Predicting SRF Performance using muSR and betaNMR

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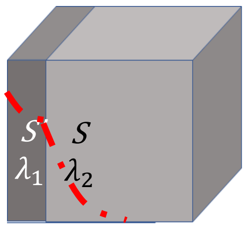
Outline

- Layered Approaches
- muSR Technique
- muSR Studies: Coated Nb
- beta-NMR Technique
- beta-NMR Upgrade
- beta-NMR Results
- Summary & Outlook

Layered Approaches

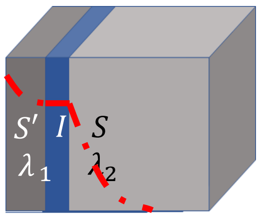
Reaching the limit of bulk Nb → **<u>Engineer the near surface</u> with layer(s)**

SS bi-layer



Extensive experimental & theoretical works

SIS



A thin coating of 'dirty' or higher λ SC + 'cleaner' SC bulk ($\lambda_1 > \lambda_2$):

Theory: Interface barrier[1]**, proximity effect**[2]

Exp: 120°C baked[3]**, Nb3Sn/Nb, N-infused/doped**[4]

Decouples S/S layer with Insulating layer

Theory: Prevent vortex avalanches[5]

Exp: NbN/MgO/Nb tri-layer[6]

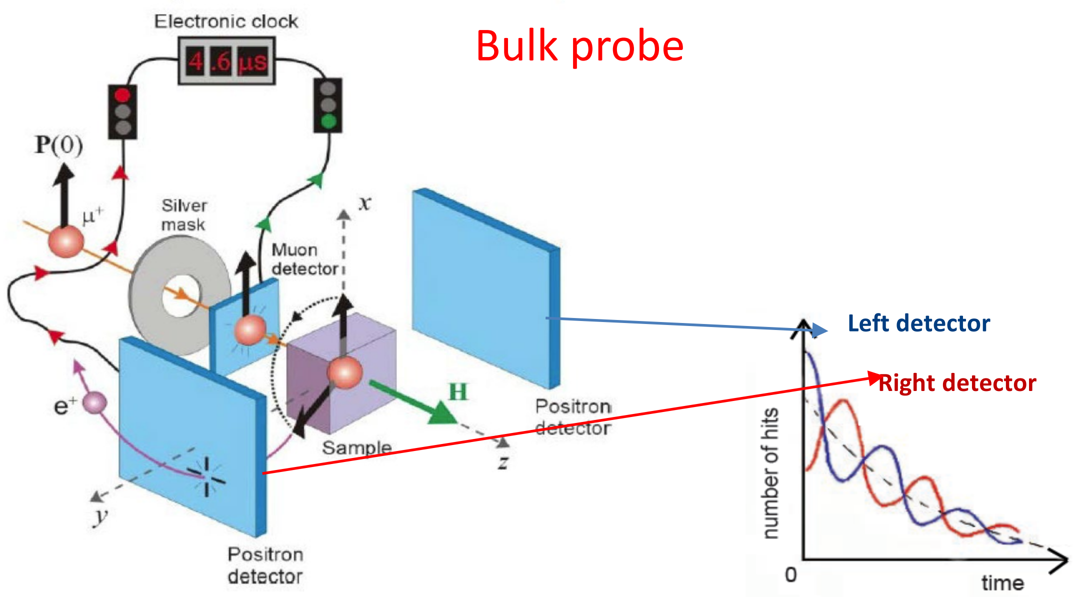
Exp. Optimization & Theories Validation

<u>Direct measure of field profile</u> &
<u>London penetration depth</u>
Implanted **muon** (bulk probe) or **radioactive NMR probe** (surface/interface probe)

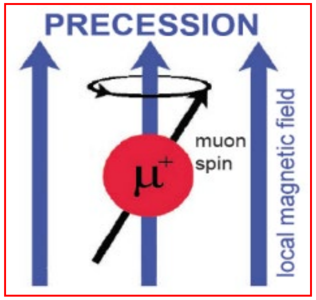
muSR Technique

1 Implant high-energy muons into SRF samples

Bulk probe



2 Muon spin precesses in B_{loc}
Muon decays & emits positron || spin



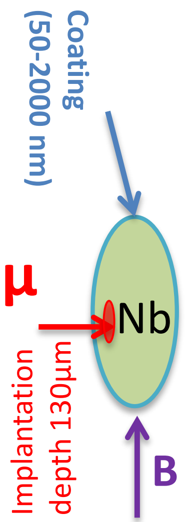
3 Measure signals with increasing field

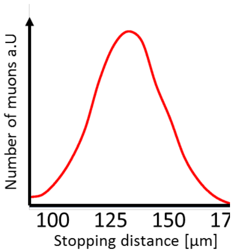
Fraction of bulk volume in the field free (Meissner) state

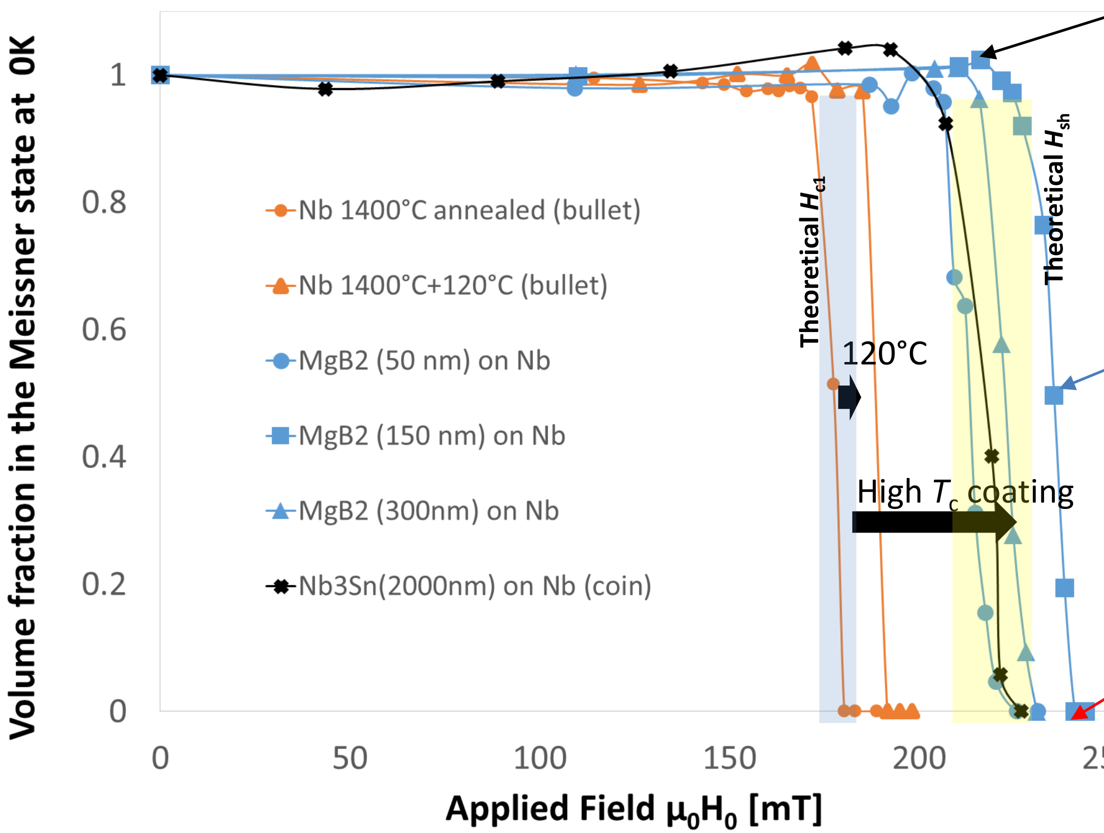
Effectiveness of coating

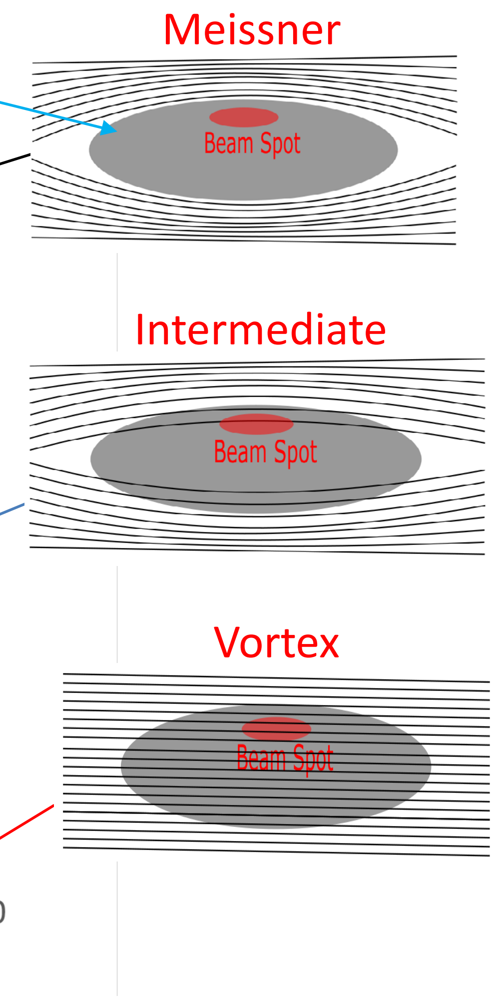
muSR Studies: Coated Nb

- Bi-layer: Nb_3Sn and MgB_2 [50-2000 nm] on Nb, 120°C baked Nb [7]
- Muons implanted 130μm in the bulk of ellipsoid samples









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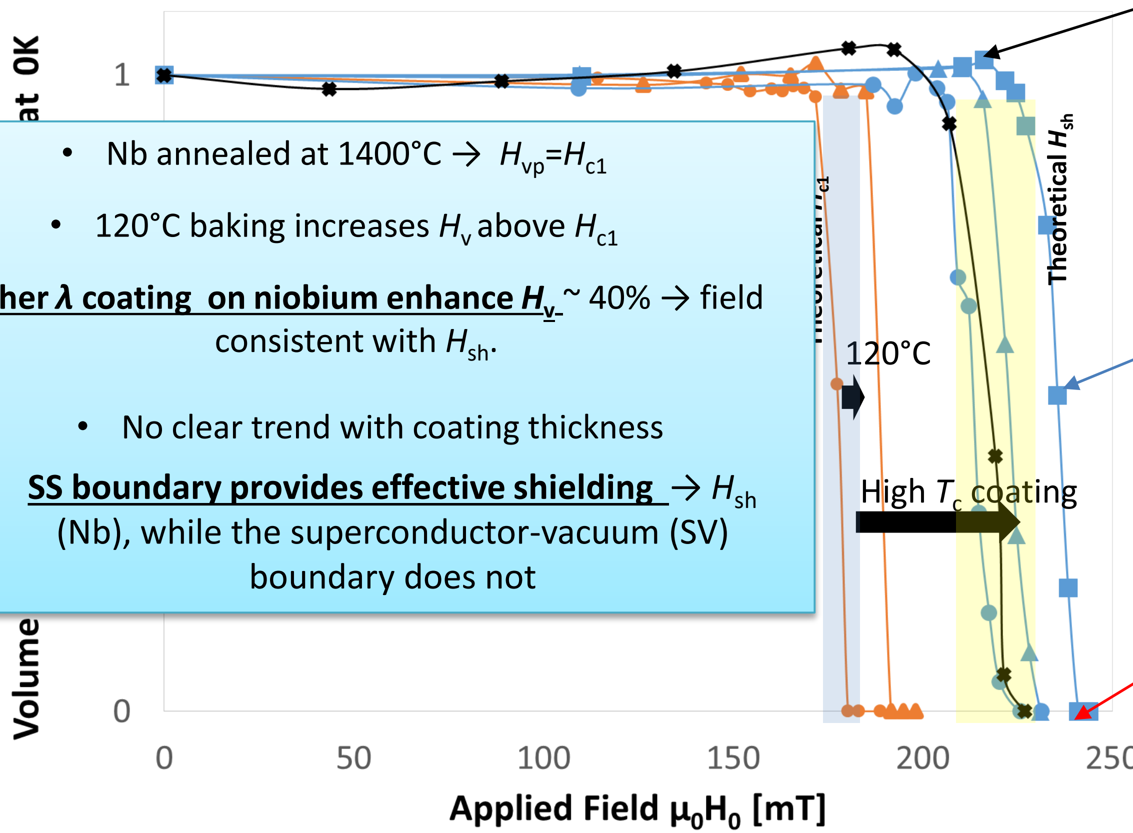
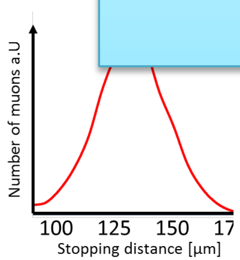
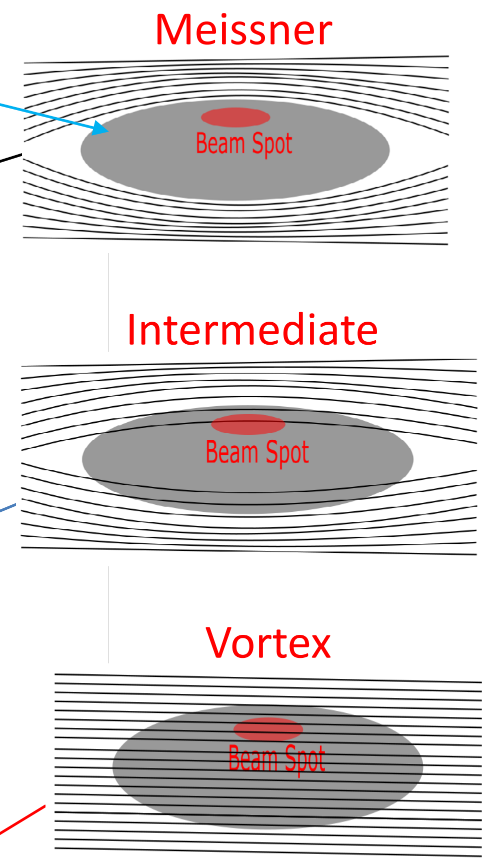


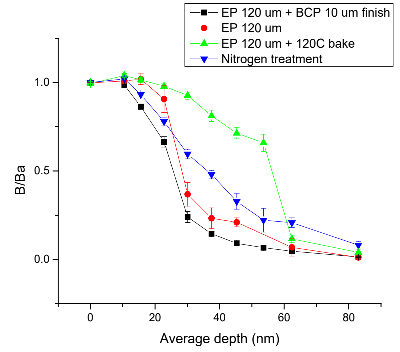


- Nb annealed at 1400°C → $H_{vp}=H_{c1}$
- 120°C baking increases H_v above H_{c1}
- **Higher λ coating on niobium enhance H_v** ~ 40% → field consistent with H_{sh}.
- No clear trend with coating thickness
- **SS boundary provides effective shielding** → H_{sh} (Nb), while the superconductor-vacuum (SV) boundary does not



beta-NMR Technique

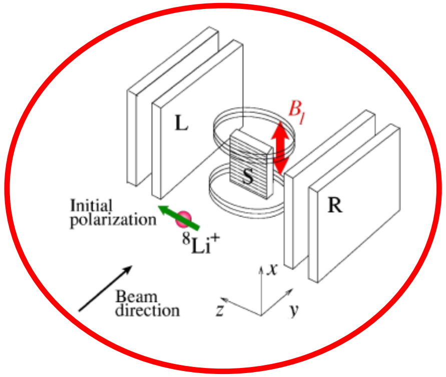
LE-musR: 120°C bake study with LE-muSR @ PSI[3]
limited to 30 mT (low-field)

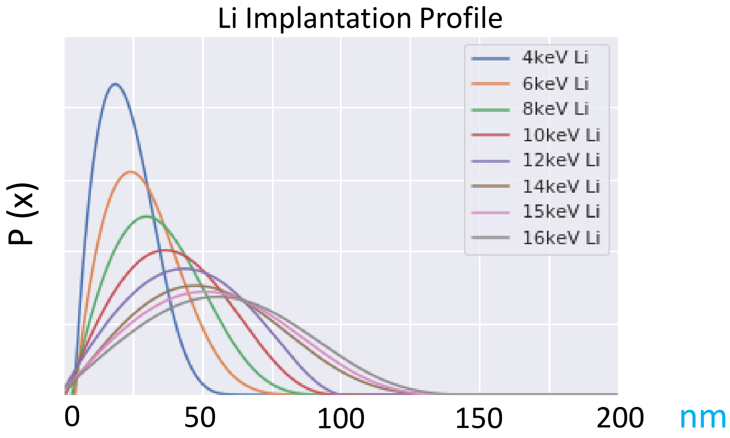


beta-NMR Probe

Implanted low energy radioactive Li-8 beam

Field || sample: currently 24 mT





Comparison with LE-muSR

Low-energy → **Surface & interface sensitive** nm-scale

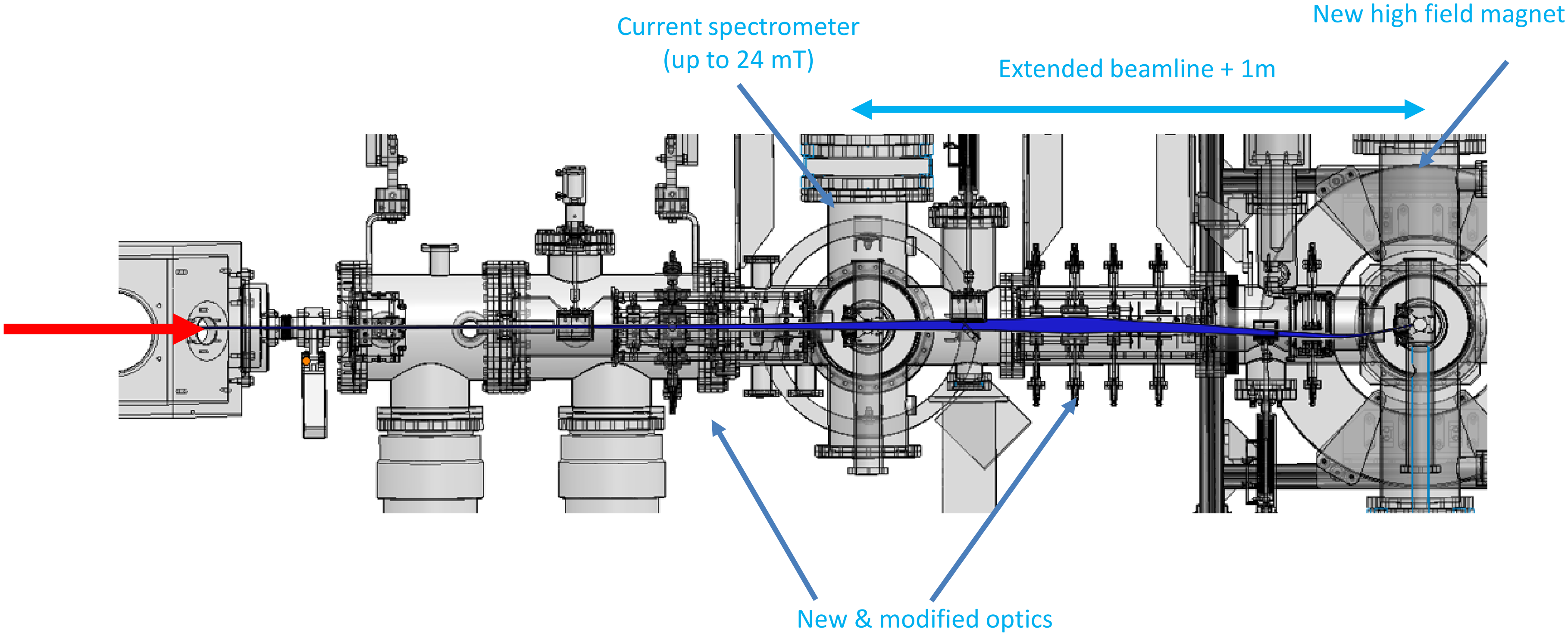
Heavier ions (vs muons) → **Larger magnetic rigidity** at high-field

HV deceleration [existing] → **Depth resolved** studies

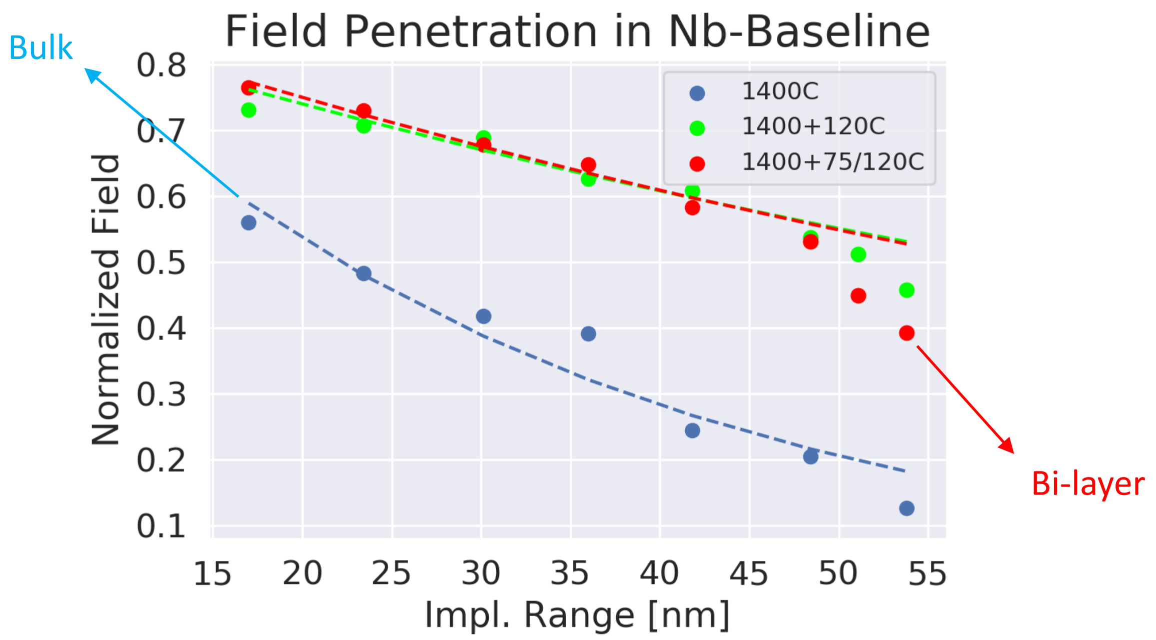
beta-NMR Upgrade

Scope of Upgrade:

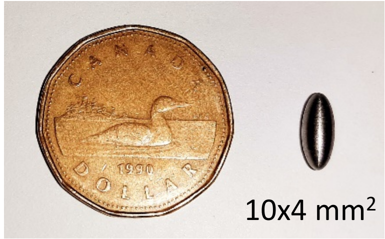
- Beam steering at higher field up to 200 mT
- Phase I: upgrade of beam optics for existing beamline
- Phase II: all equipment received in hand & ongoing installation
- Scheduled for completion April 2020.
- **Will allow depth resolved studies of local magnetism at field up to 200mT parallel to the sample surface**



beta-NMR Results



Ellipsoid Samples



bNMR Technique Development w/ Existing Low-field

- Depth-resolved field penetration for three Nb samples:

Baseline (1400°C annealed), Baseline + 120°C baked, Baseline + 75/120°C baked[8]

- Consistent with 120°C LE-muSR bi-layer
- Indication of different bi-layer behavior: 120°C vs 75°C pre-baked → measurements at deeper implantation

Summary & Outlook

Summary

- Extensive experimental and theoretical studies: multilayers enhance flux shielding
- Optimization and theoretical validation: local measurement of field inside sample, muSR
- More advanced capabilities: depth-resolved (LE-muSR, low-field) and higher field (upgraded beta-NMR, 200 mT)
- Initial result: low-field beta-NMR → consistent with LE-muSR

Upcoming Experiments: beta-NMR technique for SRF

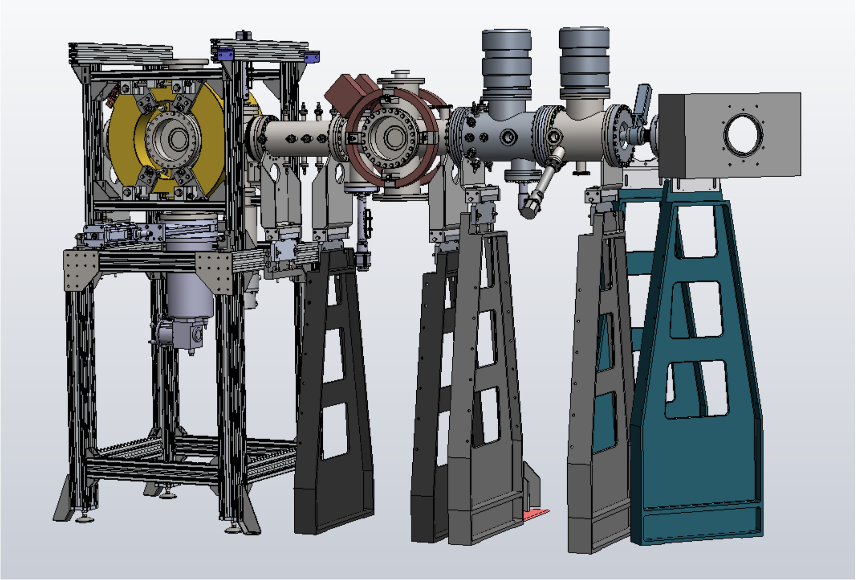
- More beam time in 2020
- N-infused ellipsoids (Fermilab)
- Higher fields spectrometer: layer-by-layer field profile & flux entry

Latest update

Assembled Coil & Support Frame:

- Coil with field up to 200 mT + frame for structural support & safeguard

Stay tuned!



Acknowledgements

- Experimenters [muSR]: D. W Storey, W. W. Wasserman, D. Bazyl, R. Dastley, M. Dehn, D. Azzoni Gravel, S. Gehdi, Z. He, R. Kiefl, Y. Ma, L. Yang, Z. Yao, H. Zhang (TRIUMF)
- Experimenters [beta-NMR]: V. Karner, D. Fujimoto, J. Ticknor (UBC), M. Stachura (TRIUMF)
- Beta-NMR High-field Upgrade: S. Saminathan, R. Baartman, B. Matheson (TRIUMF)
- TRIUMF Centre for Molecular & Materials Science: D. Arseneau, B. Hitti, G. Morris, D. Vyas, R. Abasalti (TRIUMF)
- Simulations: W. W. Wasserman (UBC)
- 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)
- Sample Prep: J. Keir, J. Wong (TRIUMF), M. Cervantes (U. Vic)

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[1] T. Kubo, Supercond. Sci. Technol.30, 023001 (2017).

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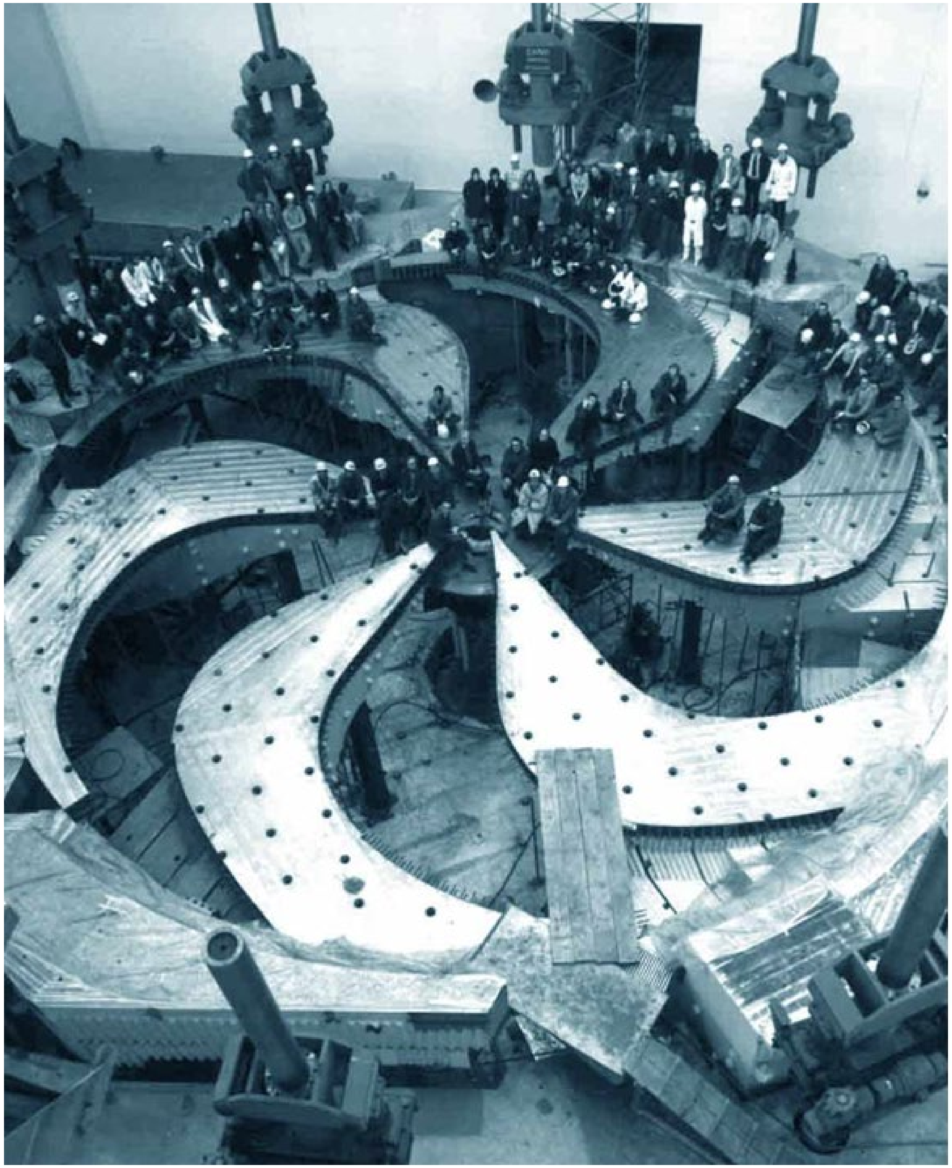
[6] C Z Antoine et al, ”Optimization of tailored multilayer superconductors for RF application and protection against premature vortex penetration”, Supercond. Sci. Technol. 32 085005 (2019).

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

[8] A. Grassellino, et al., “Accelerating fields up to 49 MV/m in TESLA-shape superconducting RF niobium cavities via 75C vacuum bake,” 2018. [Online]. Available: https://arxiv.org/abs/1806.09824

Thank you
Merci



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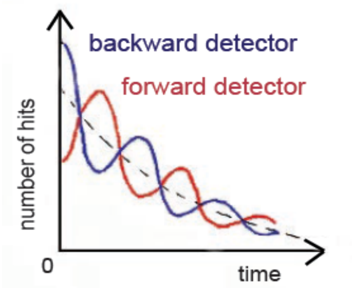
muSR Signal

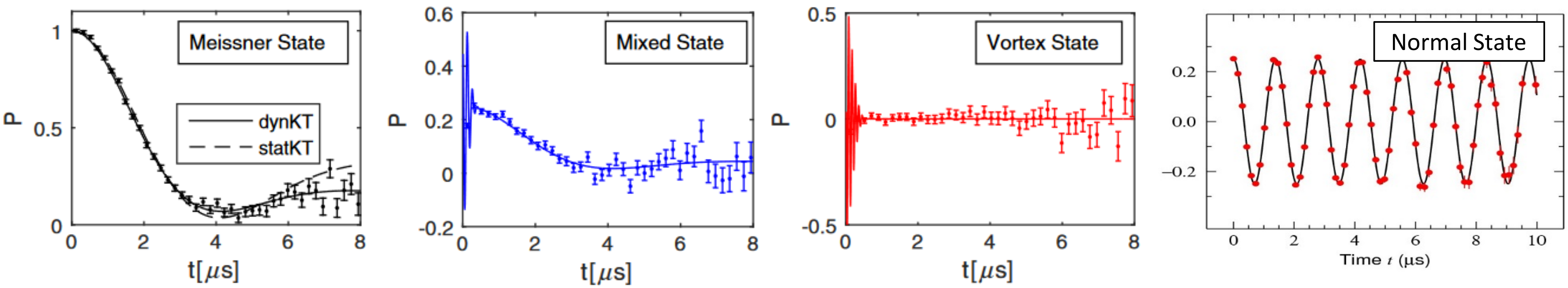


$$a_0 P_y(t) = \frac{N_L - N_R}{N_L + N_R}$$

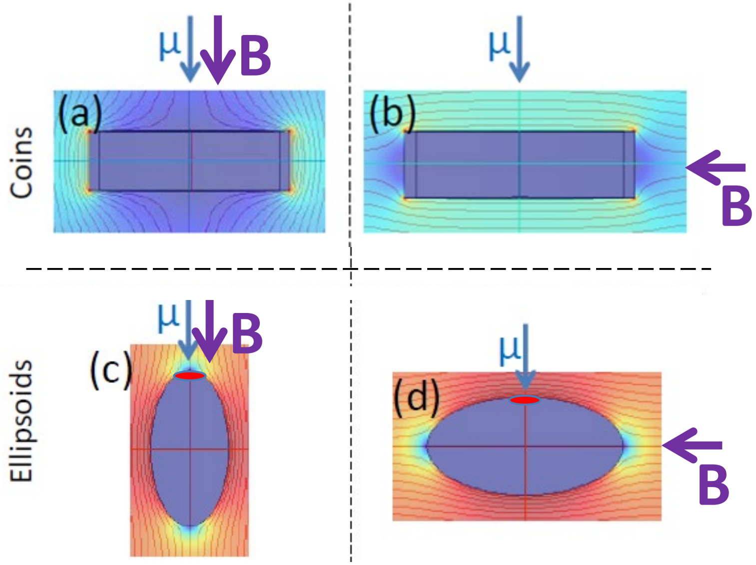
Fit Function

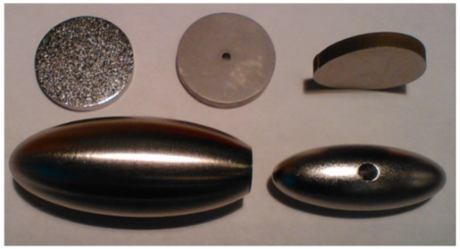
$$P(t) = a_0 \cdot P_{ZF}^{dyn}(t) + a_1 \cdot \exp\left(-\frac{1}{2}\Delta^2 t^2\right) \cdot \cos\left(\omega t + \frac{\pi\phi}{180}\right)$$

$$\tilde{a}_0 = \frac{a_0(H > 0)}{a_0(H \approx 0)}$$: Volume fraction in the Field free Meissner state



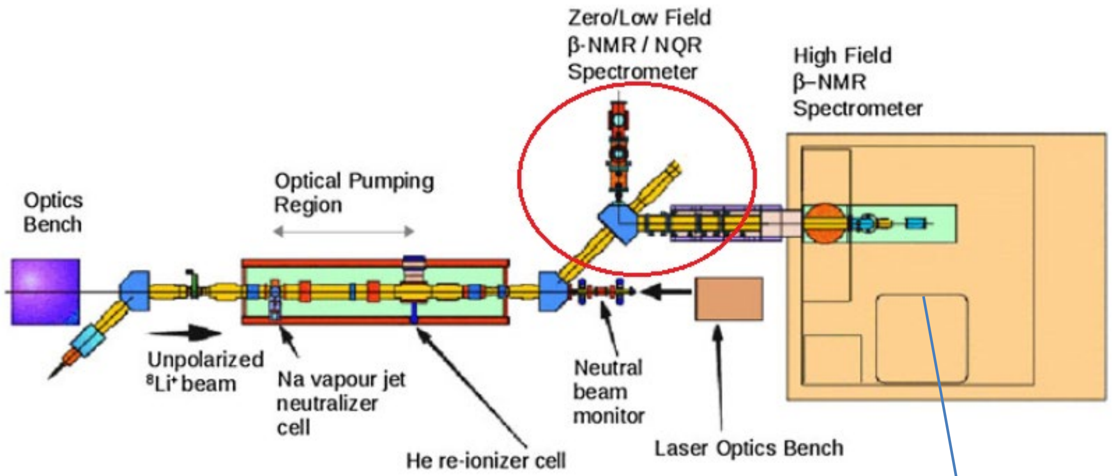
muSR Experiments

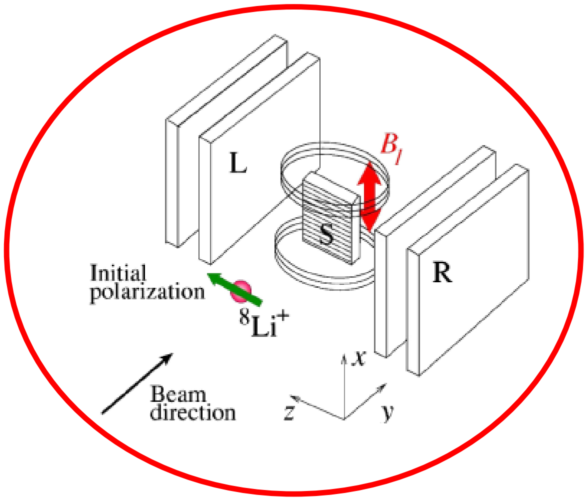


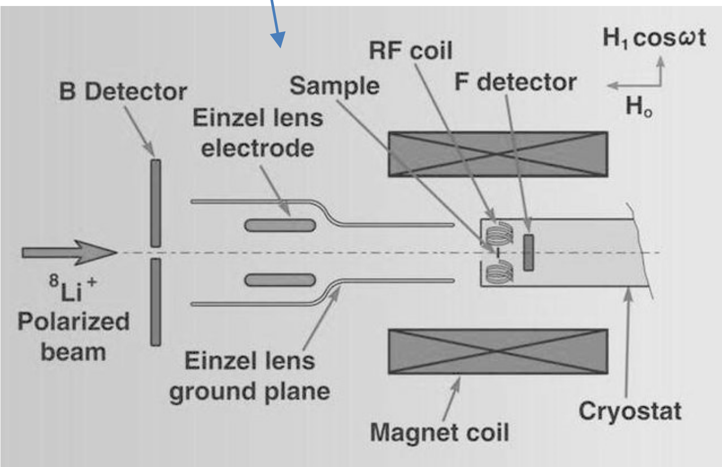


- Results are strongly geometry dependent (geometrical pinning)
- Coins, cavity cut-outs and ellipsoids have been used in four different cases

Beta-NMR Low Field Beamline

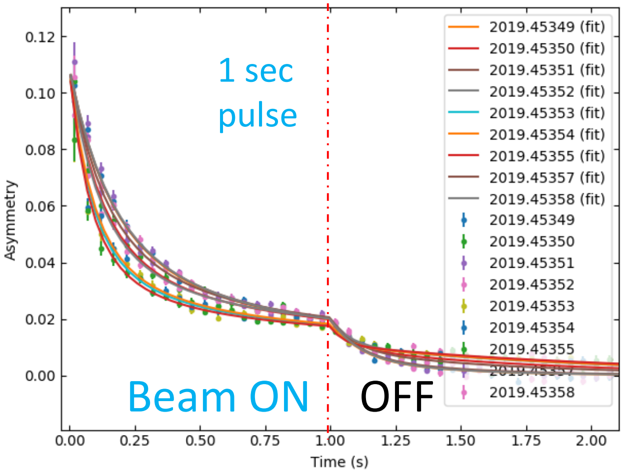


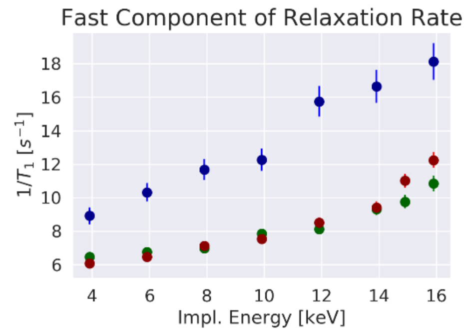




Beta-NMR Low Field Signal

$$P(t) = f_a \cdot \exp(-t/T_{1a}) + (1 - f_a) \cdot \exp(-t/T_{1b})$$

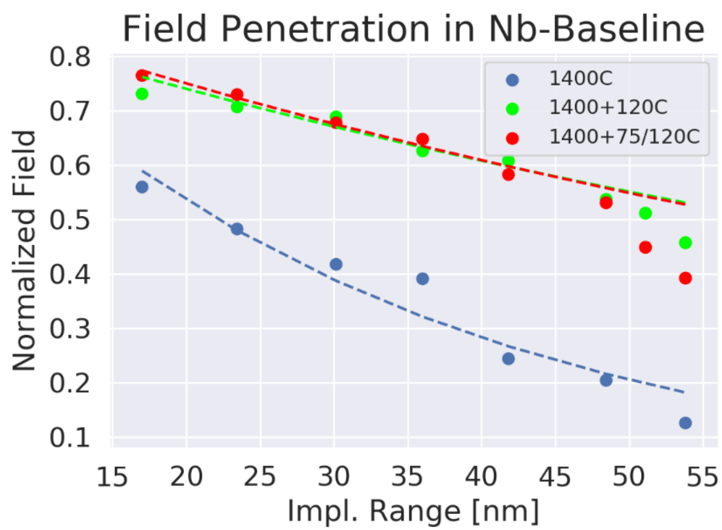




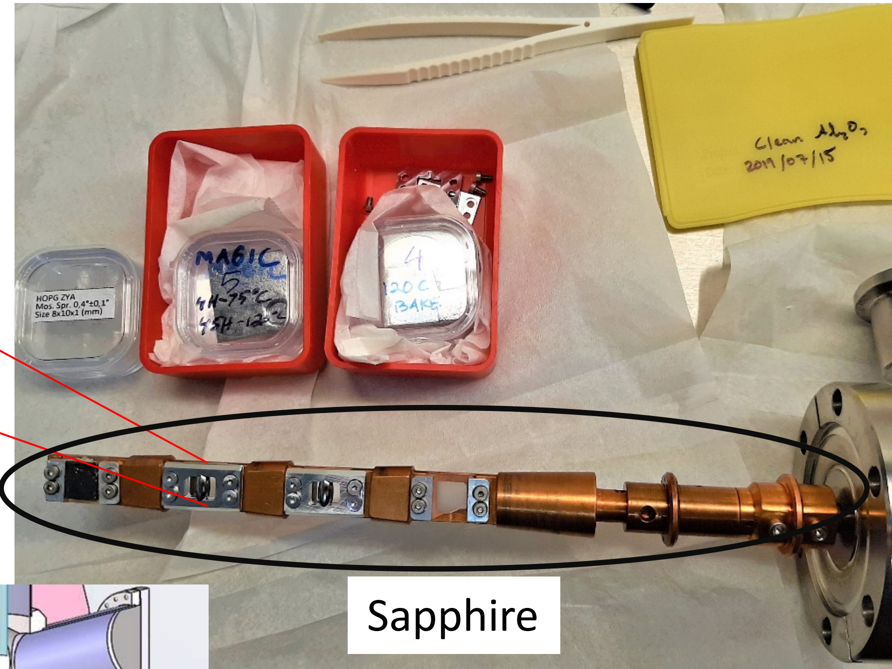
Spin-Lattice Relaxation
SC State at 24 mT

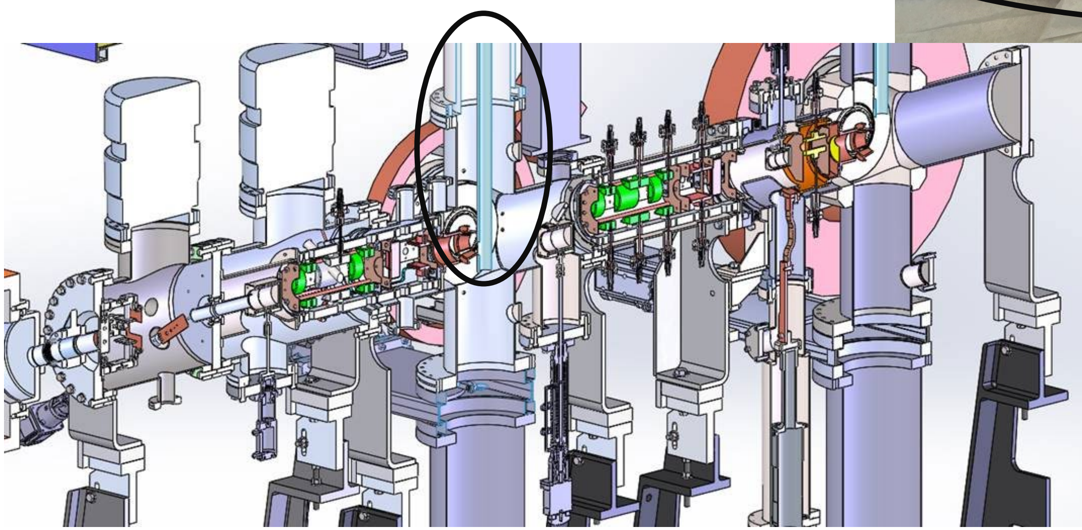
$$\frac{1}{T_1} = \frac{(\gamma B_d)^2 \tau_c}{1 + (\gamma B \tau_c)^2},$$ vs. Depth

B: Local Field



Beta-NMR Experiments





Beta-NMR Layout