muSR studies of SS' Structures for High Gradients

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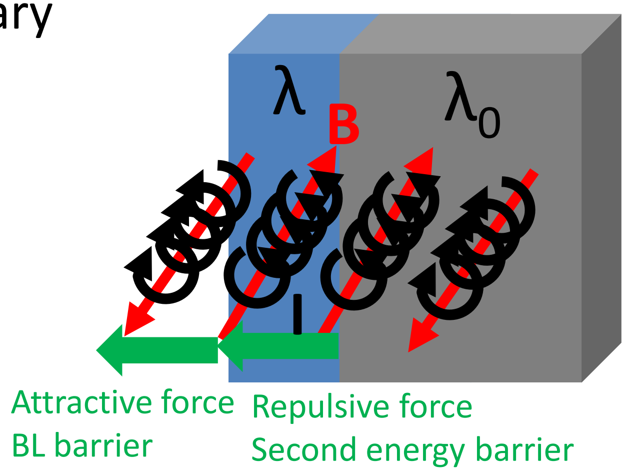
Content

- Review of bi-layer approach
- Introduction to muSR
- muSR results on bilayers
- Planned beta-NMR upgrade
- First beta-NMR results on 120°C and 70/120°C baked niobium

Superconductor Bilayer (SS)

- Consider parallel vortex at the SC/vacuum boundary
  - Add image vortex to fulfil boundary condition
  - → Attractive force (Bean-Livingston barrier)
- If $\lambda > \lambda_0$ - second energy barrier at the interface between layer and substrate (T. Kubo SUST)
  - Wide layer → two force peaks
  - Thin layer → forces summation → one peak
    (M. Checchin et al, LINAC16)



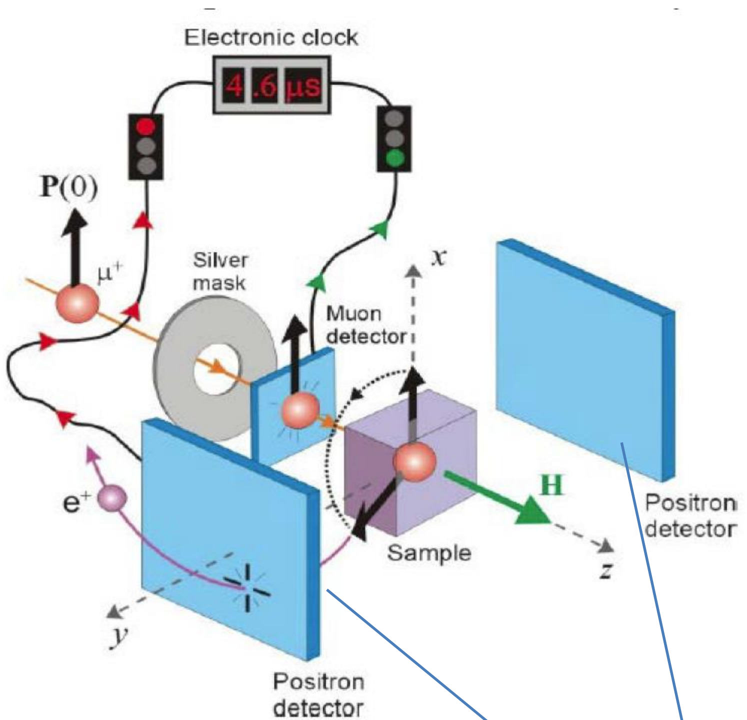
- Interface barrier more effective than the BL barrier due to the proximity effect (T. Junginger et al. SUST)
- 120°C baked niobium can be considered as bilayer as λ changes with depth (Romaneko et al. APL)
- Ideal layer thickness unknown
  - Are two force peaks necessary to achieve substrate Hsh?
    - 120°C baked cavities only reach the reduced H_{sh} of dirty niobium
  - What is the minimal thickness for efficient order parameter recovery at interface?
  - What is the maximum thickness to avoid vortex dissipation in the layer?

muSR and betaNMR Techniques

Technique	Max parallel magnetic field (mT)	Implantation depth in niobium	Measurement capabilities relevant to SRF
Surface muSR	300	130 µm	Pinning strength [1,2] **Field of first vortex penetration** [2,3,4]
Low energy muSR	25	10-100 nm	**London penetration depth/magnetic screening profile in London layer** [4,5,6,7] Hydrogen diffusion and magnetic impurities [7]
beta-NMR	24 (current) 200 (upgrade)	10-100 nm	**Vortex penetration in the London layer** [8]

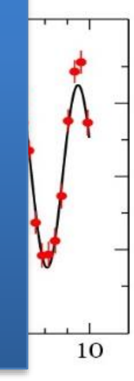
[1] Grassellino, A., et al. "Muon spin rotation studies of niobium for superconducting rf applications." Physical Review Special Topics-Accelerators and Beams 16.6 (2013): 062002.
[2] Junginger, T., et al. "Field of first magnetic flux entry and pinning strength of superconductors for rf application 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

Muon Spin Rotation (muSR)



- Muons are deposited one at a time in a sample and spin rotate in the local magnetic field
- Muons decay (τ~2.2μs) emitting a positron preferentially aligned with the muon spin
- Right and left detectors record positron correlated with time of arrival
- The time evolution of the asymmetry in the two signals gives a measure of the local field in the sample

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



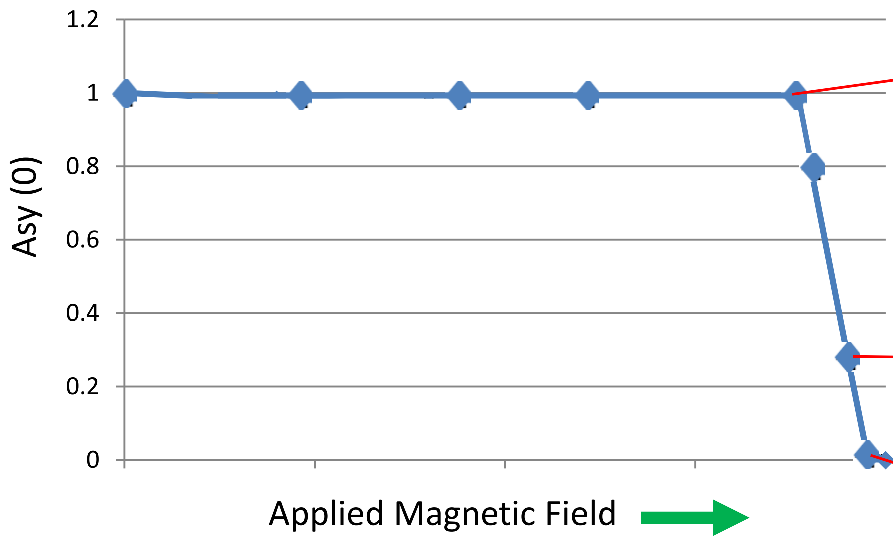
μ+

- muSR is a sensitive probe for the detection of the presence of local magnetic field and can thus be used to detect the transition from the Meissner to a vortex state
- muSR has been used for SRF studies since 2010*

* 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.

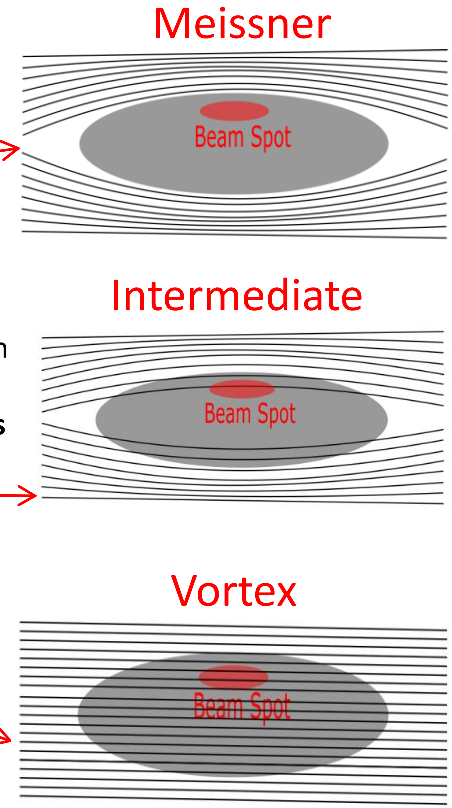
muSR as a local magnetometer

Time evolved asymmetry signal gives information on the local magnetic field experienced by the probe



Intermediate State

- Some areas probed are in the Meissner other areas in the vortex state
- **For a pin-free ellipsoid this state is never observed**

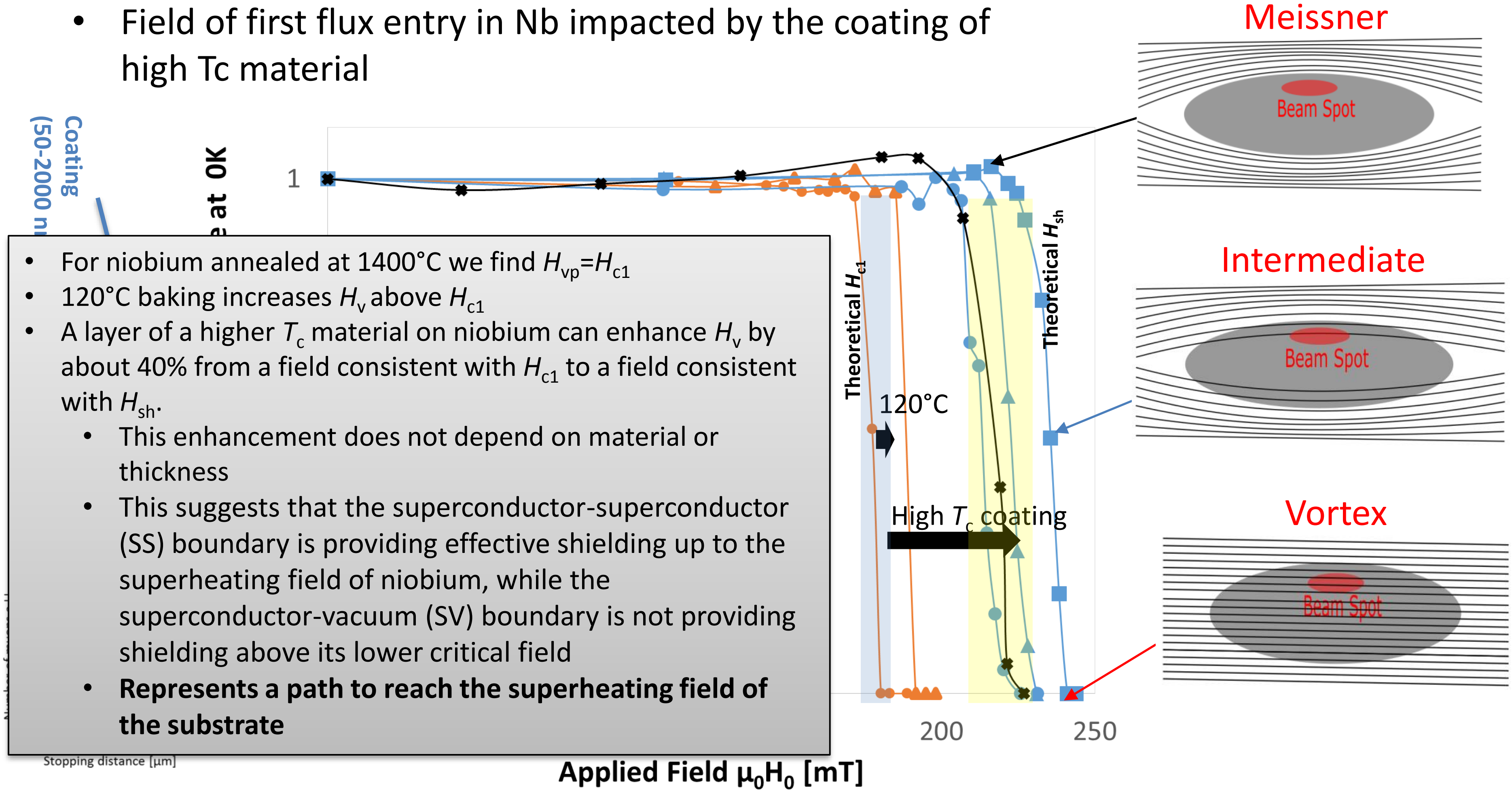


Derived value Asy (0) represents the fraction of the sampled volume that does not contain field

Field of first vortex penetration H_{vp} is when the volume fraction in the Meissner state significantly deviates from 1

Coated Niobium - First Flux Entry

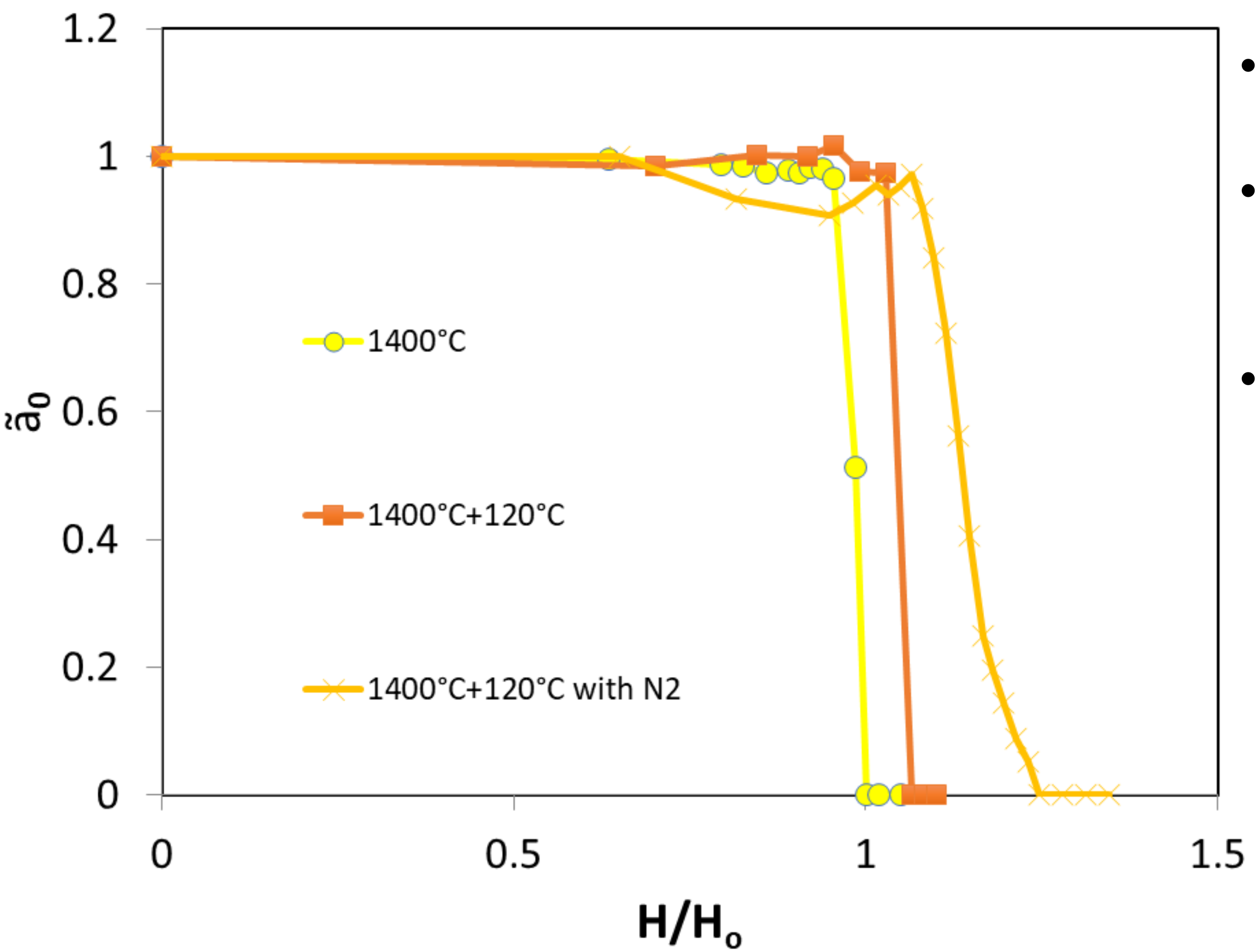
- Nb_3Sn and MgB_2 with 50-2000nm thickness on niobium
- Muons implanted 130µm in the bulk
- Field of first flux entry in Nb impacted by the coating of high Tc material



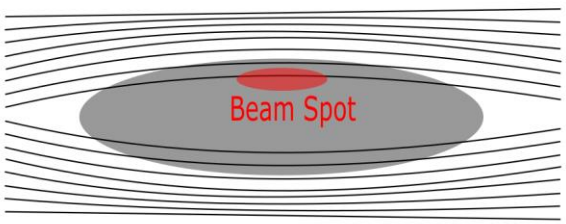
- For niobium annealed at 1400°C we find $H_{vp}=H_{c1}$
- 120°C baking increases H_v above H_{c1}
- A layer of a higher T_c material on niobium can enhance H_v by about 40% from a field consistent with H_{c1} to a field consistent with H_{sh}.
  - This enhancement does not depend on material or thickness
  - This suggests that the superconductor-superconductor (SS) boundary is providing effective shielding up to the superheating field of niobium, while the superconductor-vacuum (SV) boundary is not providing shielding above its lower critical field
  - **Represents a path to reach the superheating field of the substrate**

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

New results on N-Infusion



- 1400^{o}C releases all pinning
- 120^{o}C after 1400^{o}C increases H_{entry} and does not re-introduce pinning
- N infusion increases H_{entry} and pinning
  - Gradual Decay of Asymmetry is a sign of pinning



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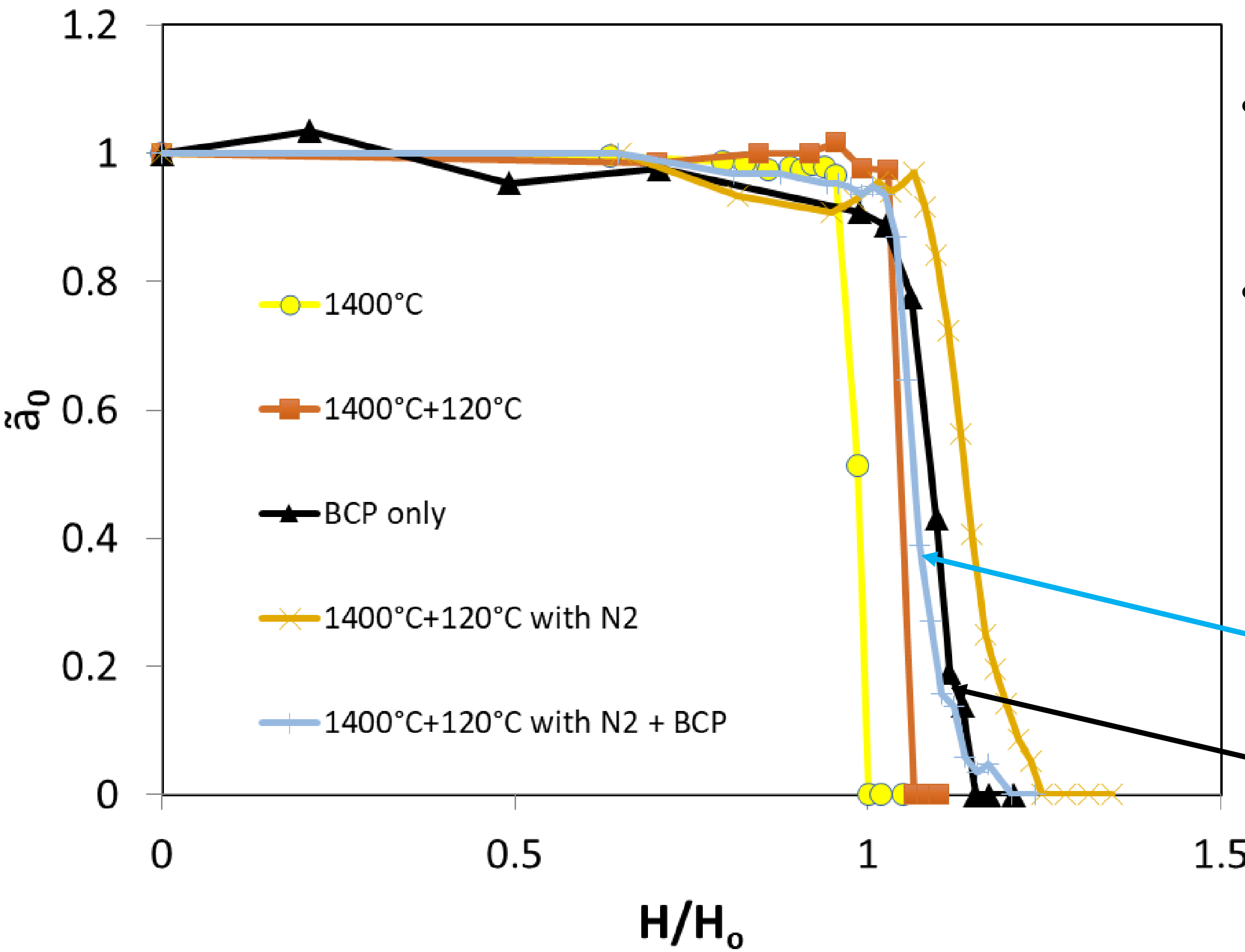

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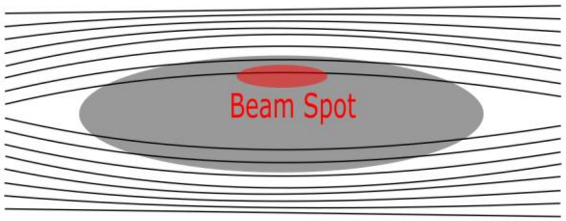
  - Subsequent etching (**5µm BCP**) gives very similar result to **unannealed** sample



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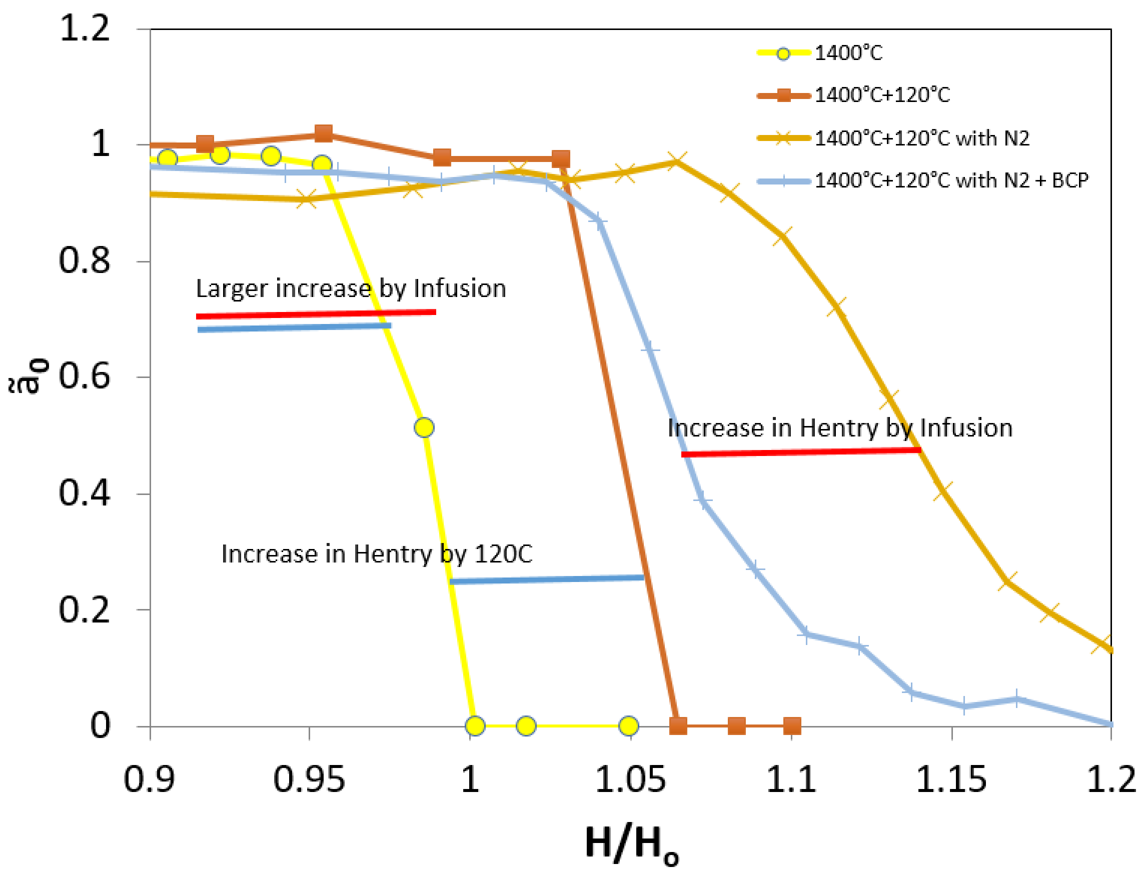

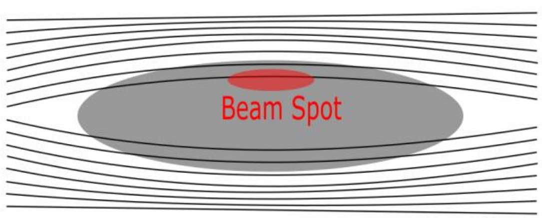

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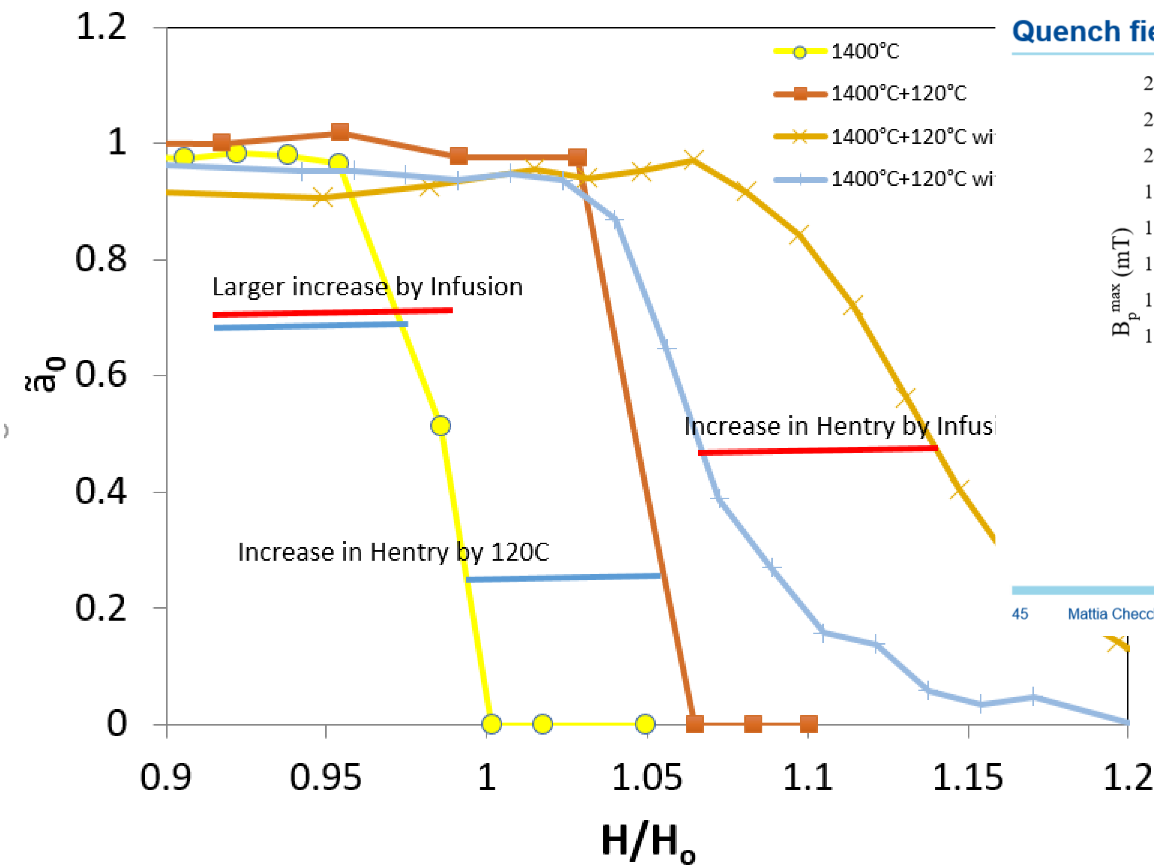
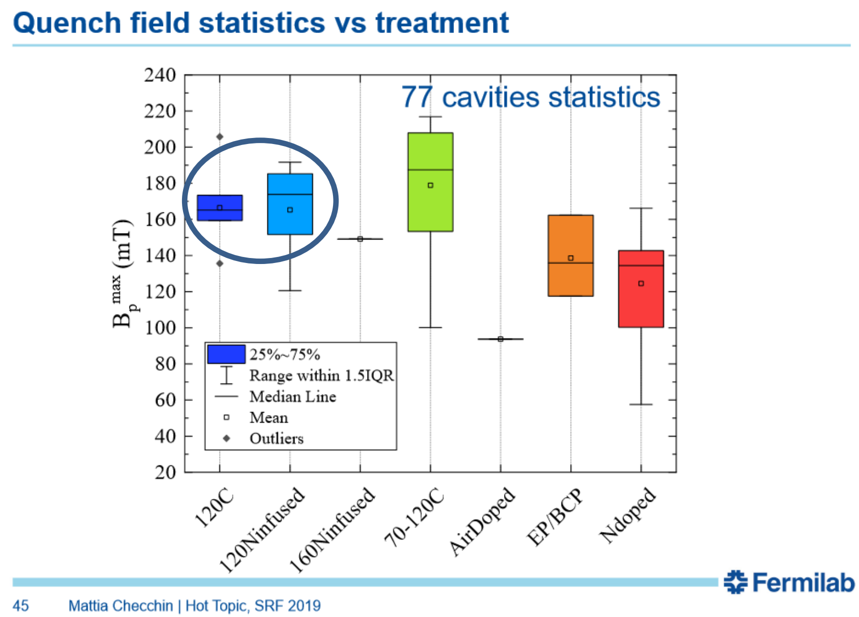
120^{o}C after 1400^{o}C increases H_{entry} and does not re-introduce pinning
N infusion increases H_{entry} and pinning

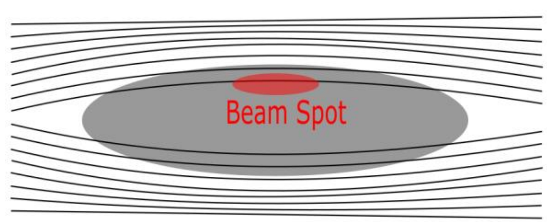
- Gradual Decay of Asymmetry is a sign of pinning
- Subsequent etching (5µm BCP) gives very similar result to unannealed sample
- Increase in Hentry is slightly higher for N-doped samples compared to 120^{o}C

New results on N-Infusion





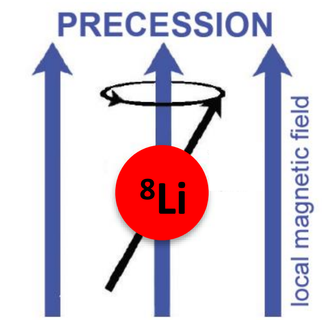
Increase in H_{entry} for 120^{o}C and N-infusion both qualitatively in agreement with RF cavity data



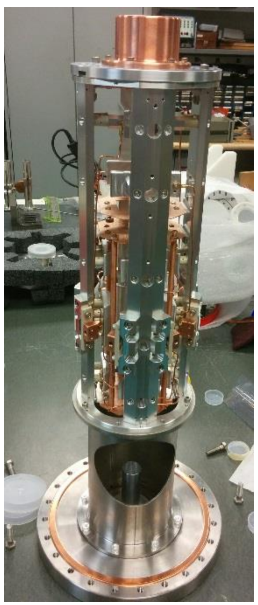
β-SRF @ TRIUMF

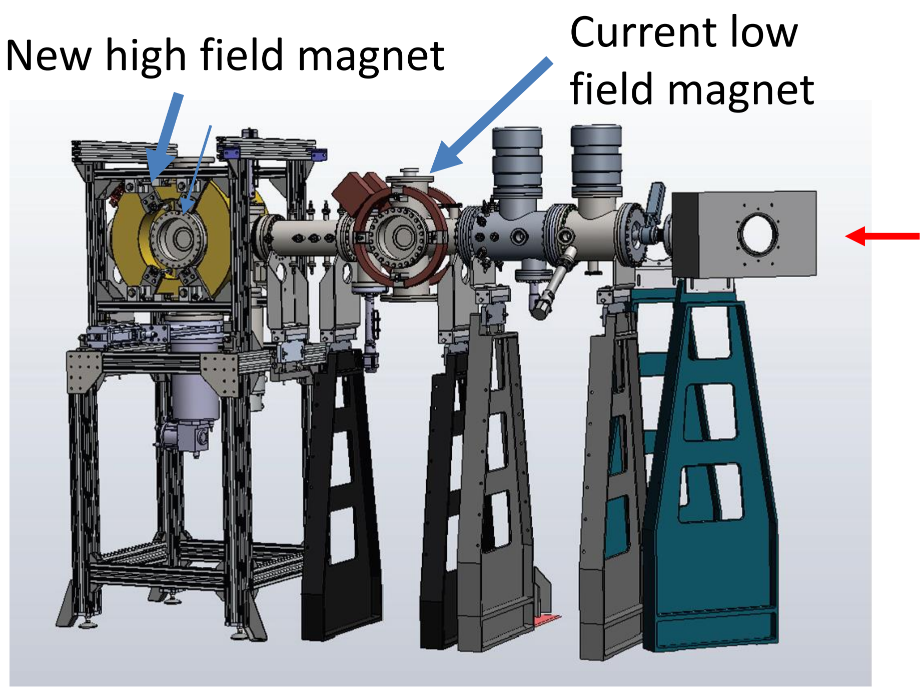
TRIUMF has beta-NMR to probe magnetism at surfaces and interfaces

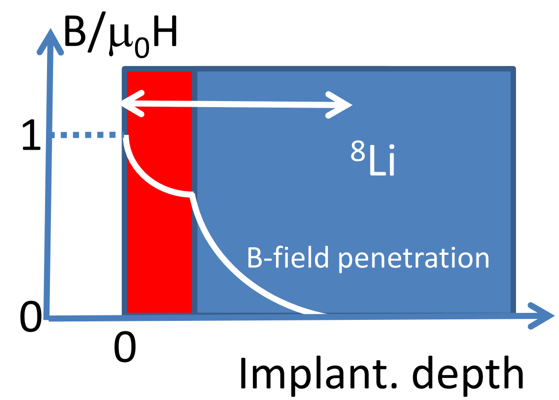
- Utilizes the beta decay of low energy (30keV) polarized 8Li ions
- 8Li are soft landed in the London layer as a local magnetic probe
- Perfect for SRF characterization of doping and new materials
- **With β-SRF we are adding a new beamline extension and Helmholtz coil to test samples in high parallel field (200mT)**

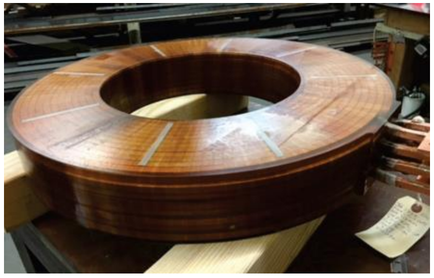


$$^{8}\mathrm{Li} \rightarrow e^{-} + \nu_{e} + {}^{8}\mathrm{Be}$$







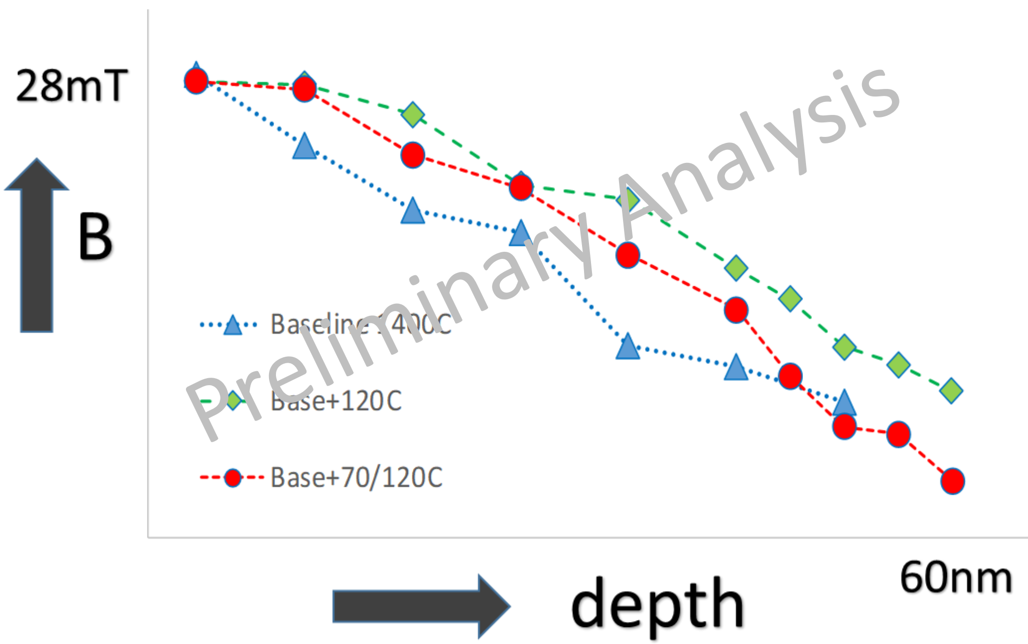


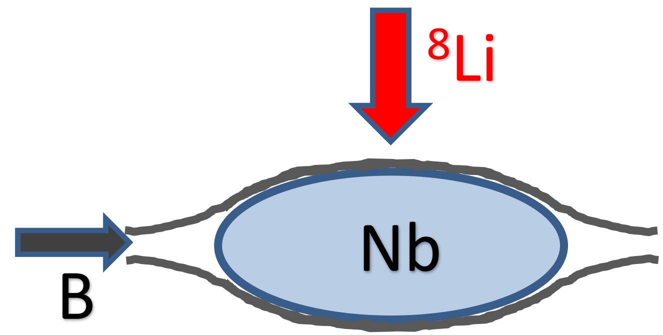
Extension of parallel field spectrometer

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

First beta-NMR Experiment with SRF samples (Thoeng et al)

Beta-NMR provides a depth resolved probe of the magnetic field at the sample surface – polarized 8Li ions can be implanted at different depths to give a measure of the local field





Evidence of change in Meissner screening from 120C and 70C/120C treatments compared to base treatment

Summary

- Superconducting bilayers (SS) can potentially yield accelerating gradients beyond state of the art by inducing superheating in the substrate
- A layer of Nb3Sn (2000nm) or MgB2 (50-300nm) pushes the DC field of first vortex penetration H_{entry} of niobium from a field consistent with H_{c1} to a field consistent with H_{sh}
- For 120^{o}C and N-infused niobium H_{entry} increases above H_{c1} but remains below H_{sh} (qualitatively consistent for RF and DC)
  - Single energy barrier?
  - Insufficient recovery of order parameter at interface?
- A new facility based on betaNMR will enable parallel magnetic fields above 200mT and depth dependent measurements in the London layer
  - First results show evidence of changed Meissner screening from 120C and 70C/120C treatments compared to base treatment

Acknowledgements

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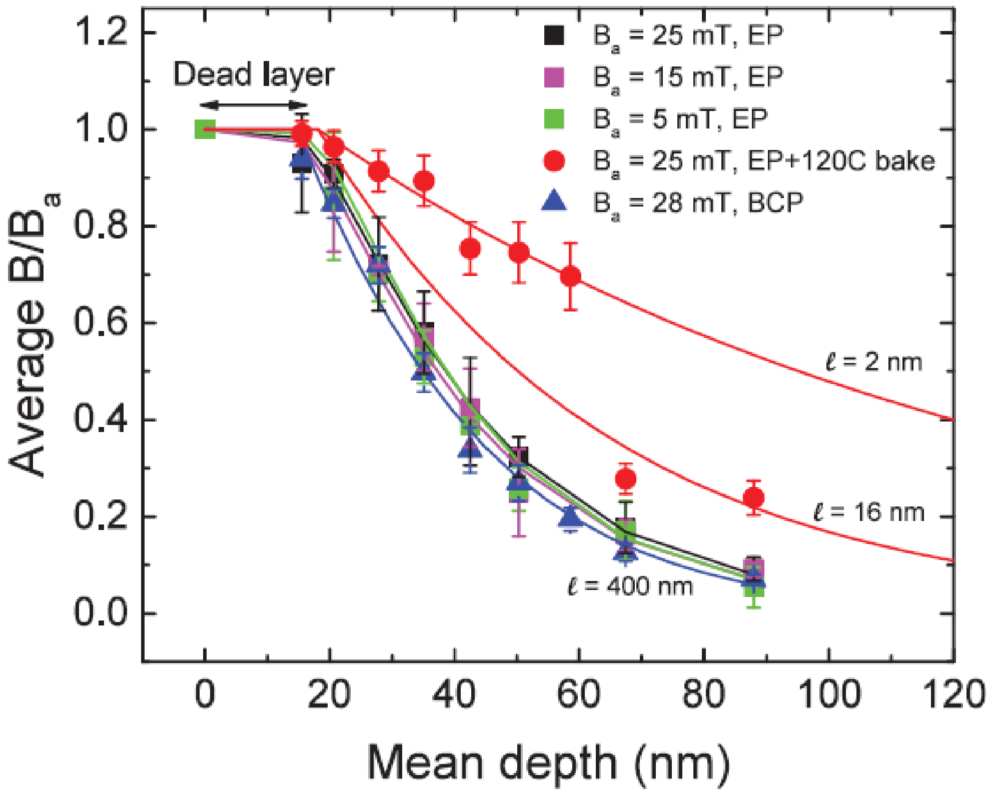
Thanks

Magnetic screening profile in London layer

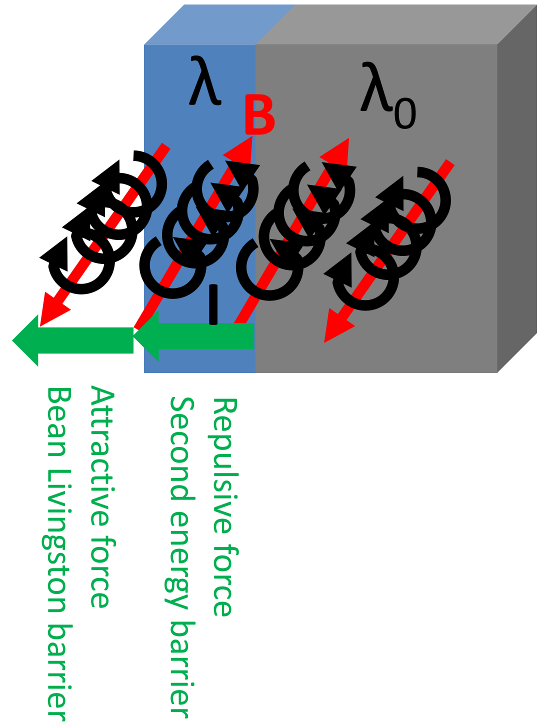


A cutout sample from a 120^{o}C baked cavity shows a large London penetration depth >100 nm in the first 50nm and a depth dependent mean free path, likely due to gradient in vacancy concentration.

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

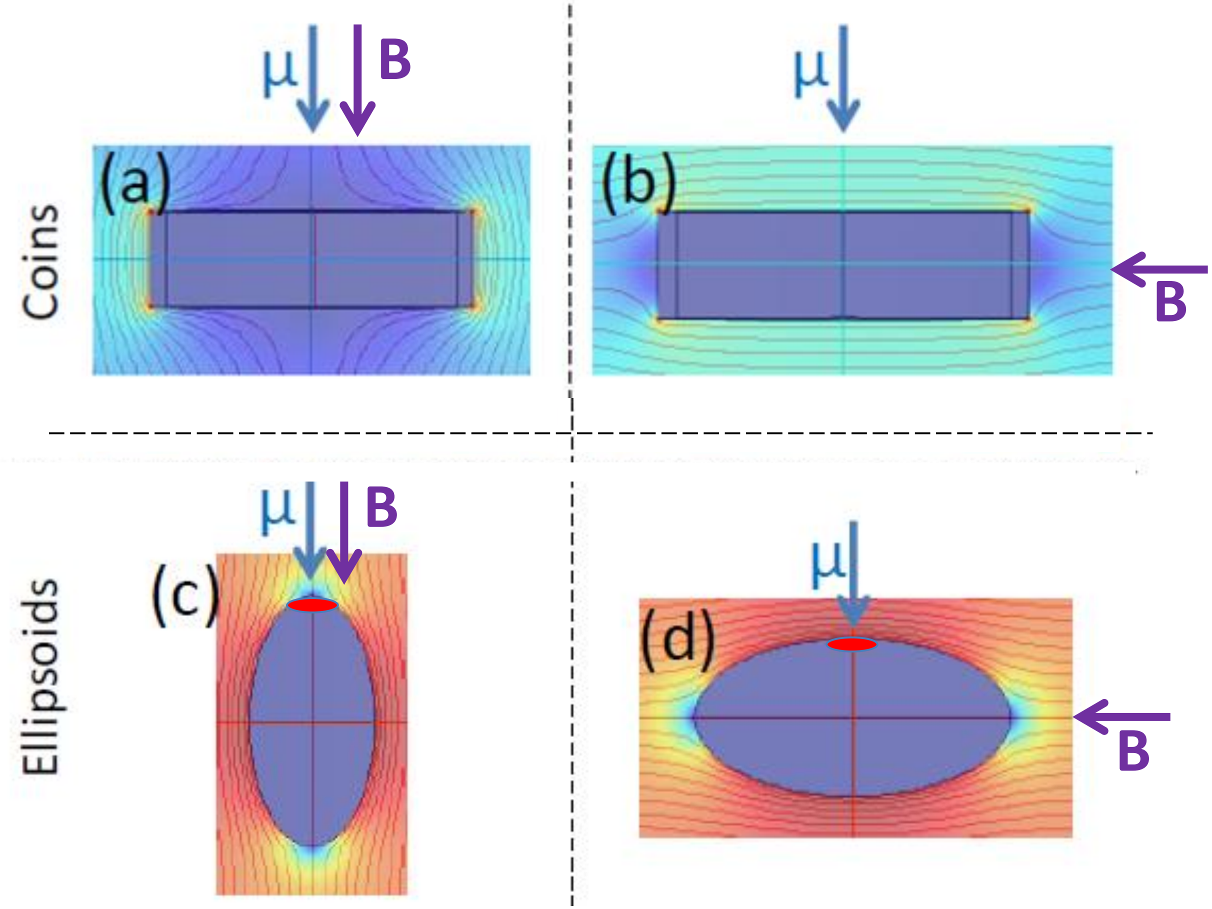
Force at the boundary

- Vortex at the SC/vacuum boundary
  - Magnetic field is parallel to the surface
  - Modelled by image vortex
  - Attractive force →Bean-Livingston barrier
- If $\lambda > \lambda_0$ there is second energy barrier at the interface between the layer and the substrate
- This force is independent of layer thickness



Samples and Geometry

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



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.