β-SRF

A Facility for Depth-Resolved Characterization of the Magnetic Field Screening in Superconducting RF Materials

Edward Thoeng

Md. Asaduzzaman, R.M.L. MacFadden

P. Kolb, G.D. Morris, J.O. Ticknor, S. Dunsiger, V.L. Karner,

D. Fujimoto, T. Junginger, R. Li, S. Saminathan

R. F. Kiefl, W.A. MAcFarlane, R.E. Laxdal

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THE UNIVERSITY OF BRITISH COLUMBIA UBC

University of Victoria

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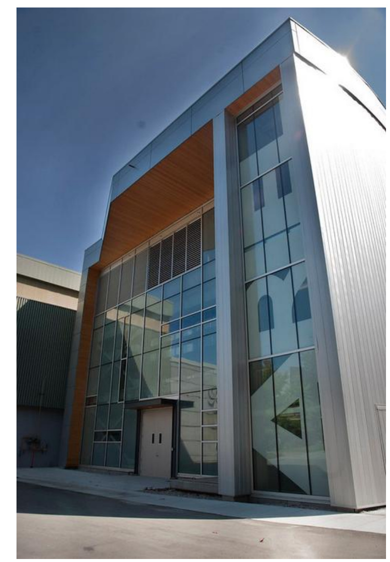
TRIUMF Facilities

TRIUMF:

- Canada's Particle Accelerator Centre
- At southern tip of UBC Campus.
- Home of the **world's largest cyclotron & μSR Facility**.

Isotope Separator and ACcelerator (ISAC):

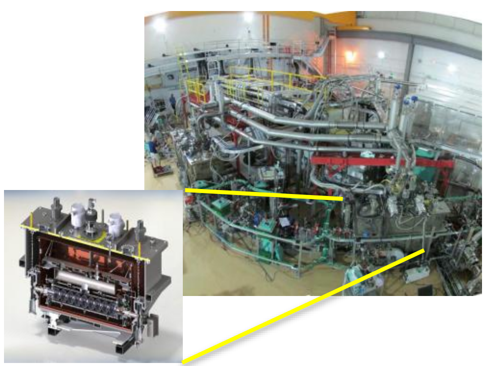
- Produces rare-isotope beam.
- Hosts **β-NMR Facility**
- Home of **superconducting post-accelerator**



ARIEL Project:

Superconducting electron linear accelerator (e-LINAC)

Triple rare isotope beam → world's most powerful ISOL complex



SRF Technology

RF Acceleration:

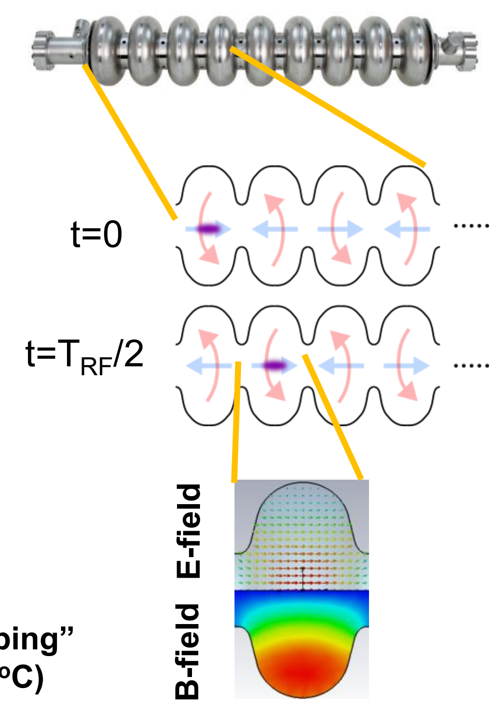
- synchronize **particle 'bunches' (beams)** ⇔ crest of **RF field**.

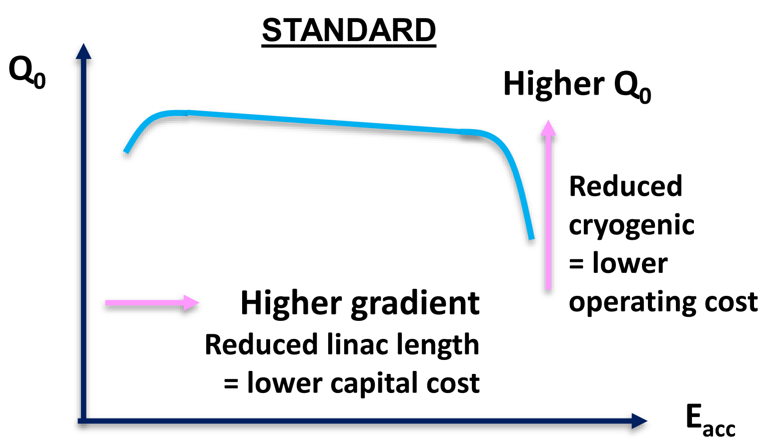
RF Cavities:

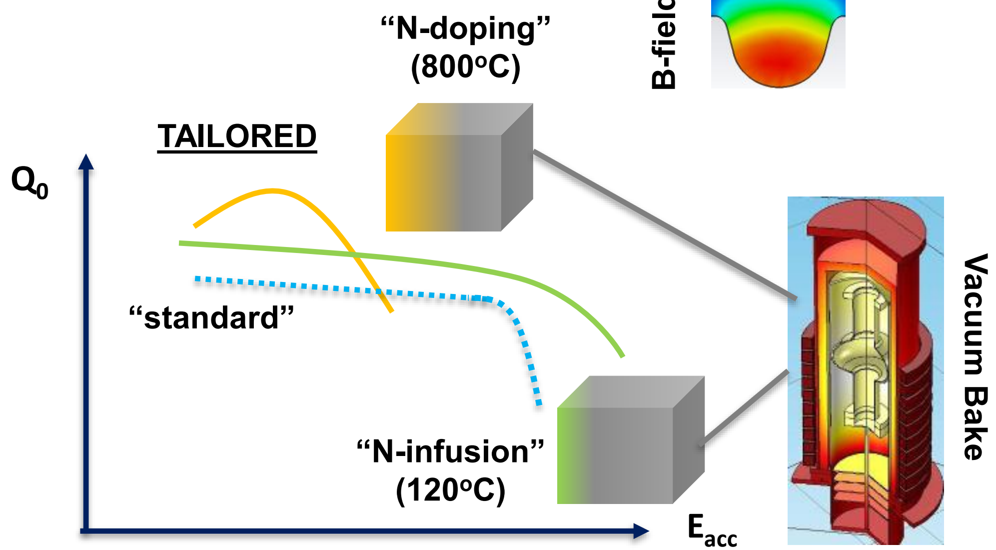
- store + transform RF energy → beam energy
- More efficient acceleration → higher energy @ shorter distance
  = increase **accelerating gradient (E_{acc})**
  → increase of dissipation from **surface B-field B_{surf}**.

Superconducting RF (SRF) Cavities

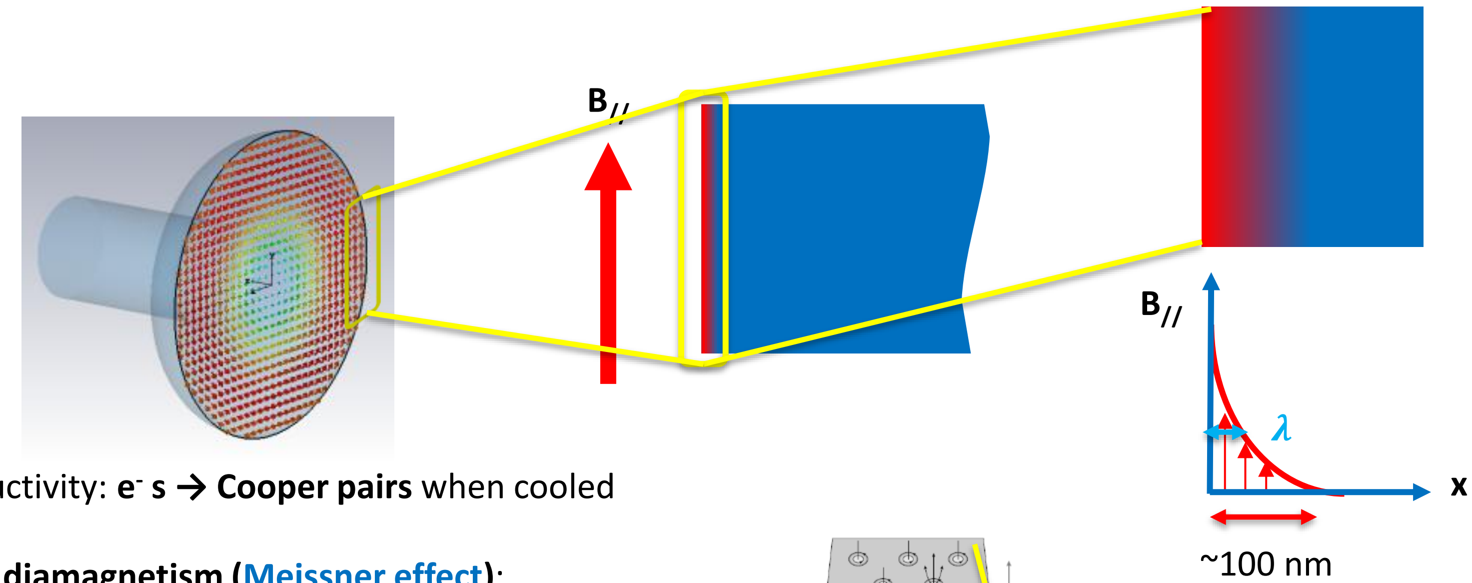
- **Five orders of magnitude lower dissipation**
- Main technology **high power + high energy accelerators**
- Performance = **Q vs E curve**:
  - **"standard practice" → "tailored recipes"**







Superconductivity Fundamentals



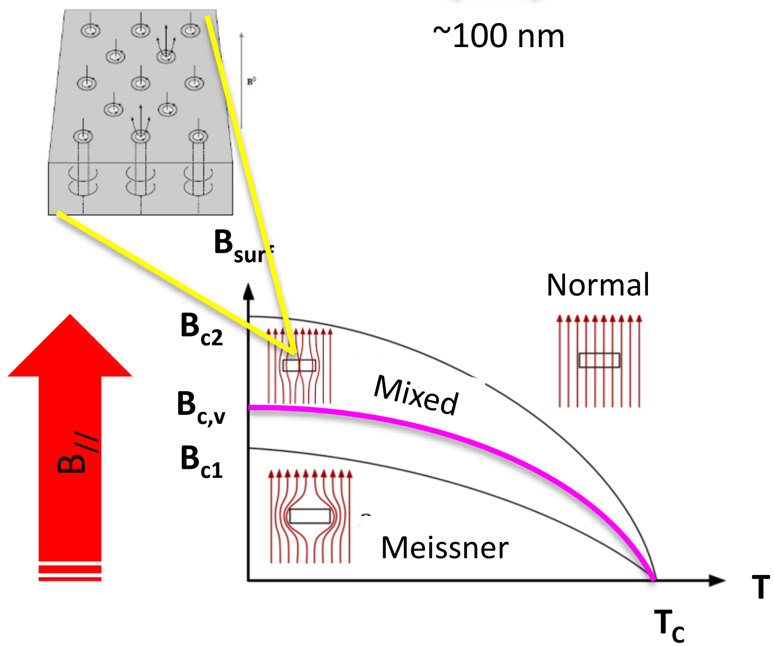
Superconductivity: **e⁻ s → Cooper pairs** when cooled below **T_c**.

- **Perfect diamagnetism (Meissner effect):**
  B_{surf} screened within **~ 100 nm** (λ).
- Zero DC resistivity. Small but **finite RF Surface Resistance R_s** contained **within** λ.

SRF cavity → **Niobium (type-II superconductor):**

- **Highest T_c** (~ 9.2 K for Nb) for elemental SC
- **Highest B_{c1}** of all SC.
  - Real **$B_{c,v}$** surface dependent **(~ 200 mT)**
  - Determines **max. E_{acc}**.

SRF regime → Meissner Phase
Max E_{acc} → $B_{c,v}$



Ideal SRF Probe

<u>We need to measure:</u>

- **Field screening B(x) within** ~100 nm
  - ➢ **Implant spin-polarized ions**
- $B_{//}$ as in SRF cavity + up to $\mathbf{B_{c,v}}$ **~ 200 mT**
  - ➢ **No facility prior to this thesis → *β*-SRF** (*β*-NMR + SRF)
  - ➢ **Heavier Li-8 ions → less transverse deflection.**

<u>Spin-Lattice Relaxation (SLR):</u>

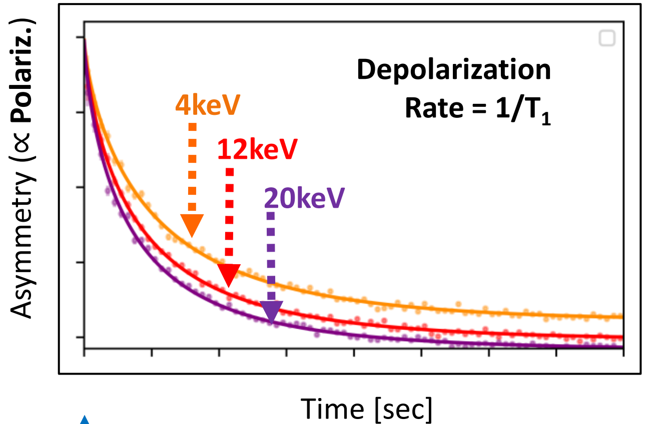
- Time evolution of **probes' spin relaxation,** via **beta-decay anisotropy (Asymmetry of detector counts ∝ P(t))**
- SLR rate $\mathbf{1/T_1}$

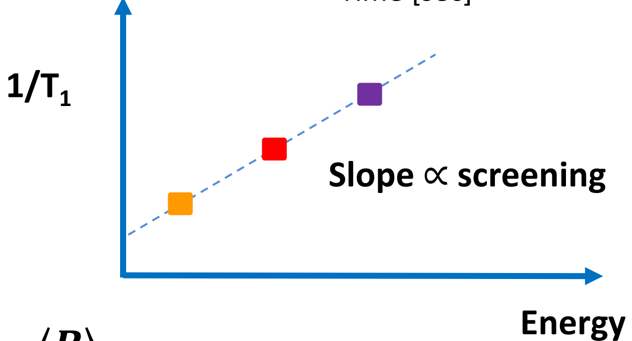
<u>Obtain magnetic field profile B(x):</u>

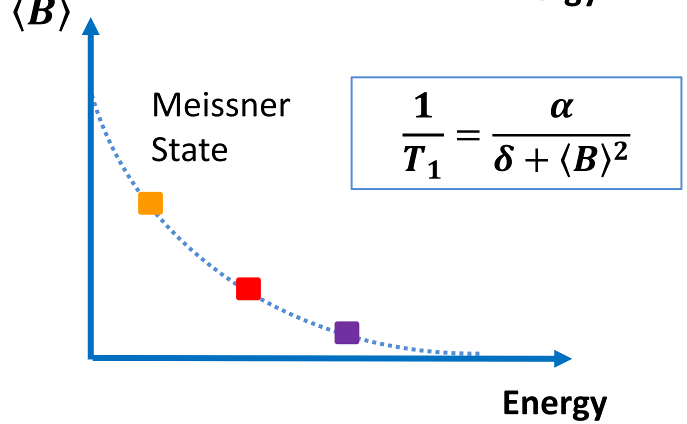
- **Stopping depth x ∝ E → $1/T_1$ vs. E**
- Measure **local** $\langle B \rangle$:

  for $B_{app} \ll 1T$, **local $\langle B \rangle$ slows down relaxation**
- **Implantation distribution $\rho_E(x)$ averaging**

$$\langle 1/T_1 \rangle_E = \int_0^{\infty} \rho_E(x)\, 1/T_1[B(x)]dx$$

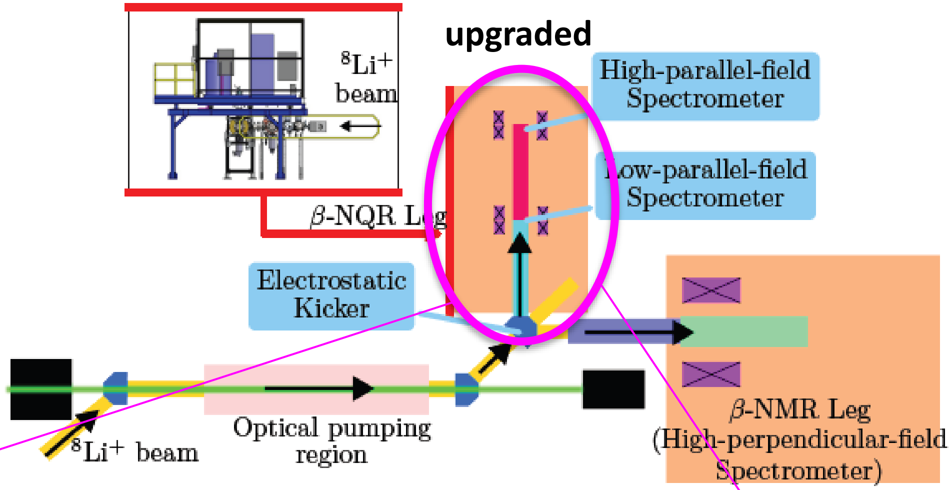


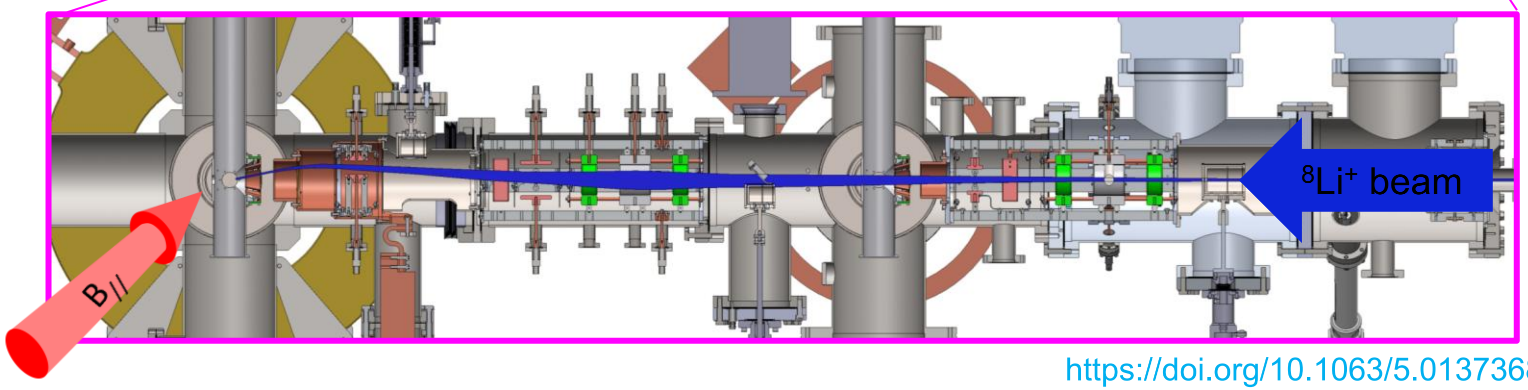




β-SRF beamline

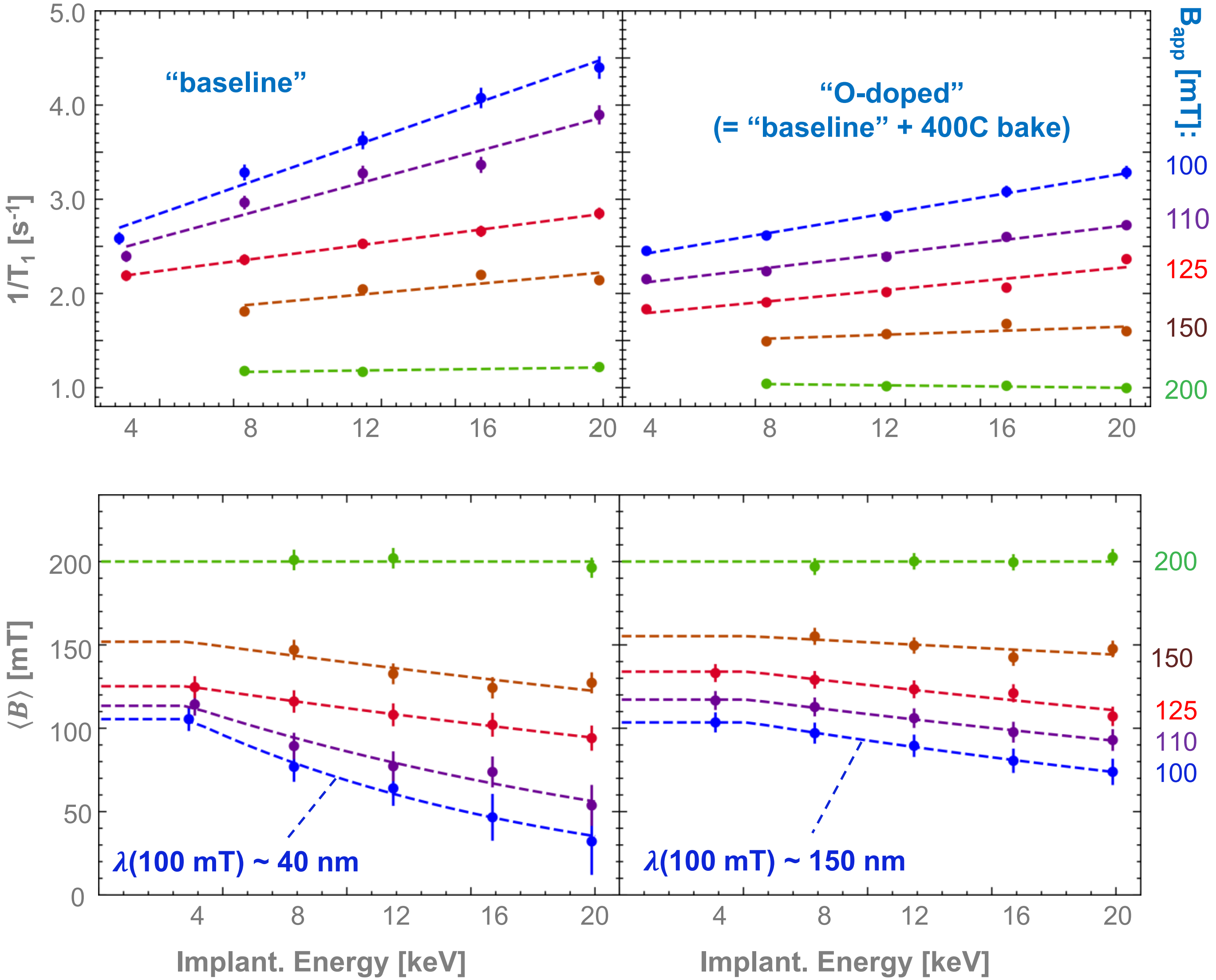
1. **β-NMR Facility:**
   - Spin-polarized $^8Li^+$ beam @ **ISAC Facility**
2. **β-SRF Beamline**:
   - New magnet: 24 mT → **200 mT**
   - New ion optics: +1 m section (**strong transverse deflection**)





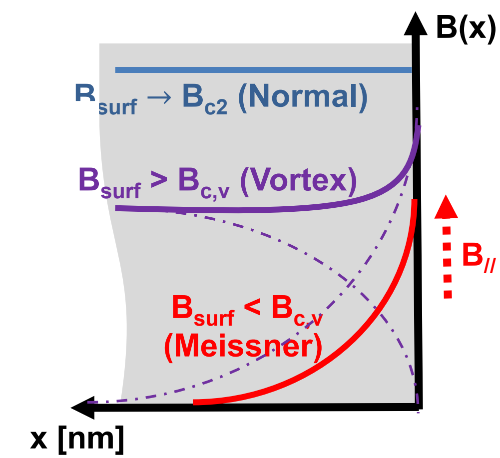
https://doi.org/10.1063/5.0137368

β-SRF First Results



Two Nb Samples:

- Distinct **field screening** → "clean" vs. "dirty" SC surface.
- Distinct **field dependence** λ vs. B_{app} → Q_0 vs E_{acc}.
- Detect **flux/vortex entry** → $B_{c,v}$ → max. E_{acc}.



https://doi.org/10.1038/s41598-024-71724-5

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July 22nd, 3:40 PM

Contribution ID: **24** Type: **Poster Presentation**

β-SRF —A Facility for Depth-Resolved Characterization of the Magnetic Field Screening in Superconducting RF Materials

A new beamline called "β-SRF" has been built at TRIUMF, allowing for the near surface characterization of materials with β-radiation-detected nuclear magnetic resonance (β-NMR) in applied magnetic fields up to 200 mT parallel to the sample surface. These capabilities are relevant for the study of Nb superconducting radiofrequency (SRF) cavities - common components in particle accelerators - where subtle modifications to their subsurface (i.e., the first ~100 nm) due to processing can drastically affect their RF dissipation and limit their maximum accelerating gradient. Understanding the mechanisms behind these surface modifications is imperative for large scale superconducting linear accelerators (linacs), as they impact both their capital and operating costs. Here, the details of the "β-SRF" beamline, along with its first measurements on two Nb samples with surfaces that mimic high-performance SRF cavities, are presented. The samples show contrasting evolution in their magnetic field screening as the applied field is increased. These unique measurements provide insight into how the impurities generated from cavity surface treatments affect Meissner screening in Nb, as well as how this dissipative field penetration evolves with increasing field.

ıtribution ID: **99** Type: **Poster Presentation**

Nanoscale Measurement of Superconducting N Intrinsic Length Scales Using Low-Energy μSF

\ superconductor's intrinsic length scales –the London penetration depth λ_L and Bardeen-(
ichrieffer (BCS) coherence length ξ₀ –are closely connected to its electronic structure and g
alient features such at its Meissner response. Leveraging recent advances in the preparation [1] and cha
zation [2] of Nb metal for technical applications (e.g., superconducting radiofrequency accelerator ca
ve quantify the elemental superconductor's λ_L and ξ₀ from depth-resolve
urements of its Meissner profile using low-energy muon spin spectroscopy (μSR). Accounting for knov
ematics [3] and subtleties [4] in the measurements, we find values for the lengths that are ~10 nm shorte
hose nominally quoted for the metal (see, e.g., [5]), but in good agreement with predictions from elec
tructure calculations and compatible with independent measurements of Nb's mass-enhancement fa
Jsing our results, we comment on the recently proposed type-I superconductivity of *pure* Nb [6].

Contribution ID: **41** Type: **Poster Presentation**

Review of μSR and β-NMR Studies on Superconductors for Radiofrequency Accelerator Technology

The performance of superconducting cavities in particle accelerators is limited by magnetic flux behavior in the near-surface region, where radiofrequency currents flow. Muon spin rotation (μSR) and beta-detected nuclear magnetic resonance (β-NMR) are uniquely suited to investigate this regime, offering access to local magnetic properties with depth resolution on the nanometer scale. This contribution reviews how these techniques have been applied to study the field of first vortex penetration, magnetic pinning, Meissner screening, and magnetic impurities in materials such as niobium, Nb_3Sn, MgB_2, and NbTiN-based heterostructures. Surface μSR enables characterization of bulk flux entry and pinning strength, while low-energy μSR and β-NMR reveal detailed screening profiles, impurity effects, and interface phenomena. These measurements provide microscopic insight into how surface treatments and material layering influence the stability of the superconducting state under high parallel magnetic fields. The results help inform material development strategies aimed at achieving higher accelerating gradients and reduced losses in next-generation particle accelerators.

July 24th, 10:40 AM

Contribution ID: **122** Type: **Poster Presentation**

Superconducting Properties of Thin Film $\mathrm{Nb_{1-x}Ti_xN}$ Studied via the NMR of Implanted ^{8}Li

We present a study of the normal-state and superconducting properties of thin-film $\mathrm{Nb_{1-x}Ti_xN}$ using depth-resolved ^{8}Li β-detected nuclear magnetic resonance (β-NMR). Spin-polarized $^8\mathrm{Li}^+$ ions were implanted ~21 nm into a $\mathrm{Nb_{0.75}Ti_{0.25}N}$(91 nm)/AlN(4 nm)/Nb sample, with their NMR response recorded at temperatures between 4.6 K to 270 K under a 4.1 T field applied normal to the film surface. The resonance spectra exhibit broad, symmetric lineshapes at all temperatures, with additional broadening observed below the superconducting transition temperature $T_c \approx 15$ K attributed to vortex lattice formation. Lineshape broadening analysis yields the film's magnetic penetration depth λ and upper critical field B_{c2}, whose values are in good agreement with literature estimates. Spin-lattice relaxation (SLR) data reveal Korringa behavior at low temperatures, with thermally activated dynamics dominated above ~100 K. Below T_c, a small Hebel-Slichter coherence peak is observed, characterized by a 2.60 meV superconducting energy gap and modest Dynes-like broadening, consistent with strong-coupling superconductivity. These results provide a foundation for future studies of the Meissner-to-vortex transition in $\mathrm{Nb_{0.75}Ti_{0.25}N}$/AlN/Nb heterostructures, which is relevant for next-generation Nb superconducting radiofrequency (SRF) cavities (common components of particle accelerators).

Contribution ID: **97** Type: **Poster Presentation**

Insight into Low-Temperature Surface Treatments Used to Prepare Nb SRF Cavities from Low- Energy μSR

Surface treatments are an integral step in the preparation of superconducting radiofrequency (SRF) cavities fabricated using Nb, which are often used in particle accelerators. Common treatment approaches involve "baking" the metal in vacuum or a gaseous atmosphere at temperatures < 200 ℃ (see, e.g., [1]), causing light chemical doping of its subsurface up to depths of ~100 nm. As this chemical adulteration is spatially inhomogeneous, it is expected to distort the element's Meissner response; however, quantifying the effect has proved challenging, with conflicting reports in the literature on the effect's magnitude [2, 3]. Here, we chronicle recent progress in understanding the phenomenon using low-energy muon spin spectroscopy (μSR) [2-5]. While the effect is subtle for the famed 48 h/120 ℃ vacuum annealing "recipe," we find evidence that the Meissner profile is deformed at depths < 40 nm, which can be difficult to distinguish from a large non-superconducting surface "dead layer." Implications for Nb SRF cavities are discussed.

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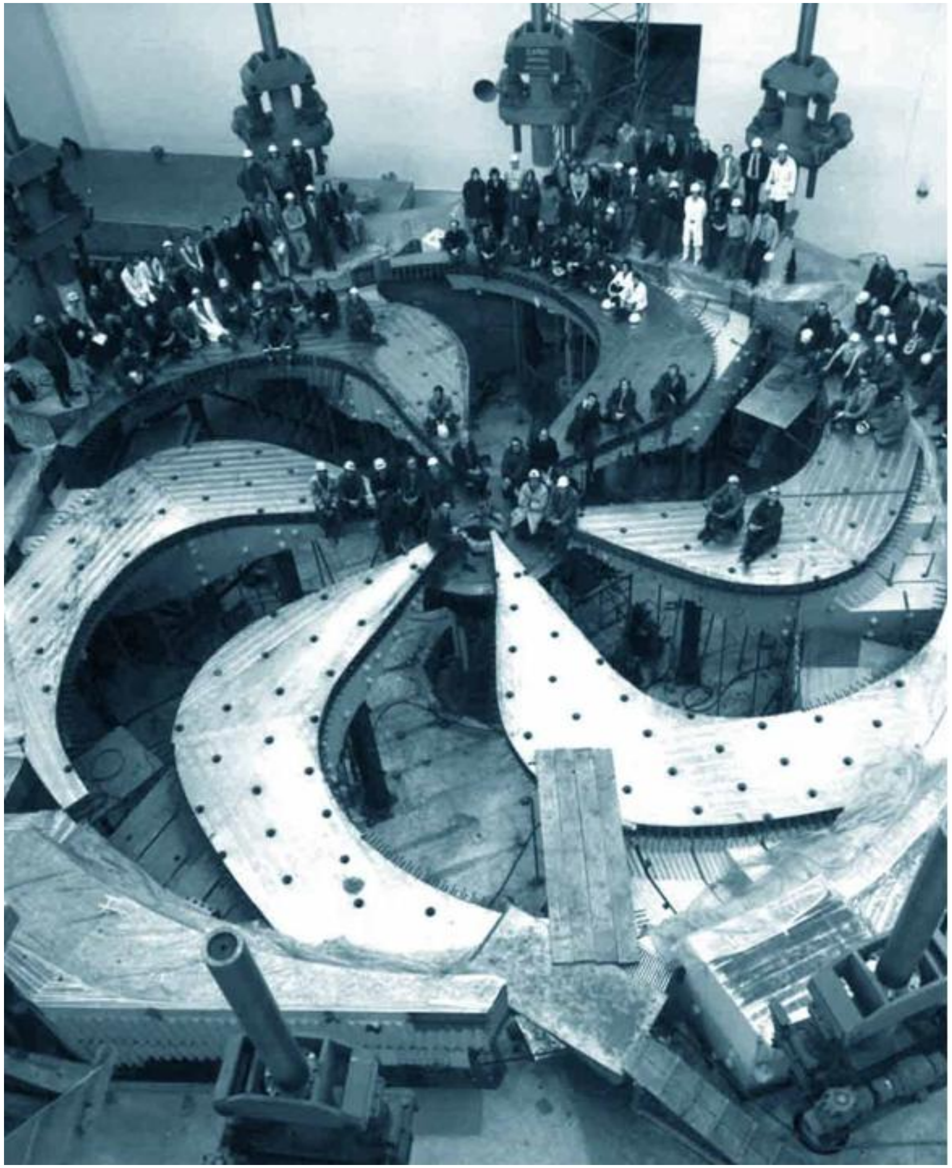
Thank you

Merci



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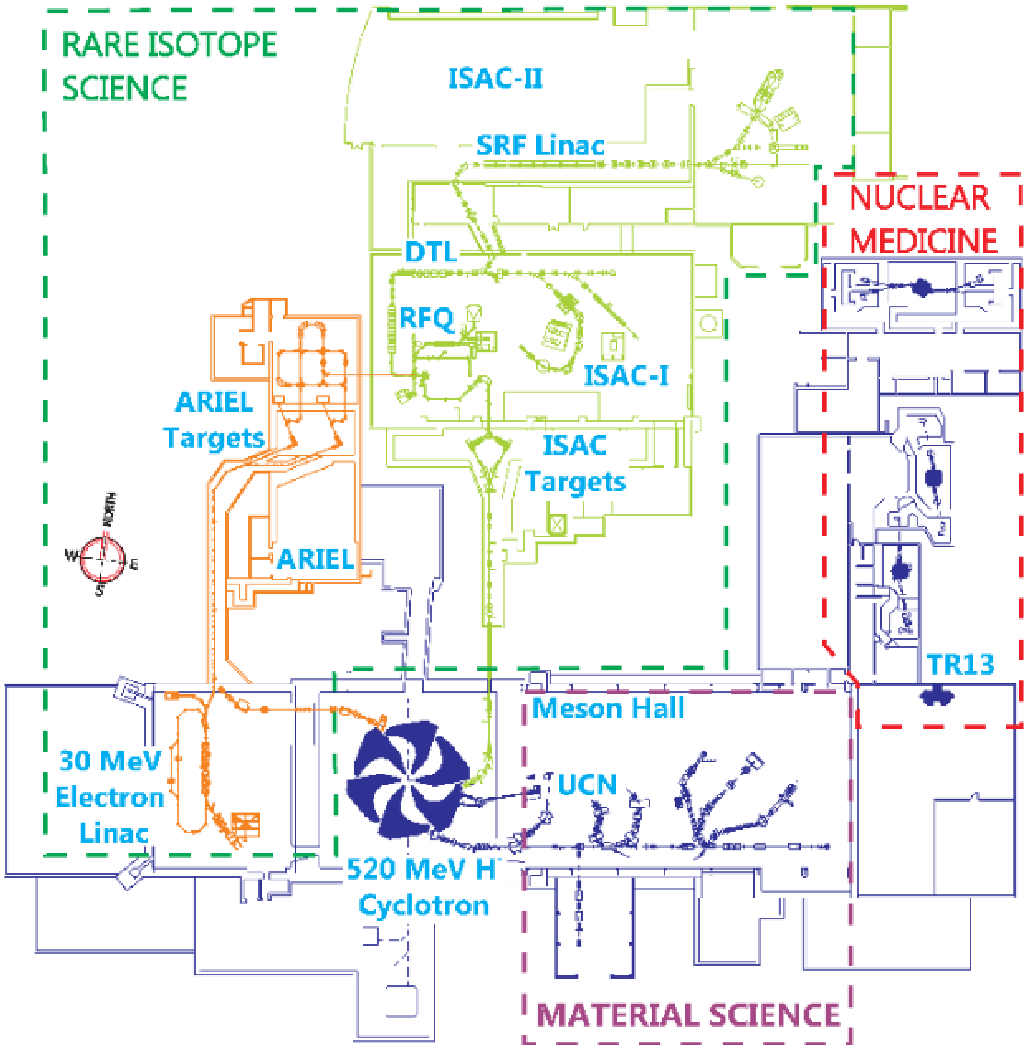
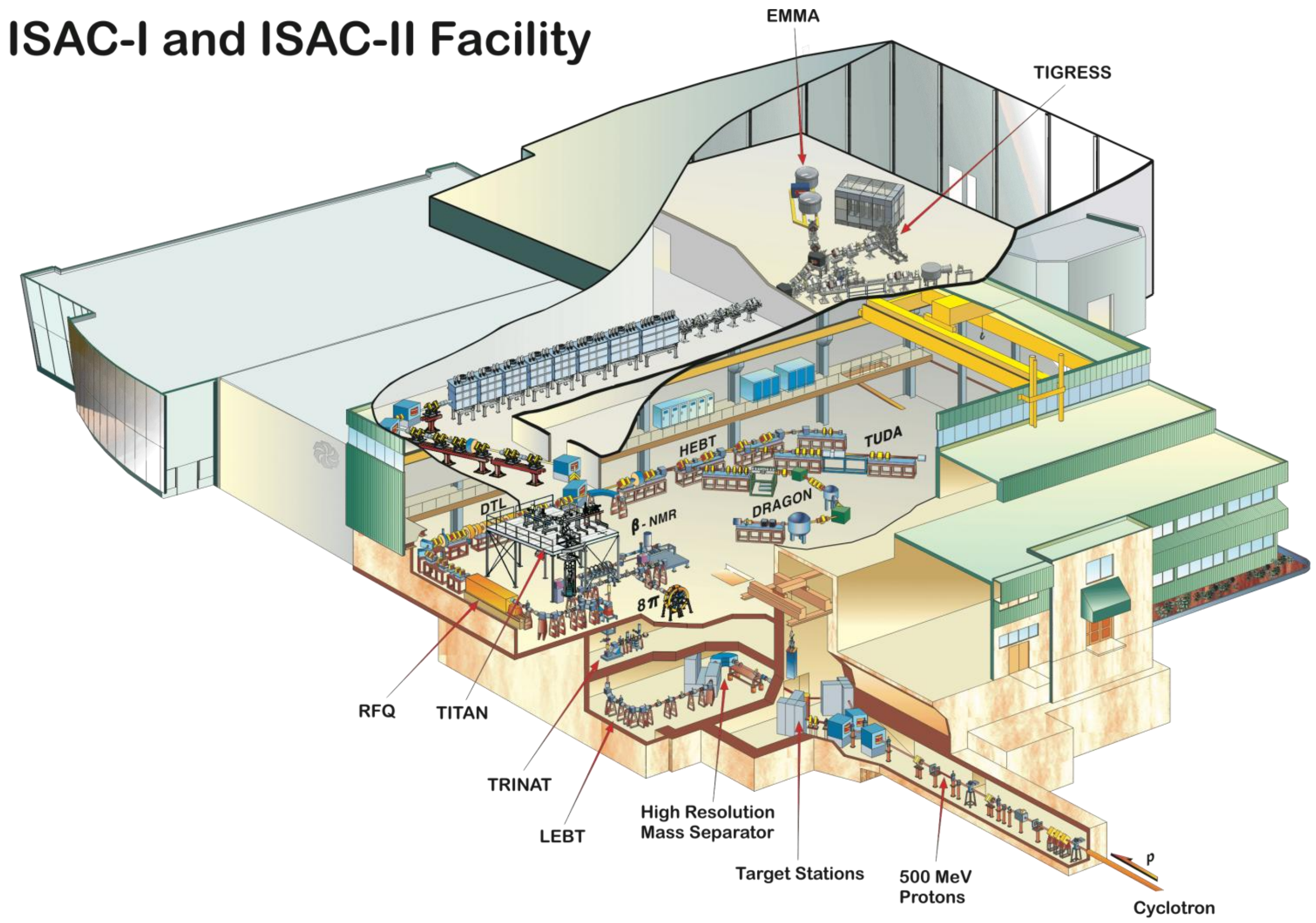


J. Bagger, et al. Proceedings IPAC2018

ISAC Facility



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