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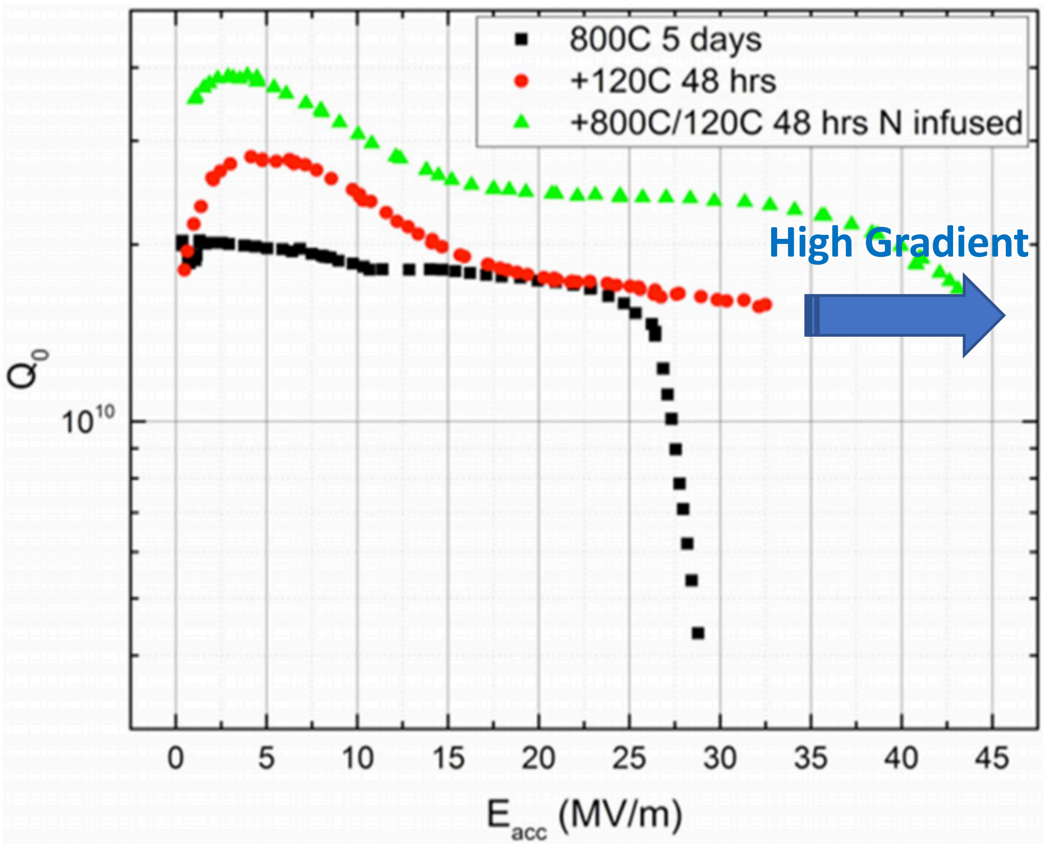
Latest material analysis on state of the art treatments (including doping and infusion cutouts)

Zuhawn Sung, Alex Romanenko, Yulia Trenikhina, and Anna Grassellino

TESLA Technology Collaboration Meeting

6-9 Feb 2018

Fundamental material studies to investigate origin of high Q and high gradient



A Grassellino, et al., Technology, "Unprecedented quality factor at accelerating gradients up to 45MV/M in niobium" Supercond. Sci. Technol. 30, 094004, (2017)

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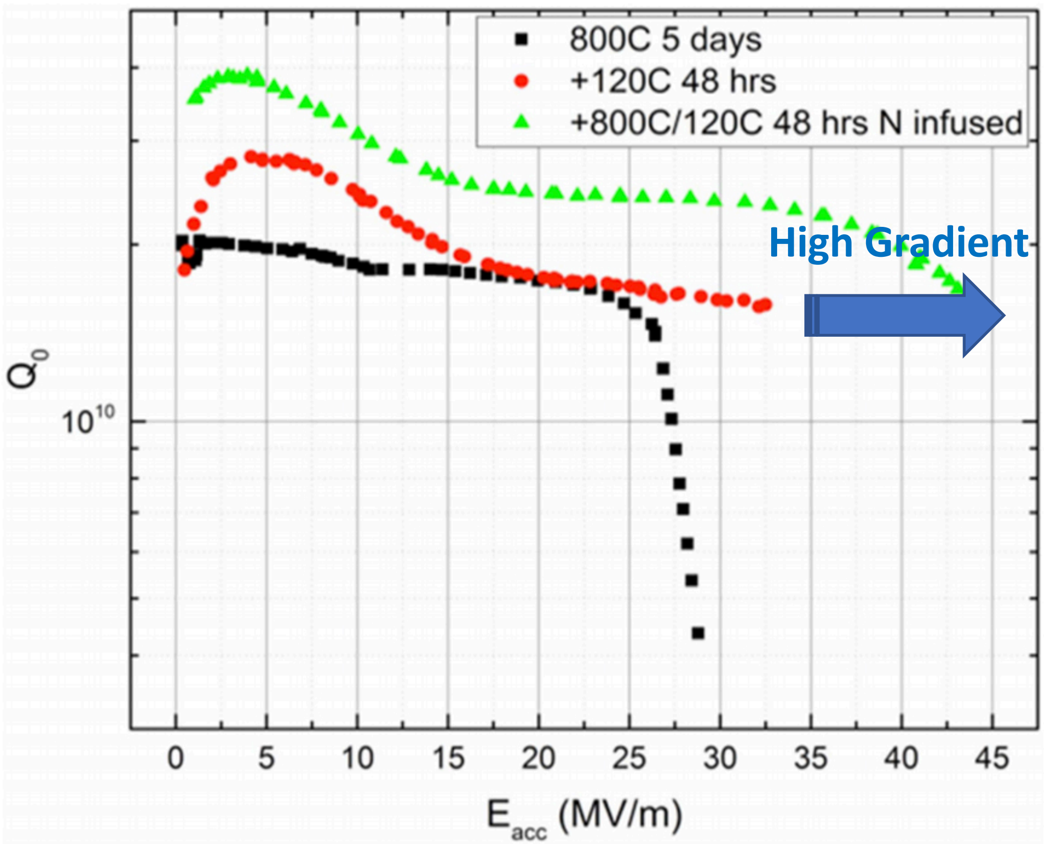

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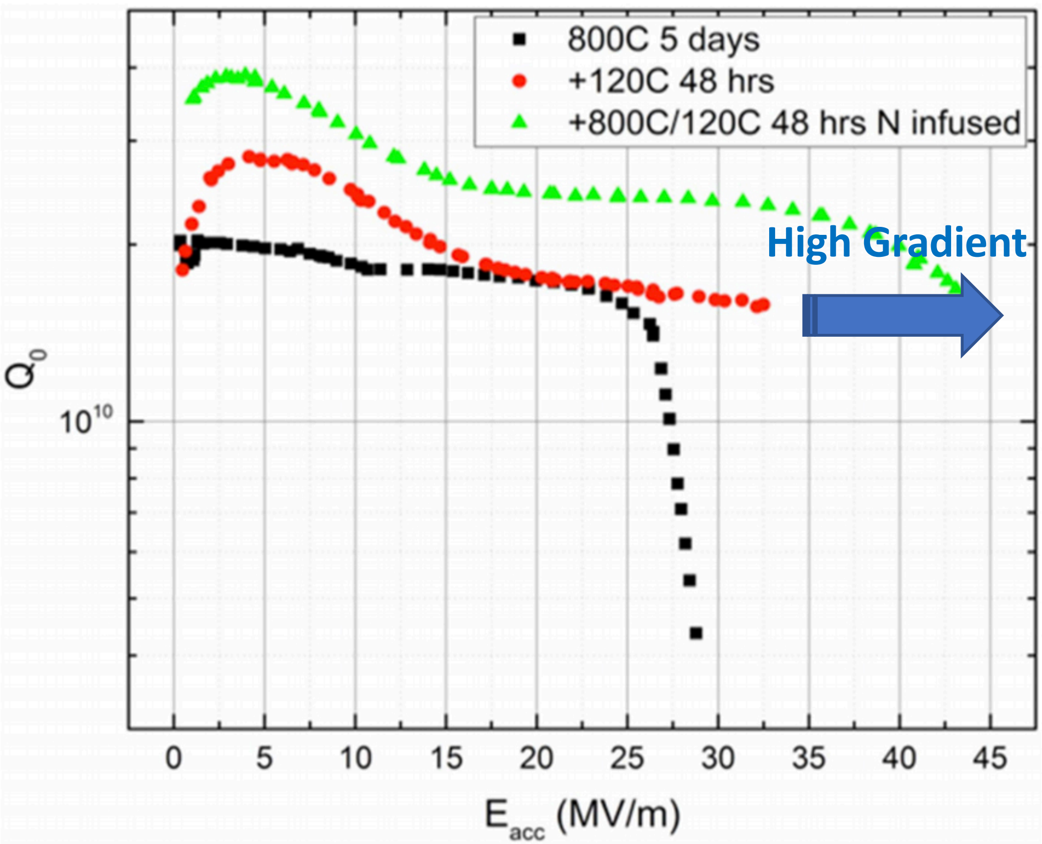
- ✓ **Cryo-Atomic Force Microscopy for $Nb_{1-x}H_x$ (hydride phase) proximity effect**
- ✓ Cryo-MFM (Magnetic Force Microscopy) for trapped vortices
- ✓ AC Susceptibility characterization for penetration dynamics of surface magnetic vortices

Fundamental material studies to investigate origin of high Q and high gradient



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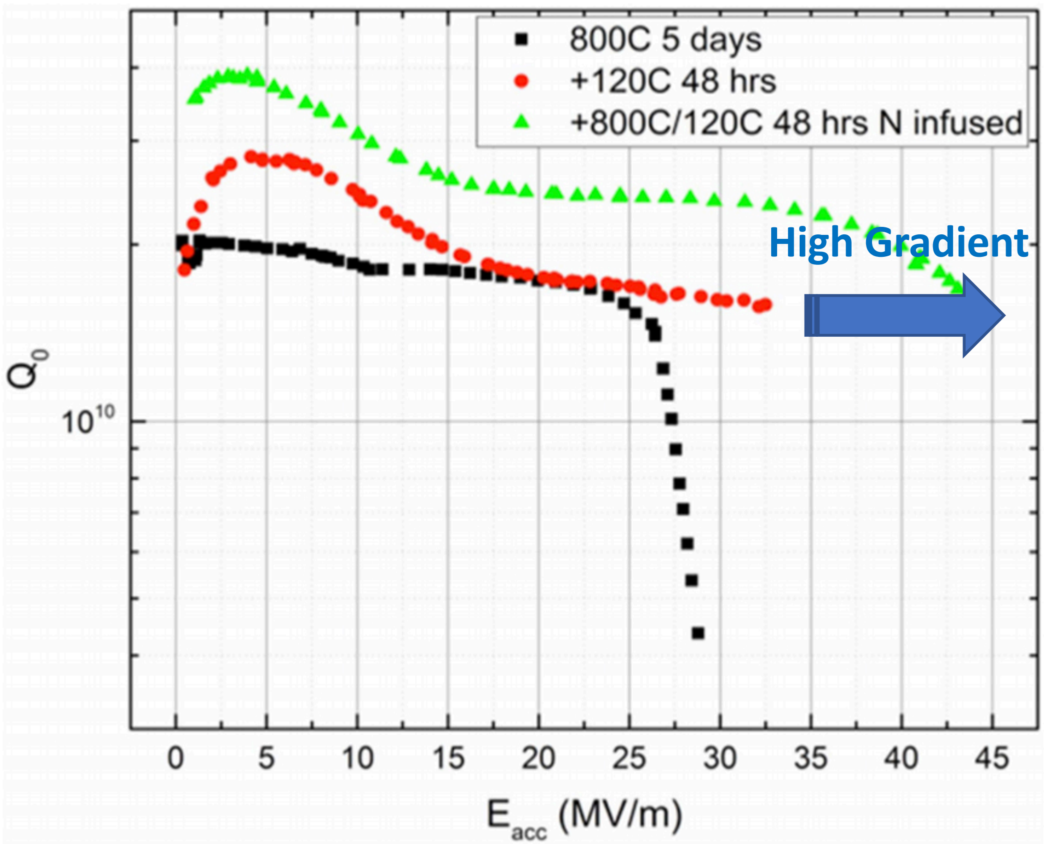

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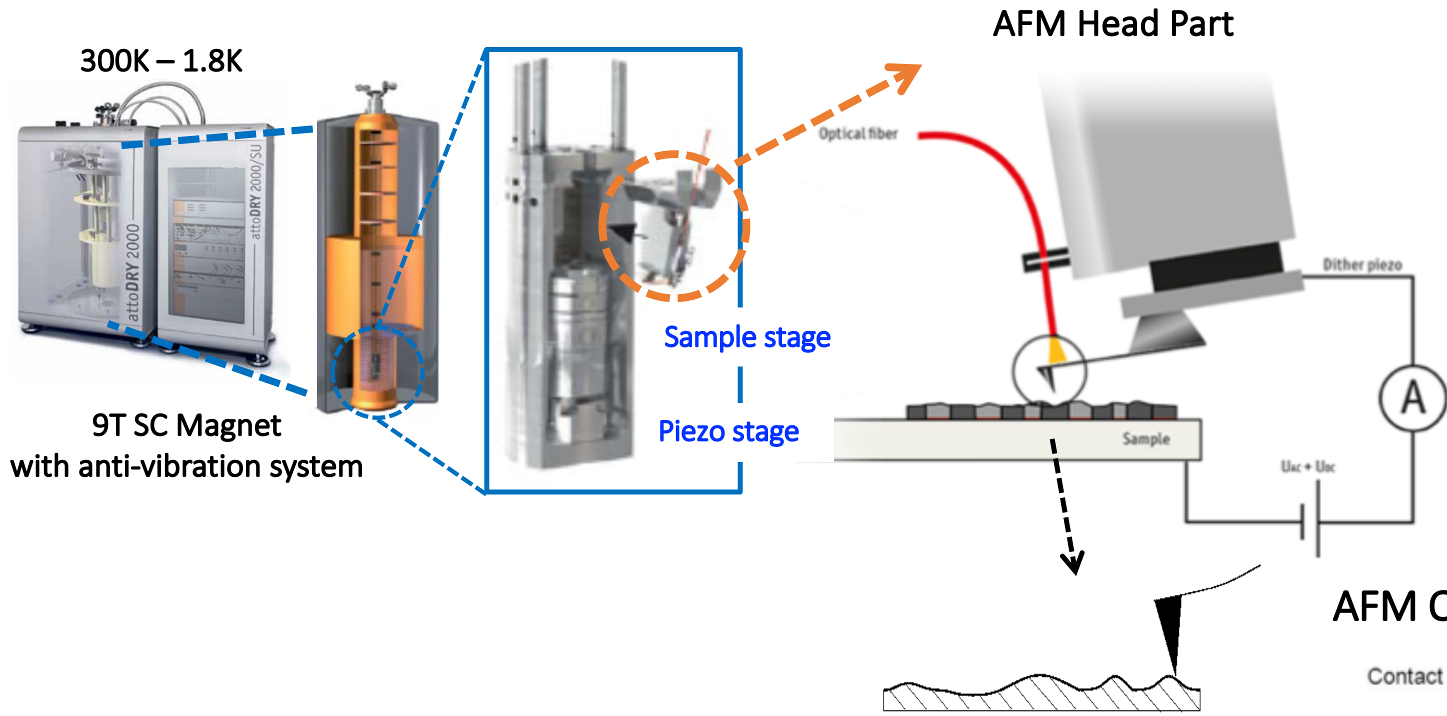
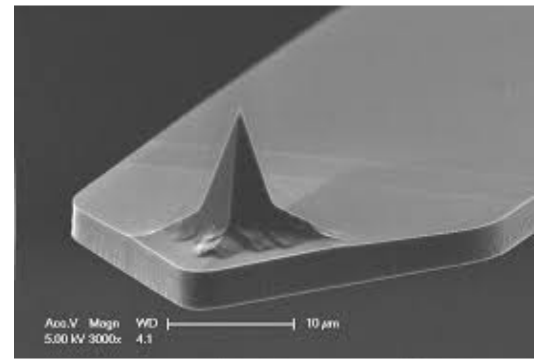
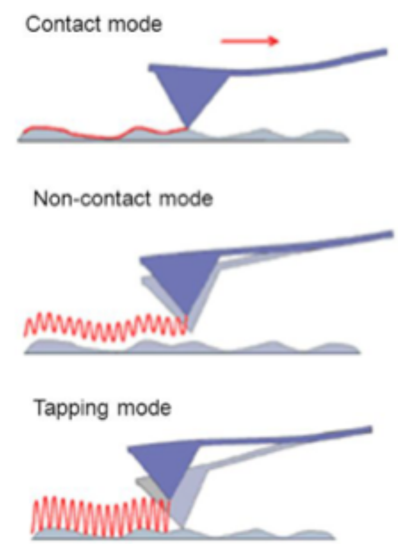
Cryogenic Atomic Force Microscope (AFM) + Magnetic Force Microscope (MFM) in 9 Tesla Superconducting Magnet @FNAL_MSL



AFM tip



AFM Operation Mode



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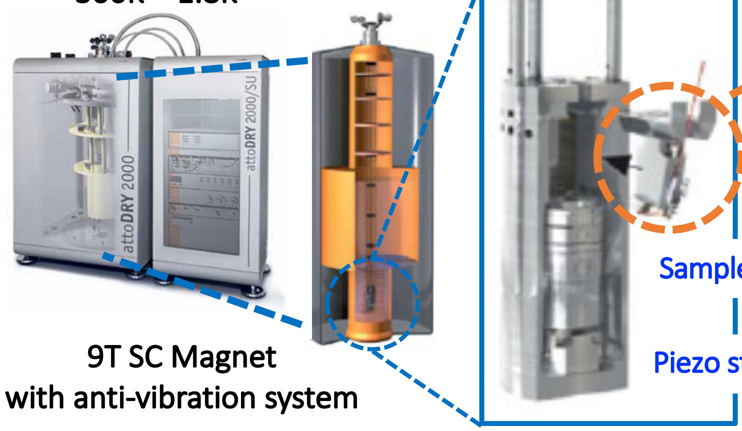
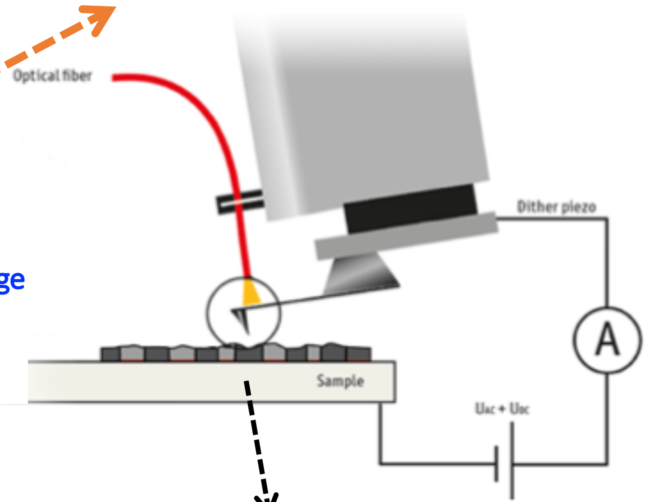
Cryogenic Atomic Force Microscope (AFM) + Magnetic Force Microscope (MFM) in 9 Tesla Superconducting Magnet @FNAL_MSL

300K – 1.8K



9T SC Magnet
with anti-vibration system

AFM Head Part



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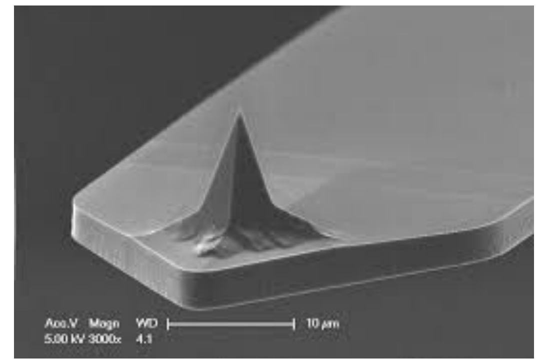
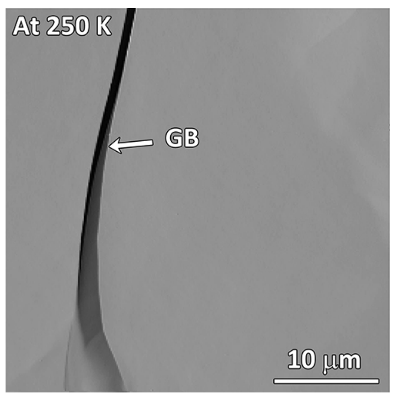
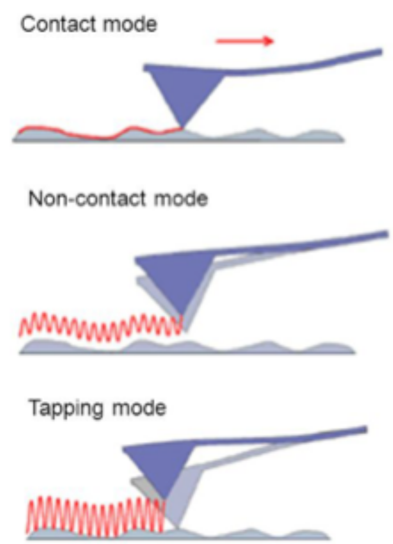


Surface topological image of cavity cut out



Surface topology

AFM Operation Mode



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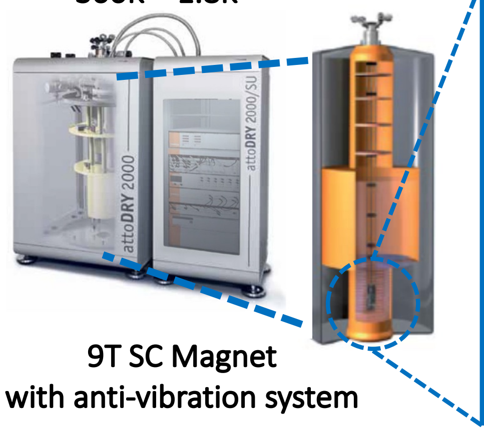

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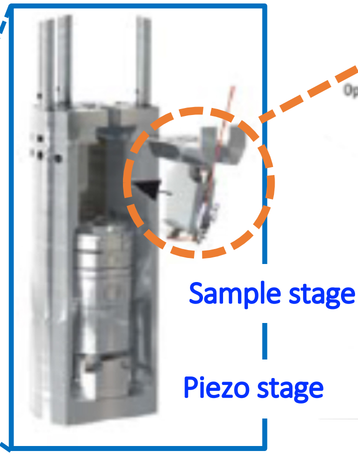

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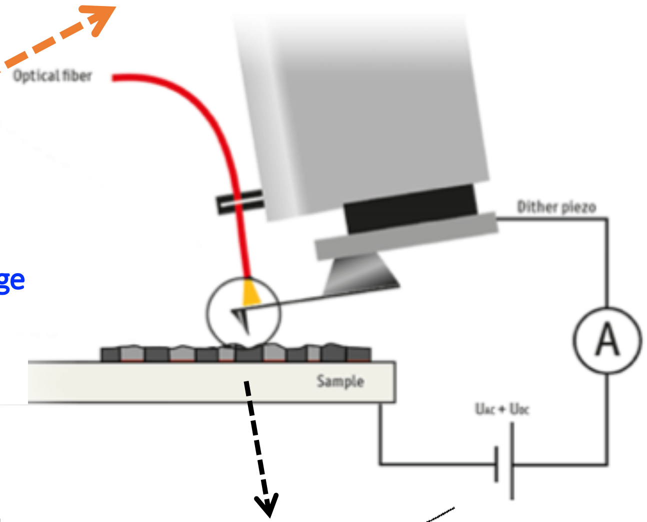

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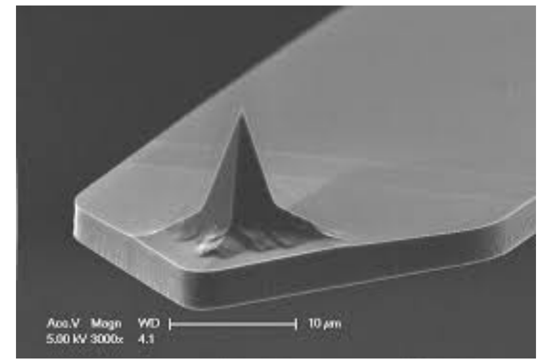

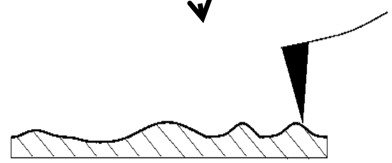

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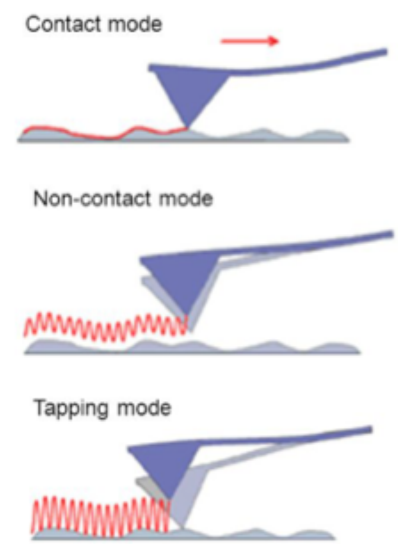
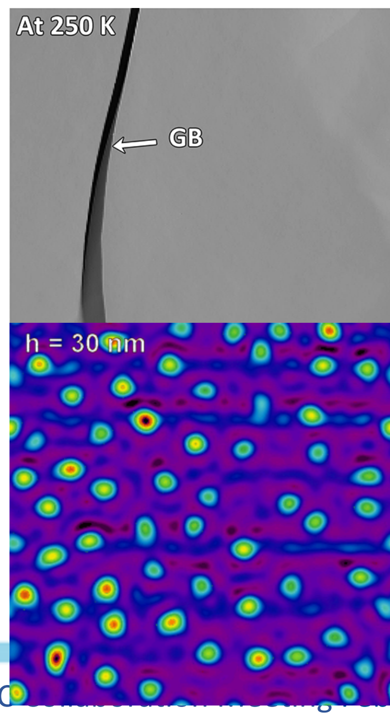


Surface topology

Magnetic topology

Surface topological image of cavity cut out

Magnetic vortices on EP'ed Nb coupon



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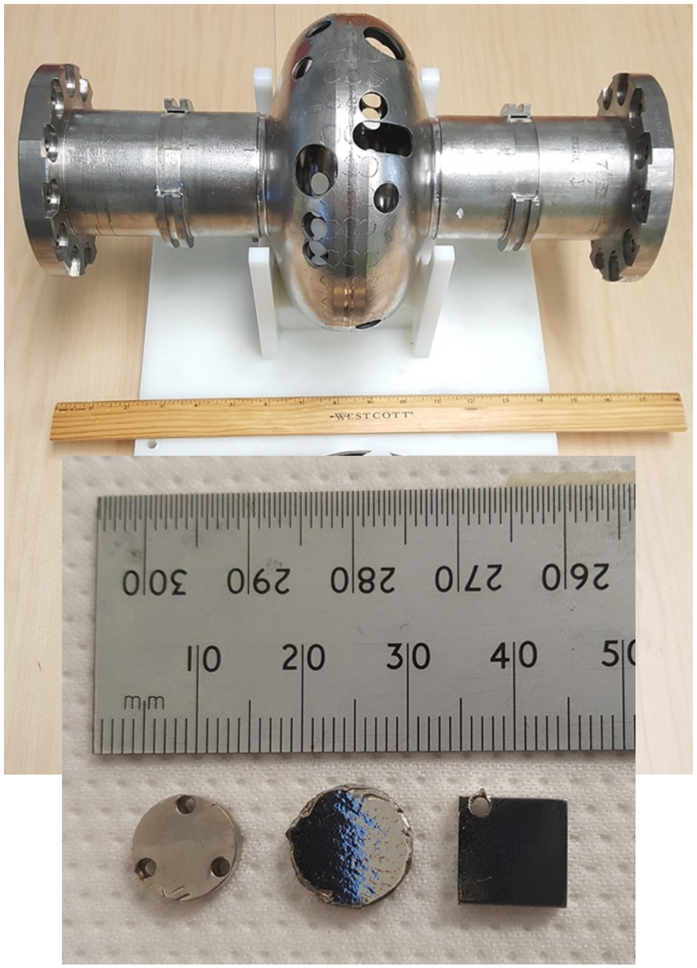
Samples for Cryo AFM and MFM Study

1.3 GHz SRF Nb cavity



Descriptions of Samples studied

No.	Sample ID	Features
1	Hot Spot	EP'ed Cavity (non-degaussed cavity)
2	800°C baked hot spot	800°C HT + 20 µm BCP applied on hot spot cut out (#1)
3	120°C baked	EP + 120°C baked cavity
4	N-doped	N-doped cavity @800°C 25mTorr (2/6)

Atomic Force Microscopy

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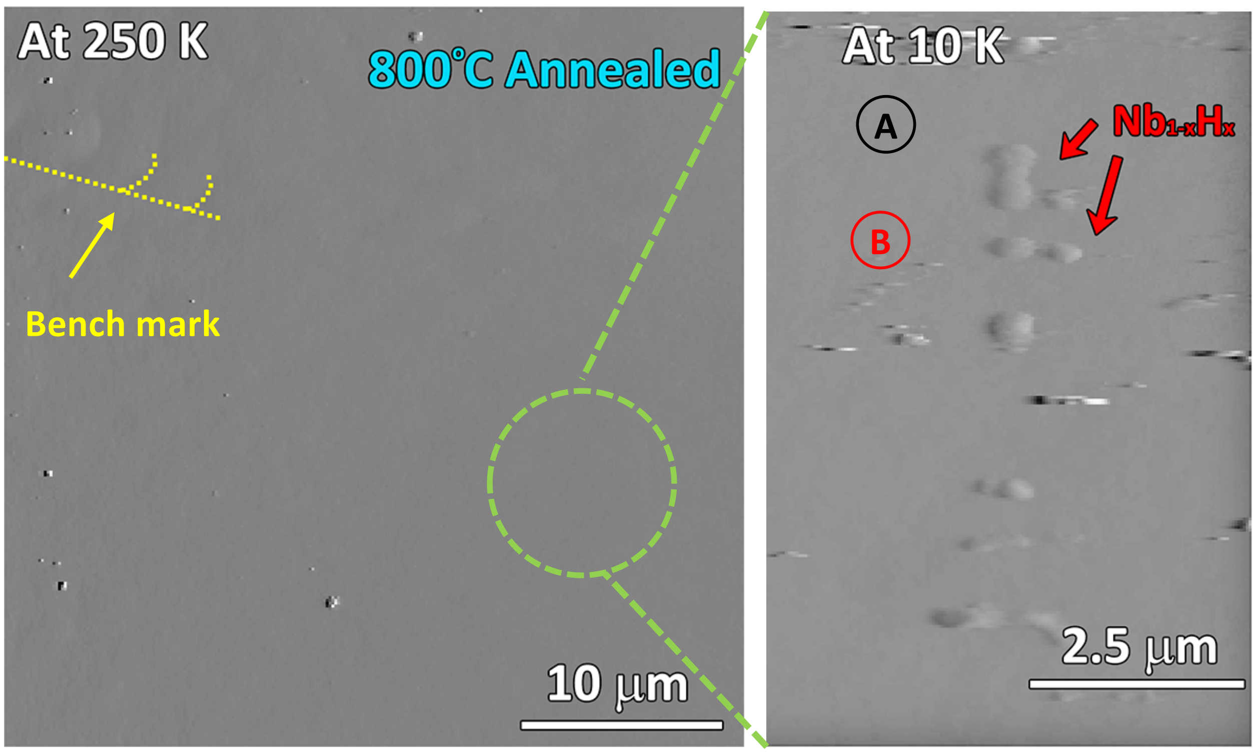
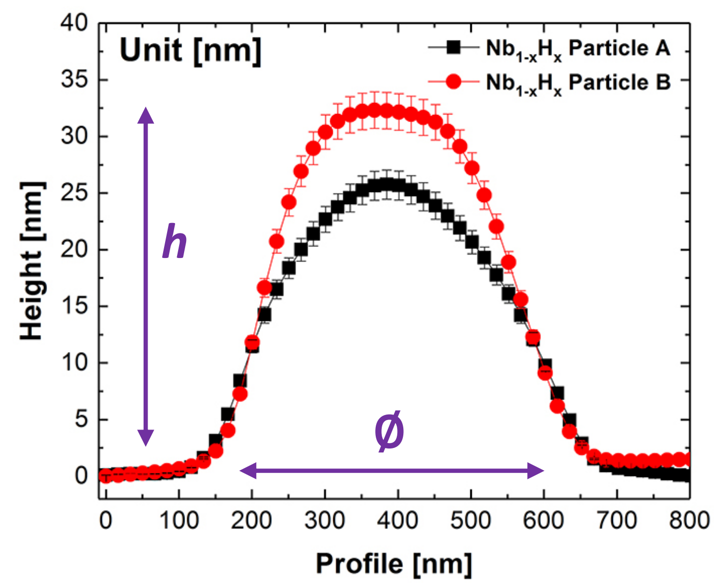
First observation of sub-μm NbH phase at cryo-state

After applied 800°C + 20 μm BCP to a hot spot cut-out from TE1ACC003 EP'ed cavity (non-degaussed), in order to clarify the effect of 800°C on H annihilation

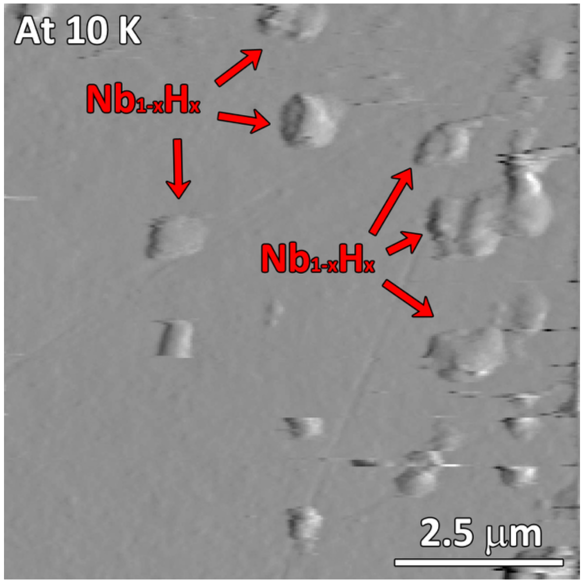


Height profile of two Nb hydrides

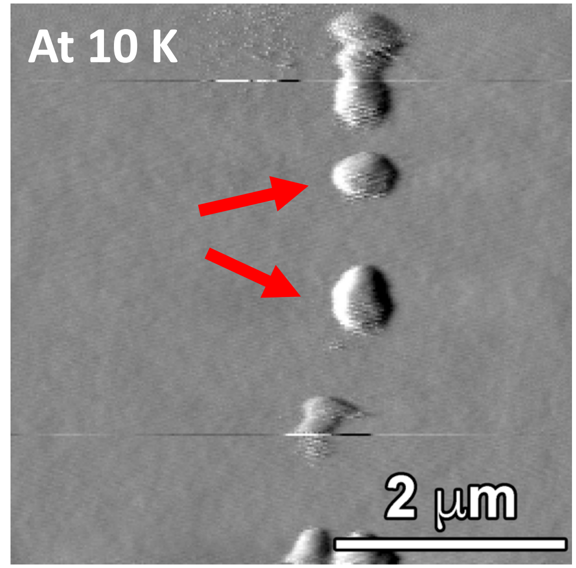


Size and Distribution of NbH phases vary with cavity surface treatment condition

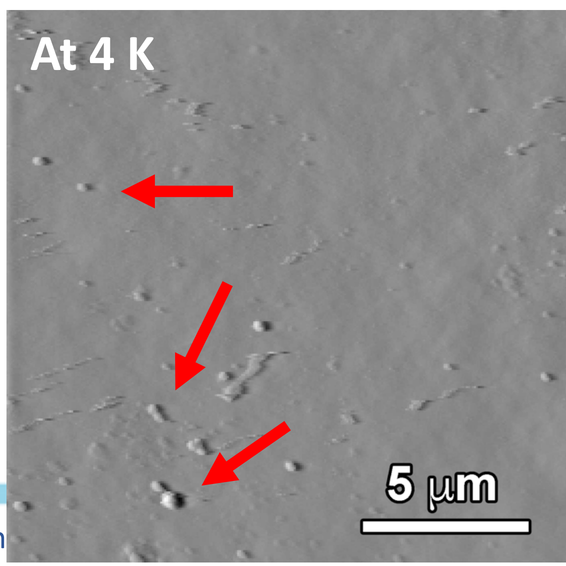
I. Hot Spot cut-out (EP'ed cavity, non-degaussed)



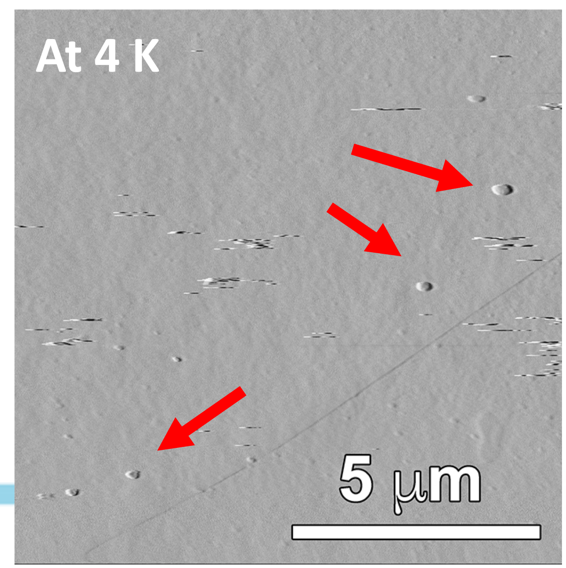
II. 800°C + BCP on hot spot cut-out



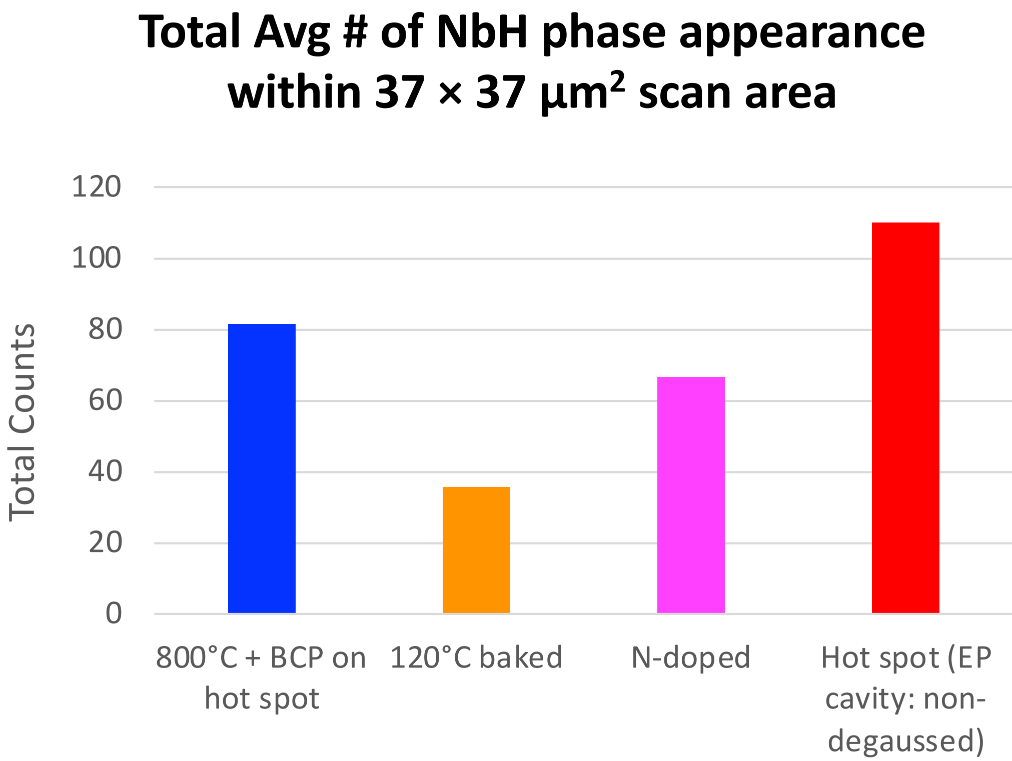
III. N-doped cavity cut-out (@800°C 25mT)



IV. 120°C baked cavity cut-out

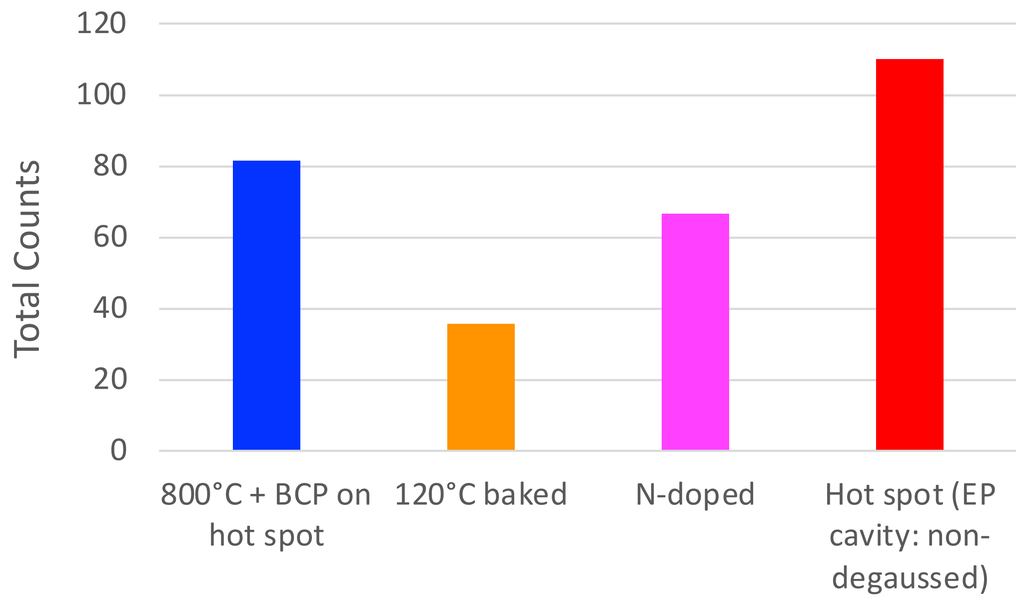


NbH appearance frequency Vs its size distribution

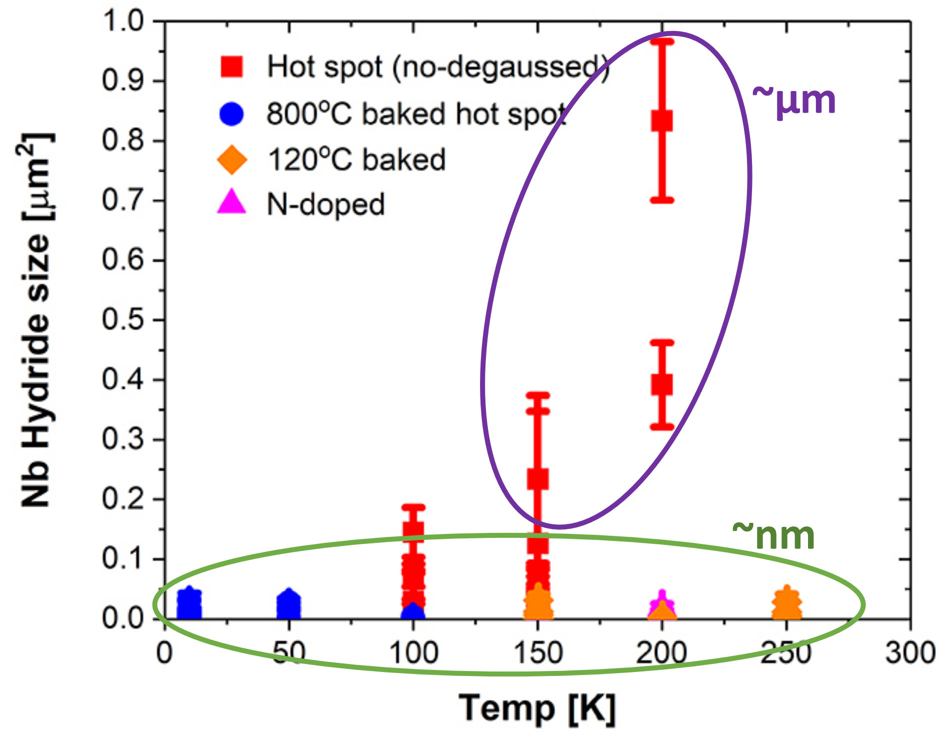


NbH appearance frequency Vs its size distribution

Total Avg # of NbH phase appearance within 37 × 37 μm² scan area



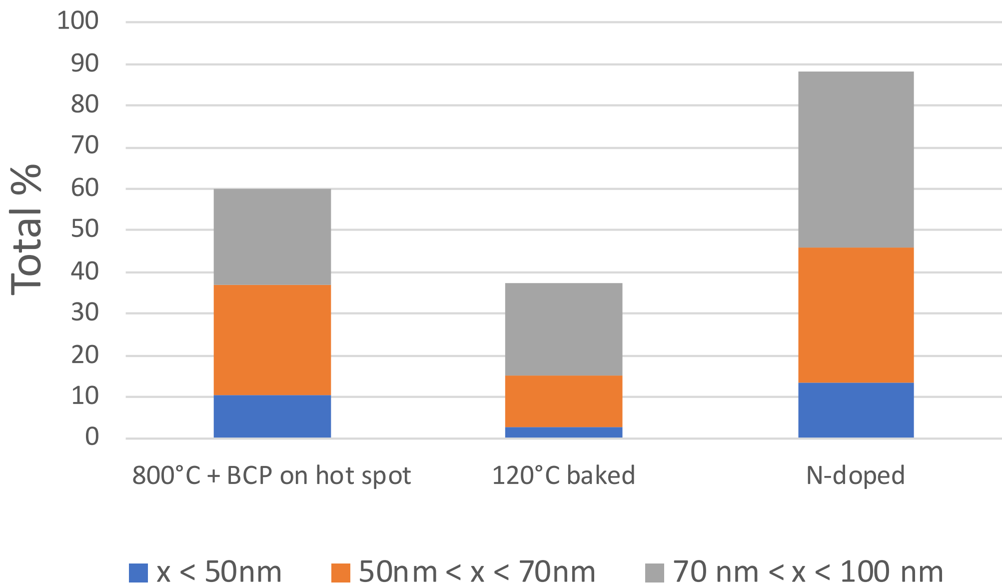
Size distribution as a f (T: 300K to 4K)



*** Size of NbH phase determined with its diameter (ϕ) and height (h) at cross section**

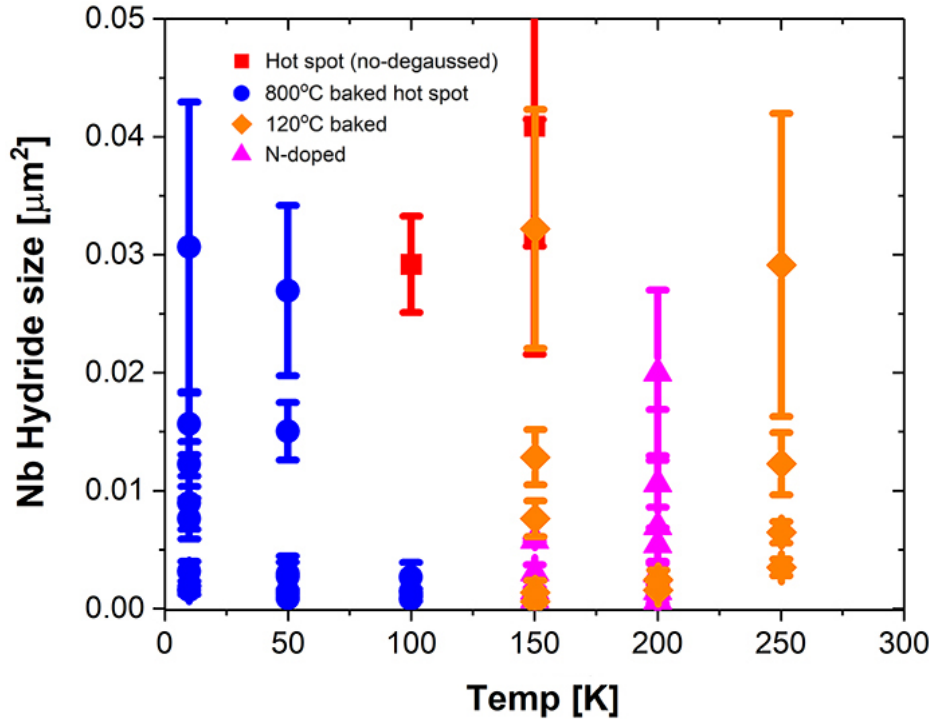
120°C baking likely suppressed NbH precipitations

Total Avg # of small NbH phase appearance within 37 × 37 μm² scan area



X: height of NbH Phase

Size distribution as a f (T: 300K to 4K)



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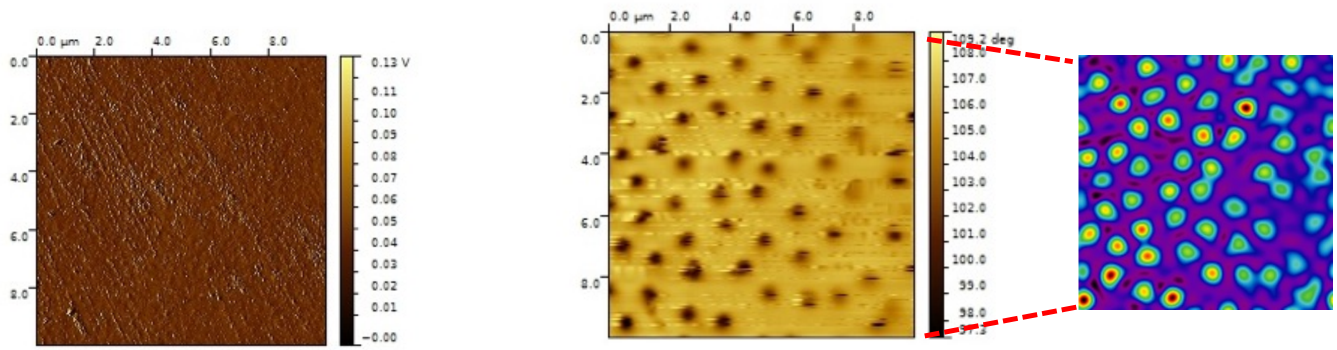
Magnetic Force Microscopy

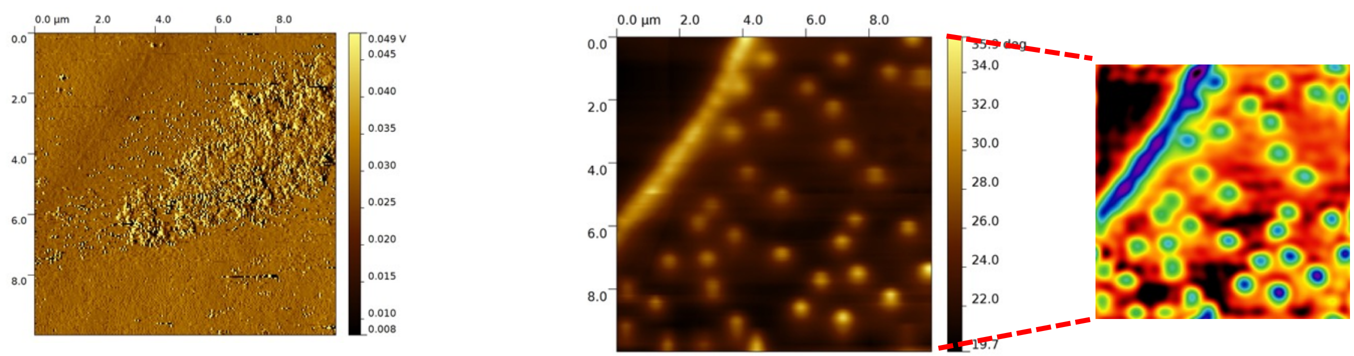
Cryo-MFM analysis for magnetic vortices behavior on SRF Nb surface

- MFM Vortices Image

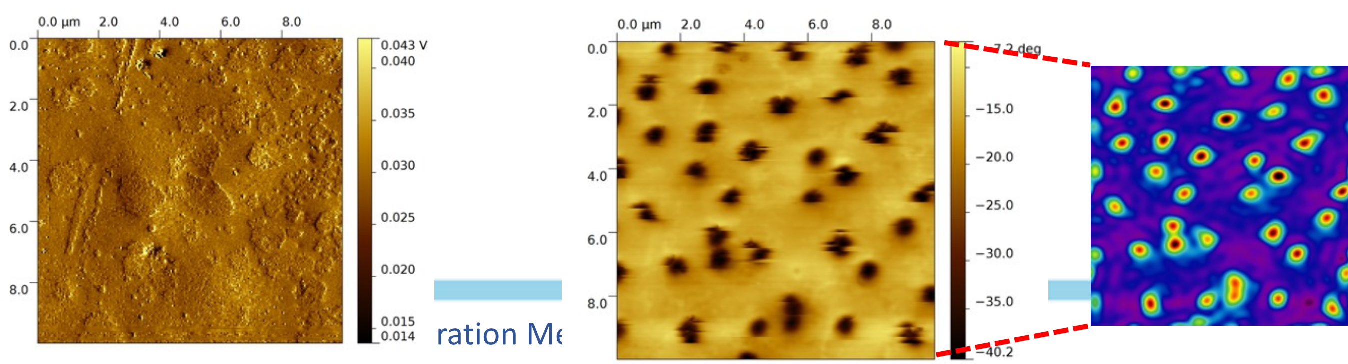
I. 150 µm EP'ed SRF grade Nb Coupon with 30 mT at 2 K



II. EP + 120°C baked Nb Cavity cut-out with 5 mT at 2 K



III. Nitrogen-Doped at 800°C Nb Cavity cut-out with 5 mT at 2 K



Cryo-MFM analysis for magnetic vortices behavior on SRF Nb surface

- MFM Vortices Image

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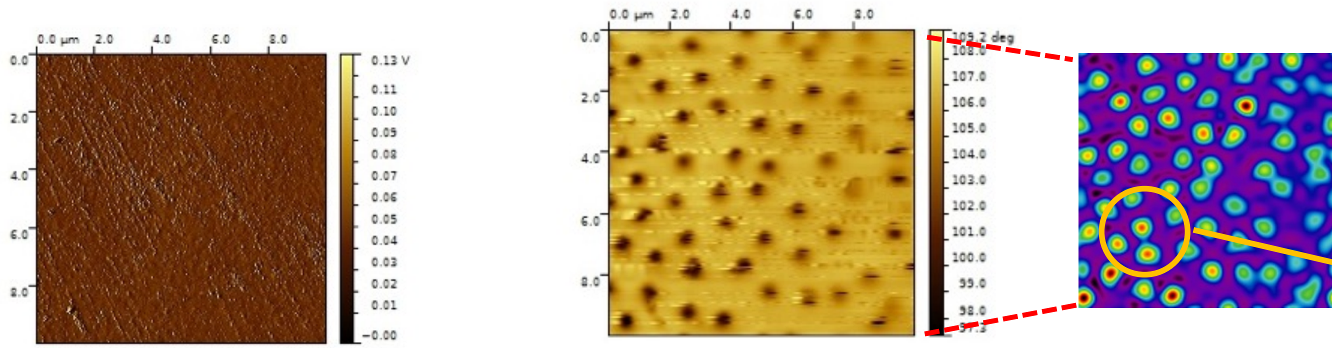
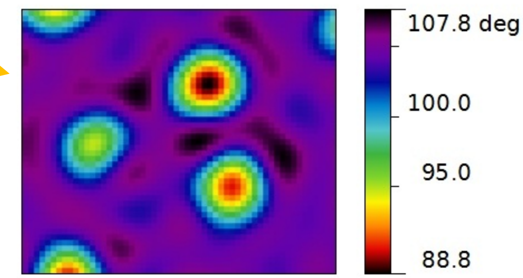
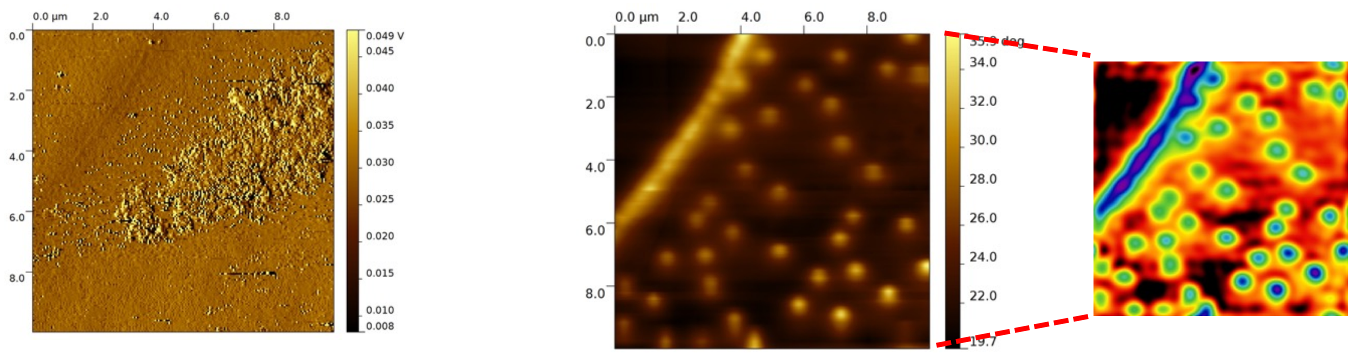


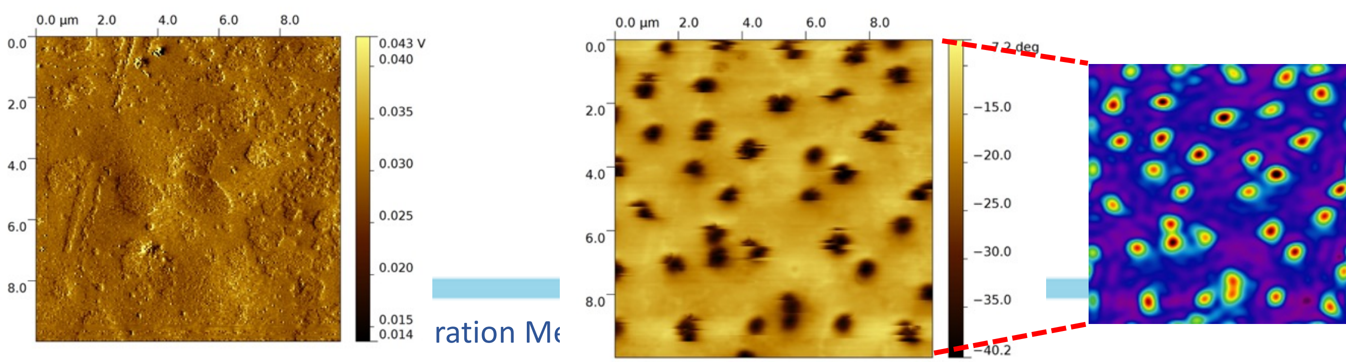


II. EP + 120°C baked Nb Cavity cut-out with 5 mT at 2 K



Individual vortex:
"$\phi \sim n \cdot \lambda$"
for SC surface property

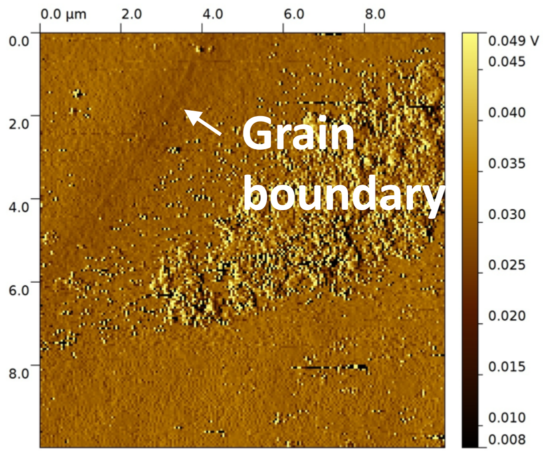
III. Nitrogen-Doped at 800°C Nb Cavity cut-out with 5 mT at 2 K



ϕ ~ diameter of a vortex
λ: SC Penetration depth

Visualizing trapped magnetic vortices on GB and intra-grain of SRF Nb sample

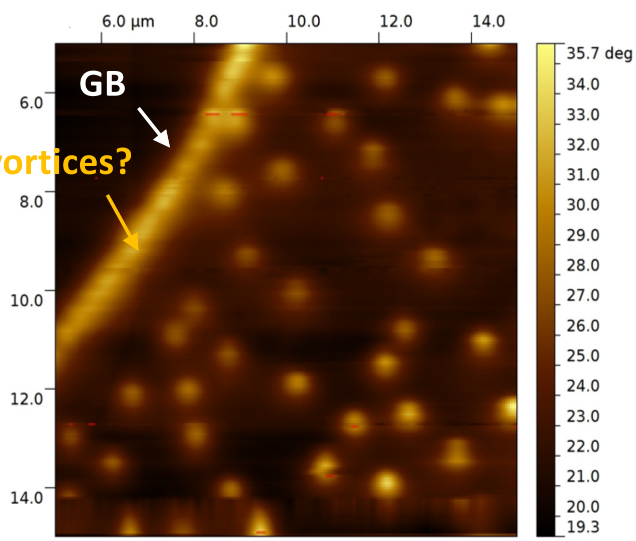
Surface topology of 120°C baked cavity cut-out



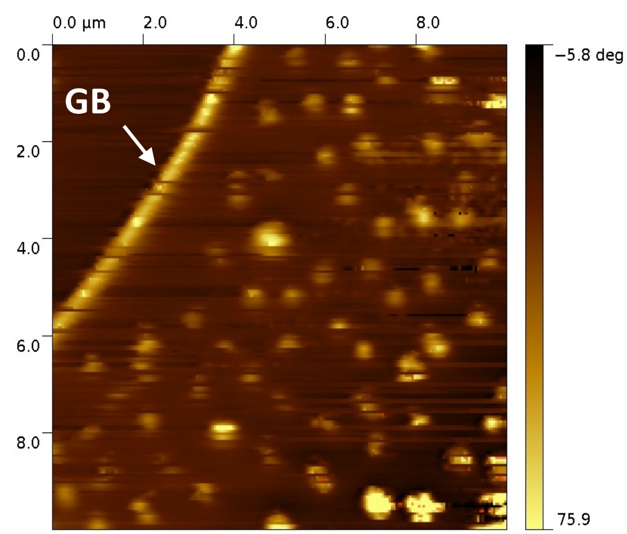
Direct observation of flux trapping using different cooling mode wt DC field (currently only slow cool, plan to study flux trapping under thermogradients)

- ✓ **Vortex pinning at GB is not different between ZFC and FC mode**
- ✓ **Disorder pattern of magnetic vortices in grain**

ZFC wt 5 mT, at 2K



FC wt 5 mT, at 2K



ZFC: Zero Field Cooling (cooling < T_c wo field)

FC: Zero Field Cooling (cooling < T_c wt field)

AC Susceptibility

AC susceptibility characterization for penetration dynamics of surface magnetic vortices in DC magnetic field

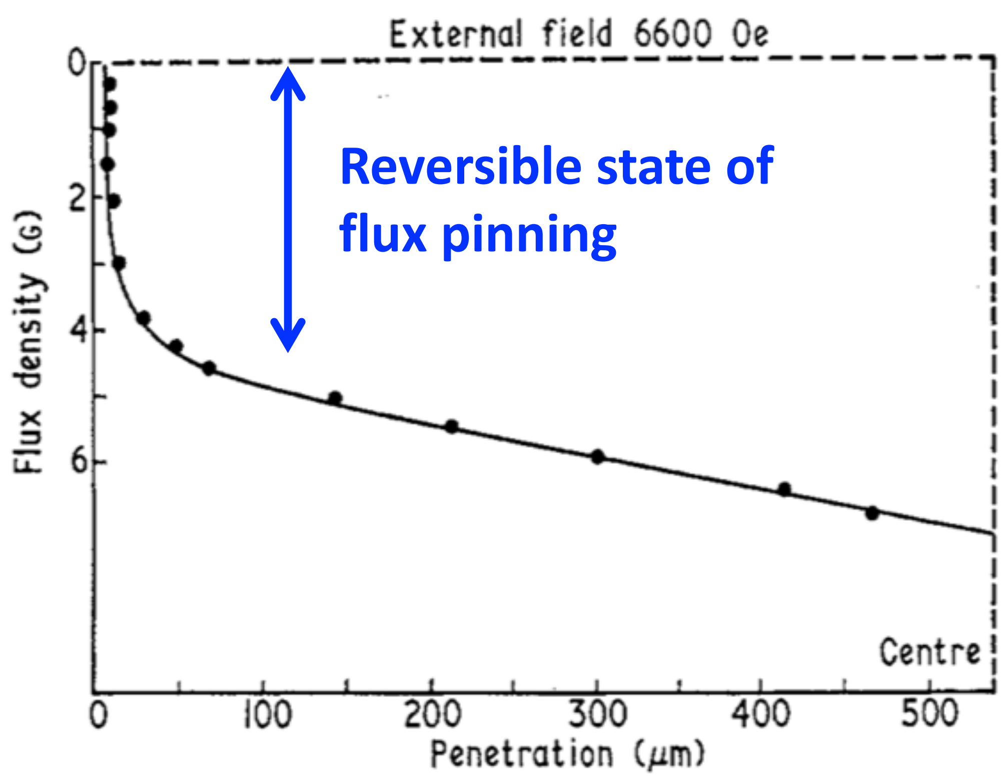


Figure 3. The flux distribution in a reversible specimen.

"This displacement after linearity is due to the reversible movement of flux lines in their potential wells in the surface layer and indicates a large penetration depth which depends on the pinning"

$$\lambda_{AC} \approx \frac{a}{2C} \cdot \frac{d\phi}{dh_0}$$

- *A. C. Campbell, J. Phys. C (Solid St. Phys.), 2, 8, (1969)*
- *A. C. Campbell, DC Magnetization and Flux Profile Techniques, pp 129-155, Magnetic Susceptibility of Superconductors and Other spin system, Springers, (1991)*

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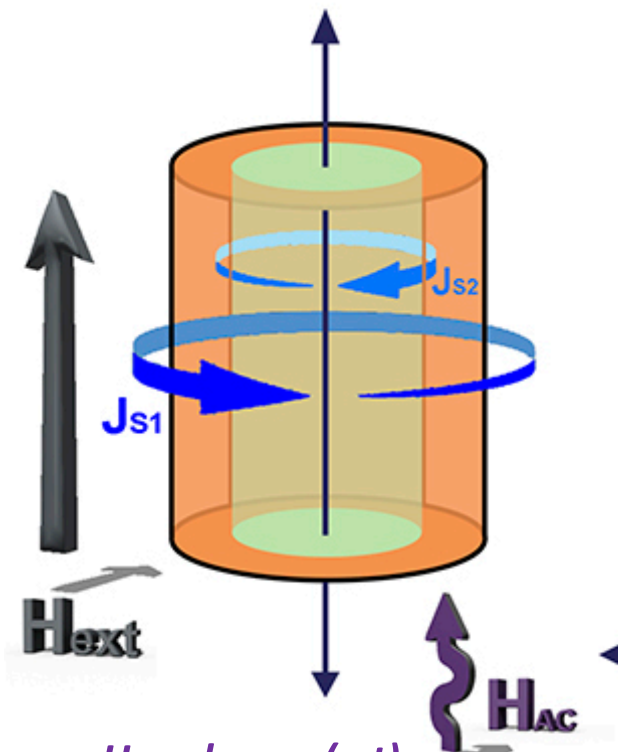
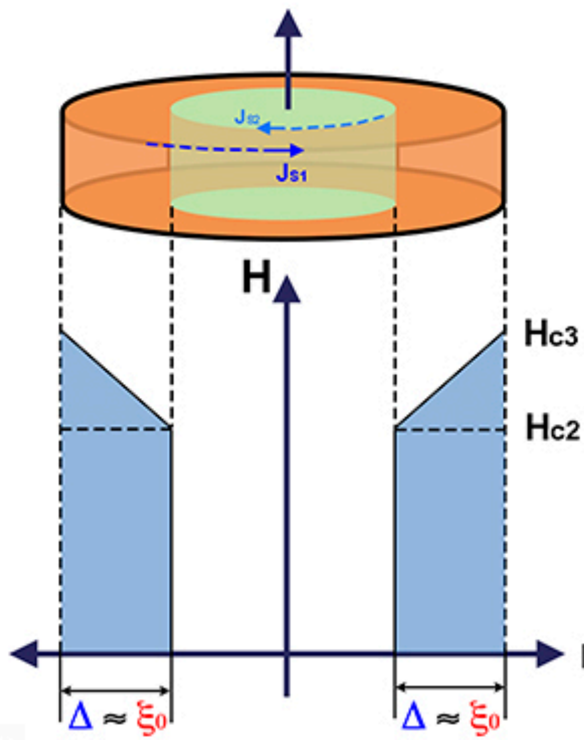
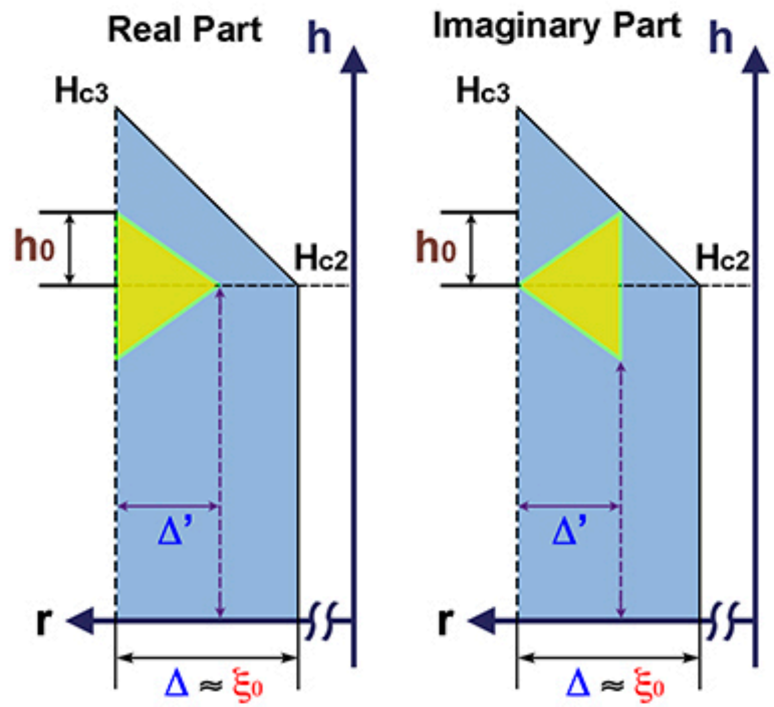
AC Susceptibility with Surface Critical Model

Reversible Depth of Penetrating Magnetic vortices (λ_{AC})







$H_{ac} = h_0 \cos (wt)$

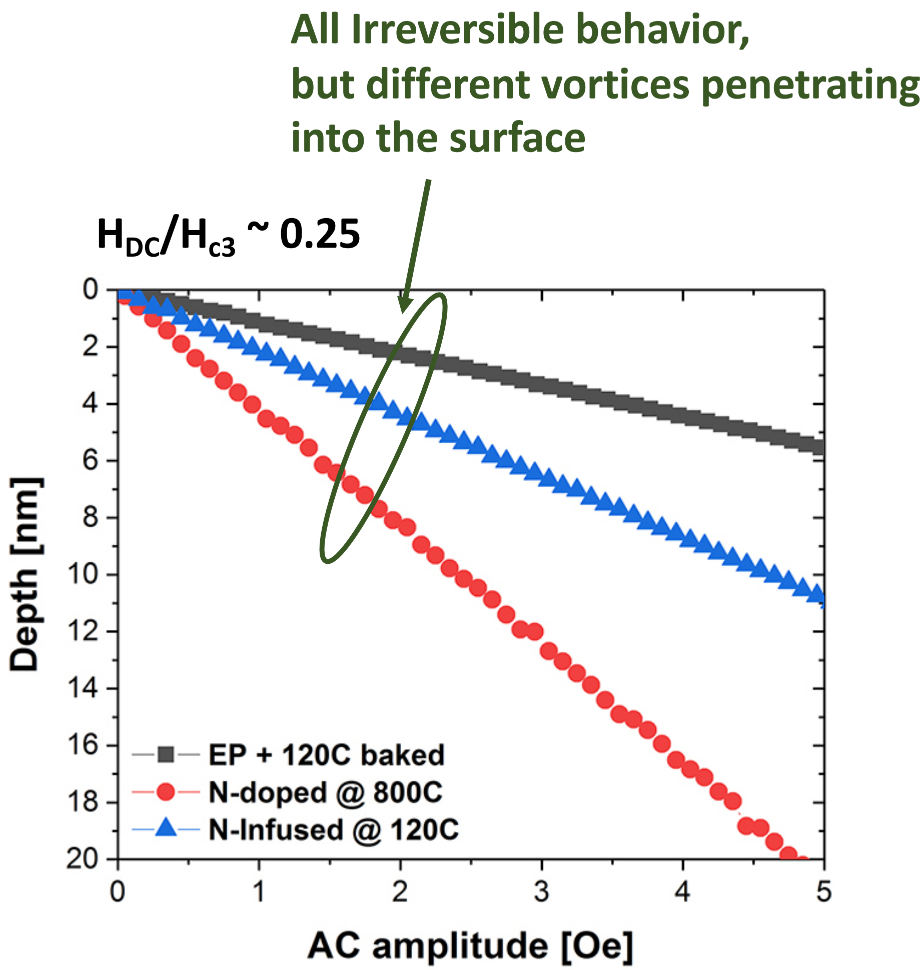
- R. W. Rollins and J. Silcox, Phys. Lett. 155, 2, (1967)
- J. R. Clem and J Perez-Gonzalez, Phys. Rev. B, 33, 3, (1986)
- J. R. Clem, Phys. Rev. B, 14, 5, (1976)
- A. C. Campbell, J. Phys. C (Solid St. Phys.), 2, 8, (1969)

h_0 : AC amplitude

YEL: Magnetization of AC Field

Blue: DC Magnetization

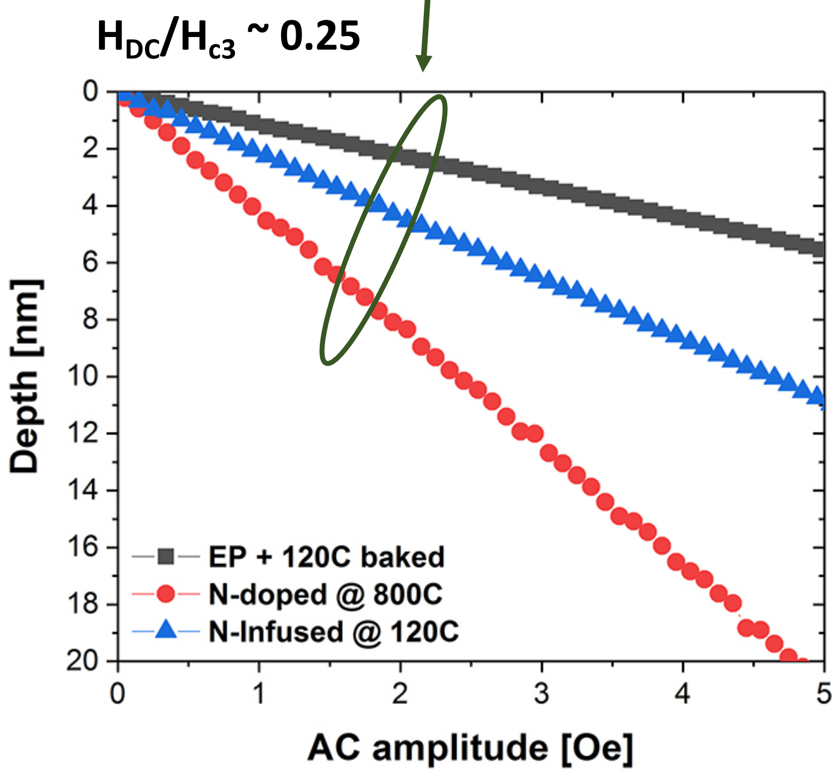
N-doping and Infusion show different mechanism of magnetic vortex behavior within 20 nm surface depth



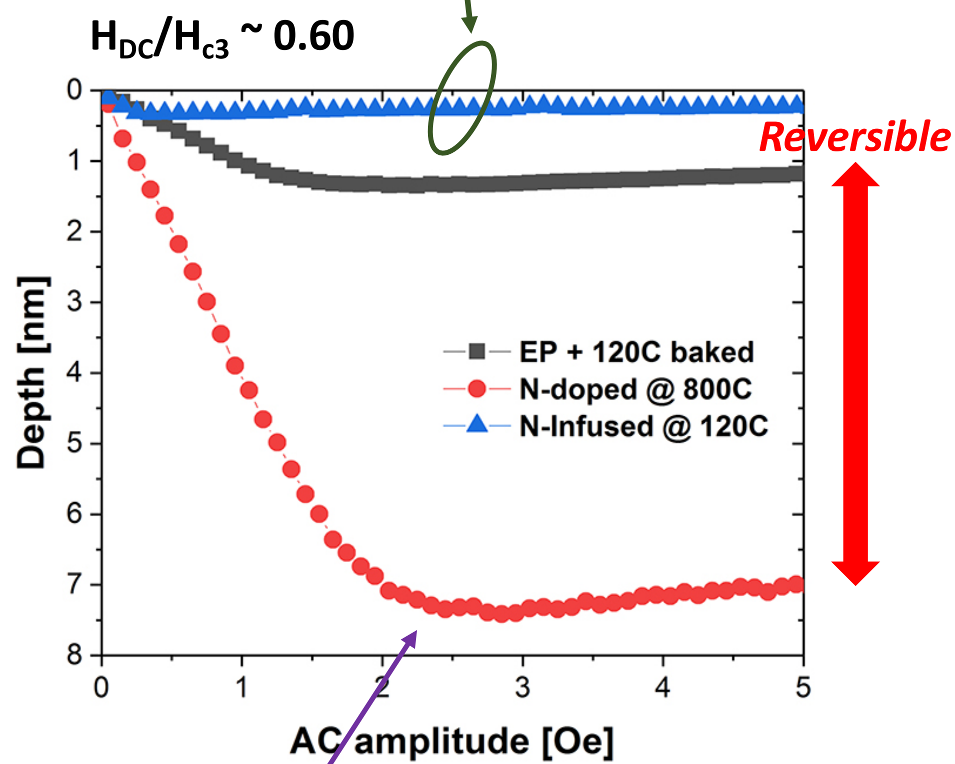
All tested samples are cylindrical shape (low F_{deg}, ϕ ~ 3mm, length ~7mm)

N-doping and Infusion show different mechanism of magnetic vortex behavior within 20 nm surface depth

All Irreversible behavior,
but different vortices penetrating
into the surface



N-infused surface significantly expel
magnetic vortices from the surface



N-doping surface has large reversible vortex penetration depth (λ_{ac})

All tested samples are cylindrical shape (low F_{deg}, ϕ ~ 3mm, length ~7mm)

Summary

- First successful observation of nanometer size Nb hydride phase on SRF Nb cavity surface.
- 120°C baking leads to earlier NbH formation, compared to 800°C HT, but likely suppressed # of its precipitation.
- Cryo-MFM is a promising tool that can directly visualize trapping of magnetic vortices on SRF Nb cavity.
- Unlike N-infusion, N-doped Nb surface likely has much deeper reversible vortices penetration depth.

Variation of the thickness (Δ) of superconducting surface with κ and H_{app}

$$\Psi = e^{ik\varphi} \cdot F(\rho)$$

$$\rho = (x/\xi) \cdot (H_0/H_{C2})^{1/2}$$

$$\Delta = \frac{1}{F^2(0)} \int_0^\infty F^2(\rho)\, dx$$

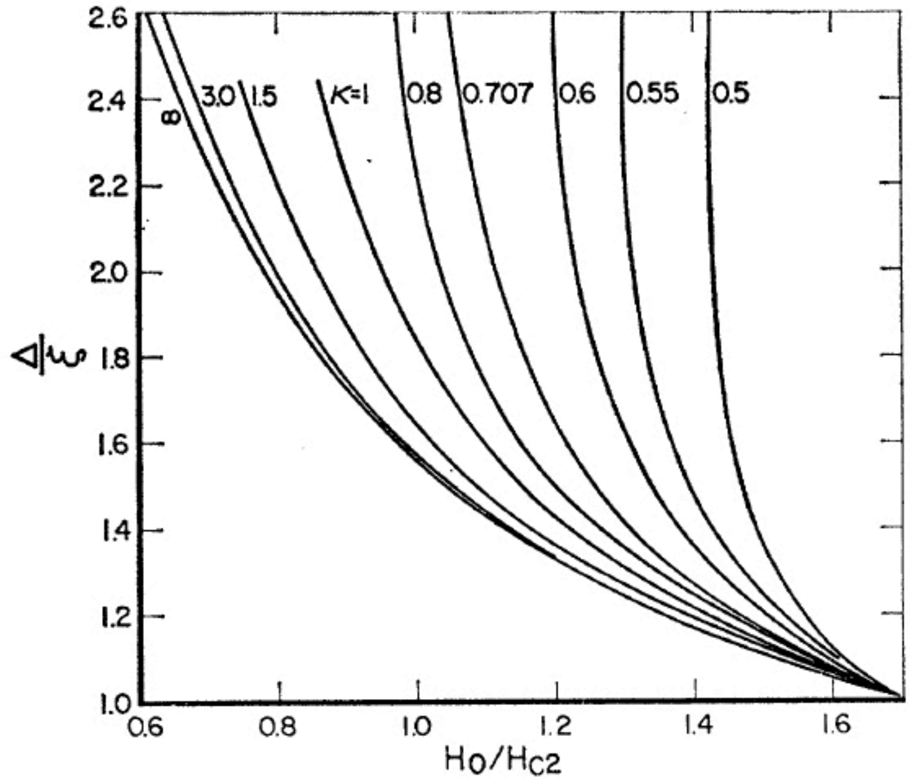
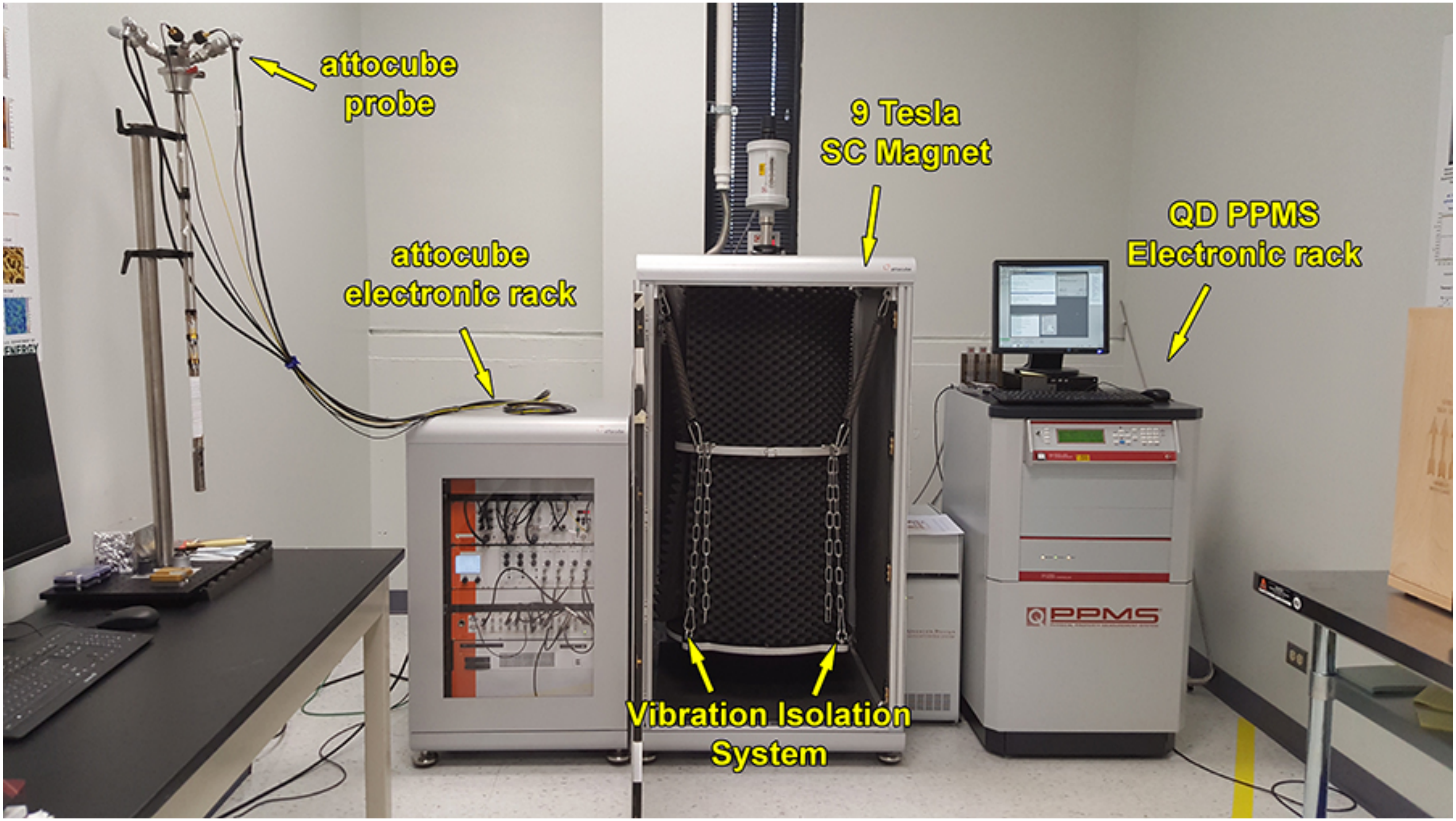


FIG. 5. The thickness of the superconducting surface sheath Δ in units of the coherence length ξ as defined by Eq. (26) is shown as a function of H_0/H_{c2} and the Ginzburg-Landau parameter κ. Near the critical fields H_c (for $0.707>\kappa>0.417$) and near H_{c1} (for $\kappa>0.707$) the thickness of the sheath becomes very large. At H_{c3} the value of Δ/ξ is 1.00764.

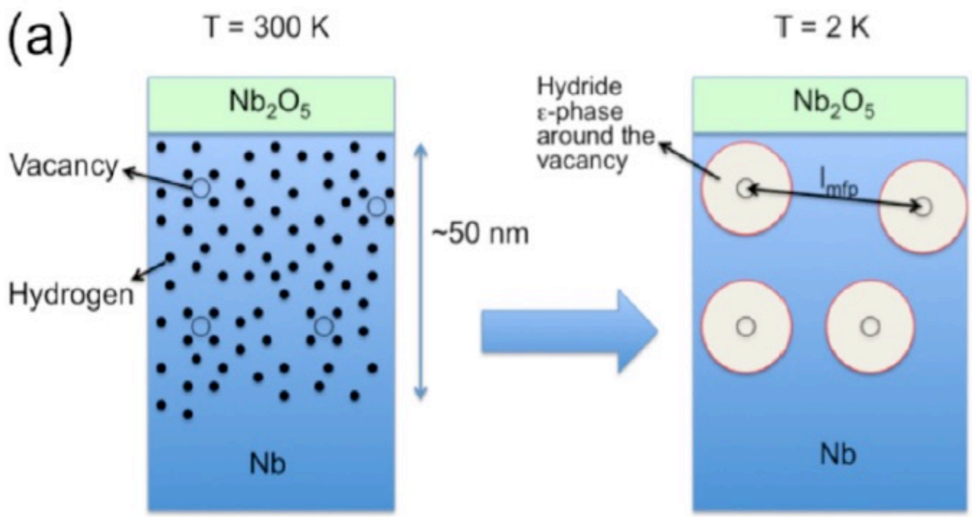
H. J. Fink and R. R. Kessinger, Phys. Rev. Lett. 140. 6A. 1937, (1965)

Cryogenic AFM/MFM (attocube) + 9T PPMS System (QD Design) @FNAL SRF MSL

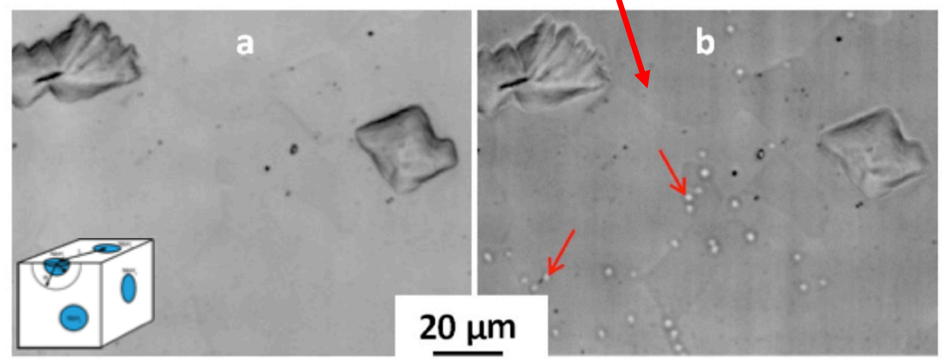


Breakdown of superconductivity by NbH proximity effect

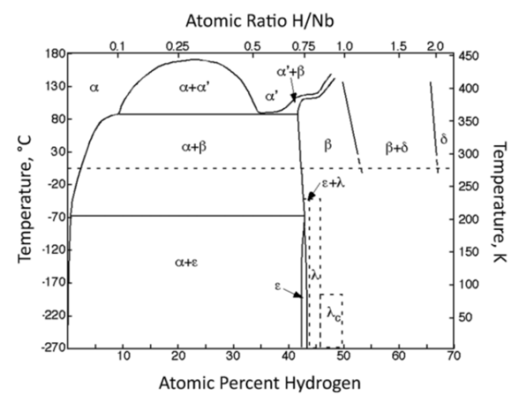
Nano size NbH phases are detectable <u>ONLY</u> by Cryo-AFM

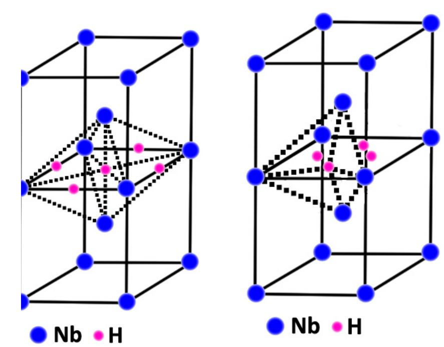


Nb-H Proximity Effect : A. Romanenko, Supercond. Sci. Technol. 26, 035003, (2013)



F. Barkov J. Appl. Phys. 114, 164904, (2013)



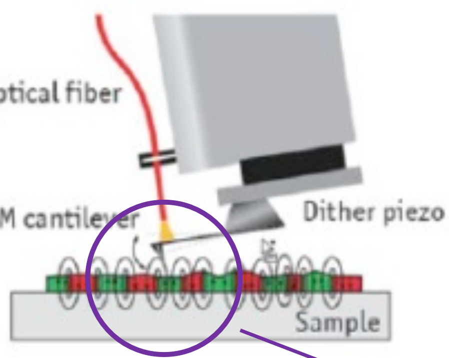


Hydrogen atoms interstitially entered in niobium bcc cells (a) Octahedral position; (b) tetrahedral positions [S. Isagawa, J. Appl Phys. 51(8), 1980]

Fermilab

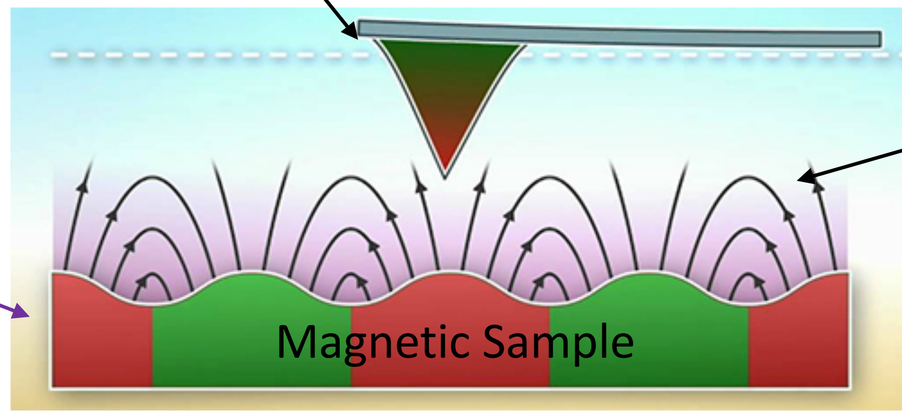
Cryogenic Magnetic Force Microscope (MFM)

AFM Head Part



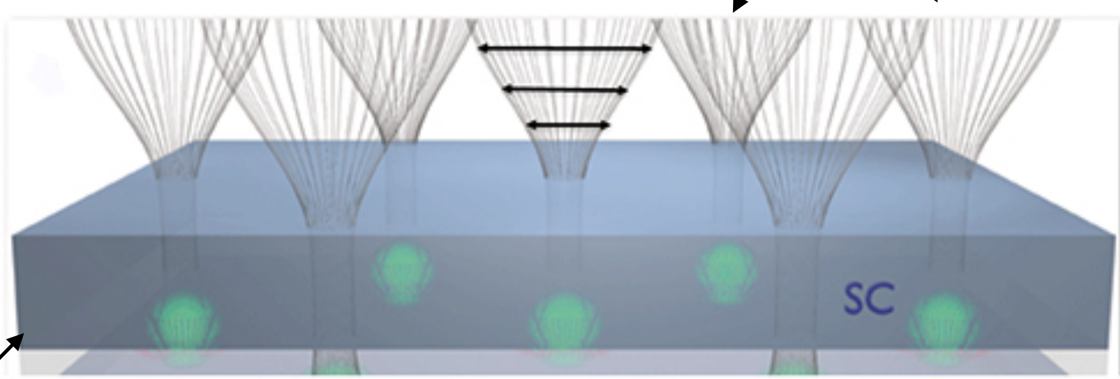
Sketch of the MFM setup. An AFM tip (here: magnetically coated), is brought into close vicinity of the sample. The deflection of the cantilever due to forces on the tip can be read for magnetic field variations using a build-in fiber interferometer

Co Coated – MFM tip



Magnetic field lines

Strays of Magnetic Vortices



Superconductor

Size variation of vortices as a f(h) on EP'ed Nb