Critical Fields of Nb_3Sn

Sebastian Keckert

7th MT meeting
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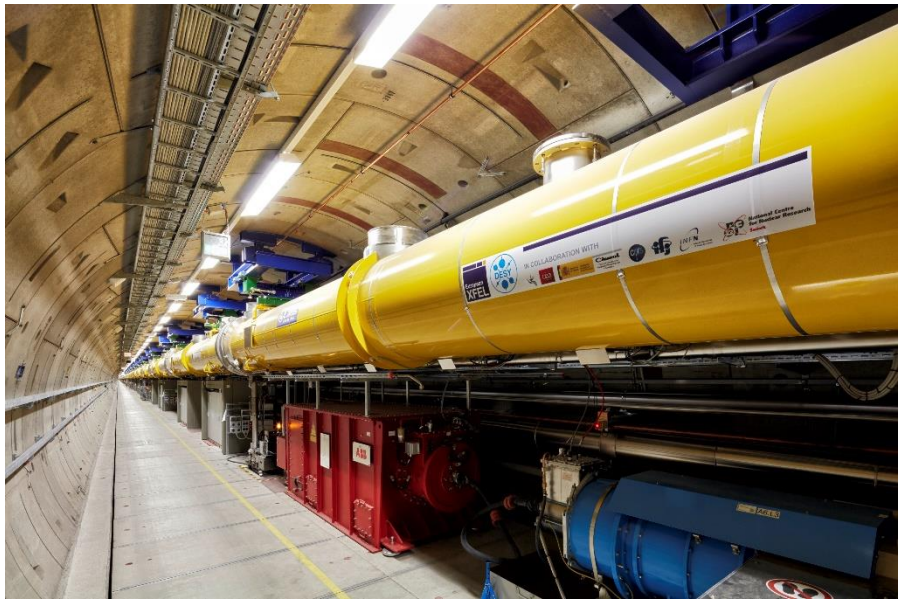
Superconducting Radio Frequency (SRF)

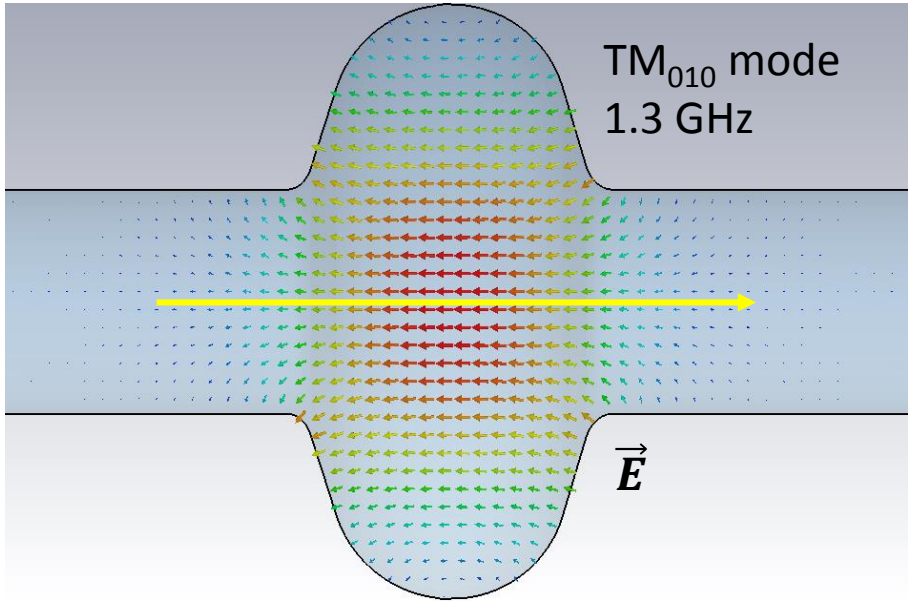


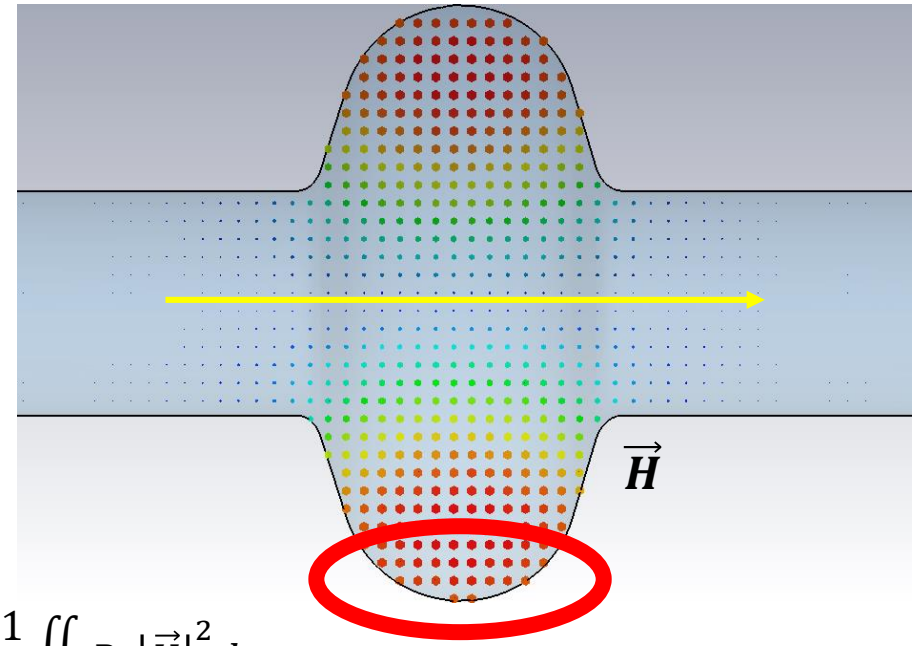
[European XFEL, Hamburg]

[LCLS-II, SLAC]

	European XFEL	LCLS-II
Beam energy	17.5 GeV	4 GeV
RF mode	pulsed, 10 Hz	CW
Acc. gradient	23.6 MV m^{-1}	16 MV m^{-1}

(S) RF cavity





$$P_{\text{diss}} = \frac{1}{2} \oiint_S R_S \left|\vec{H}\right|^2 ds$$

- $R_S \neq 0 \Longrightarrow$ any RF field causes dissipation $\Longrightarrow$ issue for CW machines
- Next issue: magnetic breakdown of superconductivity (quench)

High RF quench fields → metastable operation of Type-II superconductors

- SRF cavity design: $\frac{\mu_0 H_{\mathrm{pk}}}{E_{\mathrm{acc}}} \approx 4 \frac{\mathrm{mT}}{\mathrm{MV/m}}$
- Fundamental limit: RF quench field, breakdown of Meissner phase
- Type-II superconductors: low H_{c1} but high H_{sh}

	T_c	$\mu_0 H_{c1}$	$\mu_0 H_{sh}$	max. E_{acc}
Nb	9.25 K	180 mT	240 mT	56 MV m^{-1}
Nb_3Sn	18 K	38 mT	440 mT	100 MV m^{-1} ?

DC vortex penetration

λ, κ, H_c

RF vortex penetration ?!

Critical Fields

PAUL SCHERRER INSTITUT PSI

TRIUMF

HZB Helmholtz Zentrum Berlin

Muon Spin Rotation

Low energy μSR

Surface μSR

RF Characterization

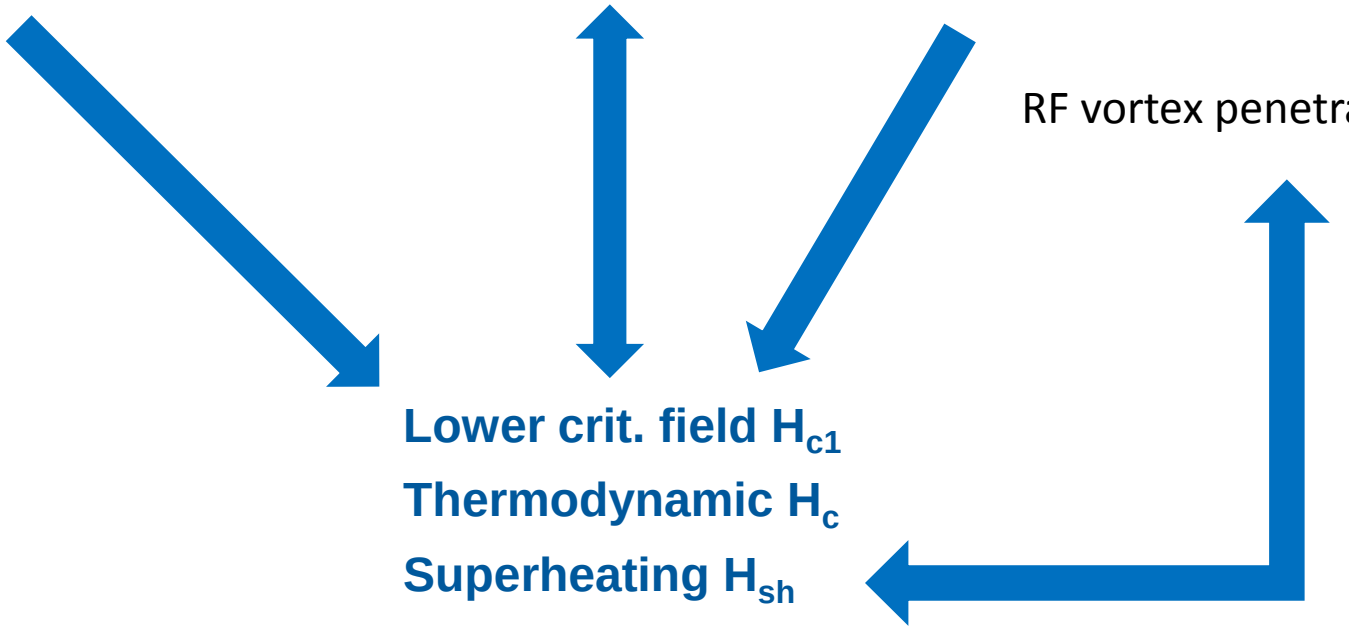
Quadrupole Resonator

DC penetration depth

DC vortex penetration

RF penetration depth

RF vortex penetration



Lower crit. field H_{c1}

Thermodynamic H_c

Superheating H_{sh}

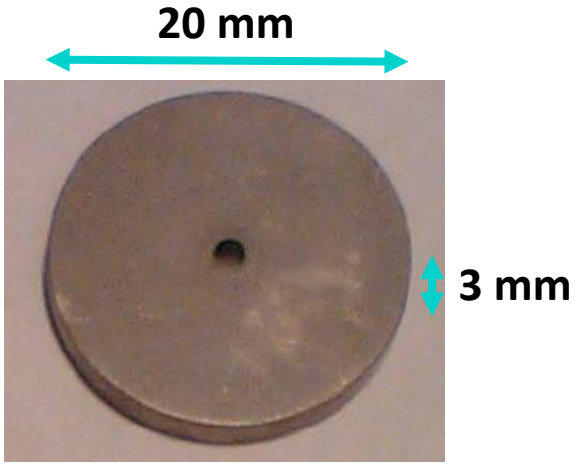
[Supercond. Sci. Technol. 32, 075004 "Critical fields of Nb_3Sn prepared for superconducting cavities"]

Samples

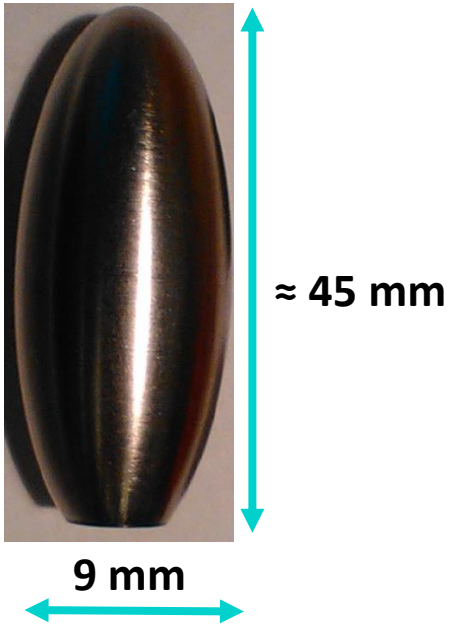
Cornell University

Muon Spin Rotation

Low-energy μSR

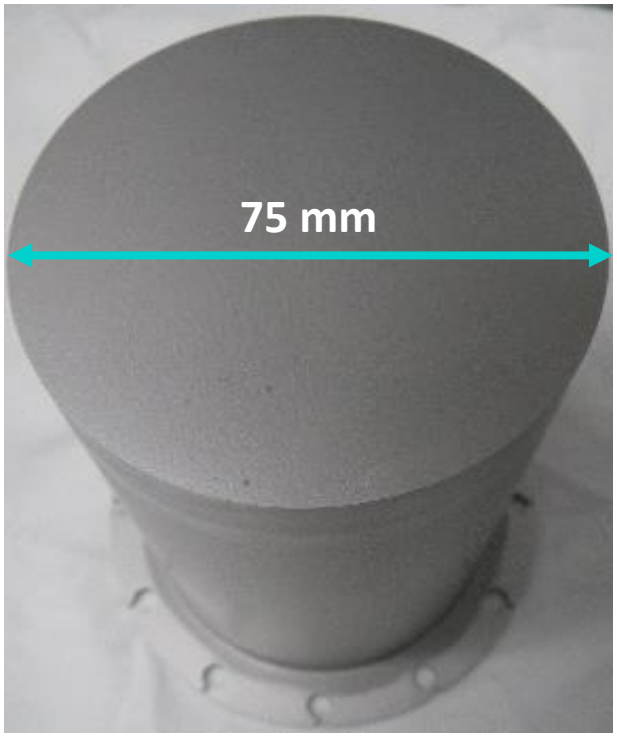


Surface μSR



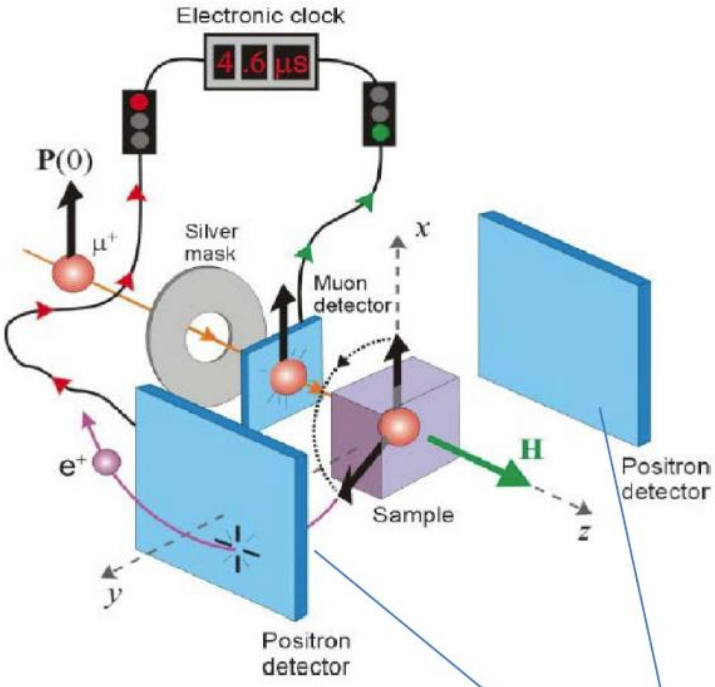
RF Characterization

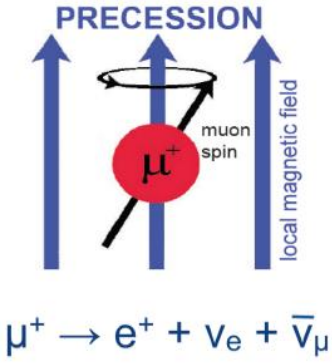
Quadrupole Resonator



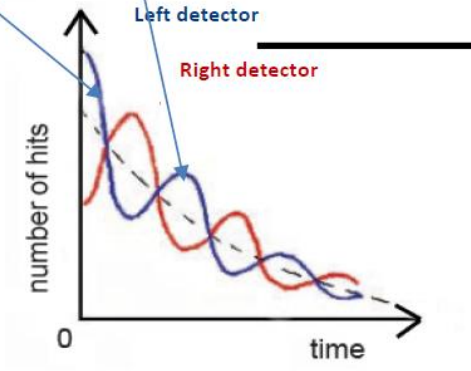
- All substrates: Niobium RRR ≥ 300
- Coatings: ≈ 2μm Nb_3Sn by vapor diffusion, Cornell „standard procedure“

Muon Spin Rotation (μSR)



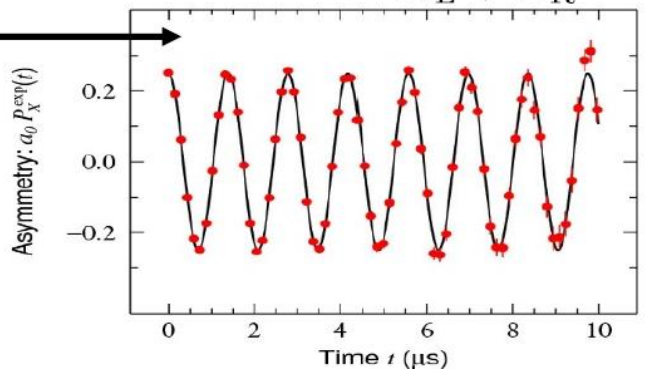


$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$



- 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

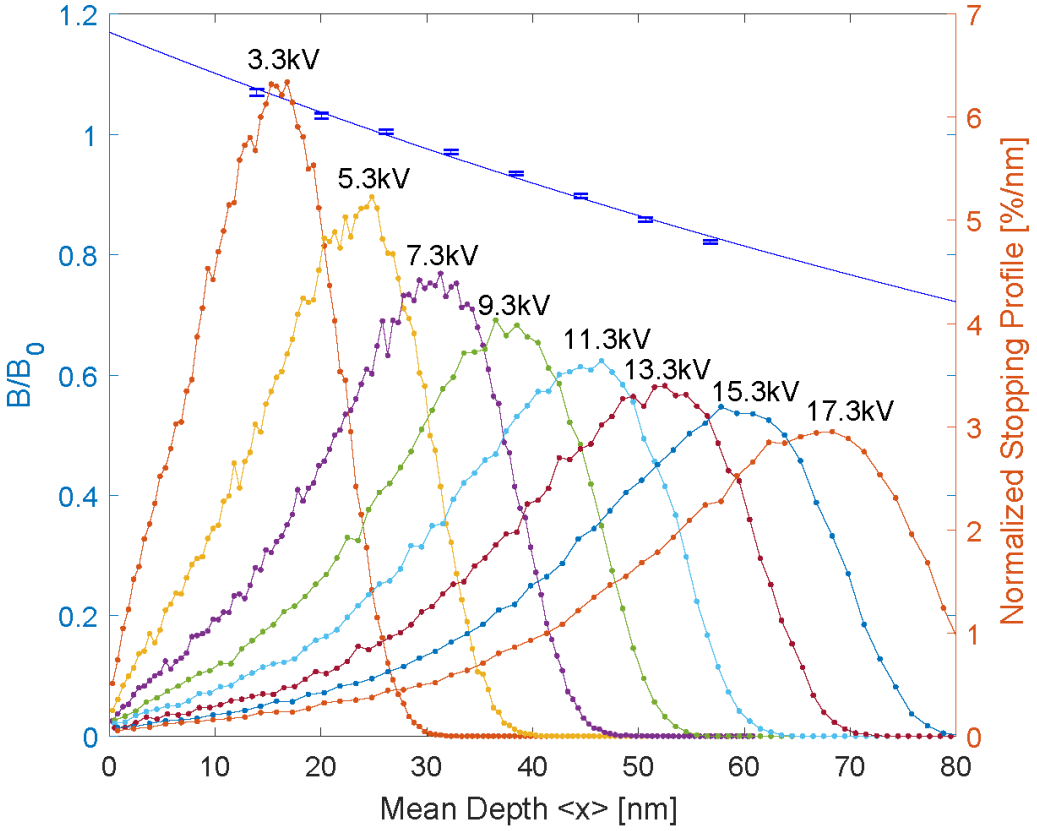
$$a_0 P_y(t) = \frac{N_L - N_R}{N_L + N_R}$$



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

DC penetration depth

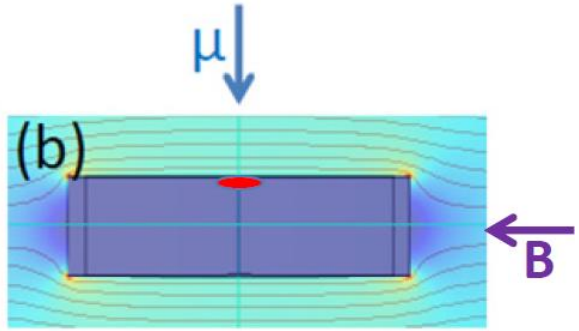
- Low-energy μSR @ PSI
- Constant ambient conditions: $T = 5\mathrm{K}$, $\mu_0 H_{\mathrm{ext}} = 10\mathrm{mT}$
- Measure local magnetic field as a function of muon implantation depth



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

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

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

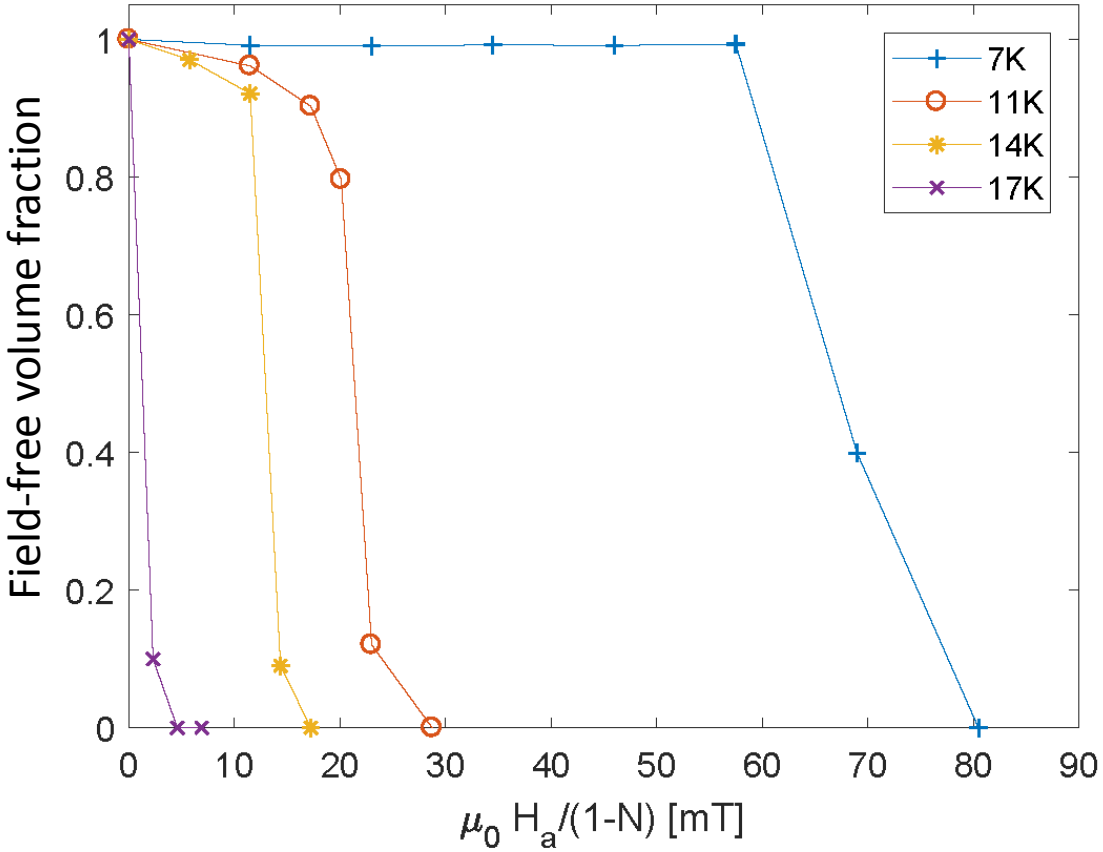


[T. Junginger, R. Laxdal, „Muon Spin Rotation Studies of Niobium and Other SRF Materials“, SRF 2019]

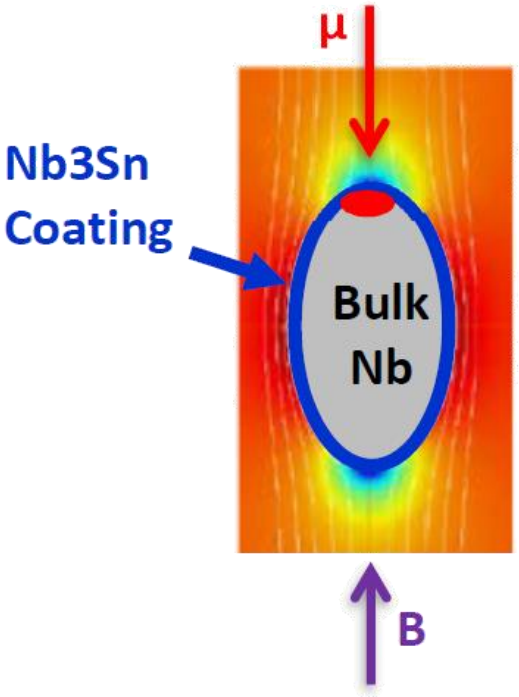
DC flux penetration

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

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

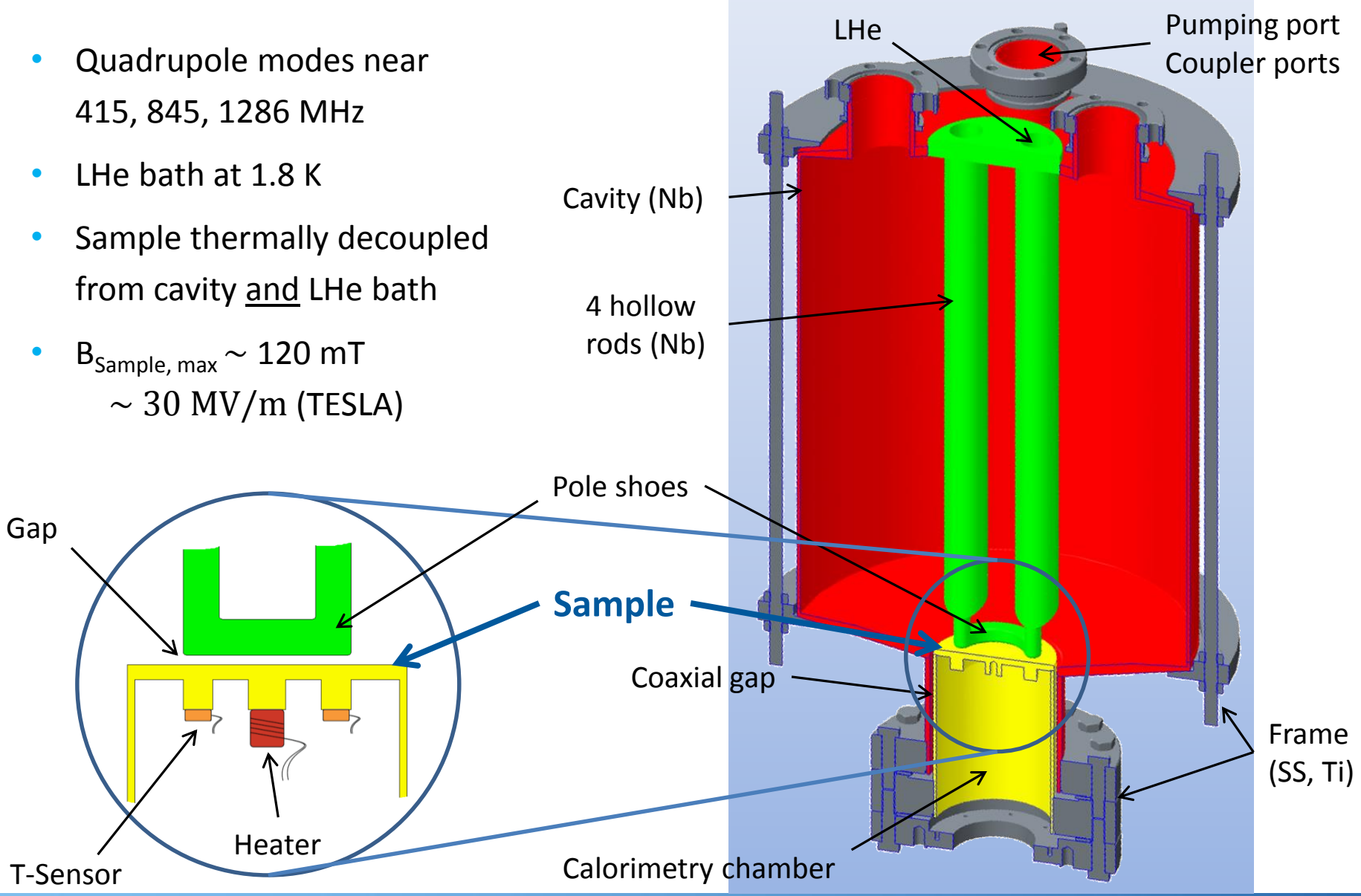


$$\mu_0 H_{\mathrm{vp,DC}} = (28 \pm 12)\ \mathrm{mT}$$



The Quadrupole Resonator (QPR)

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

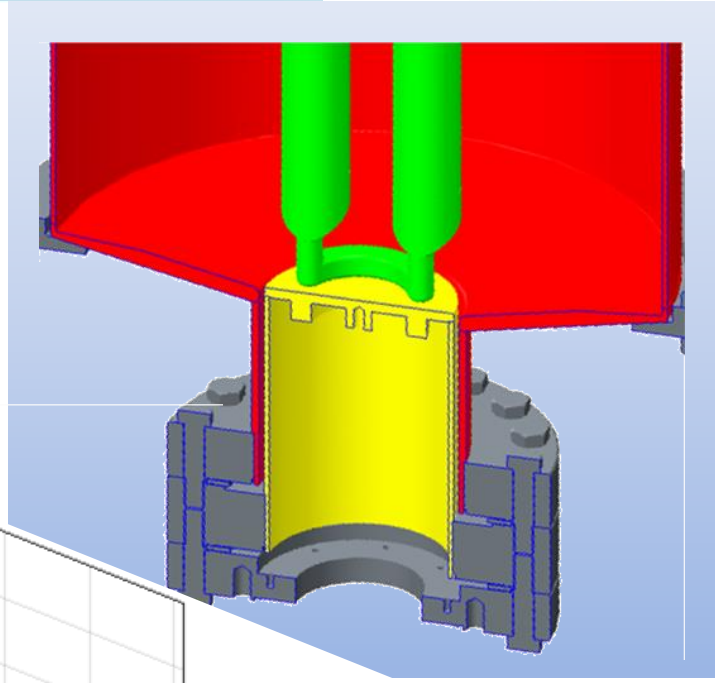


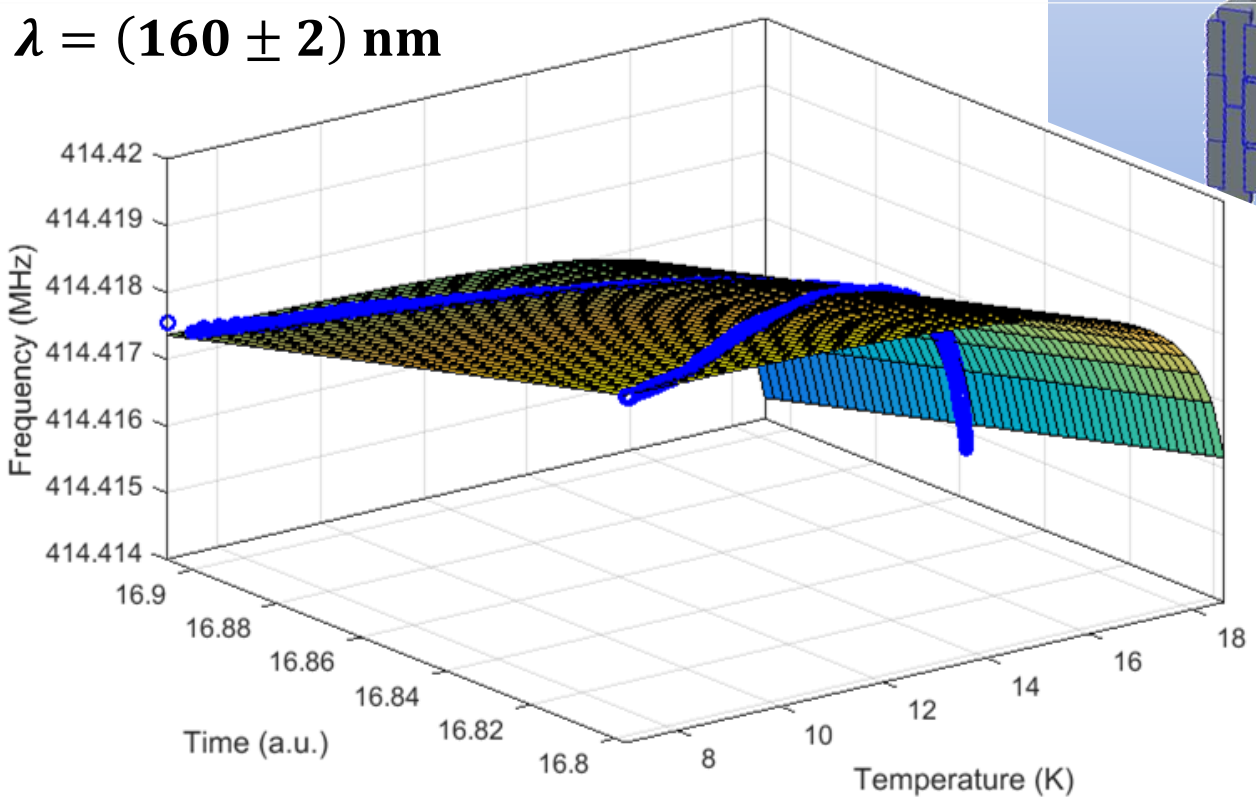
RF penetration depth

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

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

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

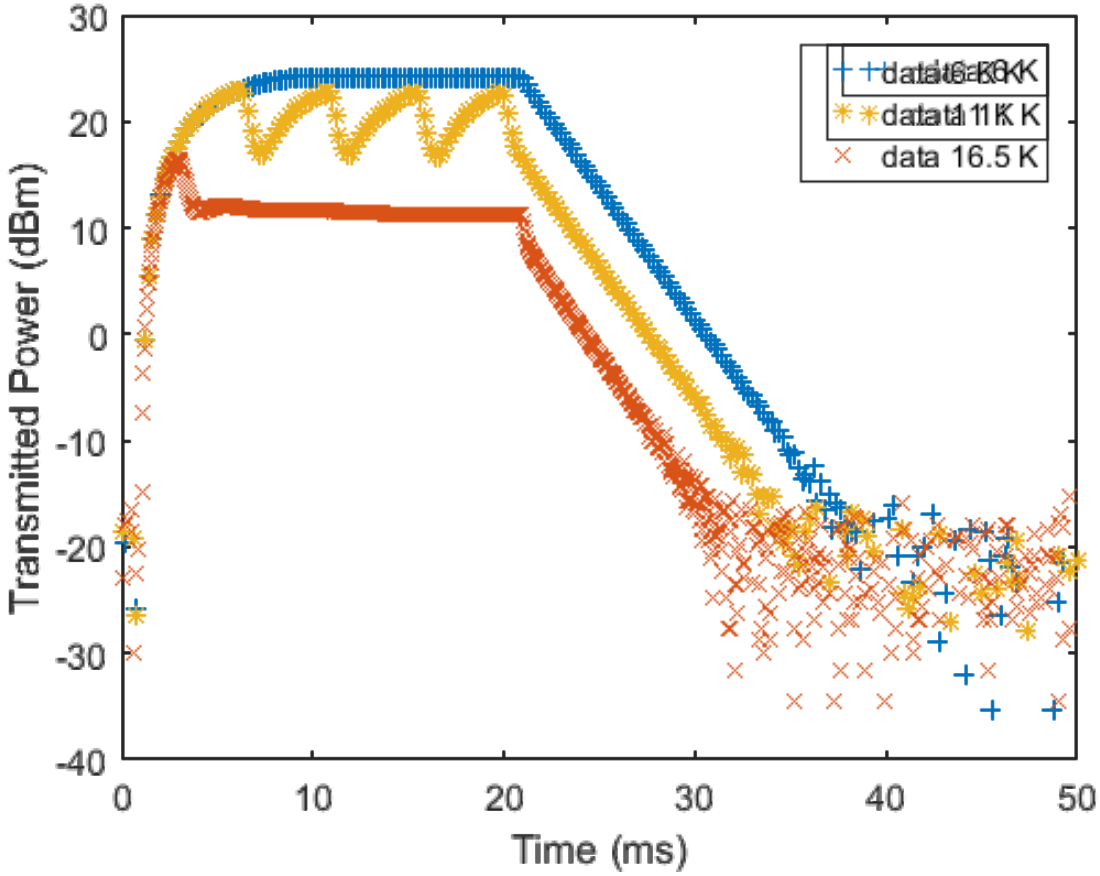




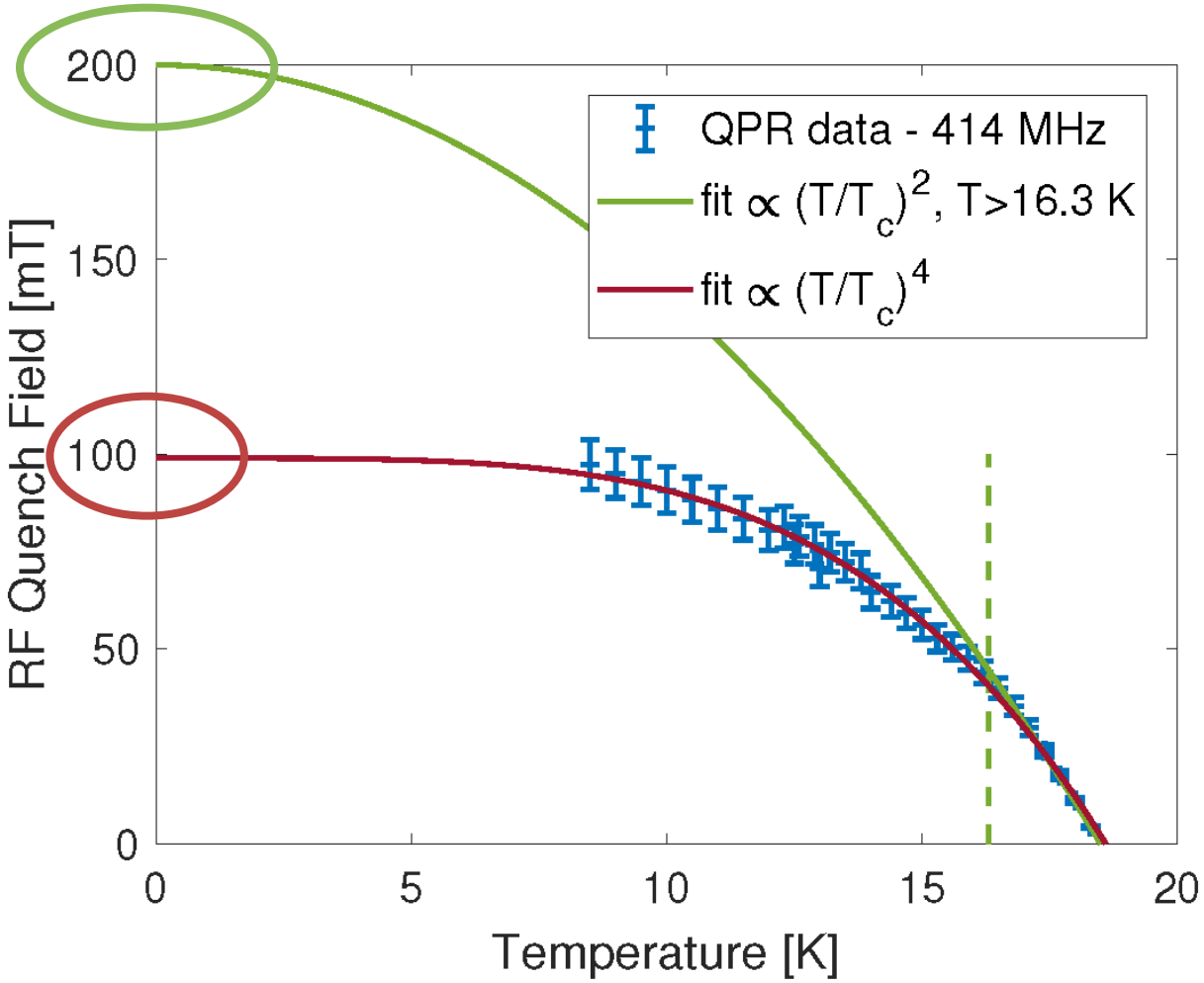
RF quench field

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

- 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

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

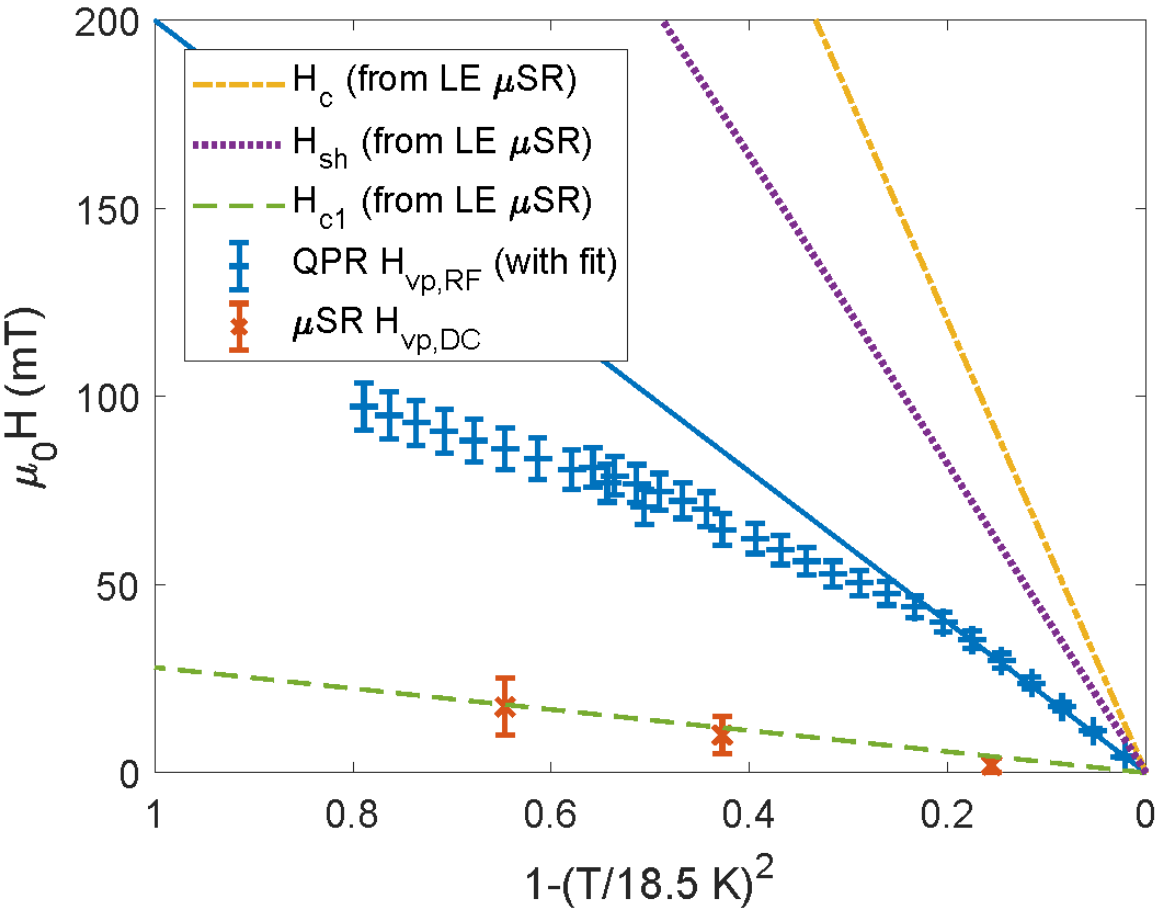
However:

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

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

Critical fields of Nb_3Sn prepared for superconducting cavities

HZB Helmholtz Zentrum Berlin

S. Keckert, T. Junginger, O. Kugeler, J. Knobloch

TRIUMF

T. Junginger, T. Buck, P. Kolb, R. Laxdal

Cornell University

D. Hall, M. Liepe, S. Posen

PAUL SCHERRER INSTITUT PSI

T. Prokscha, Z. Salman, A. Suter

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