Experimental evidence of counter current flow in superconductor-superconductor bi-layers

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Contributors

Name	Role	Affiliation
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Ryan M. L. McFadden Tobias Junginger	Supervisors	University of Victoria TRIUMF

Agenda

- Motivation: Experimental evaluation of counter-current flow in SS bilayers to overcome Nb fundamental field limit
- Microscopic properties of SS bi-layers
  - Direct observation of depth resolved magnetic field profile (LE-μSR technique)
- Experimental results
- Summary

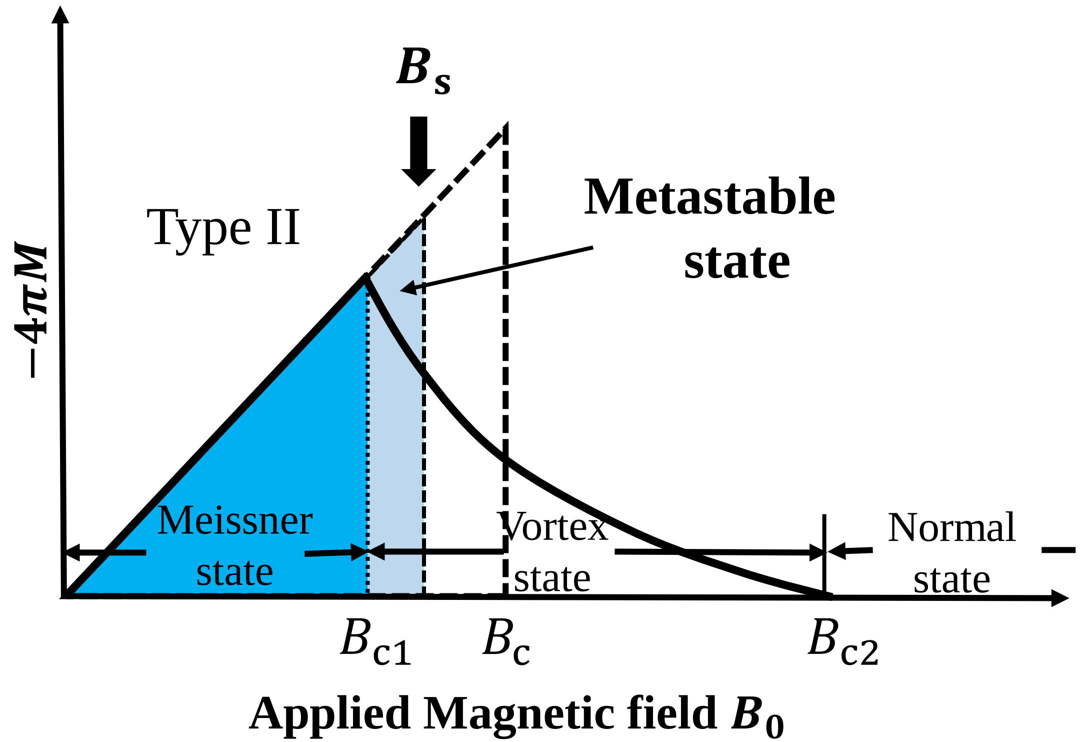
Superheating field of a superconductor

- In type-II superconductor Meissner state can persist as a metastable state up to a maximum field above B_{c1} named by superheating field (B_s)
- Superheating field (B_s) at $T \ll T_c$:

$$B_s \simeq 0.84 B_c$$

$$B_c = \frac{\phi_0}{2\sqrt{2}\pi\lambda\xi} = \mu_0 \lambda J_{max}$$

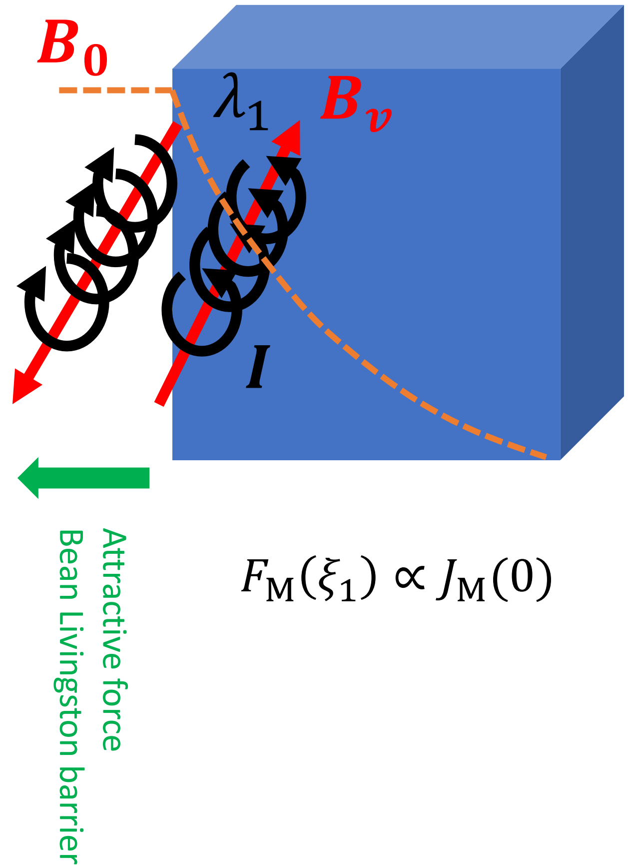
J_{max} = maximum screening current that can withstand against vortex penetration.



Catelani. G., PHYSICAL REVIEW B 78, 224509 (2008)
Pei-Jen Lin. F., PHYSICAL REVIEW B 85, 054513 (2012)

When does the vortex penetrate into a superconductor material?

- Vortex at the SC/vacuum boundary
  - Magnetic field is parallel to the surface
  - F_{M} → force from Meissner current (due to existence of applied field) which pushes the vortex inside the superconductor and
  - F_{B} → force due to interaction of vortex and the boundary (image current of an image antivortex) which attracts vortex to the surface
  - Modelled by image vortex
  - Vortex penetrates at $|F_{\mathrm{M}}(\xi_1)| > |F_{\mathrm{B}}(\xi_1)|$



$F_{\mathrm{M}}(\xi_1) \propto J_{\mathrm{M}}(0)$

T. Junginger et al., JACoW-IPAC2018 (2018)

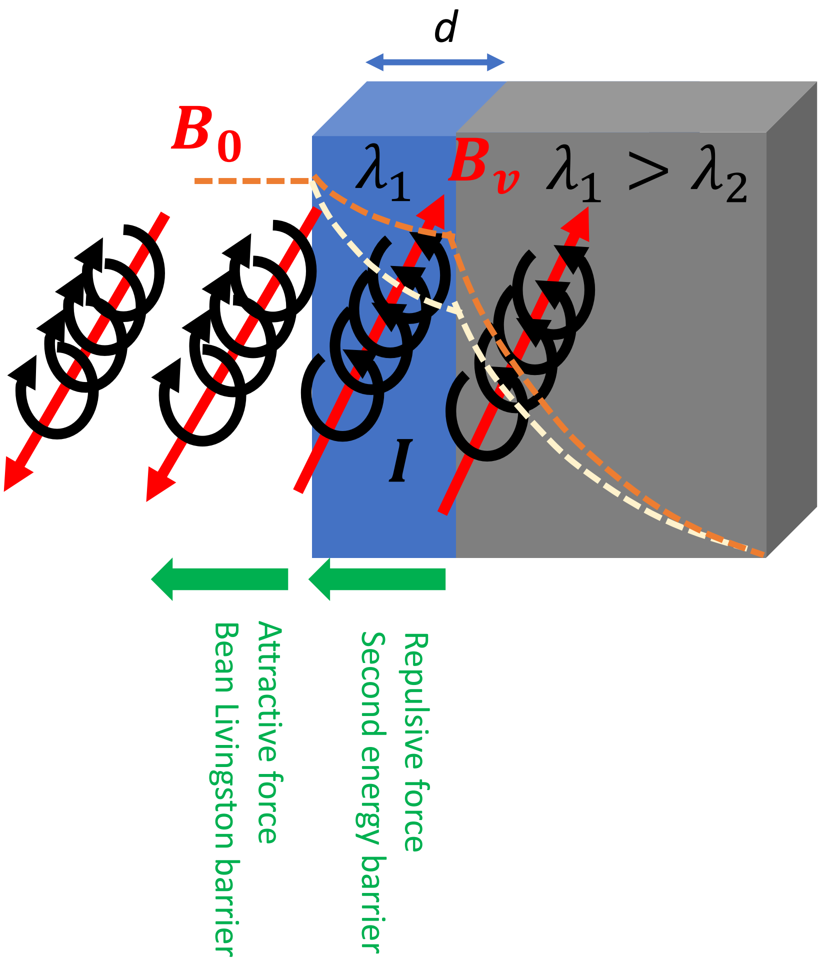
T. Kubo et al., Appl. Phys. Lett. 104, 032603 (2014)

When does the vortex penetrate into a bi-layers superconductor?

- The force $F_\mathrm{B}(\xi_1)$ on the vortex in the substrate layer when $\lambda_1 > \lambda_2$ can also be observed by method of images (satisfying the boundary conditions)

- Vortex at the SC/vacuum boundary
    - Vortex penetrates at $|F_\mathrm{M}(\xi_1)| > |F_\mathrm{B}(\xi_1)|$

- If $\lambda_1 > \lambda_2$: the current density at the interface reduces the Meissner current in the top layer and increases vortex penetration field.



T. Junginger et al., JACoW-IPAC2018 (2018)

T. Kubo et al., Appl. Phys. Lett. 104, 032603 (2014)

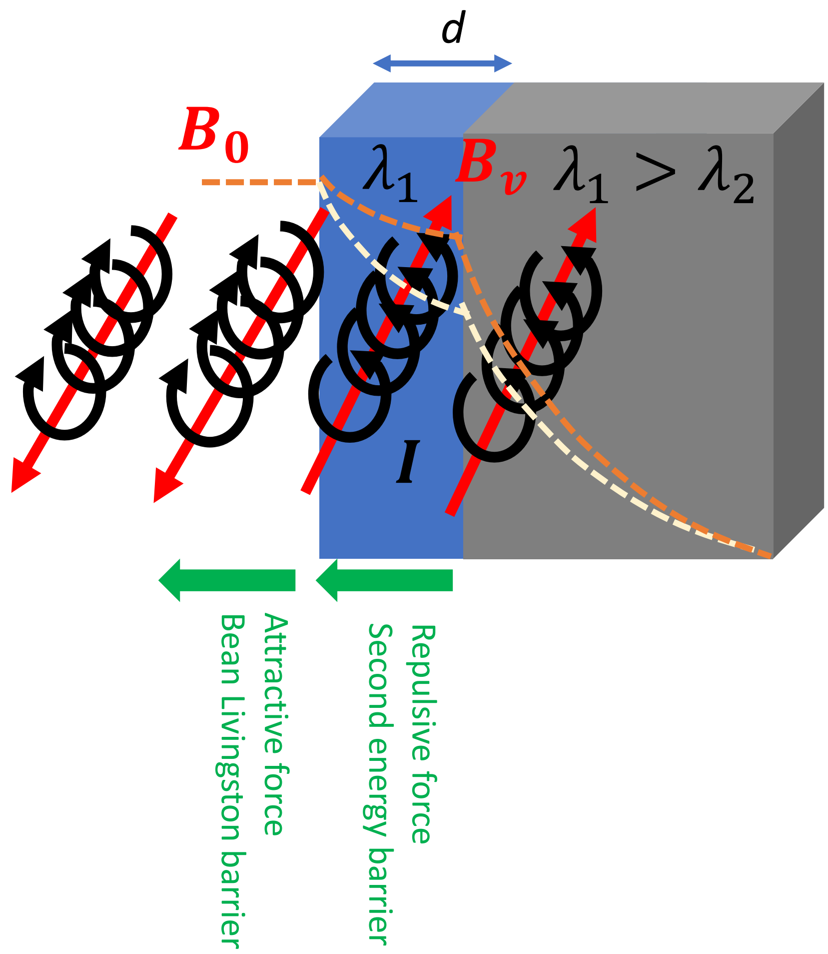
Counter current and forces in interfaces in SS bilayers

- What is counter current?

In the Meissner state in SS bilayers, the current that flows in the bottom layer (which suppress the Meissner current in the top layer) in order to satisfy boundary conditions (which is zero current density normal to the interfaces).

- Vortex penetrates at

$$|F_{\mathrm{M}}(\xi_1)| > |F_{\mathrm{B}}(\xi_1)|$$



T. Junginger et al., JACoW-IPAC2018 (2018)

T. Kubo et al., Appl. Phys. Lett. 104, 032603 (2014)

Counter current flow modifies the Meissner screening profile in SS bilayers

- The surface current is reduced in the Nb-Ti-N layer due to the counter current flow in the Nb layer (blue curve)

Simple London model:

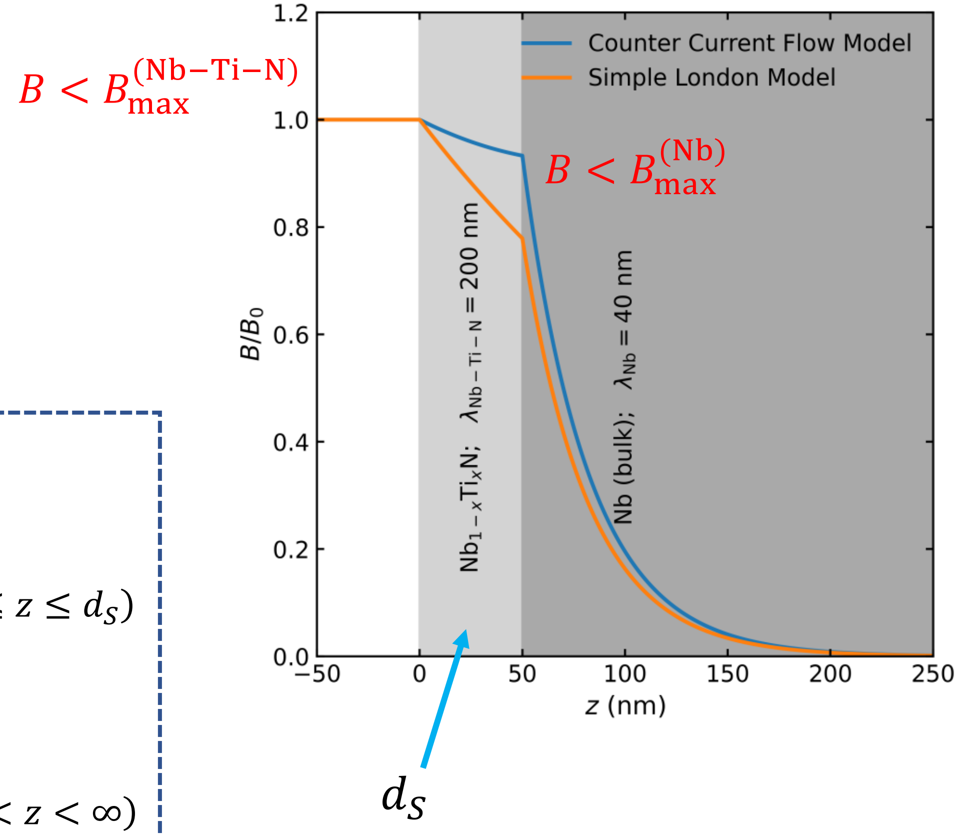
$$B(z) = \sum c_j B_j(z)$$

$$B_j(z) = B_0 \times \exp\left(-\frac{d_j}{\lambda_j}\right) \quad \text{and } \sum c_j = 1$$

Counter current flow model:

$$B(z) = B_0 \frac{\cosh\frac{d_S - z}{\lambda_1} + \frac{\lambda_2}{\lambda_1}\sinh\frac{d_S - z}{\lambda_1}}{\cosh\frac{d_S}{\lambda_1} + \frac{\lambda_2}{\lambda_1}\sinh\frac{d_S}{\lambda_1}} \qquad (0 \leq z \leq d_S)$$

$$B(z) = B_0 \frac{e^{-\frac{z - d_S}{\lambda_2}}}{\cosh\frac{d_S}{\lambda_1} + \frac{\lambda_2}{\lambda_1}\sinh\frac{d_S}{\lambda_1}} \qquad (d_S < z < \infty)$$

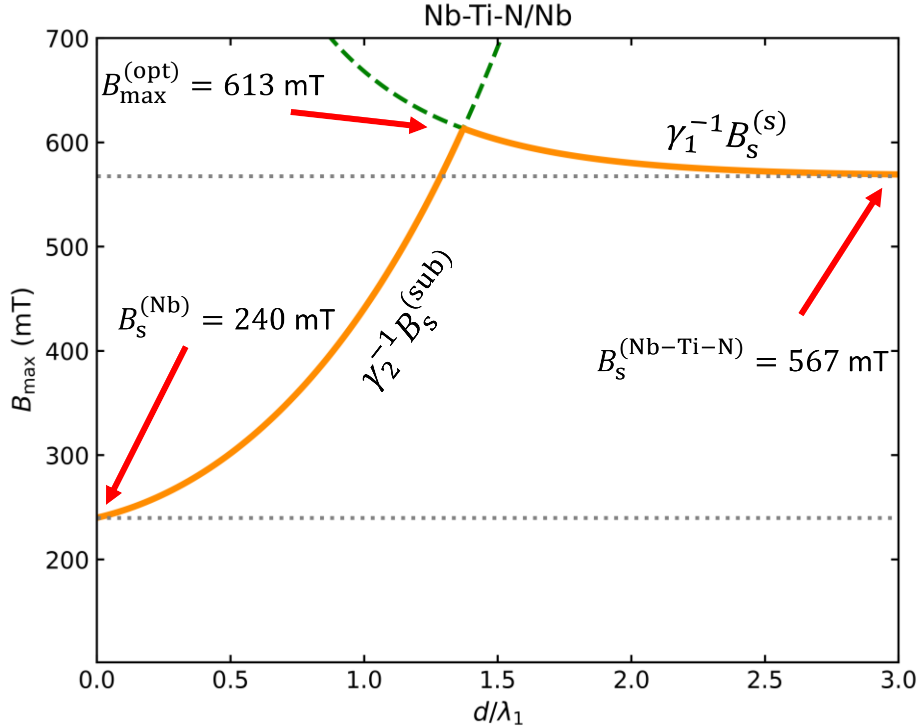


F. London et al., Proc. R. Soc. Lond. A149 (1935)
T. Kubo, Supercond. Sci. Technol. 30 023001 (2017)

Theoretical field limit in SS bilayers as a function of surface layer thickness d

e.g., Two superconductors (Nb-Ti-N/Nb) with different λ in the Meissner state

- By solving the relation between applied field and screening current density differential equation in London model B_{max} can be derived as a function of Nb-Ti-N thickness.
- $B_{\mathrm{max}}^{\mathrm{opt}} = \min\{\gamma_1^{-1} B_s^{(s)}, \gamma_2^{-1} B_s^{(\mathrm{sub})}\}$
- SS bilayers can remain in the Meissner state under applied field that exceed the intrinsic field limits of individual materials

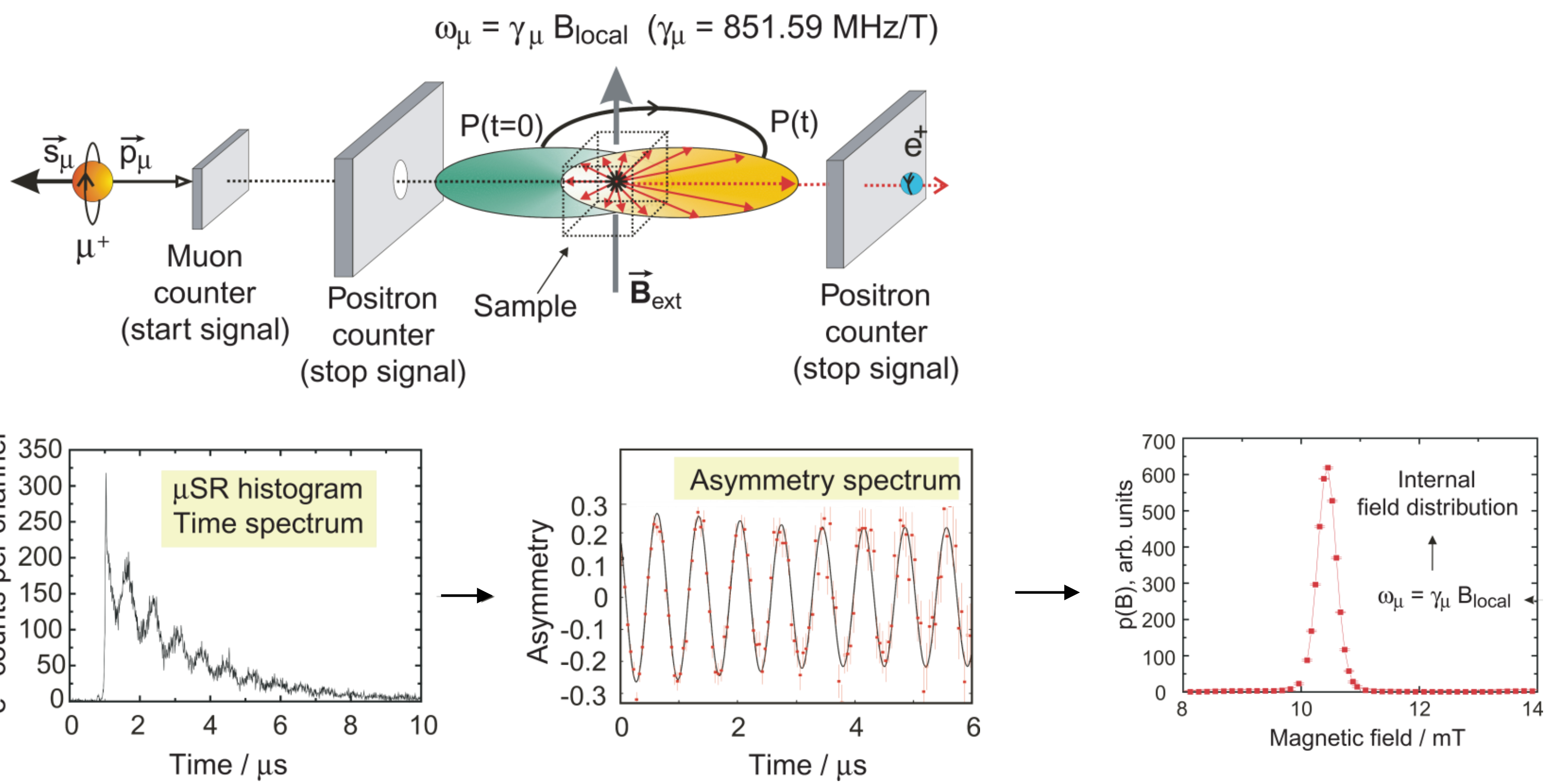


Here $\lambda_1 = 201$ nm, $B_s^{(S)} = 0.84 B_c^{(S)} = 567$ mT

$\lambda_2 = 50$ nm, $B_s^{(\mathrm{Sub})} = 240$ mT

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

Experiment: Low Energy Muon Spin Rotation (LE-μSR)

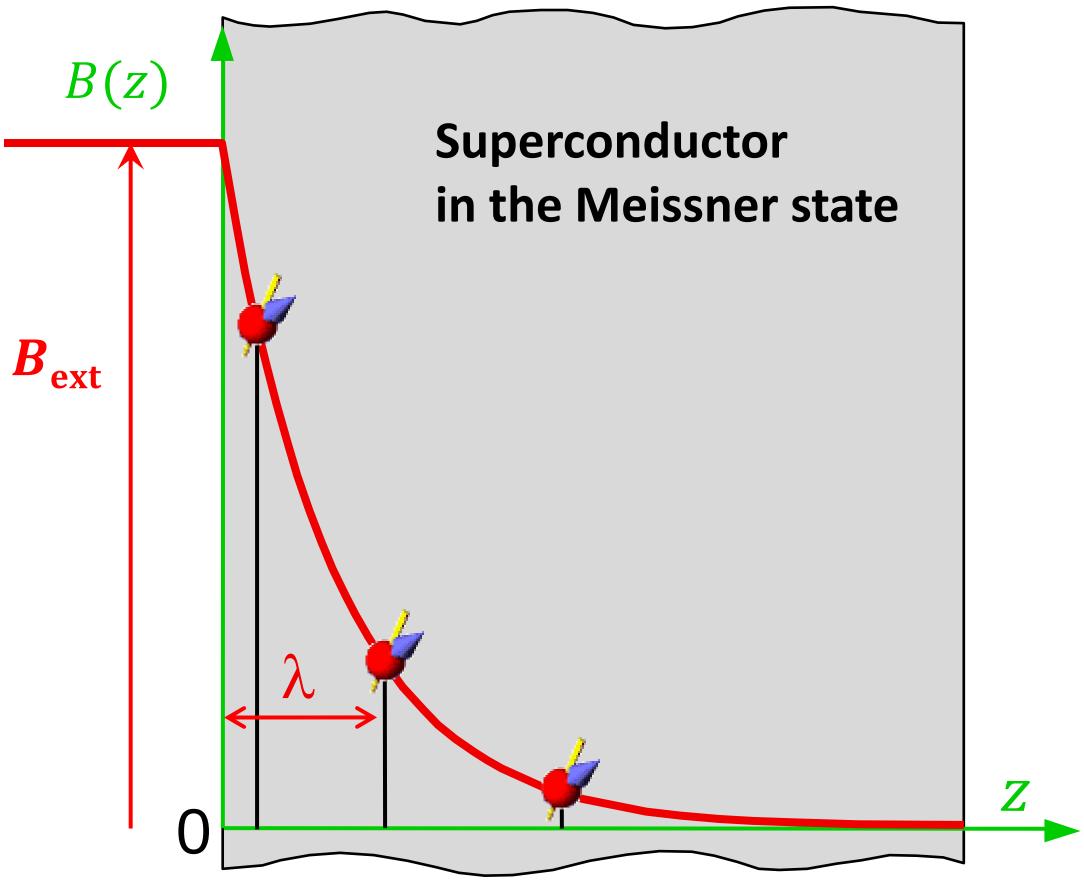


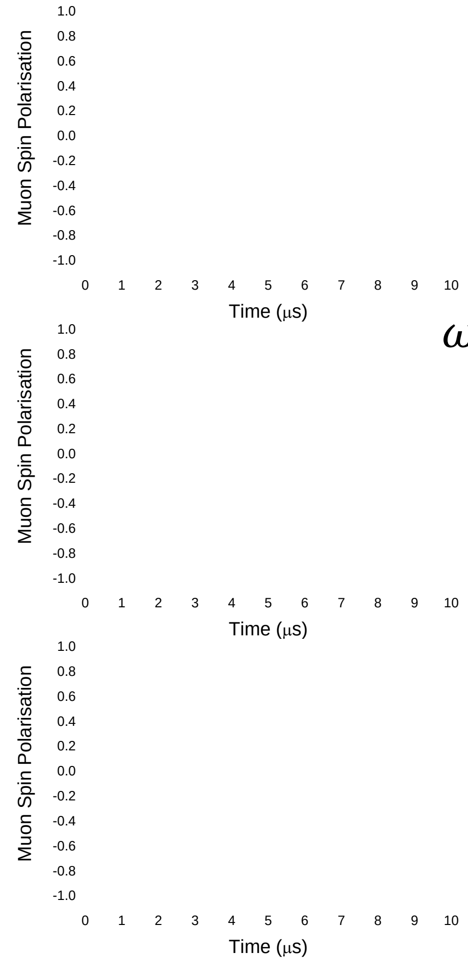
Frequency → **Average local magnetic field**
Damping rate → **The width of the magnetic field distribution**

P Bakule et al., Contemporary Physics, 45:3 (2004)

Experiment: Low Energy Muon Spin Rotation (LE-μSR)

- LE-μSR is a sensitive probe for the detection of the local magnetic field.





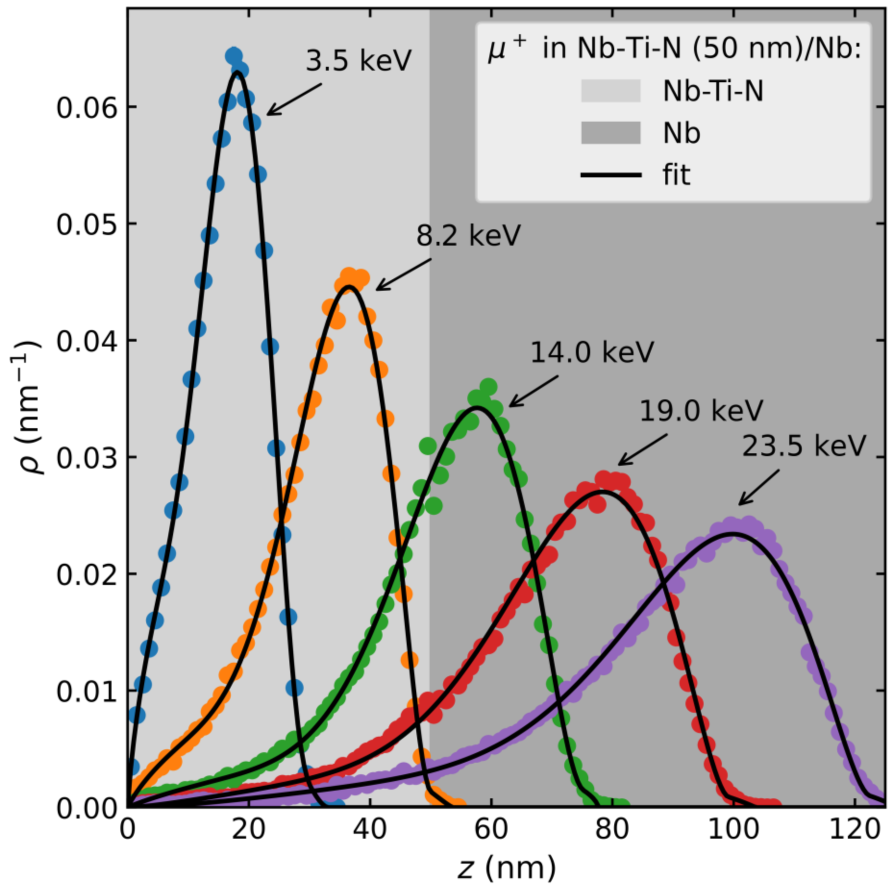
$$\omega_\mu(z) = \gamma_\mu B(z)$$

Frequency → **Average local magnetic field**
Damping rate → **The width of the magnetic field distribution**

LE-μSR has depth resolution over the Meissner screening profile

e.g., Nb-Ti-N (50nm)/Nb stopping profile, simulated using the Monte Carlo code TRIM.SP.

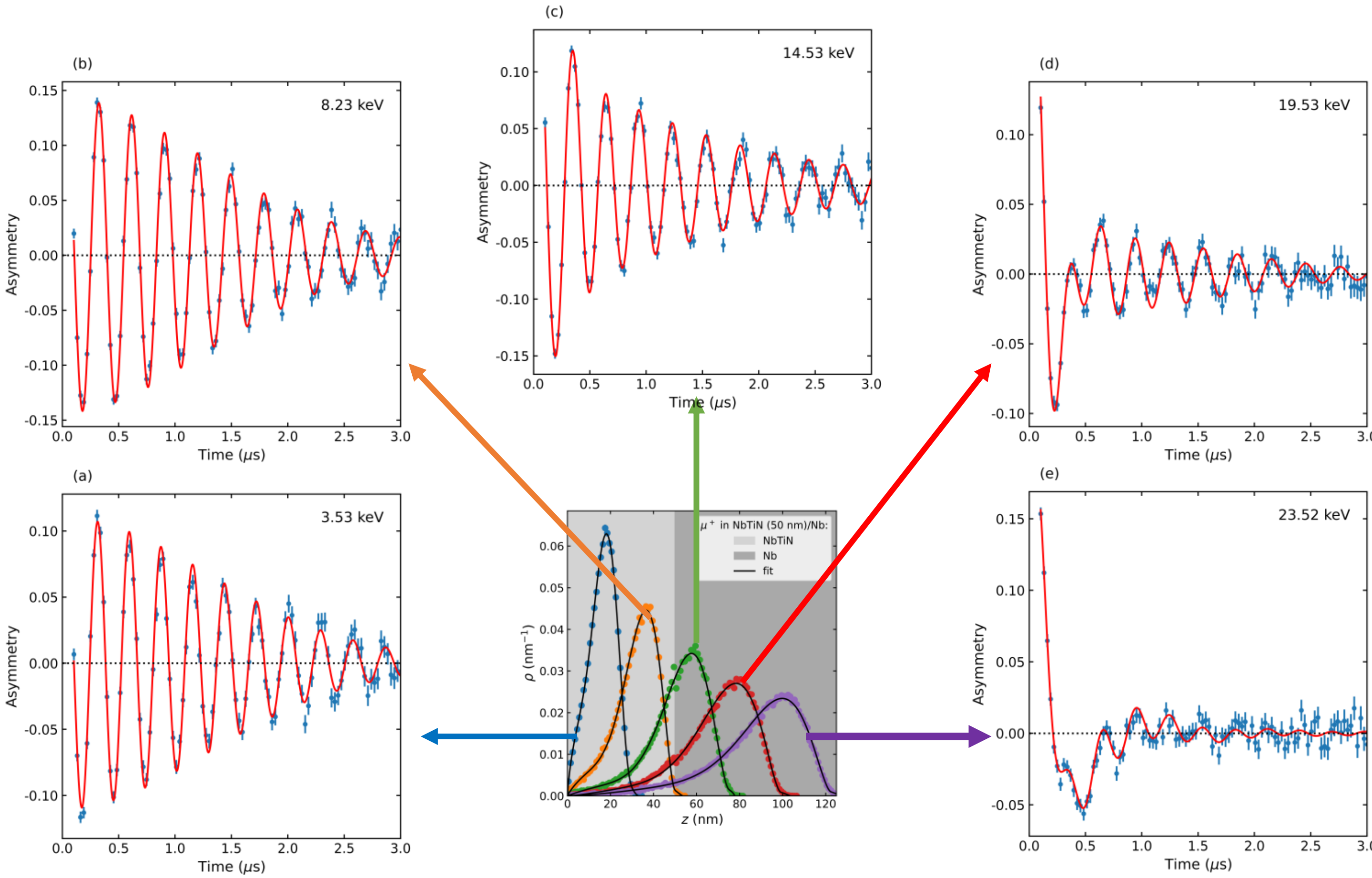
- LE-μSR has depth **resolution** and can thus measure the depth dependent field profile



W. Eckstein, Springer, Berlin, (1991)

Results: LE-μSR time spectra in the Meissner State

Time spectra; $A(t) = A_0P(t)$ in Nb-Ti-N (50 nm)/Nb at $B_0 \approx 250$ G in the Meissner State ($T \approx 2.7$ K)



The asymmetry signal is more strongly damped at high implantation energies in SS bilayers

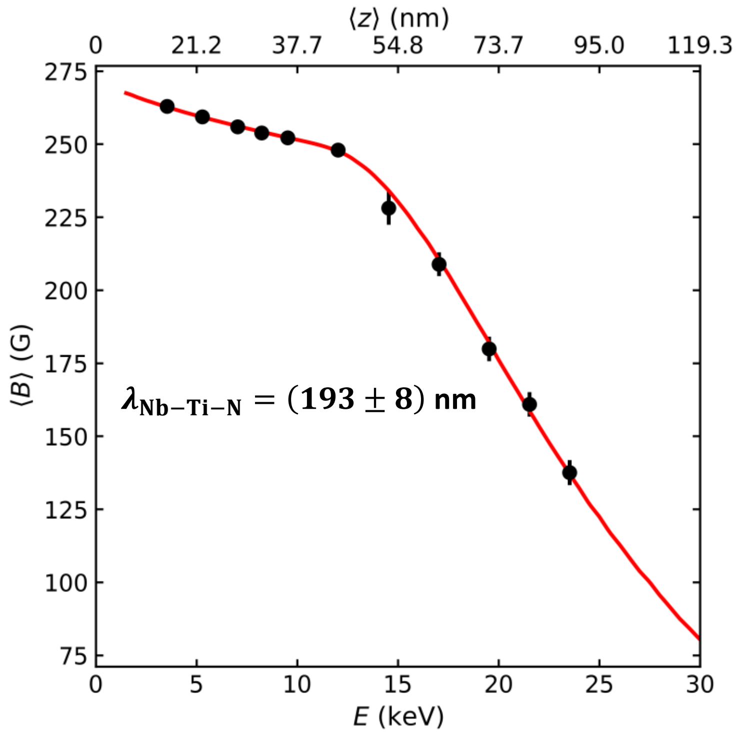
Does the counter current flow model validate the value of $\lambda_{\mathrm{Nb-Ti-N}}$?

Nb-Ti-N (50 nm)/Nb Meissner screening profile

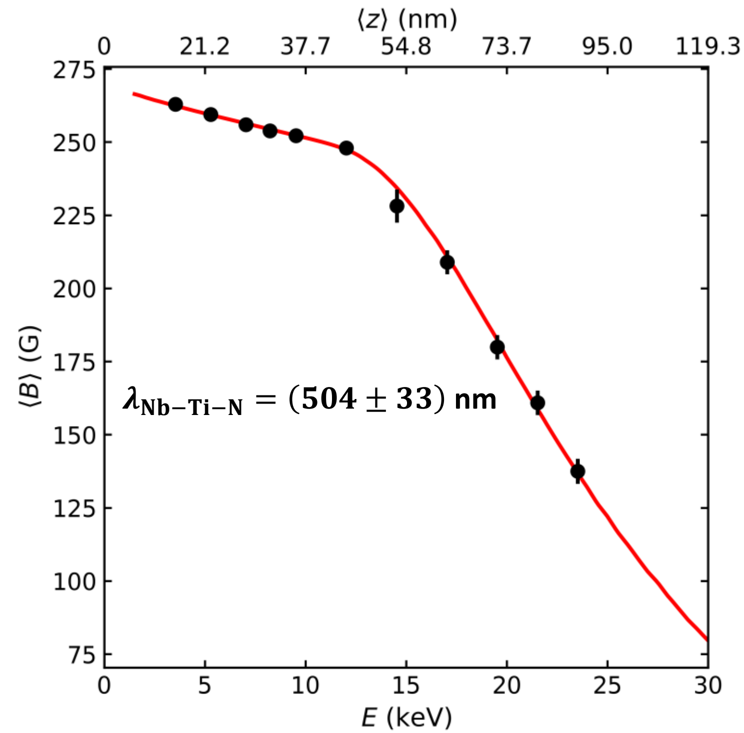
$\lambda_{\mathrm{Nb-Ti-N}} \longrightarrow$ Agrees with the literature!

$\lambda_{\mathrm{Nb-Ti-N}} \longrightarrow$ too large by a factor of ~2.5!

Counter current flow model:



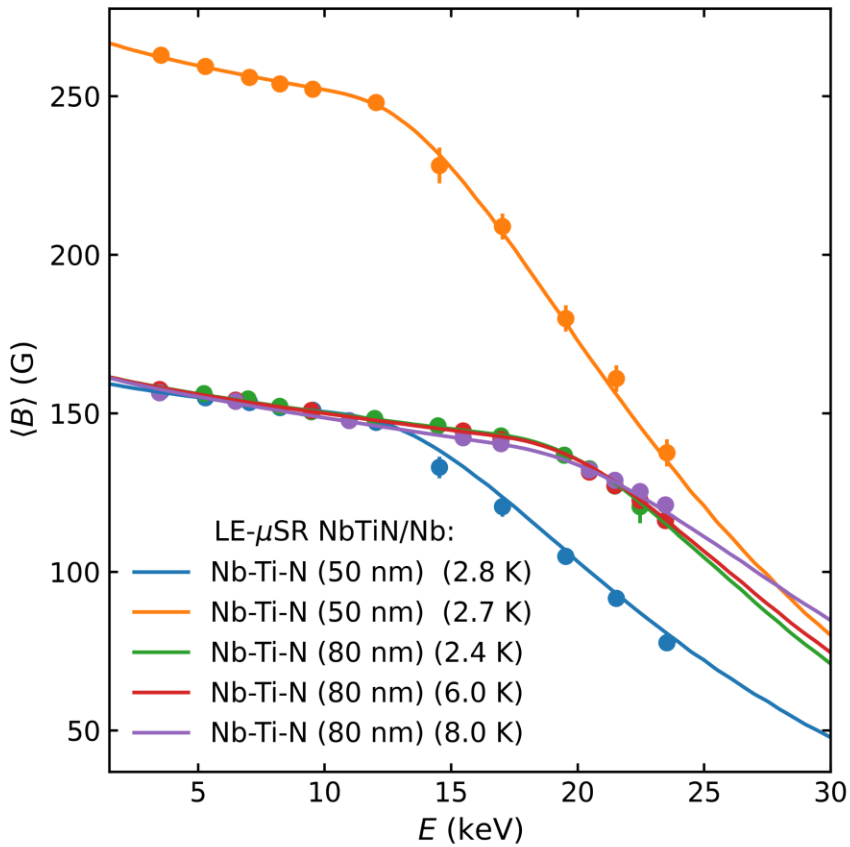
Simple London model:



Justifying the model with other Nb-Ti-N/Nb samples at different T and B_0

Global fit (counter current flow model) to the Meissner screening profile of

- Nb-Ti-N (50 nm)/Nb and
- Nb-Ti-N (80 nm)/Nb



Extracted penetration depths (at 0 K)

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$\boldsymbol{\lambda_{\mathrm{Nb-Ti-N}} = (201 \pm 4)\ \mathrm{nm}}$
$\boldsymbol{\lambda_{\mathrm{Nb}} = (50.4 \pm 2.2)\ \mathrm{nm}}$

Extracted film thicknesses

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$\boldsymbol{d_{\mathrm{Nb-Ti-N}} = (56.3 \pm 0.9)\ \mathrm{nm}}$ [50 nm]
$\boldsymbol{d_{\mathrm{Nb-Ti-N}} = (83.3 \pm 0.8)\ \mathrm{nm}}$ [80 nm]

Predicted $B_{\max}$ in SS bilayers

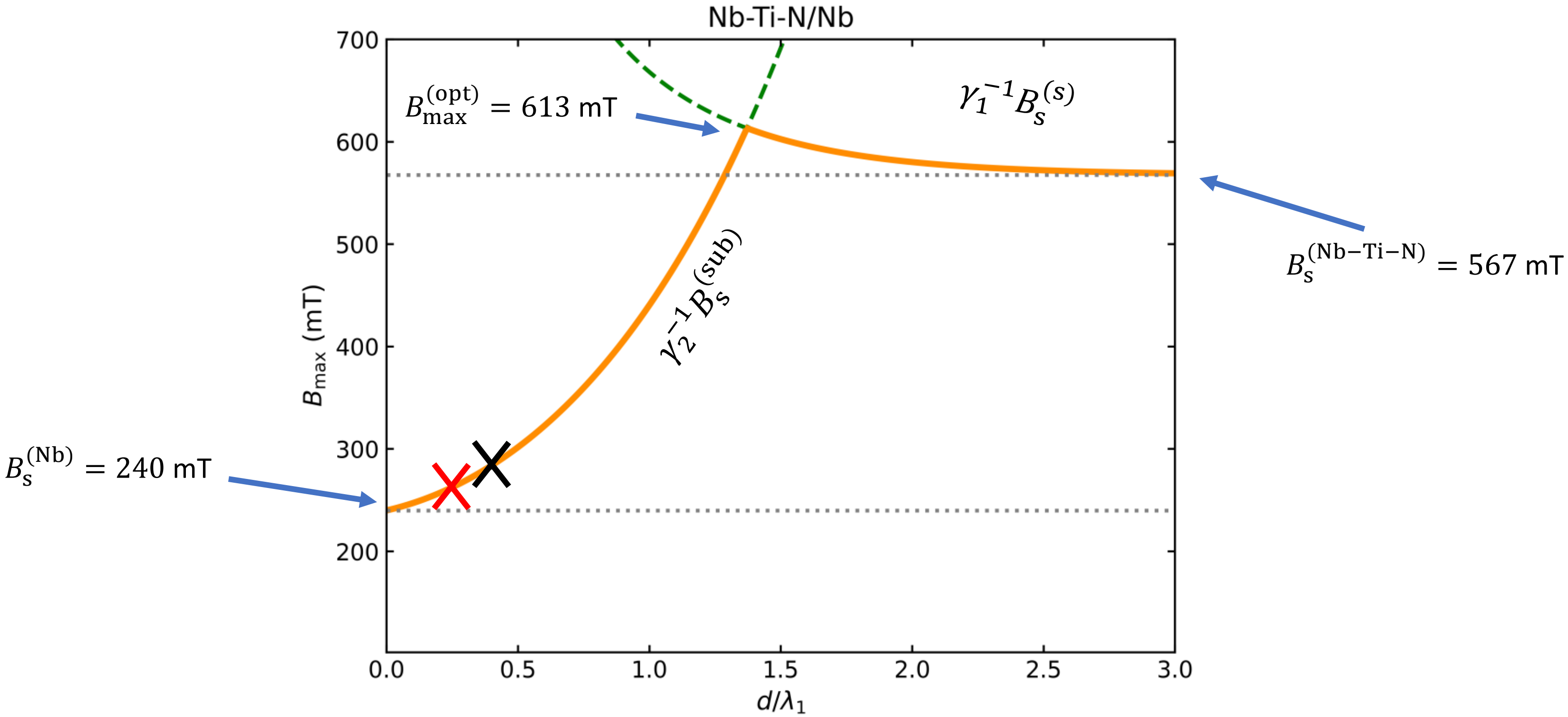
Based on our experimental result

$\times \rightarrow$ 50 nm Nb-Ti-N = 262 mT

$\times \rightarrow$ 80 nm Nb-Ti-N = 284 mT

Here $\lambda_1 = 201$ nm, $B_s^{(S)} = 0.84 B_c^{(S)} = 567$ mT

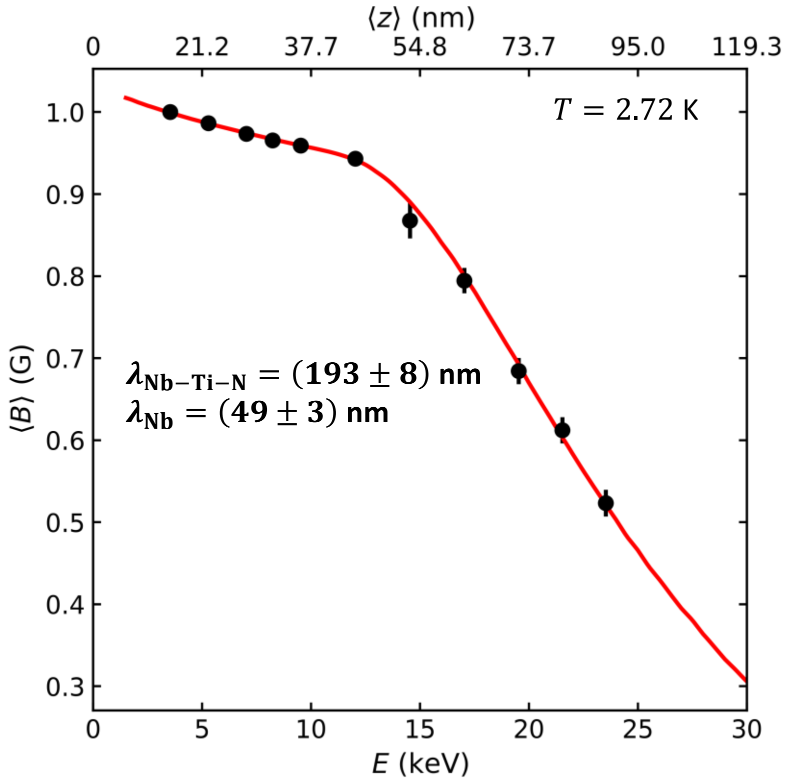
$\lambda_2 = 50$ nm, $B_s^{(Sub)} = 240$ mT



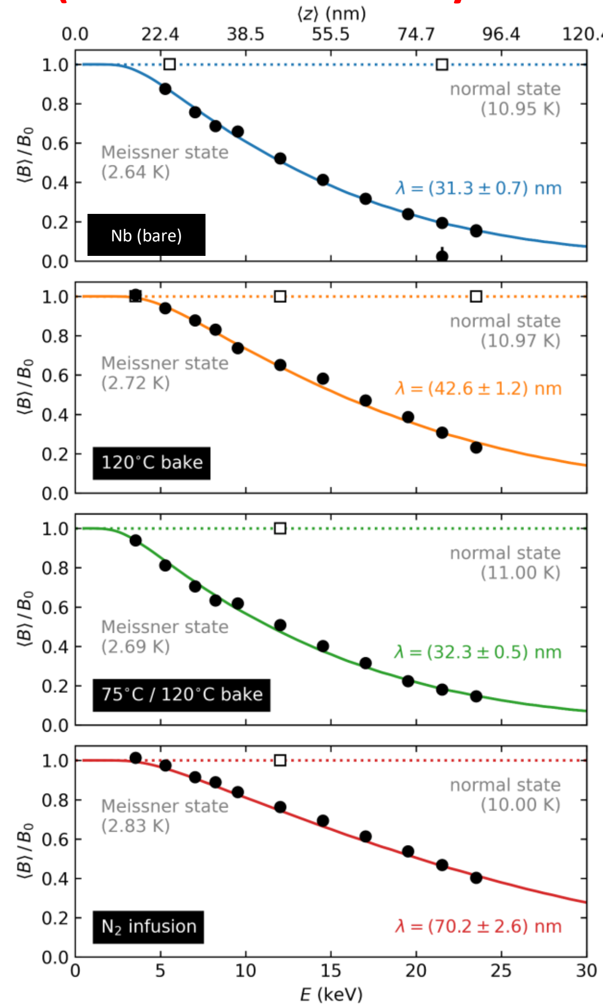
T. Kubo, Supercond. Sci. Technol. 30 023001 (2017)

Does low temperature baked Nb produce an effective bilayer?

Nb-Ti-N/Nb



Nb (Heat and chemically treated)



Summary

- We used LE-μSR to measure the Meissner screening profile into SS bilayers.

- Fits of our data to counter current flow model yielded $\lambda_{\mathrm{Nb-Ti-N}}$ in good agreement with the literature in contrast to a naïve (bi)exponential model.

- The results imply the validity of counter current flow model in SS bilayers and that they are a viable means of exceeding the Nb field limits.

- We did not observe bilayer behavior in Low Temperature Baked Nb. Meissner state field screening profile is just an exponential.

Thank you
Questions?