Muon Spin Rotation Studies of Niobium and Other SRF Materials

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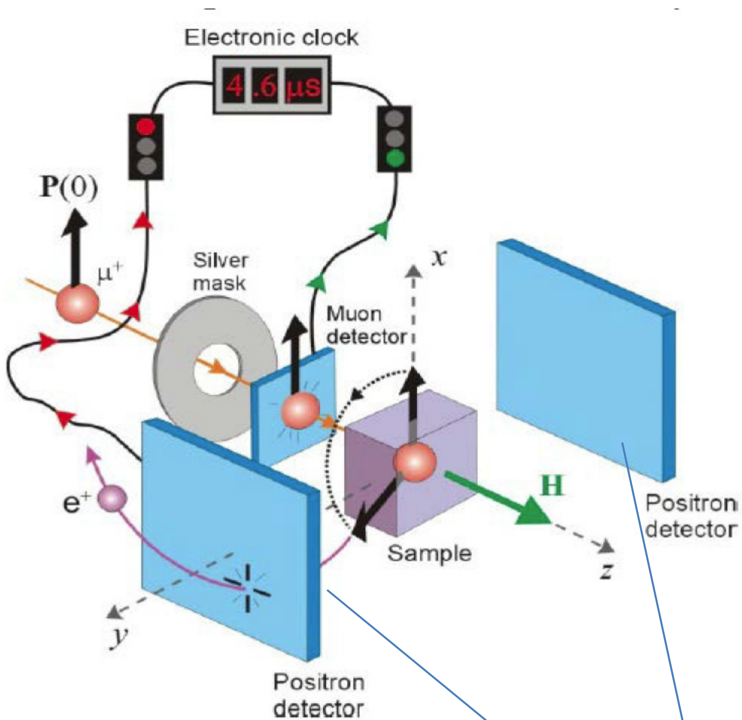
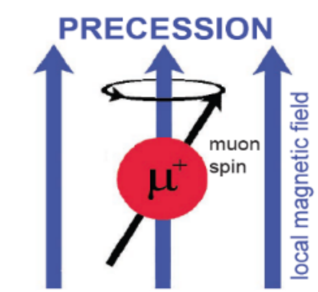
  - Example: Nb3Sn critical fields
- Future perspectives: betaSRF (TRIUMF)
- Summary of methods, capabilities and results

Muon Spin Rotation (muSR)

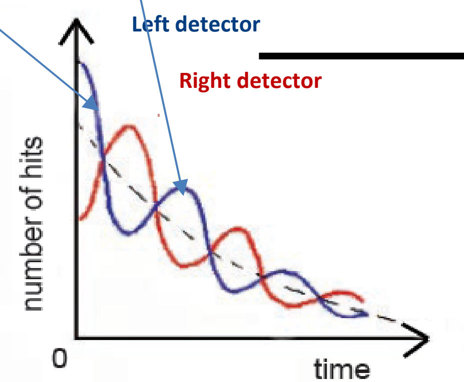


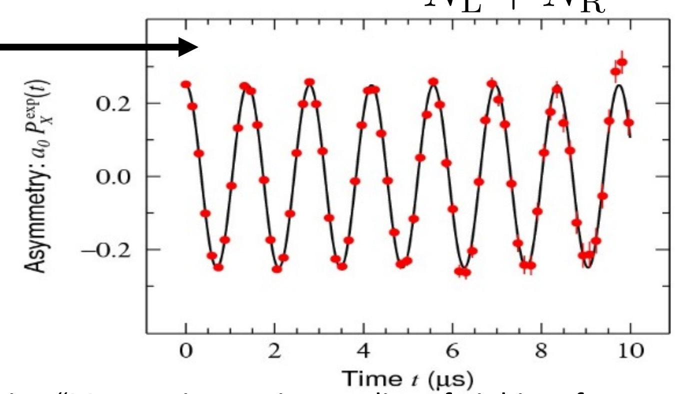
- TRIUMF SRF group has ben engaged in muSR characterization of SRF samples since 2010*
- 100% spin polarized Muons are deposited one at a time in a sample and spin rotate in the local magnetic field
- The muons decay with emitted positrons correlated with the spin direction.
- The time evolution of the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

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



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

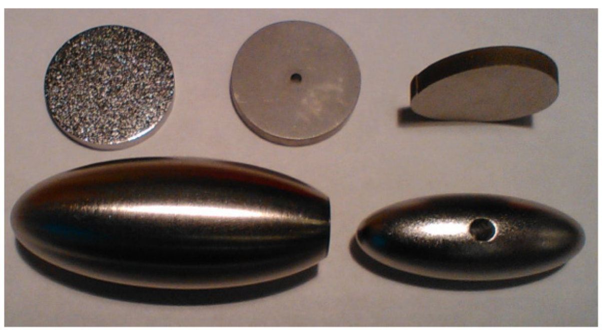




*A. Grassellino, C. Beard, P. Kolb, R. Laxdal, N. S. Lockyer, D. Longuevergne, and J. E. Sonier. “Muon spin rotation studies of niobium for superconducting rf applications”. Phys. Rev. ST Accel. Beams, 16:062002, 2013.

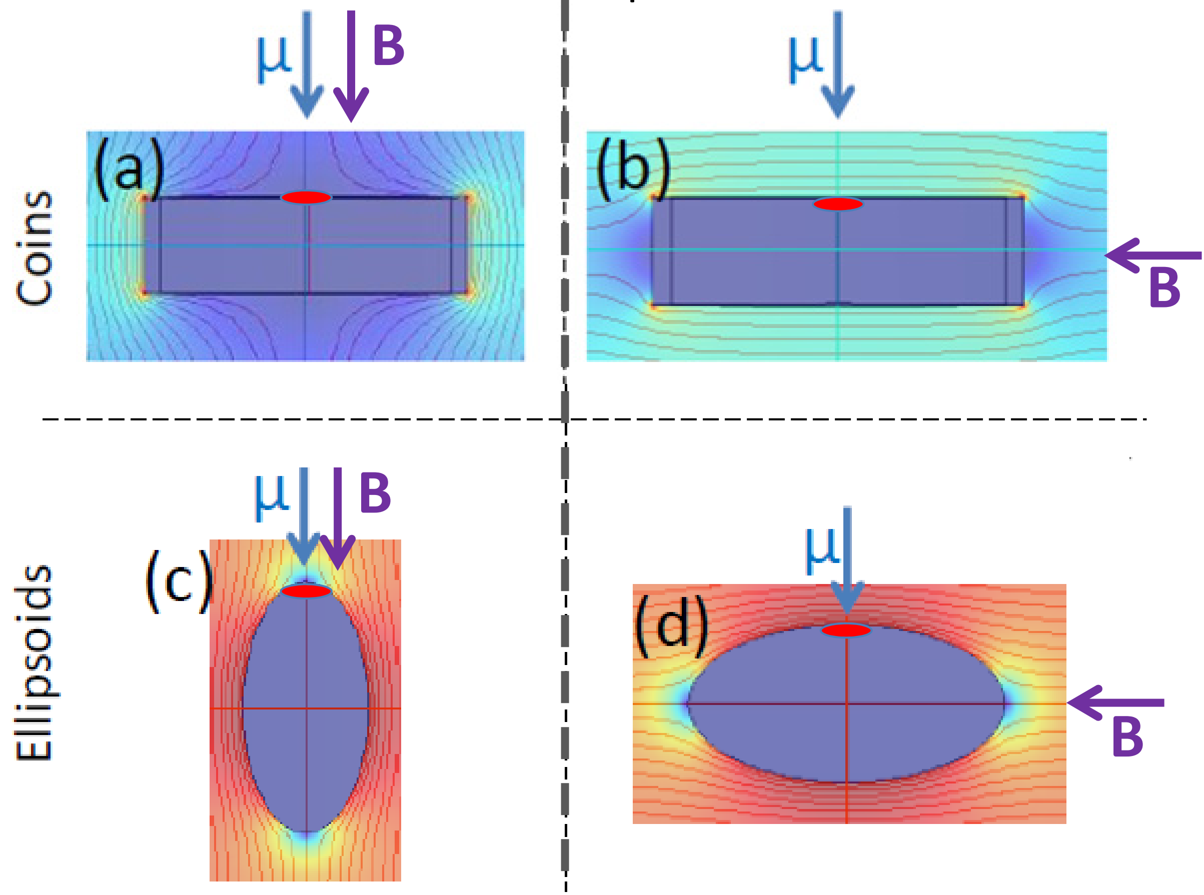
Samples and Geometry

- Results are strongly geometry dependent
- Coins, cavity cut-outs and ellipsoids have been used in different orientations
- Cases preferentially highlight either field of first flux entry or pinning strength
- Both are of interest to SRF



Initial spectrometer for transverse fields

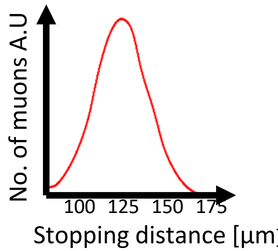
New SRF spectrometer for parallel fields

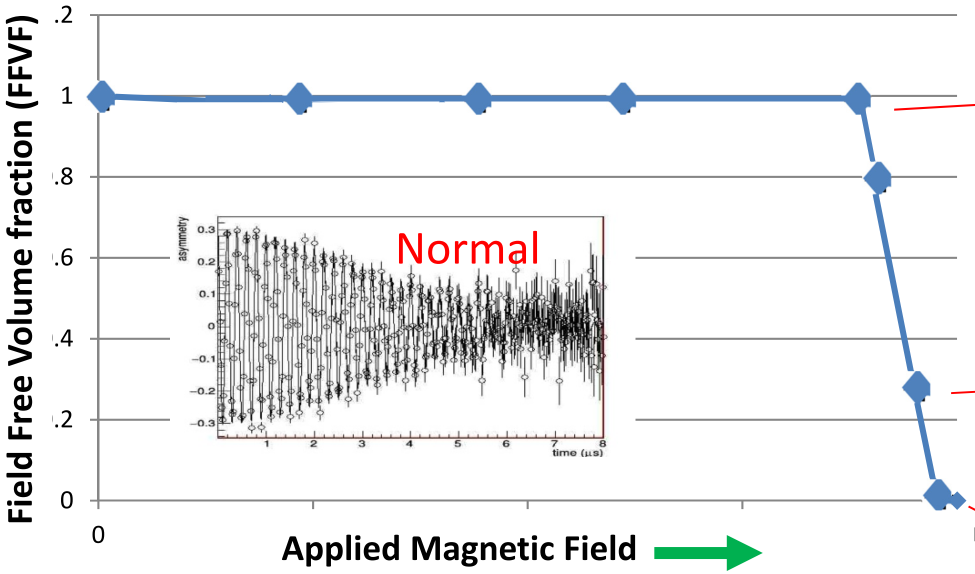


T. Junginger, S.H. Abidi, R. Astley, T. Buck, M. Dehn, S. Gheidi, R. Kiefl, P. Kolb, D. Storey, E. Thoeng, W. Wasserman, R.E Laxdal. "Field of first magnetic flux entry and pinning strength of superconductors for rf application measured with muon spin rotation." Physical Review Accelerators and Beams 21.3 (2018): 032002.

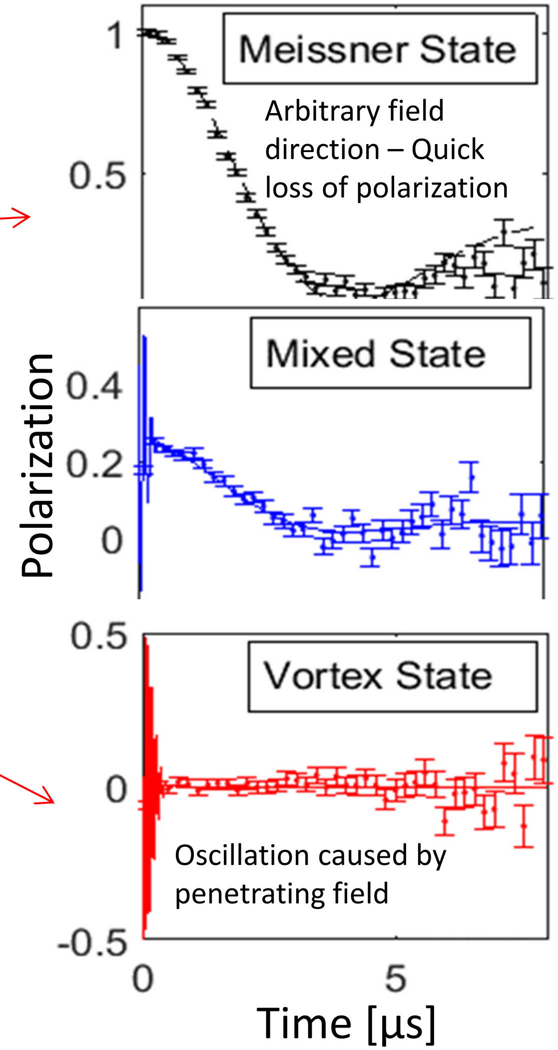
TRIUMF muSR as a local magnetometer

At TRIUMF `surface' muons (4MeV) are implanted 130μm into the surface (bulk probe)





Time evolved asymmetry signal

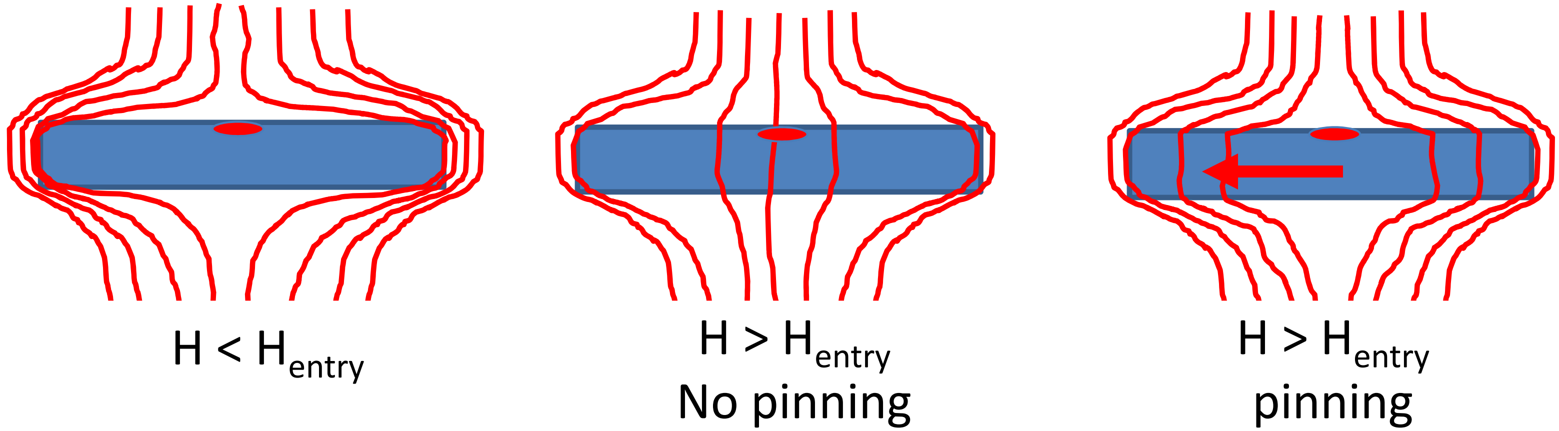


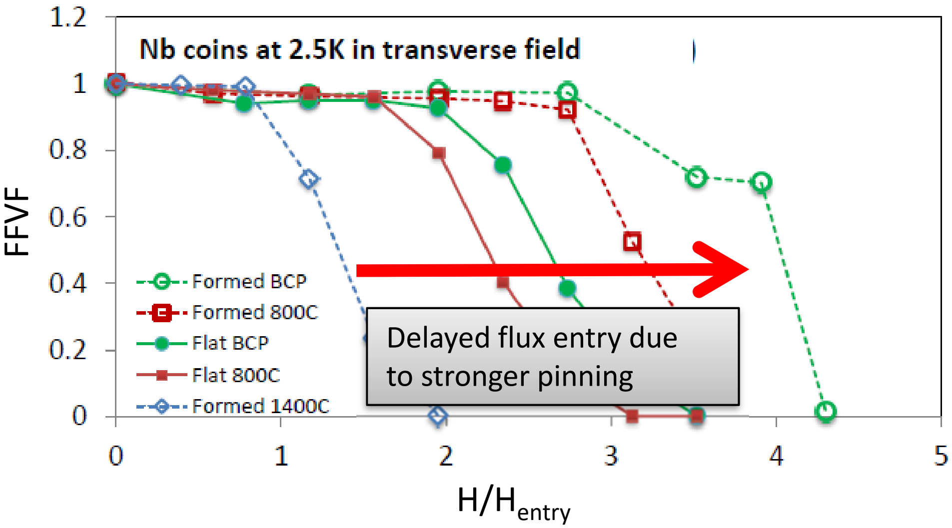
Samples are cooled in zero field and the field internal to the sample is measured for various applied fields

Asymmetry data is used to extract the fraction of the sampled volume that does not contain field as a function of the applied field H_a

Perpendicular Field

Field breaks in at the edges first at H_{entry} and will redistribute to the center – pinning resists redistribution requiring higher field to reach the center





Example:

- Comparing formed vs flat coins
- Forming significantly enhances pinning
- 800C heat treatment reduces but does not eliminate pinning from forming
- 1400C eliminates pinning from forming dislocations

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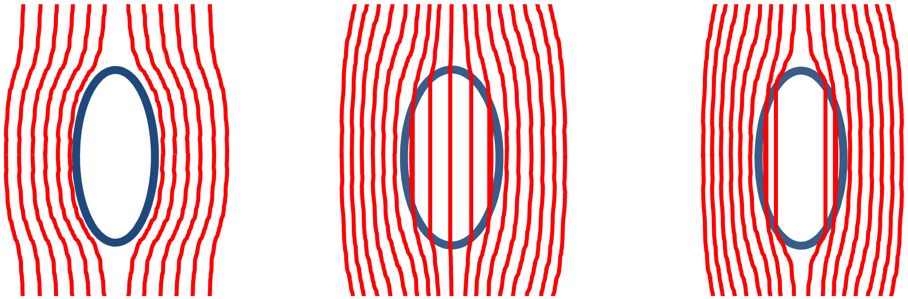
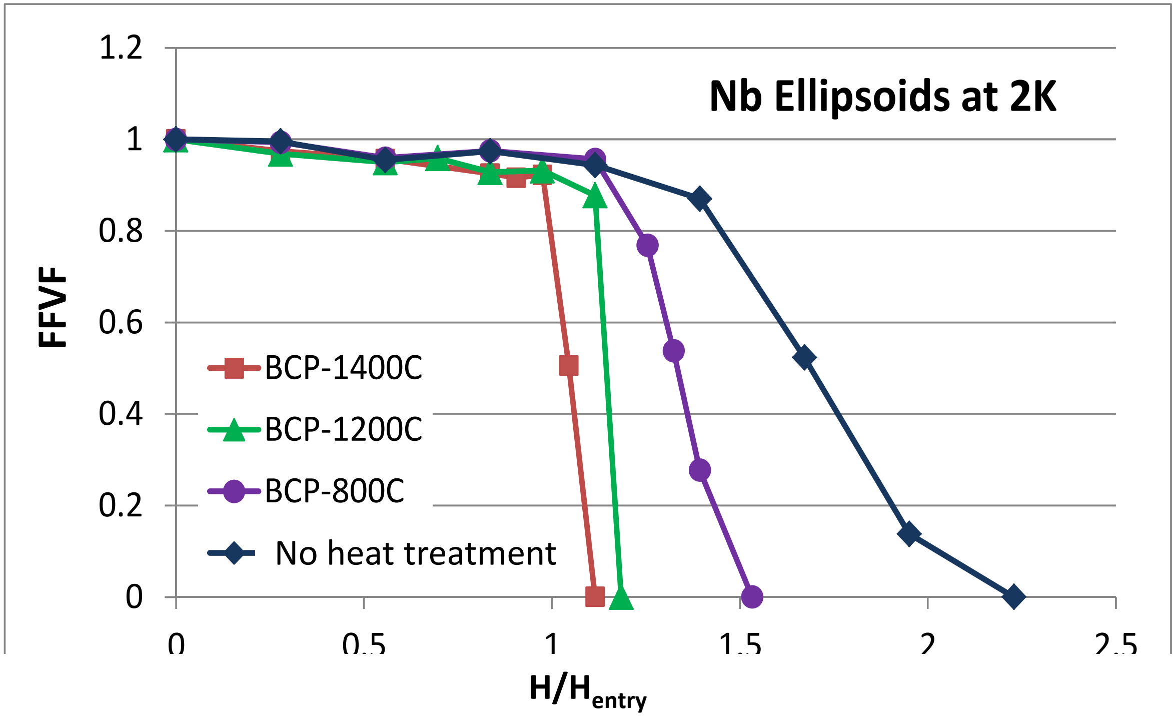
Pinning and heat treatment



In ellipsoids flux breaks in at the equator and redistributes uniformly for pin-free material – pinning resists flux distribution

Example: muSR measurements highlight the effectiveness of heat treatments at reducing pinning.



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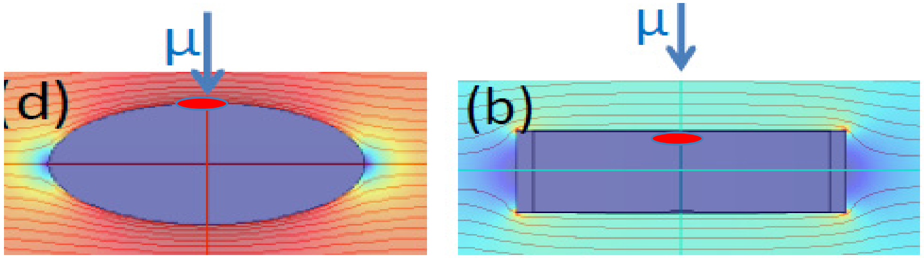
Parallel Geometries

A new SRF installation allows strong fields to be applied perpendicular to the muon path and parallel to the material surface

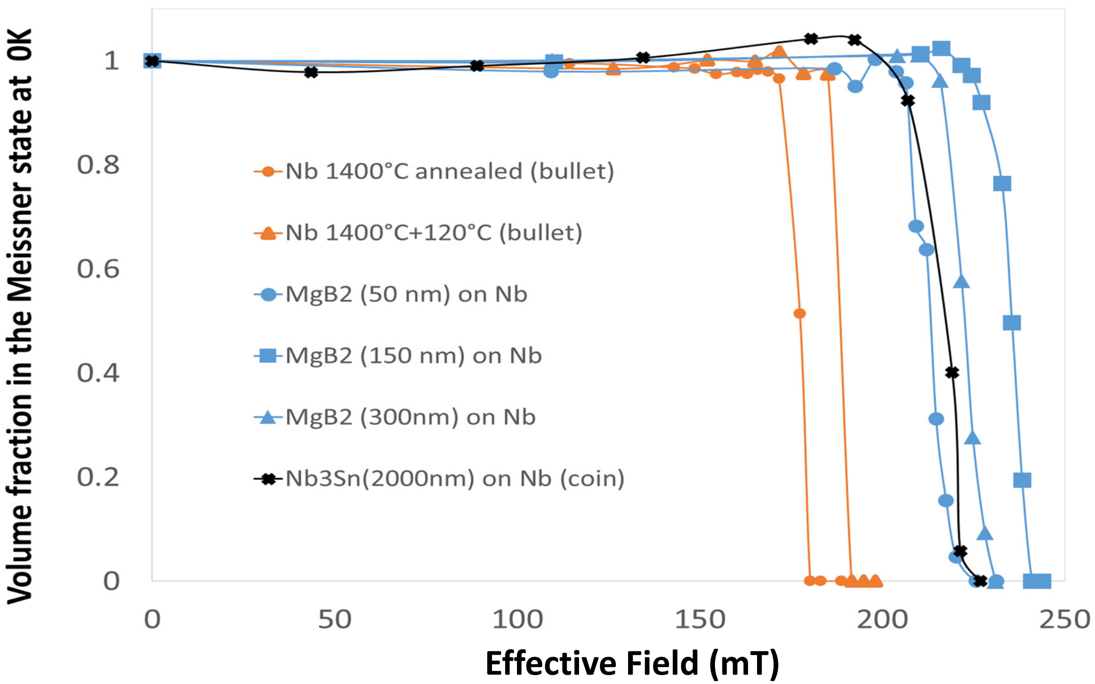
- the muon impinges in the region where field is expected to break in so is relatively free from pinning
- Focus - field of first entry studies



Parallel fields up to 300mT are possible in new SRF spectrometer

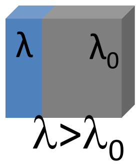
Example: Field of first flux entry on coated samples in parallel field

- Annealed (1400C) sample
- + 120C bake (adds `dirty layer')
- Nb_3Sn and MgB_2 with 50-2000nm thickness coated on niobium
- Field of first flux entry in Nb impacted by the coating

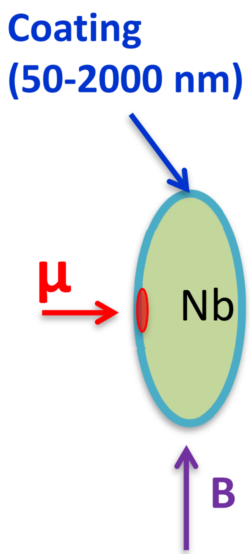


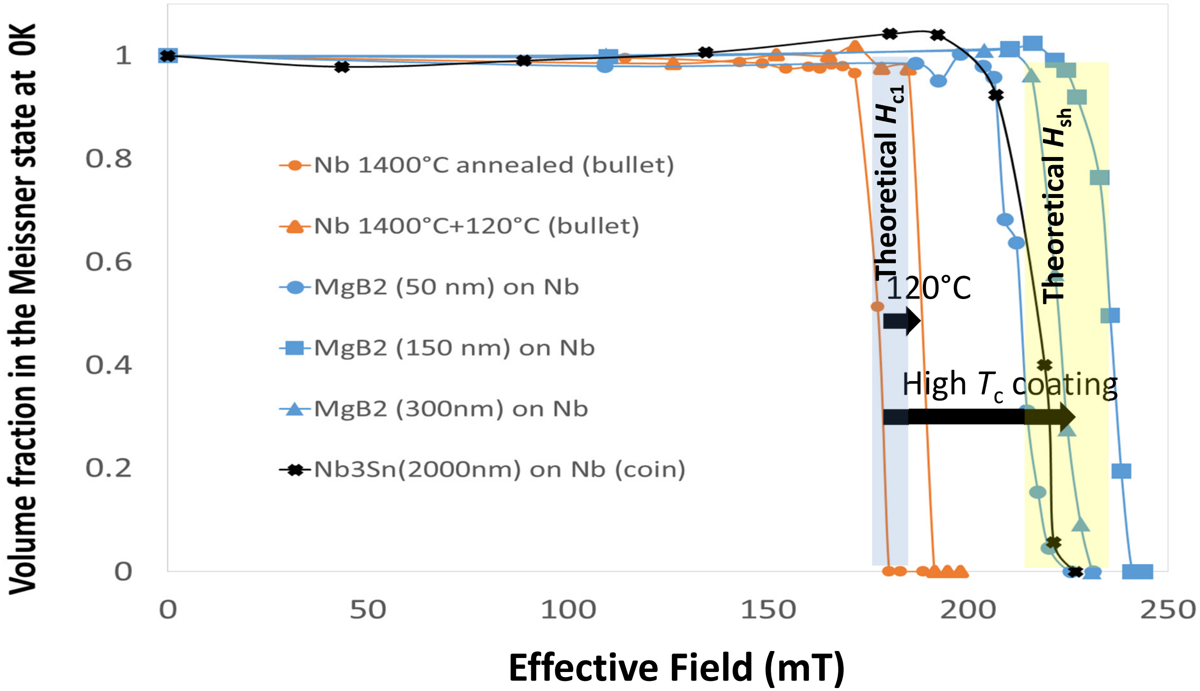
T. Junginger, R.E Laxdal and W.Wasserman Superconductor Science and Technology 30 (12), 125012

Coated Niobium - First Flux Entry



- For niobium annealed at 1400°C we find $H_{entry}=H_{c1}$
- 120°C baking increases H_{entry} above H_{c1} consistent with `dirty' layer hypothesis
- A layer of a higher T_c material on niobium can enhance H_{entry} by about 40% from a field consistent with H_{c1} to a field consistent with H_{sh}.
  - This enhancement does not depend on material or thickness suggesting that the superconductor-superconductor (SS) boundary is providing effective shielding up to the superheating field of niobium

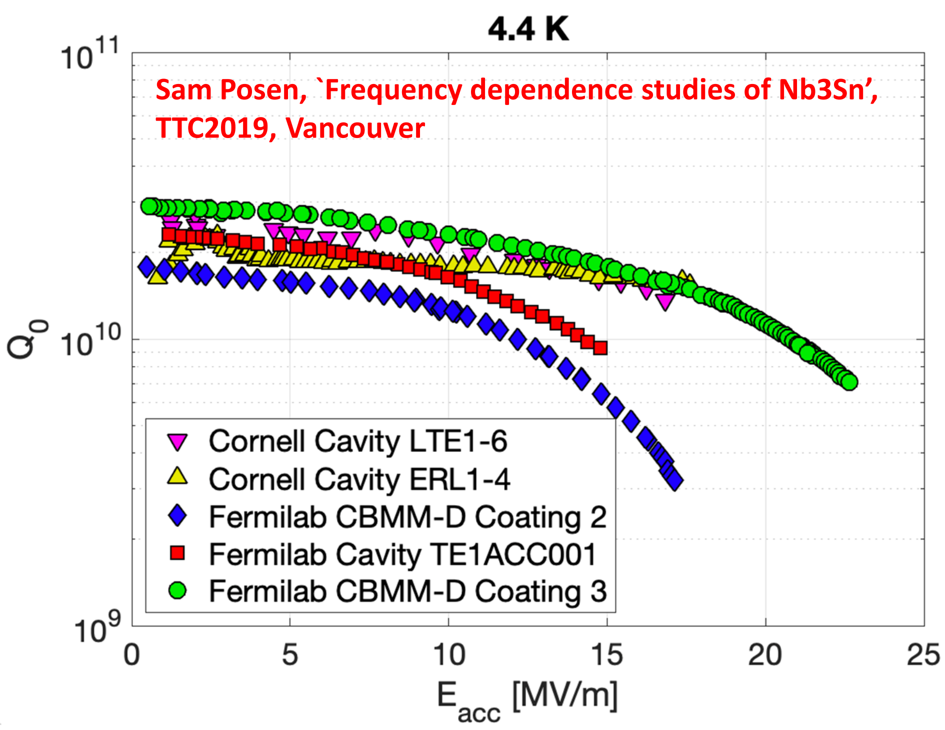




T. Junginger, R.E Laxdal and W.Wasserman, `Superheating in Coated Niobium', Superconductor Science and Technology 30 (12), 125012

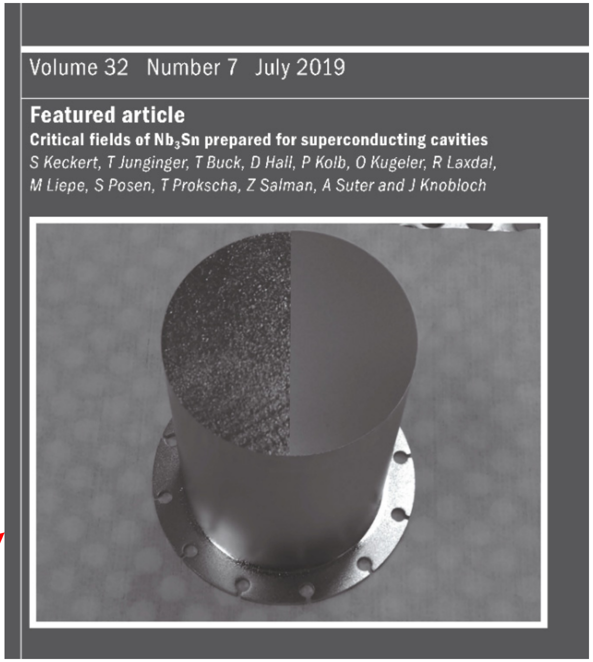
Critical Fields of Nb3Sn

Results from Cornell and FNAL show that Nb3Sn 1.3GHz cavities are reaching 17MV/m (70mT) and now 22.5MV/m (95mT)



Example: What can muSR tell us about the Nb3Sn critical fields?

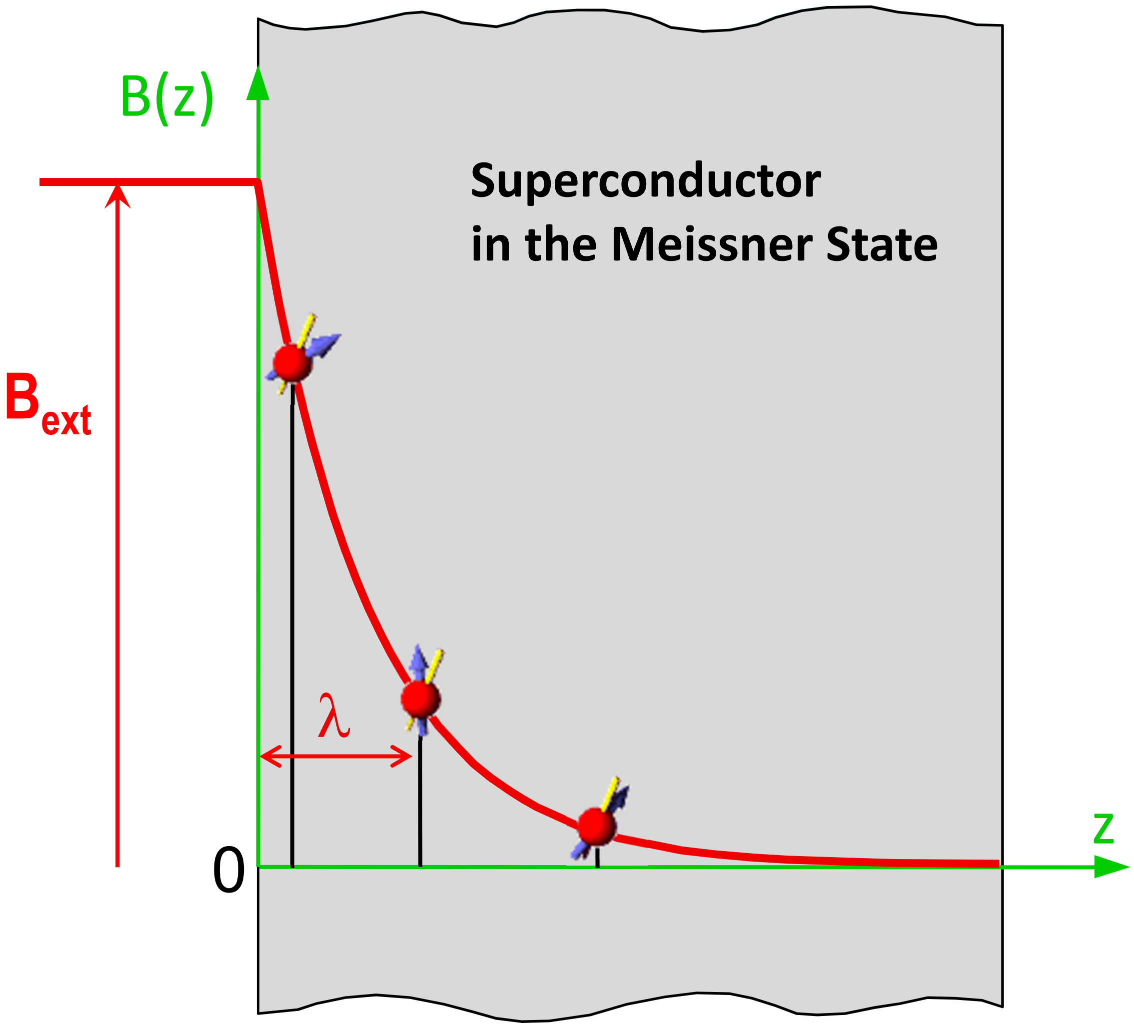
- LEmuSR (PSI) -> London Penetration Depth -> H_{c1}
- muSR TRIUMF -> DC flux penetration -> H_{c1}
- Quadrupole resonator -> RF critical field

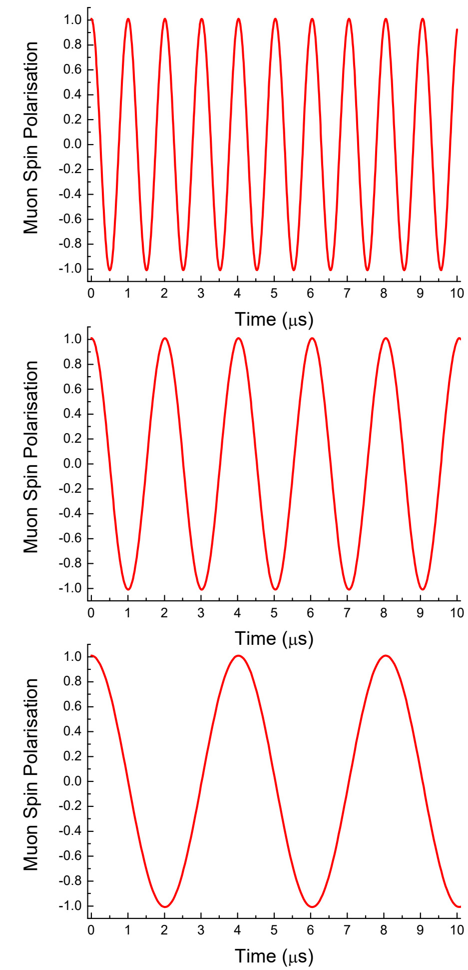


S Keckert, T Junginger, T Buck, D Hall, P Kolb, O Kugeler, R Laxdal, M Liepe, S Posen, T Prokscha, Z Salman, A Suter and J Knobloch, "Critical fields of Nb3Sn prepared for superconducting cavities", SUST, Volume 32 Number 7 July 2019

Low energy μSR (PSI)

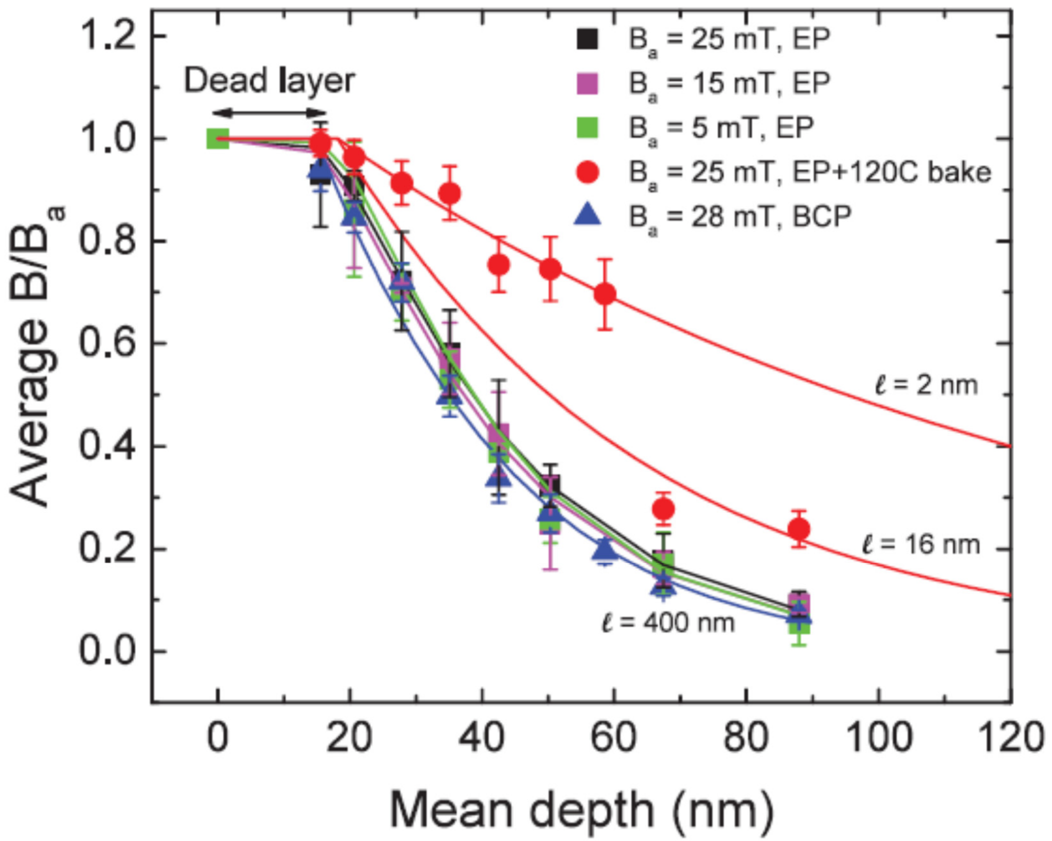
Depth resolved implantation of the low energy muons allows direct measurement of field attenuation in the Meissner state and hence the London Penetration Depth





$$\omega_\mu(z) = \gamma_\mu B_{\text{loc}}(z)$$

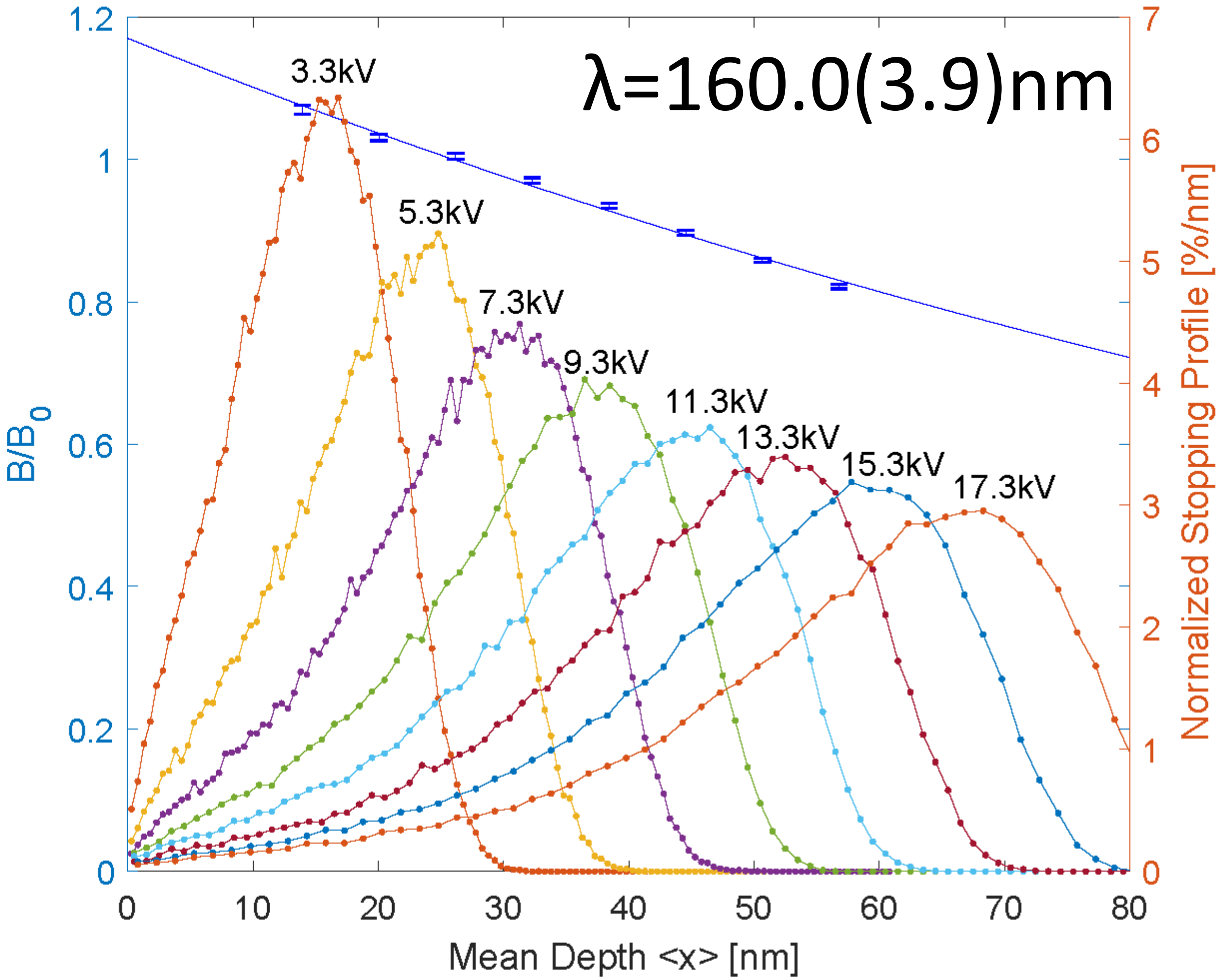
Magnetic screening in London layer



Shows impact of 120C bake (`dirty layer’) on London penetration depth and MFP compared to `clean’ sample

Romanenko, A., et al. "Strong Meissner screening change in superconducting radio frequency cavities due to mild baking." Applied Physics Letters 104.7 (2014): 072601.

Nb3Sn LPD – LE-muSR (PSI)



Low energy muSR is used to directly measure the London penetration depth λ and extract H_{c1} and H_{sh}

$$\kappa = {}^{\lambda}/_{\xi}$$

$$H_{c1} = \frac{\phi_0}{\pi\lambda^2}\ln(\kappa + 0.5)$$
$$= \mathbf{28(2)\ mT}$$

$$\phi_0 = {}^{h}/_{2e}$$

$$H_{sh} = H_c\left(\frac{\sqrt{20}}{6} + \frac{0.55}{\kappa}\right)$$
$$= \mathbf{500(120)\ mT}$$

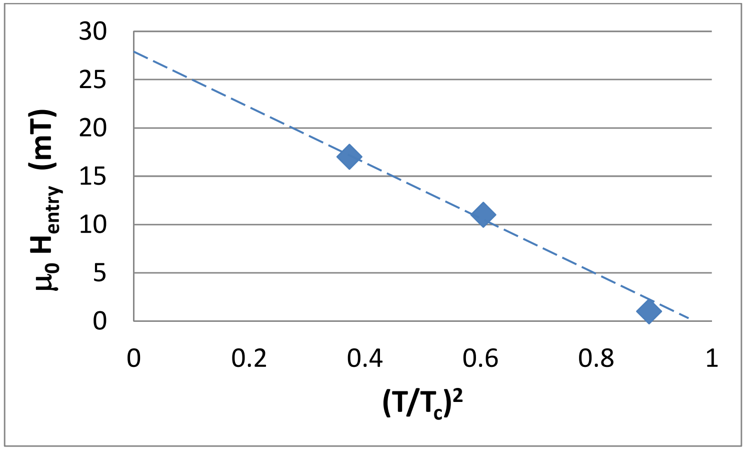
Coin sample from TRIUMF flux penetration study

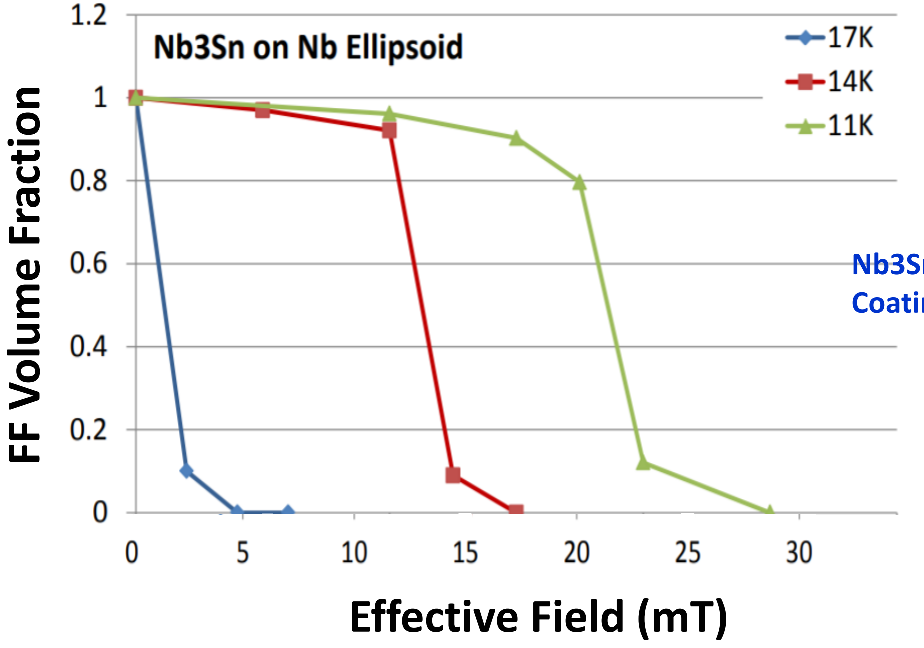
DC Flux penetration TRIUMF

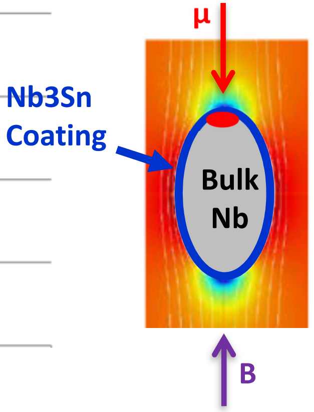
The DC flux penetration is measured on a Nb ellipsoid coated with 2μm of Nb_3Sn as a function of temperature

Above T=9K the Nb is normal and the Nb_3Sn is a superconducting shell – $H_{entry}(0)$ is extracted from fitting $H_{entry}(T)$

$$H_{ent}(T) = H_{ent}(0)\left[1 - \left(\frac{T}{T_c}\right)^2\right]$$



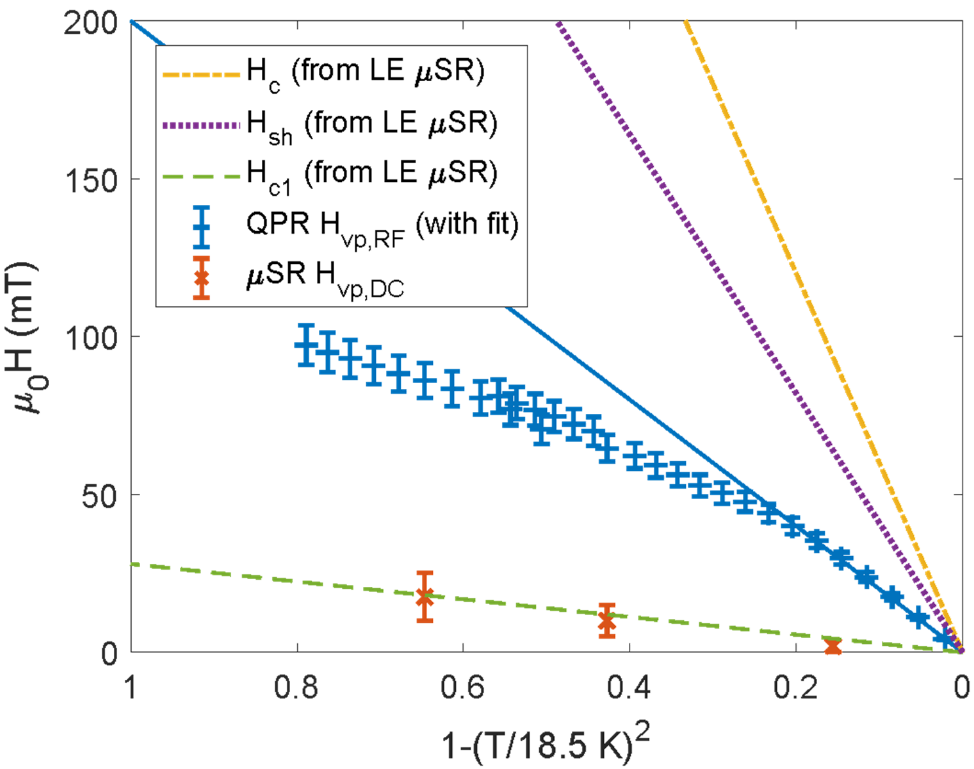




$H_{entry}(0) = 28(12)$ mT

Consistent with H_{c1}

Nb3Sn - LE+surface muSR+QPR



- $H_{entry,DC}$ is consistent with H_{c1}
- Fitting only $H_{entry,RF}$(T) from QPR for T>16.3K yields 200(5)mT
- $H_{entry,RF}$ exceeds $H_{entry,DC}$ and H_{c1}
  - Metastability reached for RF
  - Still well below H_{sh} - Consistent with local suppression of the superheating field at coating flaws.

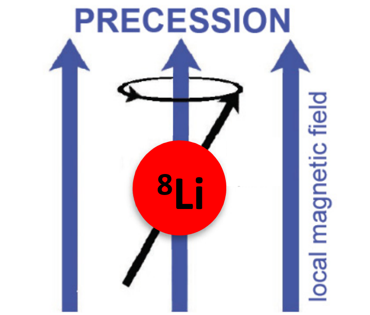
1.3GHz FNAL [mT]	$\mu_0 H_{entry,RF}$ [mT] QPR	$\mu_0 H_{entry,DC}$ [mT] muSR	$\mu_0 H_{c1}$ [mT] LE-muSR	$\mu_0 H_{sh}$ [mT] LE-muSR
95	200(5) (T^2 fit)	28(12)	28(2)	500(120)

S Keckert, T Junginger, T Buck, D Hall, P Kolb, O Kugeler, R Laxdal, M Liepe, S Posen, T Prokscha, Z Salman, A Suter and J Knobloch, *"Critical fields of Nb3Sn prepared for superconducting cavities"*, SUST, Volume 32 Number 7 July 2019

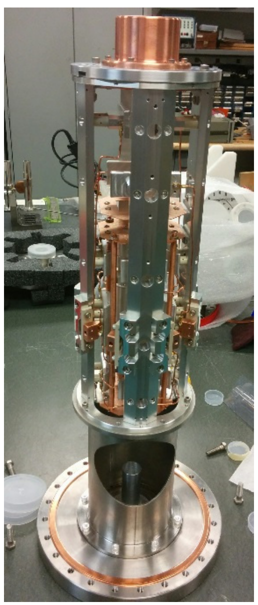
β-SRF @ TRIUMF (THP047)

TRIUMF has beta-NMR to probe magnetism at surfaces and interfaces

- Utilizes the beta decay of low energy (30keV) polarized 8Li ions
- Low energy 8Li beam allows depth profiling in the London layer
- **With β-SRF we are adding a new beamline extension and Helmholtz coil to test samples in high parallel field (200mT)**
- **Operational in June 2020**

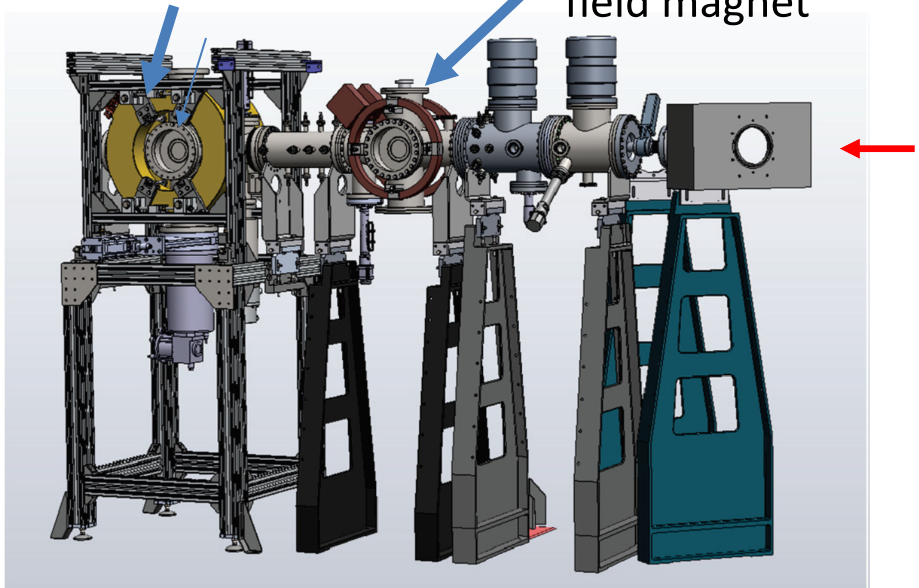


$$^{8}\mathrm{Li} \rightarrow e^{-} + \nu_{e} + {}^{8}\mathrm{Be}$$

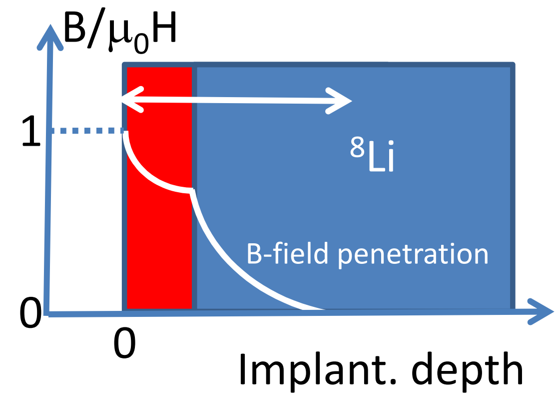


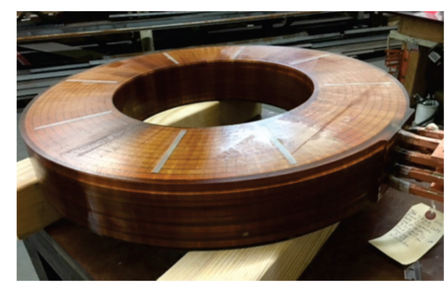
New high field magnet

Current low field magnet



Extension of parallel field spectrometer





Thoeng, E., et al. "Beta-SRF-A New Facility to Characterize SRF Materials near Fundamental Limits. " 9th Int. Particle Accelerator Conf.(IPAC'18)

Techniques

Technique	Max parallel B field (mT)	Implantation depth in niobium	Measurement capabilities relevant to SRF
muSR (TRIUMF)	300	130 µm (bulk probe)	Pinning strength [1,2] Field of first vortex penetration [2,3,4]
LE - muSR (PSI)	25	10-100 nm (surface probe)	London penetration depth/magnetic screening profile in London layer [4,5,6,7] Hydrogen diffusion and magnetic impurities [7]
Beta-SRF TRIUMF	200	10-100 nm (surface probe)	Vortex penetration in the London layer [8]

[1] Grassellino, A., et al. "Muon spin rotation studies of niobium for superconducting rf applications." Physical Review Special Topics-Accelerators and Beams 16.6 (2013): 062002.
[2] Junginger, T., et al. "Field of first magnetic flux entry and pinning strength of superconductors for rf application measured with muon spin rotation." Physical Review Accelerators and Beams 21.3 (2018): 032002.
[3] Junginger, T., W. Wasserman, and R. E. Laxdal. "Superheating in coated niobium." Superconductor Science and Technology 30.12 (2017): 125012.
[4] S Keckert, et al., "Critical fields of Nb3Sn prepared for superconducting cavities", SUST, Volume 32 Number 7 July 2019
[5] Romanenko, A., et al. "Strong Meissner screening change in superconducting radio frequency cavities due to mild baking." Applied Physics Letters 104.7 (2014): 072601.
[6] Junginger, Tobias, et al. "Critical Fields of SRF Materials." 9th Int. Particle Accelerator Conf.(IPAC'18), Vancouver, BC, Canada, April 29-May 4, 2018
[7] Junginger, T., et al. "A low energy muon spin rotation and point contact tunneling study of niobium films prepared for superconducting cavities." Superconductor Science and Technology 30.12 (2017): 125013
[8] Thoeng, B., et al. "Beta-SRF-A New Facility to Characterize SRF Materials near Fundamental Limits. " 9th Int. Particle Accelerator Conf.(IPAC'18), Vancouver, BC, Canada, April 29-May 4, 2018

Summary

- muSR is used since 2010 for SRF studies
- Dedicated spectrometers has been developed at TRIUMF for measurements in strong parallel or transverse fields
  - Methods to characterize materials in terms of pinning strength or field of first vortex penetration have been established
- Examples:
  - Forming increases pinning while heat treatment reduces pinning
  - A layer of a superconductor with a larger penetration depth pushes the field of first vortex penetration of niobium from a field consistent with H_{c1} to a field consistent with H_{sh}
  - Combined QPR, surface and low energy muSR results confirm that Nb3Sn cavities are indeed operated in a metastable state but are limited to early flux penetration below H_{sh}
- A new facility based on betaNMR will enable parallel magnetic fields above 200mT and depth dependent measurements in the London layer

Acknowledgements

- *Experimentalists muSR:* E. Thoeng, D. W Storey, W. W. Wasserman, D. Bazyl, R. Dastley, M. Dehn, D. Azzoni Gravel, S. Gehdi, Z. He, R. Kiefl, P. Kolb, Y. Ma, L. Yang, Z. Yao, H. Zhang (TRIUMF)
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- *LE-muSR:* A. Suter, Z. Salman, T. Prokscha (PSI)
- *Quadrupole Resonator:* S. Keckert, O. Kugeler, J. Knobloch (HZB)
- *Sample Providers:* D. L. Hall, Matthias Liepe (Cornell University), A. Grassellino, S. Posen (Fermilab), T. Tan (IMP), W. K. Withanage, M. Wolak, X. Xi (Temple University)


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