Energy Barrier at Superconductor-Superconductor Interfaces

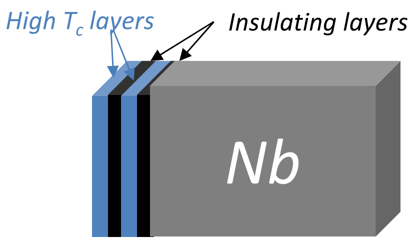
Tobi Junginger (UVIC+TRIUMF)

Content

- *In this talk I will argue that*
  - *SRF heterostructures have the potential to achieve accelerating gradients beyond niobium's fundamental limitation*
  - *Low temperature baked niobium cannot be considered as an effective bilayer of dirty and clean niobium at the relevant length scale*
- *My arguments are based on experimental results from muSR, low energy muSR and magnetometry*

Larger Accelerating Gradients through Heterostructures

- *The multilayer approach has been proposed in 2006 by A. Gurevich*
  - *No thermodynamically stable parallel vortices in decoupled S layers thinner than λ*
- *Further investigations found*
  - *Reduced surface current in the outer layers (boundary and continuity conditions) Md Asaduzzman WEIXA01*
  - *The boundary of two SCs introduces a* **force that pushes a vortex to the direction of the material with larger penetration depth.**
    - *These features do not require insulating layers. An SS bilayer system can be used to test these predictions and potentially enable larger E_{acc}*
- *Low temperature baking changes the mean free path and therefore the penetration depth potentially forming an effective bilayer system.*



SIS-Multilayer

SS-Bilayer

Low temperature baking

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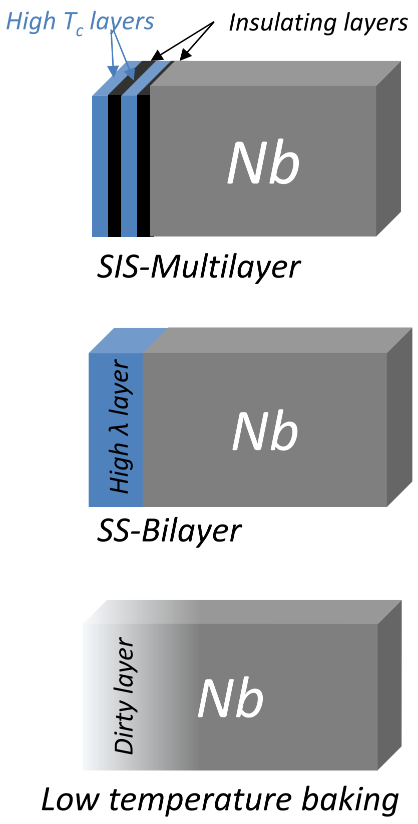
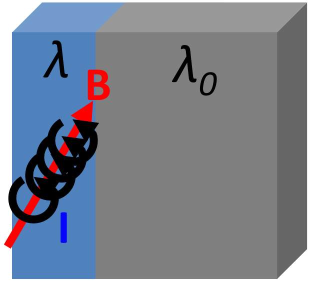
Bilayer superconductors can potentially enable larger E_{acc} and be used to test general features of heterostructures



Force at the boundary

- *Consider vortex at the SC/vacuum boundary*
  - *Magnetic field parallel to the surface creates force that pushes vortex inwards*
  - *Flux from this vortex has to vanish at the SC/vacuum interface → Image vortex → Force towards vacuum (Bean-Livingston barrier)*
- *For $\lambda>\lambda_0$ there is a second energy barrier at the interface between the layer and the substrate which pushes the vortex outwards*
  - *This force is independent of layer thickness*



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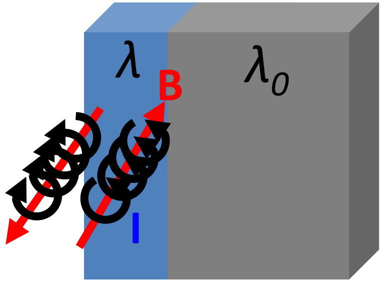

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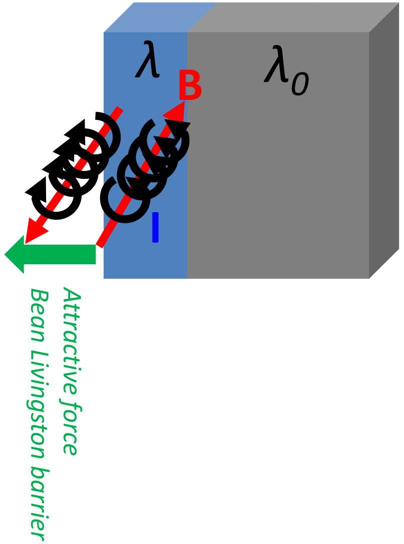

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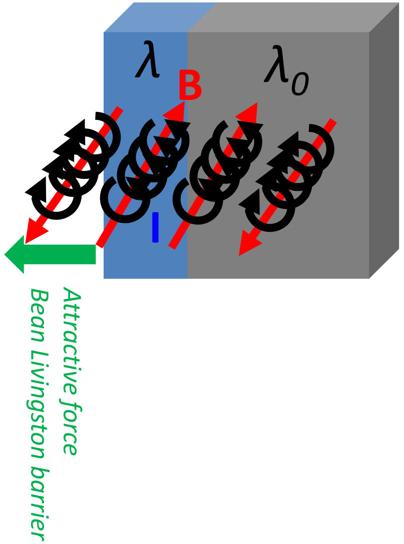

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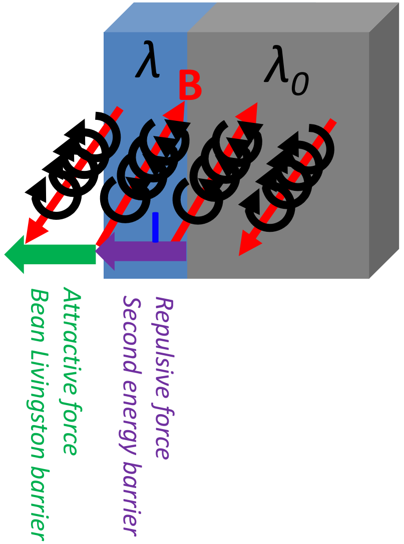

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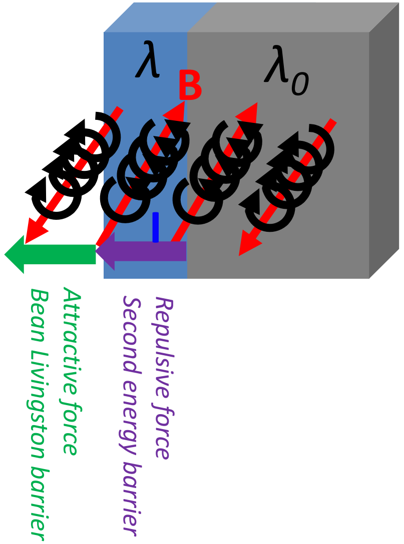


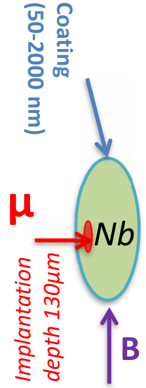
Prediction:

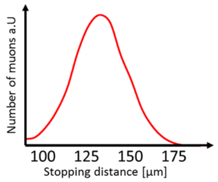
Surface Bean Livingston barrier $H_{vp} = H_{sh,layer}$

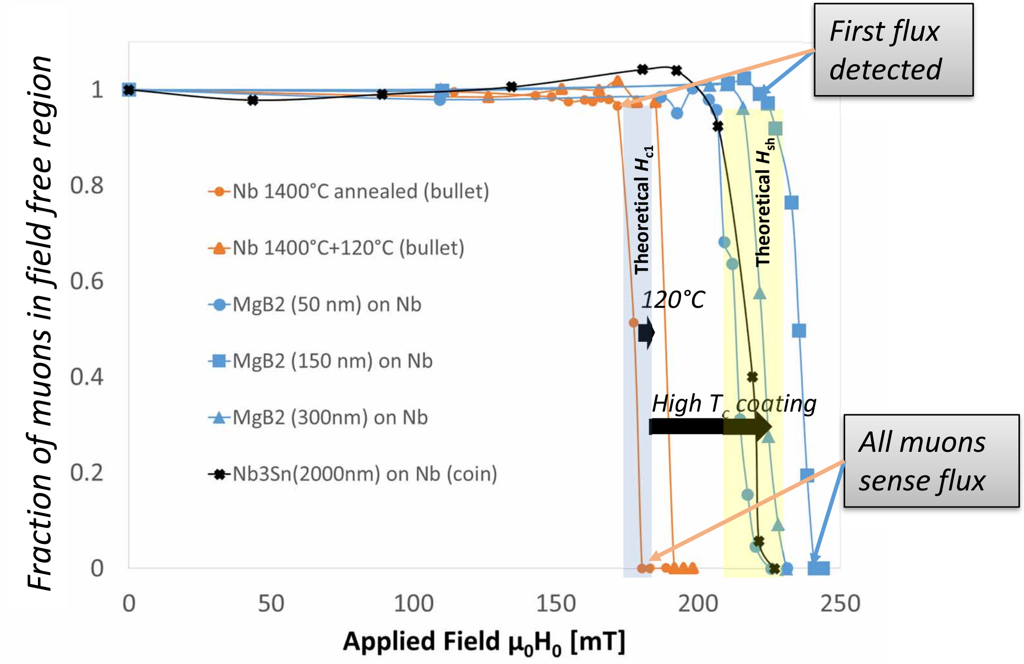
Interface barrier $H_{vp} = H_{sh,substrate}$

Review Coated Niobium – First Flux Entry

- *Muon Spin Rotation can measure H_{vp}*
  - *The fraction of implanted muons in field free region is probed*
  - *Localized beam with mean implantation depth 130µm*
- *Nb_3Sn and MgB_2 with 50-2000nm thickness on Nb and 120°C baked Nb tested*







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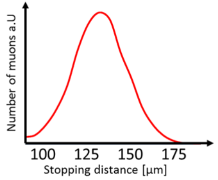
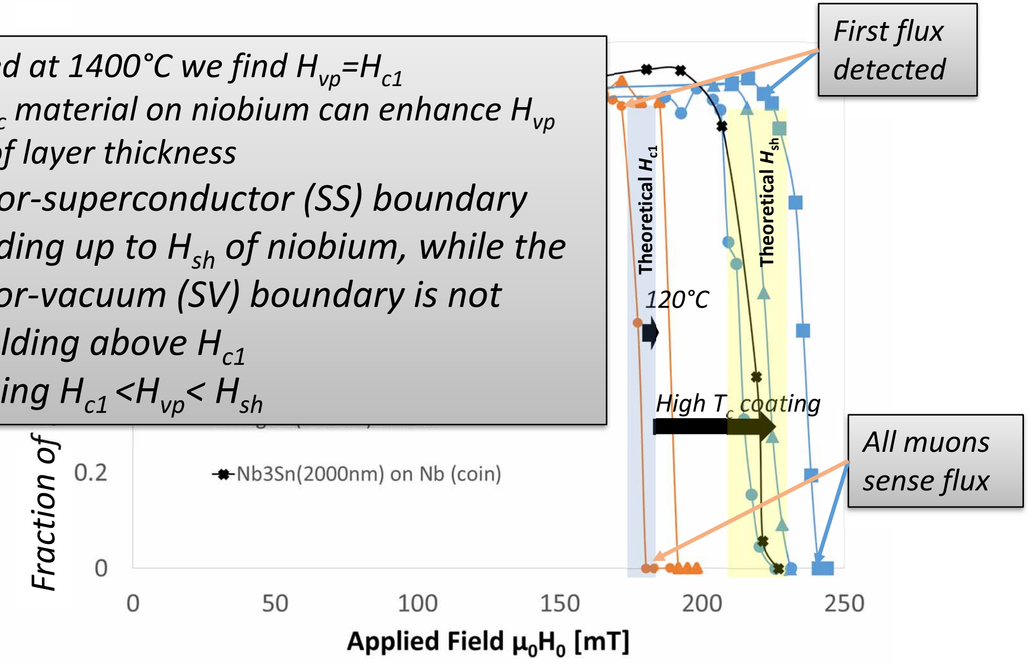
- *For niobium annealed at 1400°C we find $H_{vp}=H_{c1}$*
- *A layer of a higher T_c material on niobium can enhance H_{vp} to H_{sh} independent of layer thickness*
  - *Superconductor-superconductor (SS) boundary provides shielding up to H_{sh} of niobium, while the superconductor-vacuum (SV) boundary is not providing shielding above H_{c1}*
  - *For 120°C baking $H_{c1} < H_{vp} < H_{sh}$*





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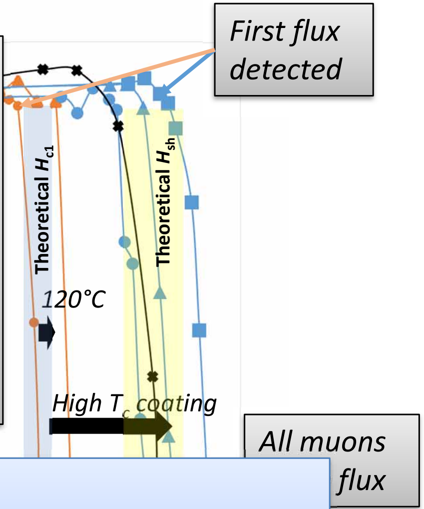

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Open questions

- **Why does LTB increase H_{vp} only slightly above H_{c1}?**
  - **Are the enhancements actual H_{vp} increases or caused by flux pinning?**
- **Can LTB niobium actually be considered as a bilayer?**

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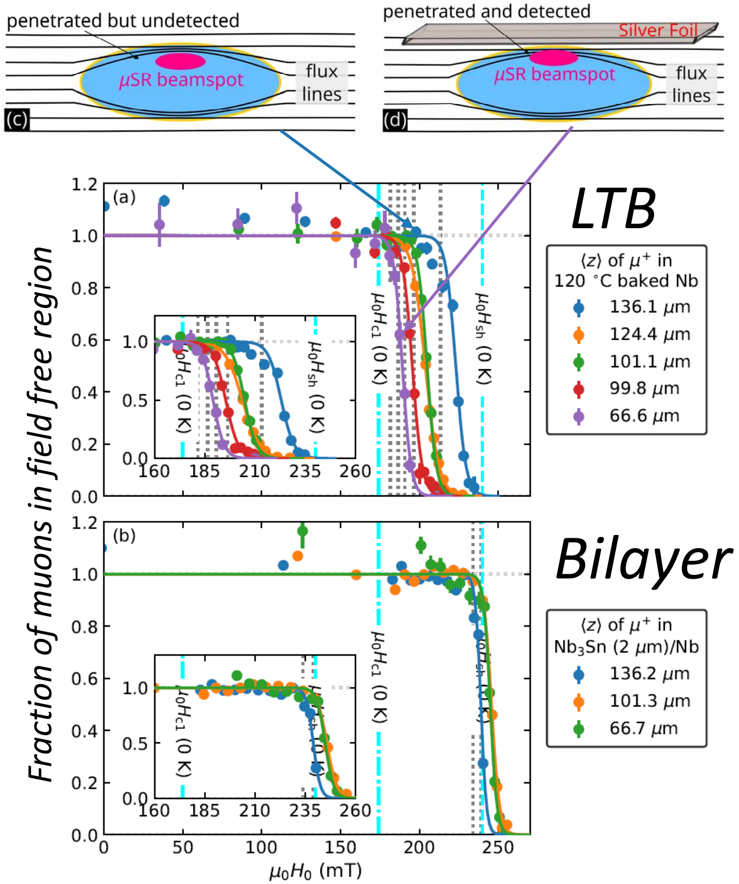
muSR with variable implantation depth

Experiment: *Silver foils are used to vary the mean implantation depth <z>*

Predicted Outcome: *In case of surface pinning the apparent H_{vp} should decrease with lower <z>. In case of an interface barrier Hvp should be independent of <z>*



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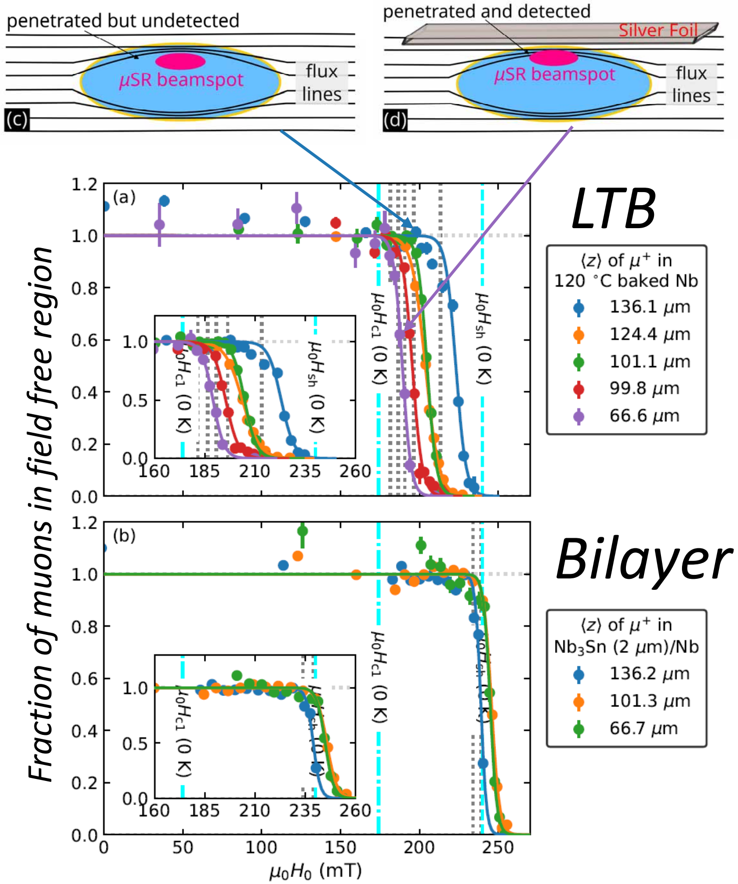
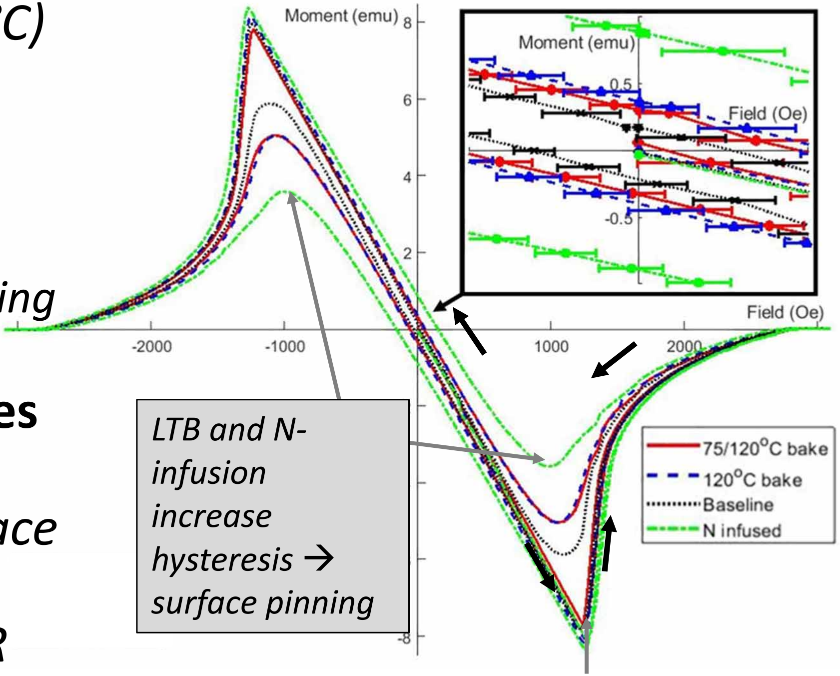
Results *suggest interface barrier for bilayers and surface pinning for LTB, see Md Asaduzzaman SUSPB002*



Magnetometry (LTB)

- *Magnetometry with fully annealed (1400°C) ellipsoids allows for accurate H_{vp} measurements*
  - *No edge effect*
  - *very weak bulk pinning*
- **Magnetometry suggests that LTB does not affect H_{vp}**
- *LTB changes the surface pinning*
- *Consistent with muSR results*



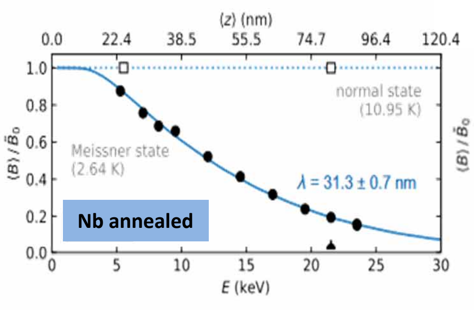
LTB and N-infusion increase hysteresis → surface pinning

No H_{vp} change for all samples

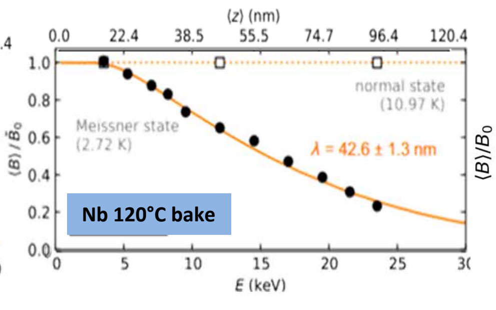
Turner, D.A., Burt, G. and Junginger, T., 2022. Scientific Reports, 12(1), p.5522.

Magnetic Screening

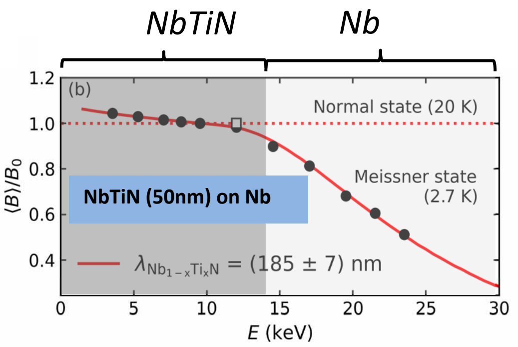
Low energy muSR is used to probe the magnetic screening as a function of depth within the London layer



Bare niobium is well described by a London decay. A refined analysis finds λ consistent with literature. Non-local effects are insignificant.



120°C baking increases the London penetration depth but no bipartite screening is observed. The data can be well fitted with a single valued λ



NbTiN on Nb shows a clear bipartite screening profile as expected for a bilayer. Md. Asaduzzman ***WEIXA01***

RML McFadden et al. - PHYS. REV. APPLIED 19, 044018 (2023)
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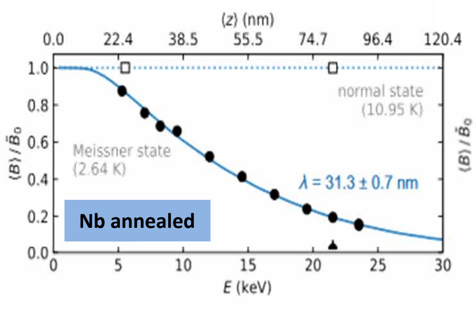

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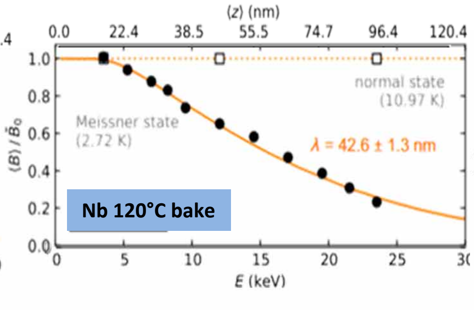

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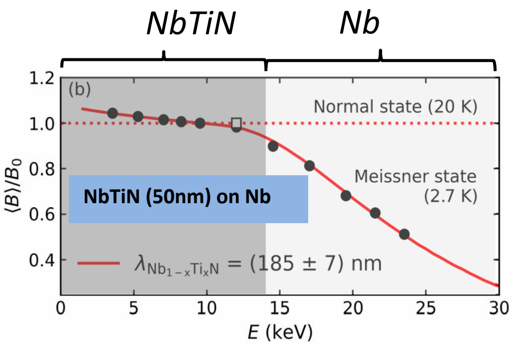

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Bipartite Meissner screening for bilayer samples but not for LTB

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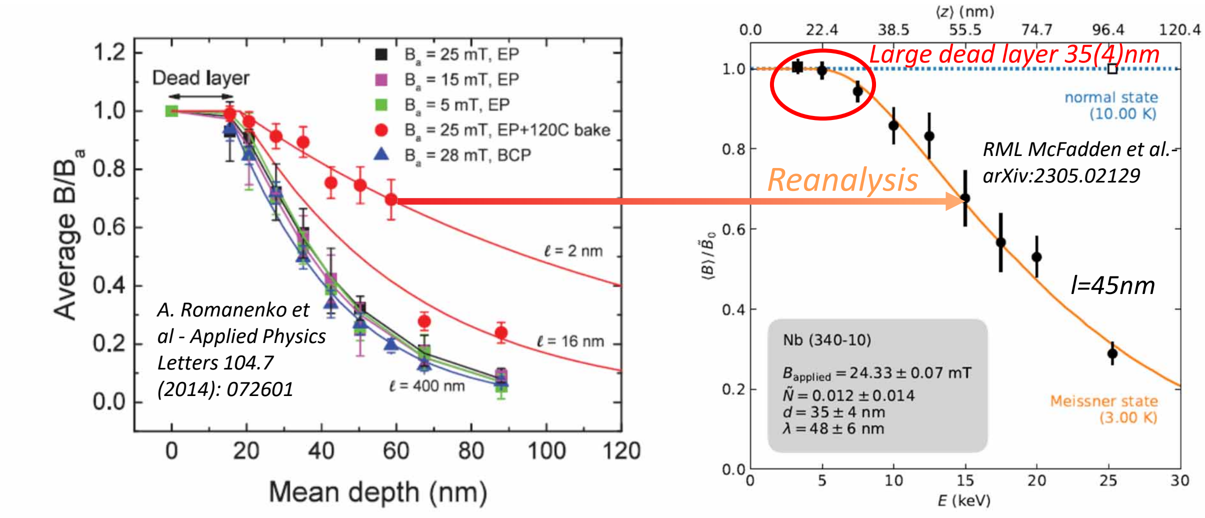
Magnetic screening profile in London layer



Reanalysis of data from Romanenko et al. data does not confirm a change in Meissner screening for 120°C baked niobium around 60nm depth

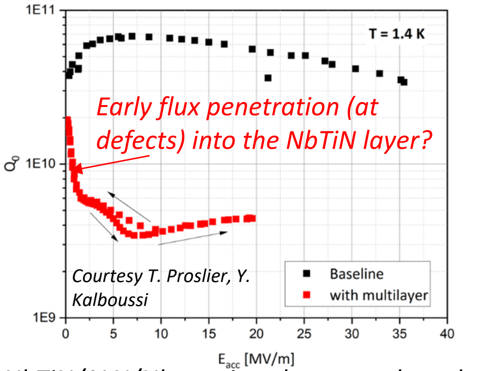
- *Single exponential London decay (no need to account for non-local effects) gives excellent fit*
- *Large dead layer suggests that the change in screening appears gradual at lower depth*
  - *Consistent with HF rinsing (nano-removal) and SIMS studies*
- **Potential reason for discrepancy:** *Short penetration length in niobium results in a wide range of fields probed for each energy → Strong damping of the muSR signal and only very few oscillations are well resolved →* **Analysis of niobium LE-muSR data for relatively large implantation depth in the Meissner state is particularly challenging**

Summary

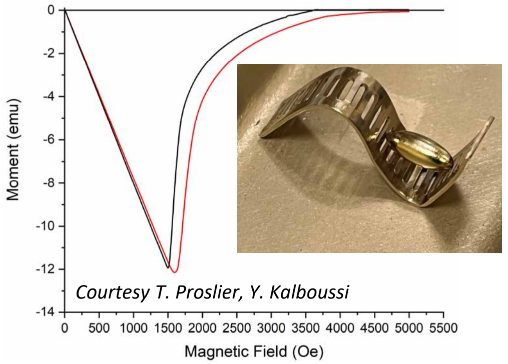
- *Low temperature baked niobium cannot be considered as an effective bilayer. Unlike for actual bilayers DC experiments find*
  - *No bipartite magnetic screening profile*
  - *No H_{vp} enhancement above H_{c1}*
- *Our experiments cannot explain why some Nb SRF cavities (LTB, N-infusion) perform above H_{c1}*
  - *This seems to be specific to RF operation, e.g. vortex nucleation time*
- *New muSR experiments further confirm that a layer of a superconductor with a larger London penetration depth on niobium can push the* **DC** *field of first vortex penetration from H_{c1} to H_{sh}*
  - *For SRF application this layer needs to be thinner than its London penetration depth and remain flux free*
  - *While this sounds promising actual RF performance of heterostructures generally lag behind Nb cavity performance*

Upcoming betaNMR experiment

- *RF performance of heterostructures generally lags behind Nb cavities*
  - *Early flux penetration into overlayer?*
- *With betaNMR we are able to detect penetration of magnetic flux with nanometer depth resolution (E. Thoeng TUIXA04)*
- *A niobium ellipsoid has been coated using atomic layer deposition with 8nm of AlN and 46nm of NbTiN and will be tested in September*



NbTiN/ALN/Nb coating shows weakened performance compared to uncoated cavity



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