beta-SRF Highlights

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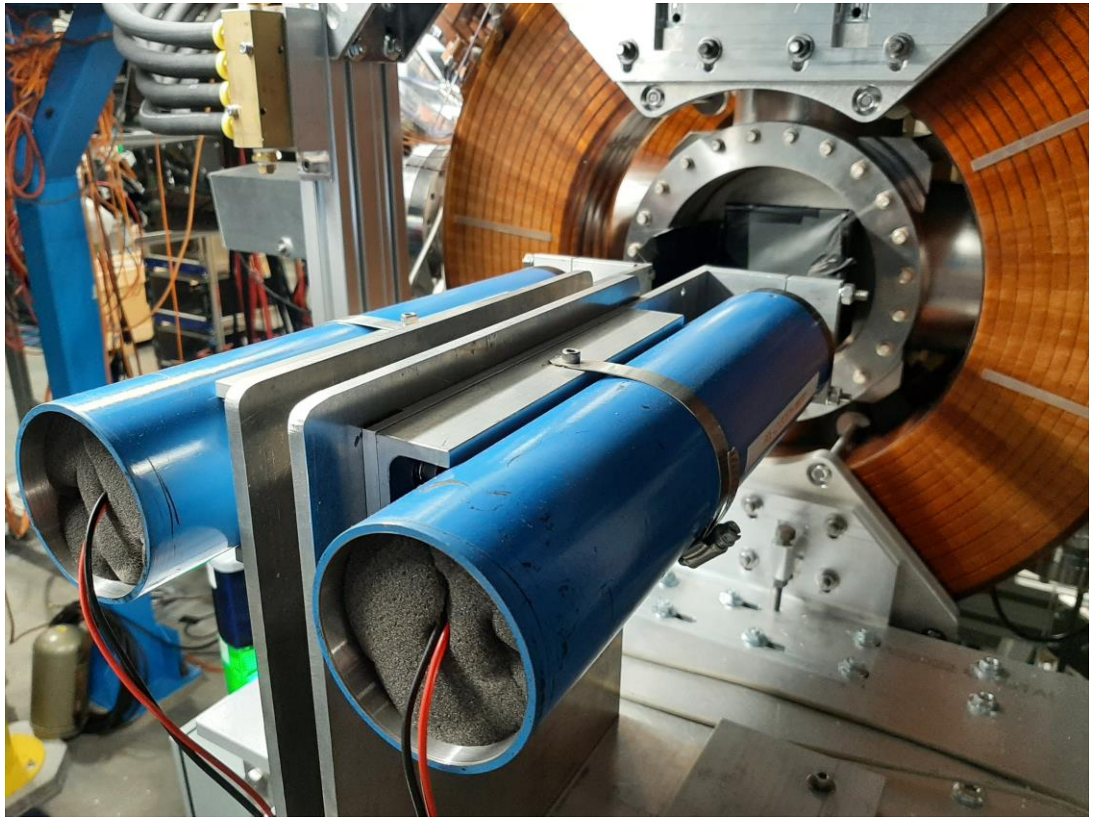
2-04

Discovery, accelerated

Outline

- Introduction/Motivation
- Beta-NMR Technique
- Results Highlights
- Summary & future outlook

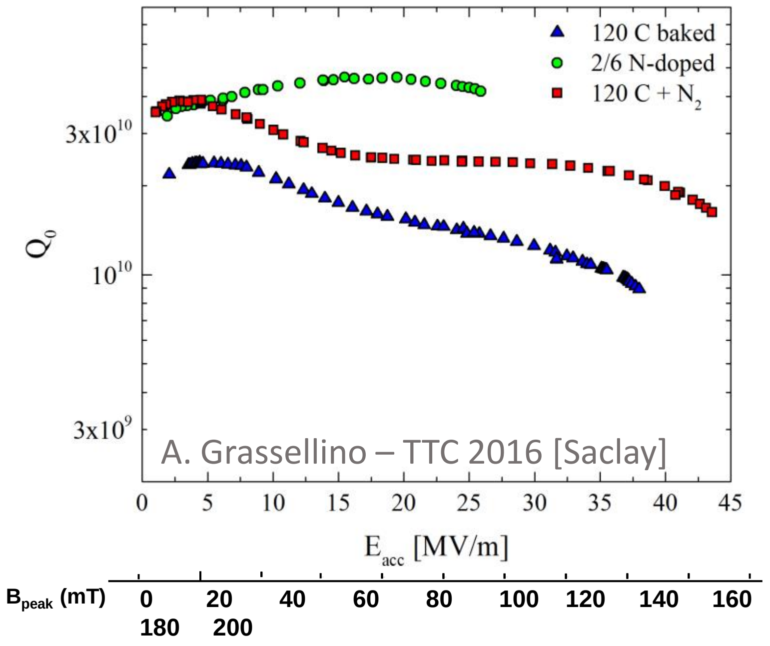


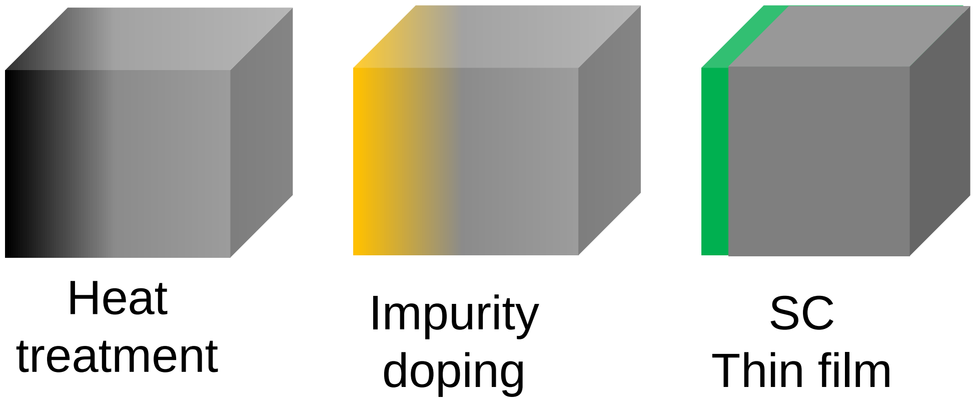
SRF Cavities Performance

- **Ultimate Goal:**
  - **high Q → cheaper operation**
  - **high gradient → shorter LINAC**

- **Underlying mechanisms ?**
  - **Macroscopic performance very sensitive to surface treatment**
  - **Nonlinear field dependence (Q-slope, B_{quench})**

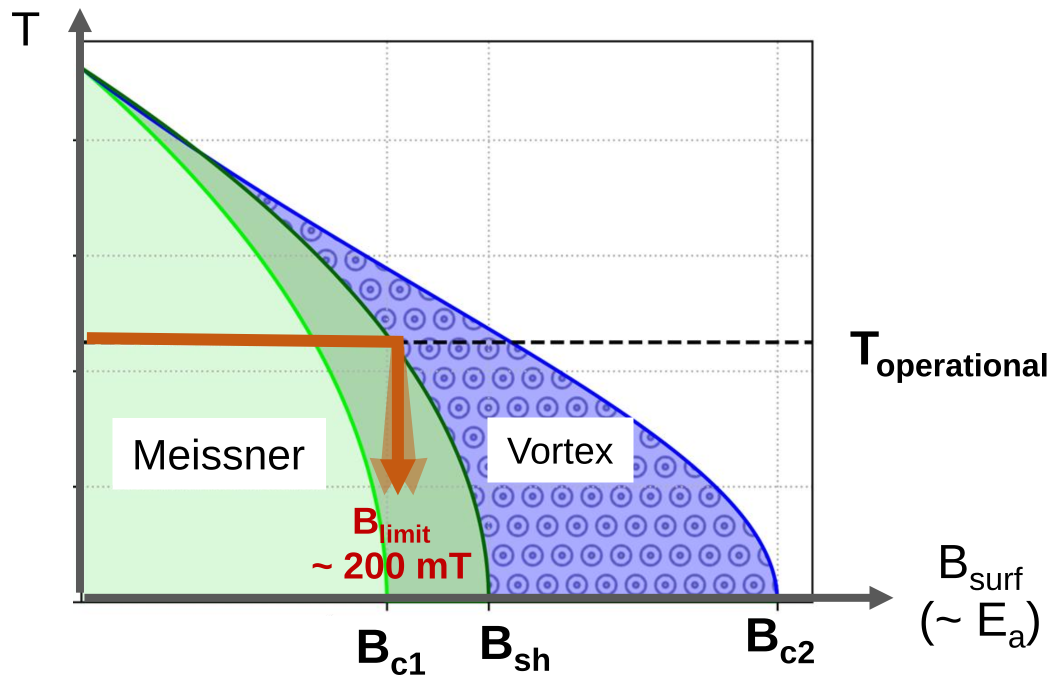
- **Empirical solutions:**
  - **Impurity engineering (baking, doping)**
  - **Thin film overlayer(s)**

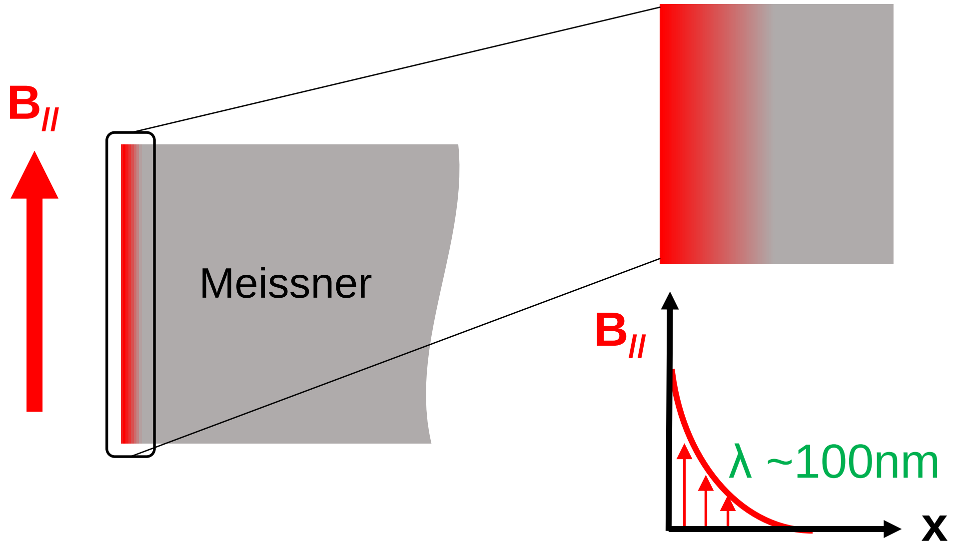




Nanometric Subsurface Role

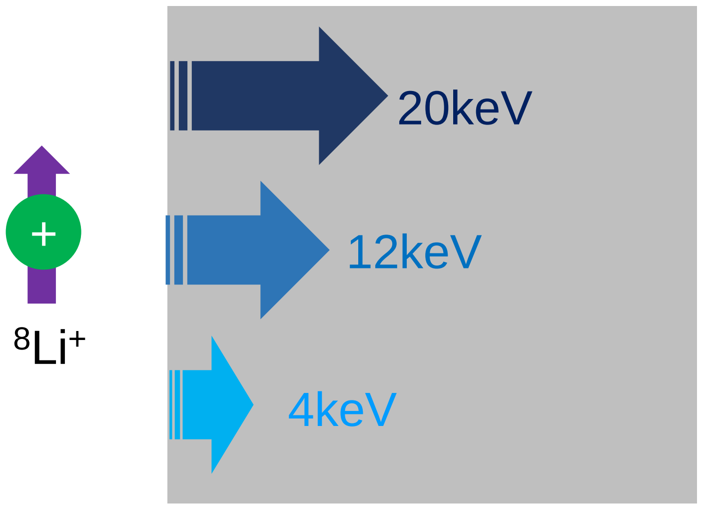
- **<u>Achieving ideal performance</u>**
  - **Accel. Gradient limit:**
    - **Sustain Meissner phase to the limiting field (B_{limit})**
  - **Screened magnetic fields within λ**
- **<u>How do the subsurface variations & modifications affect</u>**
  - **Meissner limiting field: B_{limit} ?**
  - **Screening response: λ vs. treatment ?**
  - **Field dependence: λ vs. B_{app} ?**





SRF Samples Characterization

- **Requirements:**
  - **local field** within the London layer
  - **depth-resolved** (within ~ 100 nm): B(x)
  - **up to B_{limit} ~ 200 mT: B(x) vs $B_{applied}$**
- **Radioactive spin-polarized ions**
  - **ion implantation E → nm-scale, depth-resolved**
  - **asymmetric radioactive decay → direct monitor of spin-polarization**
  - **local field → evolution of spin-polarization**



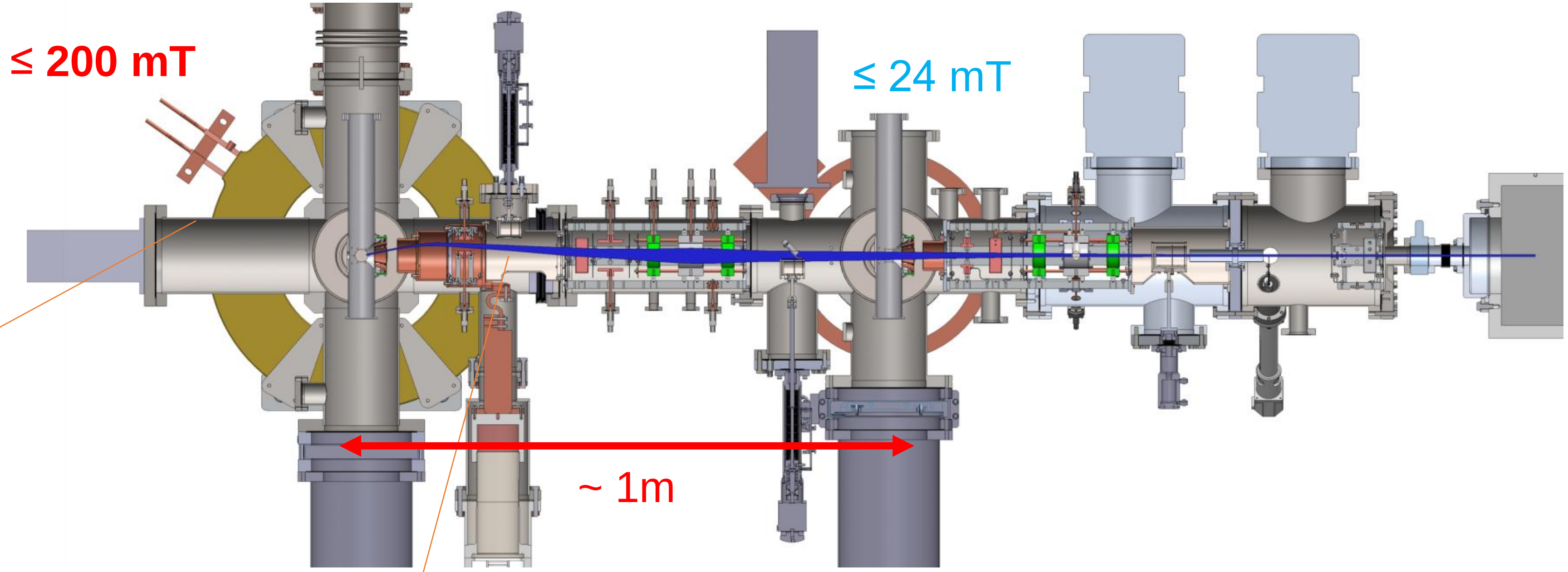
- **Two facilities at TRIUMF**
  - **HE-μSR: bulk probe (100 μm)**
  - **<u>β-NMR: nm depth resolved (0 – 100 nm)</u>**

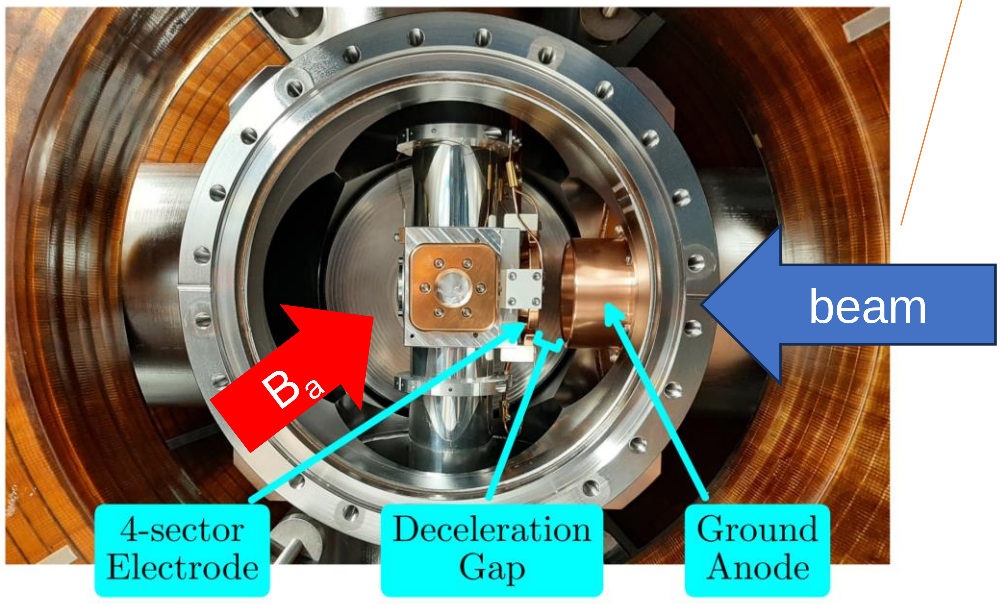
upgrade

<u>β-SRF beamline:</u>

- **<u>high-parallel fields (200 mT)</u>**
- **<u>nm-scale depth resolved</u>**
- **<u>local field measurements</u>**

βSRF beamline





Main challenge

- **Low energy (decelerated) ions in large stray fields → strong (transverse) deflection**
- **Beam steering optics + diagnostics**
- **Design + commissioning + first measurements:**

Rev Sci Instrum 94, 023305 (2023)

The beta-SRF Experiments

SAMPLES

Two Nb samples measured: RRR Niobium

- **“Baseline”**:
  - ➢ 1400 ^{o}C annealing for 4 hours + BCP
- Custom treated with mid-T bake (**“Oxygen doped”**):
  - ➢ “Baseline” **+ 400^{o}C for 3 hours**

- **Field screening with applied fields 100 → 200 mT**

Sample ladder

LOCAL FIELD EXTRACTION

A) Relaxation Rate

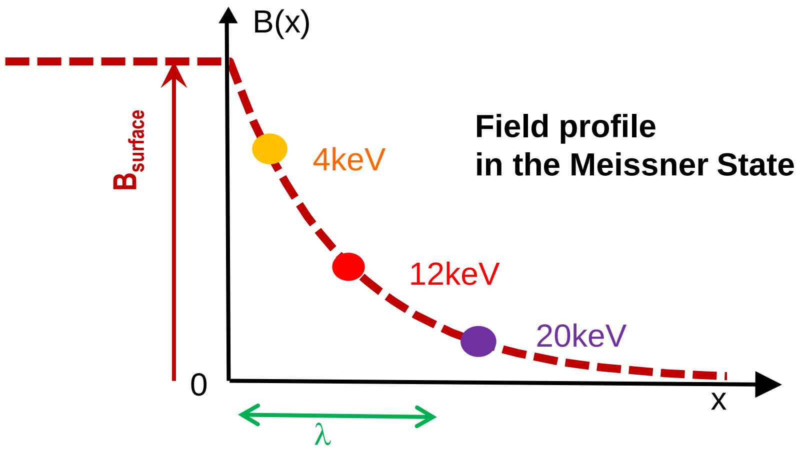
B) Average Field

C) Local Field

A) Spin-lattice relaxation rate

1. Depth-resolved:

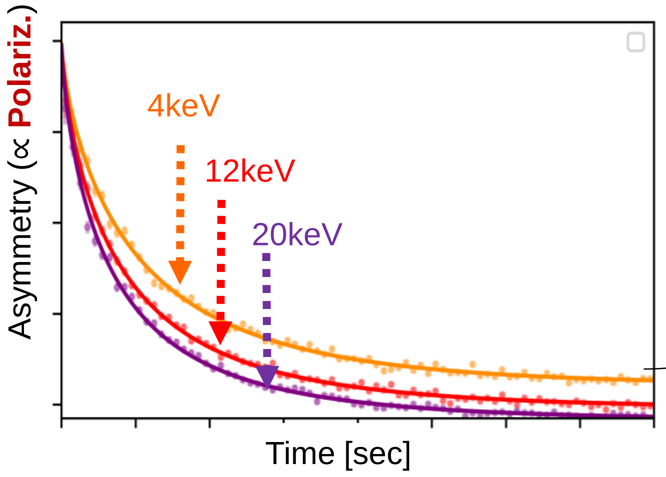
- **Varies implantation energies**
- **Energy ~ depth**

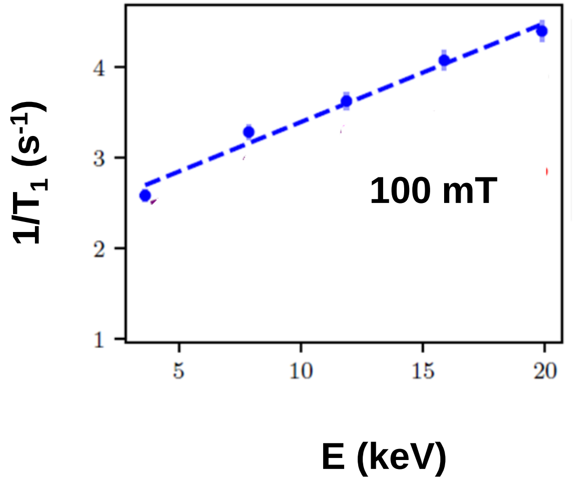


2. Local field sensitivity:

- **Probes spins depolarizes in sample → direct monitor β-decay**
- **Char. depol. time = SLR rate $1/T_1$**
- **Local B-field "slows-down" relaxation**

$$\frac{1}{T_1} = \frac{a}{b + B^2}$$



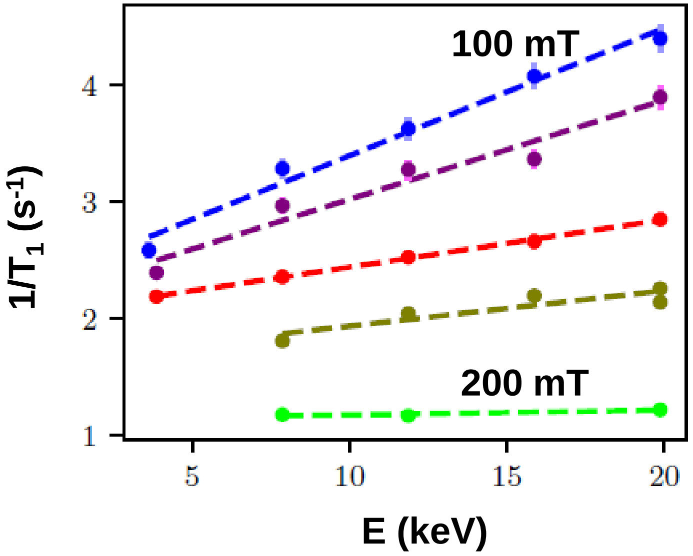


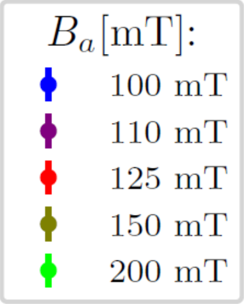
- **Slope = screening**

A) Spin-lattice relaxation rate data

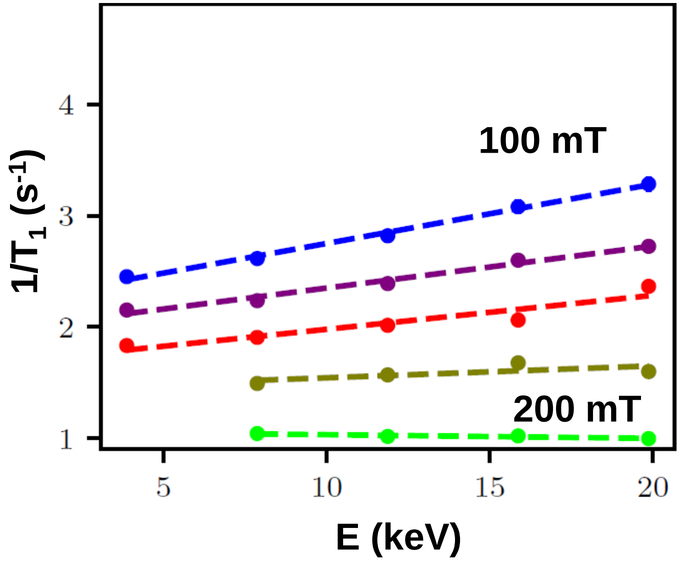
3. Increase $B_{applied}$:

Baseline

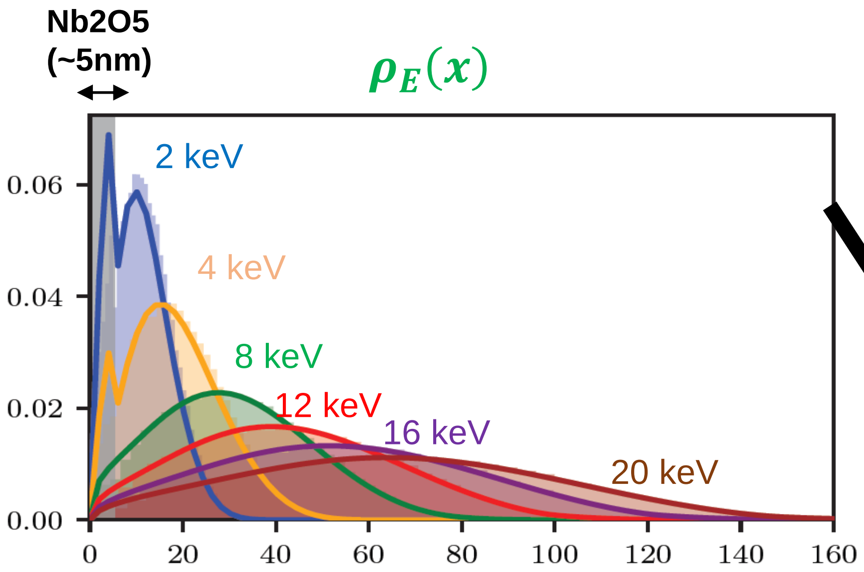




O-doped

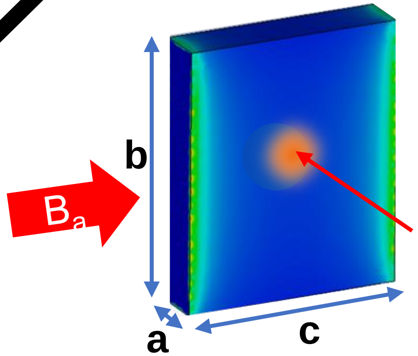


B) Mapping 1/T1 to Average Field $\langle B \rangle_E$



$$B(x) = B_{surf}\, exp(-(x - \tilde{d})/\tilde{\Lambda})$$

$\tilde{\Lambda}$: screening penetration depth
$\tilde{d}$: dead layer



B_{surf} **(Meissner)**

- Baseline: 8.1%
- O-doped: 4.3%

$\langle B \rangle_E$

$$\left\langle \frac{1}{T_1} \right\rangle (E) = \frac{a}{b + {\langle B \rangle_E}^2}$$

CALCULATED

VS.

$$\left\langle \frac{1}{T_1} \right\rangle (E)$$

MEASURED

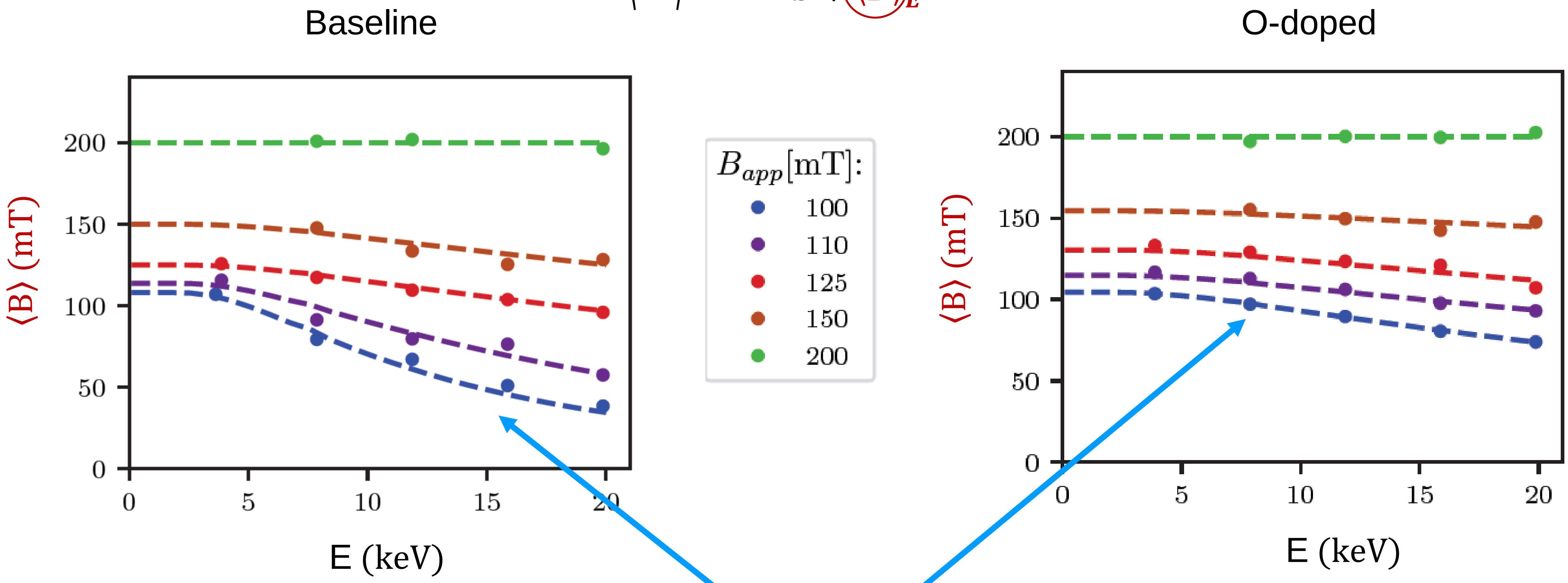
<u>Due to stopping distribution</u>:

- **Measured = average** $\langle 1/T_1 \rangle$
- B $\rightarrow \langle B \rangle_E = \int \rho_E(x) B(x)\, dx$

Lorentzian Mapping:
Applied to other fields – extract $\tilde{\Lambda}(B_a)$, $B_{surf}(B_a)$

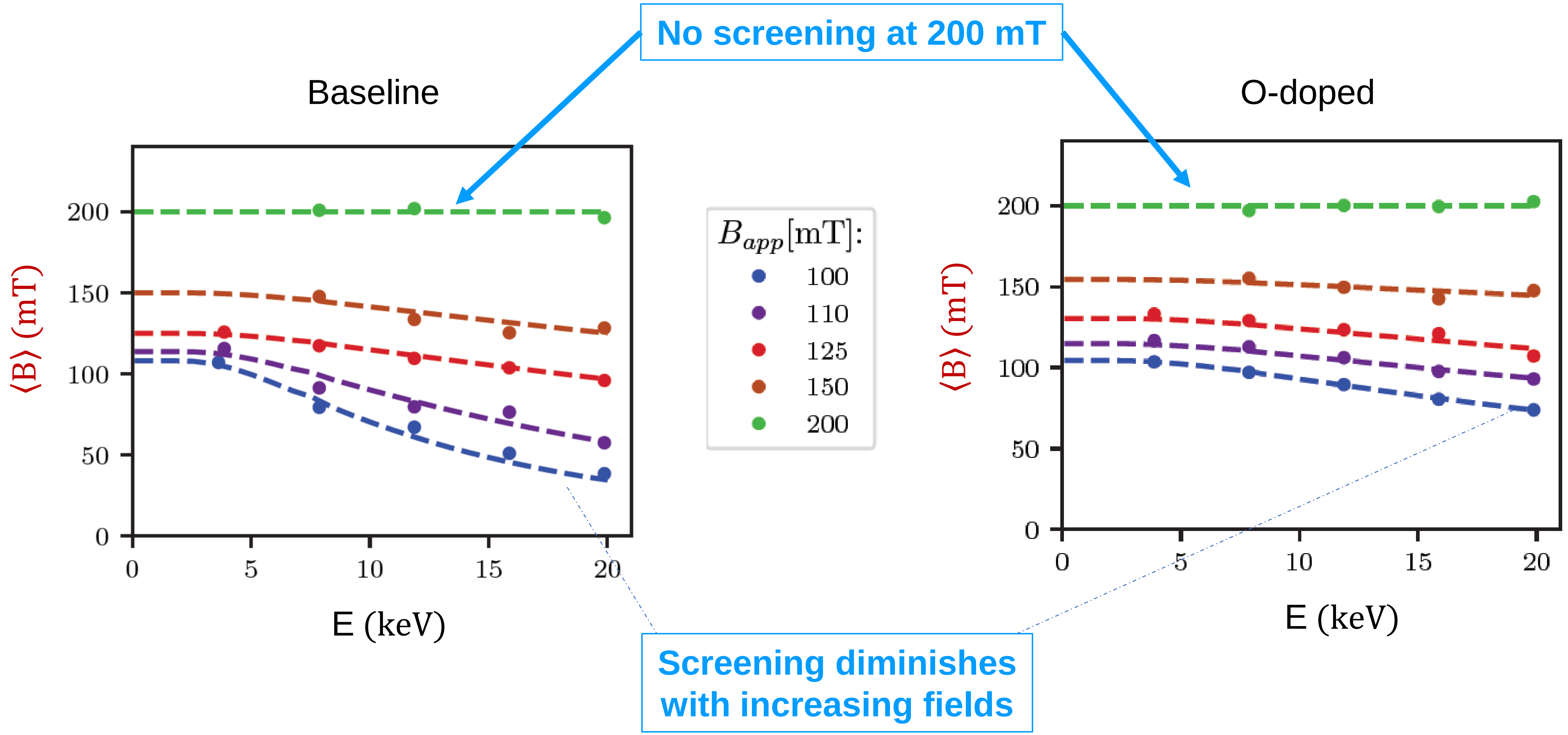
B) Average Field Results

$$\left\langle \frac{1}{T_1} \right\rangle (E) = \frac{a}{b + \langle B \rangle_E^{\,2}}$$



Different screening between the two samples

B) Average Field Results



C) Local Field Analysis

More refined analysis:

- Directly average $\langle 1/T_1 \rangle_E$ **instead of** $\langle B \rangle_E$
  - individual ion relaxes with rate $1/T_1(x)$
  - No E-mapping: $\langle 1/T_1 \rangle_E \to \langle B \rangle_E$
- Map B(x) to $1/T_1(x)$: more accurate modified Lorentzian $\mathcal{L}^*$ (different probe vs. Nb nuclear spins)
- Same B(x) model

$$B(x) = B_{surf}\, exp(-(x-\tilde{d})/\tilde{\Lambda})$$

$$\frac{1}{T_1}(\mathrm{x}) = \mathcal{L}^*\,[\mathrm{B(x)}]$$

100 mT, 200 mT

$$\left\langle \frac{1}{T_1} \right\rangle_E = \int \rho_E(x) \frac{1}{T_1}(x)\, dx$$

Calculated

VS.

$$\left\langle \frac{1}{T_1} \right\rangle (E)$$

Measured

Best $\mathcal{L}^*$

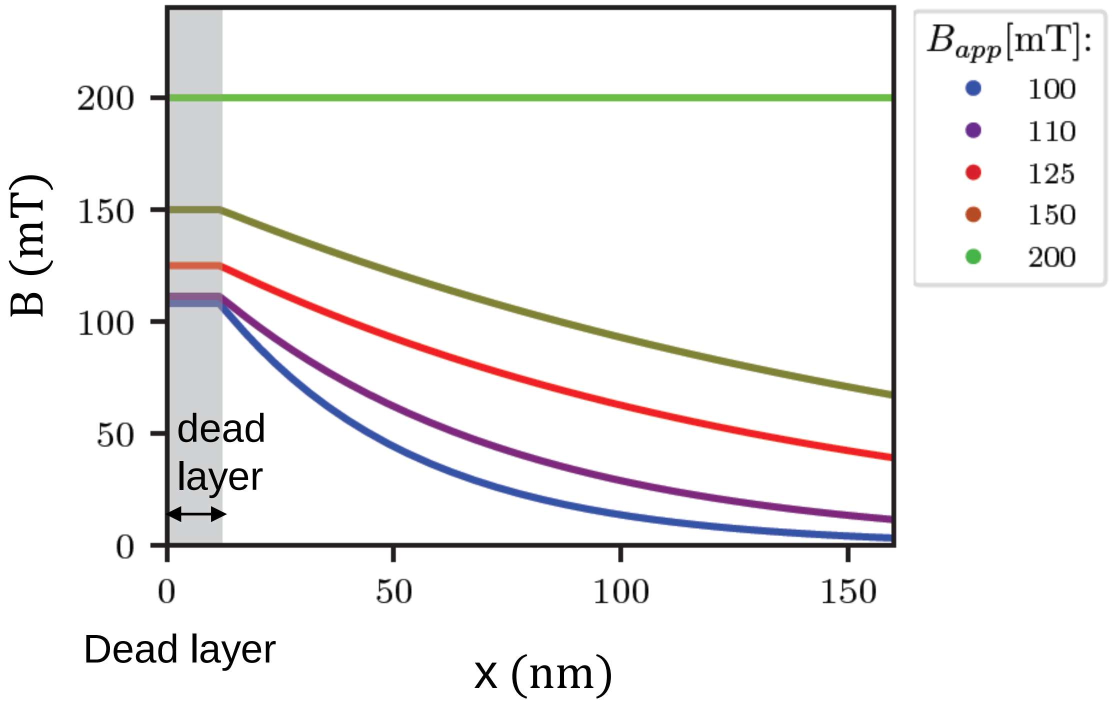
Using best-fit $\mathcal{L}^*$, extract:

- $\tilde{\Lambda}(B_{app})$: screening penetration depth
- $B_{surf}(B_{app})$: enhanced field at surface

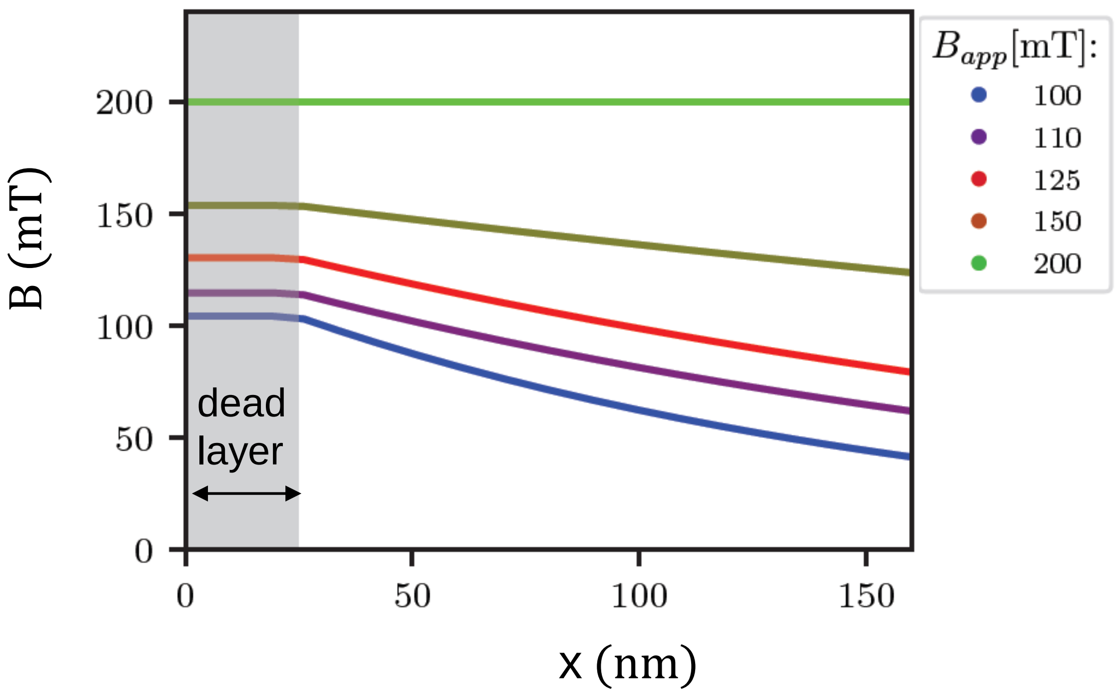
C) Local Field Analysis Results

$$\left\langle \frac{1}{T_1} \right\rangle_E = \int \rho_E(x)\, \mathcal{L}^*\, [\mathbf{B(x)}]\, dx$$

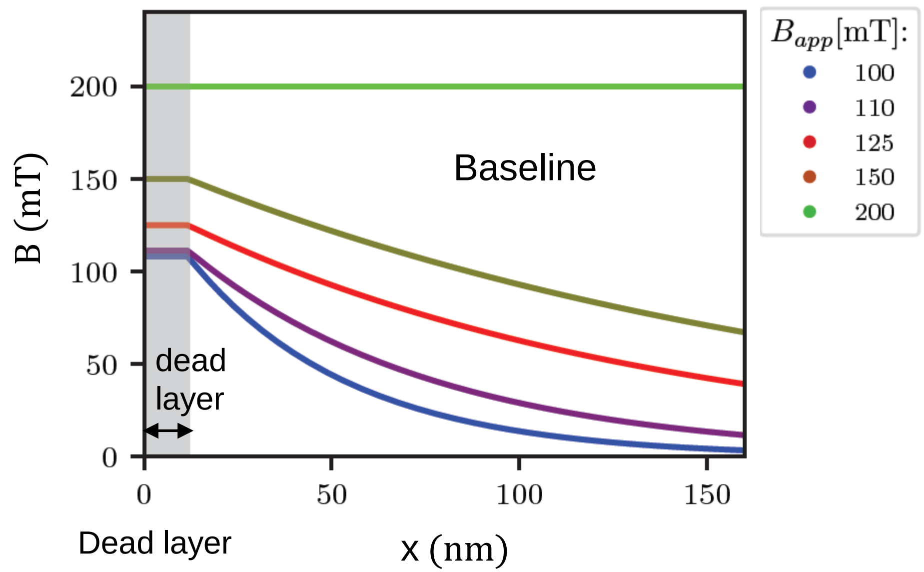
Baseline

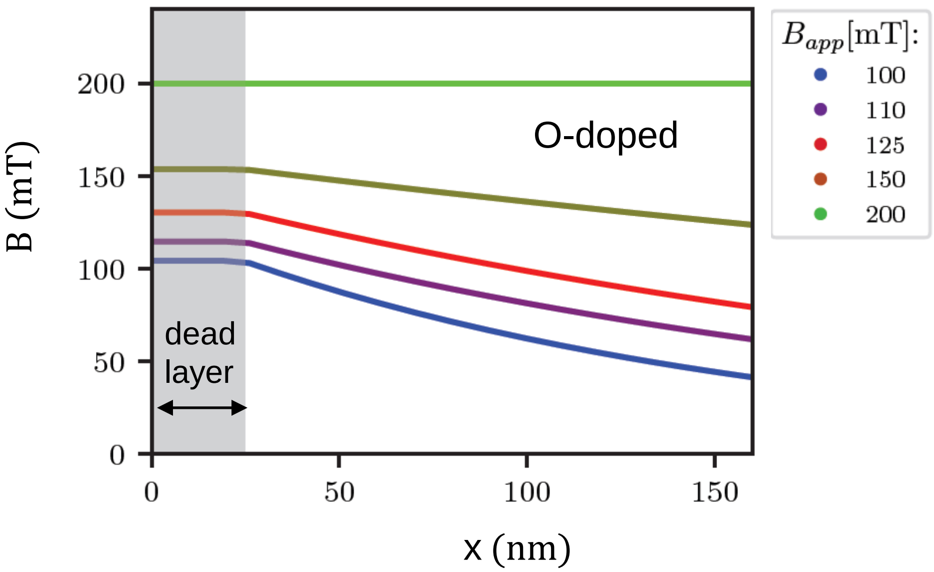


O-doped



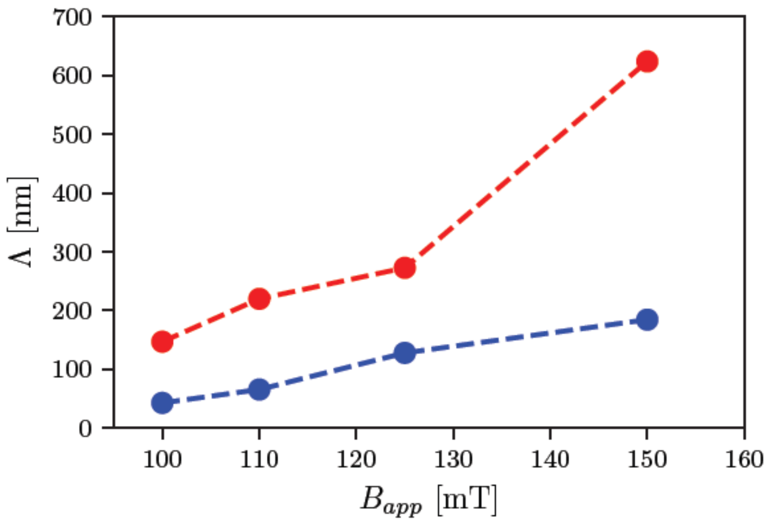
Results: Field-dependent Screening Penetration Depth (Λ)





B_{app}	Λ (Baseline)	Λ (O-doped)
(mT)	(nm)	(nm)
100	43	147
110	66	220
125	128	273
150	184	624

$$\lambda(0\ K) = \lambda_L \sqrt{1 + \frac{\xi_0}{l}}$$



Λ = $\langle \lambda, n_v(x) \rangle$

- λ: Meissner
- $n_v(x)$: Vortex

Results Highlights: Meissner Region

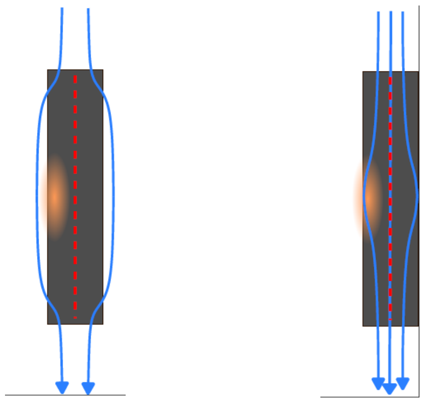
Flux entry detection via

- ❖ reduced surface enhancement B_{surf}
- ❖ Define χ [0,1], ~ flux free volume fraction :
  - ○ χ = 1 (Meissner)
  - ○ χ < 1 (mixed state)
  - ○ Χ = 0 (vortex state)

Brandt's formulation:

$B_{entry} = B_{c1} \times \tanh\left(\sqrt{0.36 * c/a}\right)$

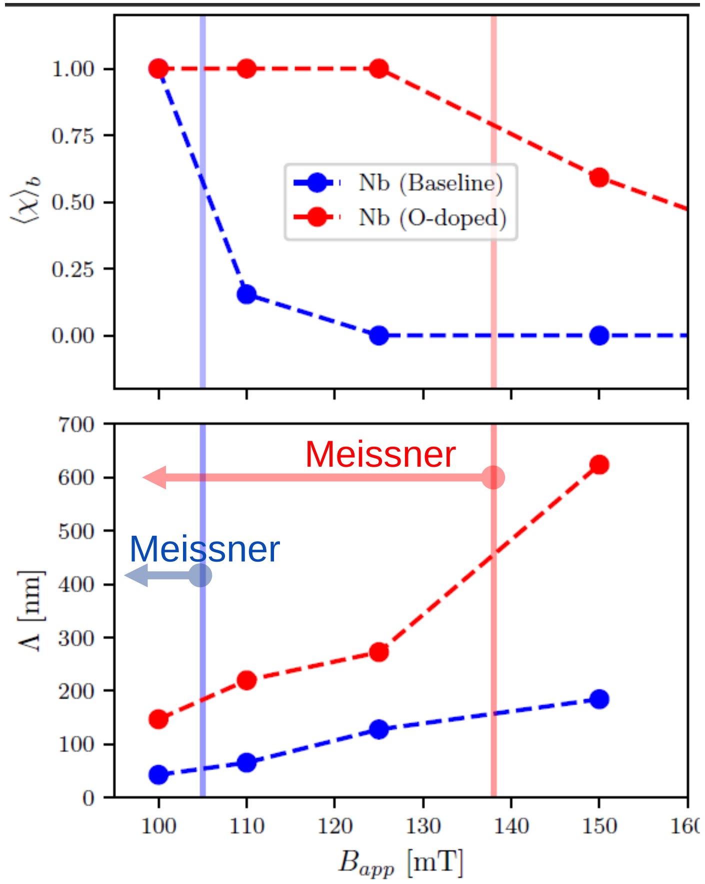
- ➢ Baseline: 121 mT
- ➢ O-doped: 127 mT



B < B_{entry} B > B_{entry}

B_{app}	χ	SPD
(mT)	-	(nm)
100	1	43
110	0.15	66
125	0	128
150	0	184
200	0	∞

B_{app}	χ	SPD
(mT)	-	(nm)
100	1	147
110	1	220
125	1	273
150	0.59	624
200	0	∞



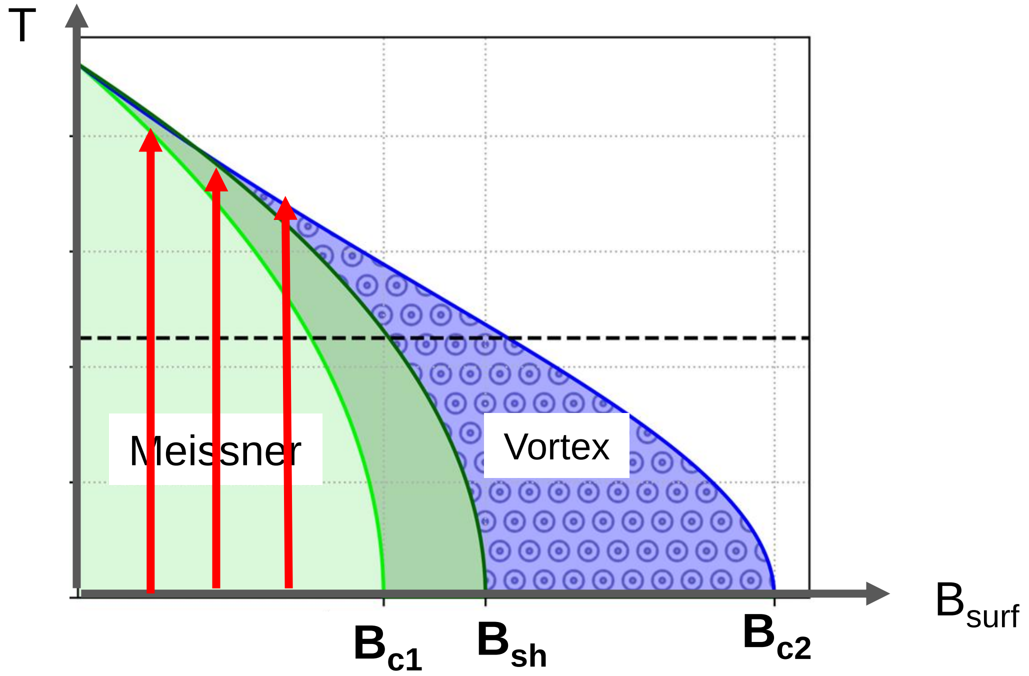
Interesting Features: Strong Field Dependence (O-doped)

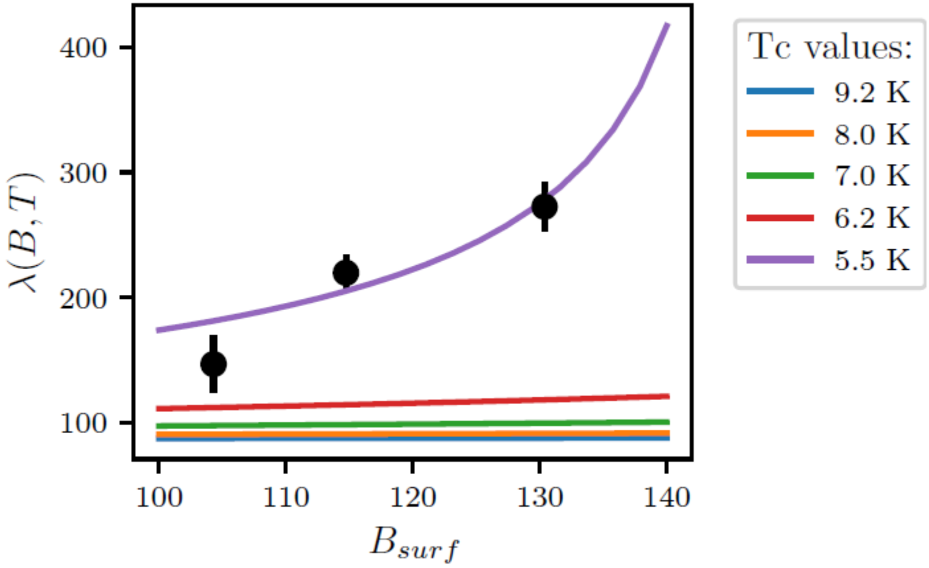
- Meissner region @ B = 100-125 mT:

- Field dependence due to T_c
  - Two-fluid model: λ diverges at T_c

$$\lambda(T) = \frac{\lambda(0)}{\sqrt{1-(T/T_c)^4}},$$

$$T_c(B) = T_c(B=0)\sqrt{\frac{1-(B/B_{c2})}{1+(B/B_{c2})}}$$





Variation of Tc due to high O-concentration (O-doping) ?

- T_c varies with O-concentration

[C.C. Koch,et al. Phys. Rev. B 9, 888 (1974)]

- Best-fit value of Tc, but seems very low

Interesting Features (2): Nonlinear Meissner Effect

- Nonlinear Meissner Effect: additional increase due to **quadratic field dependence**

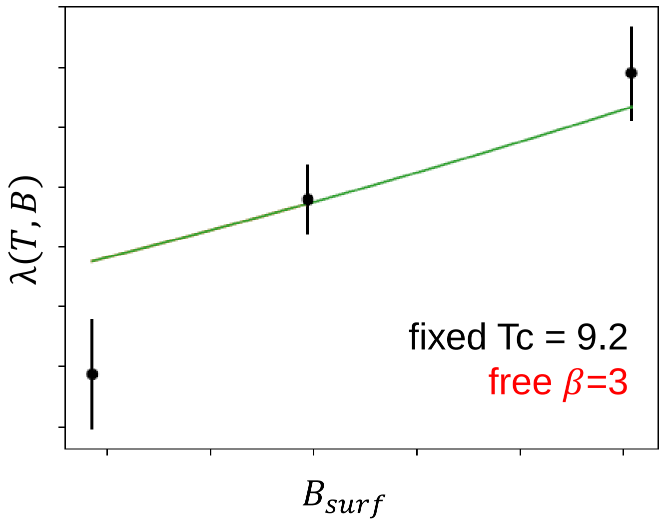
$$\lambda(T,B) = \lambda(T,0)\left[1 + \beta\left(\frac{B_{surf}}{B_c}\right)^2\right]$$

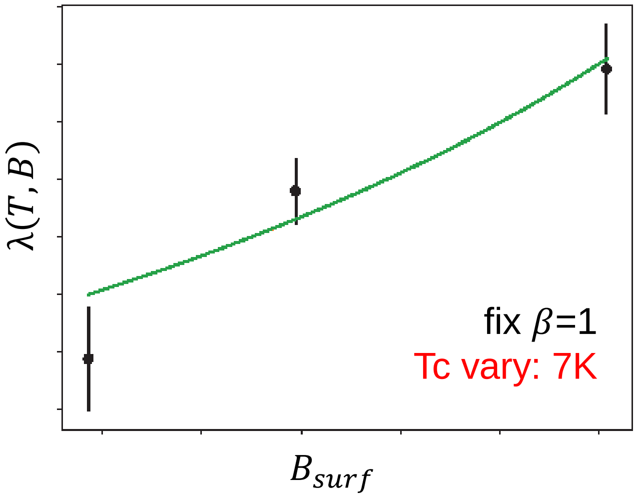
- from Ginzburg-Landau (GL) theory:

$$\beta = \frac{\kappa(\kappa+2^{3/2})}{8(\kappa+2^{1/2})^2}$$ [J. Makita,et al. Phys. Rev. Research41 013156 (2022)]

  - predicts $\beta \sim 0.12.$ Best-fit at $\beta \sim 3$, **prefactor 25x larger than GL**

- **combined NLME + reduced Tc:**
  - if β_{max} bounded to $\beta = 1$ + vary T_c , best fit for $T_c \sim$ 7K due to e.g., O-concentration ~ 2 [at%] [C.C. Koch,et al. Phys. Rev. B 9, 888 (1974)]





- Localized vortex nucleation ?

Summary & Future Outlook

Demonstrates β-SRF ability for:

- **Clear differences in penetration depth between different treatment**
- **Clear evolution from Meissner state into mixed state**
- **Strong field dependence of penetration depth**
- **Proof of principle +** potential to **shed new light of SRF materials**
- **Details** → **manuscript in preparation**

Recent studies:

1. SIS multilayer: NbTiN/AlN/Nb:

Md. Asaduzzaman + T. Junginger (Y. Kalboussi + T. Proslier, CEA Saclay)

- ❖ Measured at perp. field spectrometer (4.1 T) → study vortex state
- ❖ Characterize suitable measurement conditions for β-SRF beamline ($B_{//} \leq 200$ mT)

2. Nb thin film + Nb oxide (Qubit): Fermilab SQMS + TRIUMF SRF/CMMS

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Thank you
Merci

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