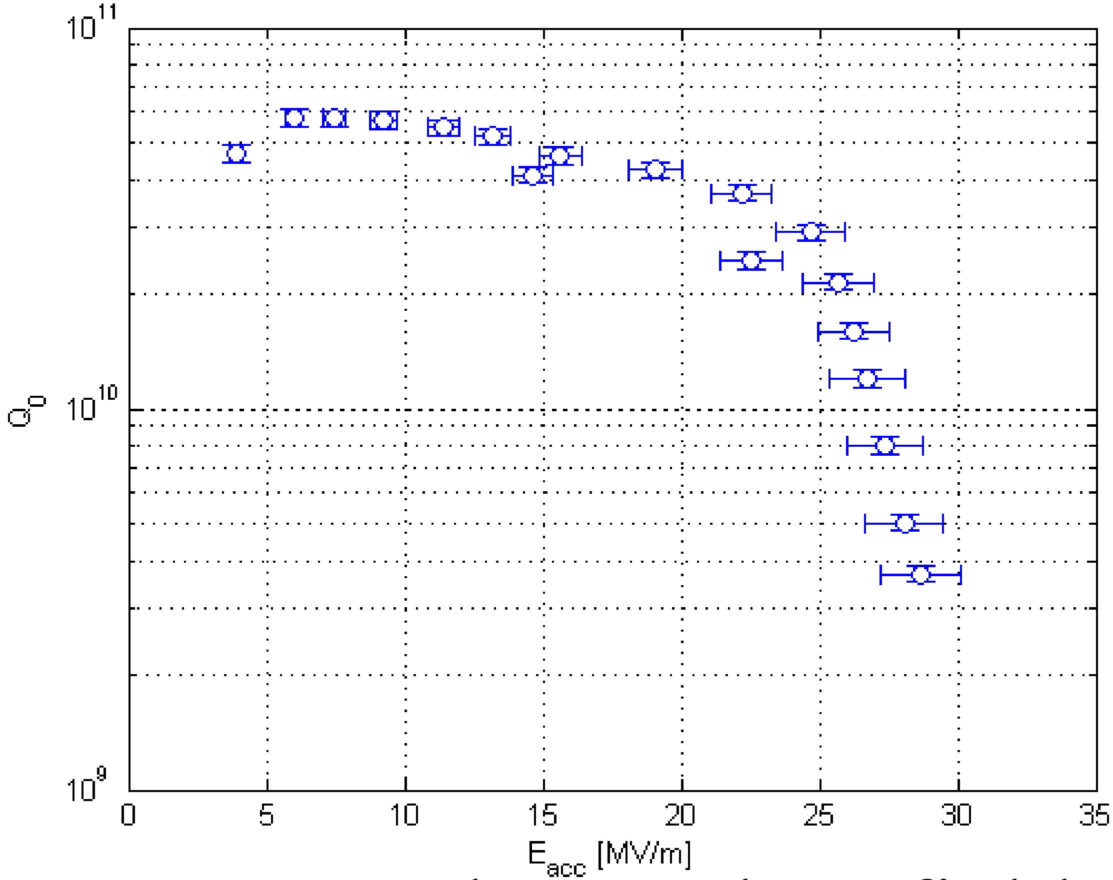


Re-entrant cavity prep:

- 800 C bake, 2 hr
- Vertical EP
- 2 hr HPR , clean assembly
- **NO 120C bake**

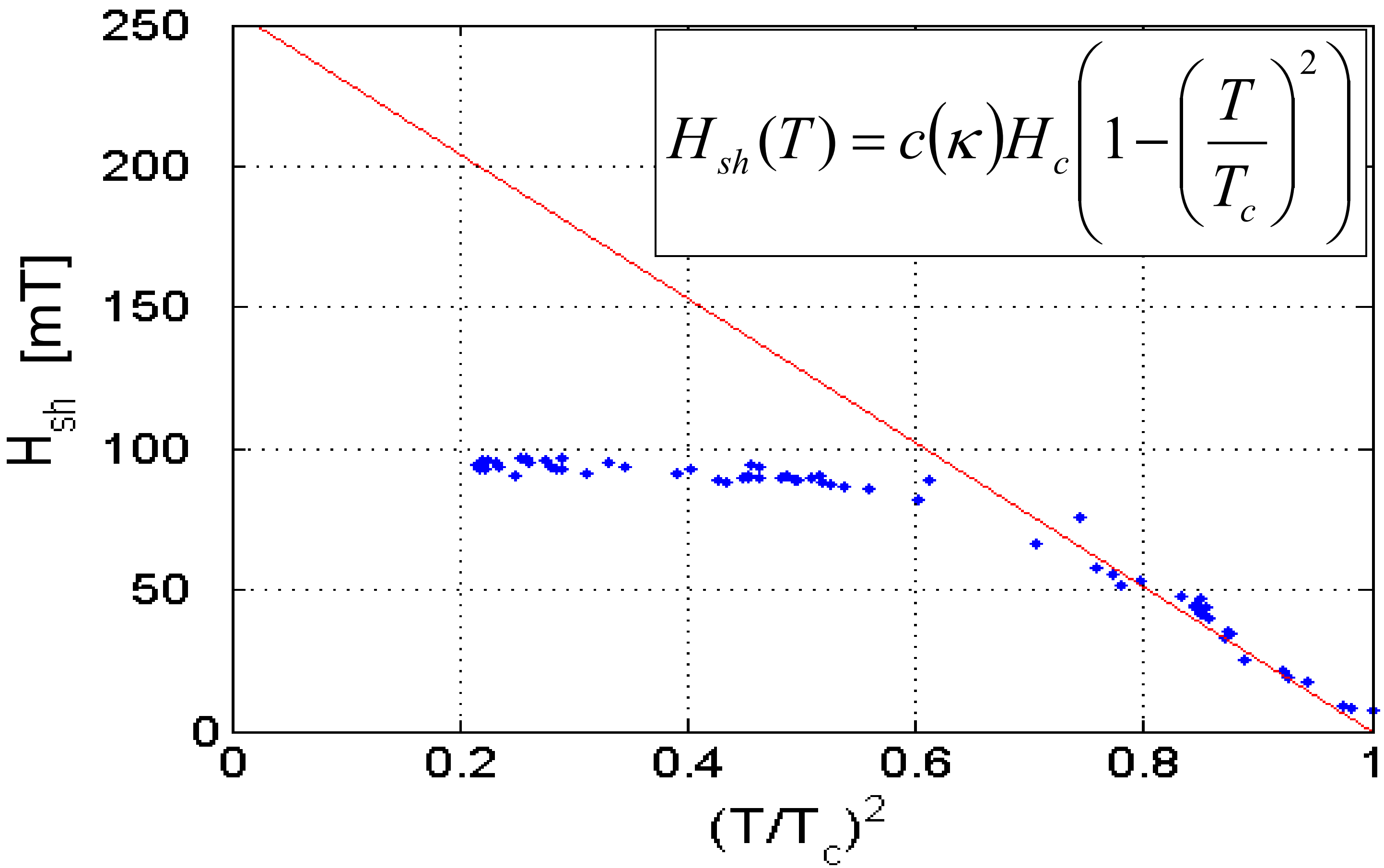
LR1-3 to measure Superheating Field

Q vs E (CW), for LR1-3



Severe Q drop at low fields.
Small radiation, no quenches

$H_{sh}(T)$ Measurement



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

$c(\kappa) = 1.28 \pm 0.06$

(Theory predicts 1.30) 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 $T \ll T_c$
- 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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