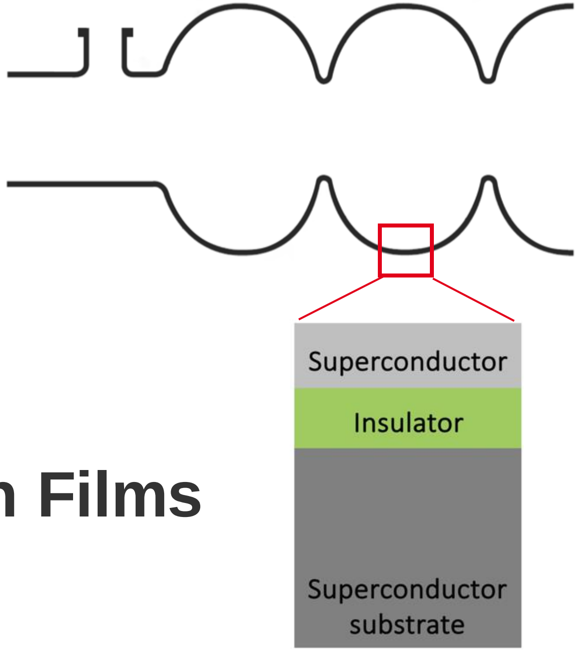
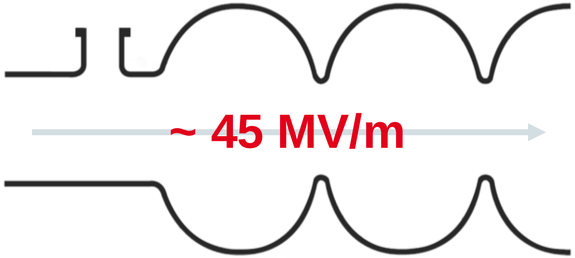


Characterization of PEALD Coated Thin Films for SRF Cavity Research

Lea Preece - on behalf of the SRF R&D Team Hamburg

11th International Workshop on Thin Films and and New Ideas for Pushing the Limits of RF Superconductivity – TFSRF2024 – Sept. 19, 2024

Motivation



- SRF cavities approach thermodynamic limit of niobium
- **Superconductor-Insulator-Superconductor (SIS) multilayers**
  - Theory shows **potential to enhance E_{acc}** and achieve lower rf losses
- SIS coating of cavities creates new **challenges**
  - Experimental realization
  - Material properties of thin multilayer systems

Motivation

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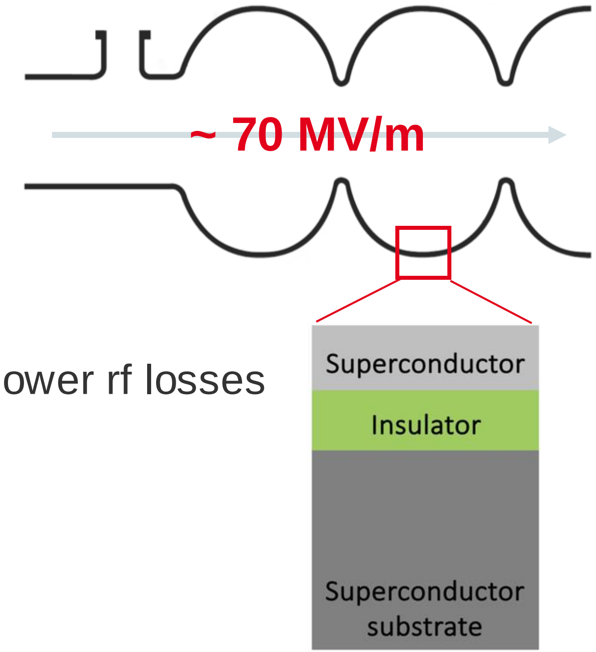
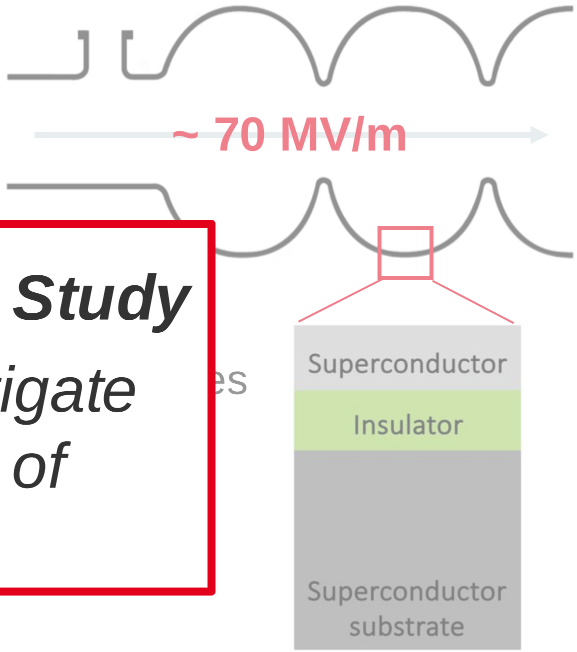


Motivation

- SRF cavities approach thermodynamic limit of niobium
- **Superconductor** ... **multilayers**
  - Theory show ... es
- SIS coating of ca
  - Experimenta
  - Material properties of thin multilayer systems

Magnetic Characterization Study

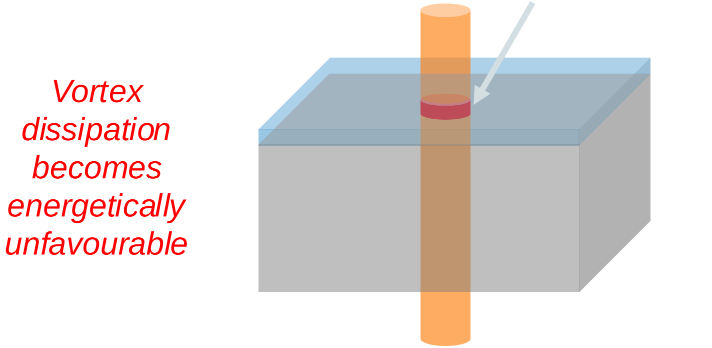
⇛ comprehensively investigate the magnetic properties of SIS layers



Thin Films and Screening Currents

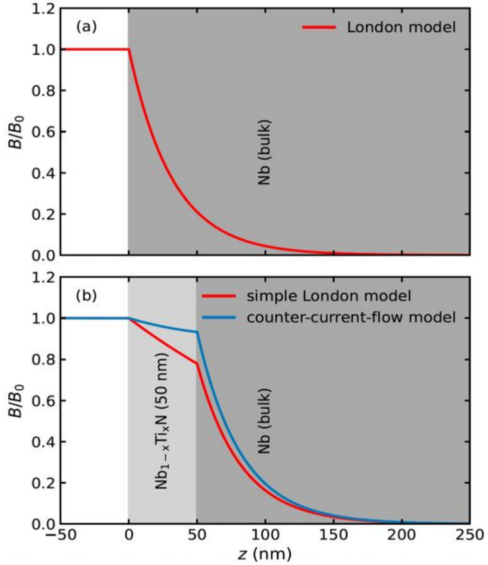
References:
A. Gurevich, APL 88 (2006),
T. Kubo, SUST 30 (2017)

- *Gurevich:* Vortices are energetically supressed in SC thin films for $d < \lambda_L$



- Insulator as vortex barrier so that global vortex penetration is prevented

- *Kubo:* Vortex penetration shifts to $H_{sh} > H_{C1}$ through "**counter current**" at interfaces



[Asaduzzaman M. et al., Direct measurement of the Meissner screening profile in superconductor-superconductor bilayers using low-energy muon spin rotation (2023)]

SIS Multilayer Theory

Reference:
T. Kubo, SUST 30 (2017)

- Top superconductor sees majority of rf field
  → **Surface resistance improves**
- Insulating layer creates more interfaces
  → **More counter currents**
- Layers must be thinner than $\lambda_{L,Top}$
  → **RF field is affected by counter currents**

<u>Theoretical maximum surface field a SIS coated cavity can withstand:</u>

$$H_{\max} = \min\{\tilde{\gamma}_1^{-1} H_{\mathrm{sh,S}}, \tilde{\gamma}_2^{-1} H_{\mathrm{sh,sub}}\}$$

$$\tilde{\gamma}_1 = \frac{\sinh\frac{d_S}{\lambda_S} + \frac{\lambda_{\mathrm{sub}}+d_I}{\lambda_S}\cosh\frac{d_S}{\lambda_S}}{\cosh\frac{d_S}{\lambda_S} + \frac{\lambda_{\mathrm{sub}}+d_I}{\lambda_S}\sinh\frac{d_S}{\lambda_S}}$$

$$\tilde{\gamma}_2 = \frac{1}{\cosh\frac{d_S}{\lambda_S} + \frac{\lambda_{\mathrm{sub}}+d_I}{\lambda_S}\sinh\frac{d_S}{\lambda_S}}$$

→ Optimal layer thickness d_S depends on λ_L and H_{C1} of the used bulk and layer materials

Literature values

Niobium (9.27 K)

cubic high-T_c superconductors **NbN** (17.3 K) and **NbTiN** (17.8 K)
AlN as insulator

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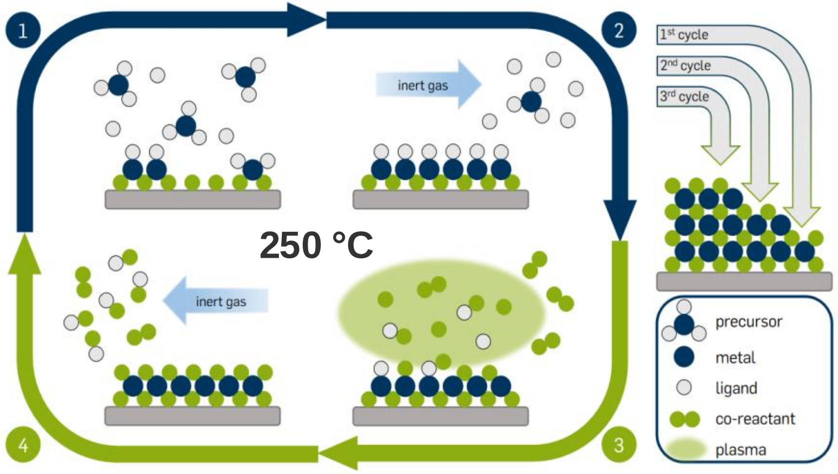
Sample Preparation

Plasma-Enhanced Atomic Layer Deposition (PEALD)

Precursors:
TMA (AlN),TDMAT (TiN), TBTDEN (NbN)

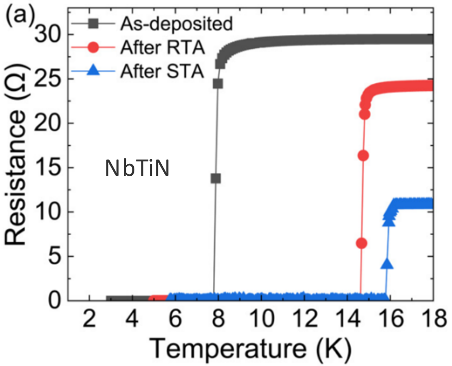


Plasma mix of H_2 and N_2

[L. Mai, DOI: 10.13154/294-7658 (2020)]

Post-Deposition Annealing to improve T_C and H_{C1}

- Recrystallisation and degas of impurities



$\mu_0 H_{C1}$ = 15 mT
$\mu_0 H_{C1}$ = 81 mT
$\mu_0 H_{C1}$ = 98 mT

$\mu_0 H_{C1,bulk} \approx$ 33 mT

[Gonzalez.I. et al., J. Appl. Phys. 134, 159902 (2023), 035301 (2023)]

900 °C annealing for 1 hour with controlled heating and cooling rates

Characterization Measurements

- **X-Ray Reflectivity (XRR) measurement**
  - Determine the PEALD growth per cycle (GPC)
- **Low Energy Muon Spin Rotation (LE-µSR) measurement**
  - Determine the London penetration depth λ_L
- **T_C measurements**
  - Contactless Inductive T_c measurement on Nb
  - Physical properties measurements on Si (electrical transport, VSM)
- **Magnetic Flux Lens (MFL) measurement**
  - Measure flux expulsion (and T_C)

*See also **Md Asaduzzaman's talk** on „Depth-resolved characterization of superconductor-superconductor bilayer properties beneficial for SRF applications " ealier today*

*See also **Daniel Turner's talk** on „Enhancement of magnetic flux expulsion in multilayer structures" ealier today*

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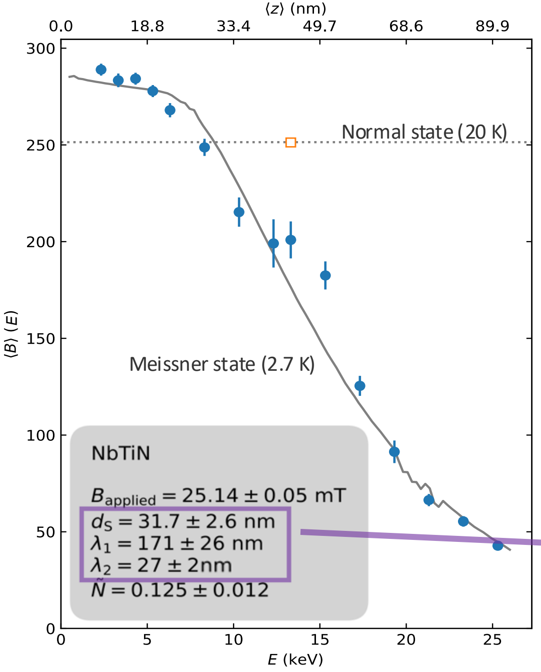
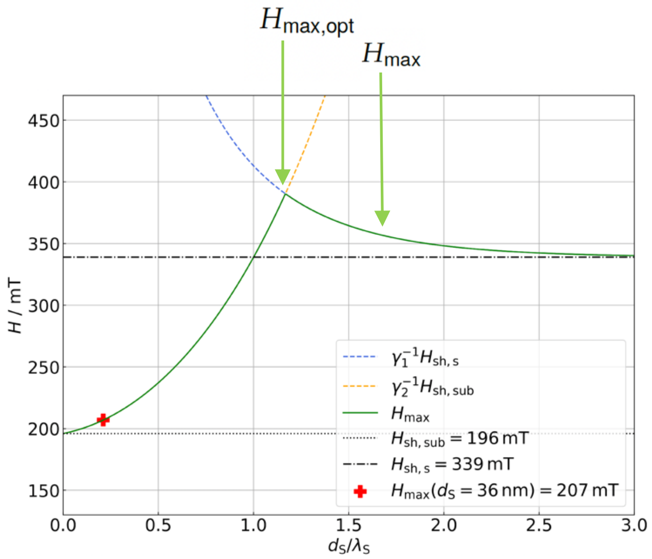
λ_L and the Estimation of H_{sh}

Meissner Screening Profile



[Credits to Ryan McFadden]

- SS bi-layer Nb/NbTiN (d ~ 36 nm)
- Expected decrease in B with increasing E and z
- Kubo's counter current model used for fit
- H_{max} **estimated** for Nb/NbTiN SS bi-layer

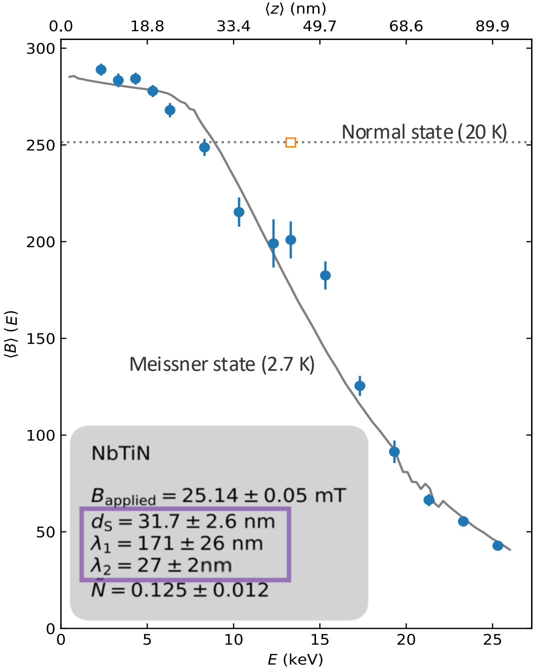


	Fit	Literature		Calculated			
Material	λ (nm)	λ_L (nm)	ξ_0 (nm)	κ (nm)	H_{c1} (mT)	H_c (mT)	H_{sh} (mT)
NbTiN	171	150 [65]	5 [65]	43	24	452	339
Nb	27	28 [56]	35 [65]	0.82	(no calc.)	200 [65]	196

Clean limit of λ_L

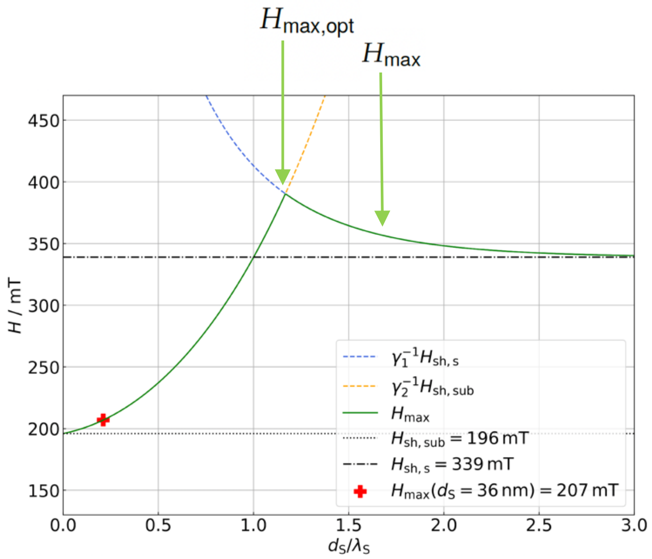
Discussion on Meissner Profile and H_{max}

Meissner Screening Profile



[Credits to Ryan McFadden]

- H_{max} **estimate** visualizes Kubo's prediction
  - $H_{max} > H_{sh,Nb}$
  - SIS multilayers needed!
- Kubo's counter current model suitable to determine λ_L



- Estimate based on Meissner Fit → improvable!
- Illustrates principle of field enhancement in an SS bi-layer

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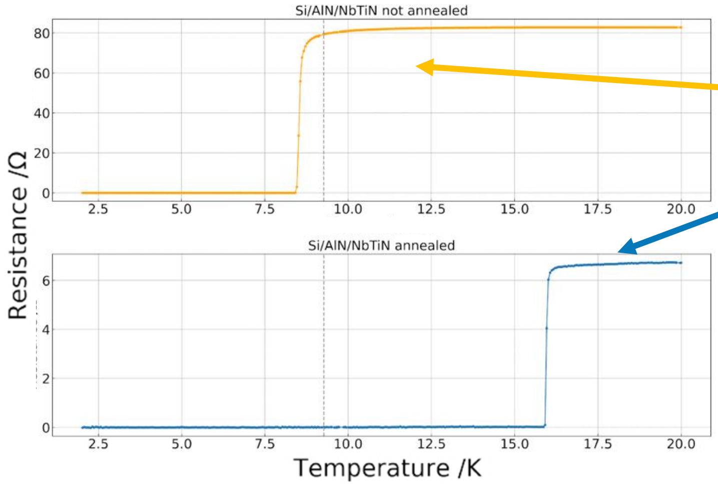
T_C Measurements on Si Substrate



Sample	Ref. to	Measurement	T_c/K	ΔT_c/K
Si/AlN/NbTiN not annealed	DESY_3_1 DESY_5_1 Tc_5_1	Electr. Transport	8.402 ± 0.271	0.931
Si/AlN/NbTiN annealed	DESY_3_2 DESY_5_2 Tc_5_2	Electr. Transport	15.960 ± 1.952	0.106
		VSM	15.566 ± 0.242	0.666
Si/NbTiN annealed	DESY_2_2 DESY_6_2 Tc_6_2	VSM	14.948 ± 0.409	0.384
Si/AlN/NbN annealed	DESY_4_2	Electr. Transport	2.732 ± 0.070	0.880

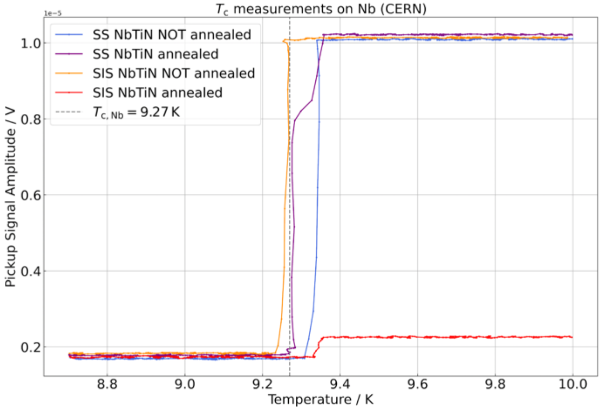
Highest value measured

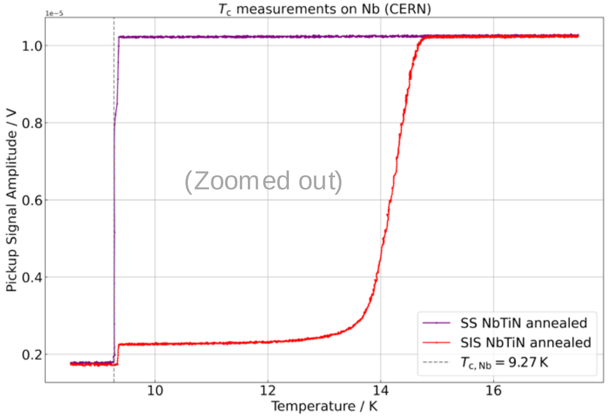
Not the same for Nb substrate!

- T_C can be clearly assigned to the SC thin film
- Highest T_C for **Si/AlN/NbTiN** in both measurement modes
- Measurement of an SIS Si/AlN/NbN sample → very low T_C

T_C Measurements on Nb Substrate

- As-deposited: T_C not higher than 7 to 8 K
- Annealed SS with NbTiN behaves similar as unannealed samples
  - ➢ $T_C \sim T_{C,Nb}$
  - ➢ Two transitions?
- Only **annealed SIS with NbTiN**
  → shows clear stepwise transition
  → reaches high T_c





[Measurement Courtesy of Erwan Reches, CERN cryolab]

Sample	**Structure**	$T_{c(1)}$/K	$\Delta T_{c(1)}$/K	$T_{c(2)}$/K	$\Delta T_{c(2)}$/K
Tc_6_1	Nb/NbTiN not annealed	9.339 ± 6.890	0.032	-	-
Tc_5_1	Nb/AlN/NbTiN not annealed	9.259 ± 6.998	0.023	-	-
Tc_6_2	Nb/NbTiN annealed	9.276 ± 10.663	0.044	9.340 ± 0.326	0.033
Tc_5_2	Nb/AlN/NbTiN annealed	9.343 ± 1.407	0.0144	14.196 ± 0.014	0.835

*See also **Daniel Turner's talk** on „Enhancement of magnetic flux expulsion in multilayer structures" ealier today*

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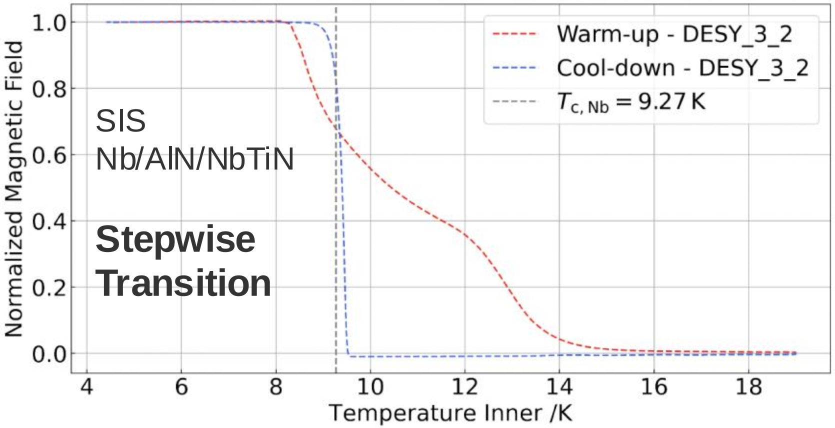
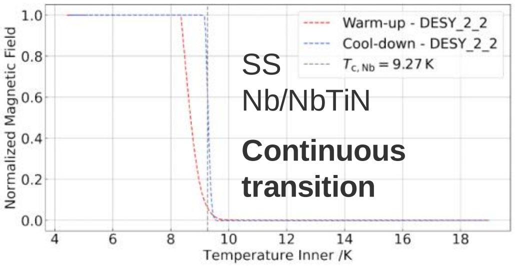
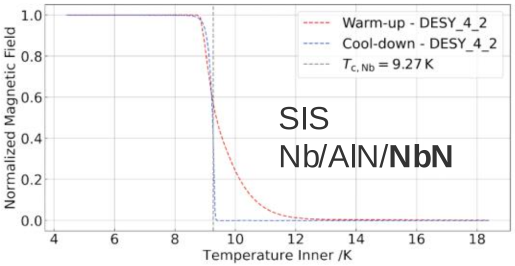
T_c Measurements with MFL

- <u>Annealed</u> Nb SIS and SS samples
- Only **SIS with NbTiN**
  → shows stepwise transition
  → reaches high T_c
- No double transition or significant increase in T_c for
  → SS Nb/NbTiN
  → SIS Nb/AlN/**NbN**
- **All T_c measurements deliver matching results!**



[Credits to Daniel Turner]





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Magnetic Flux Expulsion

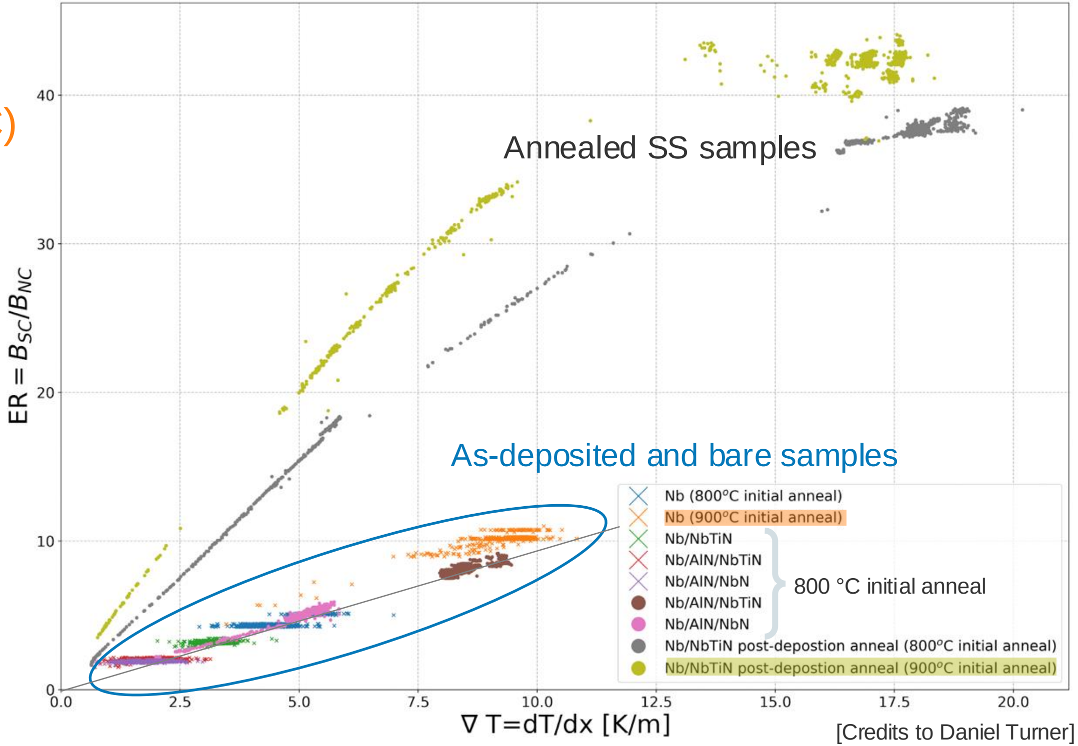
*See also **Daniel Turner's talk** on „Enhancement of magnetic flux expulsion in multilayer structures" ealier today*

As-deposited SIS and SS thin films

- ER(Nb@900 °C) > ER(Nb@800 °C)
- Limited spatial thermal gradient

Annealed SS thin films

- Much higher flux expulsion
- Greater expulsion for 900 °C initial anneal



[Credits to Daniel Turner]

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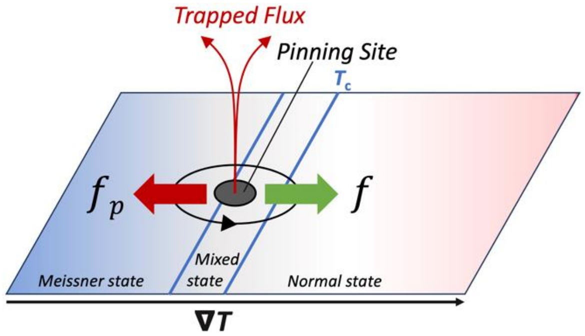
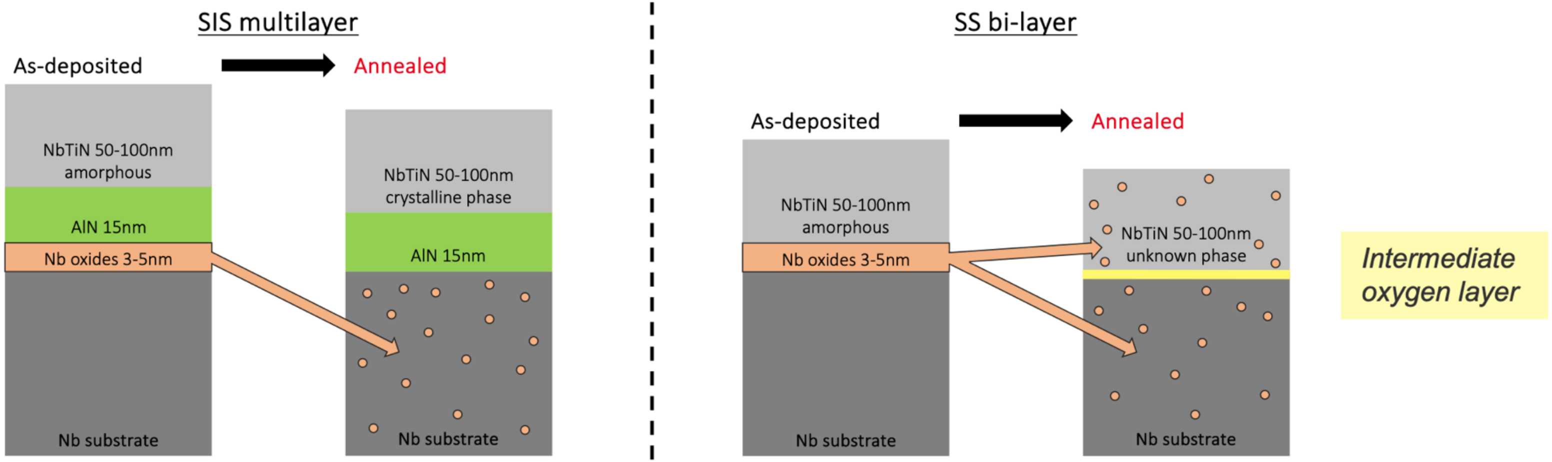
Discussion on T_C and Flux Expulsion

- Better flux expulsion for 900 °C initial anneal *(also observed in other labs)*
  - Increase in grain size with higher T_{anneal}
  - Reduction in pinning sites
- Post-deposition annealing enhances flux expulsion
  - Even for SS Nb/NbTiN if no high T_C is achieved
  - Assumption: Pancake effect adding additional force that counteracts pinning force



Discussion on T_C and Flux Expulsion

- High-*T* annealing required to *activate* the thin film and achieve high T_C
- Insulating layer on Nb required to ensure increase in T_C
  - Barrier layer prevents oxygen from diffusing into NbTiN layer
  - XRD of NbTiN on Si confirm high-T_C δ-phase formation for SS sample



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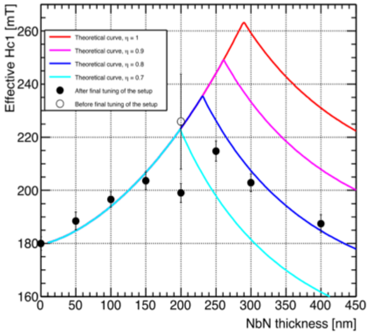
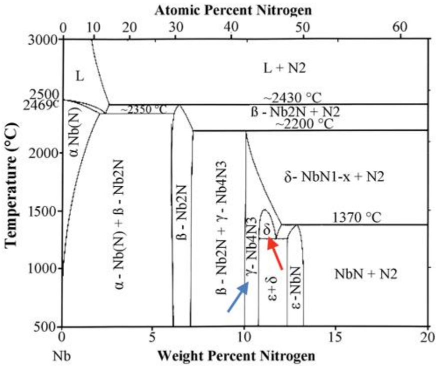
Conclusion

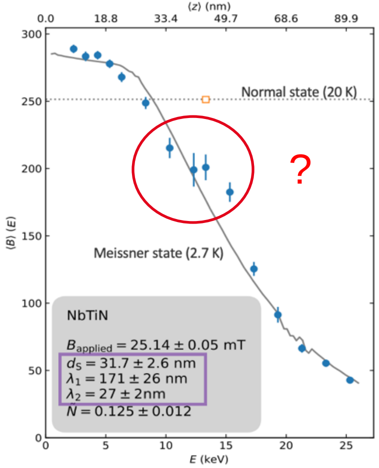
Soon: NbTiN H_{C1} measurement @ KEK!



Ito, H. et al. [arXiv: 1907.03410] (2019)

- Unclear if reduction of T_C implies reduction of H_C
  - Experimental determination required
  - Useful comparison with estimation of H_{max} following Kubo's model
- Findings on oxygen diffusion allow new considerations on μSR data analysis
  - Intermediate layer in the SS bi-layer Nb/NbTiN?
  - Electron Microscopy probably shows oxygen-enriched phase with varying stoichiometry *(Ongoing TEM studies with EPFL)*
- 900 °C annealing of SIS Nb/AlN/**NbN**
  - Does **not** form intended high-T_C δ-phase
  - Ti as stabiliser of the cubic high-T_C δ-phase
  - **NbN excluded from SIS studies**





Summary

- Further improvement of Nb SRF cavity performance neccessary... **and possible with PEALD coated SIS multilayer!**
  - Coating thin high-T_C superconducting and insulating layers
  - Pushing the field of first flux penetration H_{ffp}
- Further characterization and experimental testing of the SIS theory required

SIS is a promising approach towards new technologies and improved future applications in SRF research!

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