Would >50 MV/m be Possible with Superconducting RF Cavities ?

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LANL

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Outline

Nb1.3 GHz 9-cell cavity to be used for European XFEL

- Background / motivation
- An innovative idea to increase the accelerator gradient using thin film superconductors
- Results of H_{c1} measurements using SQUID magnetometry at LANL
- Results of RF surface resistance and quench field measurements at SLAC
- Discussion of issues
- Conclusion

While experimental results at LANL and SLAC are mostly discussed in this talk, a lot of people have been involved in this study. **Many thanks to them!!**

- **LANL**
  - Nestor Haberkorn and Leonardo Civale (**MPA-STC**): DC magnetization measurements,
  - Ray DePaula and Isaiah Apodaca (MPA-STC): Alumina coatings
  - Roland Schulze and his student (**MST-6**): AES/XPS analyses
  - Dave Devlin (**MST-7**): discussions on cavity coating techniques.
  - Marilyn Hawley (**MST-8**): AFM analyses and discussions

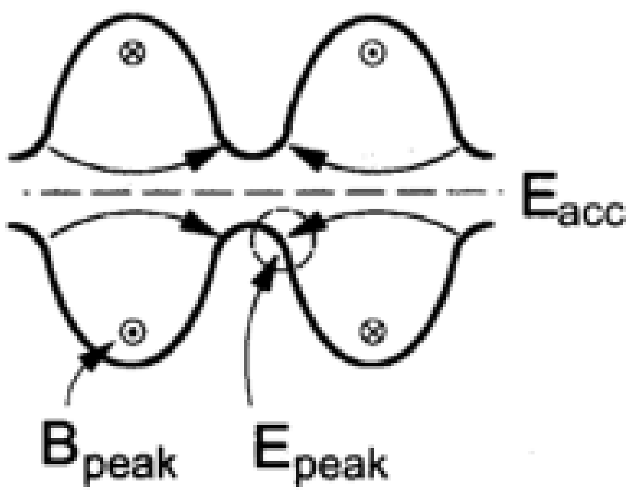
- **External collaborations**
  - Jiquan Guo, Sami Tantawi and their co-workers (**SLAC**): high-power RF testing at SLAC
  - Thomas Proslier and Mike Pellin (**ANL**): some ALD coatings
  - Brian Moeckly and Chris Yung (**STI**): preparation of MgB_2 samples using reactive co-evaporation technique
  - Peter Kneisel, Grigory Eremeev, Binping Xiao (**Jlab**): providing Nb materials and R_s measurements
  - Akiyoshi Matsumoto, Hideki Abe and Minoru Tachiki (**NIMS**, Tsukuba, Japan): discussions
  - Eiichiro Watanabe, Daiju Tsuya and Hirotaka Ohsato (NIMS, Tsukuba, Japan): ALD of alumina layers
  - Toshiya Doi, Takafumi Nishikawa, Tomoaki Nagamine and Kazuki Yoshihara (**Kagoshima University, Japan**): preparation of some MgB_2 samples using E-beam co-evaporation technique
  - Hitoshi Inoue (**KEK, Tsukuba, Japan**): vacuum baking of some Nb samples for coating

Background / motivation

- **Niobium (Nb) Superconducting RF (SRF) cavities have been replacing Cu cavities for the last ~30 years due to better energy efficiency and other benefits.**
- **The highest accelerating gradient (E_{acc}) of existing accelerators as user facilities is ~ 20 MV/m.**
- **In the last few years, the technology to achieve >35 MV/m with 1.3 GHz 9–cell cavities has been maturing**
- **But, it is doubtful that we can get >50 MV/m SRF cavities in a practical sense using Nb technology (a traveling wave structure might have a chance, but it will not be discussed in this talk.)**

What sets the fundamental limit of Nb SRF cavities?

- **The fundamental limit that prevents niobium cavities from reaching >50 MV/m is the thermodynamic critical magnetic field of Nb, $H_c \cong 2000$ Oe ($B_c \cong \mu_0 H_c = 200$ mT)**



$$E_{peak} \simeq 2 \cdot E_{acc}$$

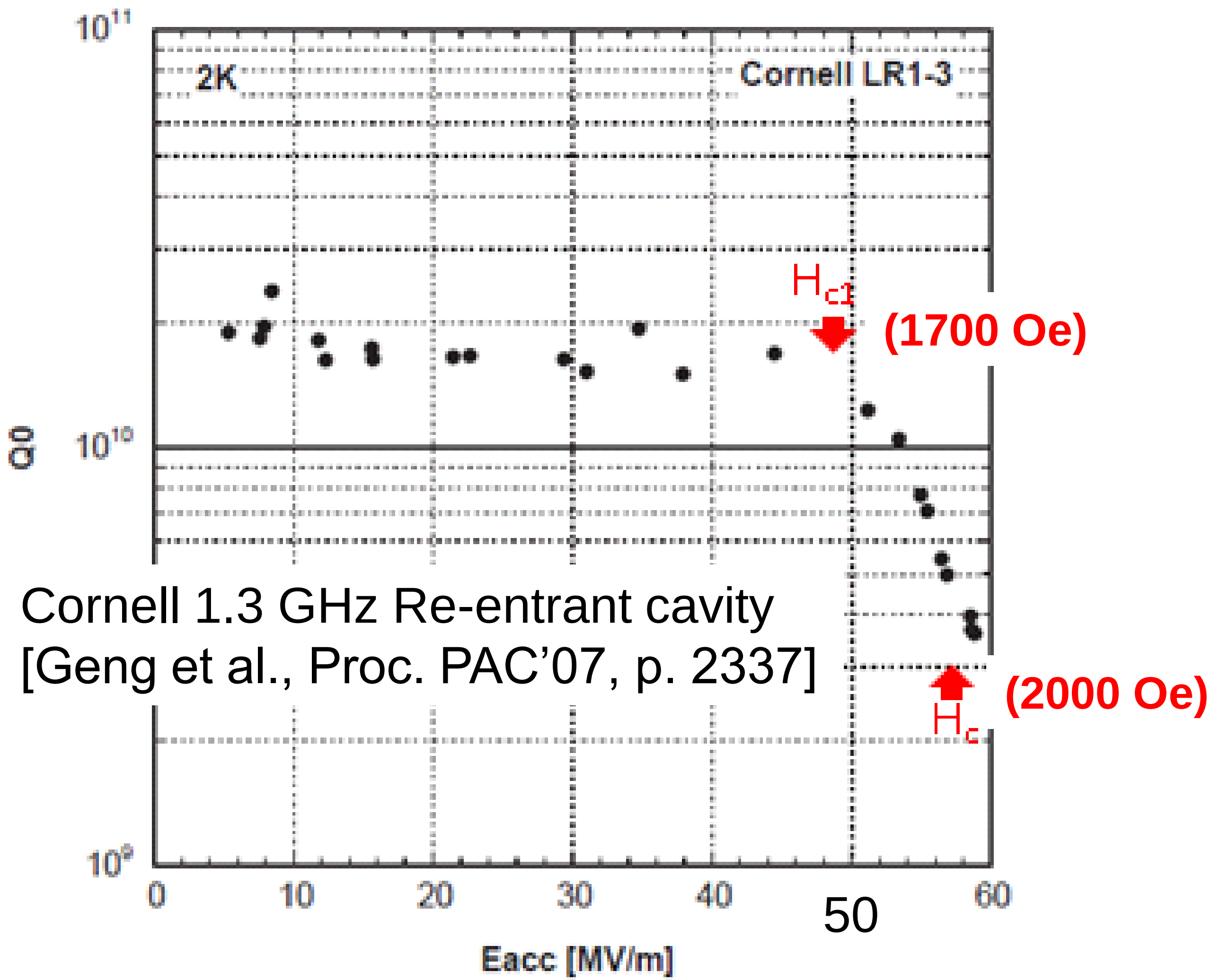
$$\frac{B_{peak}}{E_{acc}} \simeq \frac{4\ \text{mT}}{\text{MV/m}}$$

Nb: $B_c \simeq 200$ mT

($H_c \cong 2000$ Oe)

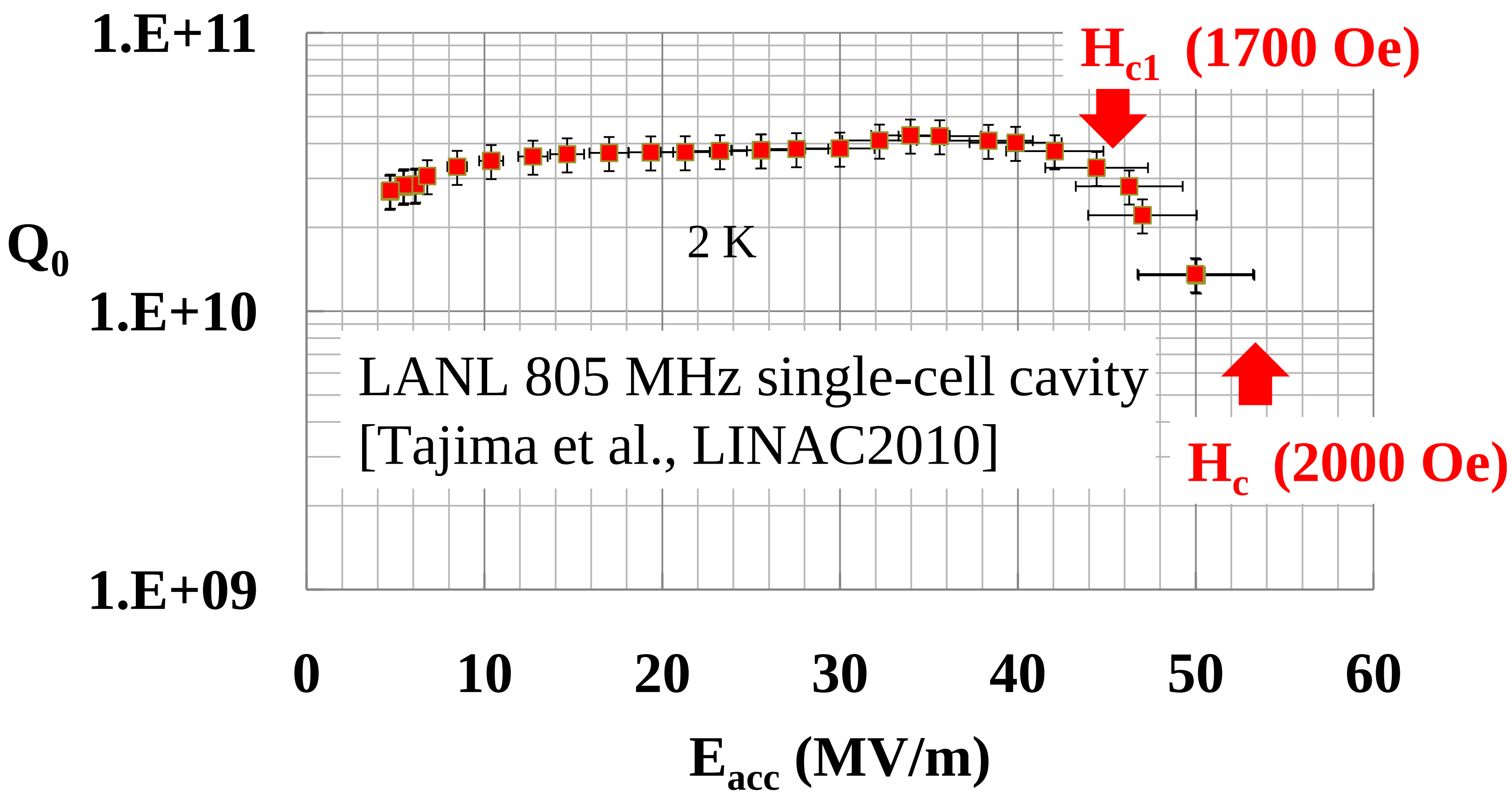
$\Longrightarrow$ max $E_{acc} \simeq 50$ MV/m

H_{c1} sets practical limit of SRF technology



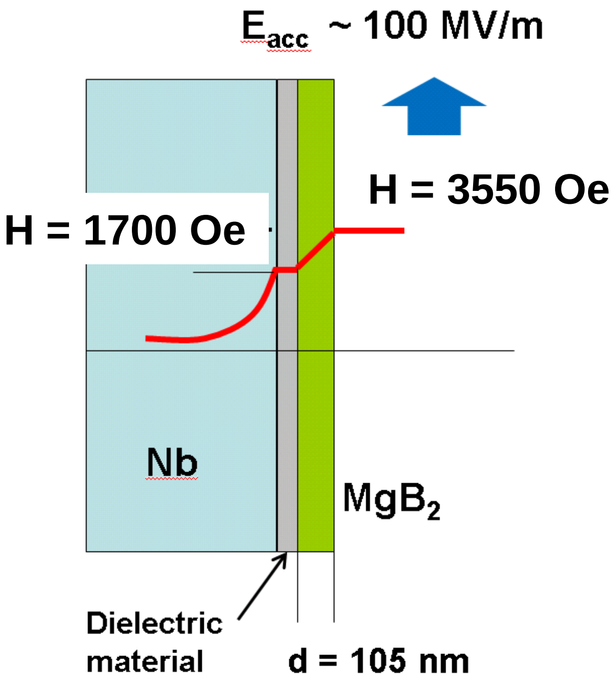
Cornell 1.3 GHz Re-entrant cavity
[Geng et al., Proc. PAC'07, p. 2337]

H_{c1} sets practical limit of SRF technology



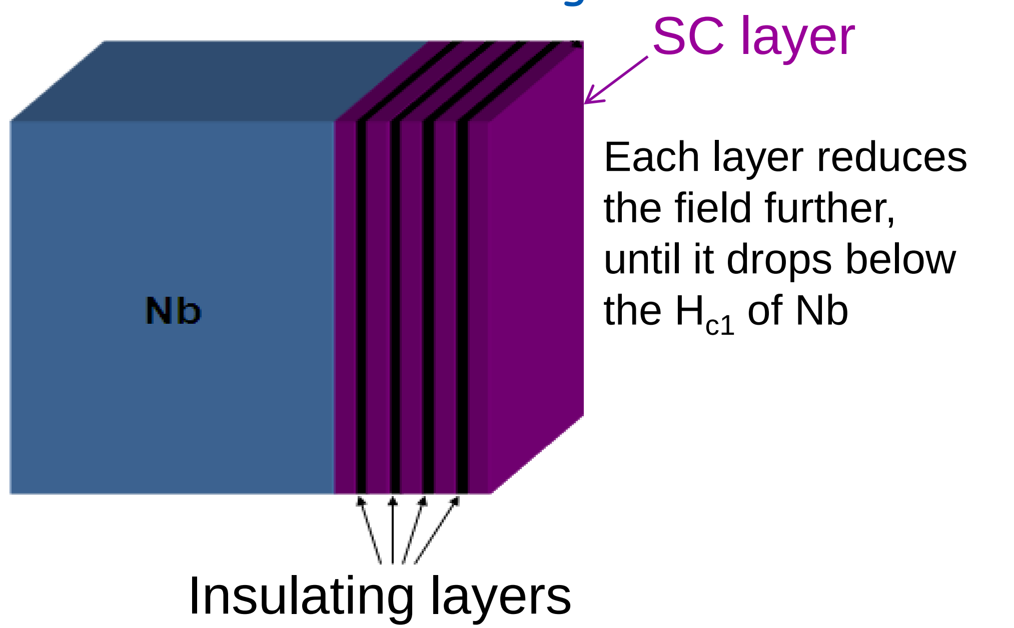
Gurevich's innovative idea: to overcome the fundamental limit of Nb cavities by using multilayers of superconducting/insulating thin films

Concept of field enhancement with a single layer of MgB_2



Problem: the thinner the layer, the smaller the field screening

Solution: multilayers to produce a "cascade" field screening effect



Each layer reduces the field further, until it drops below the H_{c1} of Nb

Gurevich only considered the limit $d \ll \lambda$
Strongest H_{c1} enhancement, but
- many layers may be needed
- coating curved walls with uniform multilayers of very thin layers is challenging

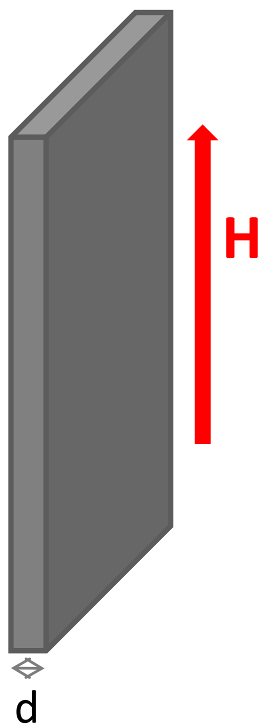
The key of Gurevich's proposal is that H_{c1} in parallel with the material surface can be increased using thin films if the thickness d ~ λ (penetration depth) or thinner

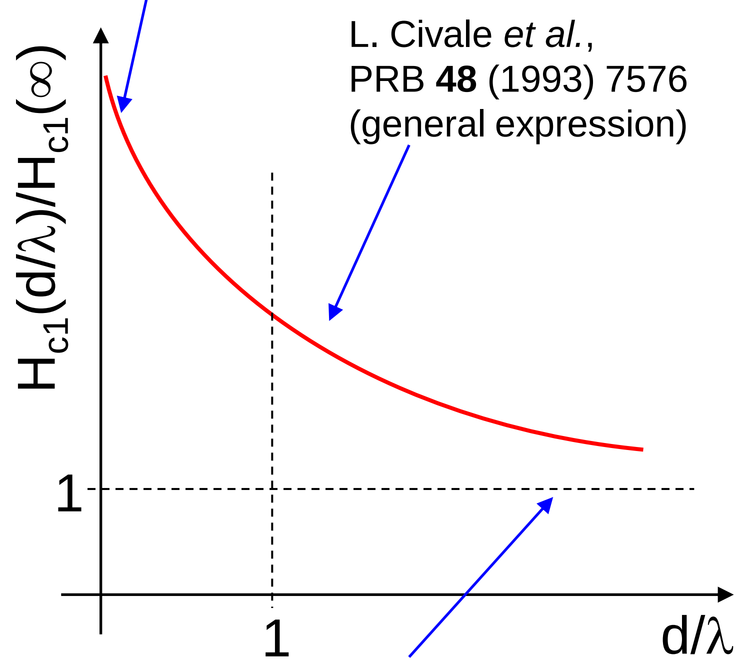
[Gurevich, APL **88** (2006) 012511]

Same as in the cavity

$$H_{c1} \approx \frac{2\Phi_0}{\pi d^2} \ln \frac{d}{\tilde{\xi}} \qquad (d \ll \lambda)$$

ξ: coherence length

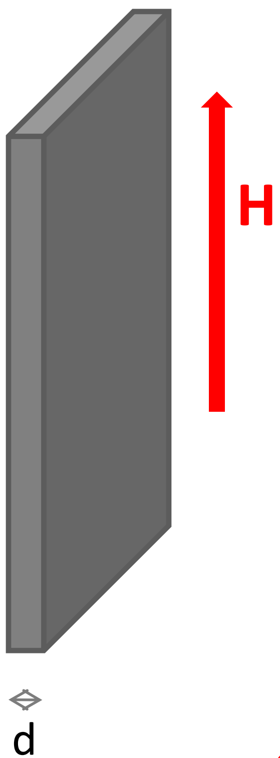


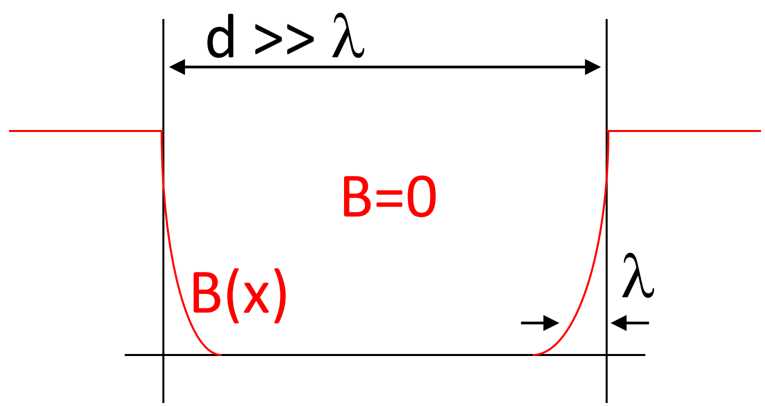


$$H_{c1} = \frac{\Phi_0}{4\pi\lambda^2} \ln \kappa \qquad (d \gg \lambda) \qquad \kappa = \frac{\lambda}{\xi}$$

The walls of a superconducting cavity must remain free of vortices. ***If not***: RF field ⇒ vortex oscillations ⇒ dissipation ⇒ drastic Q decrease

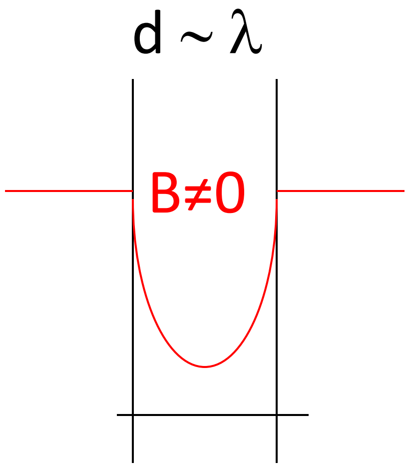
Superconducting film with H//surface





Energy cost of expelling field: ∝ H
Energy of a vortex: H independent
H_{c1}: vortex nucleation becomes thermodynamically favorable

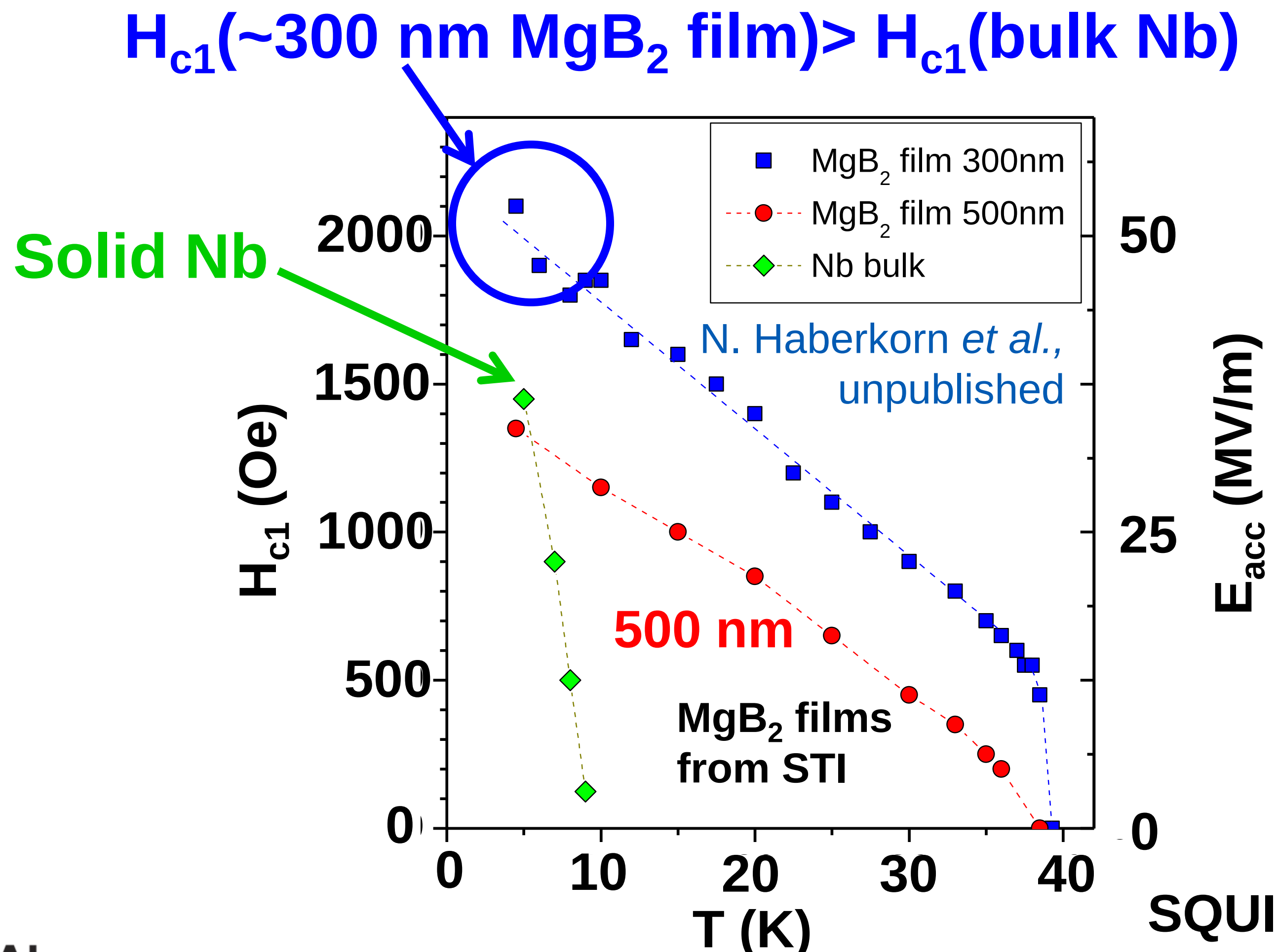
Cavities must operate below H_{c1}



Cost of expelling field decreases
H_{c1} increases (thermodynamics)

Possibility: coat the inside of the cavity with a superconducting thin film

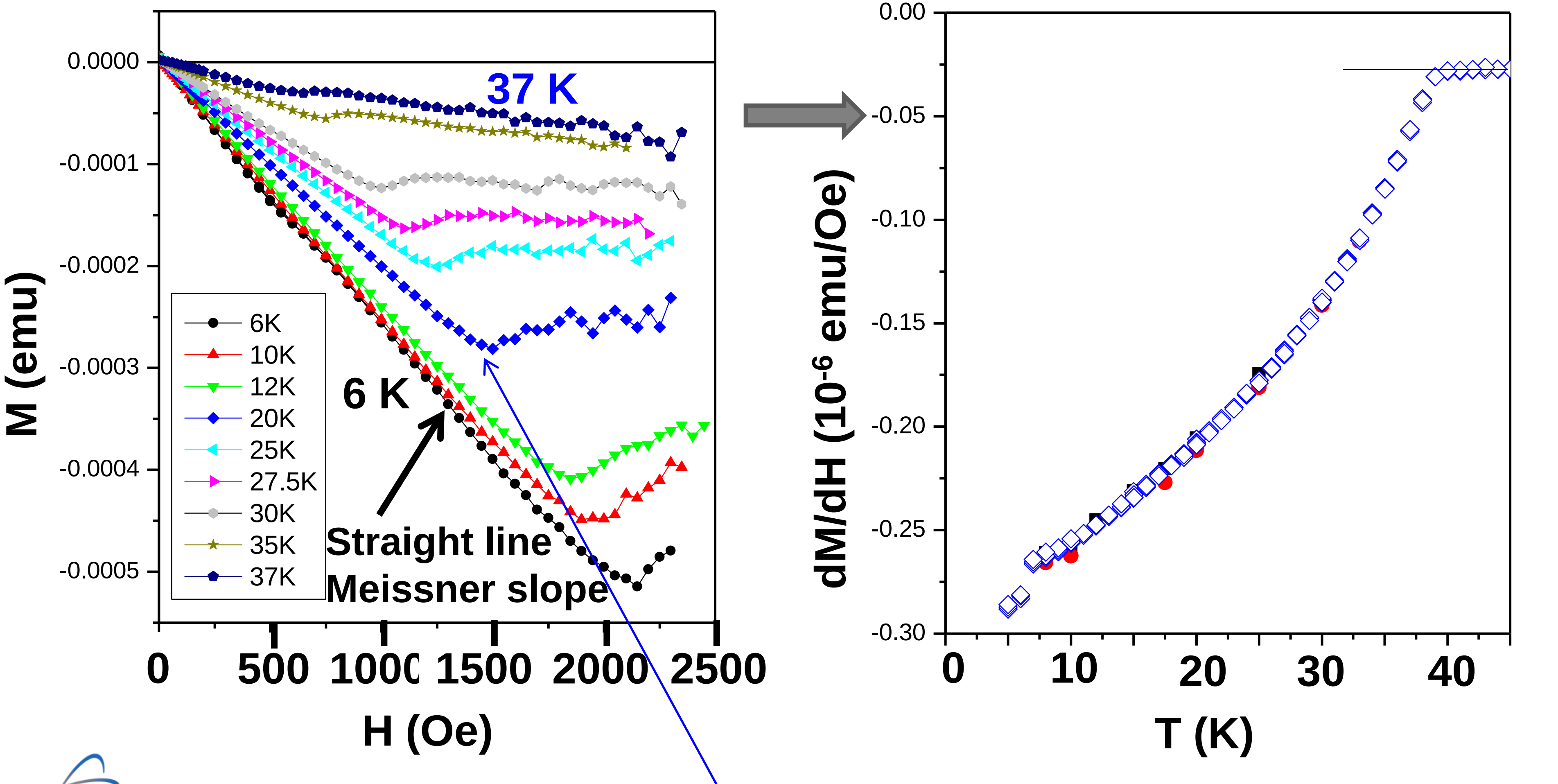
H_{c1} of 300 nm MgB_2 film shows higher H_{c1} than Nb by ~25 % ! At 4.5 K, the lowest measured temperature, H_{c1} > 2000 Oe



Converted Using H_{peak}/E_{acc} = 40

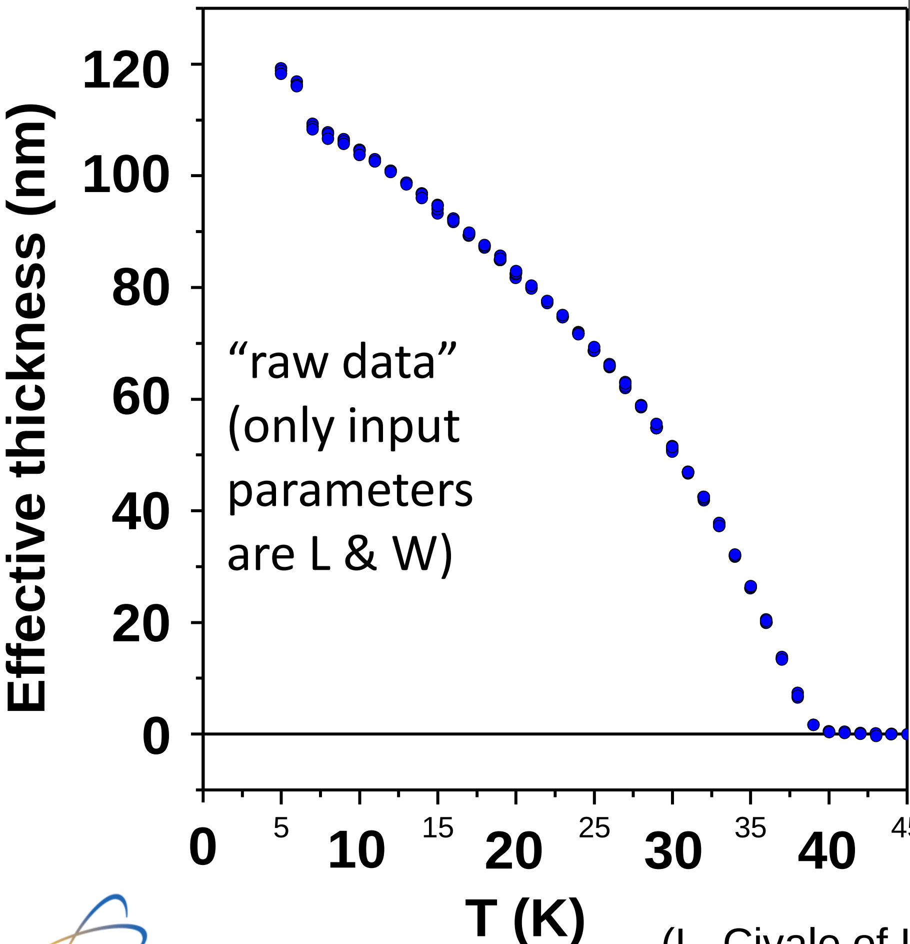
SQUID magnetometry at LANL

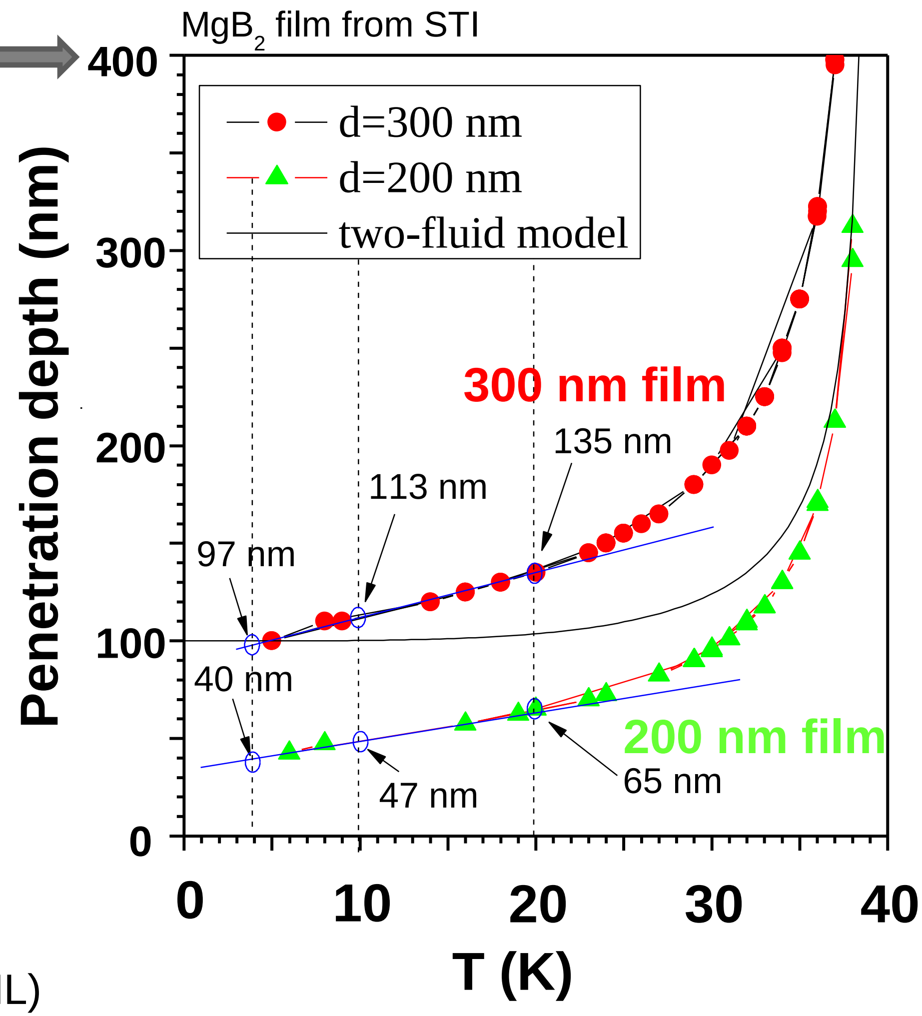
Preliminary results of 200 nm MgB_2 film: SQUID magnetometry (L. Civale of LANL)



Point where a large number of vortices start to enter

Penetration depth increases with higher temperature! This causes the reduction of effective thickness!!

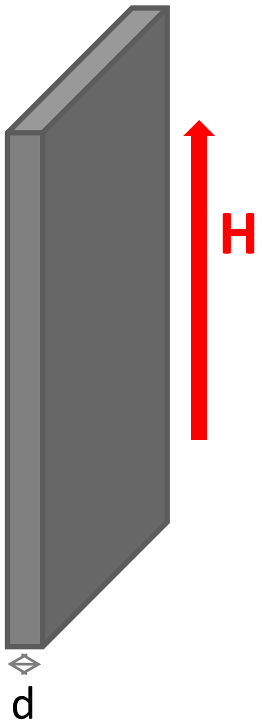




(L. Civale of LANL)

Magnetization measurements for <100 nm films have been difficult. We are considering a new method to detect field of vortex penetration into very thin films & multilayers based on ac transport techniques

Standard method:
SQUID magnetometer to detect deviation from Meissner response



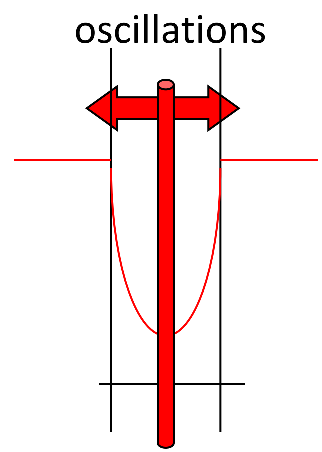
Meissner state:

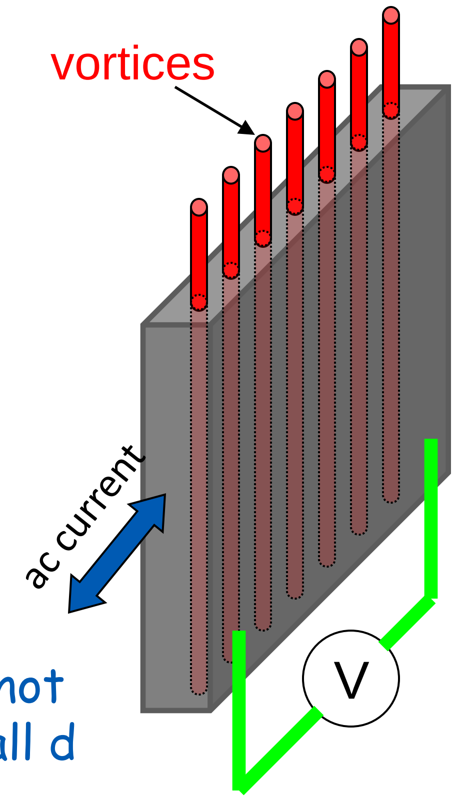
$m = -(H/4\pi)V_{eff} \propto d_{eff}$

$d_{eff} \sim d - 2\lambda \tanh(d/2\lambda)$

Problem:
Very small signal.
Present resolution:
$d \sim 100$nm (for $\lambda \sim 100$nm)

Proposed alternative method:
Lock-in detection of voltage due to vortex oscillations driven by ac electric currents





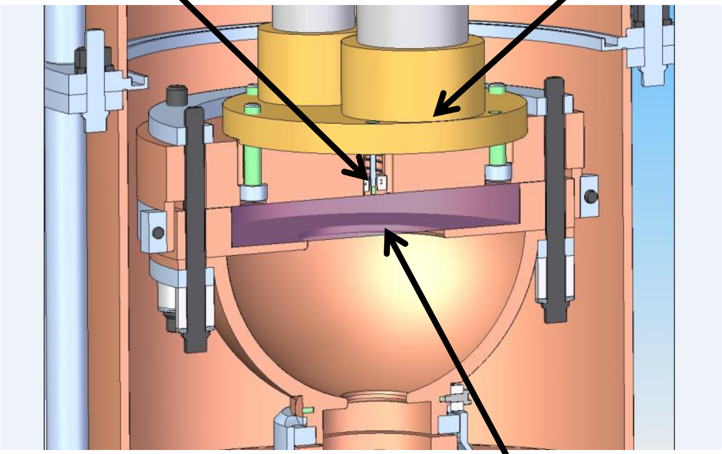
Sensitivity does not decrease for small d

RF measurements of 2-inch (~5 cm) diameter wafers (~1 mm thick) have been carried out at SLAC using 11.4 GHz pulsed power (~1.6 μs) [J. Guo, S. Tantawi et al.]

Hemi-spherical TE_{013}–mode cavity with magnetic fields in parallel with the sample surface

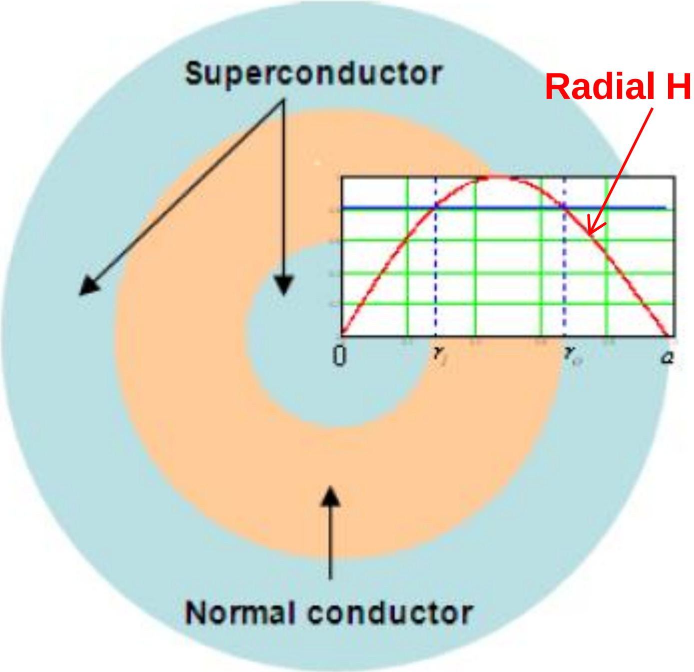
Temperature sensor

Cold head



Sample: <1.5 mm thick

Typical distribution of superconducting and normal-conducting regions after quench



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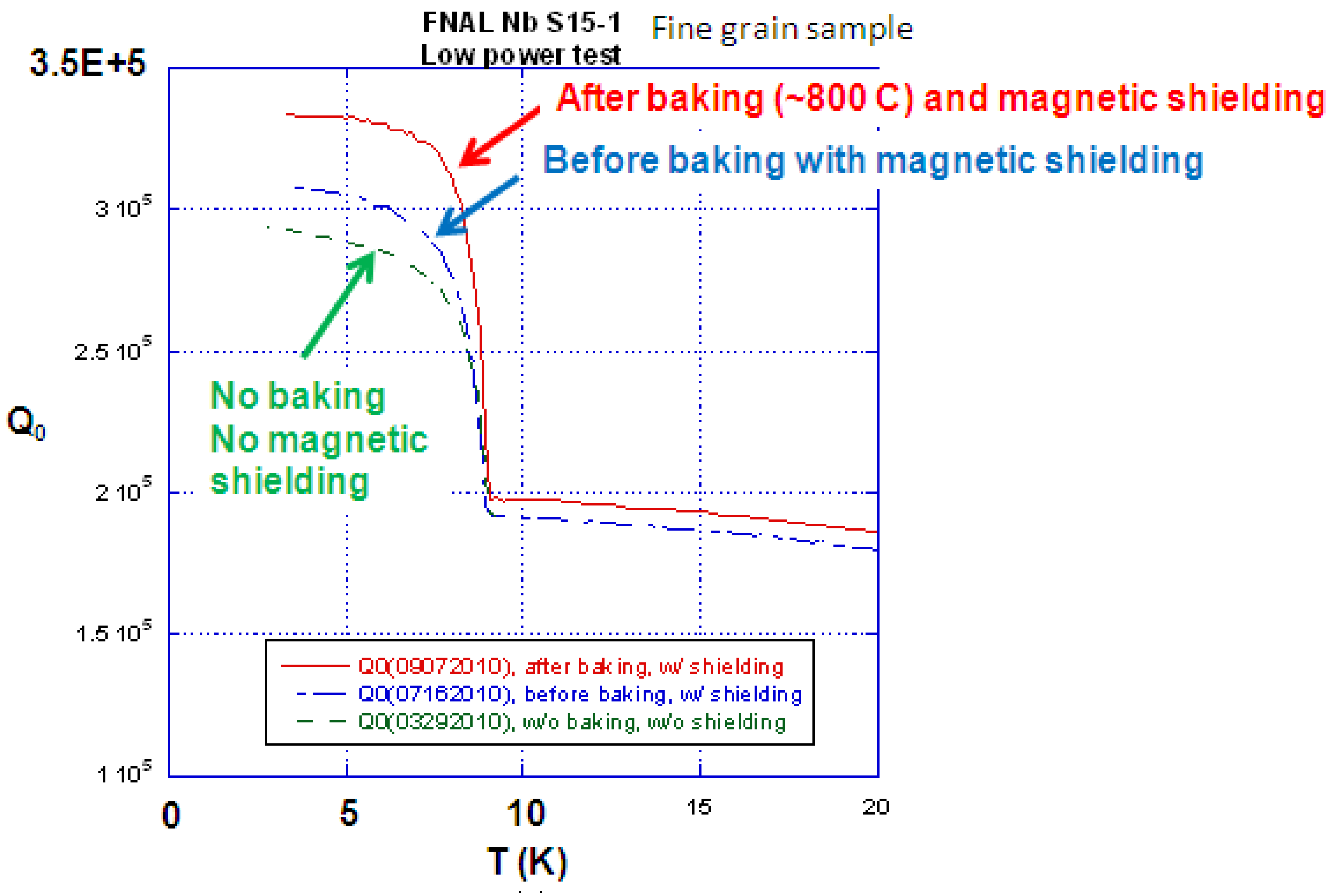
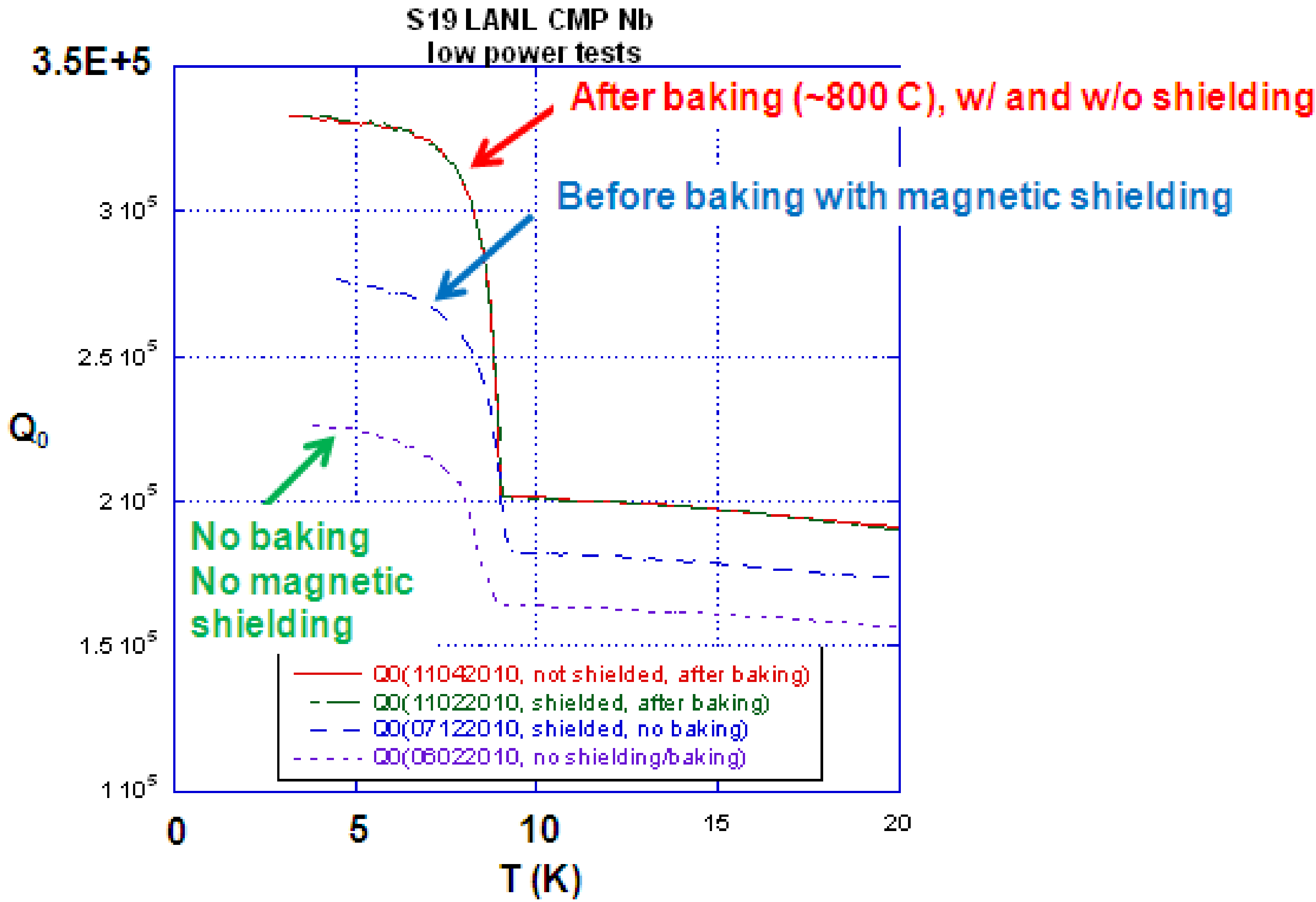
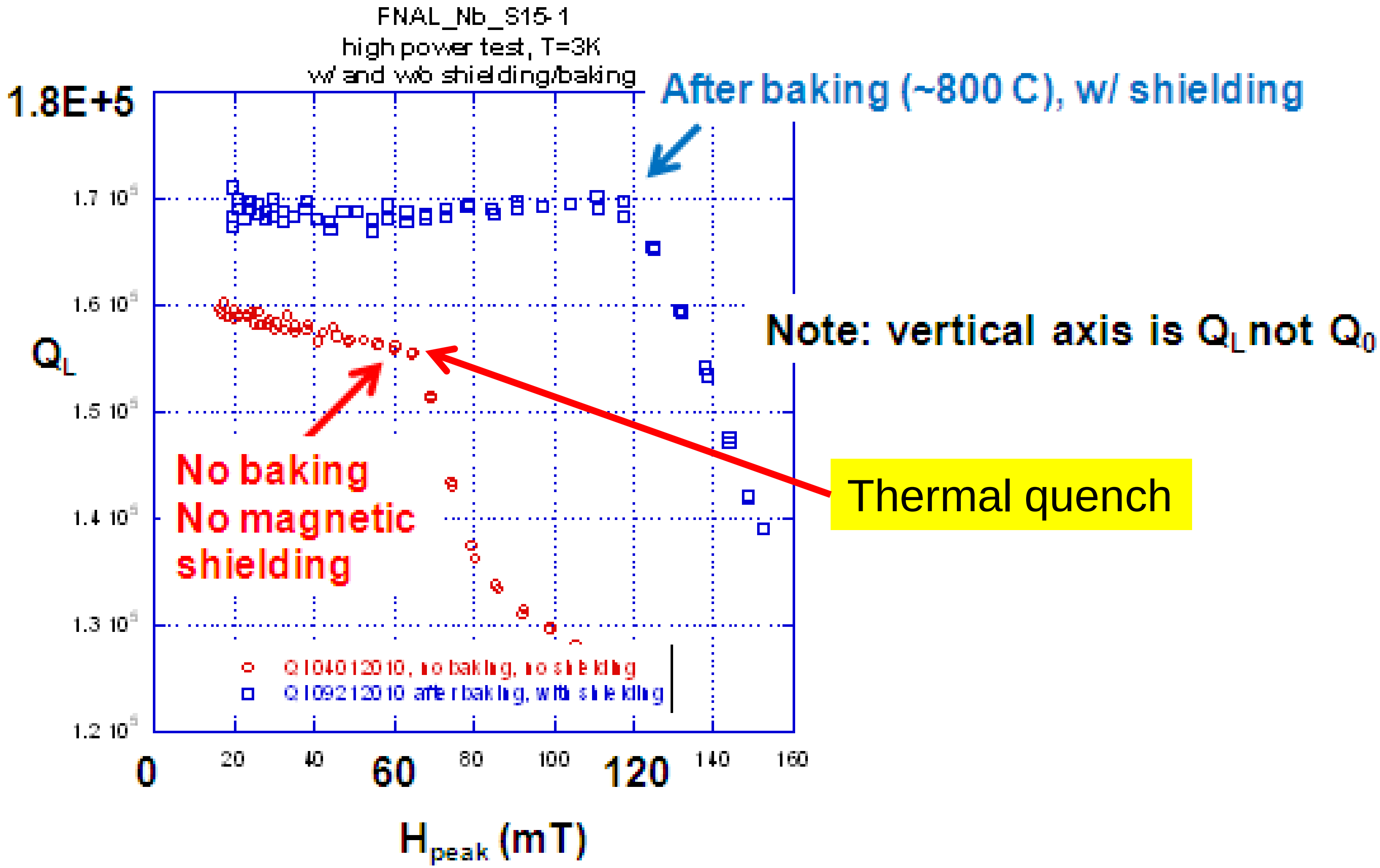
Some results from Nb samples have shown that surface condition affects the surface resistance (R_s) and quench field [J. Guo et al., poster TUP102 in this conference]



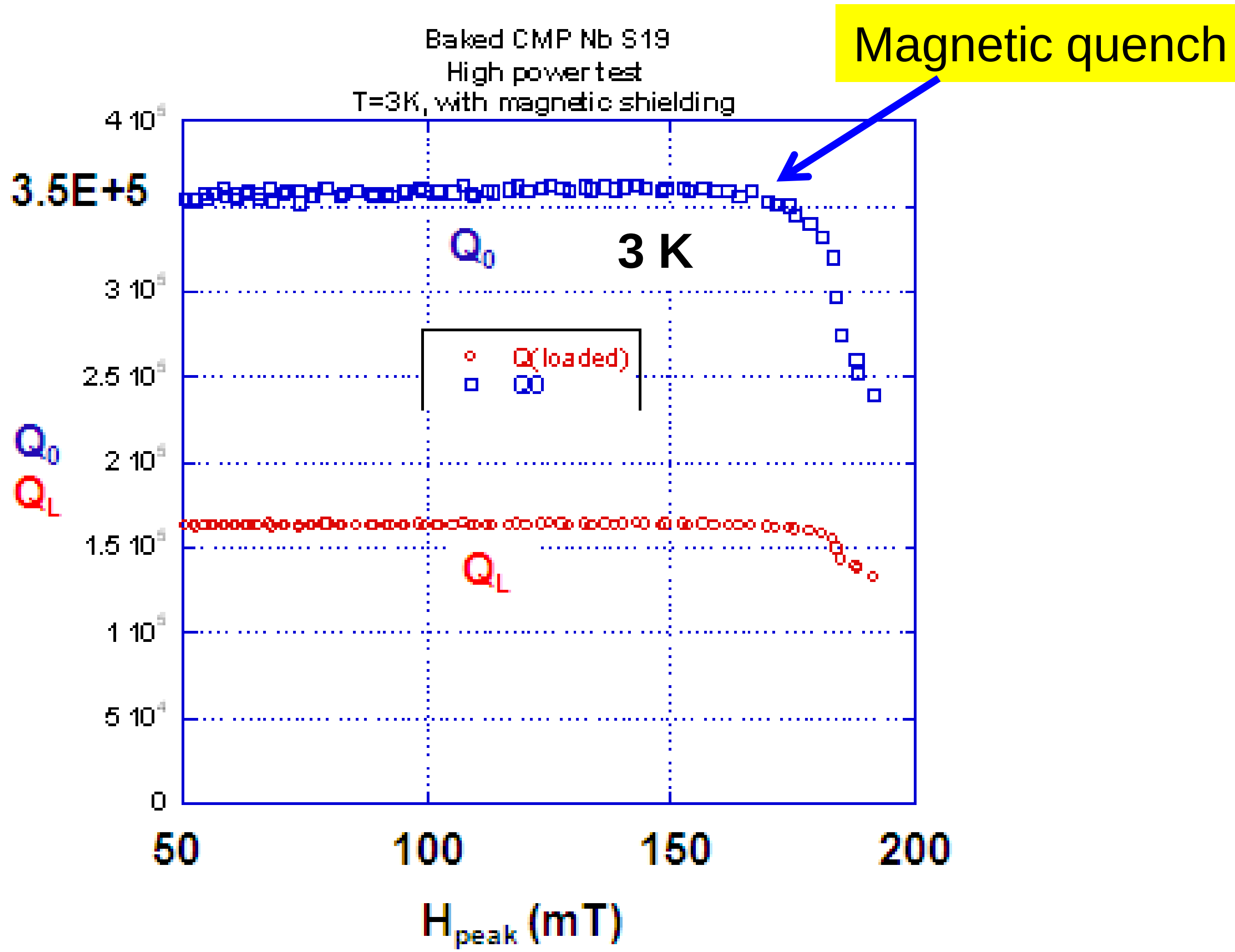
Q_0 vs. T of LANL single-grain sample, polished to R_a <1 nm



Q_L vs. H_{peak} of a FNAL fine-grain sample, indicating thermal quench due to high surface resistance

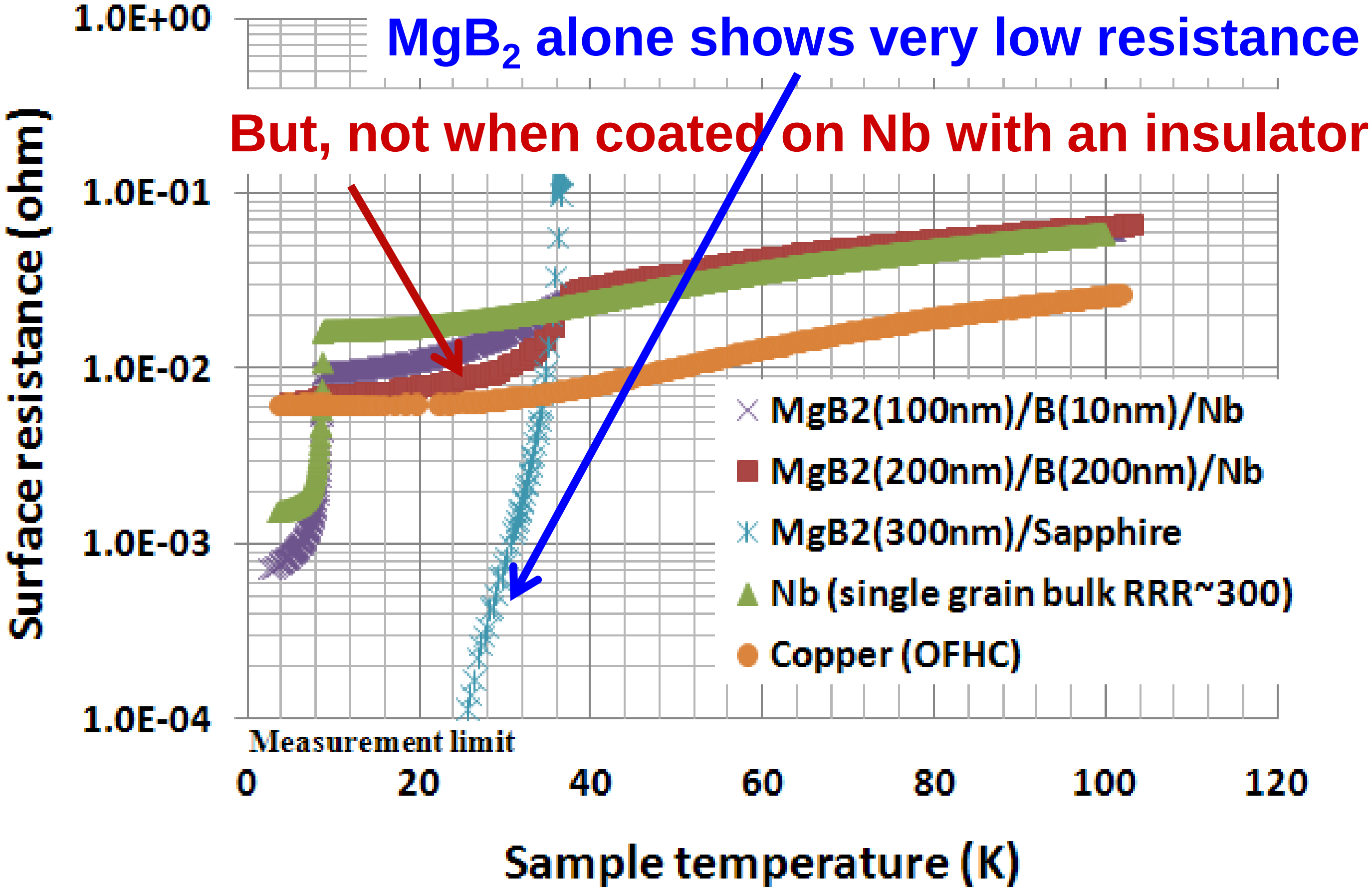


A LANL single-grain, polished and baked sample, has shown the highest quenching field (170-180 mT) so far



So, what about MgB_2 ?

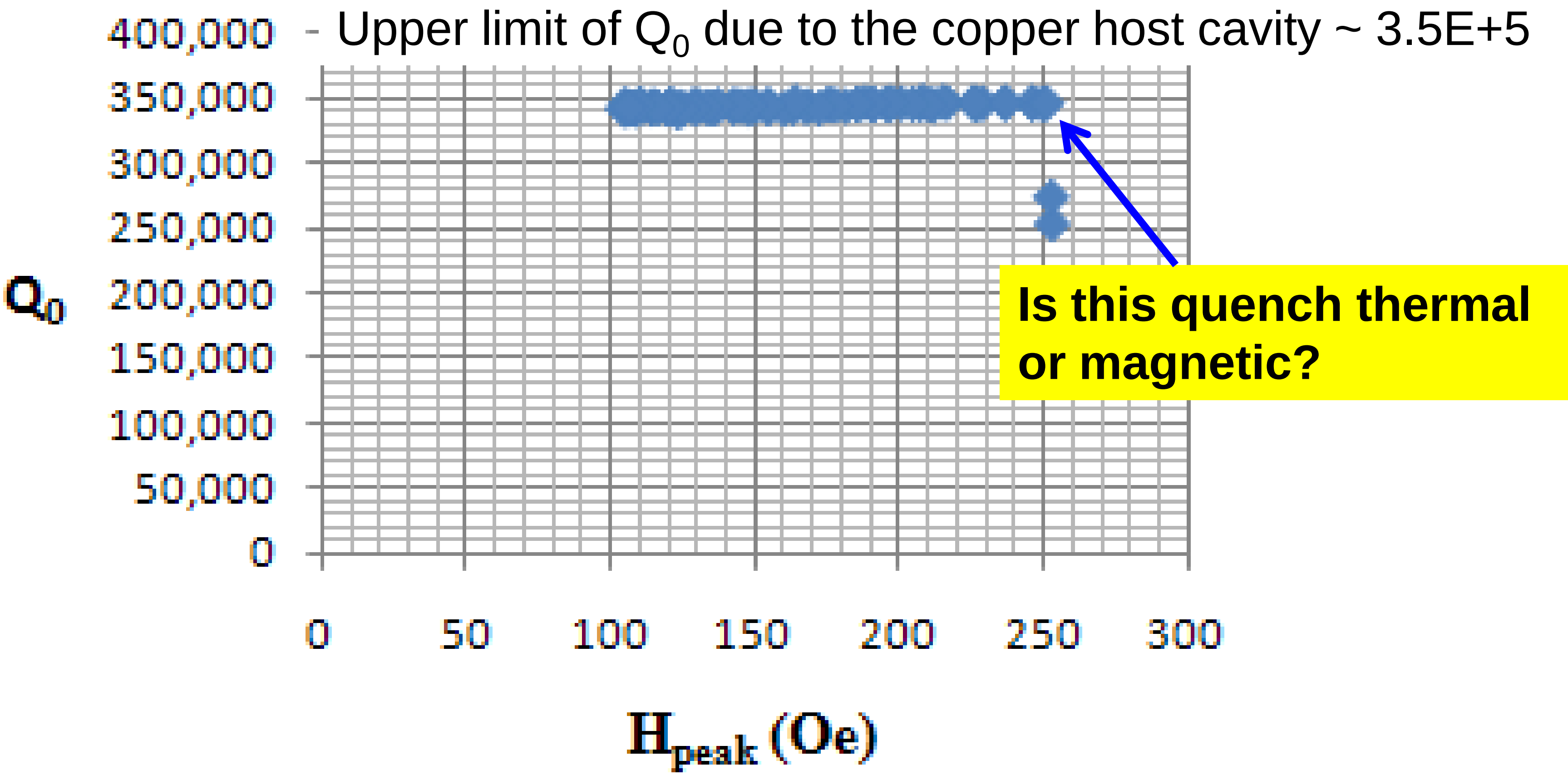
11.4 GHz



BCS resistance at 11.4 GHz at 5 K ~ 1E-4, at 3 K ~ 1.5E-5 ohm

300 nm MgB_2 films have shown low quenching field (250 Oe) at SLAC tests, which is puzzling, considering H_{c1} >2000 Oe from DC magnetization measurements

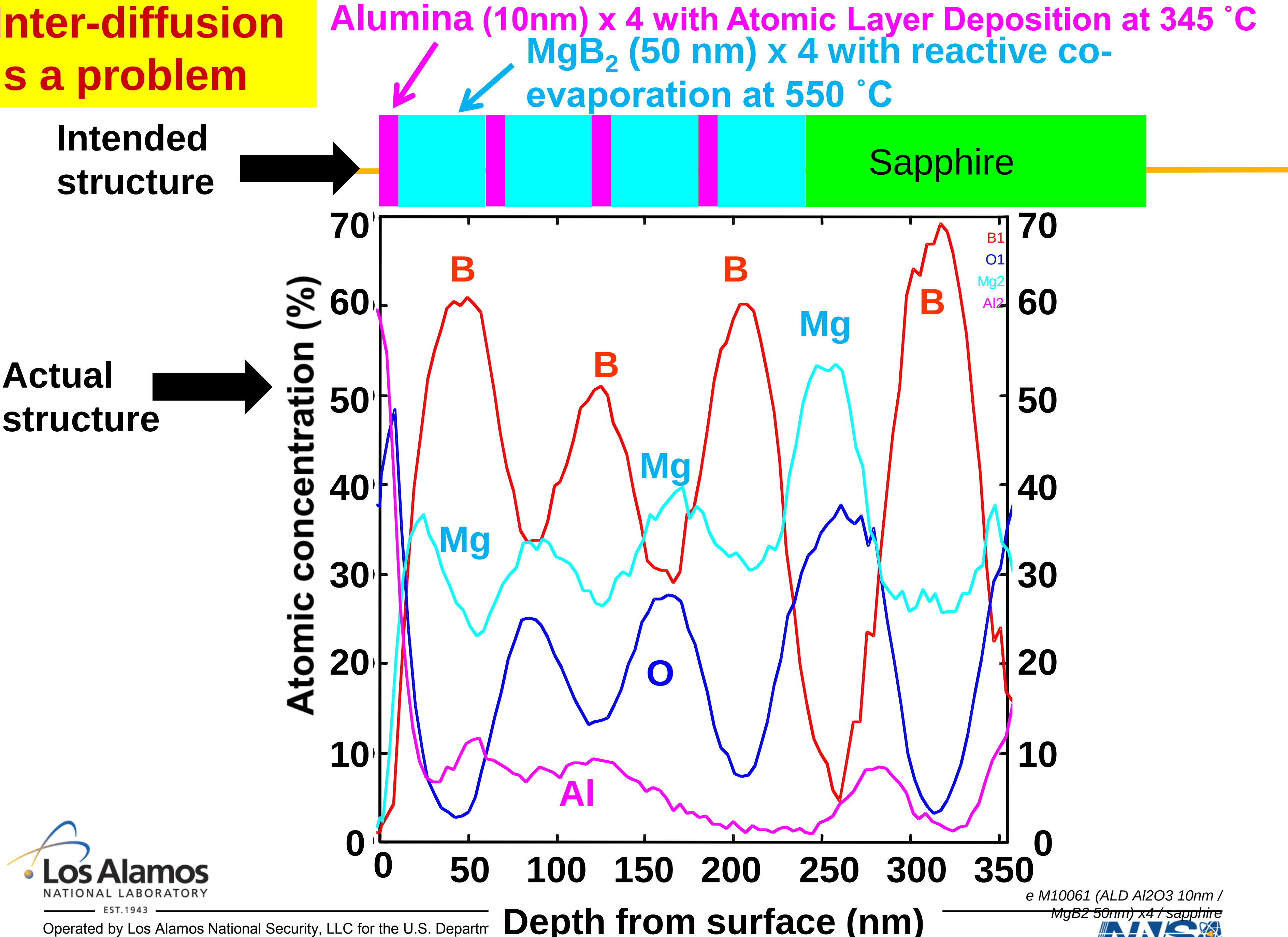
MgB_2(300nm)/Sapphire (430µm)



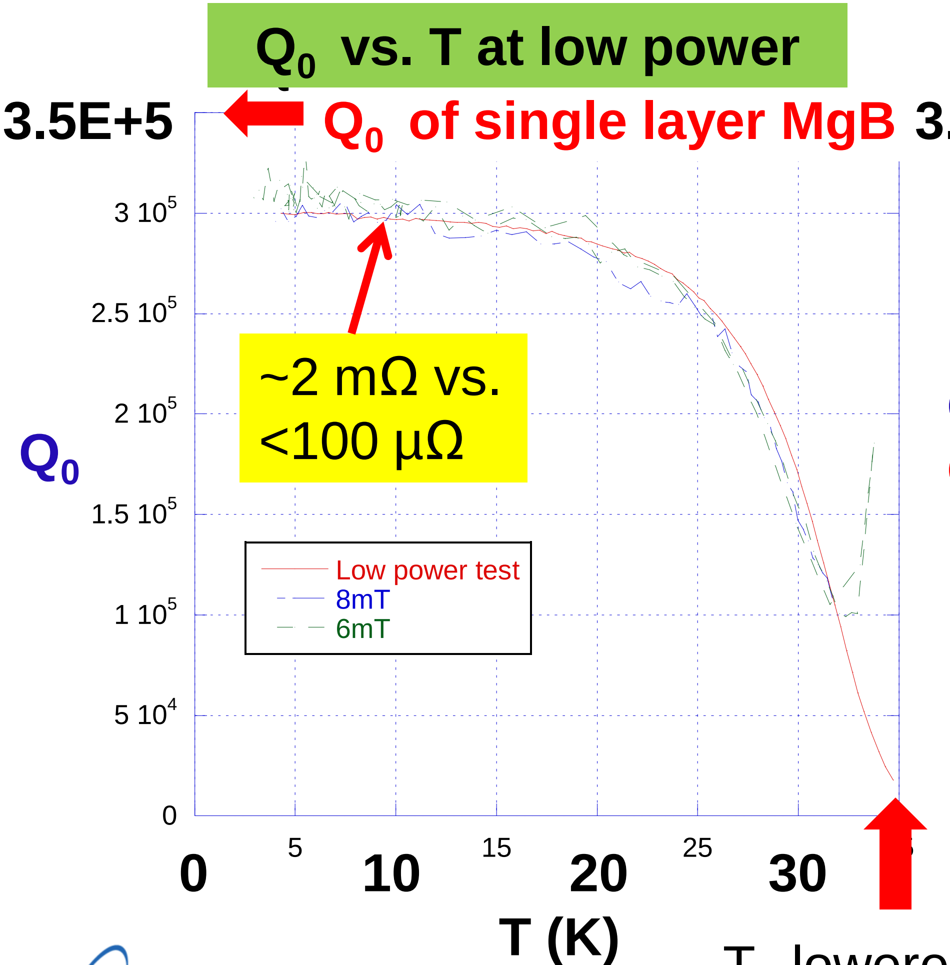
Issues on coating

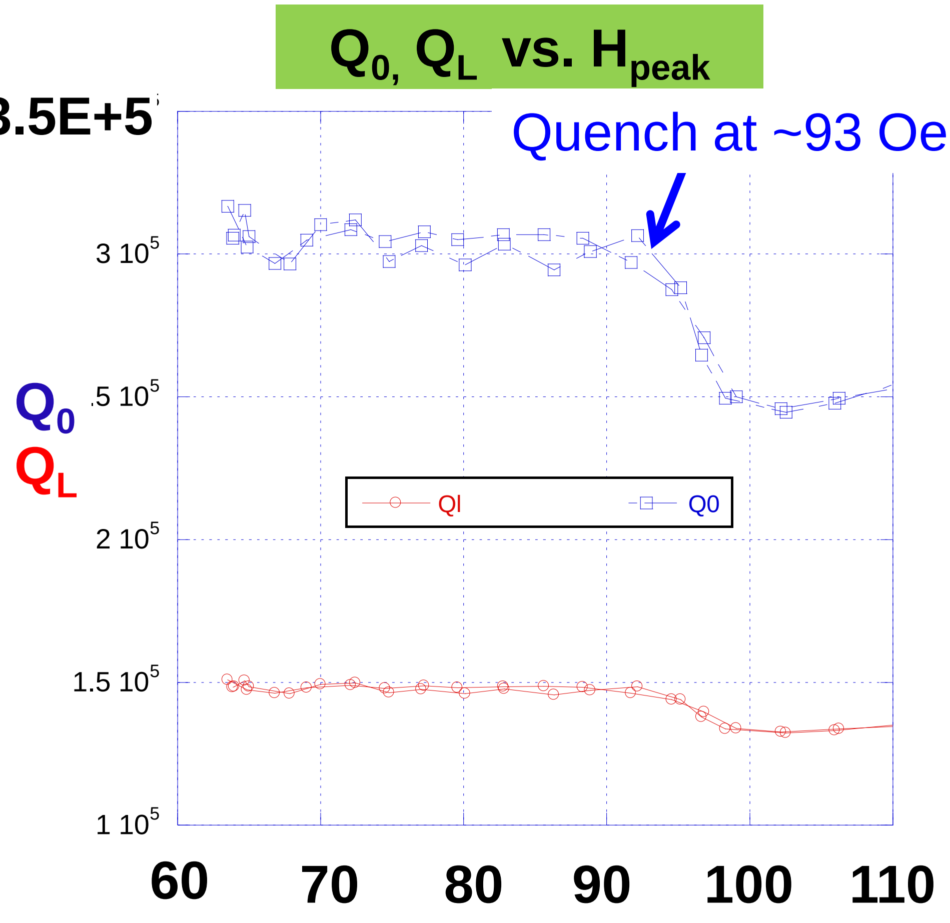
- **Degradation of Nb surface due to decomposition of stable natural Nb_2O_5 layer into a thick lossy NbO_x layer during coating processes at elevated temperatures (e.g., ALD Alumina at 300-345 ˚C and reactive co-evaporation MgB_2 at 550 ˚C)**
- **Inter-diffusion of elements (e.g., O, Al, Mg, etc.) that degrade the quality of MgB_2 and increase RF losses**

Inter-diffusion is a problem



SLAC test results of [Alumina(10nm)/MgB_2(50nm)]x4/sapphire structure showed degradation of MgB_2 and quench field





T_c lowered from 39 K

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Conclusion

- **H_{c1} , a practical limit of SRF cavities, can be increased by thin superconductor films. A >25 % higher H_{c1} (>2000 Oe) than bulk Nb with ≤300 nm MgB_2 films at 4.5 K was demonstrated. Found that effective thickness must be considered for a layered structure!**
- **High-power RF tests at SLAC have shown low quench field of 250 Oe with 300 nm MgB_2 films, which needs to be understood. (>300 Oe has been reported elsewhere.)**
- **Preventing the increase of RF losses due to the degradation of Nb surface and coated superconductor will be the next step of development.**

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Thanks for your attention!