beta-SRF Highlights

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Outline

• Introduction/Motivation
• Beta-NMR Technique
• Results Highlights
• Summary & future outlook
SRF Cavities Performance

- **Ultimate Goal:**
  - high $Q \rightarrow$ cheaper operation
  - high gradient $\rightarrow$ shorter LINAC

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

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

- **Achieving ideal performance**
  - Accel. Gradient limit:
    - Sustain Meissner phase to the limiting field ($B_{\text{limit}}$)
  - Screened magnetic fields within $\lambda$

- **How do the subsurface variations & modifications affect**
  - Meissner limiting field: $B_{\text{limit}}$ ?
  - Screening response: $\lambda$ vs. treatment ?
  - Field dependence: $\lambda$ vs. $B_{\text{app}}$ ?
SRF Samples Characterization

- **Requirements:**
  - *local field* within the London layer
  - *depth-resolved* (within ~ 100 nm): $B(x)$
  - up to $B_{\text{limit}}$ ~ 200 mT: $B(x)$ vs $B_{\text{applied}}$

- **Radioactive spin-polarized ions**
  - ion implantation $E \rightarrow$ nm-scale, depth-resolved
  - asymmetric radioactive decay → direct monitor of spin-polarization
  - local field → evolution of spin-polarization

- **Two facilities at TRIUMF**
  - HE-$\mu$SR: bulk probe (100 µm)
  - $\beta$-NMR: nm depth resolved (0 – 100 nm)

**β-SRF beamline:**
- high-parallel fields (200 mT)
- nm-scale depth resolved
- local field measurements
βSRF beamline

Main challenge

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

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The beta-SRF Experiments

SAMPLES

Two Nb samples measured: RRR Niobium

- **“Baseline”**: 
  - 1400 °C annealing for 4 hours + BCP
- Custom treated with mid-T bake ("Oxygen doped"): 
  - “Baseline” + 400°C for 3 hours
- Field screening with applied fields 100 → 200 mT
A) Spin-lattice relaxation rate

1. Depth-resolved:
   - Varies implantation energies
   - Energy ~ depth

2. Local field sensitivity:
   - Probes spins depolarizes in sample → direct monitor $\beta$-decay
   - Char. depol. time = SLR rate $1/T_1$
   - Local B-field “slows-down” relaxation

\[
\frac{1}{T_1} = \frac{a}{b + B^2}
\]
A) Spin-lattice relaxation rate data

3. Increase $B_{\text{applied}}$: 

Baseline

![Graph showing 1/T1 vs. E for Baseline with lines for 100 mT and 200 mT]

O-doped

![Graph showing 1/T1 vs. E for O-doped with lines for 100 mT and 200 mT]
Due to stopping distribution:

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

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

\[
B(x) = B_{surf} \exp\left(-\frac{(x - \tilde{d})}{\tilde{\Lambda}}\right)
\]

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

\( B_{surf} \) (Meissner)

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

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

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

Different screening between the two samples
B) Average Field Results

Baseline

No screening at 200 mT

Screening diminishes with increasing fields

O-doped

\[ B_{\text{app}} \text{[mT]}: \]
- 100
- 110
- 125
- 150
- 200

\[ \langle B \rangle \text{ (mT)} \]

E (keV)

E (keV)
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: \( \langle 1/T_1 \rangle_E \rightarrow \langle B \rangle_E \)
- Map \( B(x) \) to \( 1/T_1(x) \): more accurate modified Lorentzian \( \mathcal{L}^* \)
  (different probe vs. Nb nuclear spins)
- Same \( B(x) \) model

\[
B(x) = B_{surf} \exp\left(-\left(x - \bar{d}\right)/\bar{\Lambda}\right)
\]

\[
\frac{1}{T_1}(x) = \mathcal{L}^* \left[B(x)\right]
\]

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

100 mT, 200 mT

Calculated

Measured

Best \( \mathcal{L}^* \)

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

- \( \bar{\Lambda}(B_{app}) \): screening penetration depth
- \( B_{surf}(B_{app}) \): enhanced field at surface
C) Local Field Analysis Results

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

Baseline

O-doped

![Graph showing magnetic field (B) as a function of depth (x) for different applied fields (B_{app}) in Baseline and O-doped samples. The dead layer is indicated by a shaded area.]
Results: Field-dependent Screening Penetration Depth (\(\Lambda\))

\[ \lambda(0K) = \lambda_L \sqrt{1 + \frac{\xi_0}{L}} \]

\(\Lambda = \langle \lambda, n_v(x) \rangle\)
- \(\lambda\): Meissner
- \(n_v(x)\): Vortex

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<th>(\Lambda) (O-doped) (nm)</th>
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Results Highlights: Meissner Region

Flux entry detection via
- reduced surface enhancement $B_{surf}$
- Define $\chi [0,1]$, ~ flux free volume fraction:
  - $\chi = 1$ (Meissner)
  - $\chi < 1$ (mixed state)
  - $\chi = 0$ (vortex state)

Brandt's formulation:
$B_{entry} = B_{c1} \times \tanh(\sqrt{0.36 \times c/a})$
- Baseline: 121 mT
- O-doped: 127 mT

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Interesting Features: Strong Field Dependence (O-doped)

- Meissner region @ B = 100-125 mT:

- Field dependence due to $T_c$
  - Two-fluid model: $\lambda$ diverges at $T_c$
    
    $$\lambda(T) = \frac{\lambda(0)}{\sqrt{1-(T/T_c)^4}}$$

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

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

- $T_c$ varies with O-concentration
  

- Best-fit value of $T_c$, 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:

\[
\beta = \frac{\kappa(\kappa + 2^{3/2})}{8(\kappa + 2^{1/2})^2}
\]  

- predicts \(\beta \approx 0.12\). Best-fit at \(\beta \approx 3\), prefactor 25x larger than GL

- **combined NLME + reduced Tc:**

- if \(\beta_{\text{max}}\) bounded to \(\beta = 1 + \text{vary } T_c\), best fit for \(T_c \approx 7\)K due to e.g., O-concentration \(\sim 2\) [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. Proslie, CEA Saclay)
   ❖ Measured at perp. field spectrometer (4.1 T) → study vortex state
   ❖ Characterize suitable measurement conditions for β-SRF beamline (B_∥ ≤ 200 mT)

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