Theoretical Field Limits for Multi-Layer Superconductors

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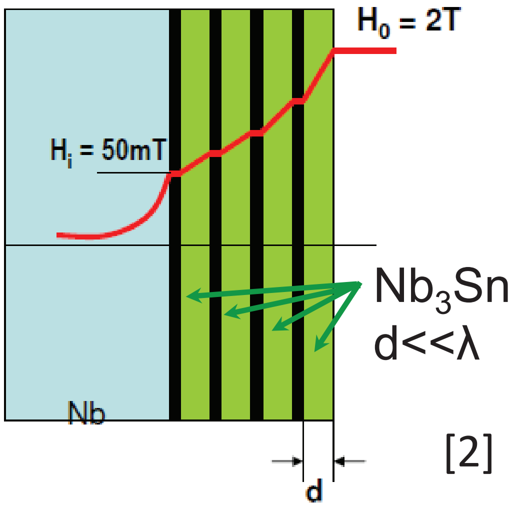
Multilayer Films

- SIS structure proposed for use in SRF cavities by A. Gurevich [1]
- Suggested advantage: Avoid risks of low B_{c1} in alternative superconductors
- Above B_{c1} superconductor is metastable state—only an energy barrier prevents vortex penetration
- Also suggestions that SIS structure could reach extremely high fields at RF frequencies



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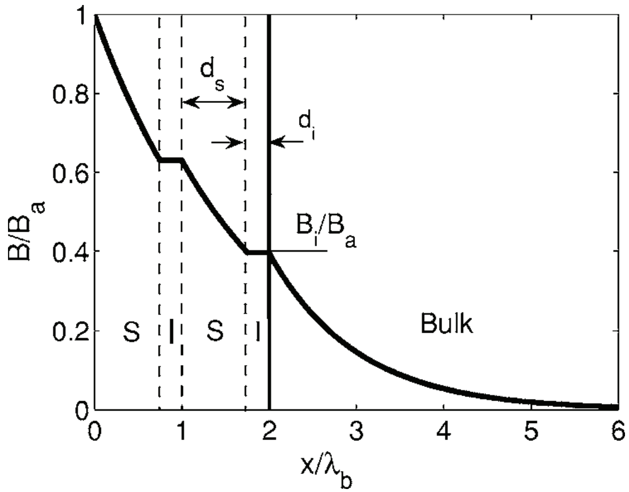
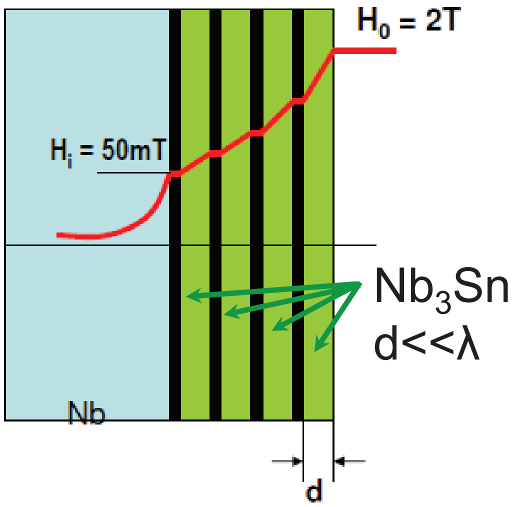
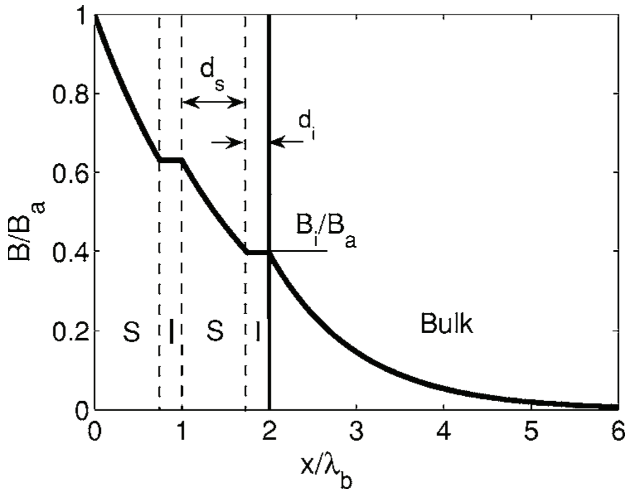


[1] A. Gurevich, App. Phys. Lett. 88, 012511 (2006)
[2] A. Gurevich, SRF Materials Workshop (2007).

Results to Be Shown in This Talk

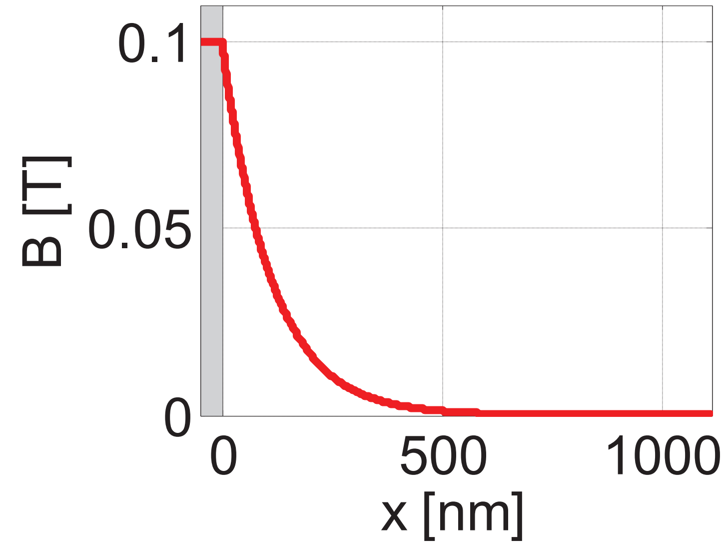
- I will show that SIS films in fact have $B_{c1} = 0$
- Both SIS multilayers and bulk films rely on energy barrier – same vulnerability for small-ξ alternative materials
- Looking at B_{sh}, no clear advantage for SIS films
- Adding more layers does not help: actually makes things worse

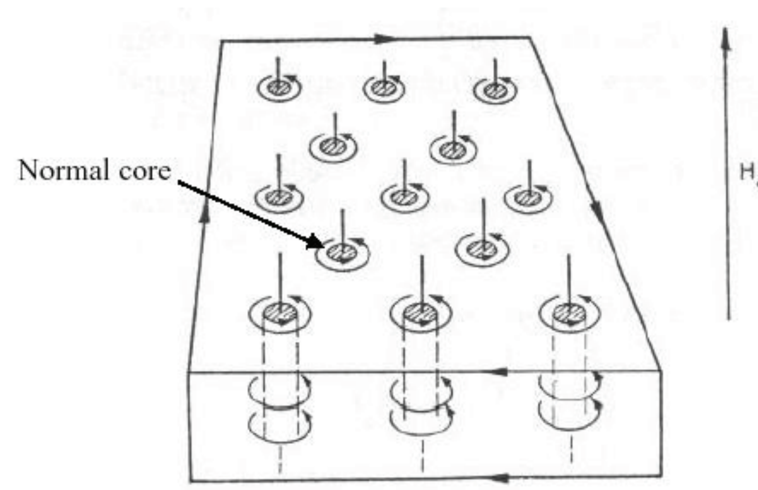




Recall: Flux vs Vortex

- **Flux** penetrates with $e^{-x/\lambda}$ into superconductor without strong dissipation
- A **vortex** is a normal conducting core with 1 quantum of flux
- Vortex penetration causes enormous dissipation in RF fields due to drag





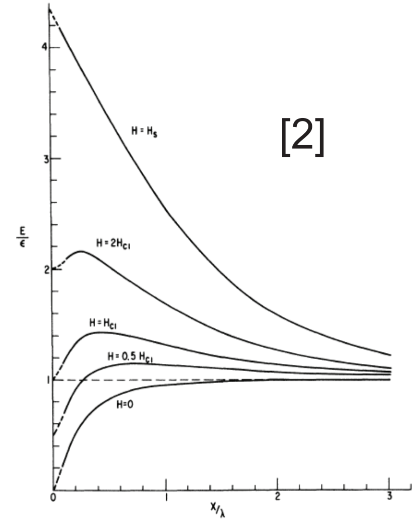
B_{c1} (or H_{c1}) in the SIS Structure

No Enhancement of B_{c1}

- "By definition, when H = H_{c1} the Gibbs free energy must have the same value whether the first vortex is in or out of the sample" [1]
- Parallel B_{c1} of a thin film is enhanced:

$$B_{c1} \approx \frac{2\phi_0}{\pi d^2} \ln \frac{d}{\tilde{\xi}}, \tilde{\xi} = 1.07\xi, d < \lambda$$

- Does this B_{c1} enhancement apply to SIS films as well?
- To find B_{c1}, calculate* G(x) for a vortex (this is how above equation was derived)



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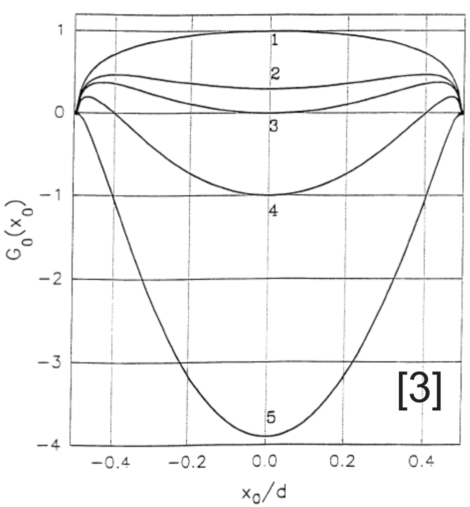


[3]

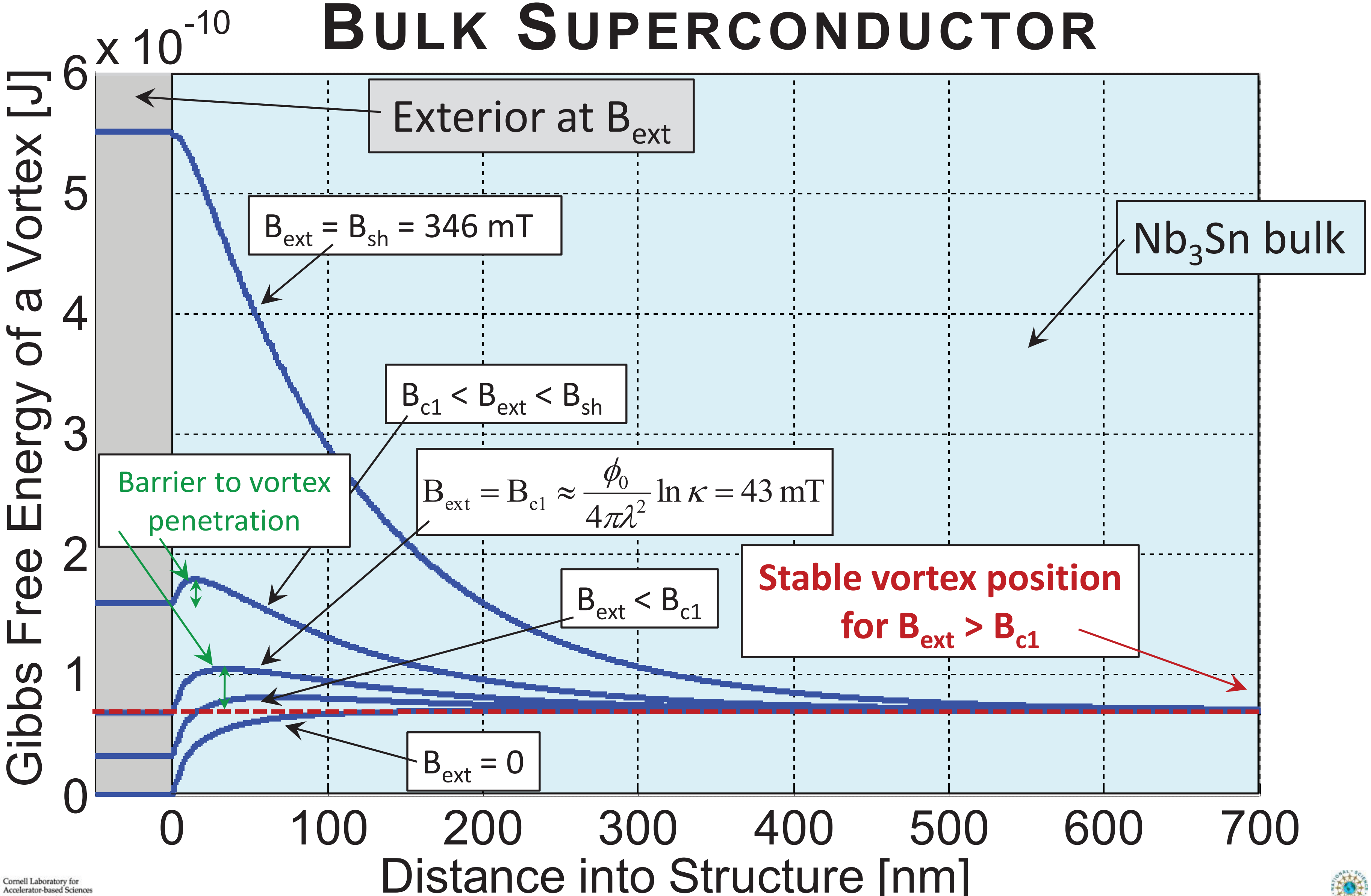
[1] M. Tinkham, Introduction to Superconductivity (New York: Dover, 1996).
[2] C. Bean and J. Livingston, Phys. Rev. Lett. 12, 14-16 (1964).
[3] G. Stejic, et al, Phys. Rev. B 49,1274 (1994).

*Details of G(x) calculation given in paper for this talk

Free Energy Calculations

SRF2013 PARIS
16th International conference on RF Superconductivity

BULK SUPERCONDUCTOR



Free Energy Calculations

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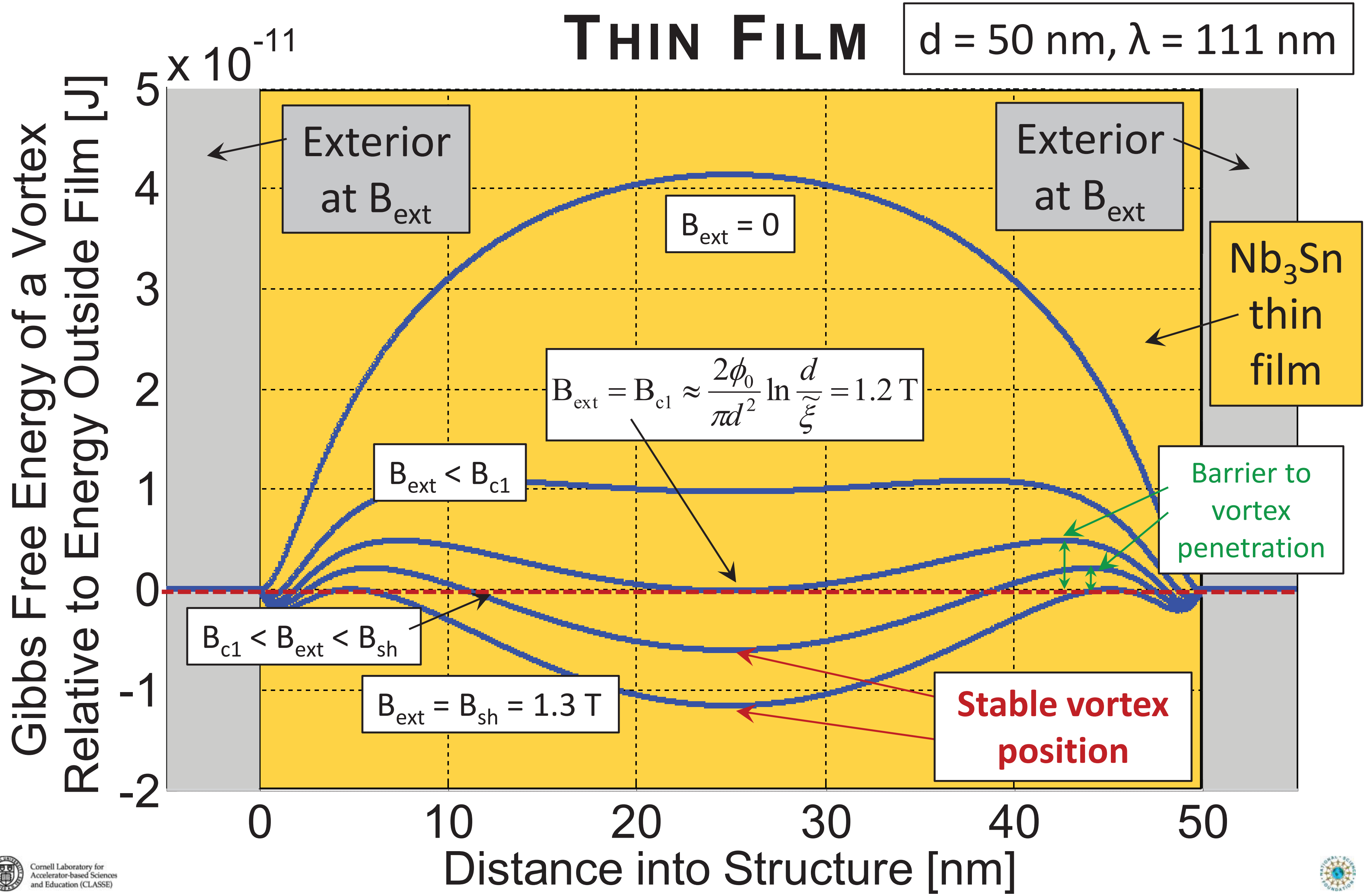
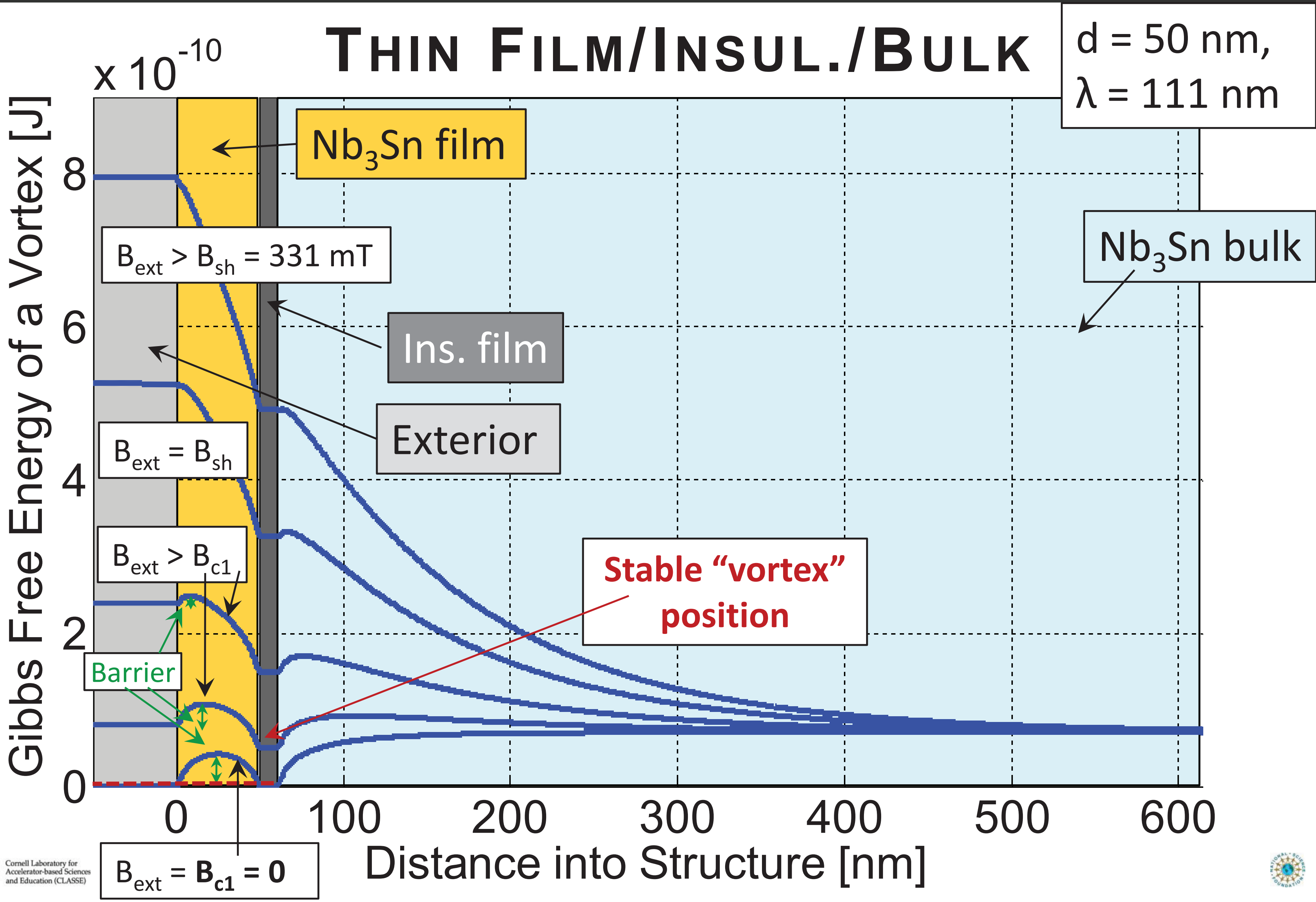


Free Energy Calculations



Conclusions

- Conclusion #1: SIS structure has $B_{c1} = 0$
  - B_{c1} enhancement argument from thin films does not apply to SIS structures

$$B_{c1} \approx \frac{2\phi_0}{\pi d^2} \ln \frac{d}{\tilde{\xi}}, \tilde{\xi} = 1.07\xi, d < \lambda$$

  - Both SIS multilayers and bulk films rely on energy barrier in RF fields to prevent vortex penetration: same vulnerability for small-ξ alternative materials
- Conclusion #2: No clear B_{sh} advantage for SIS films
  - SIS layers need correct thicknesses for high B_{sh}
  - **Optimal SIS film about as good as bulk film**
  - Multiple layers are worse: smaller maximum field

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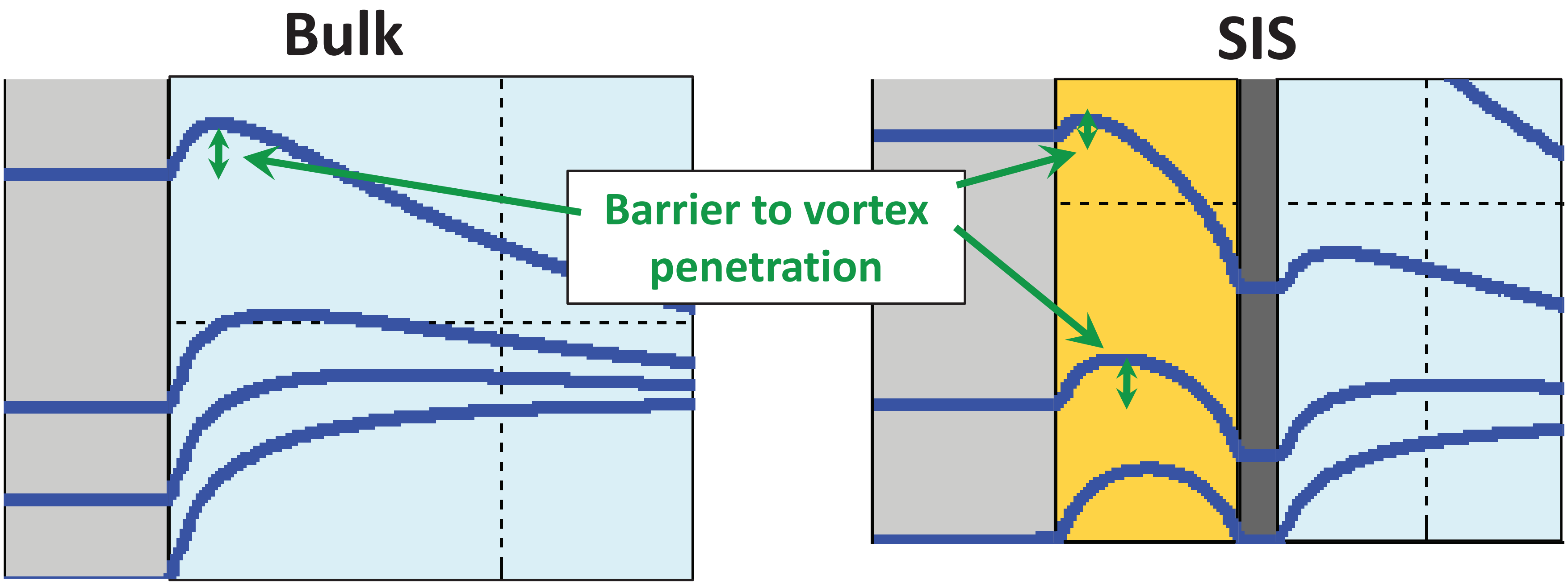
Vortex Dissipation

- Can SIS or bulk superconductors survive vortex penetration at RF freq?
- No: heating is enormous if vortices pass through the film every half cycle
- Calculation from Gurevich: $\frac{P}{A} = \frac{2\omega d}{\pi\mu_0\lambda_f}\left(\lambda_b + \delta + \frac{d}{2}\right)B_v\left(B_0 - B_v\right)$
- 1 mT above B_{sh} for 50 nm film Nb_3Sn/I/ bulk Nb_3Sn at 1.3 GHz = ~9 W/cm^2 of heating
- Above B_{c1}, in RF fields, we have to rely on metastability (both SIS and bulk)

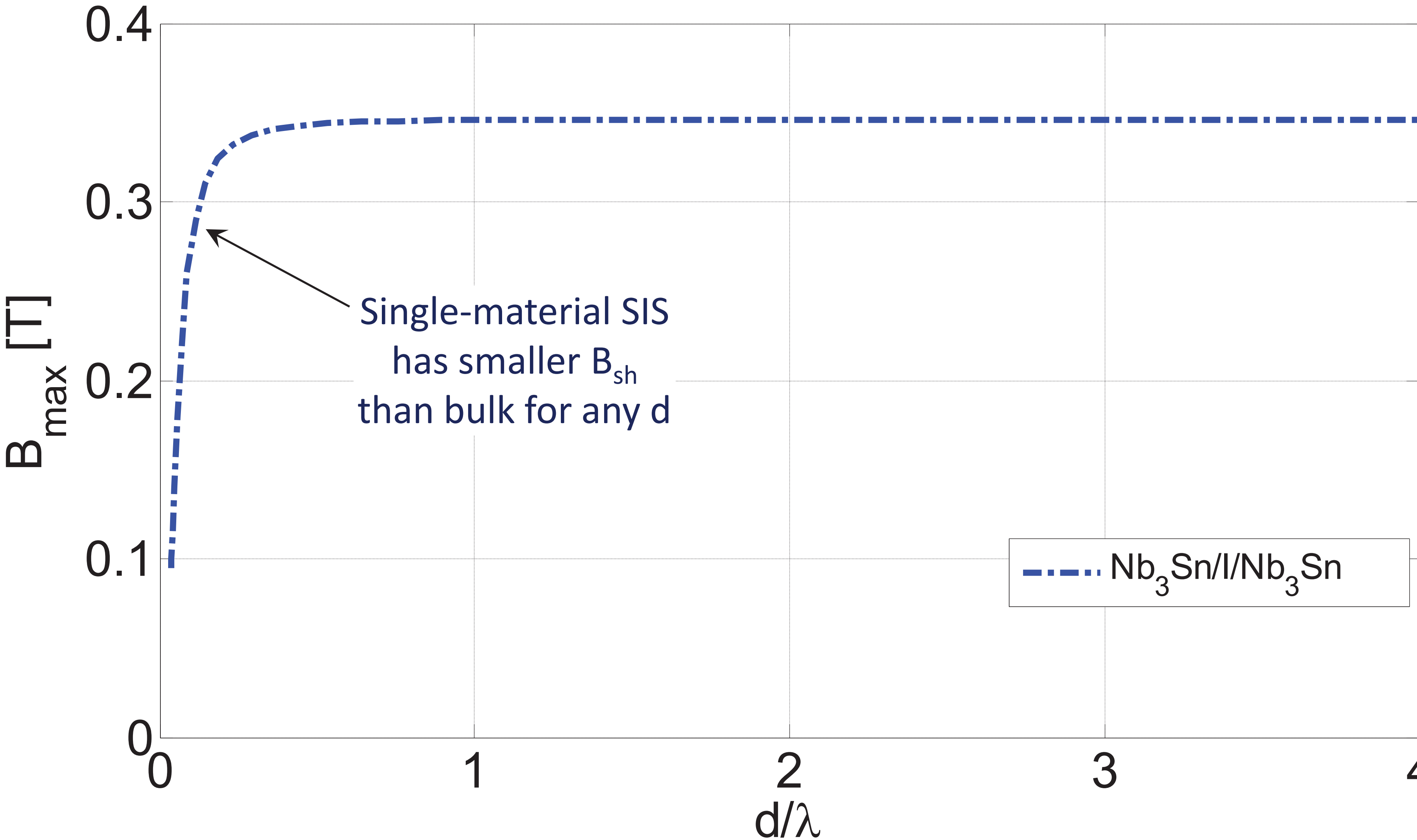
B_{sh} in the SIS Structure

Energy Barrier

- Both SIS and bulk films rely on energy barrier to prevent flux penetration up to B_{sh}
- Can ideal SIS reach higher maximum fields than ideal bulk film?



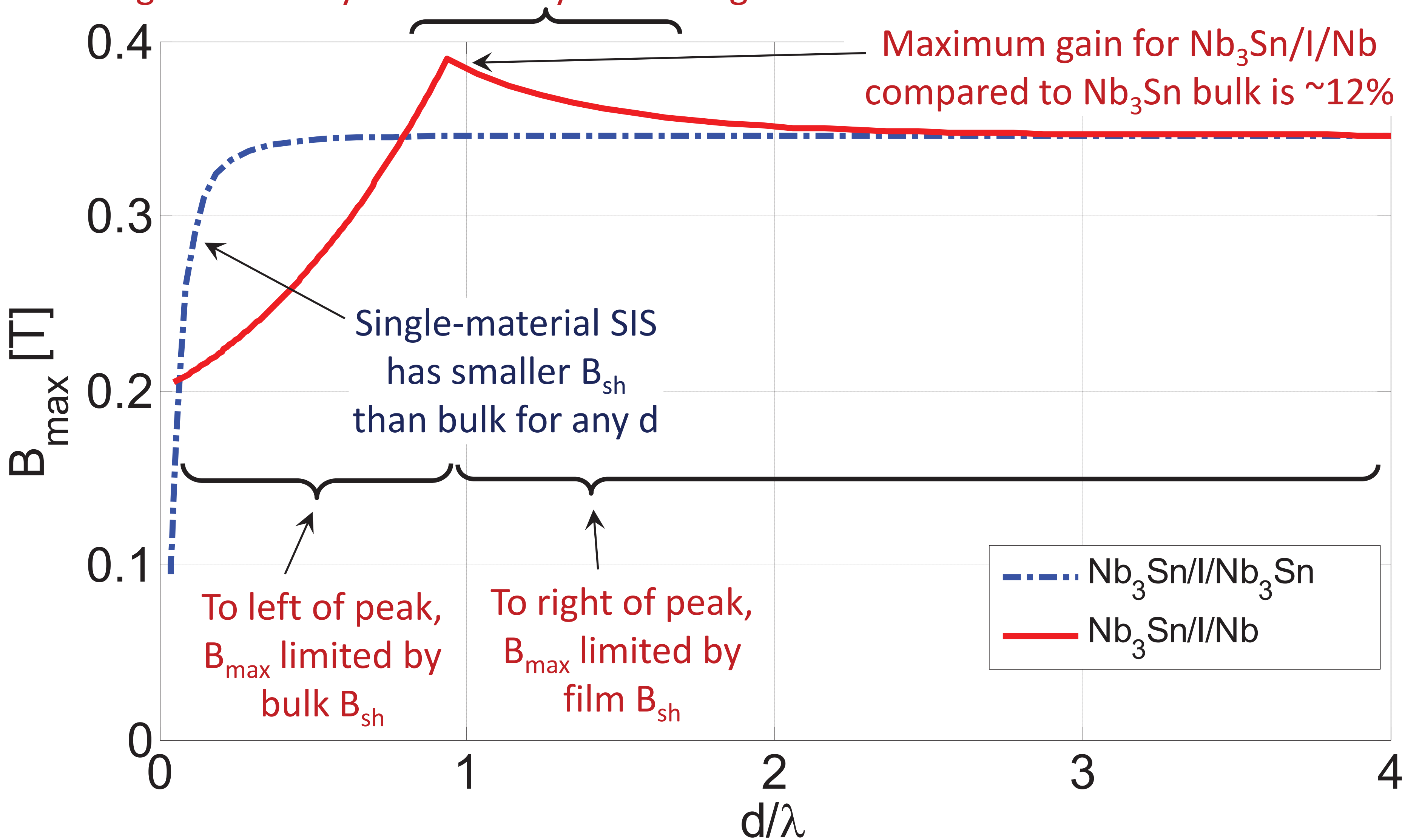
Superheating Field



Note: Similar B_{sh} calculations done previously by Kubo, Iwashita, and Saeki

Superheating Field

Gain is significant only for relatively small range in d



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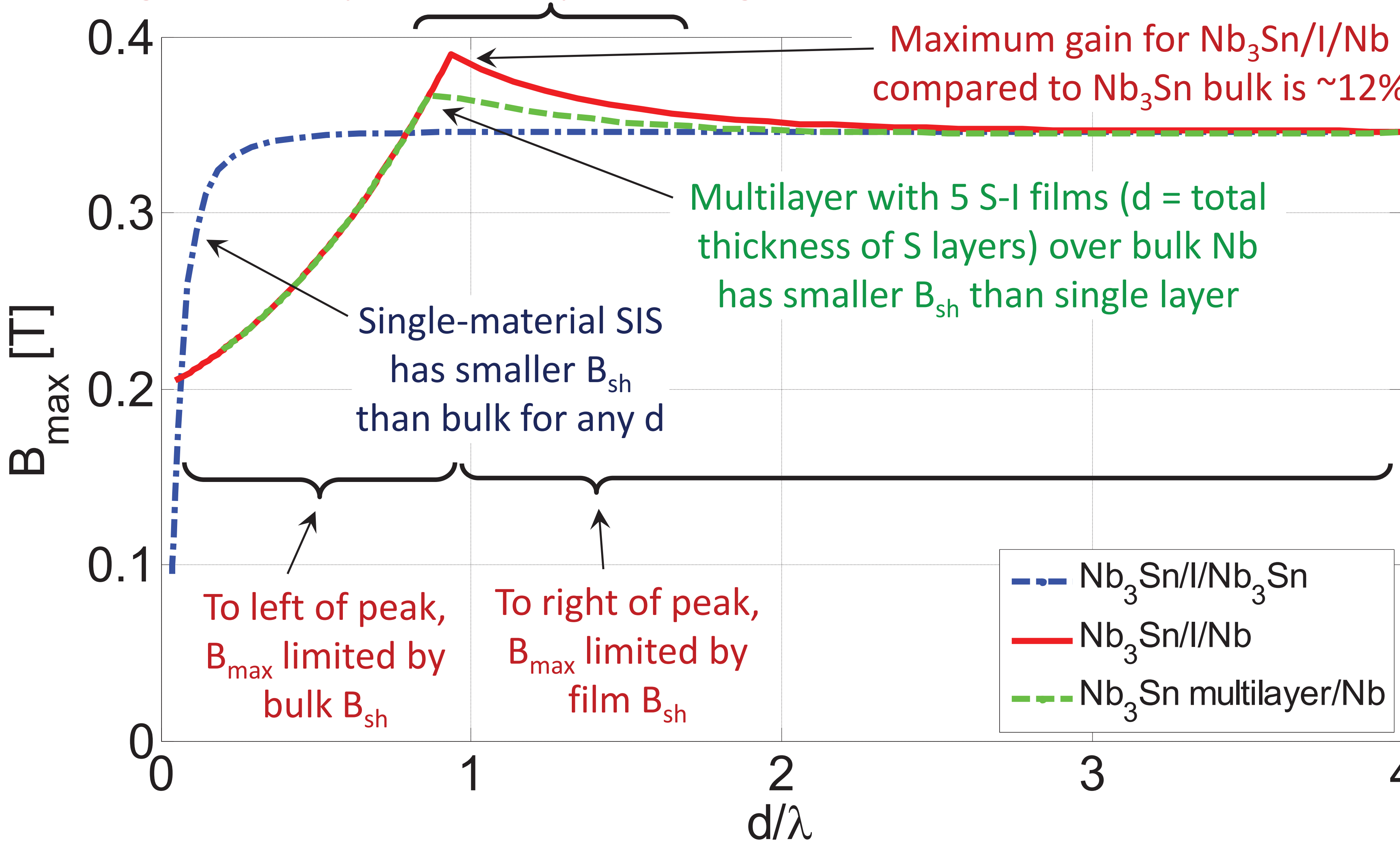

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→ **Choose bulk films over SIS films for SRF**

DC – Enhanced Screening

- From these arguments, SIS multilayers are not superior for SRF applications
- In DC and low frequency AC, vortex penetration can be tolerated without excessive heating
  - SIS multilayers can be useful in DC and low frequency AC applications

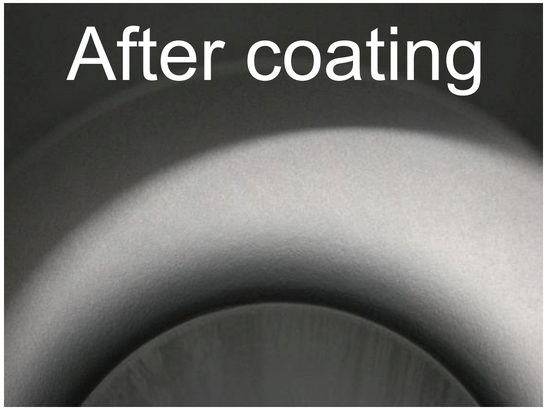
Hope for the Future

Hope for the Future

- Both SIS and bulk films rely on operation above B_{c1}
- Can superconductors survive in the metastable state when the coherence length is small?
- Will small surface defects cause vortex penetration in alternative materials?
- Is there hope for Nb_3Sn, Nb(Ti)N, MgB_2?

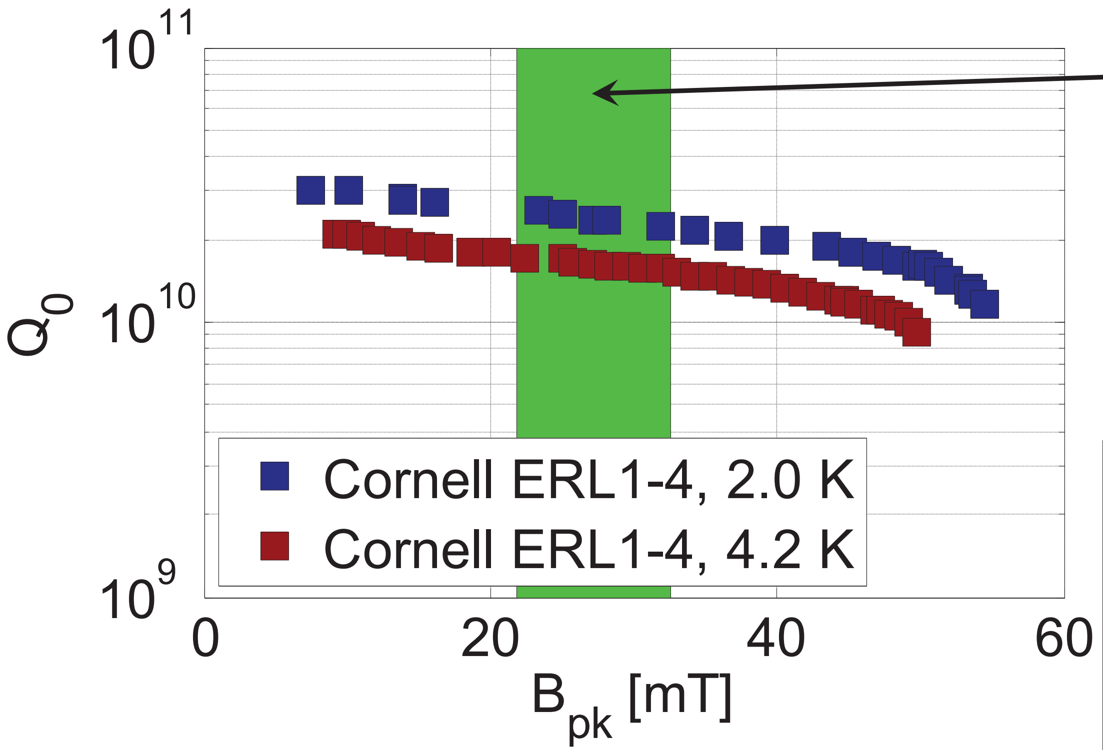
Bulk Film Experiment

- I designed, assembled, and commissioned a Nb_3Sn coating chamber for cavities
- I coated and tested a single cell Nb_3Sn cavity, which showed exceptional RF performance



Bulk Film Experiment

- Small ξ (3.2 ± 0.2 nm) bulk film, but far exceeds B_{c1} with no indication of vortex penetration
- Q-slope in previous Nb_3Sn cavities not fundamental—proof that **even for small ξ, B_{c1} is NOT a limit**



Clearly above B_{c1} = 27 ± 5 mT for Nb_3Sn cavity without strong Q-slope!

See also TUP027 by D. Gonnella for small-ξ Nb well above B_{c1} with no indication of vortex penetration

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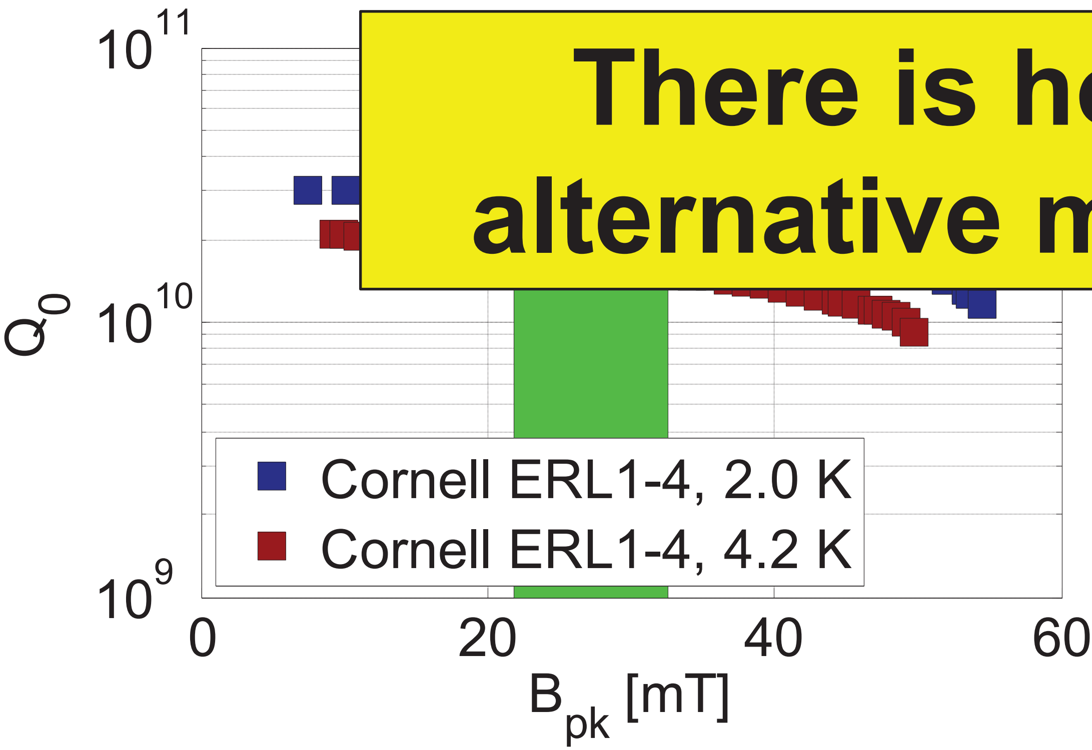

There is hope for alternative materials!

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hout
strong Q-slope!

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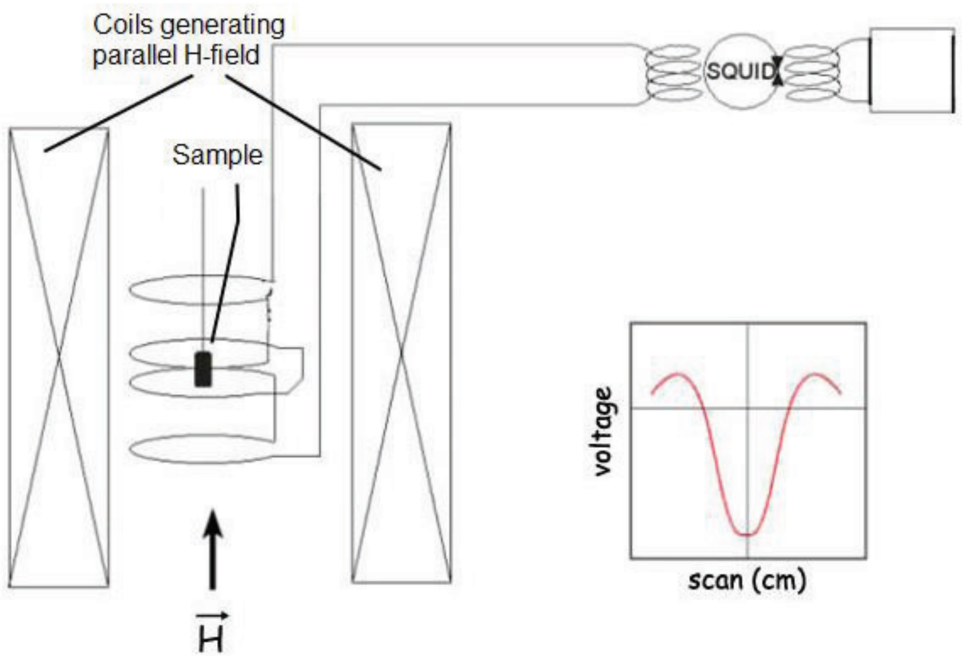
Summary and Outlook

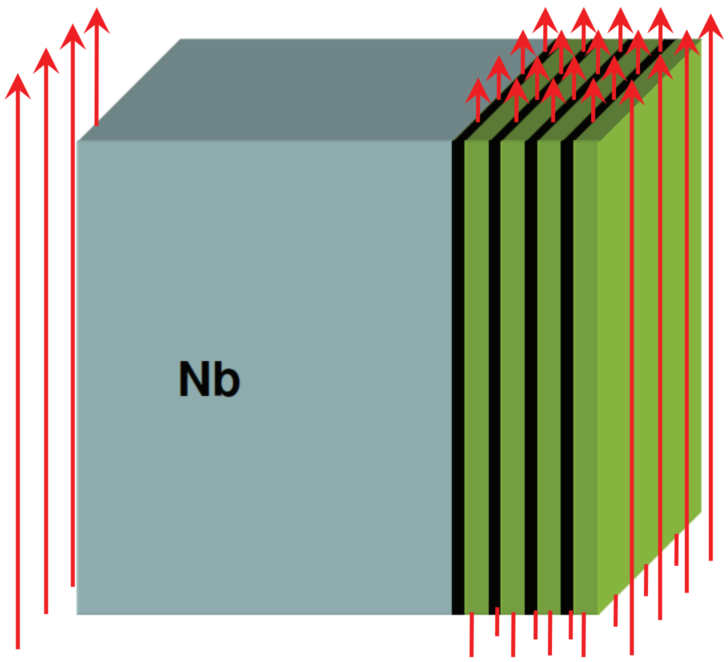
- SIS multilayer films have $B_{c1} = 0$
- They rely on energy barrier as the bulk does
  - SIS B_{sh} is very close to bulk B_{sh}
  - Adding more layers does not help
  - Small potential gain but very difficult to fabricate
- Not superior for SRF applications—they are useful in DC applications
- B_{c1} is not a limit for cavities made from small-ξ superconductors! No need for B_{c1} enhancement!
- **SIS multilayers may not protect alternative SRF materials, but new developments give reason for strong optimism for bulk films**

Backup Slides

SQUID Measurements



http://www.icmmo.u-psud.fr/Labos/LCI/Service_SQUID/squid.php

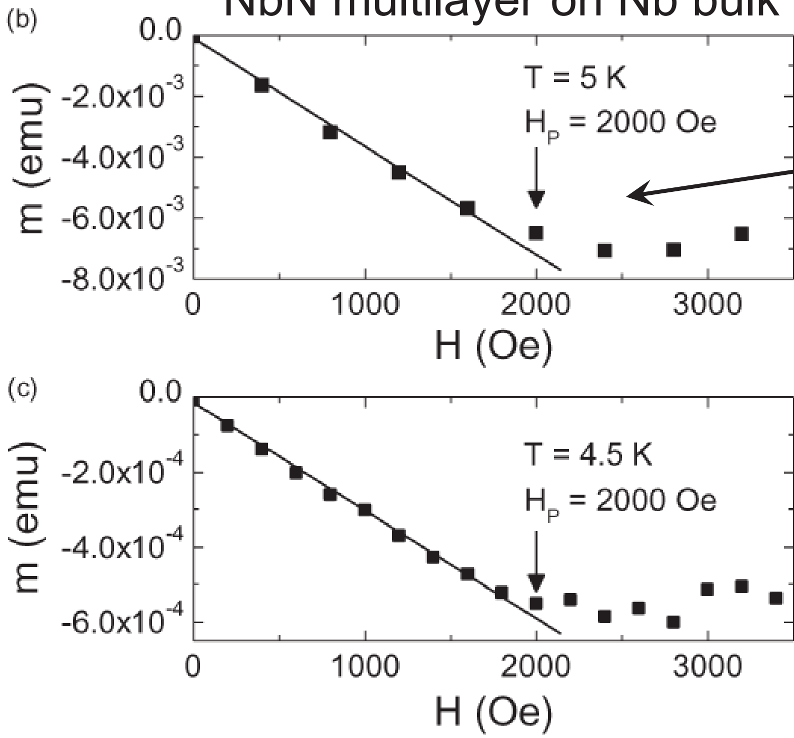


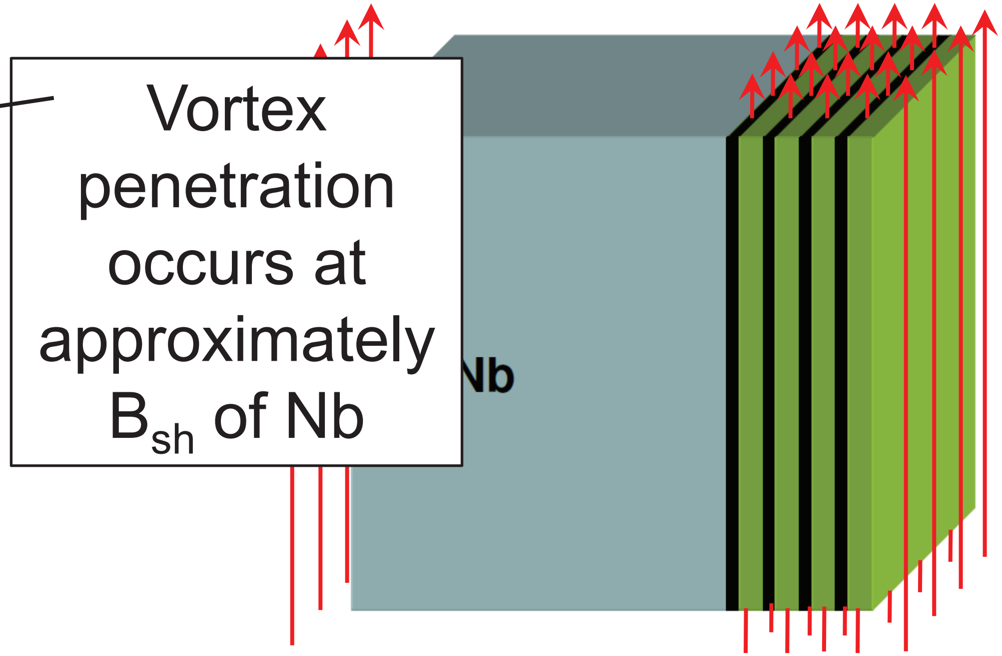
A. Gurevich, TFSRF Workshop, 2005

- External field can “sneak” between layers
- Each layer acts independently – SQUID sees vortex penetration into most vulnerable layer, likely Nb bulk

SQUID Measurements

NbN multilayer on Nb bulk





W. Roach et al., IEEE Trans. App. S. 8600203 (2013)

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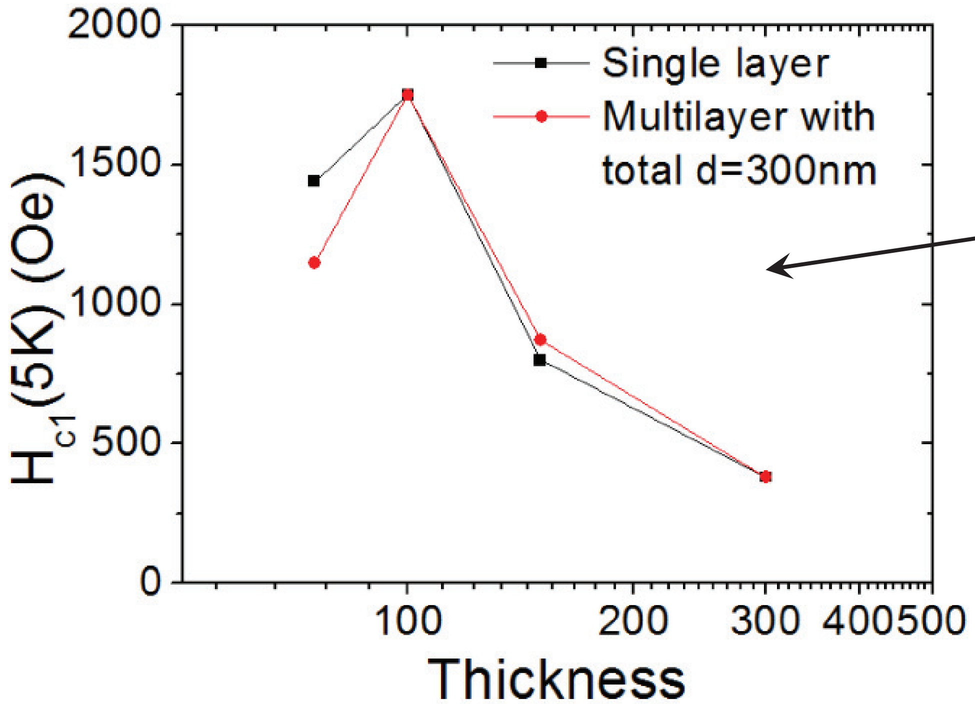
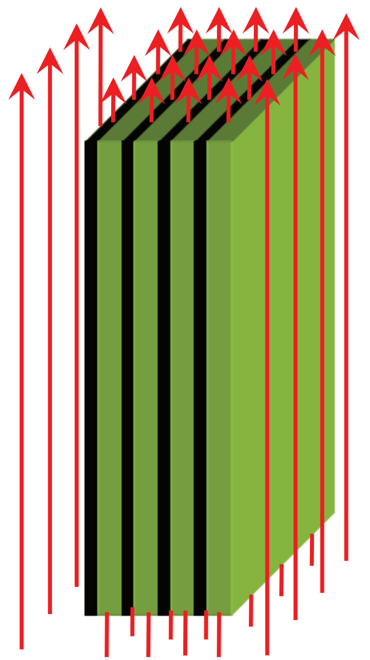


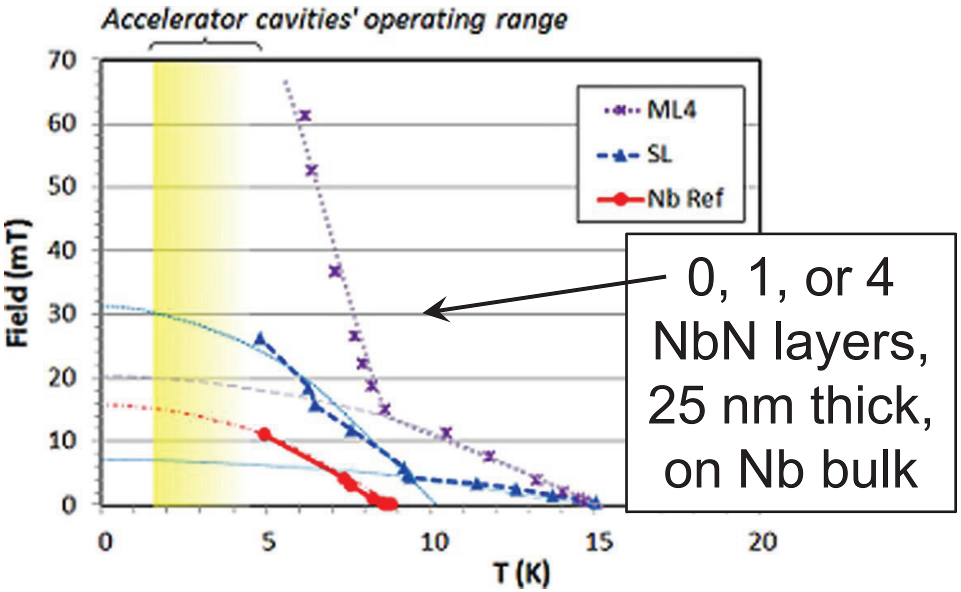
Xiaoxing Xi, TFSRF Workshop, 2012

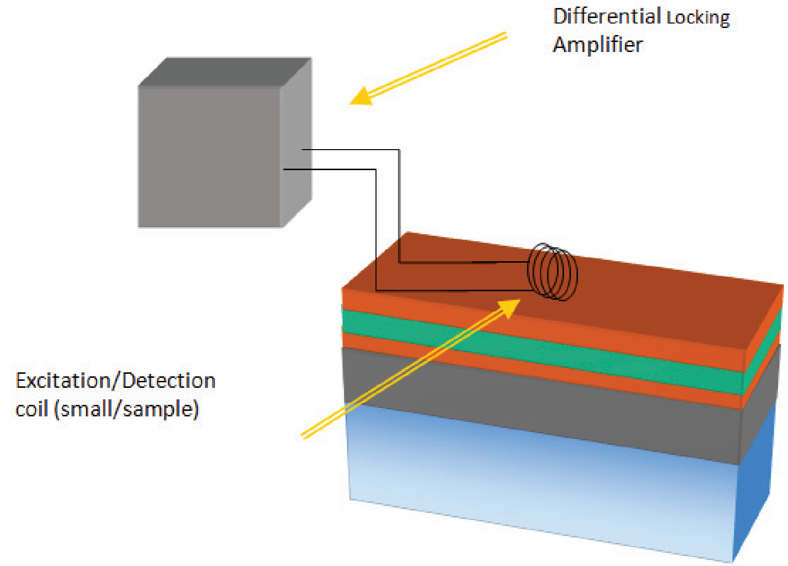
No significant change between using 1 layer vs 2, 3, or 4



- External field can "sneak" between layers
- With no bulk, simply observe well understood B_{c1} enhancement, just for several layers at once

3rd Harmonic Measurement





C. Antoine, APL 102603 (2013) and TFSRF Workshop 2010

- Clear that NbN helps and that more NbN is better (due to more total thickness? Importance of perpendicular fields?)

DC and Low Frequencies

- In general, one must be careful when conducting measurements of multilayers at low frequencies
- Vortices can pass through the superconducting films into the insulating region with minimal dissipation
- At RF frequencies the vortex dissipation would be intolerable (linear with f)

Material Properties

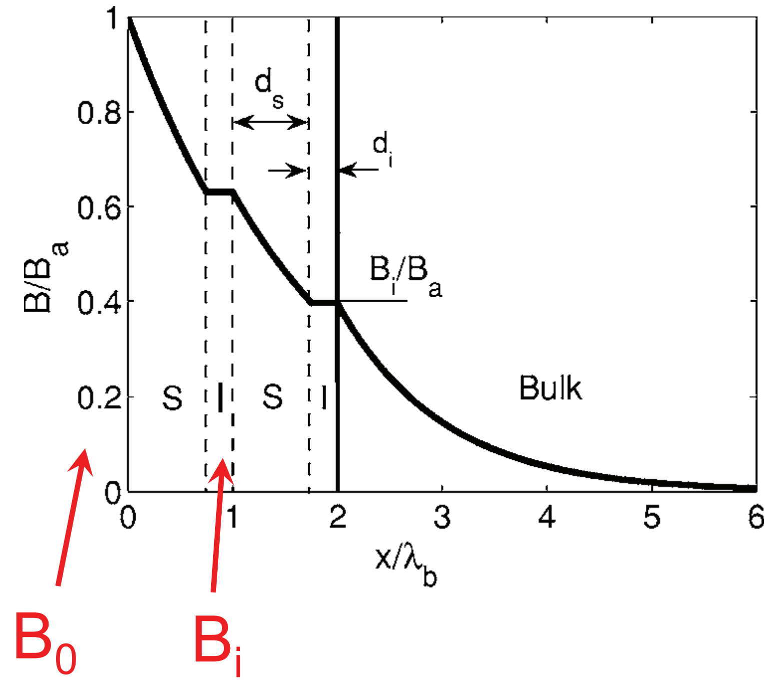
Material	λ [nm]	ξ [nm]	B_{c1} [T]	B_{sh} [T]
Nb	40	27	0.13	0.24
Nb_3Sn	111	4.2	0.042	0.36
NbN	375	2.9	0.006	0.15
MgB_2	185	4.9	0.017	0.19

λ is calculated using Eqn 3.131 in [1]. ξ is calculated using the equations in [2]. For Nb a RRR of 100 was assumed. For MgB_2, λ and ξ are not calculated, as the experimental values are given in the reference. For calculations, $B_c=\varphi_0/(2\mathrm{sqrt}(2)\pi\xi\lambda)$ is used [1]. B_{c1} for Nb found from power law fit to numerically computed data from [3] and for strongly type II materials is found from Eqn 5.18 in [1]. B_{sh} for Nb is found from [4] and for others calculated from $B_c$sqrt(20)/6 (valid only for strongly type II materials near T_c) [5]. Nb data from [6], Nb_3Sn data from [3], NbN data from [7], and MgB_2 data from [8]. Note that the two gap nature of MgB_2 may require more careful analysis than is performed here.

[1] M. Tinkham, Introduction to Superconductivity (New York: Dover, 1996).
[2] T. Orlando, et al., Phys. Rev. B 19, 4545 (1979).
[3] M. Hein, *High-Temperature Superconductor Thin Films at Microwave Frequencies* (Berlin: Springer, 1999).
[4] A. Dolgert, S. Bartolo, and A. Dorsey, Erratum [Phys. Rev. B 53, 5650 (1996)], Phys. Rev. B 56, 2883 (1997).
[5] M. Transtrum, G. Catelani, and J. Sethna, Phys. Rev. B 83, 094505 (2011).
[6] B. Maxfield andW. McLean, Phys. Rev. 139, A1515 (1965).
[7] D. Oates, et al., Phys. Rev. B 43, 7655 (1991).
[8] Y. Wang, T. Plackowski, and A. Junod, Physica C 355, 179 (2001).

No B_{c1} Enhancement

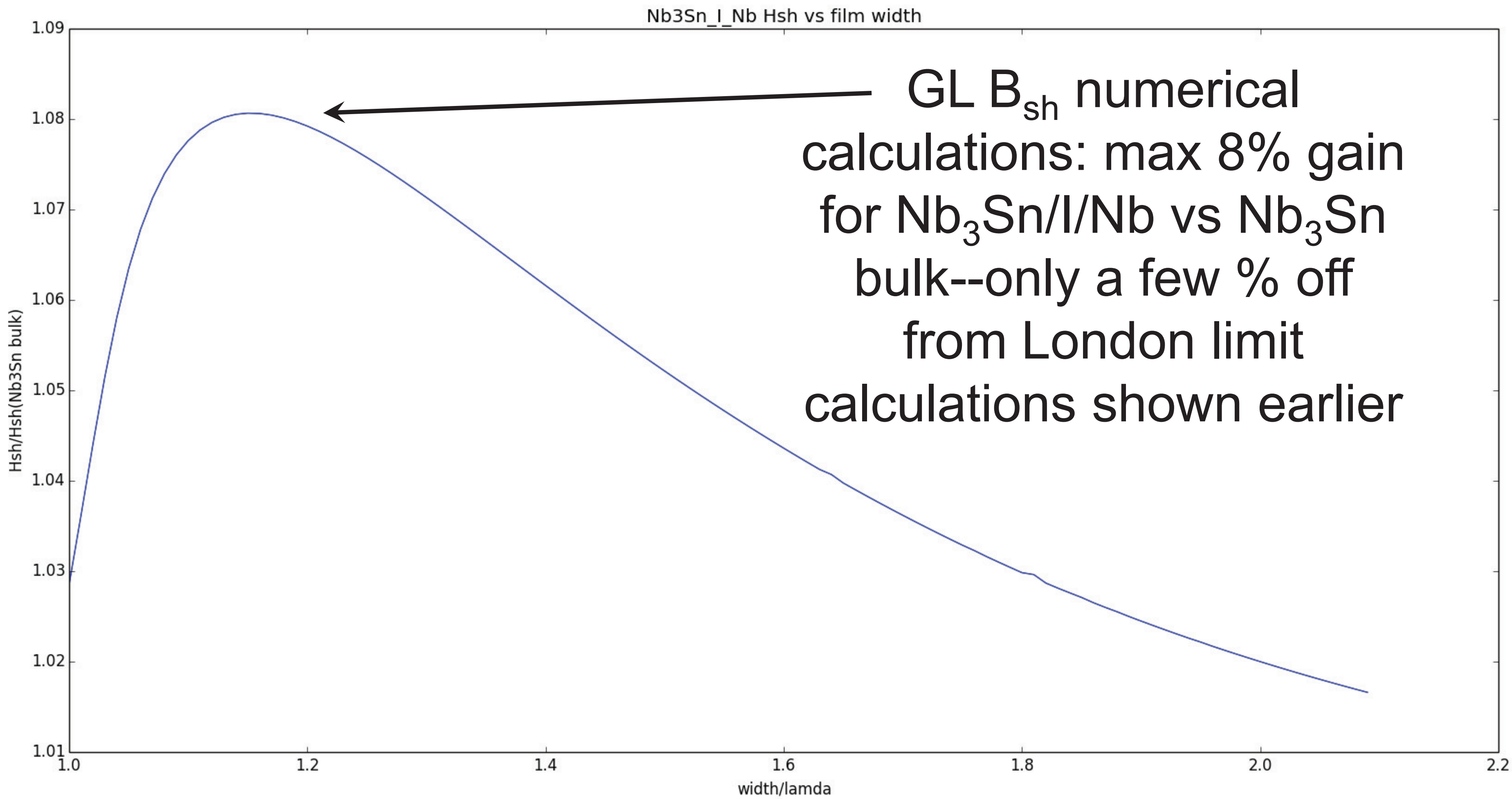
- Can also show $B_{c1} = 0$ from simple argument
- Free energy for flux quantum in vacuum or insulator is $B\phi_0/\mu_0$ (invalid for superconductor)
- Field and therefore free energy is higher in external region than in insulator
- Structure is clearly above B_{c1}, metastable



$B_0 > B_i$

$B_0\phi_0/\mu_0 > B_i\phi_0/\mu_0$

Lowest energy position for vortex is in film


Nb3Sn_I_Nb Hsh vs film width
Hsh/Hsh(Nb3Sn bulk)
width/lamda
1.09
1.08
1.07
1.06
1.05
1.04
1.03
1.02
1.01
1.0
1.2
1.4
1.6
1.8
2.0
2.2
GL B_{sh} numerical calculations: max 8% gain for Nb_3Sn/I/Nb vs Nb_3Sn bulk--only a few % off from London limit calculations shown earlier