Progress in understanding magnetic-flux-entry in coated Nb using β-detected NMR

Ryan M. L. McFadden

TRIUMF

4004 Wesbrook Mall, Vancouver, BC V6T 2A3

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WG-1: Latest Activities on High-G and High-Q Performances

Session 2 — Surface Processing R&D

2026-06-09

TESLA TECHNOLOGY TTC COLLABORATION

Outline

Outline

Motivation

β-NMR Experiment

Results

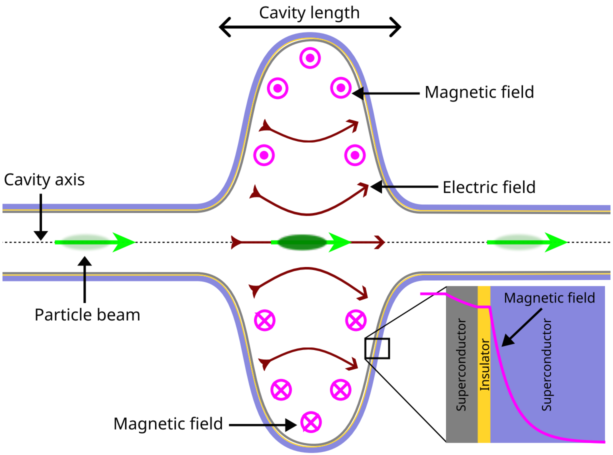
Summary

Motivation: use *multilayer* coatings for higher $E_{acc.}$

e.g., a superconductor-insulator-superconductor (SIS) cavity

Potential benefits:

- Top layer "damps" magnetic flux before reaching the substrate.
- Buried interface provides an "extra" (Bean-Livingston-like) energy barrier.
- Insulating layer intoduces a "short" for flux-travel above the substrate.



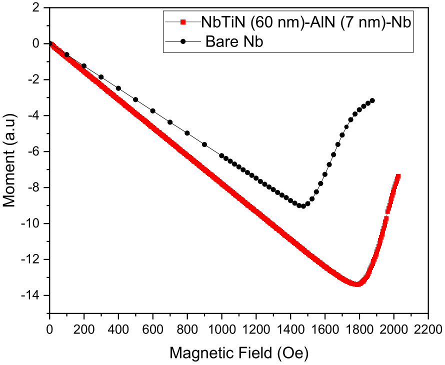
see, e.g.:

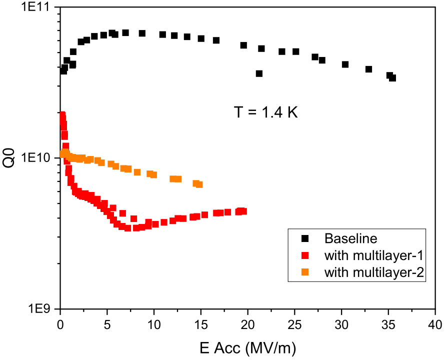
A. Gurevich, Appl. Phys. Lett. **88**, 012511 (2006)
T. Kubo, Supercond. Sci. Technol. **30**, 023001 (2017)

Image credit:
M. Asaduzzaman

Problem: *contradictory* behaviour in different settings?

e.g., $Nb_{1-x}Ti_xN$(x nm)/AlN(7 nm)/Nb [$x = 50$ nm or 60 nm]





Magnetometry	$Nb_{1-x}Ti_xN$(60 nm)/AlN(7 nm)/Nb	RF tests	$Nb_{1-x}Ti_xN$(50 nm)/AlN(7 nm)/Nb
✔	[ellipsoid]	✘	[1.3 GHz cavity]

Y. Kalboussi et al., in Proceedings of SRF'23, International Conference on RF Superconductivity 21 (Sept. 2023), pp. 615–620

Proposal: study flux-entry at the *nanoscale*!

Using ^{8}Li β-NMR & TRIUMF's *purpose-built* "β-SRF" instrument!

Review of Scientific Instruments — ARTICLE — scitation.org/journal/rsi

A new high parallel-field spectrometer at TRIUMF's β-NMR facility

Cite as: Rev. Sci. Instrum. **94**, 023305 (2023); doi: 10.1063/5.0137368
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Edward Thoeng,[1,2,a)] Ryan M. L. McFadden,[2,3,a)] Suresh Saminathan,[2] Gerald D. Morris,[2] Philipp Kolb,[2] Ben Matheson,[2] Md Asaduzzaman,[2,3] Richard Baartman,[2] Sarah R. Dunsiger,[2,4] Derek Fujimoto,[1,5,b)] Tobias Junginger,[2,3] Victoria L. Karner,[5,6,b)] Spencer Kiy,[2] Ruohong Li,[2] Monika Stachura,[2,7] John O. Ticknor,[5,6] Robert F. Kiefl,[1,2,5] W. Andrew MacFarlane,[2,5,6] and Robert E. Laxdal[2,3,a)]

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Depth-resolved characterization of Meissner screening breakdown in surface treated niobium

Edward Thoeng[1,2✉], Md Asaduzzaman[1,3], Philipp Kolb[1], Ryan M. L. McFadden[1], Gerald D. Morris[1], John O. Ticknor[4,5], Sarah R. Dunsiger[1,6], Victoria L. Karner[1], Derek Fujimoto[1], Tobias Junginger[1,3], Robert F. Kiefl[1,2,5], W. Andrew MacFarlane[1,4,5], Ruohong Li[1], Suresh Saminathan[1] & Robert E. Laxdal[1]

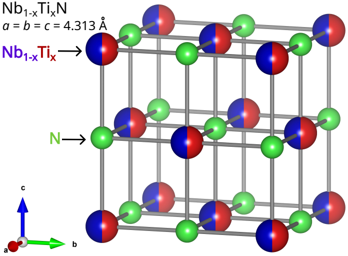
E. Thoeng et al., Rev. Sci. Instrum. **94**, 023305 (2023)
E. Thoeng et al., Sci. Rep. **14**, 21487 (2024)
E. Thoeng, PhD Thesis (University of British Columbia, Vancouver, BC, 2025)

TRIUMF's β-NMR facility — home to two dedicated instruments;
"β-SRF" is located in the rightmost cage!

Outline

Samples: $Nb_{0.75}Ti_{0.25}N$(91 nm)/AlN(4 nm)/Nb

Grown by thermal atomic layer deposition (ALD) — for good conformal coating

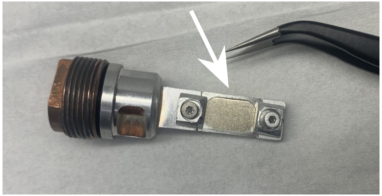


Cubic *B*1 (rocksalt) structure; spacegroup No. 225 ($Fm\bar{3}m$).

Flat sample dimensions:

8 mm × 12 mm × 0.5 mm

✔ Studied previously using β-NMR!

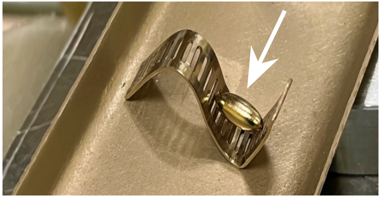


↑ Mounted in holder for β-NMR.

Ellipsoid sample diameters:

10 mm × 4 mm × 4 mm

Focus of this work!



↑ Resting in synthesis holder.

see, e.g.:

Y. Kalboussi, PhD thesis (Université Paris-Saclay, Orsay, 2023)
M. Asaduzzaman et al., J. Phys.: Condens. Matter **37**, 395701 (2025)

Samples provided by:

Y. Kalboussi, I. Curci, and T. Proslier
@ CEA Saclay

Experiment: ^{8}Li β-NMR *setup*

β-NMR ≡ beta-radiation-detected nulcear magnetic resonance

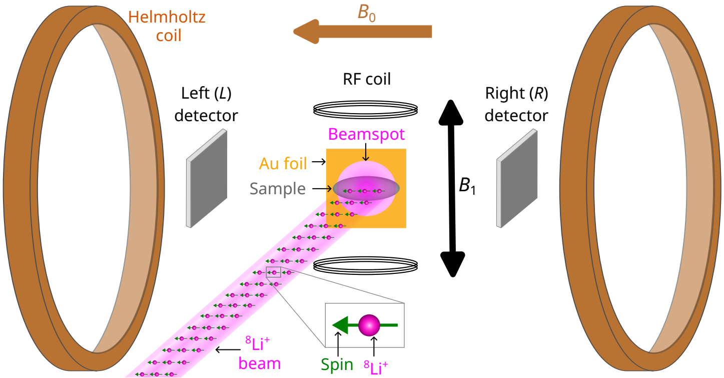


Image credit:
M. Asaduzzaman

^{8}Li properties:

- Nuclear spin $I = 2$.
- Radioactive lifetime $\tau = 1.21\,\mathrm{s}$.
- β-rays (electrons) are emitted *anti-parallel* spin direction!

Measurement details:

- Apply static field B_0 parallel sample's semi-major axis.
- Implant ^{8}Li^{+} in $Nb_{0.75}Ti_{0.25}N$ layer (and surrounding gold foil).
  - Mean stopping depth $\approx 26\,\mathrm{nm}$
- *Resonantly manipulate* ^{8}Li spins using *transverse* RF field B_1.
- Monitor β-decay *asymmetry* in left/right detectors at different RF frequencies ν.

Experiment: ^{8}Li β-NMR *data*

Anatomy of the measured signal

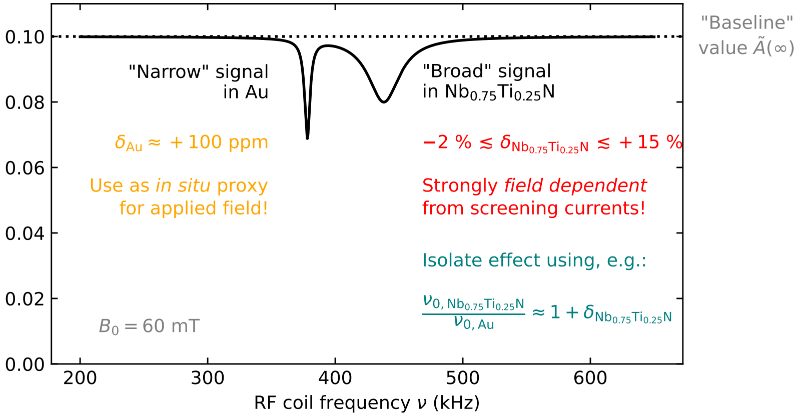
Resonance position:

$$\nu_{0,i} = \gamma_{^{8}\mathrm{Li}} B_0 (1 + \delta_i)$$

$\gamma_{^{8}\mathrm{Li}}$ is ^{8}Li's gyromagnetic ratio
B_0 is the applied field
δ_i is the NMR "shift"

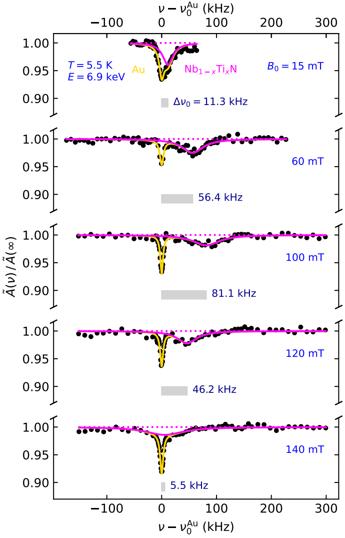
^{8}Li β-decay Asymmetry

$$\tilde{A}(\nu) = \frac{L(\nu) - R(\nu)}{L(\nu) + R(\nu)}$$



Outline

Results: field in $Nb_{0.75}Ti_{0.25}N$ is *highly* sensitive to B_0



Measurement protocol:

Zero-field-cool to 5.5 K.

Qualitative findings:

Resonance in $Nb_{0.75}Ti_{0.25}N$ *broadens* with increasing B_0.

Changes are *monotonic*.

Resonance in $Nb_{0.75}Ti_{0.25}N$ *shifts* with increasing B_0.

Changes are *non-monotonic*.

Interpretation:

flux-entry into *film*!

flux-entry into *film & substrate*!

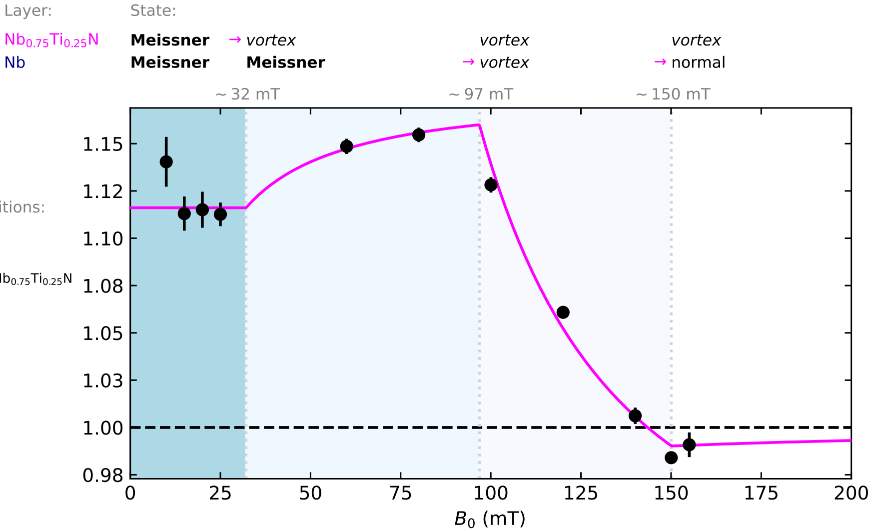
Results: flux-entry is *resolved for each layer*!

Ratio of resonance positions:

$$\frac{\nu_{0,\,\mathrm{Nb_{0.75}Ti_{0.25}N}}}{\nu_{0,\,\mathrm{Au}}} \approx 1 + \delta_{\mathrm{Nb_{0.75}Ti_{0.25}N}}$$

Measurement conditions:

$T = 5.5$ K
$E = 6.9$ keV



Outline

Summary

✓ Technique development

Used ^{8}Li β-NMR to study flux-entry in an SIS *multilayer*!

✓ Novel information

Sensed *first-flux-entry* with *layer-by-layer* resolution!

Future applications

- ? Importance of *insulating* layer?

  e.g., directly compare SS and SIS equivalents

- ? Nature of *vortices* in SIS structure?

  i.e., use *depth-resolution* to look for "pancakes"

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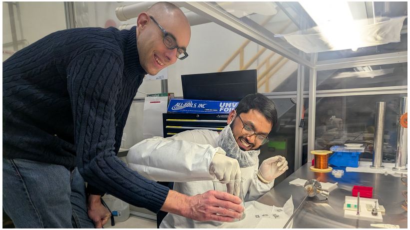
L. Wallace	G. D. Morris	J. O. Ticknor	I. Curci
	R. Li		
	I. McKenzie		



Main contributors

- ★ T. Juginger (*left*)
- ★ M. Asaduzzaman (*right*)

← Preparing samples / holder for the β-NMR experiment.

Thanks!

(end of slides)

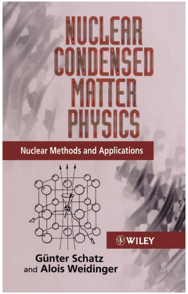
Outline

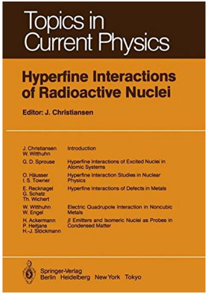
Nuclear-decay spin-probe techniques

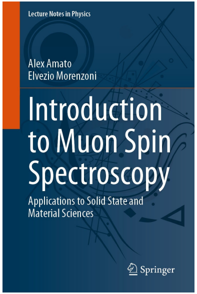
Advantages over “conventional” approaches for interrogating matter

- ✔ High-energy radiation (e.g., β-decay products) is easy to detect. ☢
- ✔ Spin-probes sense the electromagnetic “weather” of their local environment.
- ✔ Ion-implanted variants have added spatial sensitivity.

- ★ μSR
- ★ β-NMR
- Mössbauer
- PAC
- etc. . .







Comparison of magnetic resonance techniques

Both LE-μSR and ^{8}Li β-NMR have *enhanced sensitivity* and *depth-resolution* on the nanoscale!

	"conventional" NMR	μSR / LE-μSR	^{8}Li β-NMR
Polarization	$\ll 1\,\%$	~100 %	~70 %
Probe	any stable nucleus non-zero spin (e.g., ^{1}H)	μ^{+}	^{8}Li
Detection method	electromagnetic	anisotropic β-decay	anisotropic β-decay
Sensitivity	$\sim 10^{17}$ spins	$\sim 10^{7}$ spins	$\sim 10^{7}$ spins
Spin	1/2 (e.g., ^{1}H)	1/2	2
Lifetime	∞ s	2.2 μs	1.21 s
$1/T_1$ range	any *	$\sim 10^{4}$–$10^{8}\,\mathrm{s}^{-1}$	$\sim 10^{-2}$–$10^{2}\,\mathrm{s}^{-1}$
Depth range	N/A	~100 μm / 10–200 nm	5–150 nm

SRF materials research using μSR and β-NMR

Overview of capabilities

TABLE 1 Measurement capabilities relevant to SRF studies of surface μSR, LE-μSR, and β-NMR.

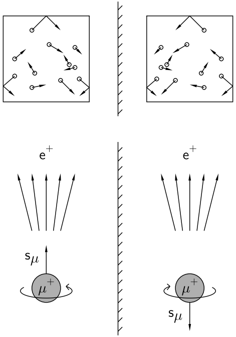
Technique	Max parallel B field [mT]	Implantation depth in niobium	Measurement capabilities relevant to SRF
Surface μSR (TRIUMF)	300	Approximately 130 μm (fixed)	Pinning strength
			Field of first vortex penetration
LE-μSR (PSI)	30	Approximately 10–100 nm (variable)	Magnetic screening
			Hydrogen diffusion
			Magnetic impurities
β-NMR TRIUMF	200	Approximately 10–100 nm (variable)	Vortex penetration in the London layer

T. Junginger et al., Front. Electron. Mater. **4**, 1346235 (2024)

β-decay violates *parity*

e.g., mirror-plane symmetry

Real world Mirror world



Gas collisions in a container — Each occurs in nature

Muon decay:

$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ — Mirror process does not occur!

Mirror plane

S. J. Blundell, Contemp. Phys. **40**, 175 (1999)

β-rays are emitted *anisotropically*

Direction depends on emitter's spin-direction (or polarization)

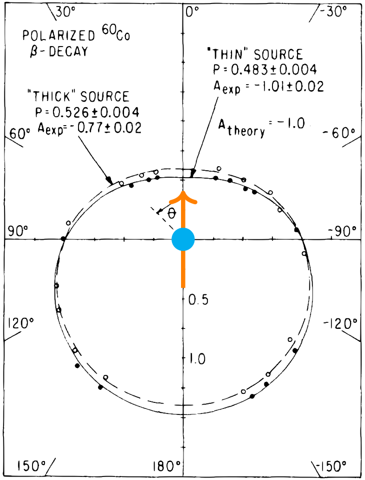
Example: β-decay of cobalt-60:

$$^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni}^{*} + e^{-} + \tilde{\nu}_{e}$$

Angular e^{-} emission probability:

$$W(\theta) \approx 1 + A_{\beta} P \cos\theta$$

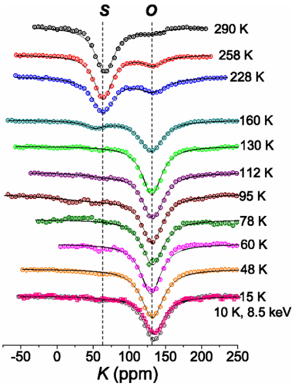
Use β-emissions to monitor probe's spin orientation!

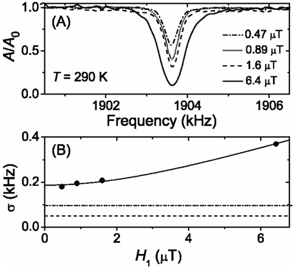


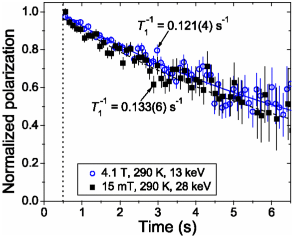
L. M. Chirovsky et al., Phys. Lett. B **94**, 127 (1980)

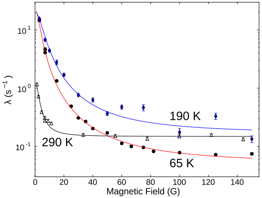
Au is an *excellent* contrast material

^{8}Li β-NMR in Au has narrow resonance(s) & slow, field-independent relaxation above ∼15 mT









T. J. Parolin et al., Phys. Rev. B **77**, 214107 (2008)
T. J. Parolin et al., Phys. Rev. B **100**, 209904 (2019)

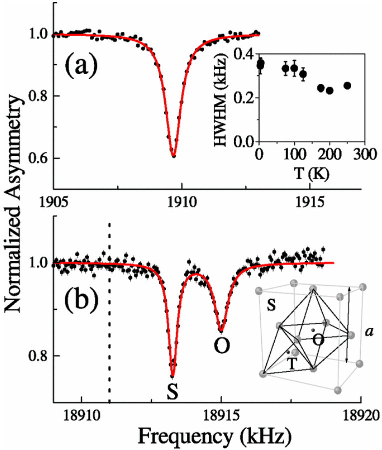
W. A. MacFarlane et al., JPS Conf. Proc. **21**, 011020 (2018)

Spectral resolution in β-NMR is *field-dependent*

e.g., ^{8}Li β-NMR in Ag(50 nm)/$SrTiO_3$ @ 5 keV

Peaks are unresolved in *low applied field*...

...but become well-separated in *high applied field*!



Measurement conditions:

0.3 T

4 K

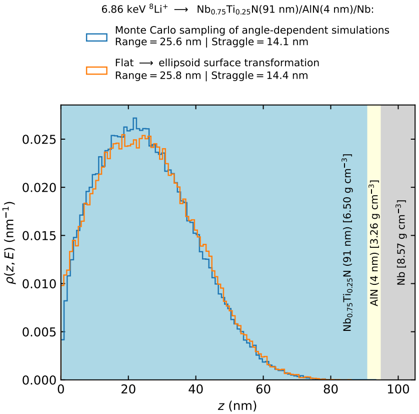
3.0 T

145 K

G. D. Morris et al., Phys. Rev. Lett. **93**, 157601 (2004)

$^{8}Li^{+}$ implantation in $Nb_{0.75}Ti_{0.25}N$(91 nm)/AlN(4 nm)/Nb

Simulations predict a mean stopping depth of ∼26 nm

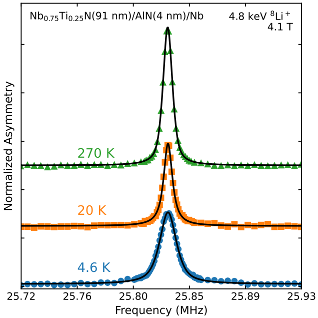


SRIM Monte Carlo code http://www.srim.org/

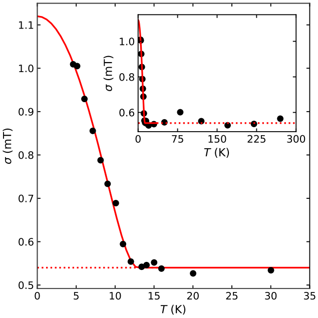
J. F. Ziegler et al., *SRIM — the stopping and range of ions in matter*, 7th ed. (SRIM Co., Chester, 2008)

^{8}Li β-NMR in the normal/vortex state of $Nb_{1-x}Ti_xN$

$Nb_{0.75}Ti_{0.25}N$(91 nm)/AlN(4 nm)/Nb



Wide resonance; symmetric broadening in vortex state.



Vortex broadening fit using Brandt/Pearl models.

Table 2. Fit parameters describing the temperature dependence of resonance linewidth's Gaussian component σ (shown in figure 4) using equations (5)–(9). Here, $d_{Nb_{0.75}Ti_{0.25}N}$ is the thickness of the $Nb_{0.75}Ti_{0.25}N$ thin film, $T_c(0\,T)$ is the critical temperature at 0 T, $\lambda(0\,K)$ is the penetration depth at 0 K, σ_{nc} is the Gaussian width in the nc state, B_0 is the applied magnetic field, and $B_{c2}(0\,K)$ represents the upper critical field at 0 K. Both $d_{Nb_{0.75}Ti_{0.25}N}$ and B_0 were determined independently and fixed during fitting.

Parameter	Value	Unit	Comment
$d_{Nb_{0.75}Ti_{0.25}N}$	91	nm	Fixed (from section 2.1)
$T_c(0\,T)$	15.4(7)	K	
$\lambda(0\,K)$	180.57(30)	nm	
σ_{nc}	540.1(19)	μT	
B_0	4.1	T	Fixed (from section 2)
$B_{c2}(0\,K)$	18(4)	T	

T_c, B_{c2}, and λ identified from fit; agree with independent measurements!

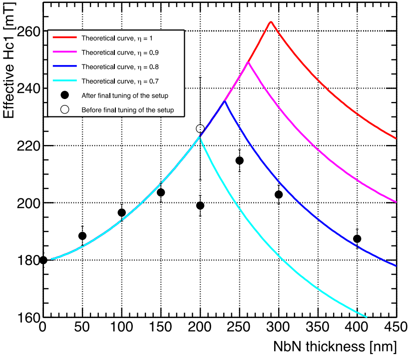
see, e.g.:

J. Pearl, Appl. Phys. Lett. **5**, 65 (1964)
E. H. Brandt, Phys. Rev. B **68**, 054506 (2003)

M. Asaduzzaman et al., J. Phys.: Condens. Matter **37**, 395701 (2025)

Importance of film quality in SIS structures?

e.g., $NbN(x\ nm)/SiO_2(30\ nm)/Nb$ [$x = 50$ nm to 400 nm]



← Results from 3rd harmonic measurements ($H_{c1} = 180$ mT assumed for "bare" Nb).

Presence of *imperfections* in the film (e.g., impurities, topographics defects, etc.) can stifle *ideal* behaviour.

Phenomenon can be quantified *ad hoc* by a *suppression factor* $0 \leq \eta \leq 1$.

How generic is this finding?

Experiment:

H. Ito et al., in Proceedings of SRF'19, International Conference on RF Superconductivity 19 (Aug. 2019), pp. 632–636

Theory:

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

Comparison of atomic layer deposition (ALD) types

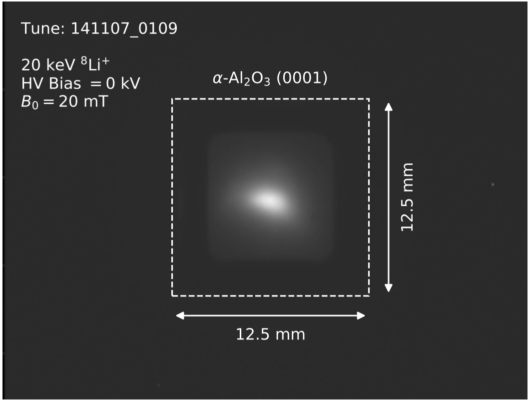
Thermal ALD provides *excellent* surface coverage for SRF sample geometries

ALD Process Type	Uniformity & Conformality	Substrate Compatibility	Process Throughput & Scalability	Coating superconducting films		
				Advantage	Disadvantage	Materials
Thermal ALD	⭐⭐⭐⭐	🔵 Robust substrates	⏳ Moderate	✅ Excellent coverage on complex shapes	❌ High temp. can degrade sensitive materials	TiN, NbN, NbSi, NbC, NbTiN, CuO, MoN, MoC
Plasma Enhanced ALD (PEALD)	⭐⭐⭐	🔵 Temperature-sensitive	⏳ Moderate	✅ Low-temp. deposition	❌ Plasma may damage substrates	TiN, NbN, NbTiN, MoCN, TaCN, LaSrCuO
Spatial ALD	⭐⭐	🔵 Large-area substrates	🚀 High	✅ Ideal for large-scale production	❌ Lower film thickness control	-
Hot-Wire ALD (HWALD)	⭐⭐	🔵 Temperature-sensitive	⏳ Moderate	✅ Low-temp, good for sensitive materials	❌ Risk of wire contamination	-
Area-Selective ALD (ASALD)	⭐⭐⭐⭐	🔵 Complex geometries/patterns	🐢 Low	✅ High-resolution patterning, multi-layering	❌ Complex, costly, preparation intensive	-

G. K. Deyu et al., Mater. Horiz. **12**, 5594 (2025)

$^{8}Li^{+}$ beamspots

Imaged using *scintillation* from a sapphire plate & a charge-coupled device (CCD) camera



see, e.g.:

R. M. L. McFadden, PhD Thesis (University of British Columbia, Vancouver, BC, 2020)