Inner workings of the 120^0C baking effect studied by positron annihilation

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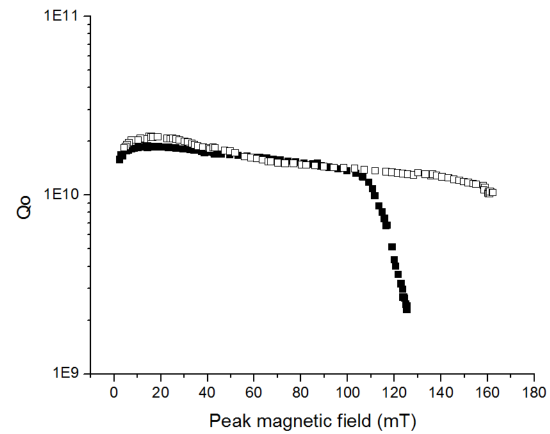
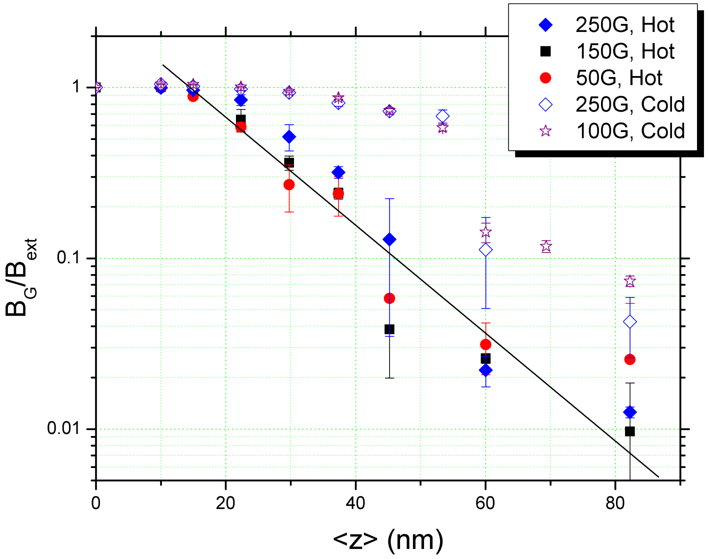
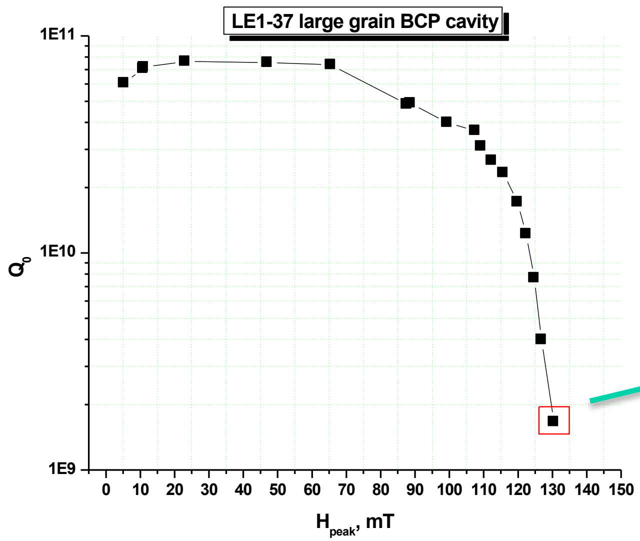
120^0C baking

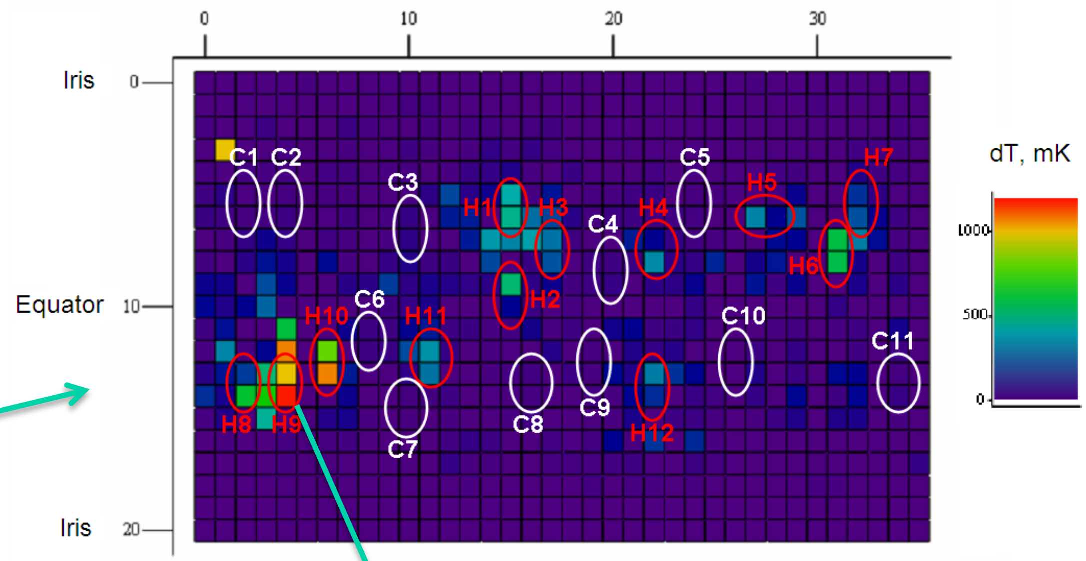
- Applied to consistently remove the high field Q-slope in EP/large grain BCP cavities
- Lowers electron m.f.p. as deduced from fits to $R_s(T)$ using BCS framework
- Drastically modifies near-surface order parameter as observed in muSR
- Effect on BCS surface resistance extends to >~ 300 nm deep
- Effect on HFQS can be eliminated by ~20 nm material removal

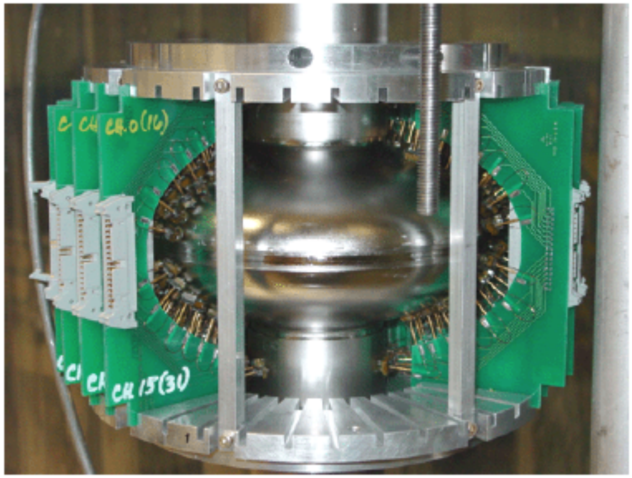


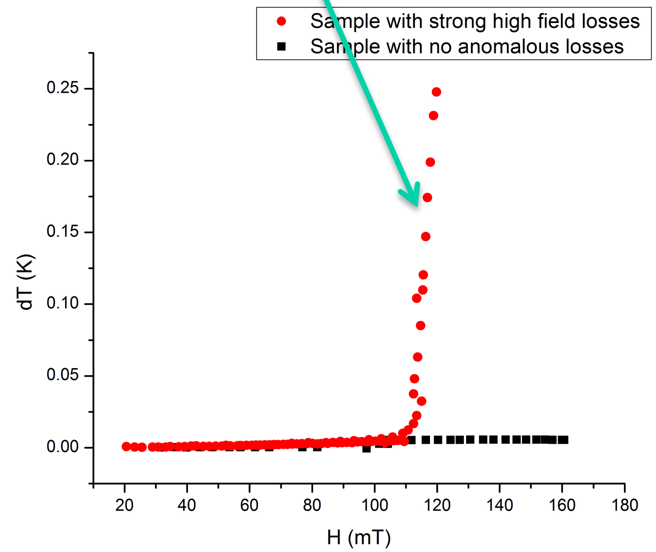


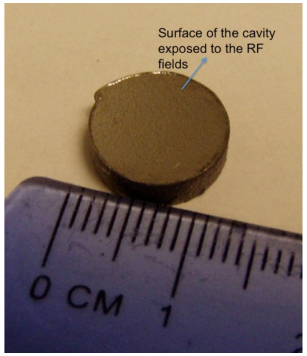
Thermometry and cutout



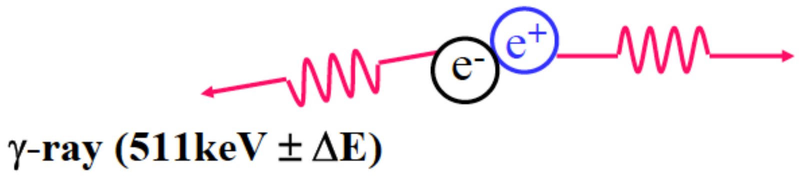


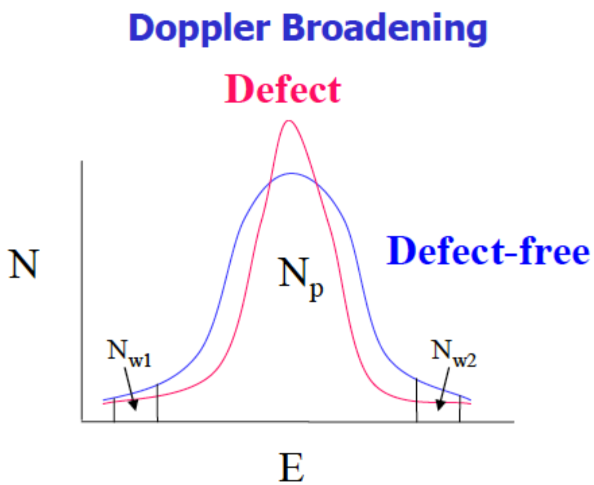






Positron annihilation Doppler broadening spectroscopy





$S = N_p / N_{total}$

$S_{defect} > S_{defect\text{-}free}$

$W = (N_{w1} + N_{w2}) / N_{total}$

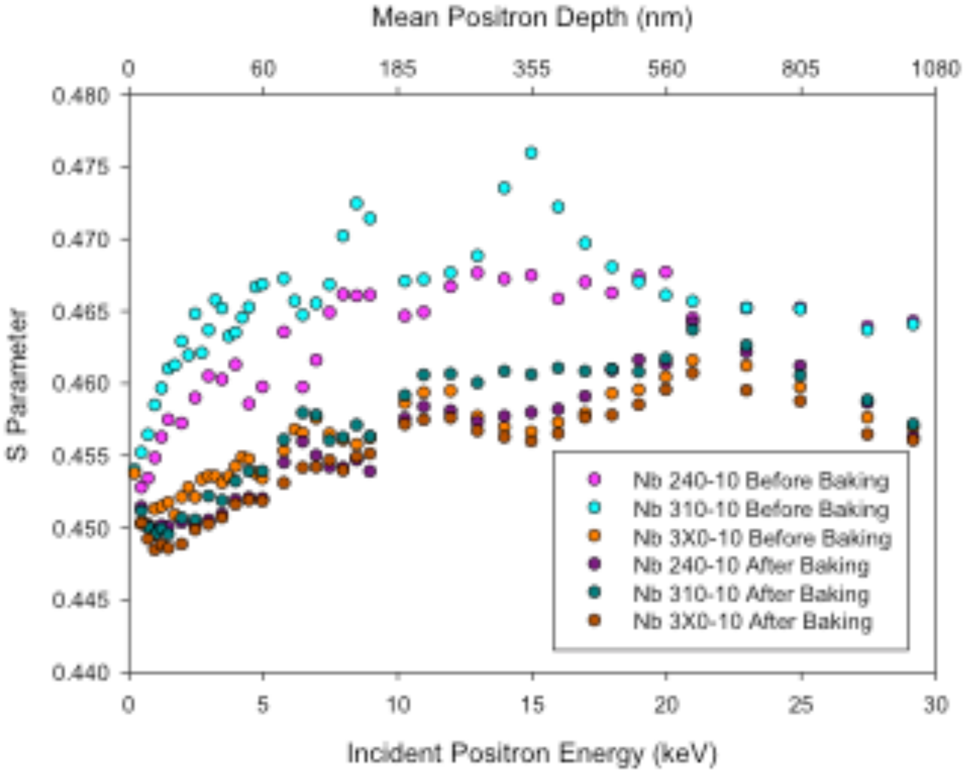
- S parameter corresponds to positron annihilation with valence electrons, W-> core electrons
- S is sensitive to open-volume defects, W-to chemical surrounding at the annihilation site
- Increase in S parameter indicates presence of vacancy defects

Depth profiling of vacancy concentration

- Change positron energy E -> change stopping depth
- Measure S(E), W(E) -> depth profile of vacancies

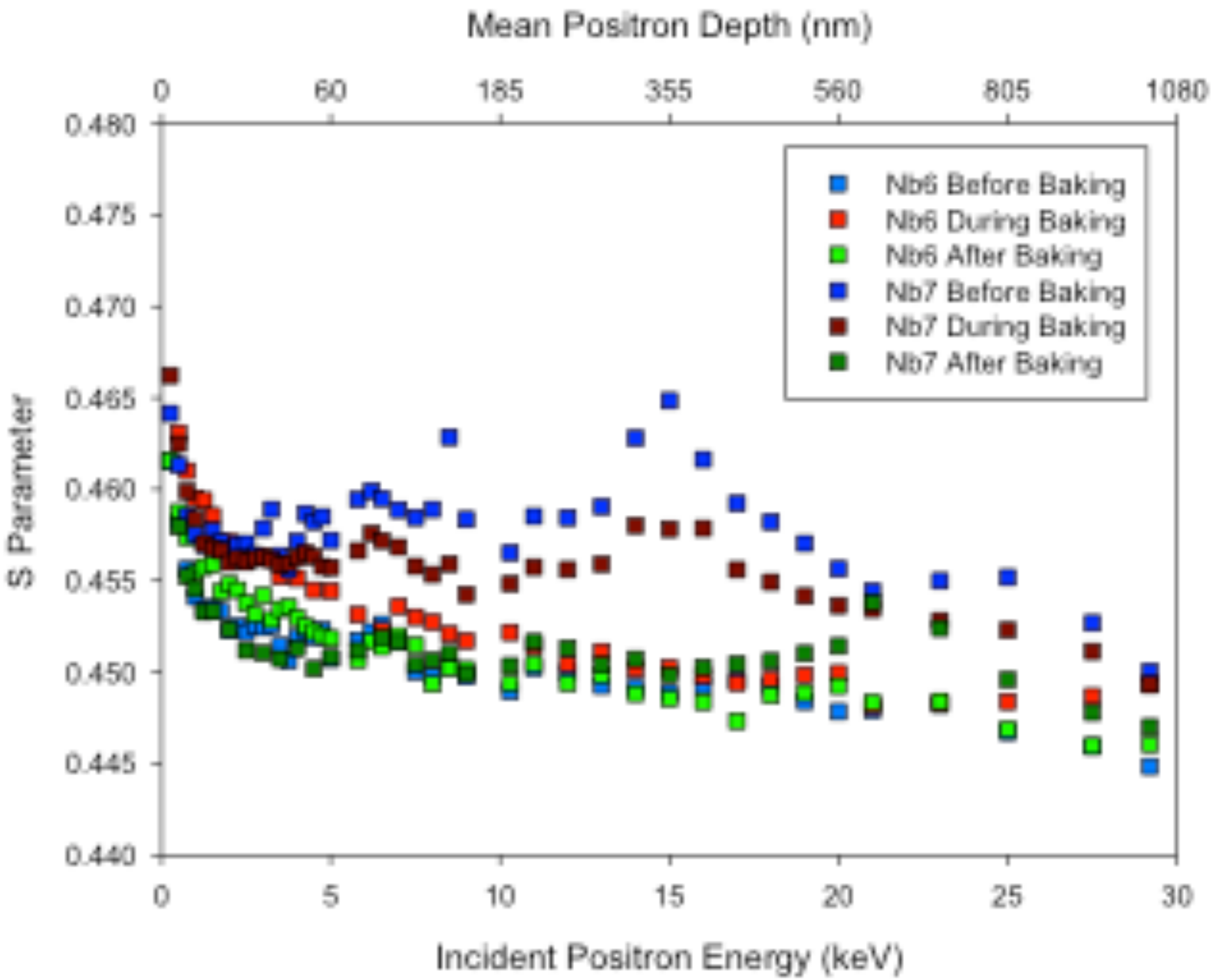
PAS results – 120C baking

- High concentration of vacancies in hot and "cold" spots
  - Consistent with ~10^{-3} at.%
  - Difference due to the presence of peaks at particular depths?
- Baking decreases vacancy concentration significantly
  - Same depth profiles after 120C for all 3 samples



310-10 -> Hot spot with strong HFQS losses
240-10 -> "Cold" spot with less HFQS losses
3X0-10 -> No HFQS losses spot from baked cavity

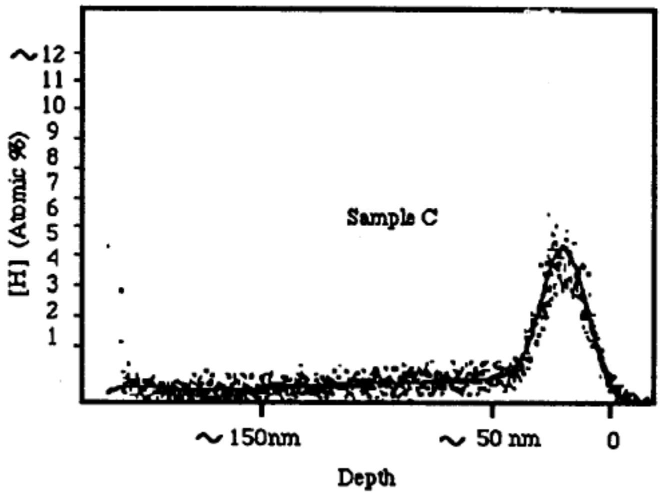
Similar on plain samples



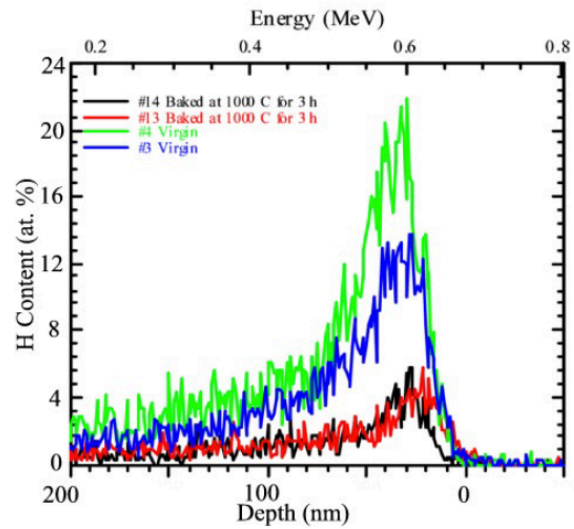
Superabundant vacancies

- Vacancies can be formed in concentrations by far (30 orders of magnitude) exceeding thermodynamic equilibrium
  - Enabled by the presence of interstitial H and can happen during: chemical treatments, furnace treatments
- Discovered in 1993
  - Y. Fukai and N. Okuma: Jpn. J. Appl. Phys. Vol. 32 (1993)
  - Phys. Rev. Lett. Vol. 73 (1994)
  - Since then found in many M-H systems including niobium!

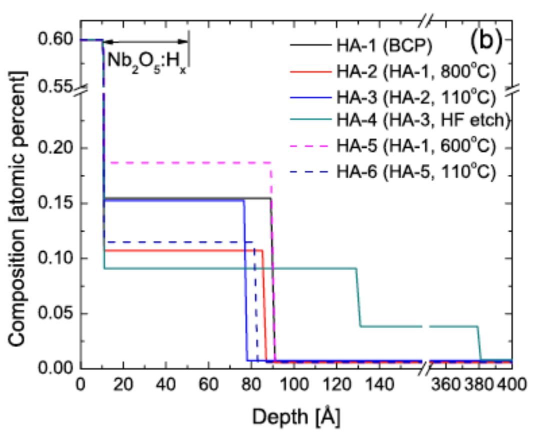
C. Antoine et al, SRF’91



T. Tajima et al, SRF’03,

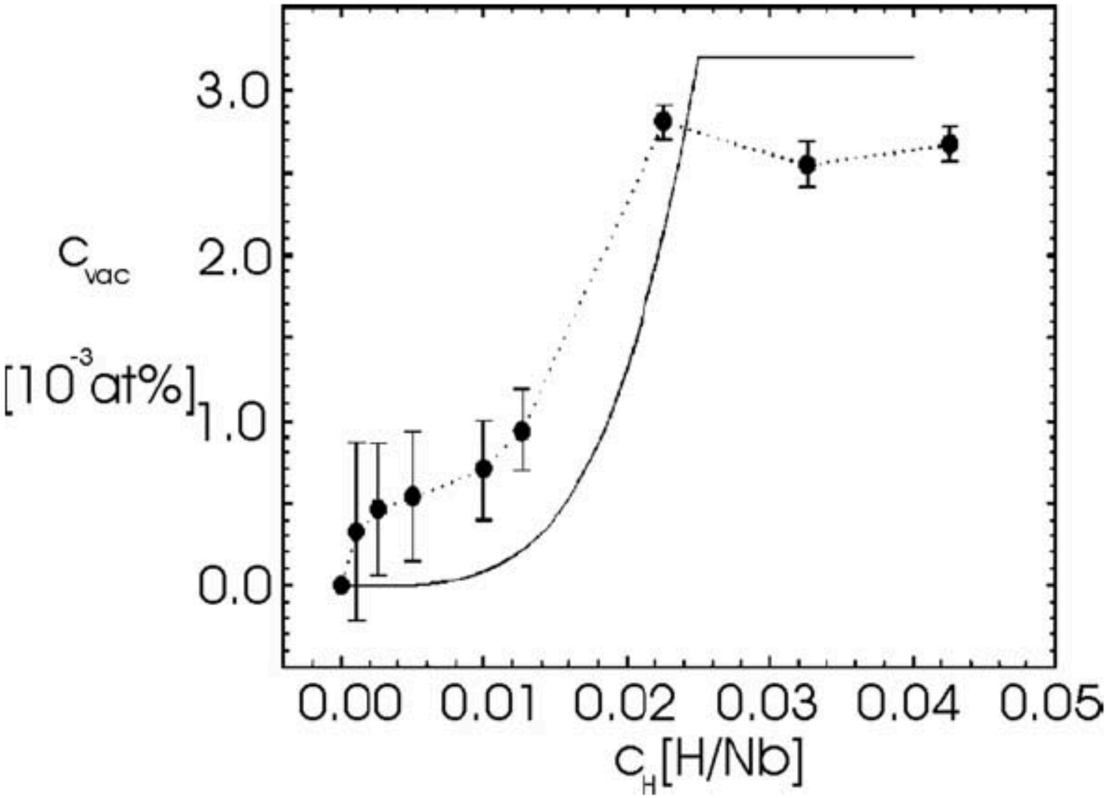


A. Romanenko and L. V. Goncharova, Supercond. Sci. Tech. 24 (2011) 105017



There exists a hydrogen-rich layer within the first several 10s of nms, which is NOT removed even after furnace treatment

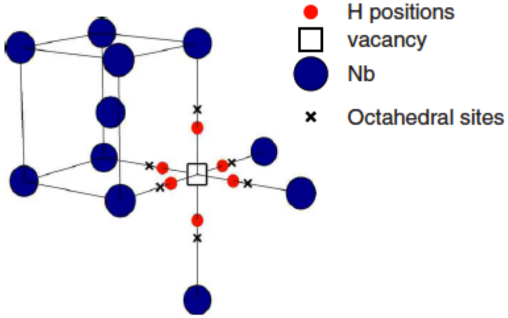
Hydrogen-induced vacancies in Nb



Cizek et al,

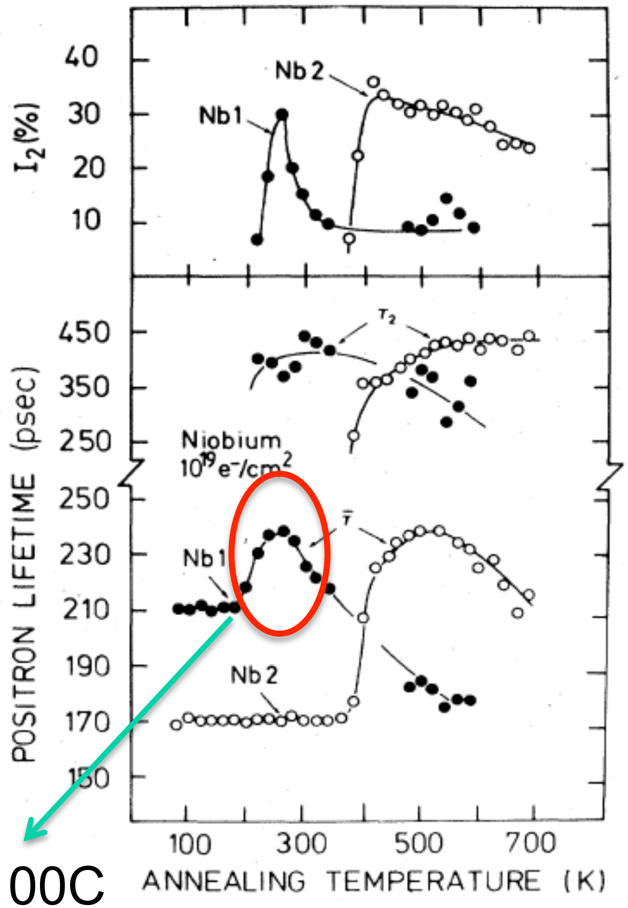
Journal of Alloys and Compounds 404–406 (2005) 580–583

Cizek et al, PRB, 79, 074108 (2009)

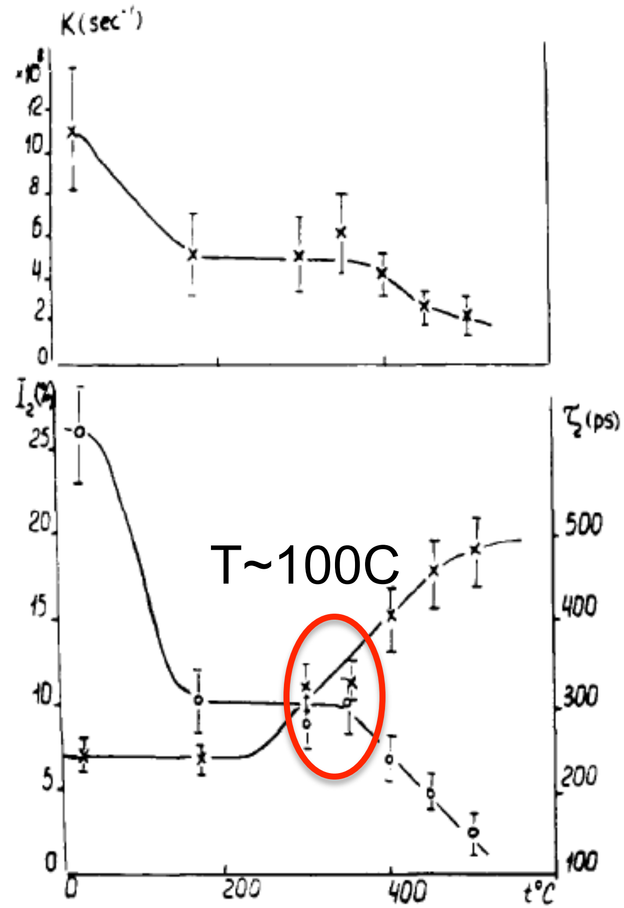


29 orders of magnitude higher concentration of vacancies possible in the presence of hydrogen as compared to thermal equilibrium

PAS results – 120C baking



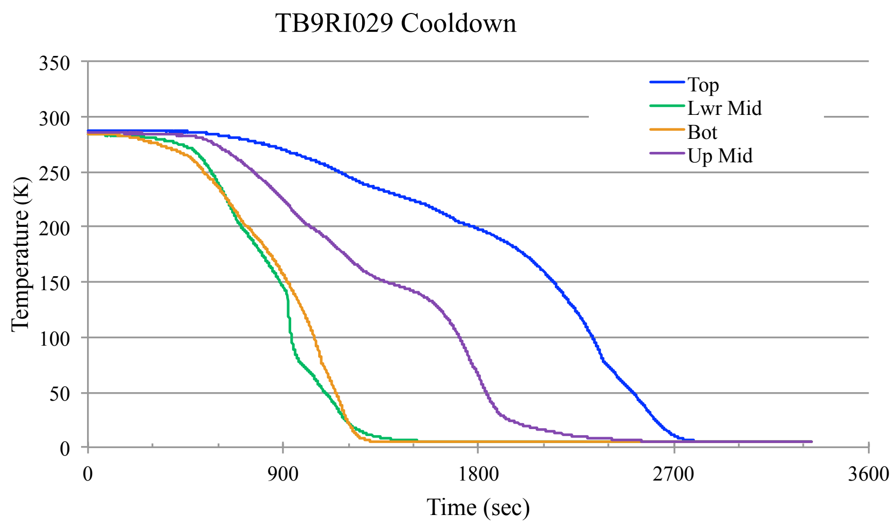
T~100C

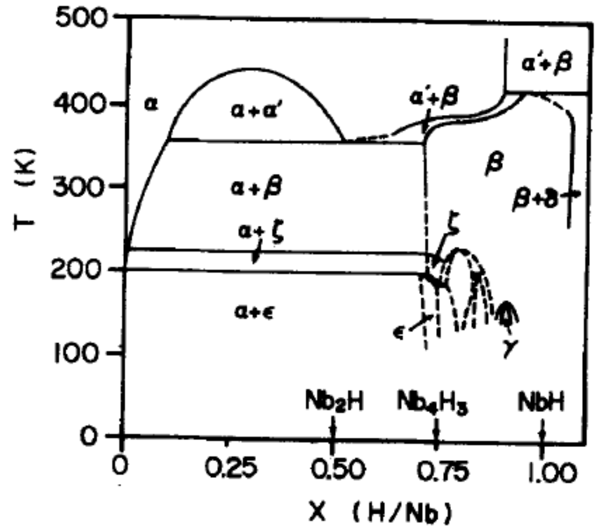


P. Hautojarvi et al, Phys. Rev. B, Vol. 32, Num. 7, 1985

O. K. Alekseeva et al, Physica Scripta. Vol. 20, 683-684, 1979

Typical fast cooldown of a cavity (FNAL)



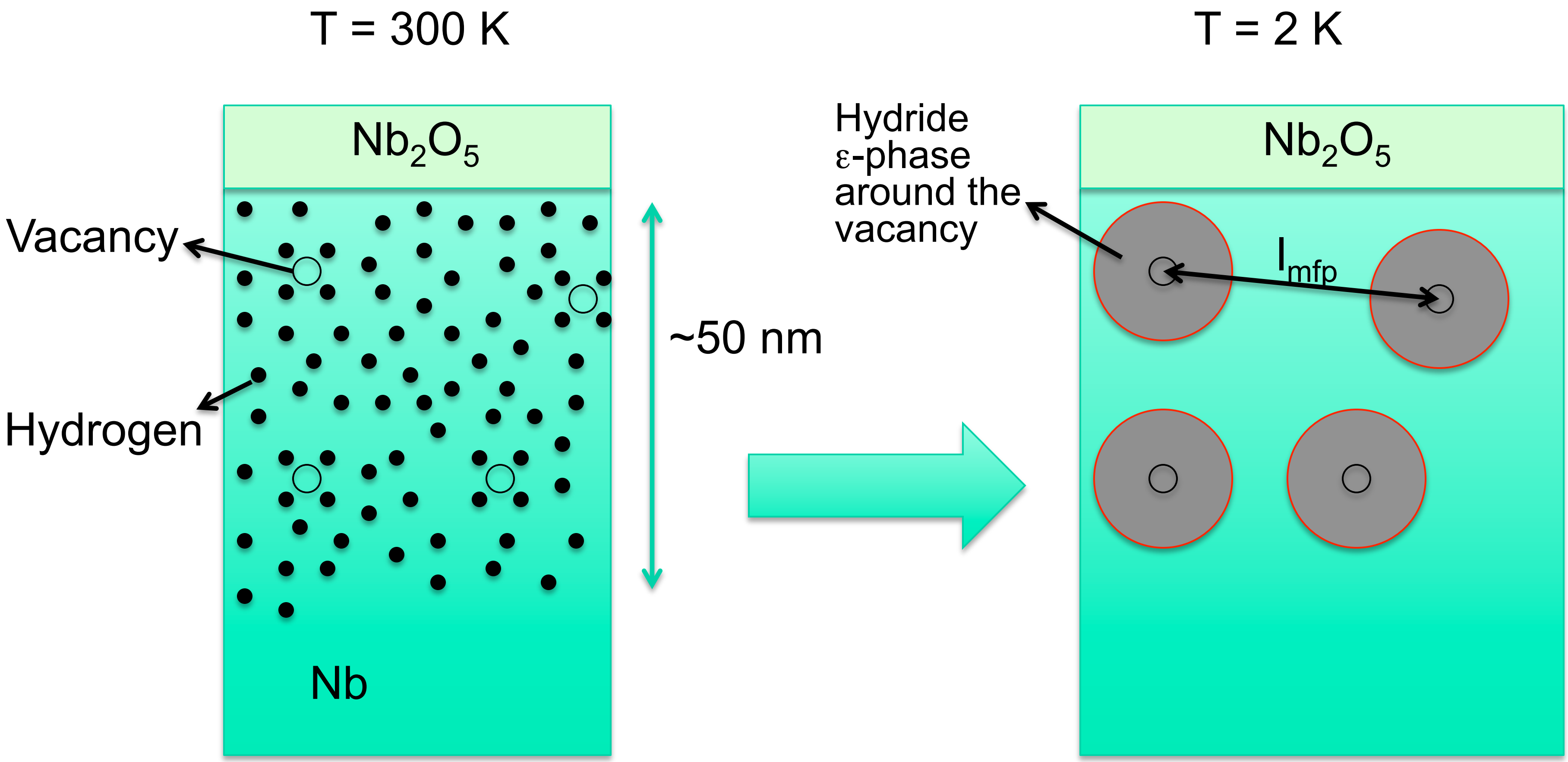


Integrate the H diffusion over the time spent in the precipitation temperature range T < 150K => L > 1 um

All H will precipitate into hydrides within the layer L if nucleation centers exist

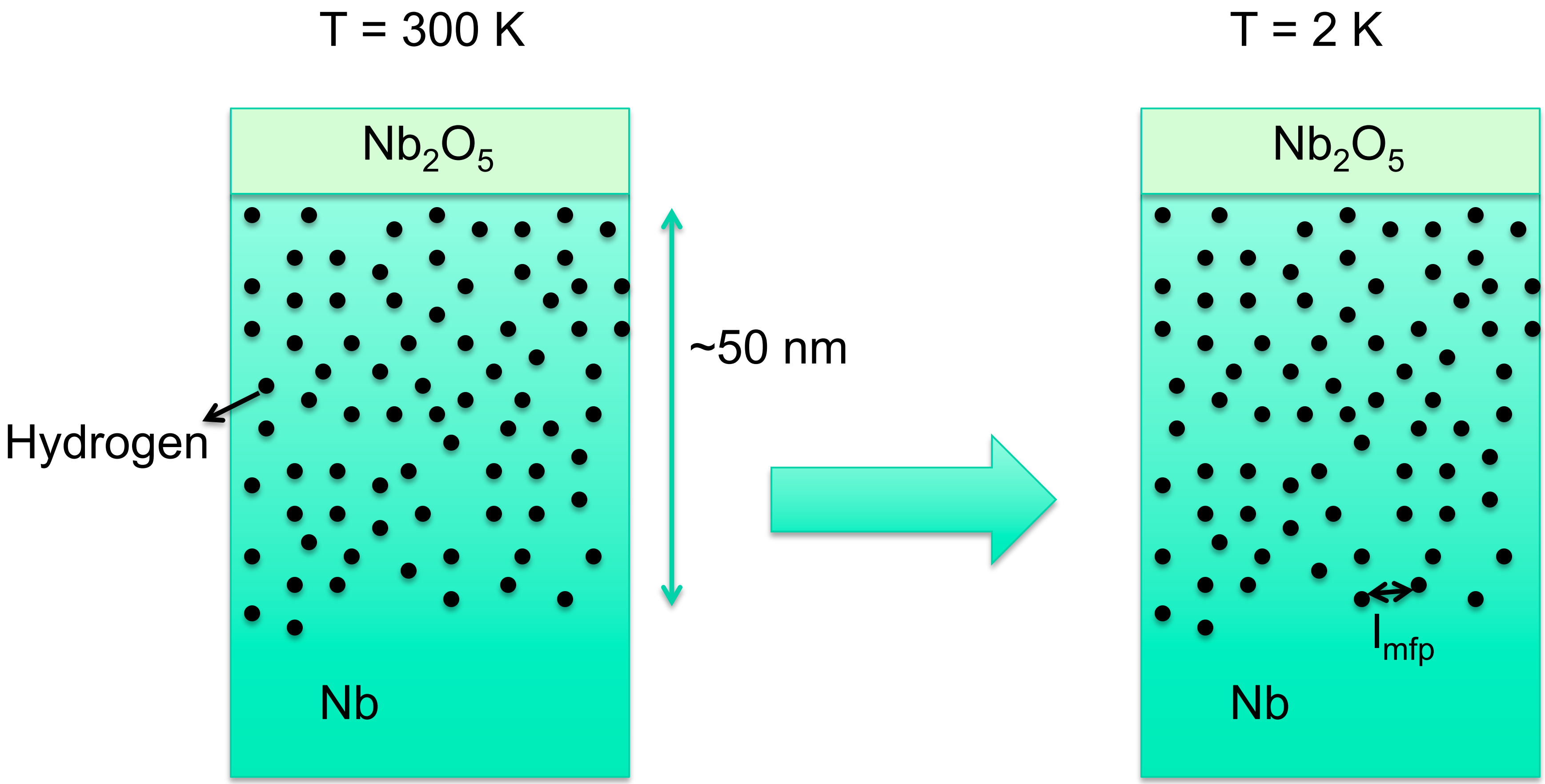
For slow cooldown L > 3 mm allowing to collect H from all the wall thickness. This (bulk supply) can be changed by 600-800^{0}C making not enough H to form large hydrides (Q-disease)

Cooldown – unbaked cavity



Mean free path increases – determined by Hydride-Hydride distance

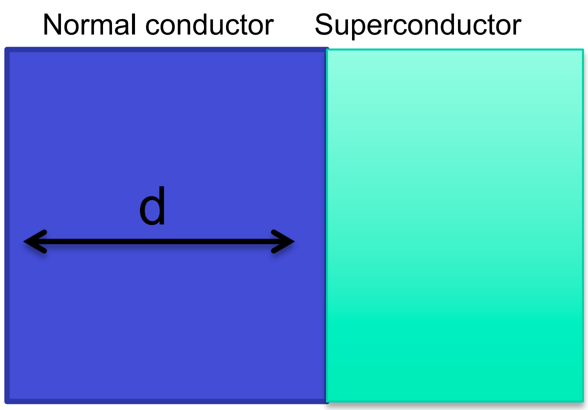
Cooldown – 120C baked cavity

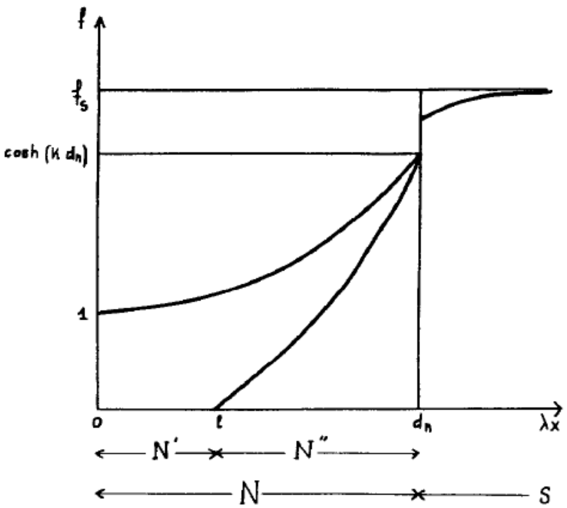


Mean free path stays low – determined by H-H distance

- Model does not require diffusion of any impurities during 120C - only vacancies
  - Near-surface vacancies diffuse to sinks and annihilate during 120C
  - Presence/absence of vacancy-H complexes as nucleation centers for hydrides matters for the precipitation state

Proximity effect





De Gennes and Hurault, Phys. Lett. 17, 3 (1965)

A. Fauchere and G. Blatter, Phys. Rev. B, 56, 21 (1997)

$$H_b(T=0) \approx \frac{1}{6}\frac{\Phi_0}{\lambda_N d},$$

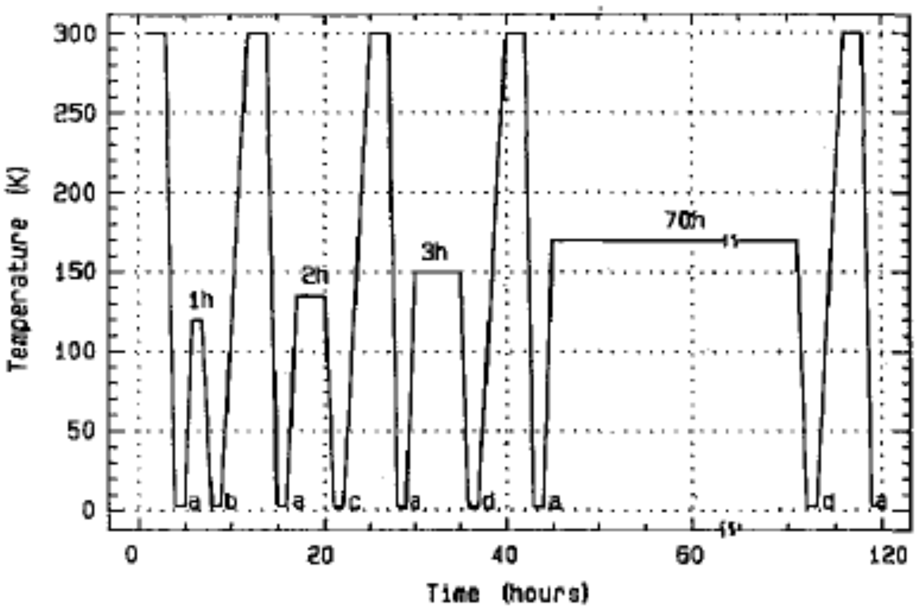
$$H_b(T \gg T_A) \approx \frac{\sqrt{2}}{\pi}\gamma(T,\Delta)\frac{\Phi_0}{\lambda_N d}e^{-d/\xi_N(T)}.$$

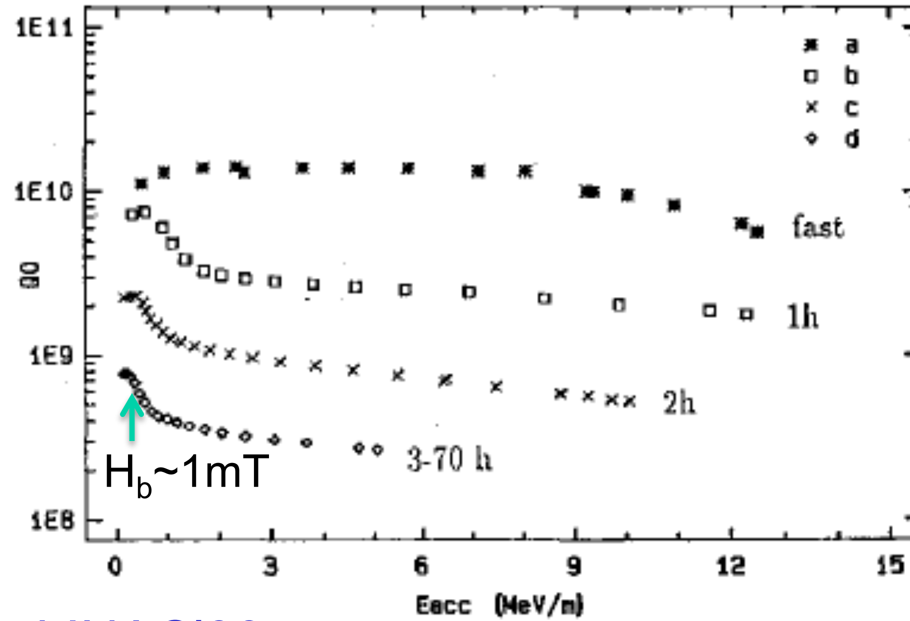
$$\xi_N = \frac{\hbar v_F}{2\pi kT} \qquad T_A = \frac{\hbar v_F}{2\pi kd}$$

$\xi_N \approx$ 800 nm for Nb at T = 2K

If d = 10 nm => T_A= 166 K, T << T_A

At H > H_b – no Meissner screeing – proximity-induced SC is destroyed





Aune et al., LINAC'90

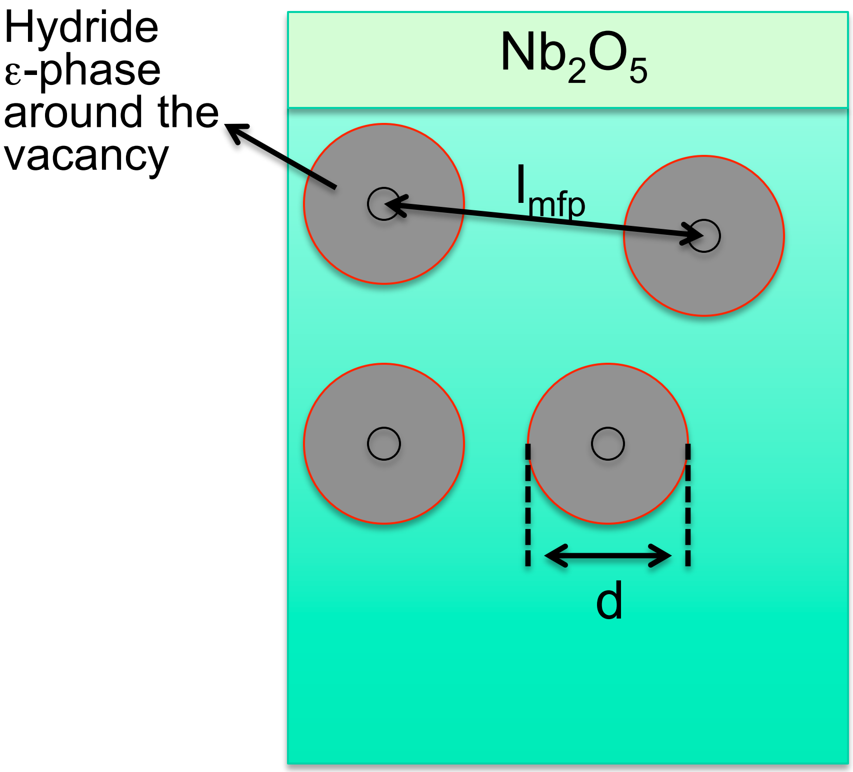
- From our experiments with hydrides (see SRF Materials 2012 talk)

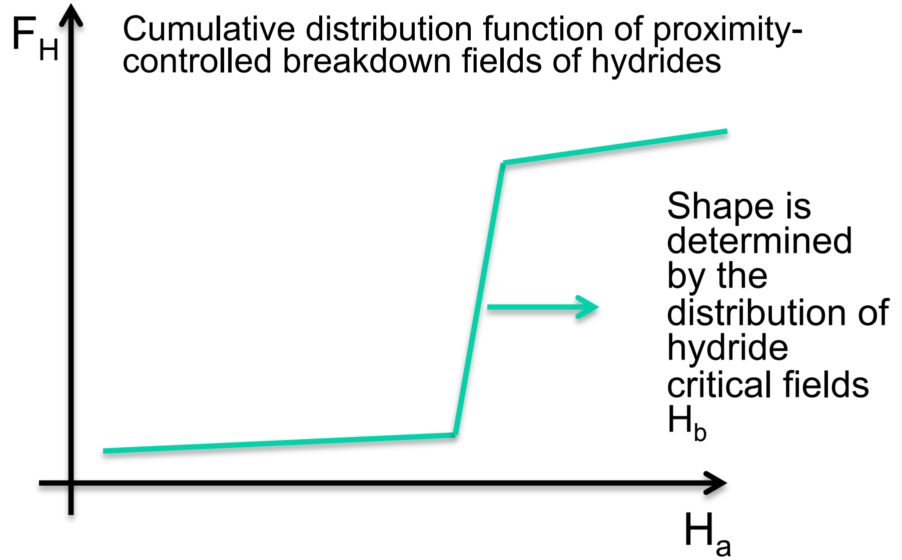
  d ~ 100 nm (150 K hold) =>

  d~100 nm ⇔ H_b~1 mT

  – => in the limit of $T \ll T_A$ if H_b=100 mT=> d~1 nm

Unbaked cavity – HFQS losses





$$R_s \sim R_0 + R_n * F_H(H_a)$$

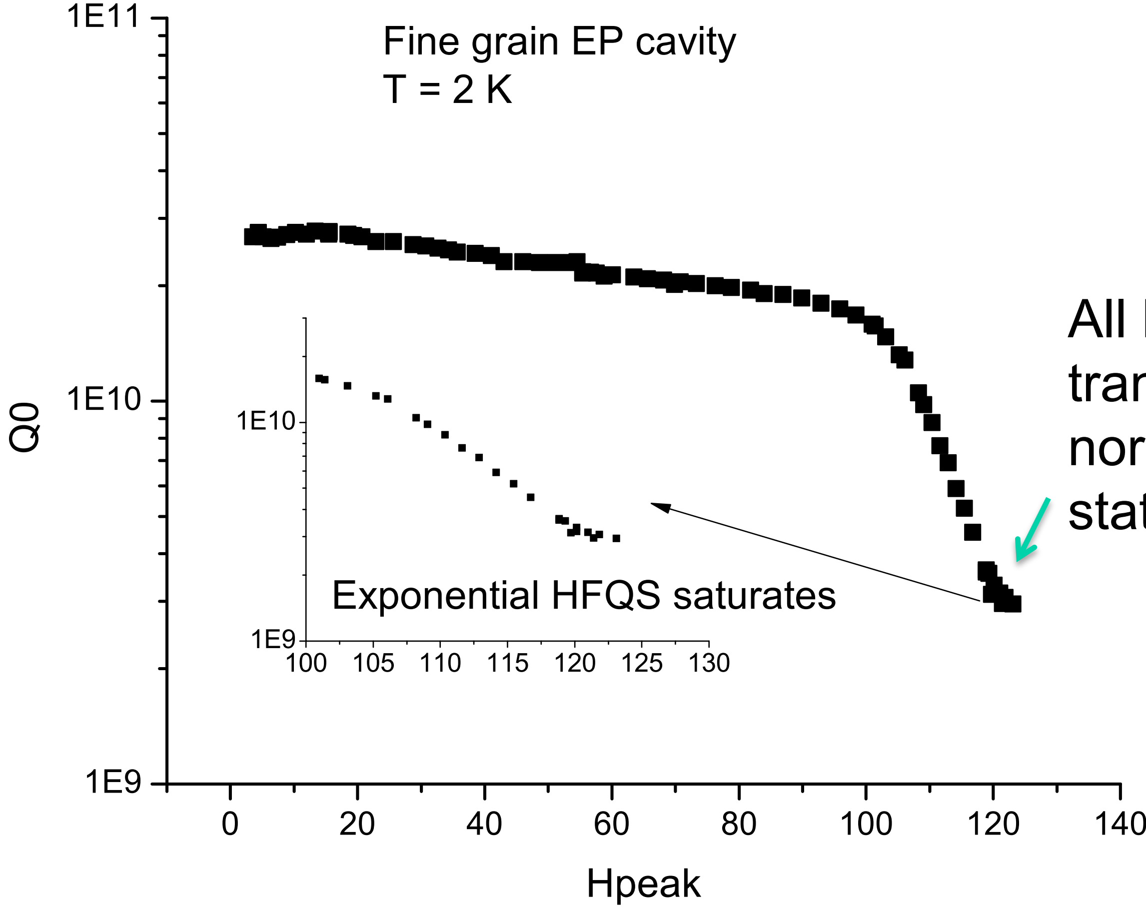
- Nanohydrides lose proximity-induced superconductivity completely => HFQS
- Change of order parameter Δ(z) with field at $H < H_b$ ->MFQS?

We can obtain $F_H(H_a)$ from the distribution of diameters d since $H_b = H_b(d)$:
(i.e. if $H_b \sim 1/d$ at $T \ll T_A$)

Predictions of the model

- Saturation of the HFQS at higher fields (similar to Q-disease)
  - Need more RF power to check (preliminary data next slide)
- Introduce vacancies into baked cavity should recreate locally high field Q-slope
  - Irradiation experiments on the cavity to be done soon
- Small hydrides should be observed directly at T<~150K
  - TEM ongoing
  - Small angle X-ray scattering scheduled

HFQS saturation



All hydrides transitioned to normal conducting state?

Conclusions

- Positron annihilation data suggests major role of vacancies in the 120C baking effect
- Precipitation of hydrides within surface layer may explain the mean free path effect of 120C bake
  - Without involving any impurity diffusion
- Nanohydrides must be present in the RF layer of SRF cavities if nucleation centers exist
  - There is always enough H and time during cooldown
- Proximity effect on nanohydrides can explain the high field Q-slope
- Is medium field Q-slope also a consequence of proximity on hydrides?
  - Or on suboxides?

Acknowledgements

- A. Grassellino, F. Barkov, Y. Trenikhina, L. Cooley – FNAL
- H. Padamsee - Cornell