Critical Fields of Nb_3Sn

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Critical Fields

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TRIUMF

HZB Helmholtz Zentrum Berlin

Muon Spin Rotation

Low energy µSR

- DC penetration depth

Surface µSR

- DC flux penetration

Quadrupole Resonator

- RF penetration depth
- RF vortex penetration

Lower crit. field H_{c1}

Thermodynamic H_c

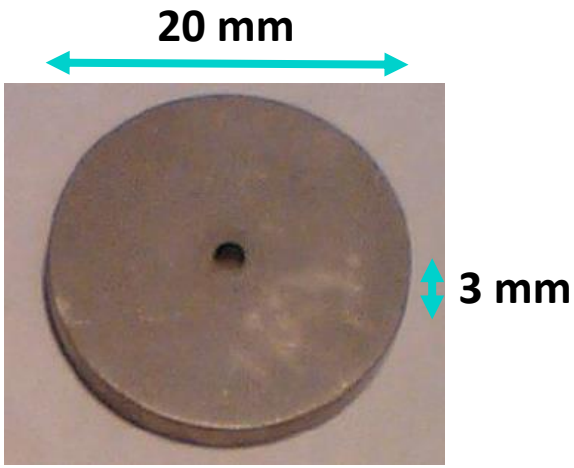
Superheating H_{sh}

[Supercond. Sci. Technol. 32, 075004 "Critical fields of Nb_3Sn prepared for superconducting cavities"]

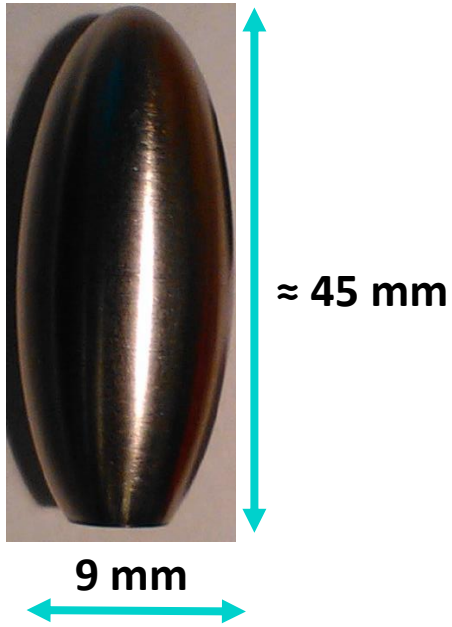
Samples

Muon Spin Rotation

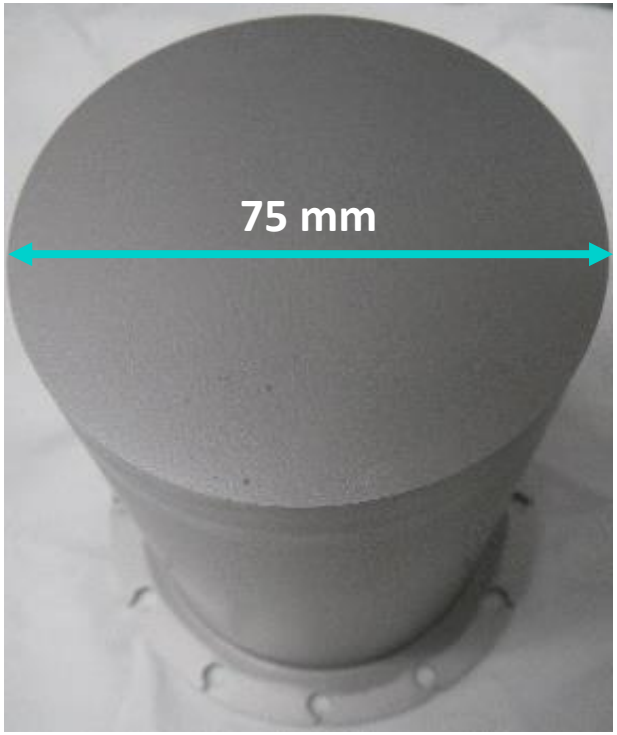
Low-energy µSR



Surface µSR

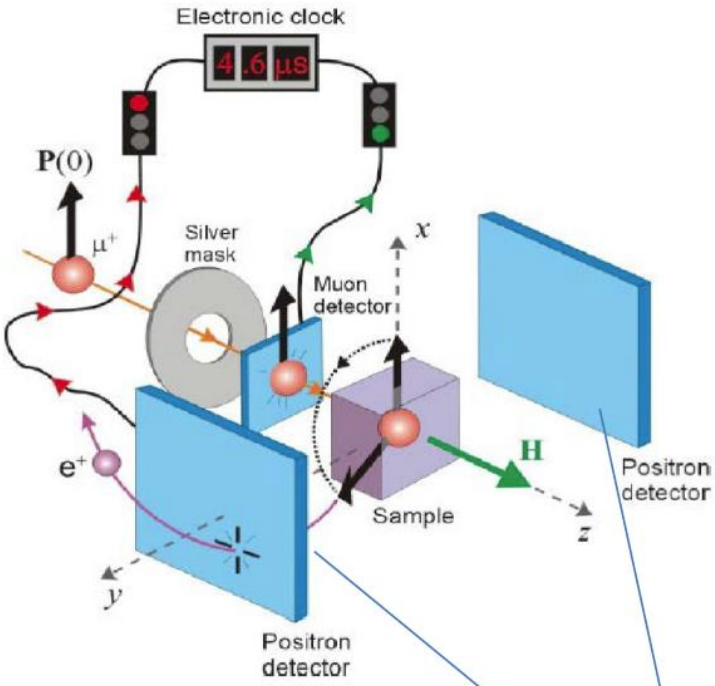


Quadrupole Resonator



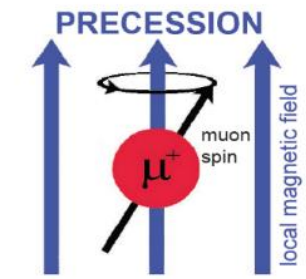
- All substrates: Niobium RRR ≥ 300
- Coatings: ≈ 2µm Nb_3Sn by vapor diffusion, Cornell „standard procedure“

Muon Spin Rotation (μSR)

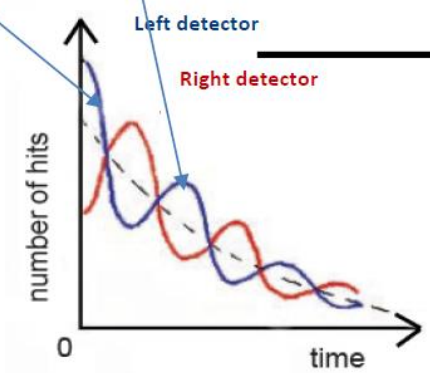


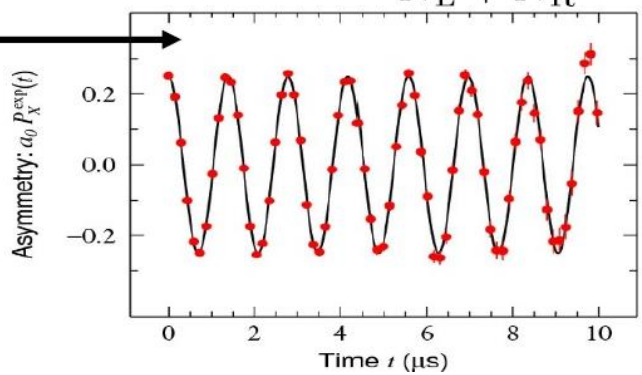
- TRIUMF SRF group has ben engaged in muSR characterization of SRF samples since 2010
- 100% spin polarized Muons are deposited one at a time in a sample and spin rotate in the local magnetic field
- The muons decay with emitted positrons correlated with the spin direction.
- The time evolution of the asymmetry of the detected positrons gives a measure of the sampled magnetic field

$$a_0 P_y(t) = \frac{N_L - N_R}{N_L + N_R}$$



$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

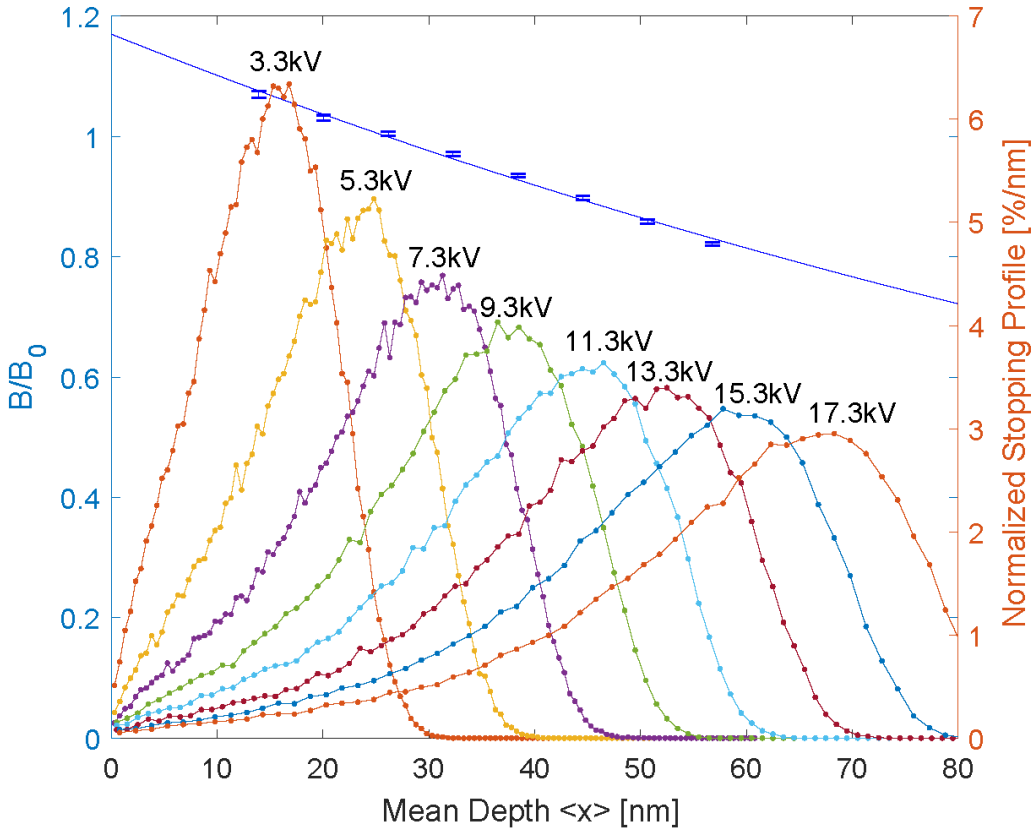




[T. Junginger, R. Laxdal, „Muon Spin Rotation Studies of Niobium and Other SRF Materials“, SRF 2019]

DC penetration depth

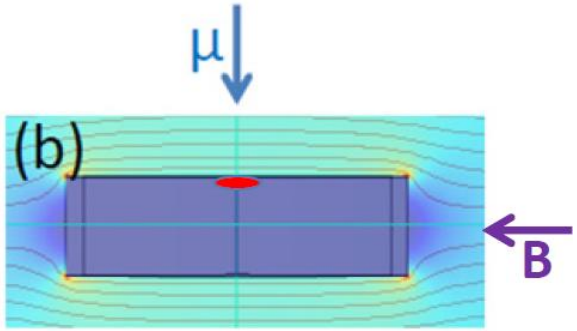
- Low-energy µSR @ PSI
- Constant ambient conditions: $T = 5\mathrm{K}$, $\mu_0 H_{\mathrm{ext}} = 10\mathrm{mT}$
- Measure local magnetic field as a function of muon implantation depth



$$B = B_0 \exp\left(-\frac{x}{\lambda(T)}\right)$$

$$\boldsymbol{\lambda = (160.0 \pm 3.9)\ \mathrm{nm}}$$

$$\Rightarrow \boldsymbol{\mu_0 H_{c1} = (28 \pm 2)\ \mathrm{mT}}$$



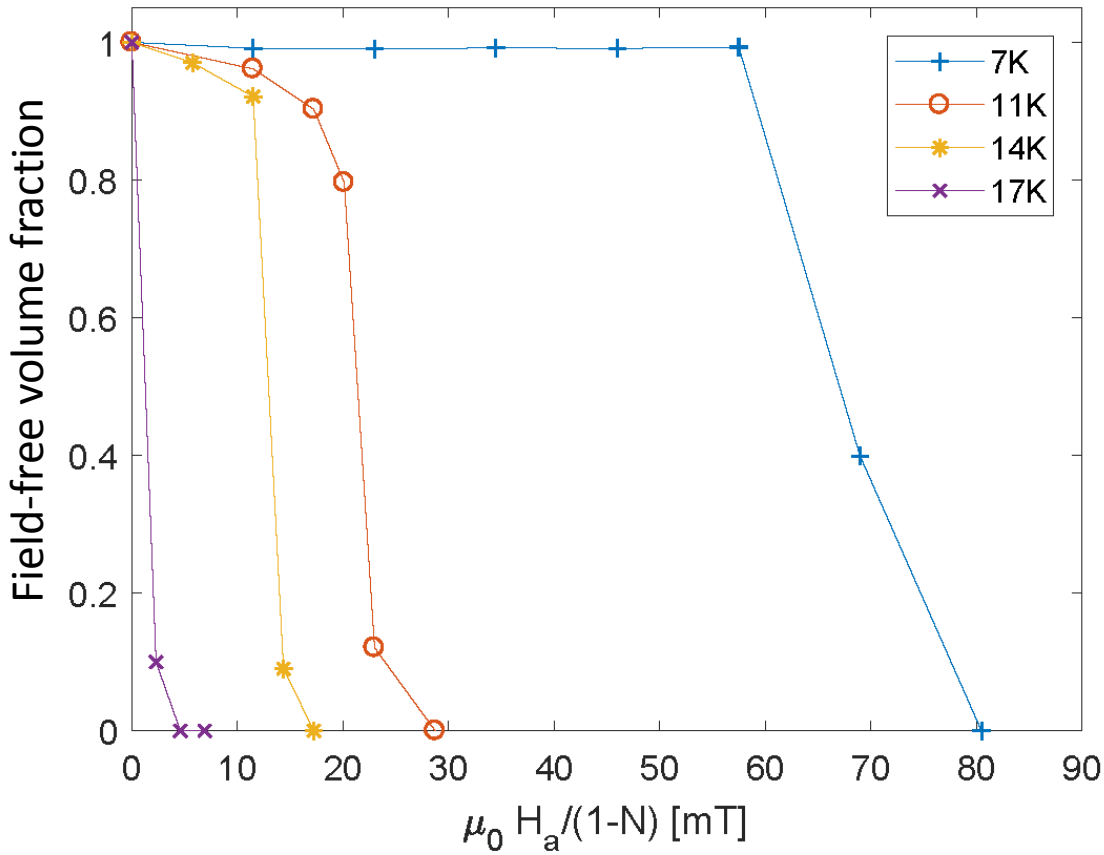
[T. Junginger, R. Laxdal, „Muon Spin Rotation Studies of Niobium and Other SRF Materials“, SRF 2019]

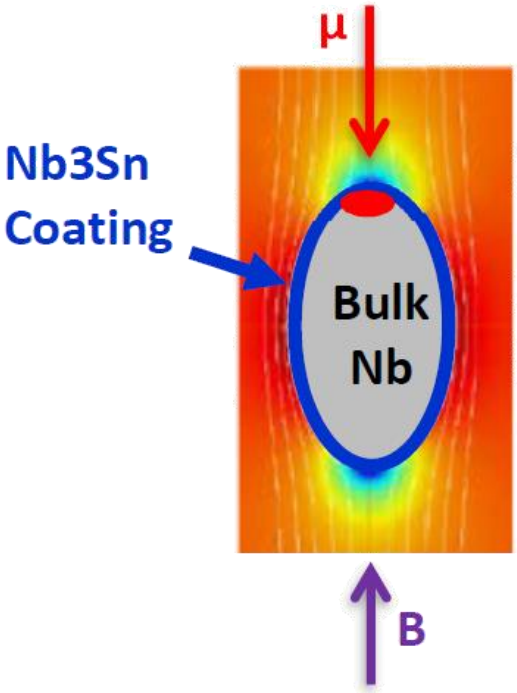
DC flux penetration

- Surface µSR @ TRIUMF
- Fixed muon energy, implanted 130 µm in the bulk
- $T > 9.25$ K: superconducting shell of Nb_3Sn

$$H_{\mathrm{vp,DC}}(T) = H_{\mathrm{vp,DC}}\left[1 - \left(\frac{T}{T_c}\right)^2\right]$$

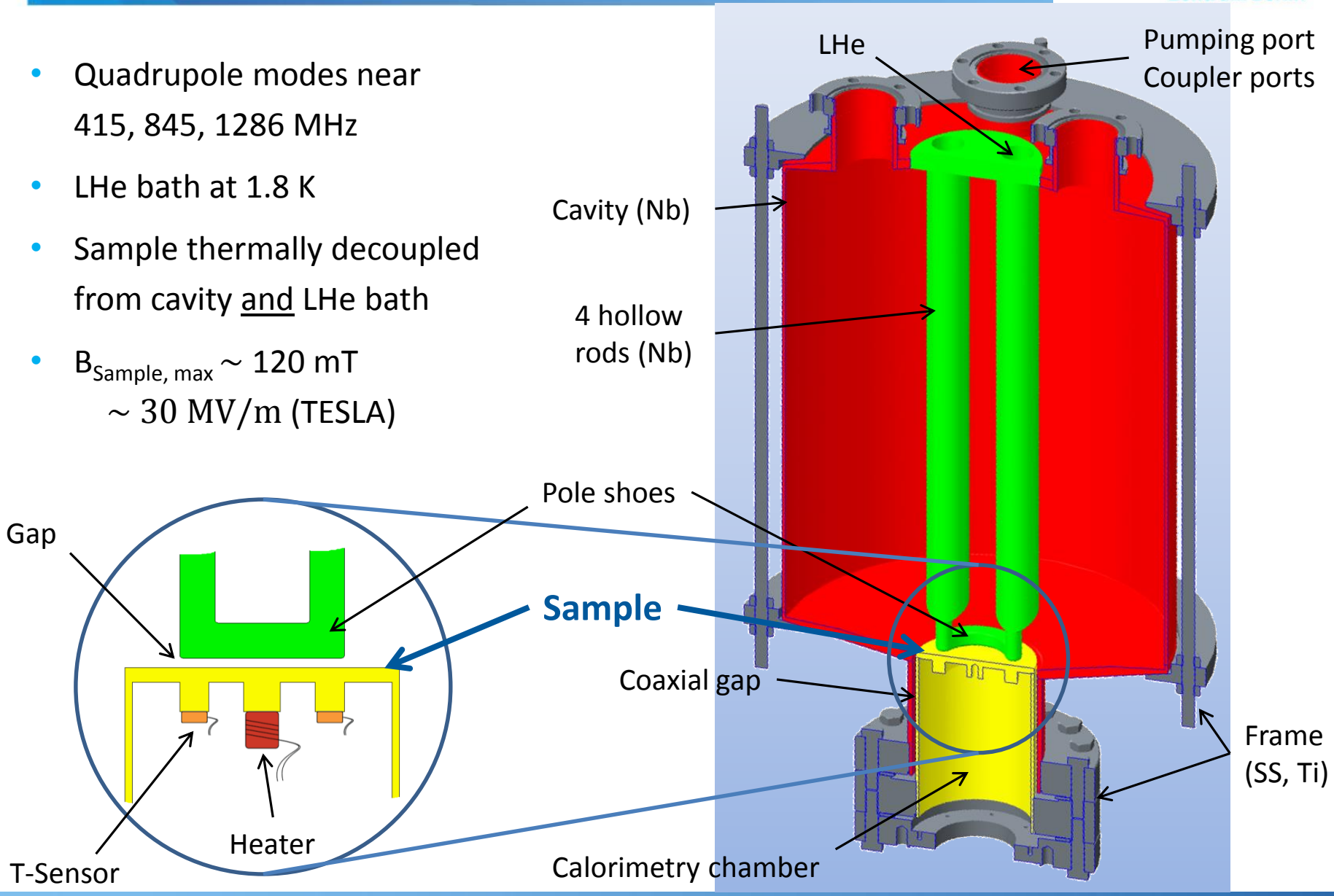
$$\boldsymbol{\mu_0 H_{\mathrm{vp,DC}} = (28 \pm 12)\ \mathrm{mT}}$$





The Quadrupole Resonator (QPR)

- Quadrupole modes near 415, 845, 1286 MHz
- LHe bath at 1.8 K
- Sample thermally decoupled from cavity <u>and</u> LHe bath
- $B_{Sample,\ max} \sim 120$ mT
  $\sim 30\ \mathrm{MV/m}$ (TESLA)

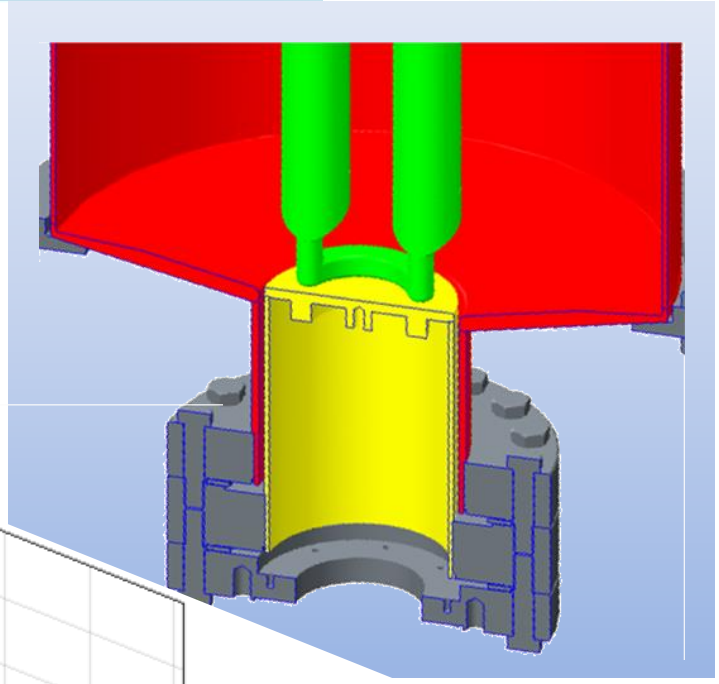


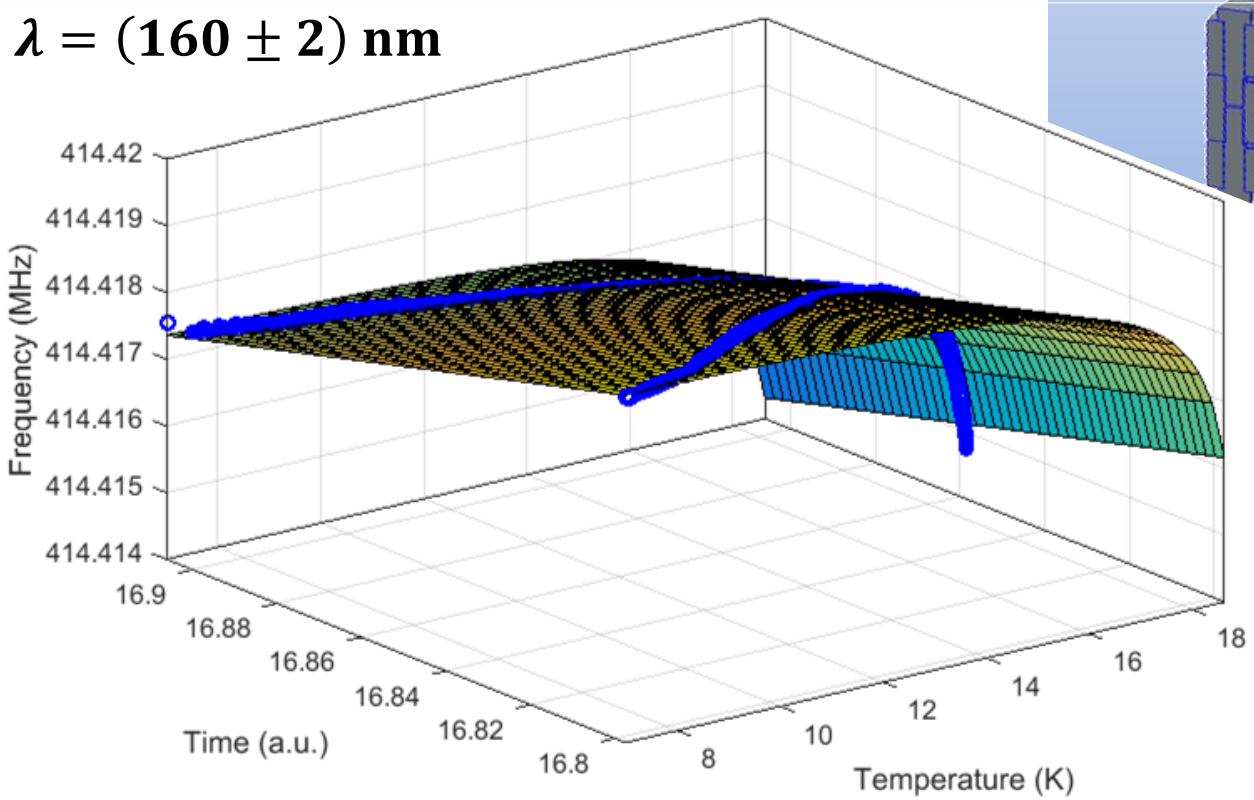
RF penetration depth

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

$$\lambda(T) = \lambda_0 - \frac{G_{\mathrm{Sample}}(f)}{\pi\mu_0 f^2}\Delta f$$

$$\boldsymbol{\lambda = (160 \pm 2)\ \mathrm{nm}}$$

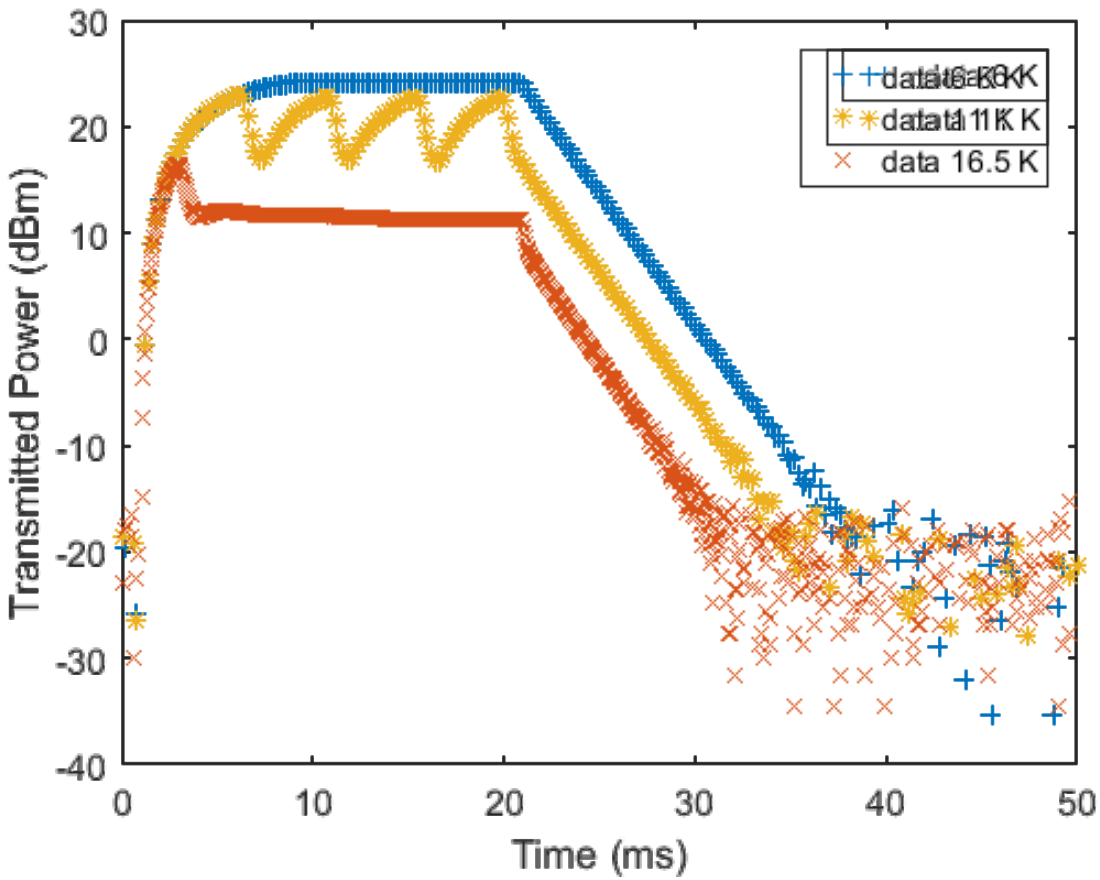




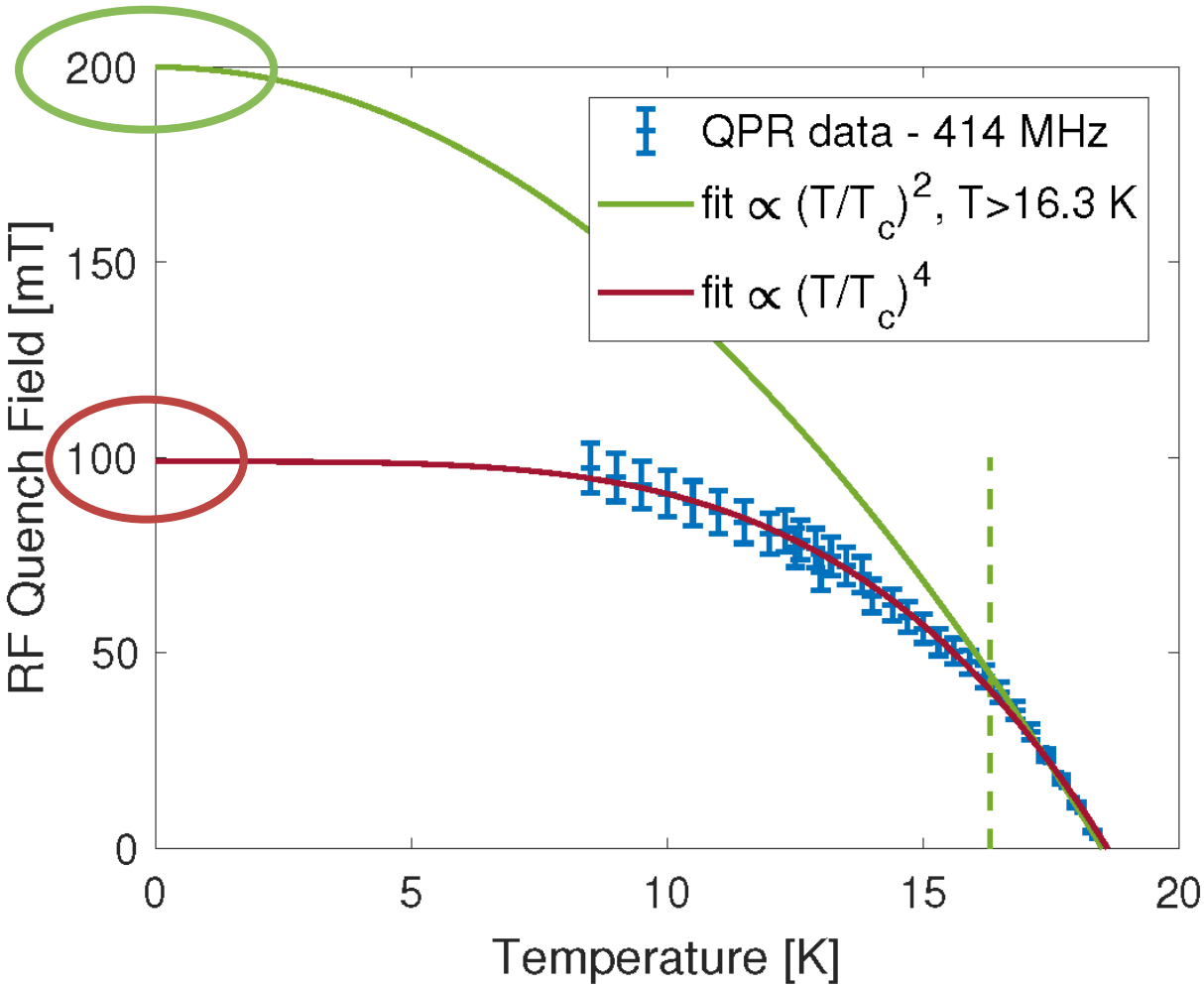
RF quench field

- $H_{\mathrm{vp,RF}}(T) = H_{\mathrm{vp,RF}}\left[1 - \left(\frac{T}{T_{\mathrm{c}}}\right)^2\right]$

- Single short pulse of RF power → sample quenches, RF heating negligible



RF quench field



Expectation:

$$B_{\mathrm{vp}} = B_0\left(1 - \left(\frac{T}{T_c}\right)^2\right)$$

with

$$\mathrm{B}_0 = \mu_0 H_{\mathrm{sh}} \approx 500\ \mathrm{mT}$$

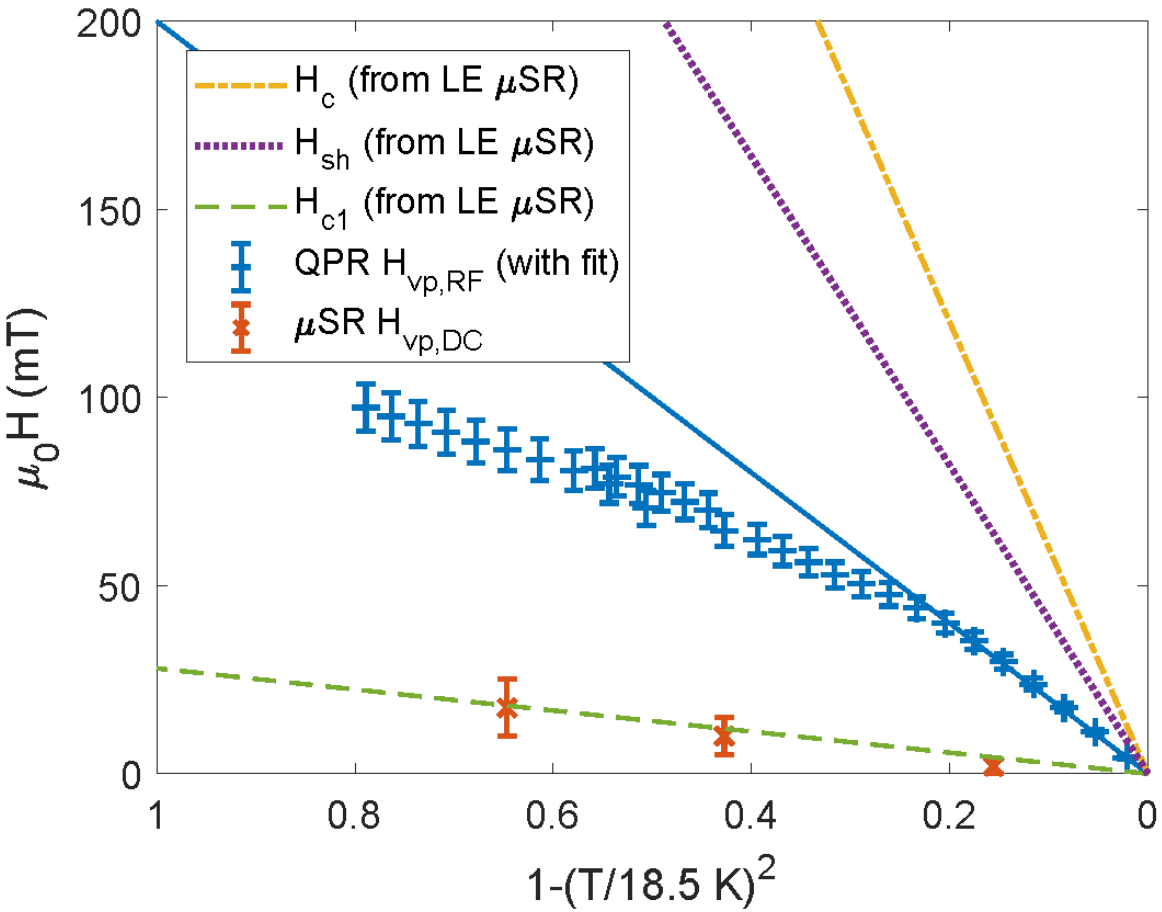
However:

$$\mathrm{B}_0 \gg \mu_0 H_{c1} \approx 28\ \mathrm{mT}$$

Bulk Nb baseline:

$$B_{\mathrm{vp}} = 220\ \mathrm{mT}$$

Summary



- 4 labs, 3 measurement setups
- 3 samples with comparable substrates and coatings
- $H_{\mathrm{vp,DC}}$ is consistent with H_{c1}
- $H_{\mathrm{vp},RF} \gg H_{c1}$
  - → Metastability for RF fields
  - → Still well below H_{sh}

λ [nm] LE-µSR, QPR	$\mu_0 H_{c1}$ [mT] LE-µSR	$\mu_0 H_c$ [mT] LE-µSR	$\mu_0 H_{\mathrm{sh}}$ [mT] LE-µSR	$\mu_0 H_{\mathrm{vp,DC}}$ [mT] µSR	$\mu_0 H_{\mathrm{vp,RF}}$ [mT] QPR
160 ± 4	28 ± 2	600 ± 100	500 ± 120	28 ± 12	200 ± 5

[SUST 32, 075004, DOI: 10.1088/1361-6668/ab119e]

Critical fields

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

$$\kappa = \frac{\lambda}{\xi_{GL}} = \frac{2\sqrt{3}}{\pi}\frac{\lambda^2}{\xi_0\lambda_L}$$

$$\mu_0 H_{c1} = \frac{\Phi_0}{4\pi\lambda^2}\ln(\kappa + 0.5)$$

$$H_c = \frac{\sqrt{2}\kappa H_{c1}}{\ln\kappa}$$

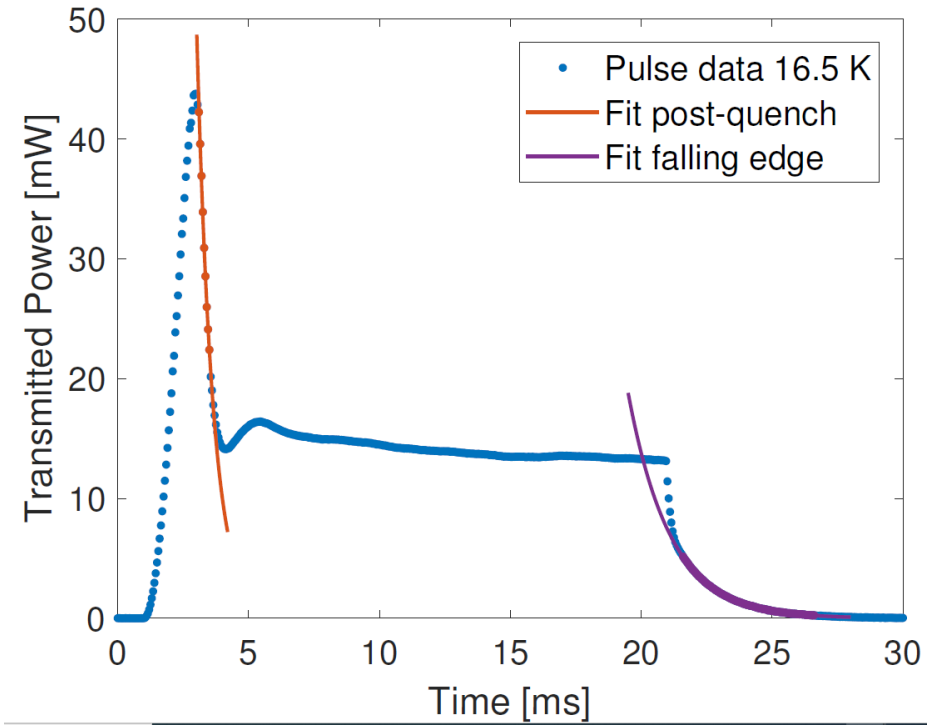
$$H_{sh} = H_c\left(\frac{\sqrt{20}}{6} + \frac{0.55}{\kappa}\right)$$

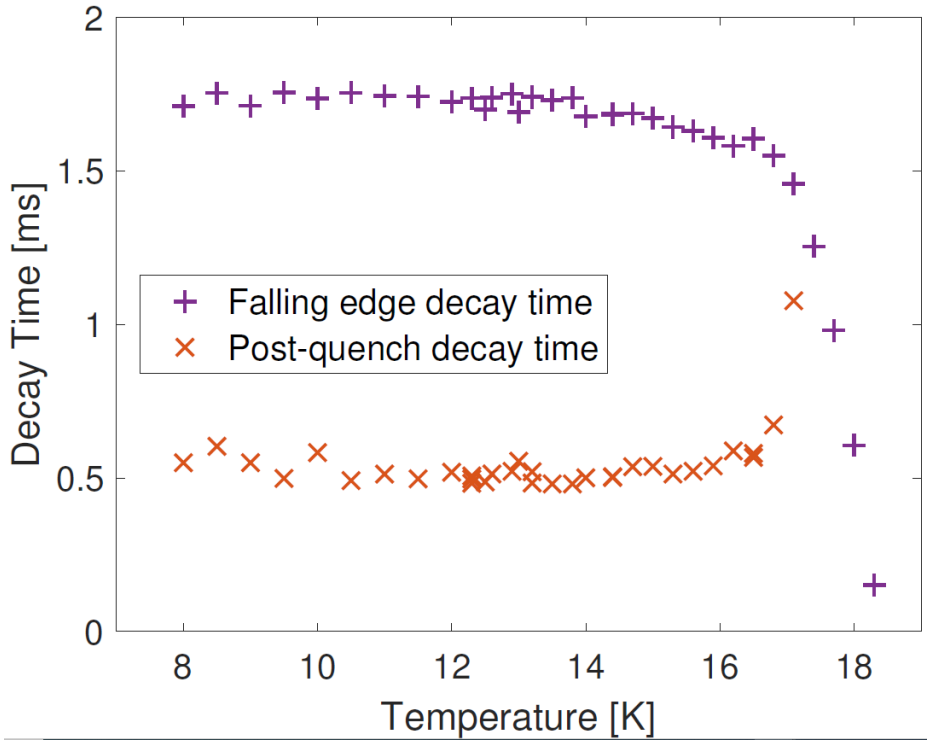
Measurements

Literature

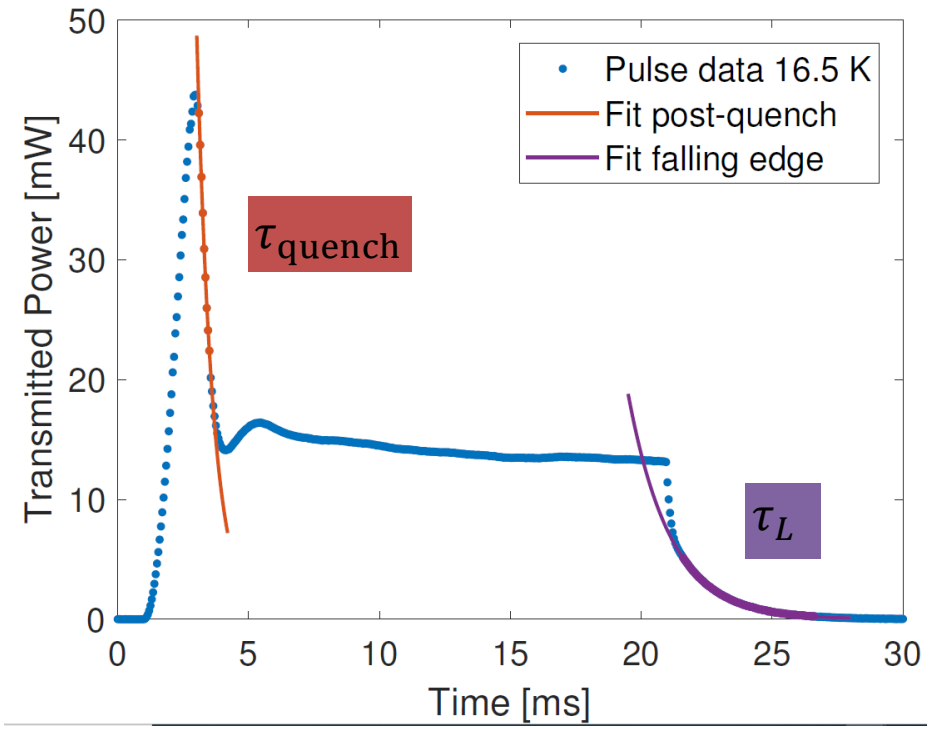
Calculated

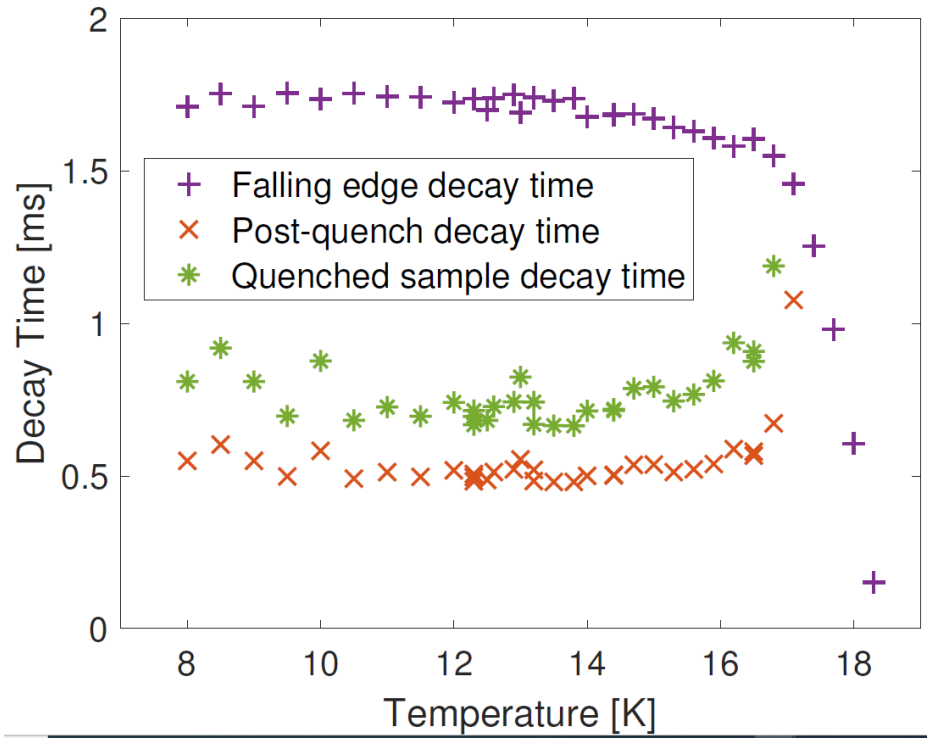
Quench field measurement: RF heating





Quench field measurement: RF heating





$$\tau_{\mathrm{q}} = \frac{\tau_{\mathrm{L}}\,\tau_{\mathrm{quench}}}{\tau_{\mathrm{L}} - \tau_{\mathrm{quench}}}$$

RF Characterization of a Nb_3Sn sample

- Tin diffusion coating process at 1100 °C
  - Cornell University, Ithaca, USA
- ~2 µm of Nb_3Sn on entire surface