Dirty layers, Bi-layers and Multi-layers: Insights from muon spin rotation experiments

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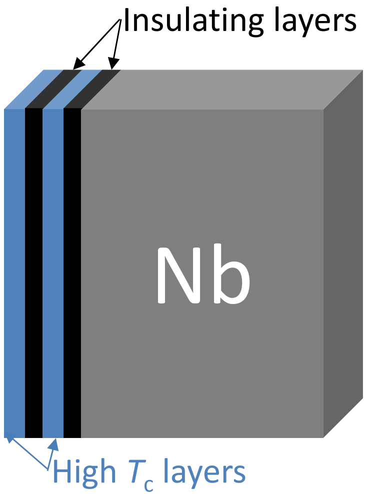
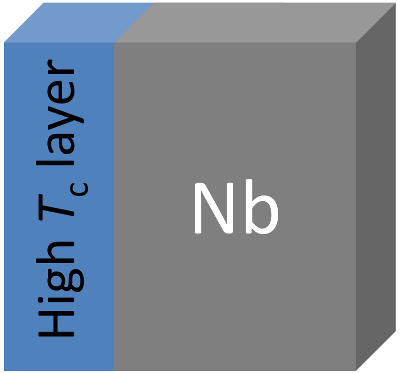
Possible advantages from multilayers

- The multilayer approach has been proposed in 2006 by A. Gurevich
  - For $d_S < \lambda$ no thermodynamically stable parallel vortices in decoupled S layers
- T. Kubo calculated the penetration profile within London theory with appropriate boundary conditions and found:
  - **Reduced surface current**
  - A boundary of two SCs introduces a **force that pushes a vortex to the direction of the material with larger penetration depth.**
  - These two features do not require insulating layers. An SS bilayer system can be used to test these predictions.
  - Low temperature baked surfaces can potentially be considered as an effective bilayer system.

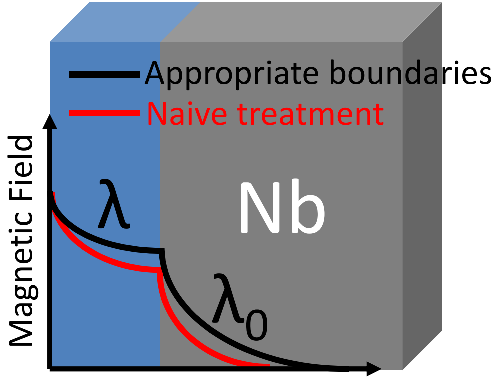




T. Kubo- Supercond. Sci. Technol. 30 (2017) 023001

Reduced surface current

- The vortex penetration field H_v is set by the competition between the repulsive force from the Meissner screening currents and the attractive force between a vortex and an image vortex necessary to fulfill the boundary condition.
- Reduced surface current=larger H_v
- There is an optimal layer thickness
  - Layer too thin=little shielding of substrate
  - Layer too thick=little reduction of current
- Requirements:
  - Superheating of layer and substrate
  - Weak proximity effect



Field of first entry for optimal layer thickness:

$$H_m = \left[H_s^2 + \left(1 - \frac{\lambda_0^2}{\lambda^2} \right) H_{s0}^2 \right]^{1/2}$$

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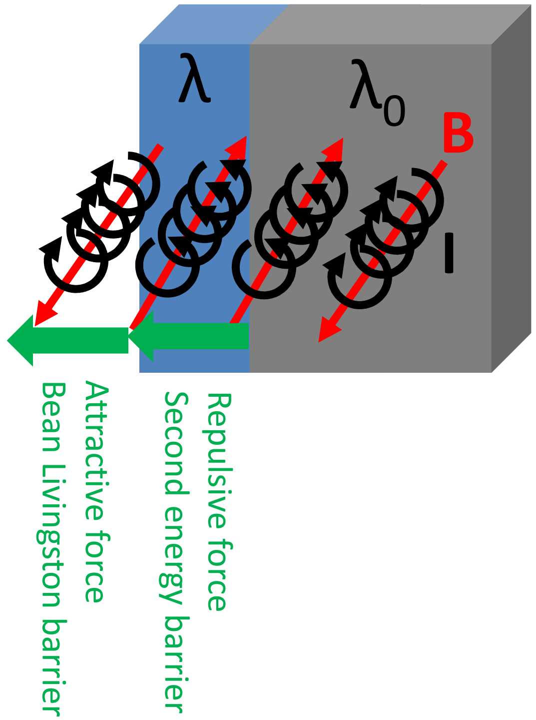
Force at the boundary

- Vortex at the SC/vacuum boundary
  - Magnetic field is parallel to the surface
  - Modelled by image vortex
  - Attractive force →Bean-Livingston barrier
- If $\lambda > \lambda_0$ there is second energy barrier at the interface between the layer and the substrate
- This force is independent of layer thickness



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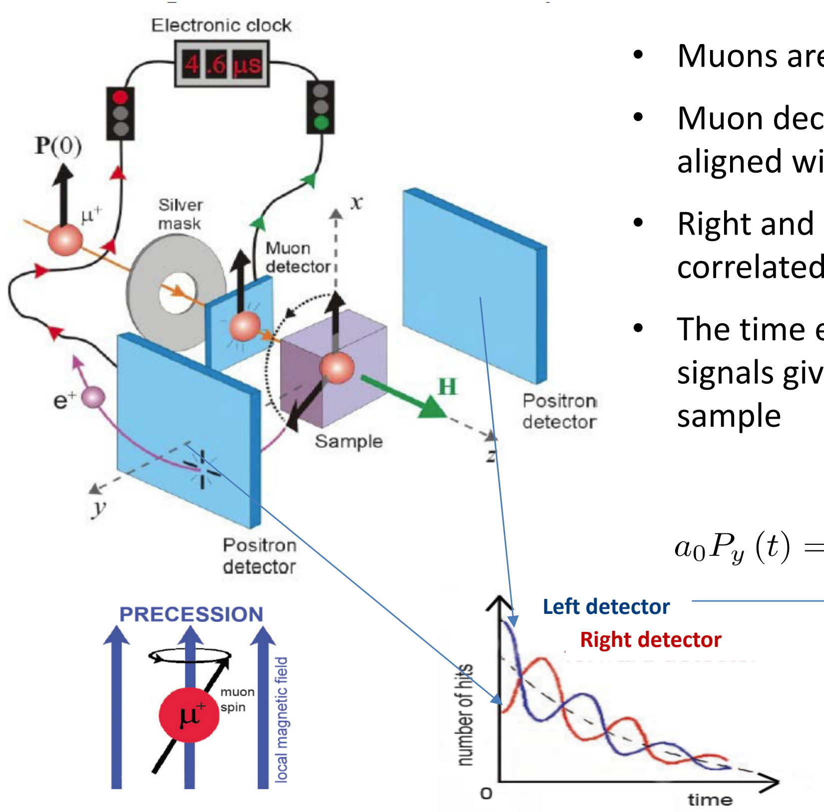
How to test these predictions?

- When analyzing cavity results the problem is that the intrinsic critical field is hard to achieve (extrinsic limitations)
- The superheating field is a DC property

→ **Ideal configuration to test these predictions:**

High-*κ* superconductors of variable thickness on top of niobium to create a large surface barrier and measure the field of first entry with a DC method

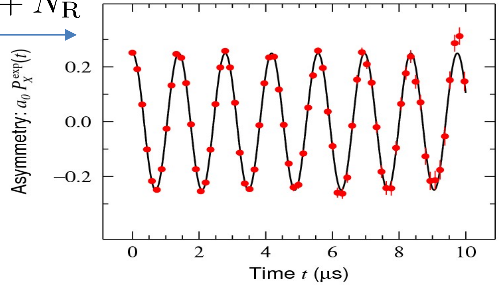
The method: Muon Spin Rotation (muSR)



$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

- Muons are deposited one at a time in a sample
- Muon decays emitting a positron preferentially aligned with the muon spin
- Right and left detectors record positron correlated with time of arrival
- The time evolution of the asymmetry in the two signals gives a measure of the local field in the sample

$$a_0 P_y(t) = \frac{N_L - N_R}{N_L + N_R}$$



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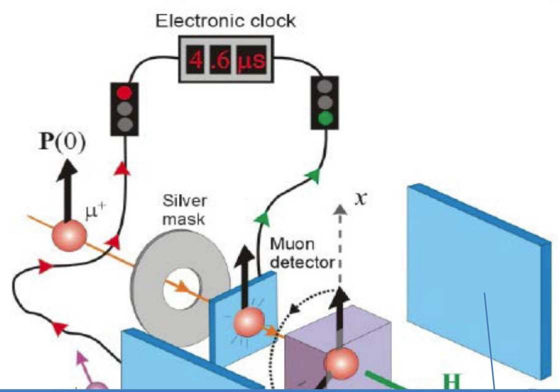

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- muSR is a sensitive probe for the detection of the presence of local magnetic field and can thus be used to detect the transition from the Meissner to a vortex state
- muSR has been used for SRF studies since 2010
- We have established a techniques to measure the **pinning strength** and the **field of first flux entry** using different spectrometers and sample shapes

https://arxiv.org/abs/1705.05480

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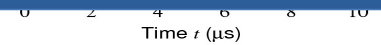
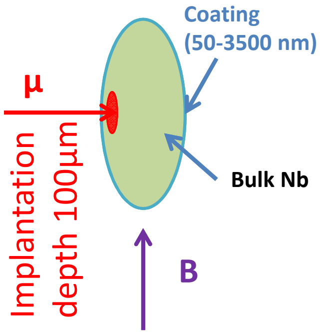
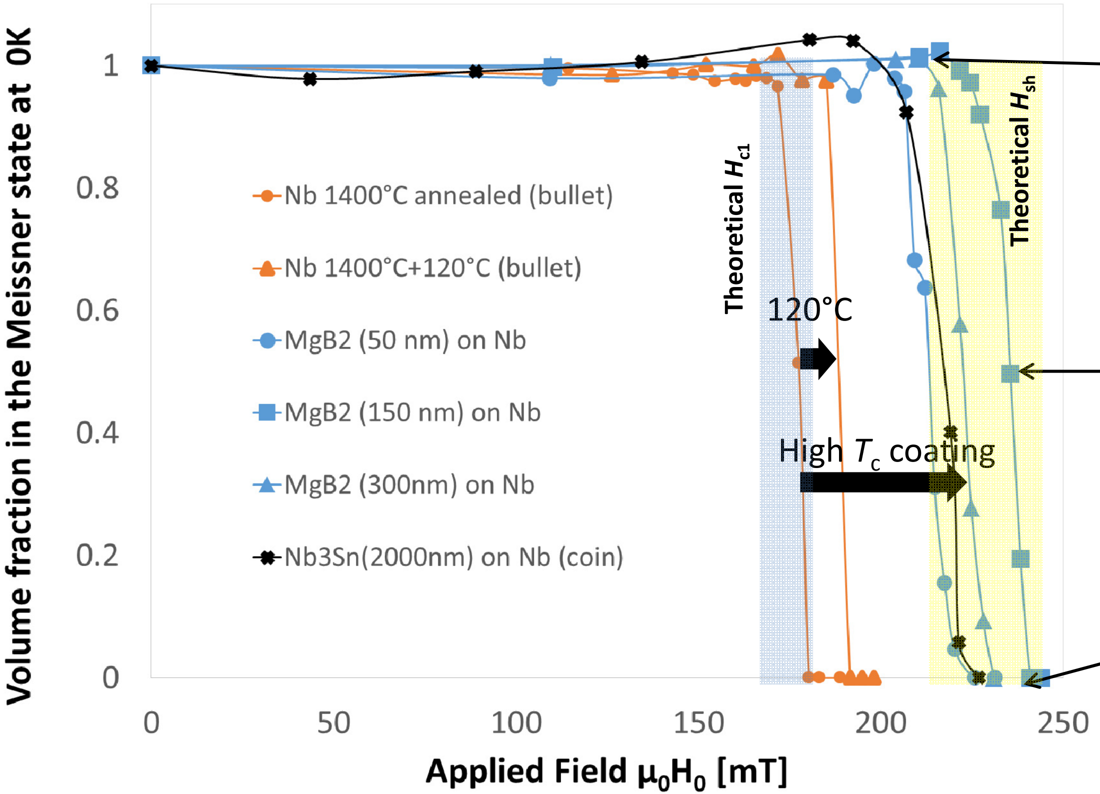
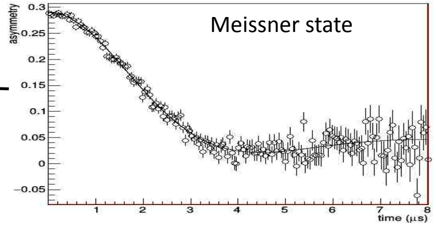
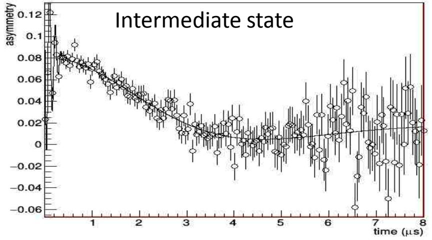


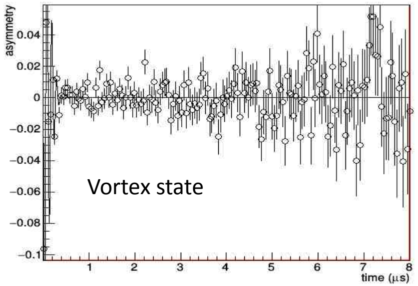
Field of first flux entry measurements





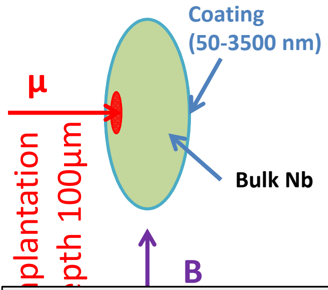


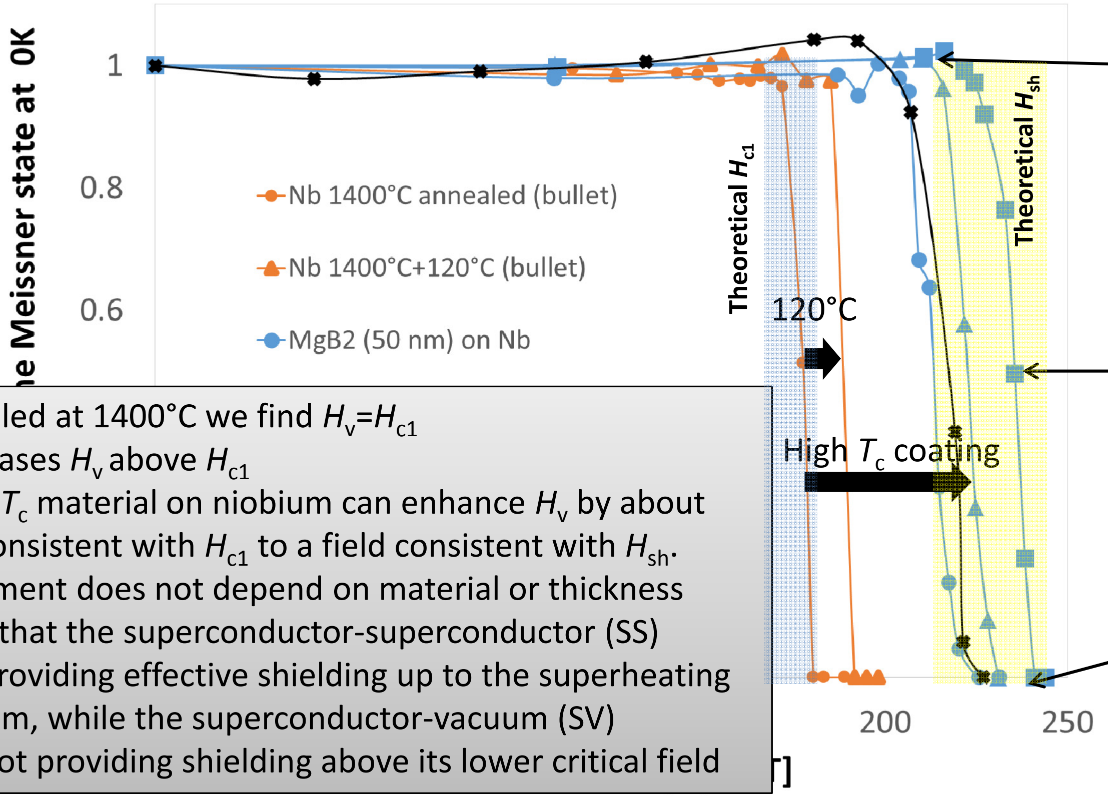


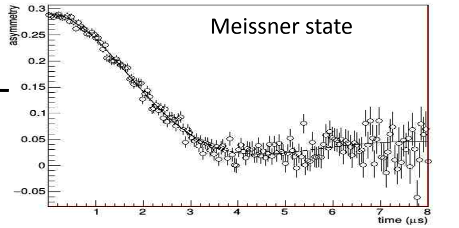


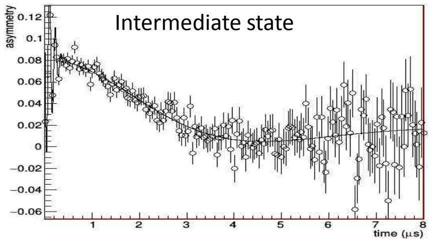
https://arxiv.org/abs/1705.06383

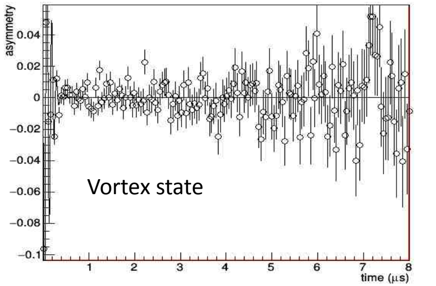
Field of first flux entry measurements











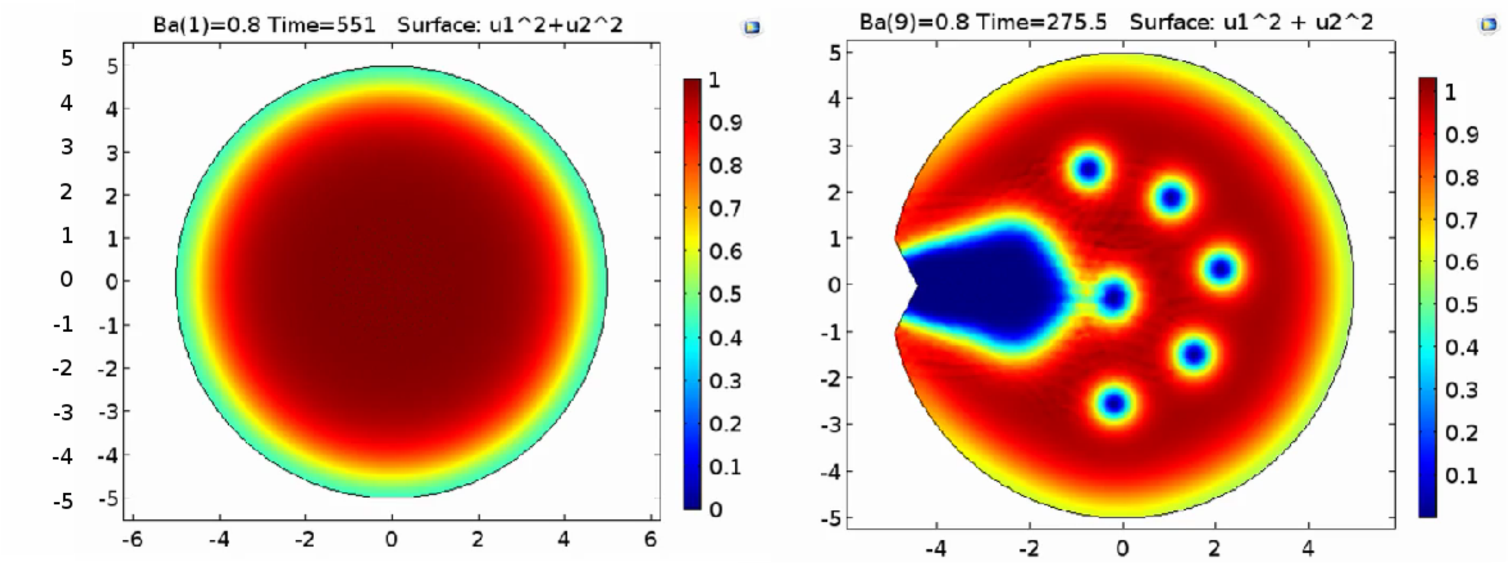
- For niobium annealed at 1400°C we find H_v=H_{c1}
- 120°C baking increases H_v above H_{c1}
- A layer of a higher T_c material on niobium can enhance H_v by about 40% from a field consistent with H_{c1} to a field consistent with H_{sh}.
  - This enhancement does not depend on material or thickness
  - This suggests that the superconductor-superconductor (SS) boundary is providing effective shielding up to the superheating field of niobium, while the superconductor-vacuum (SV) boundary is not providing shielding above its lower critical field

https://arxiv.org/abs/1705.06383

Defects and the proximity effect

Why does the SS but not the SV boundary provide shielding above H_{c1}?

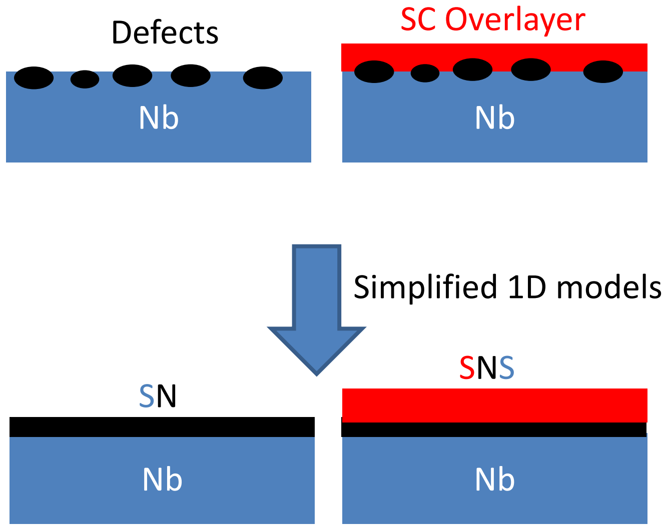
- Physical (geometric) defects can act as vortex nucleation sites, by causing a local depression of the order parameter.
- Can the proximity effect smooth out a non-ideal interface, which may have been previously allowing vortex nucleation?



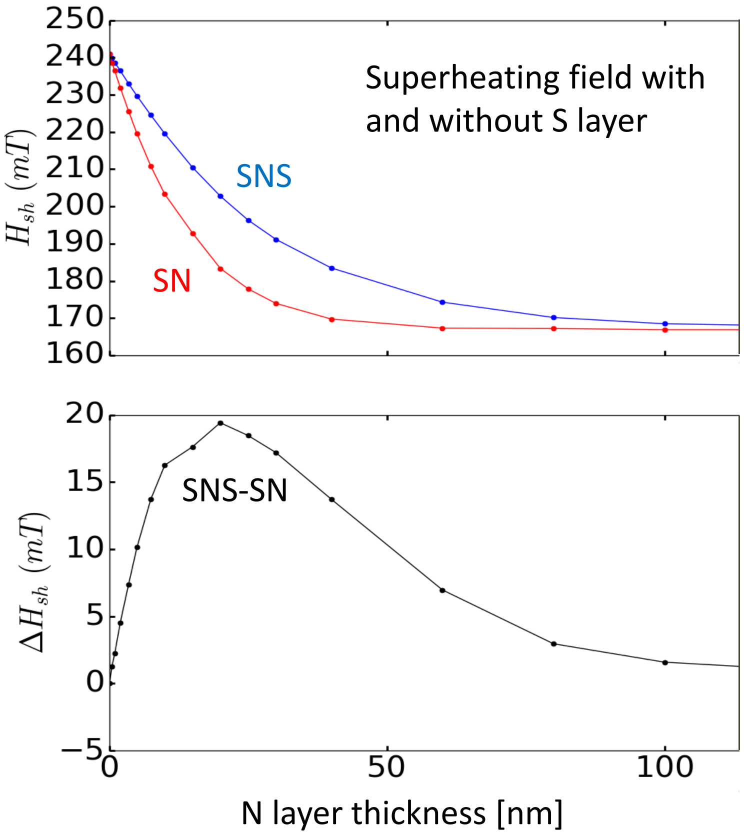
Order parameter for a cylinder. Right: With a defect of roughly the size of of the penetration depth.

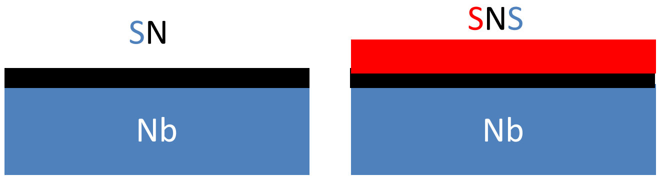
Modeling physical defects in 1D

- A realistic surface contains pollution
- Consider a superconductor with normal conducting defects
- If we add a SC overlayer: Could the proximity effect smooth out the apparent interface?
- Simplified geometries
  - An SN system, which depresses the order parameter at the surface.
  - Then we apply another layer of superconductor, see if there is any recovery



Simulation results





- Solutions to the modified Ginzburg-Landau equations which include superconducting charge carriers within the normal conducting domain
- To facility the simulation
  - Only identical superconductors
  - Material parameters in S/N layer represent super/normal conducting niobium
  - For a more realistic 2-D model FEM methods are necessary

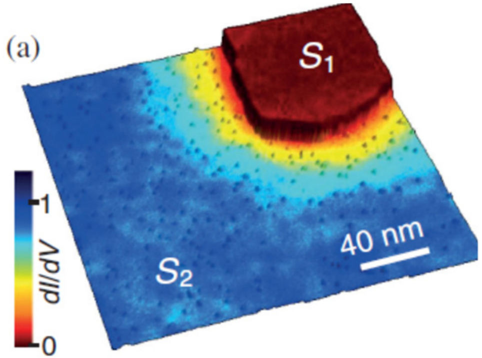
The proximity effect can recover the stability of the superheating field, for small N layers.

https://arxiv.org/abs/1705.06383

Calculations based on:
Chapman, S.J., Du, Q. and Gunzburger, M.D. (1995) "A Ginzburg–Landau type model of superconducting/normal junctions including Josephson junctions", *European Journal of Applied Mathematics*, 6(2), pp. 97–114

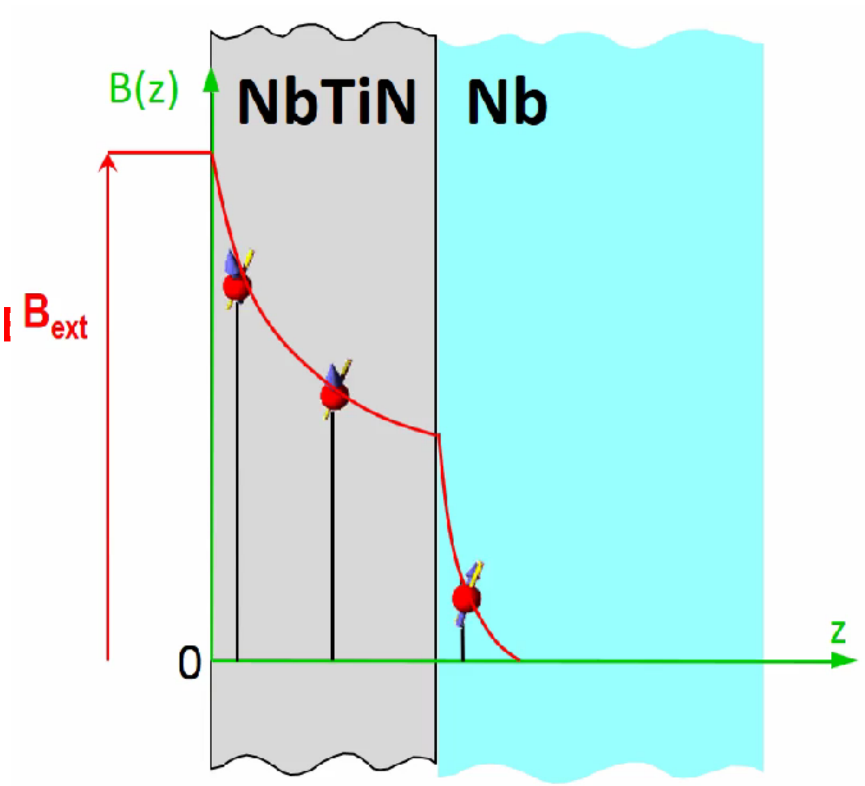
Reduced surface current?

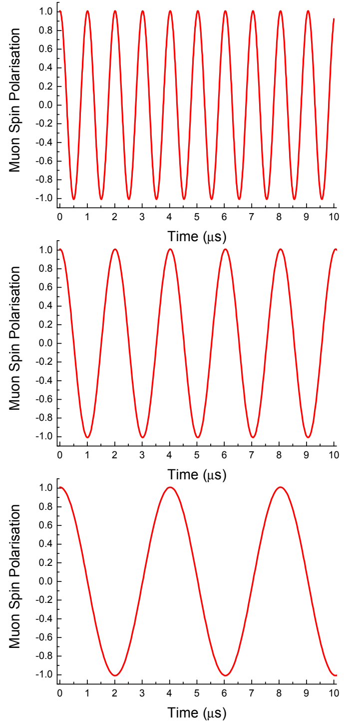
- Kubo calculated the penetration profile neglecting the proximity effect
- However point contact tunneling experiments show that the proximity effect between two superconductors can extend over 10s of nm
- Low energy muons (PSI) can be stopped in a variable depth between 0 and ~100nm
- Our samples
  - NbTiN(80nm) on Nb
  - NbTiN(80nm)/AlN(20nm) on Nb



V. Cherkez et al.– PHYSICAL REVIEW X 4, 011033 (2014)

Depth dependent (low energy) μSR

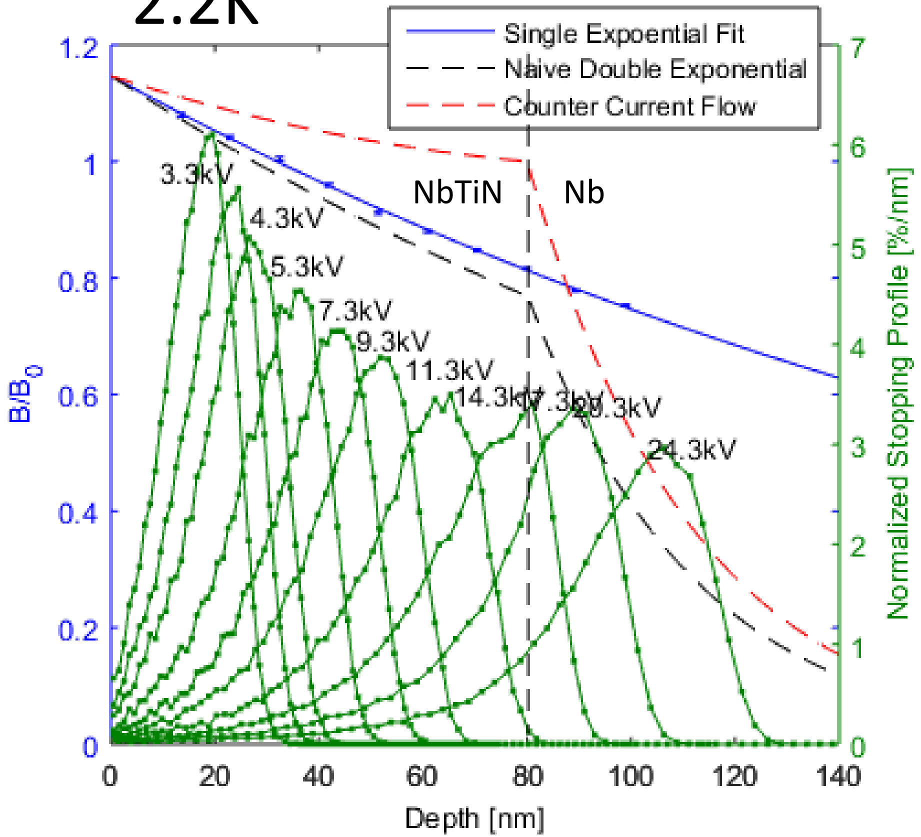




$$\omega_\mu(z) = \gamma_\mu B_{\rm loc}(z)$$

Penetration profile into SS and SIS samples

2.2K



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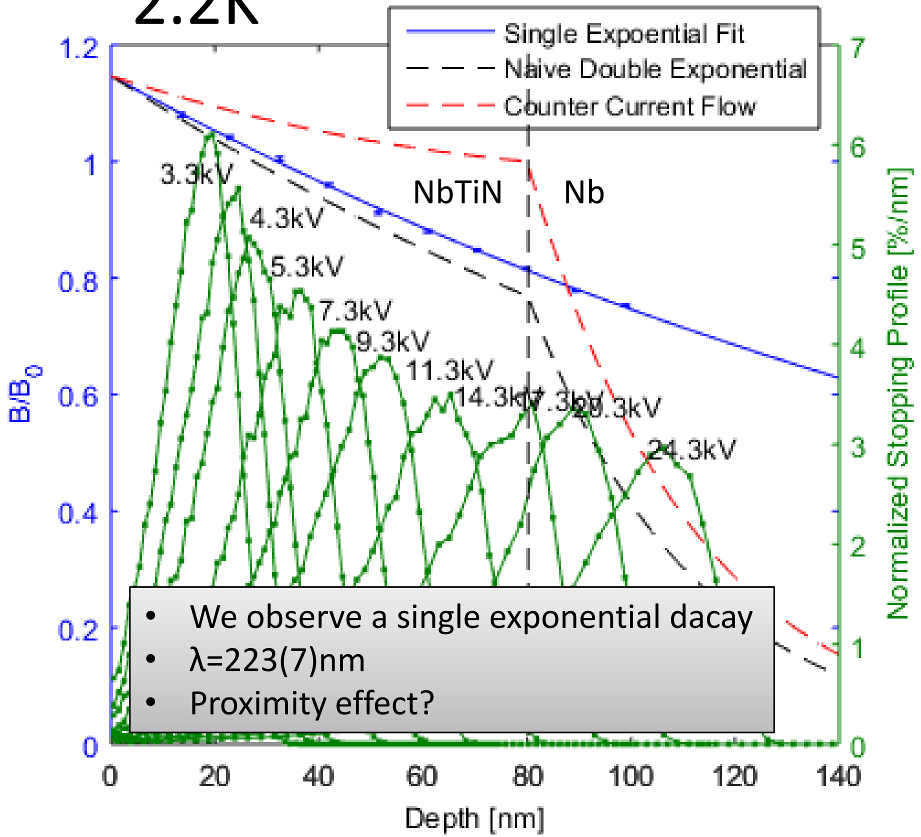

- We observe a single exponential dacay
- λ=223(7)nm
- Proximity effect?

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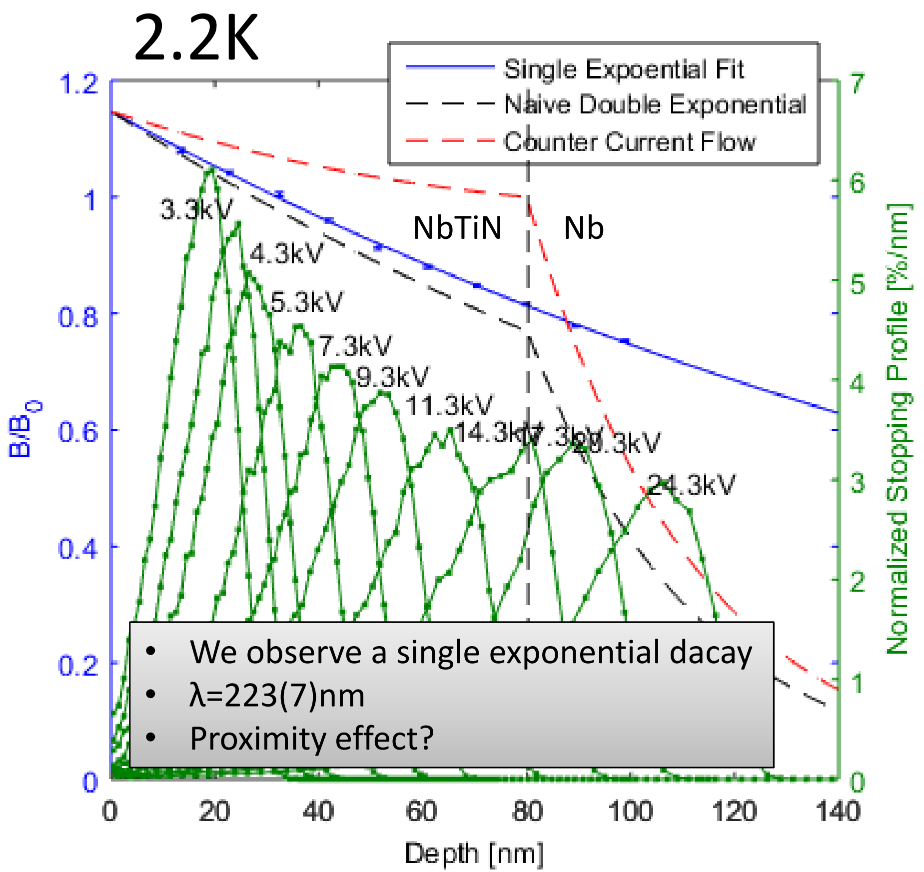

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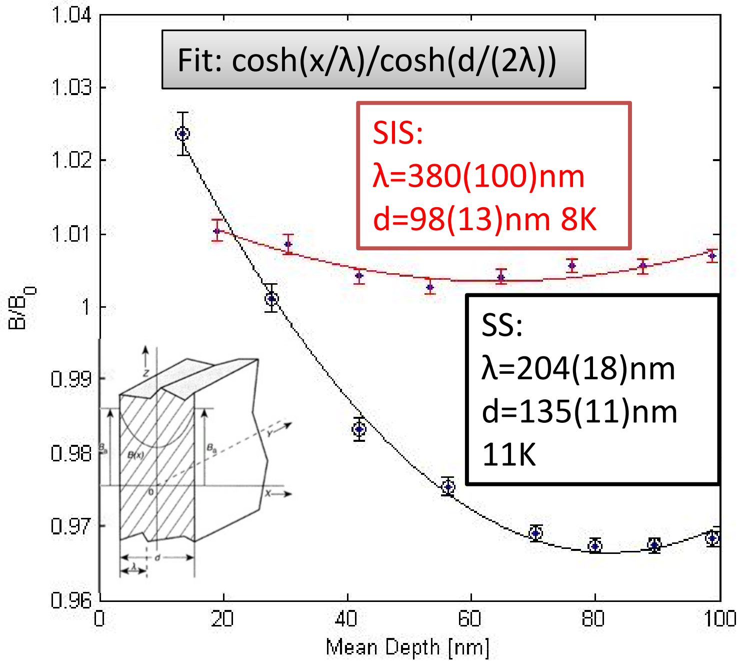

- Measure above T_c of niobium
  - Field enters from both sides
- Comparison with SIS sample (no proximity)
- **Significantly diffrent *λ* and *d* support proximity effect for SS**

Summary

Using muSR we have tested two prediction of the SS and SIS technique

1. Force at the SS boundary

- A layer of higher Tc material on niobium can push the field of first flux entry by 40% from a field consistent with H_{c1} to a field consistent with H_{sh}.
- Enhancement is independent of layer thickness and material.

→The boundary between two superconductors can provide an effective energy barrier for vortex penetration up to the superheating field of the substrate. We propose that the proximity effect recovers the stability of the superheating field.

2. Reduced surface current

- For multilayer systems without insulator there is a wide range proximity effect to be considered. No suppression of surface current for NbTiN on Nb measured.
- To benefit from this mechanism an insulating layer is essential.

Acknowledgement

- *Experimentalists:* D. Bazyl, R. Dastley, M. Dehn, D. Azzoni Gravel, S. Gehdi, Z. He, R. Kiefl, P. Kolb, Y. Ma, L. Yang, Z. Yao, H. Zhang (TRIUMF)
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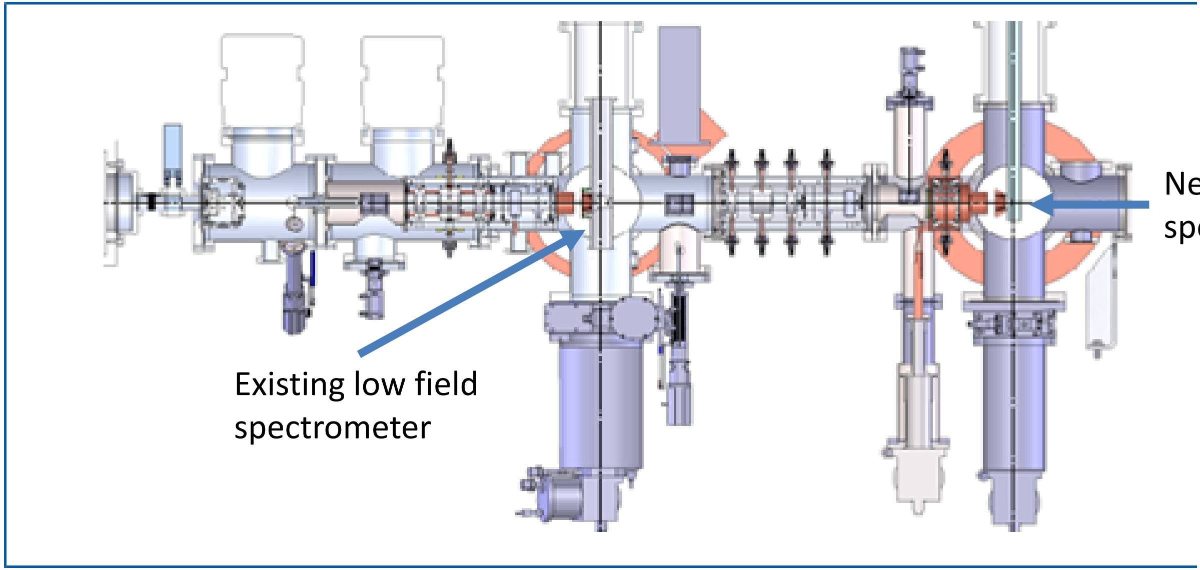
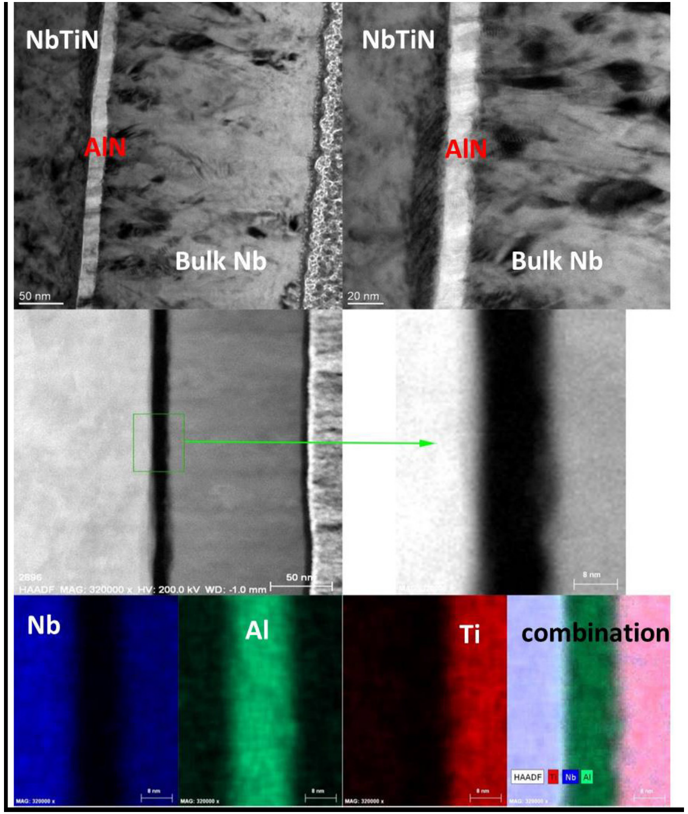
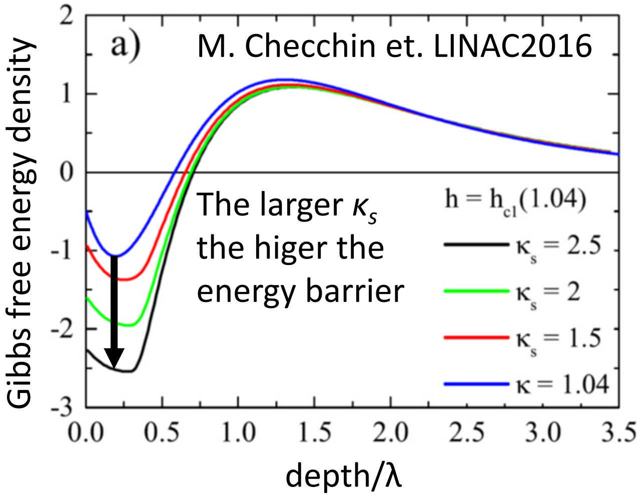
New beta-NMR beamline at TRIUMF for SRF studies

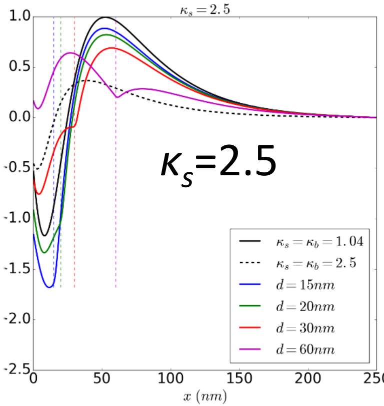
- muSR at TRIUMF fixed implantation depth (≈100µm) LE-muSR at PSI limited to 25 mT parallel fields
- betaNMR is similar to muSR but uses radioactive ions like 8Li implanted in bunches not one by one
- TRIUMF will provide a unique facility in the world for diagnosing new treatments (doping), new materials (Nb3Sn) and new structures (SIS layer) with variable implantation depth and parallel magnetic fields up to 200mT

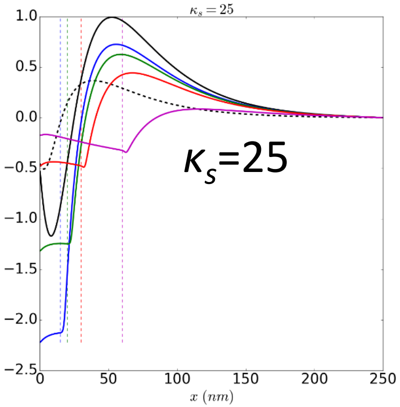



NbTiN
AlN
Bulk Nb
50 nm
NbTiN
AlN
Bulk Nb
20 nm
HAADF MAG: 320000 x HV: 200.0 kV WD: -1.0 mm
50 nm
8 nm
Nb
Al
Ti
combination
HAADF
Nb
Al

Checchin´s model







M. Checchin et al. propose that **a dirty layer on top of niobium can stabilize the metastable Meissner state and therefore pushes the field of first entry from H_{c1} up to H_{sh}**

We have used their approach to calculate how the surface barrier depends on the thickness of the layer:
Especially for a large *d* and κ_s (surface GL parameter) the interface barrier becomes uneffective