Critical Fields of Nb₃Sn

Critical Fields

Muon Spin Rotation
Low energy $\mu$SR
- DC penetration depth

Surface $\mu$SR
- 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$_3$Sn prepared for superconducting cavities”]
All substrates: Niobium RRR ≥ 300
Coatings: ≈ 2μm Nb₃Sn by vapor diffusion, Cornell „standard procedure“
Muon Spin Rotation (µSR)

- TRIUMF SRF group has been 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

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

[Precession]

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

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

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

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

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

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

[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$_3$Sn

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

$$\mu_0 H_{vp,DC} = (28 \pm 12) \text{ mT}$$
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
- $B_{\text{Sample, max}} \sim 120$ mT
  $\sim 30$ MV/m (TESLA)
RF penetration depth

\[ \lambda(T) = \frac{\lambda(0 \text{ K})}{\sqrt{1 - (T/T_c)^4}} \]

\[ \lambda(T) = \lambda_0 - \frac{G_{\text{Sample}}(f)}{\pi \mu_0 f^2} \Delta f \]

\[ \lambda = (160 \pm 2) \text{ nm} \]
RF quench field

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

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

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

with

\[ B_0 = \mu_0 H_{sh} \approx 500 \text{ mT} \]

However:

\[ B_0 \gg \mu_0 H_{c1} \approx 28 \text{ mT} \]

Bulk Nb baseline:

\[ B_{vp} = 220 \text{ mT} \]
4 labs, 3 measurement setups

3 samples with comparable substrates and coatings

$H_{vp,DC}$ is consistent with $H_{c1}$

$H_{vp,RF} \gg H_{c1}$

→ Metastability for RF fields

→ Still well below $H_{sh}$

<table>
<thead>
<tr>
<th>$\lambda$ [nm]</th>
<th>$\mu_0 H_{c1}$ [mT]</th>
<th>$\mu_0 H_c$ [mT]</th>
<th>$\mu_0 H_{sh}$ [mT]</th>
<th>$\mu_0 H_{vp,DC}$ [mT]</th>
<th>$\mu_0 H_{vp,RF}$ [mT]</th>
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</thead>
<tbody>
<tr>
<td>LE-µSR, QPR</td>
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<tr>
<td>160 ± 4</td>
<td>28 ± 2</td>
<td>600 ± 100</td>
<td>500 ± 120</td>
<td>28 ± 12</td>
<td>200 ± 5</td>
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</table>
Critical fields

\[
\lambda(T) = \frac{\lambda(0 \text{ K})}{\sqrt{1 - (T/T_c)^4}}
\]

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

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

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

\[
H_{sh} = H_c \left( \frac{\sqrt{20}}{6} + \frac{0.55}{\kappa} \right)
\]
Quench field measurement: RF heating

- **Graph 1**: Transmitted Power vs. Time [ms]
  - **Data Points**: Pulse data 16.5 K
  - **Lines**: Fit post-quench, Fit falling edge

- **Graph 2**: Decay Time vs. Temperature [K]
  - **Pluses**: Falling edge decay time
  - **Crosses**: Post-quench decay time

S. Keckert, 10.11.2020
Quench field measurement: RF heating

\[ \tau_q = \frac{\tau_L \tau_{\text{quench}}}{\tau_L - \tau_{\text{quench}}} \]
RF Characterization of a Nb$_3$Sn sample

- Tin diffusion coating process at 1100 °C
  - Cornell University, Ithaca, USA
- ~2 μm of Nb$_3$Sn on entire surface