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Q-Slope Studies at Fermilab: New Insight From Cavity and Cutouts Investigations

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Outline

- New experimental findings on Q slopes
  - Decomposition of the components of surface resistance (R_{BCS} and R_{res})
    - Shows which Q slope is due to what component
- New superconducting measurements
  - Low energy muon spin rotation
    - Baked/unbaked cutouts
    - N doped
- New proximity effect model of the high field Q slope
  - Evidence from cryogenic TEM investigations in cutouts
- New model of the 120C baking
  - Vacancy-based 120C baking mechanism and supporting evidence from cutouts
  - Suppression of the second phase of hydrides in direct observations
- Conclusions

Decomposition of Rs into components

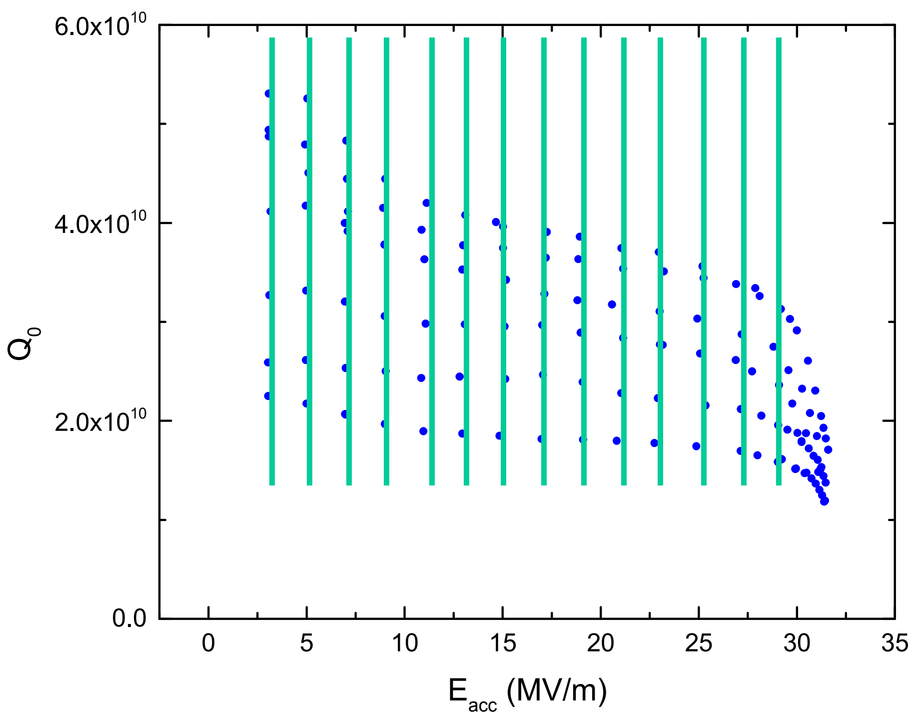
- Using different temperature dependence to deconvolute the components of average surface resistance at ALL fields

$$R_s(T) = R_{BCS}(T) + R_{res}$$

$R_{BCS}(T)$: Due to thermally excited quasiparticles

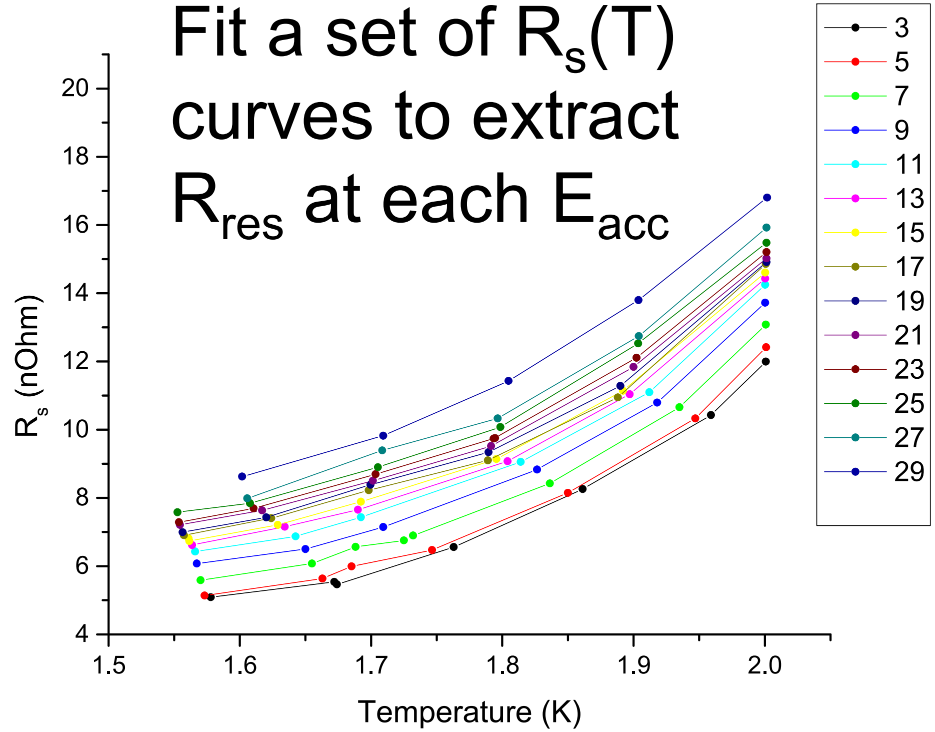
R_{res}: Non-T-dependent, saturation value at T -> 0

Rs(B) decomposition



Measure $Q(E_{acc},T)$ at many different T<2.17K and E_{acc}

Fit a set of $R_s(T)$ curves to extract R_{res} at each E_{acc}

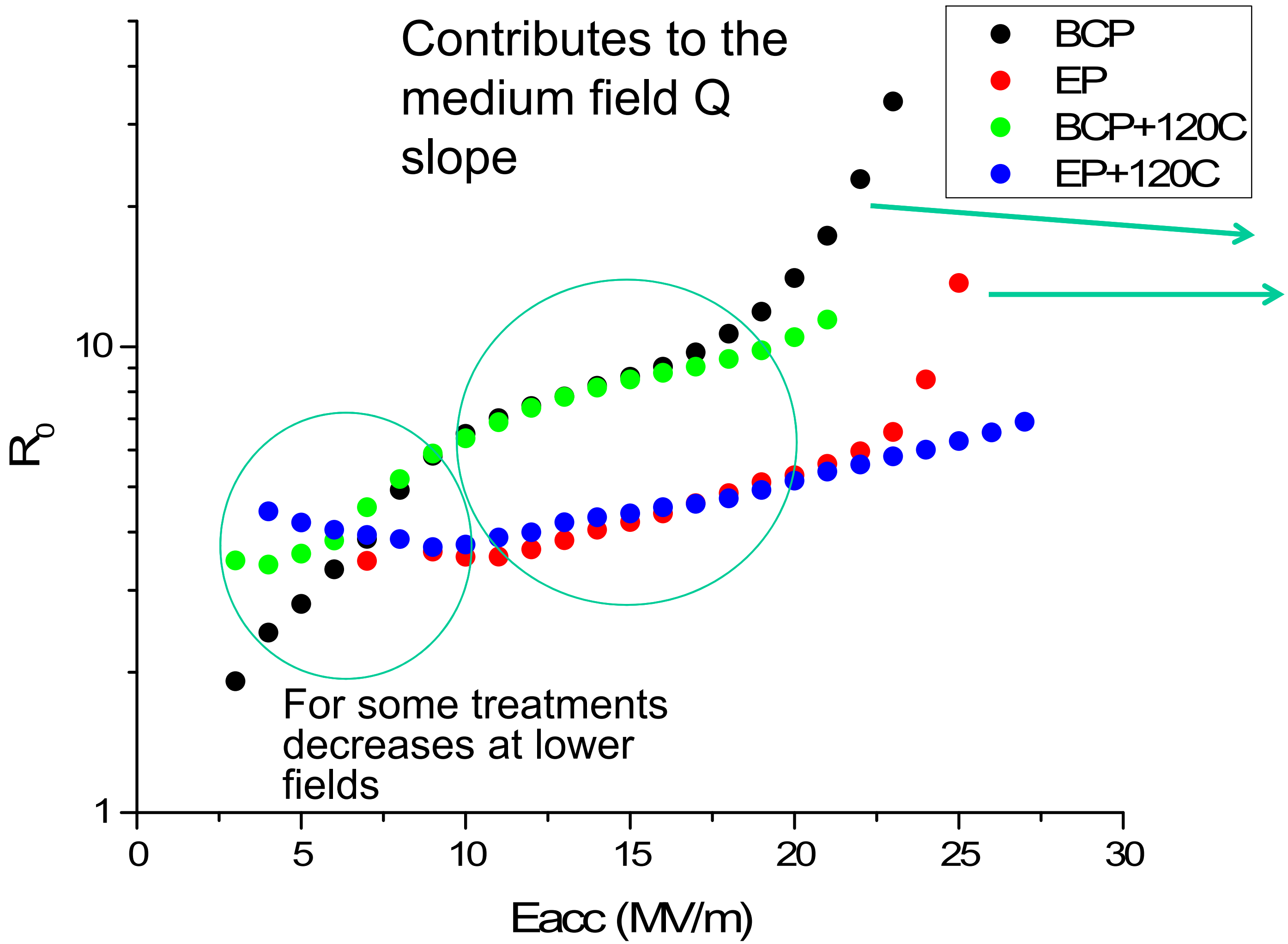


Can be fitted using both approximate formula $R_{BCS}(T)=A/T \exp(-⊗/kT)$, and by more precise BCS calculation based on Halbritter's program – virtually no difference in the results

A. Romanenko and A. Grassellino, Appl. Phys. Lett. 102, 252603 (2013)

Residual resistance

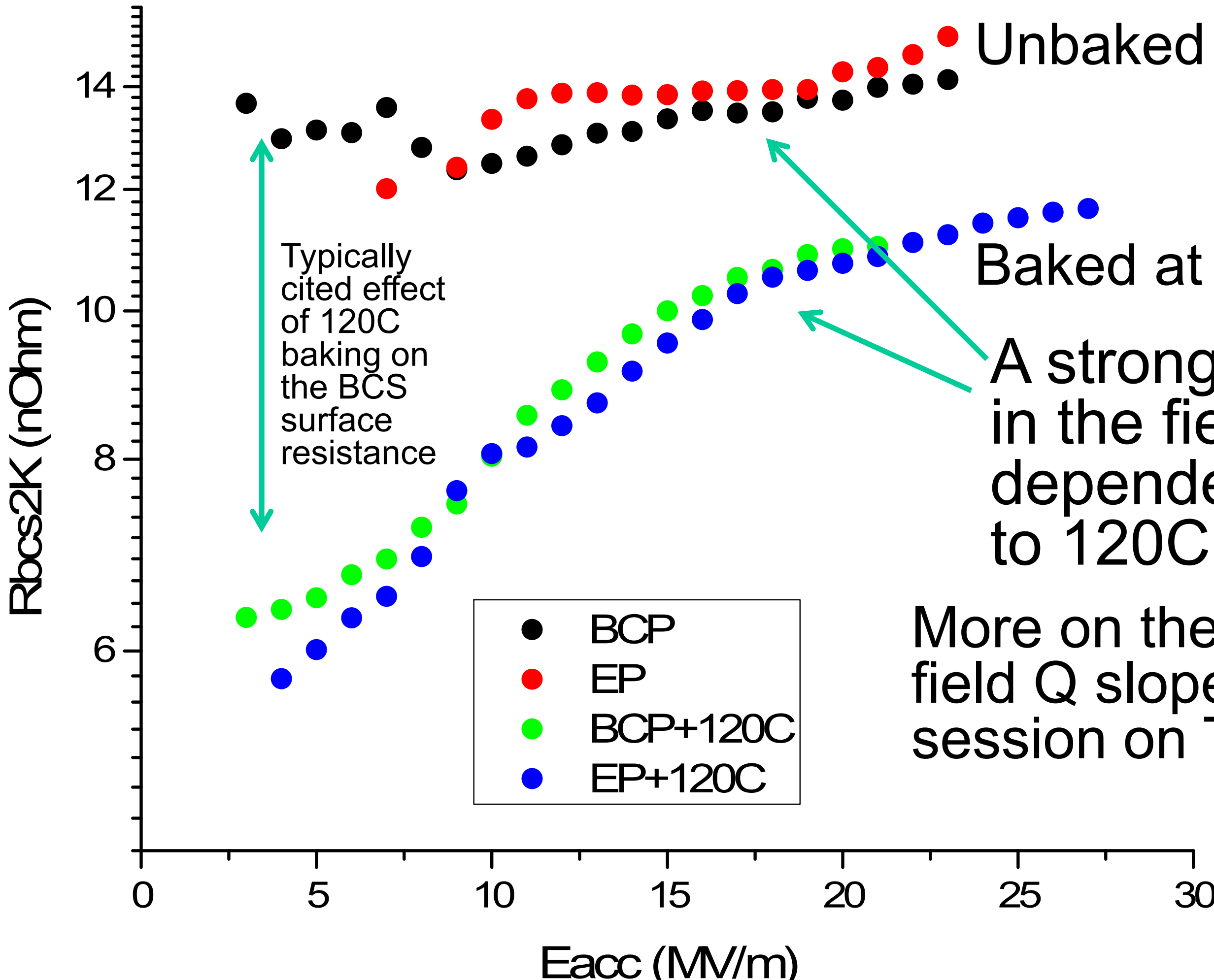
A. Romanenko and A. Grassellino, Appl. Phys. Lett. 102, 252603 (2013)



High field Q slope is clearly a residual resistance effect

BCS resistance

A. Romanenko and A. Grassellino, Appl. Phys. Lett. 102, 252603 (2013)



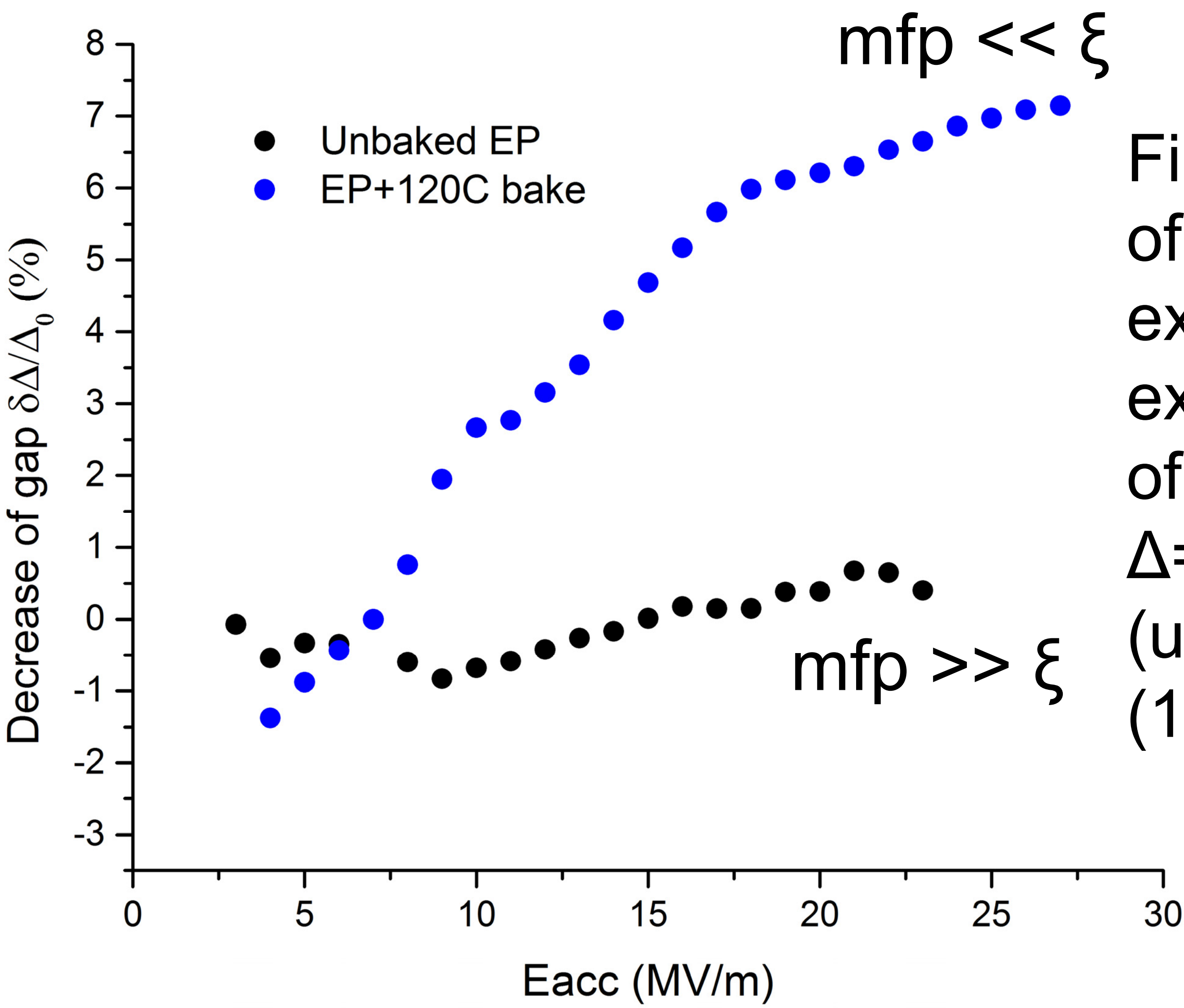
Unbaked

Baked at 120C

A strong change in the field dependence due to 120C bake

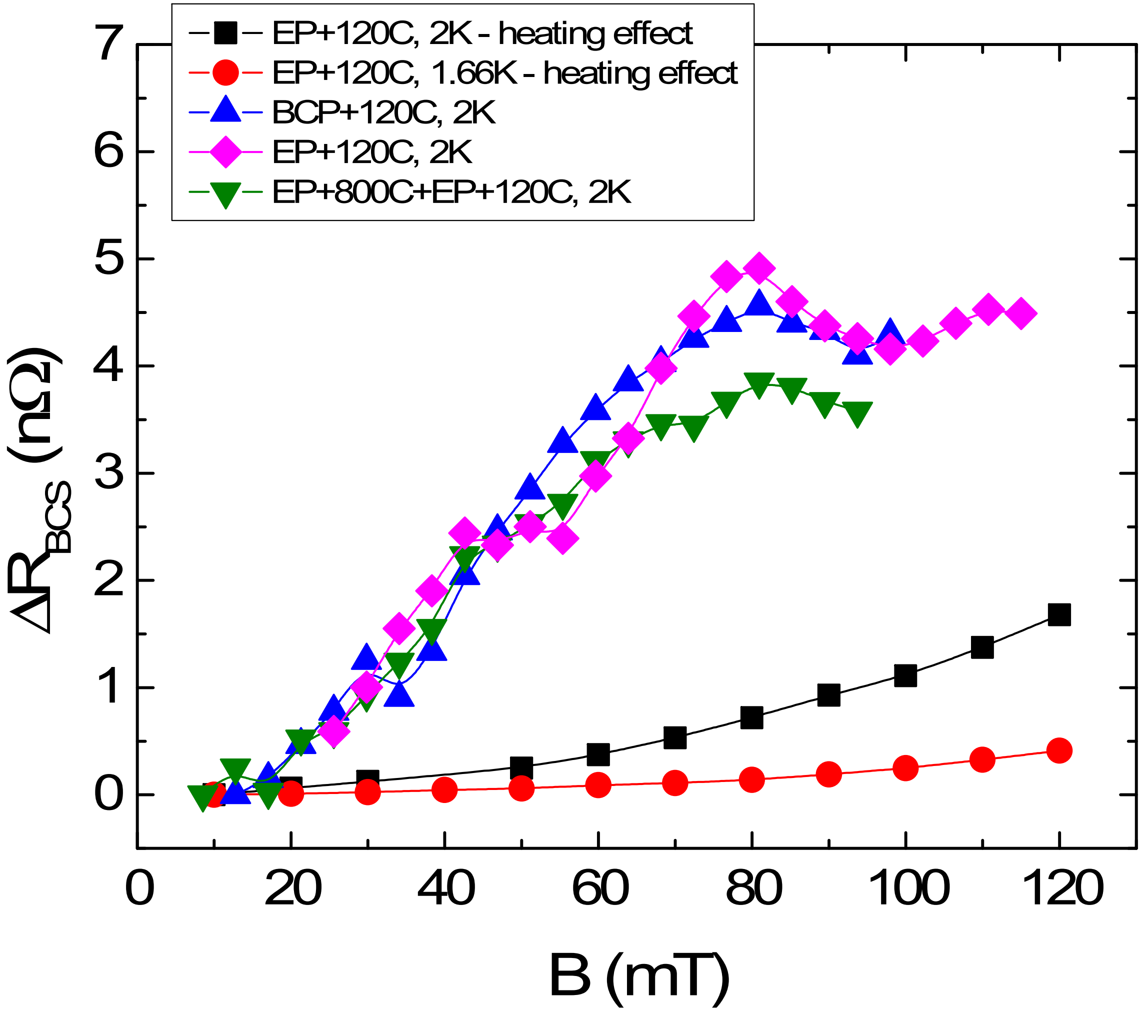
More on the medium field Q slope – hot topic session on Thursday

SC gap change with field



Field dependence of R_{BCS} may be explained by the expected changes of pairing potential Δ=Δ (H) in clean (unbaked) and dirty (120C baked) limits

Role of thermal "feedback"

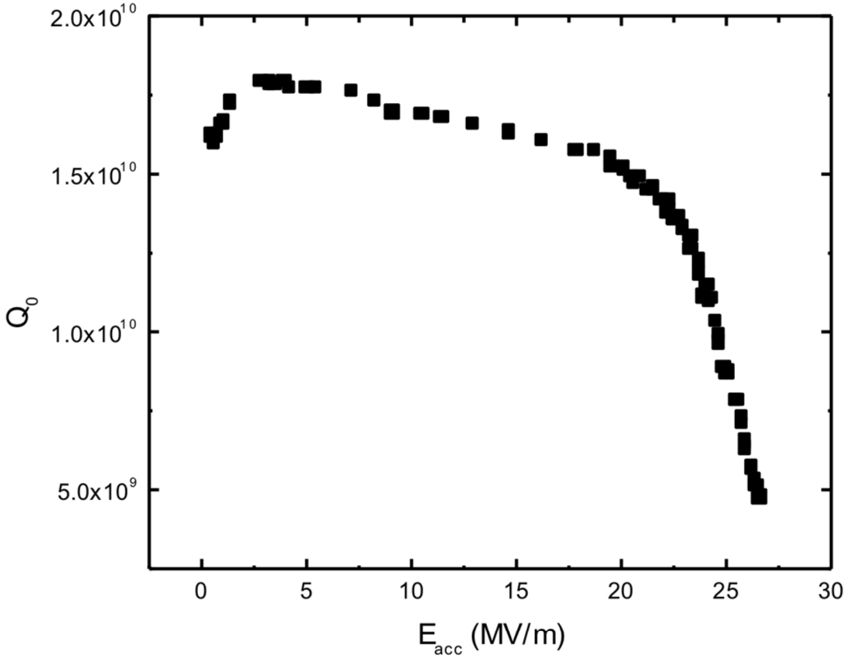


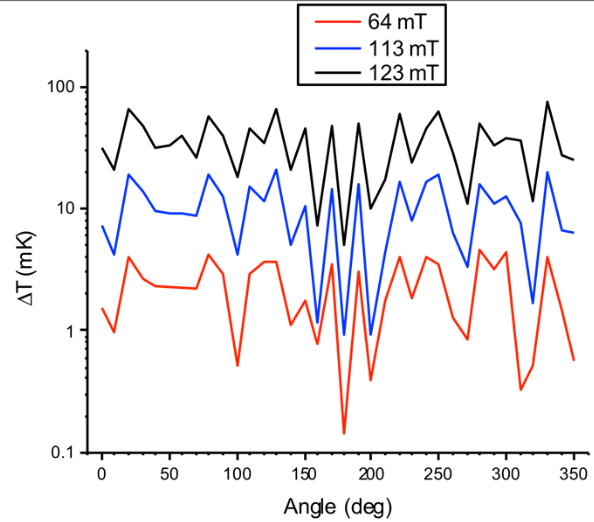
Instead of modeling the full temperature transfer with only $R_s=G/Q_0$ as an input use temperature mapping to measure the outside wall temperature

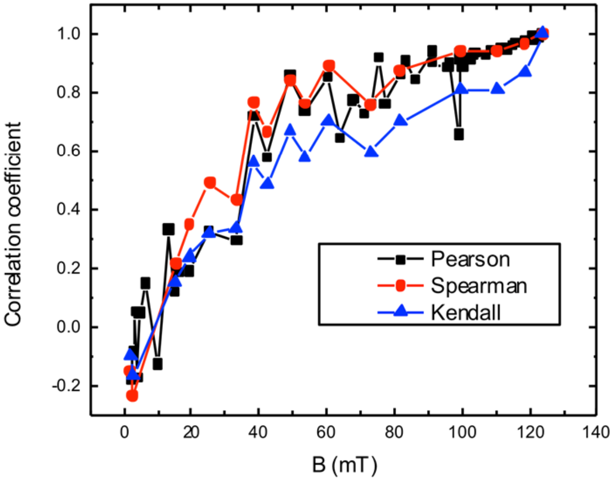
Negligible effect on R_{BCS} at T <= 2K

More – hot topic session on Thursday

Correlation between medium and high field Q slopes in unbaked cavities







T-map data shows that local surface resistance in HFQS regime is highly correlated to Rs at lower fields (MFQS)

More info – please see [A. Romanenko et al, TUP101]

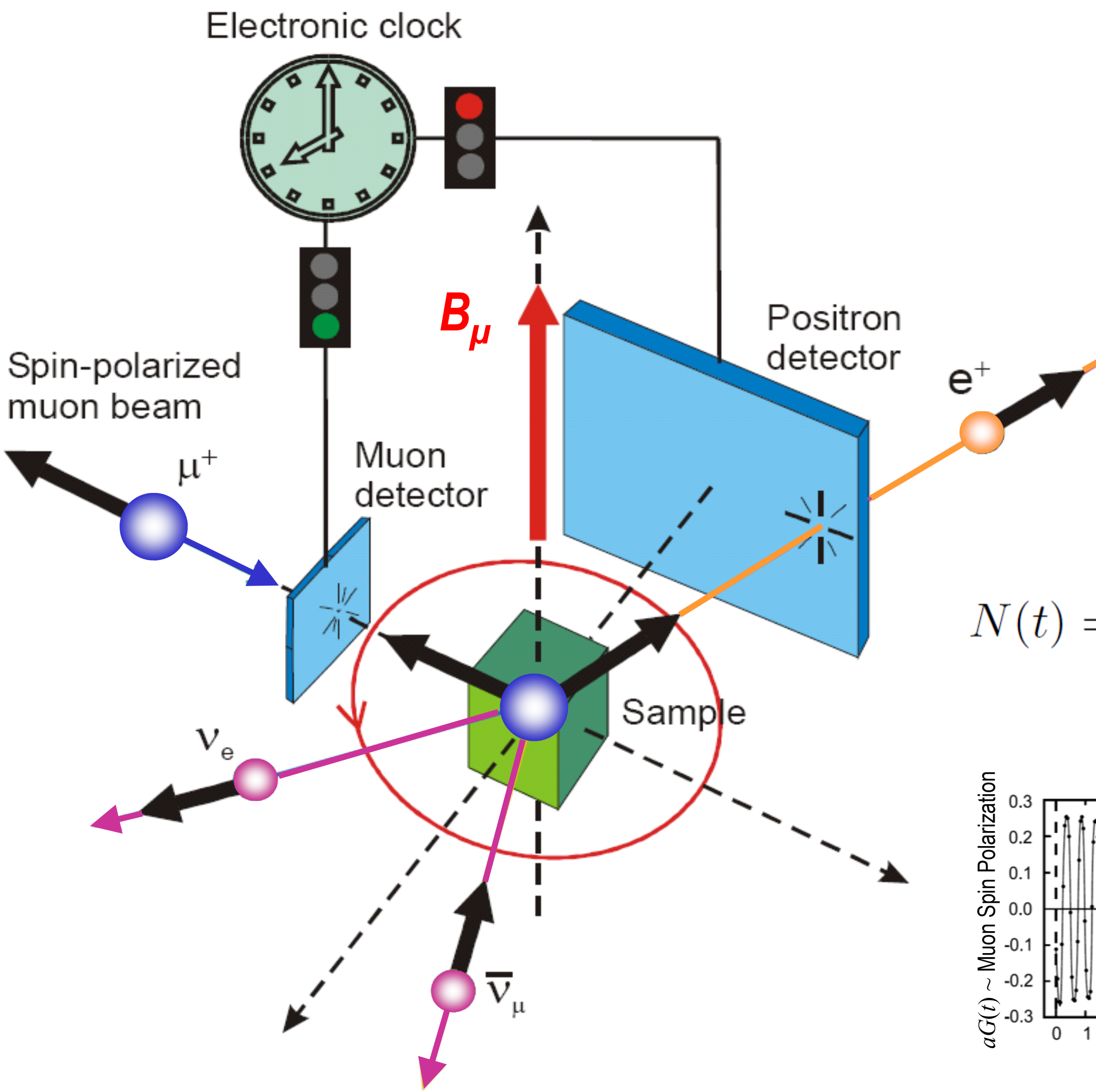
New cavity data allows to “filter” models

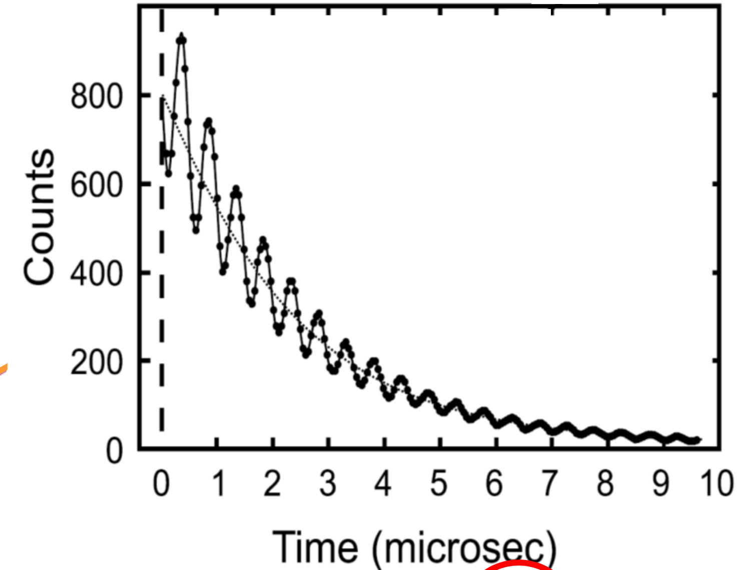
- High field Q slope is due to residual
  - Not SC gap closing, thermal feedback etc.
- Medium field Q slope is a combination of R_{BCS} and R_{res}
  - Not due to the difference in Trf and Tbath
  - Correlation between high and medium fields in unbaked cavities
- Low field Q slope is likely due to residual

New superconducting measurements

- Bulk muon spectroscopy
  - A. Grassellino et al, TUP031
- Low energy muon spectroscopy
  - A. Romanenko et al, TUP038
- Bitter decoration
  - F. Barkov et al, TUP016

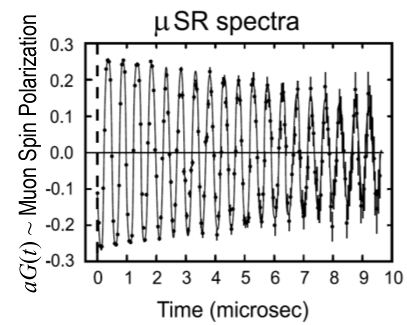
Muon spin rotation





$$N(t) = N_0 \exp(-t/\tau_\mu)\,[1 + a\,G(t)] + \mathrm{Bkg}$$

Contains physics

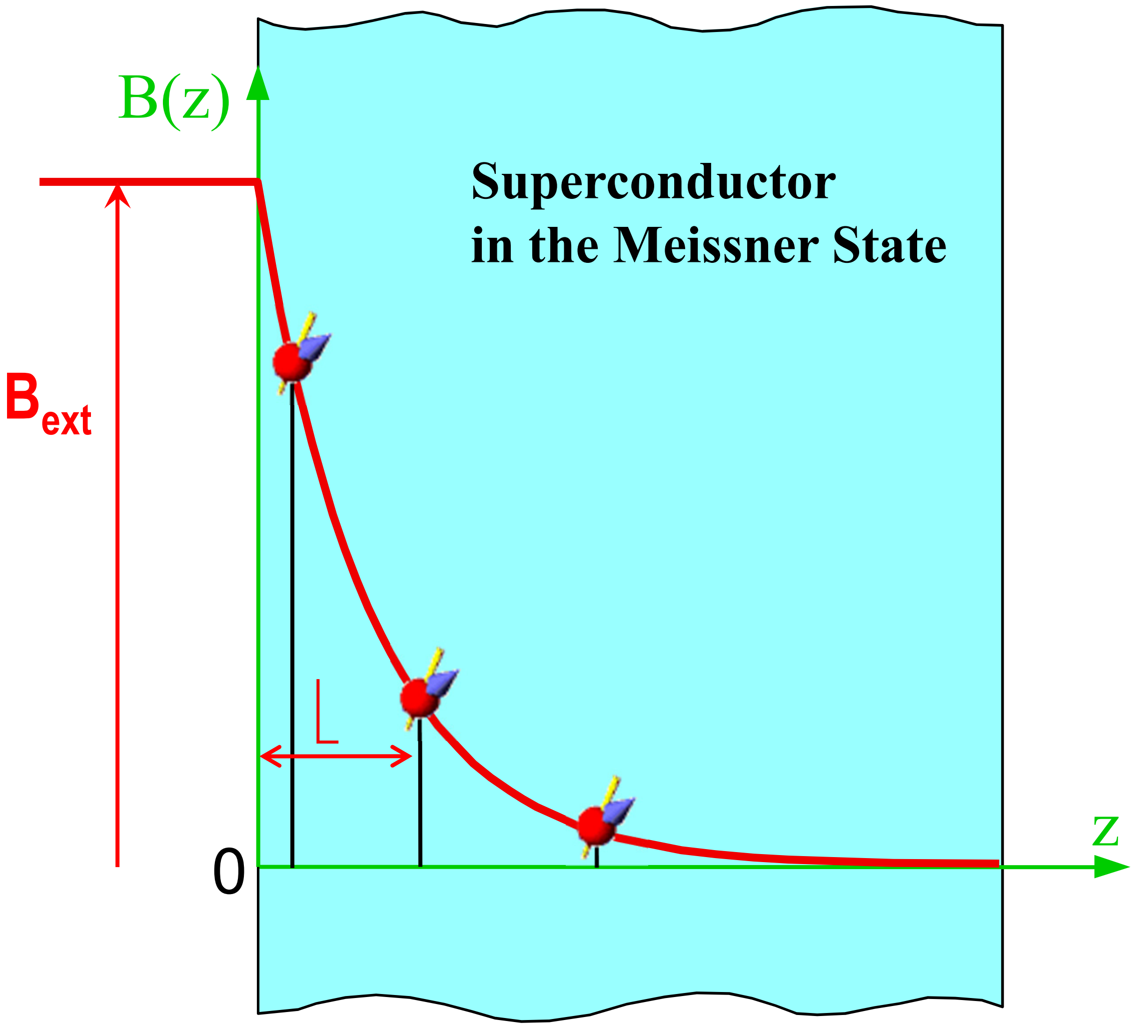


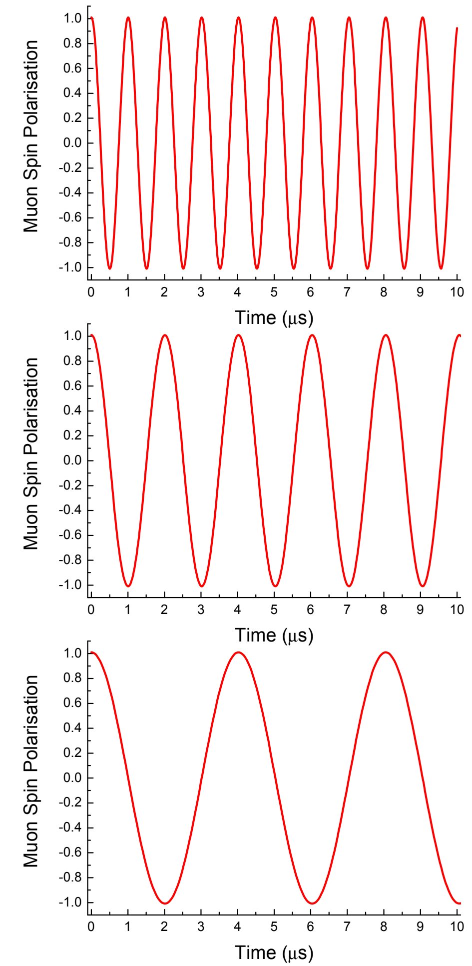
$$\omega_\mu(z) = \gamma_\mu B_{\mathrm{loc}}(z)$$

Frequency – field amplitude

Damping – field non-uniformity

Muon spin rotation – measure B(z)

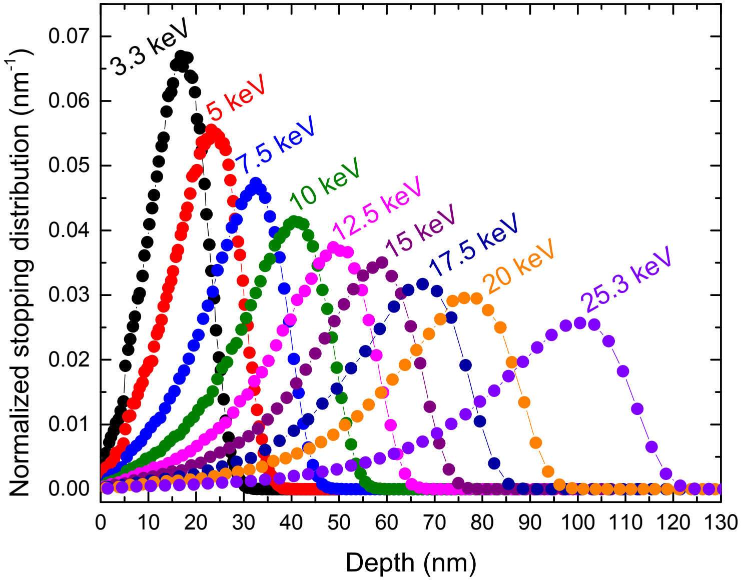


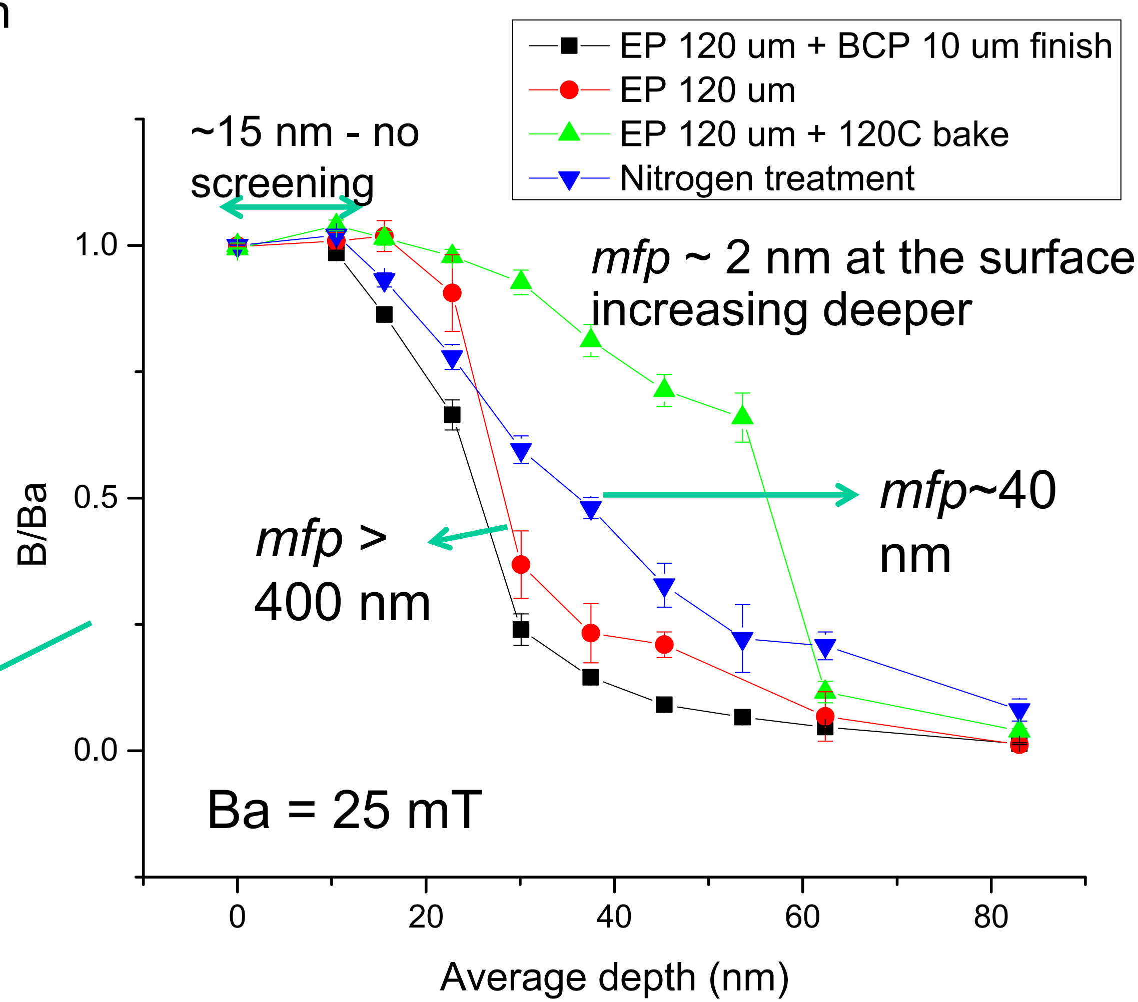


$$\omega_\mu(z) = \gamma_\mu B_{\mathrm{loc}}(z)$$

LEM – data on EP baked/unbaked

Use variable energy muons, which stop in the first ~100nm





BCP and EP unbaked -> strong screening, excellent fit provided by the clean limit Pippard/BCS model

EP+120C bake-> strongly suppressed m.f.p., gradient of the m.f.p. from the surface, dirty limit

N-doped -> intermediate m.f.p., no gradient

Fit by Gaussian model for the field at the muon site – approximate, qualitative comparison

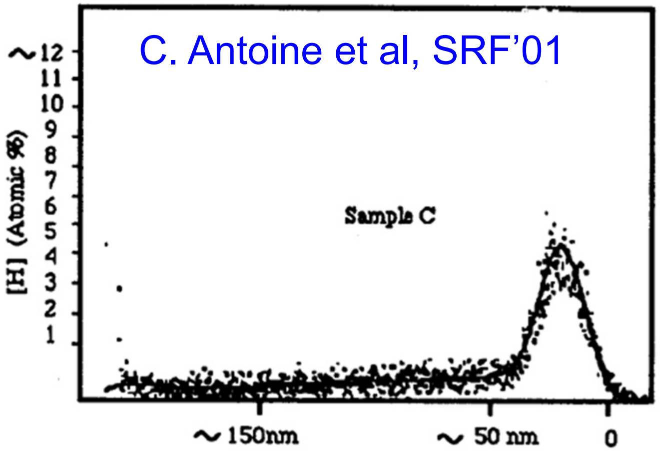
New model of the HFQS

- Main element: presence of small proximity effect coupled nanohydrides within the penetration depth
  – Q disease "in miniature"
- Consistent with all experiments, provides quantitative description
- Falsifiable
  – Testable predictions

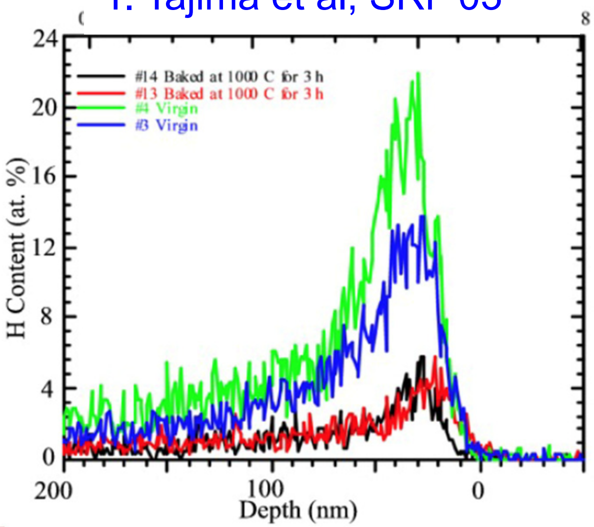
A. Romanenko, F. Barkov, L. D. Cooley, A. Grassellino, Supercond. Sci. Technol. 26 (2013) 035003

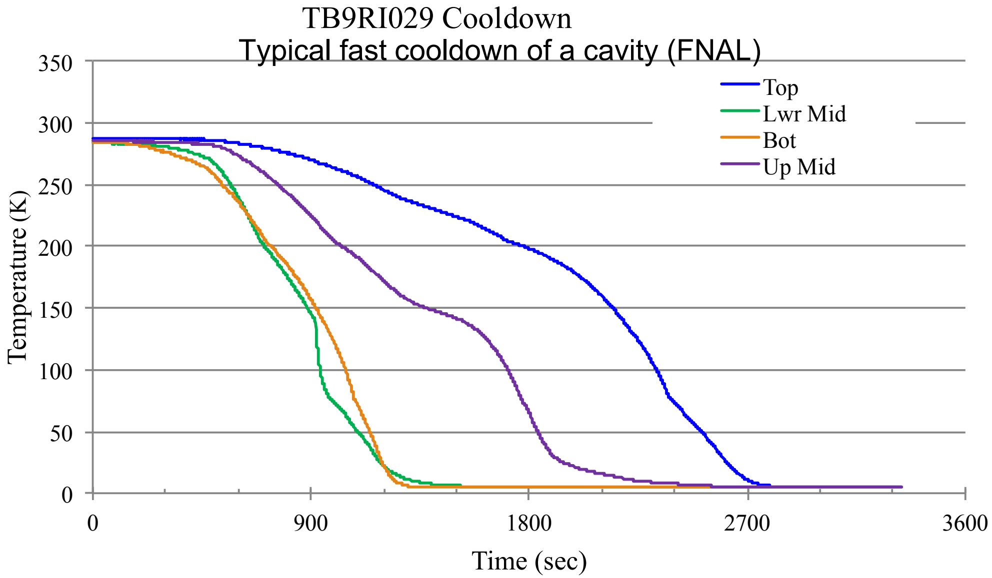
Neither standard 800C degassing nor "fast" cooldown help

Near-surface H-rich layer is still there after standard H degassing treatments



T. Tajima et al, SRF'03

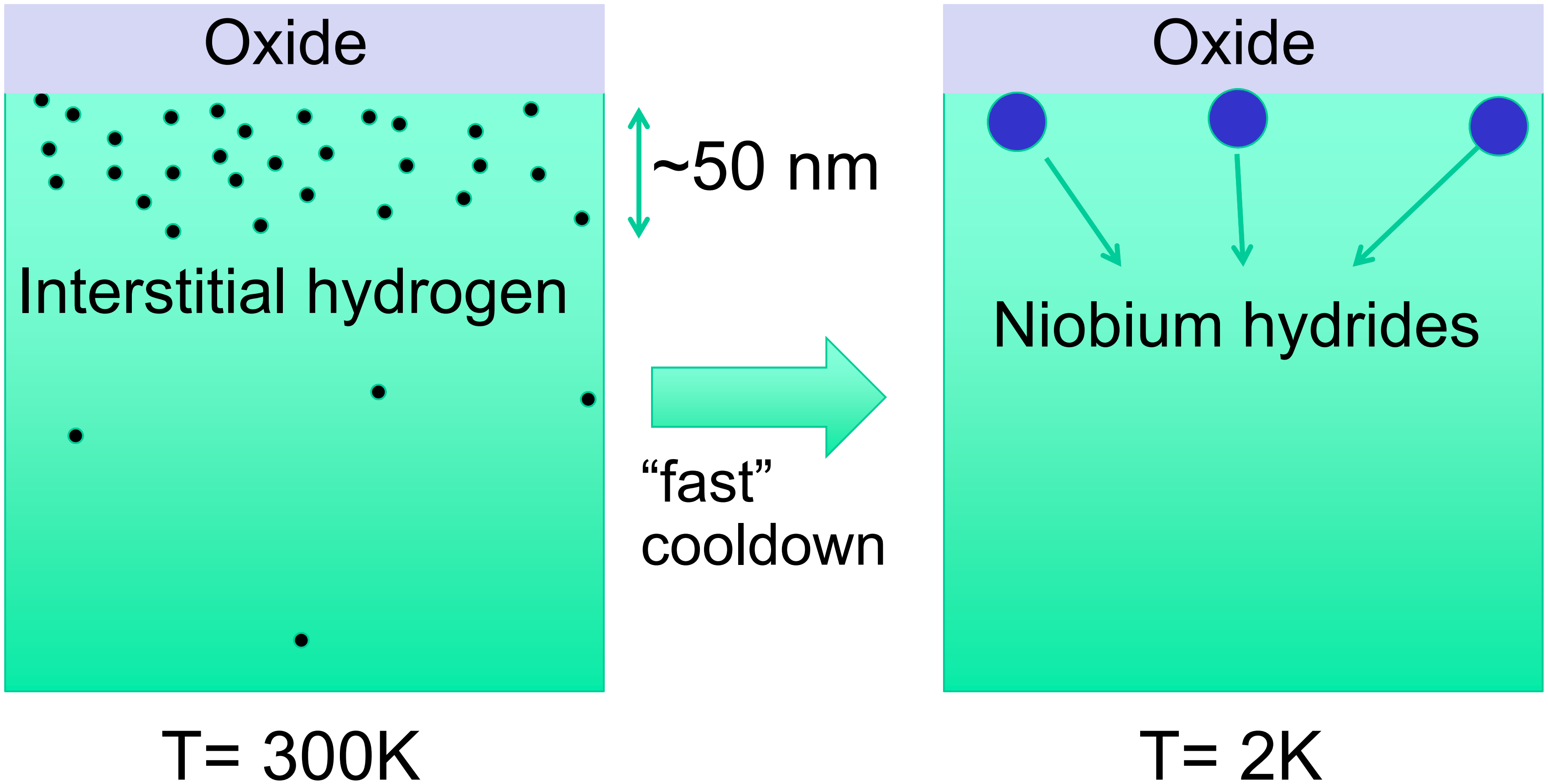




Integrate the H diffusion over the time spent in the precipitation temperature range T < 160K => L > 1 um

All free near-surface H will precipitate into hydrides

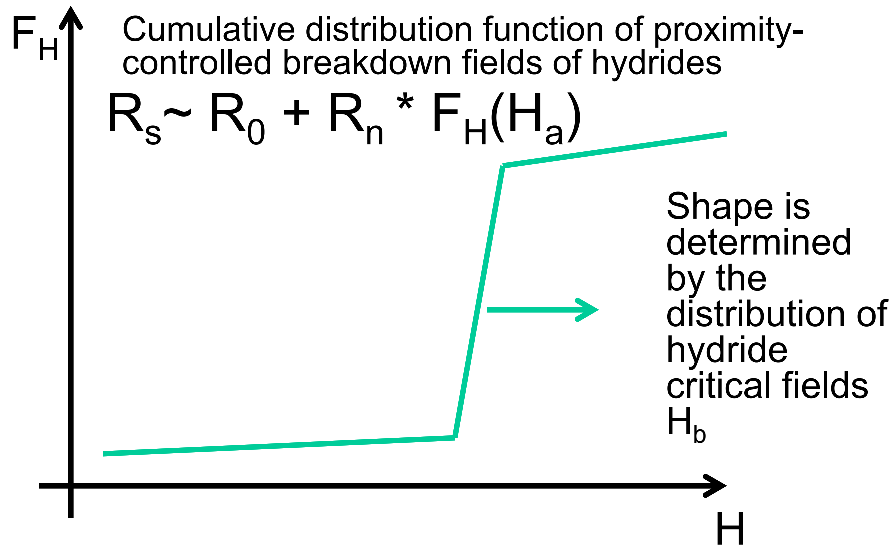
Not 120C baked sample



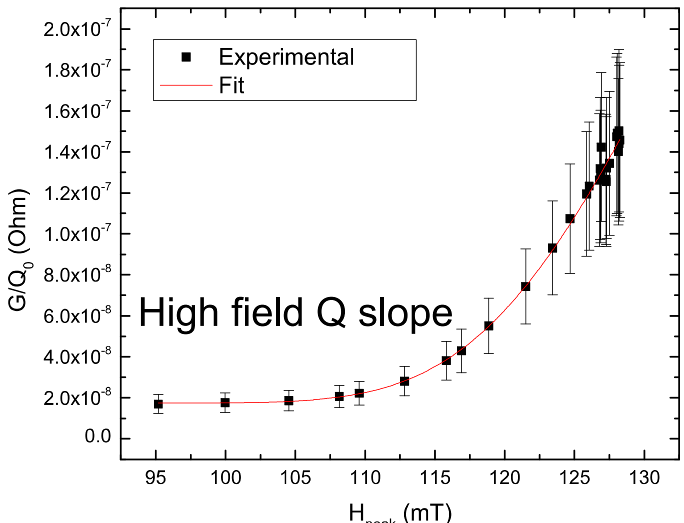
Note drastic change in the hydrogen-related m.f.p.

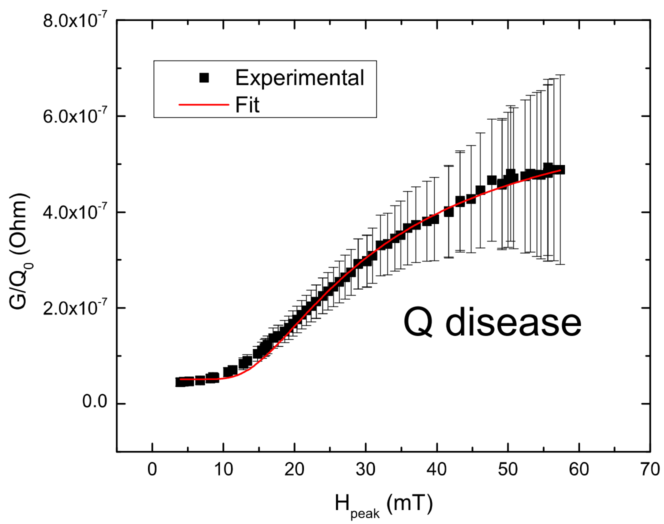
Proximity effect model

- Normal conducting hydrides of size *d* are superconducting by proximity effect up to the field $H_b \sim 1/d$



- Excellent fits



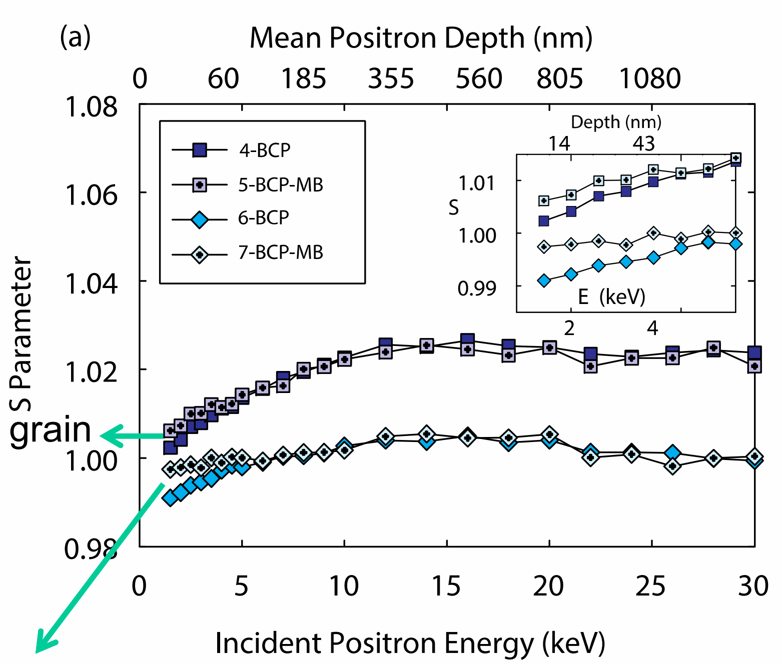


A. Romanenko, F. Barkov, L. D. Cooley, A. Grassellino, Supercond. Sci. Technol. 26 (2013) 035003

- So what happens with 120C bake?

Positron annihilation on cavity cutouts

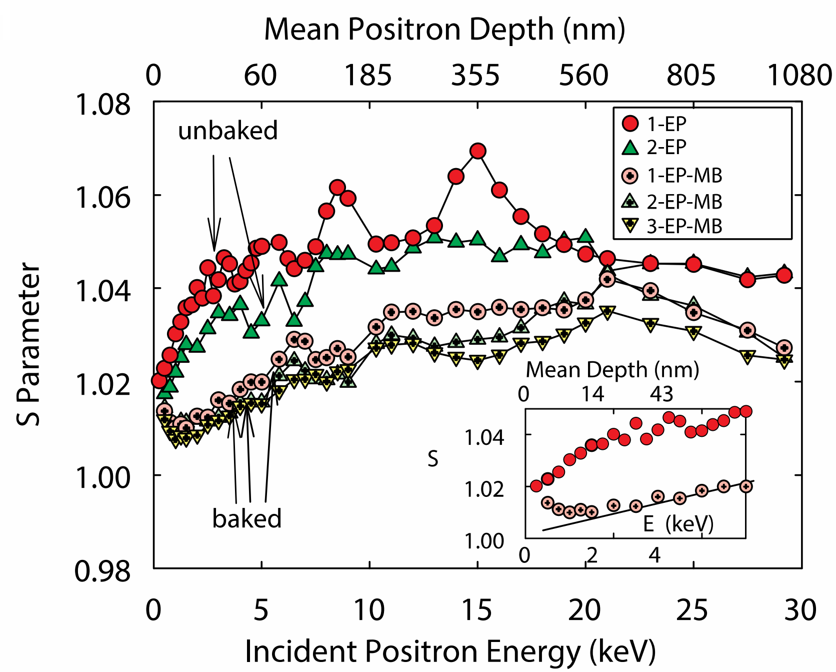
A. Romanenko, C. J. Edwardson, P. G. Coleman, P. J. Simpson, Appl. Phys. Lett. **102**, 232601 (2013)



Fine grain

Large grain

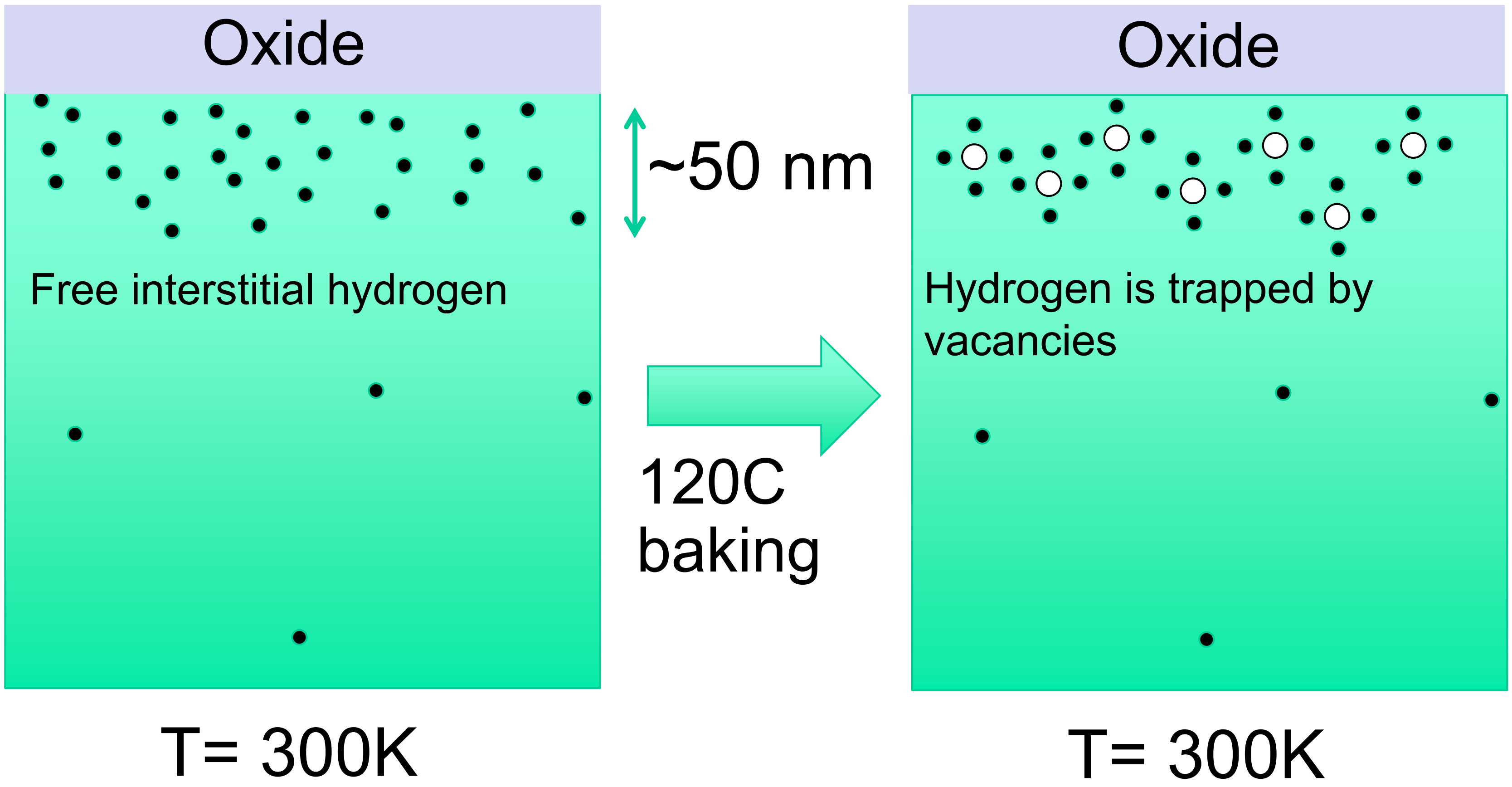
BCP



EP

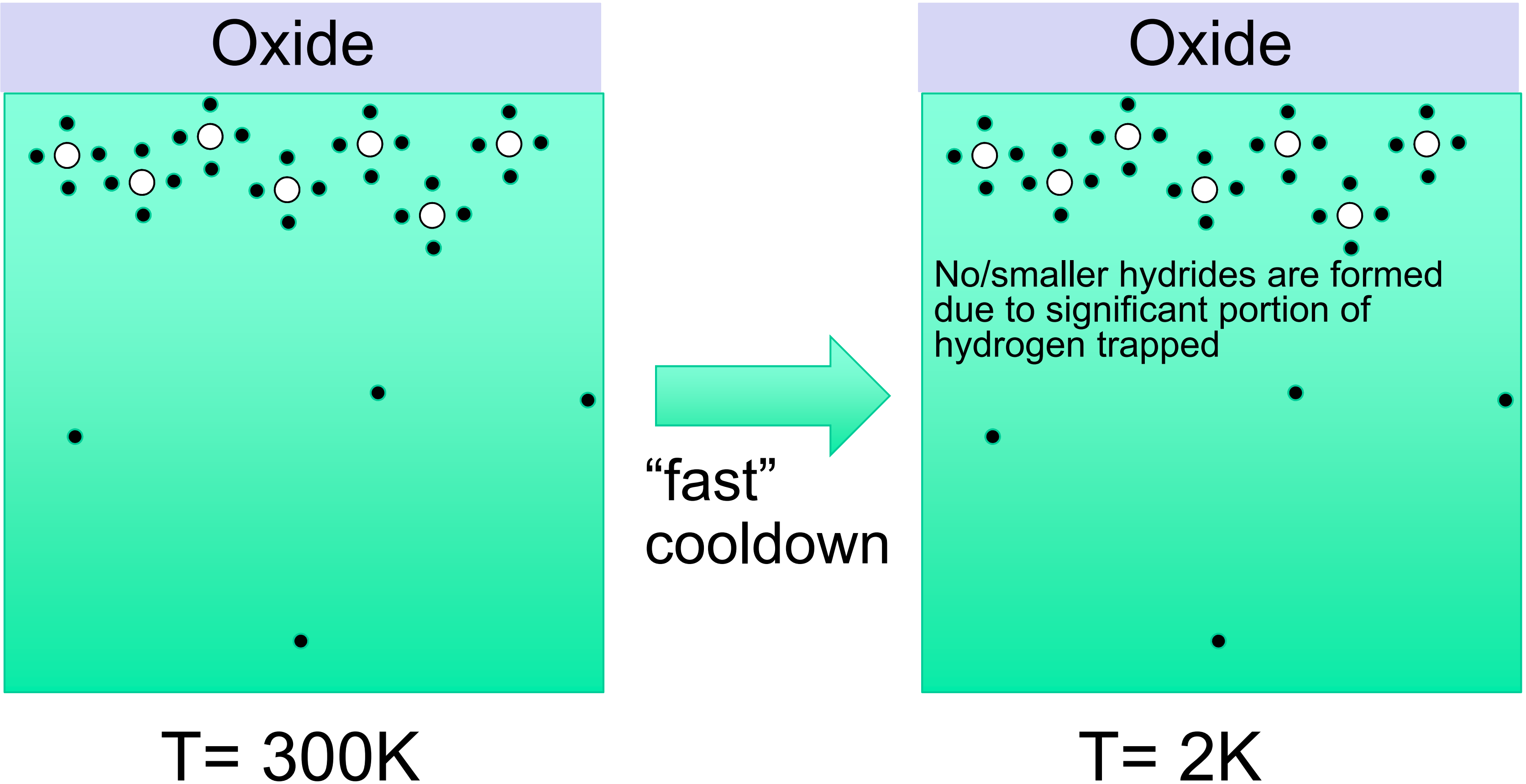
- Positron annihilation spectroscopy: 120C baking results in “doping” of the first ~50 nm from the surface with defects, most likely vacancies
  - EP itself introduces some vacancies in ~1 um – may be the reason for more efficient 120C baking in EP cavities

Effect of 120C baking



A. Romanenko, C. J. Edwardson, P. G. Coleman, P. J. Simpson, Appl. Phys. Lett. **102**, 232601 (2013)

Cooling down of 120C baked niobium

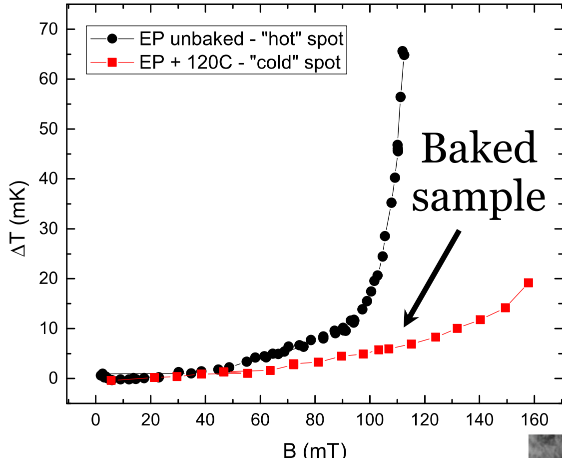


Note no change in the hydrogen-related m.f.p. – remains low

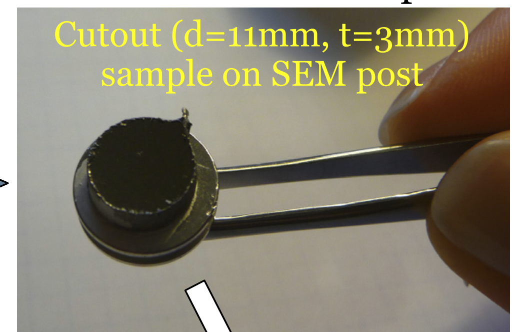
TEM evidence for nanohydrides

- Direct imaging of the cross-sections of cavity cutouts in cryo-TEM [see Y. Trenikhina et al, TUP043]

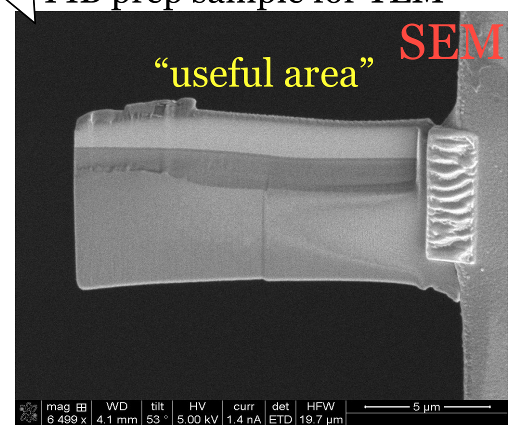
Cold: 120C in situ bake for 48hours
Hot: no such bake

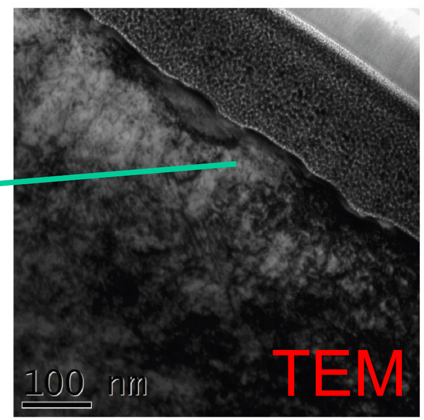


Heating: comparison of "cold" and "hot" spots



FIB prep sample for TEM





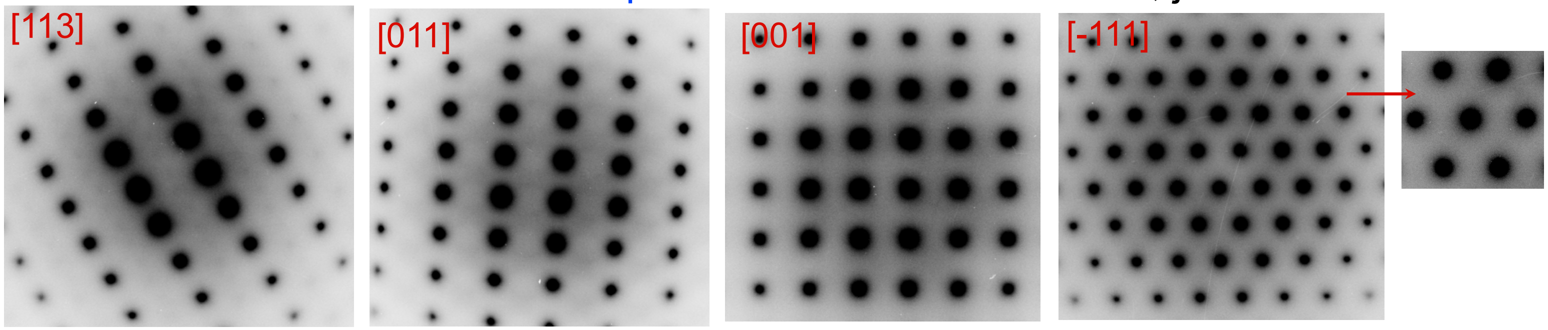
Look at this area with subnanometer resolution in TEM at room AND T<100K temperatures

See also R. Tao et al, J. Appl. Phys. **114**, 044306 (2013) and TUP042 for cryoimaging of H-reach Nb samples

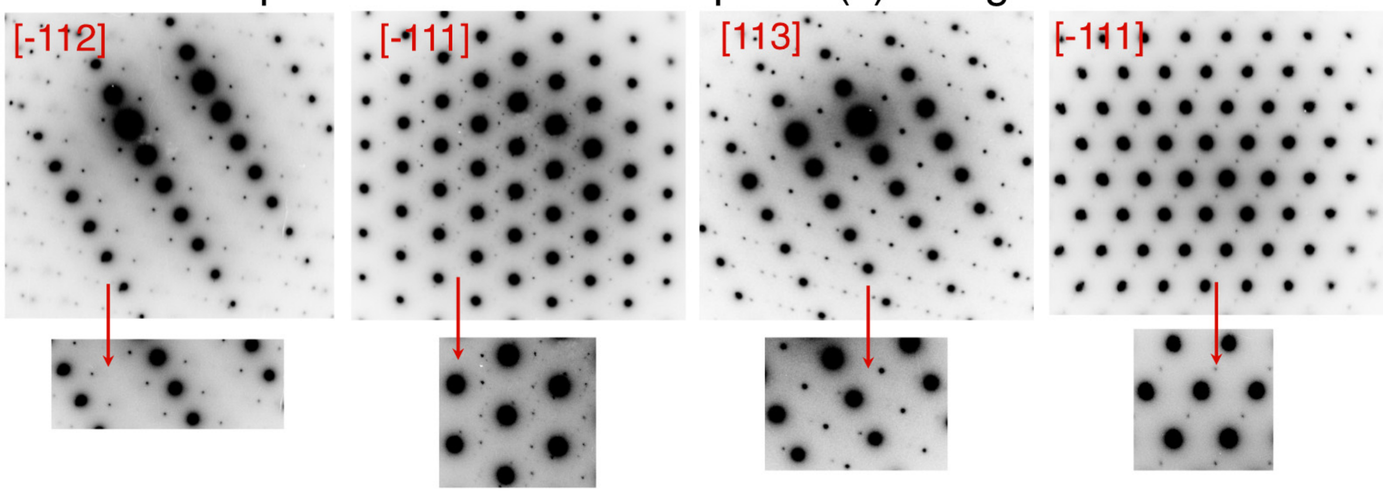
Direct evidence for nanohydrides

Y. Trenikhina et al, TUP043

NED at room T Hot and Cold spot: NO additional reflections, just Nb



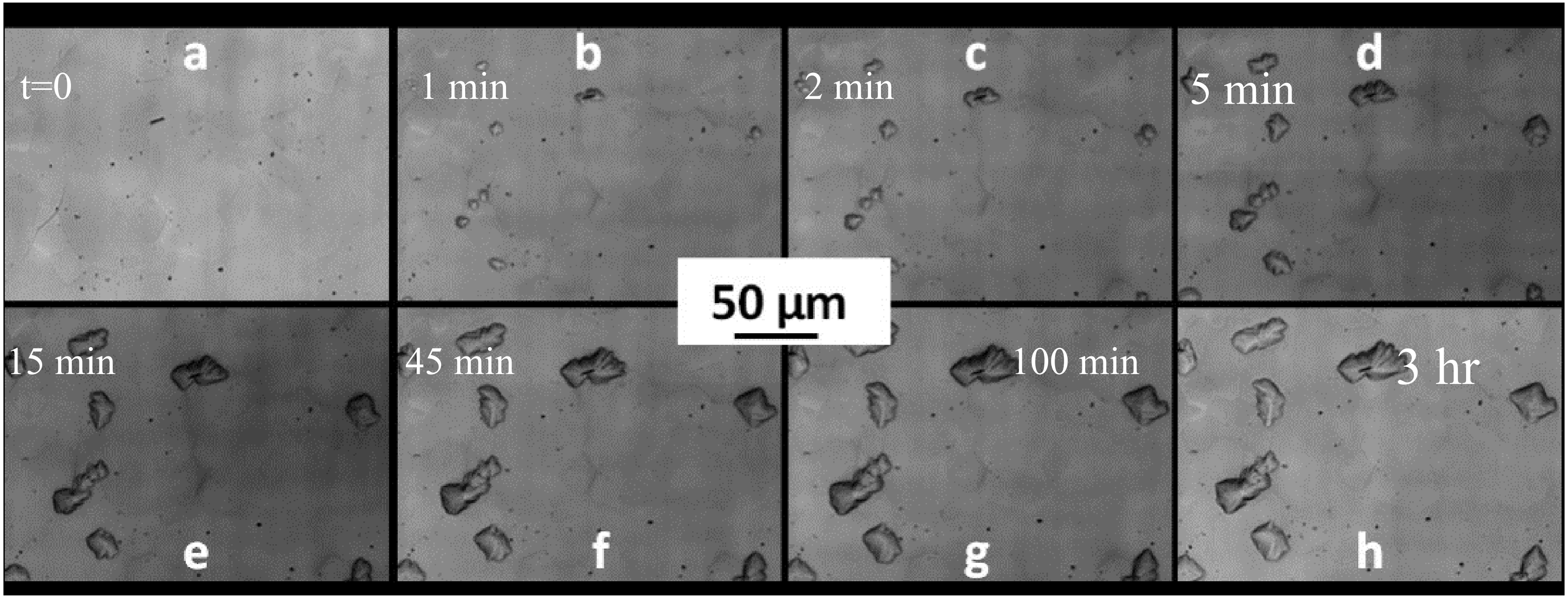
Hot spot NED at 94K: low T phase(s) along with Nb



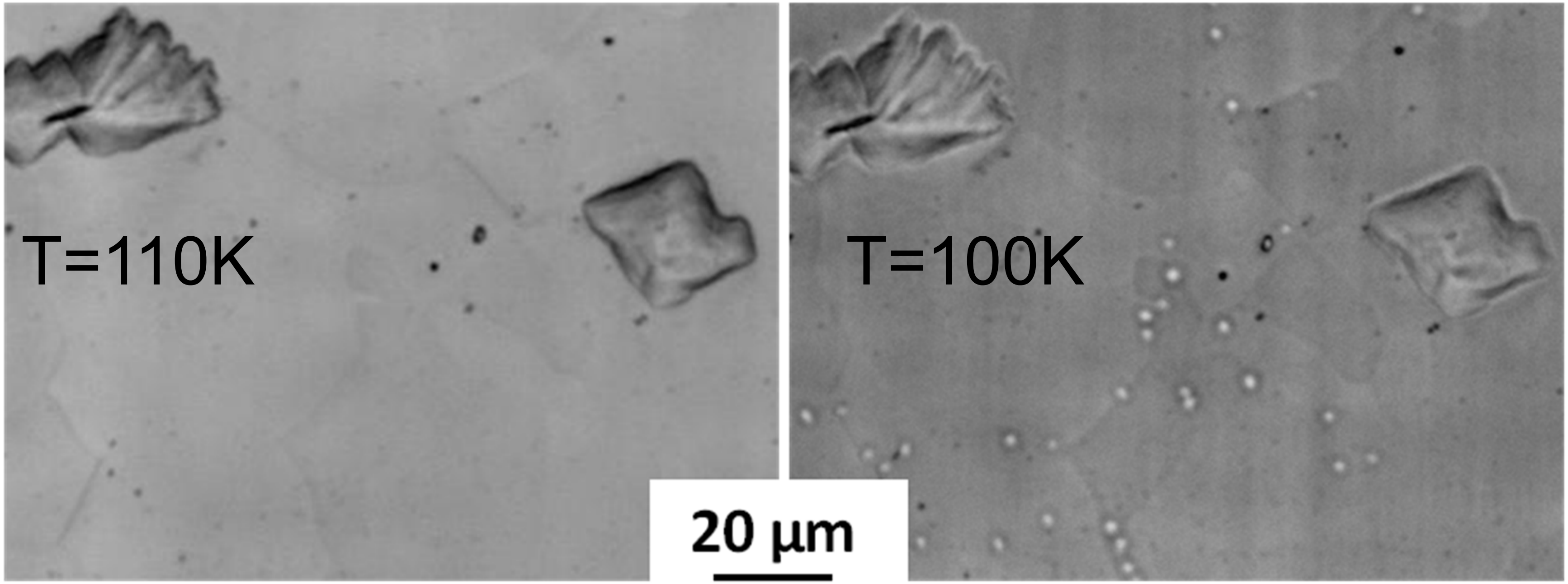
“Statistics” of the second phase appearance: 44%-68% of the probed spots

F. Barkov et al, TUP014

Growing of hydrides at T=160K in a mechanically polished sample



Further evidence: 100K and 120C baking effect



- Second phase (lower concentration, lower temperature) forms at 100K
  - NOT observed on 120C baked samples

Summary

- Both residual and BCS surface resistances carry a field dependence
  - Analysis of Q slopes should only be done on components
- Mean free path/ Meissner screening is lowest, depth-dependent in 120C baked material, highest in unbaked, N-doping leads to the "intermediate" situation
- Nanohydrides may be an omnipresent entity not appreciated before
  - May be THE cause of the high field Q slope
    - Proximity-induced superconductivity breaks down at lower fields than host (Nb)
  - May be related to the residual resistance field dependence
    - Dominant source of the medium field Q slope in unbaked cavities
  - Absence of nanohydrides may be behind the effect of doping
  - Plausible mechanism of 120C baking -> trapping of hydrogen by vacancies -> preventing/decreasing size of nanohydrides

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- Cornell Univ.: H. Padamsee