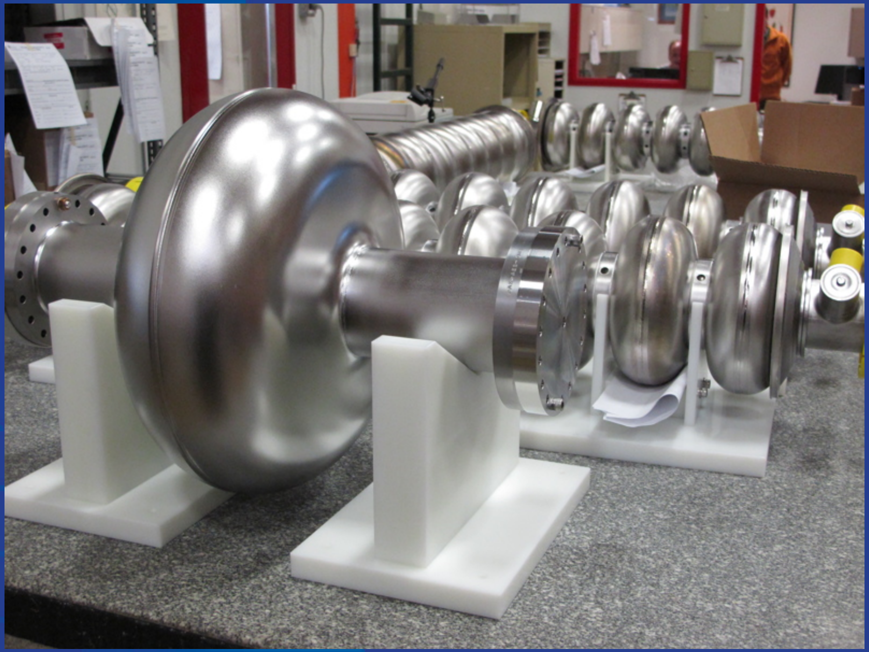
Advances in SRF Material Science aimed at High Q cavities



Anna Grassellino

SRF Development Department, TD

Fermilab

NA-PAC 2013

Pasadena, California

Outline

- Motivation for pushing for higher quality factors
- New insights on understanding of origin and causes of RF losses
  - *Hydrides formation*
  - *Flux trapping*
  - *Surface resistance decomposition*
- New surface processing techniques for high Q cavities
  - *Doping with small amount of interstitial impurities*
- Q ‘preservation’ in a real machine
- Outlook and conclusions

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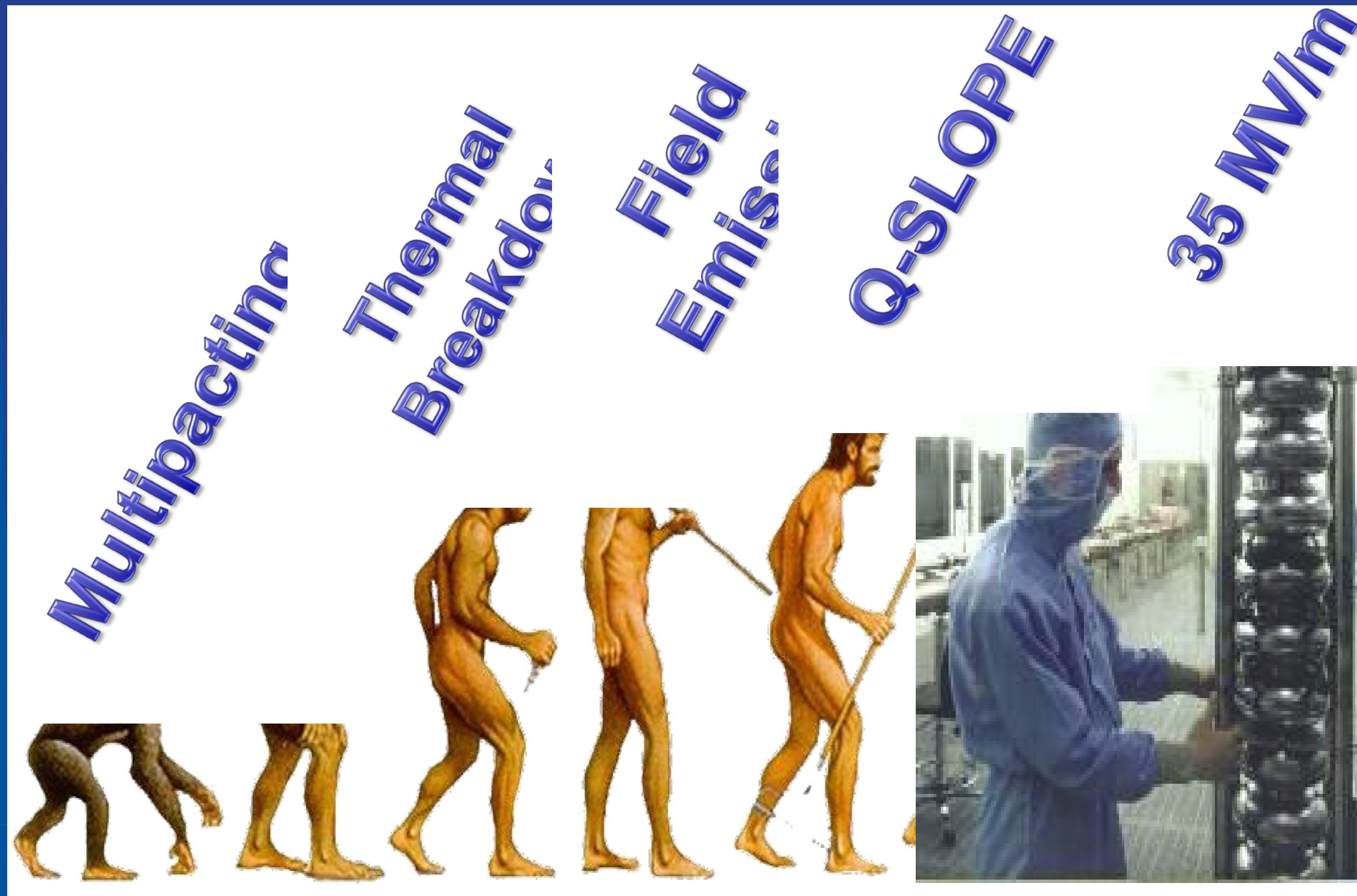
SRF evolution (courtesy of H. Padamsee)



Steady progress due to basic understanding of limiting phenomena and invention of effective cures

SRF core technology for accelerators worldwide

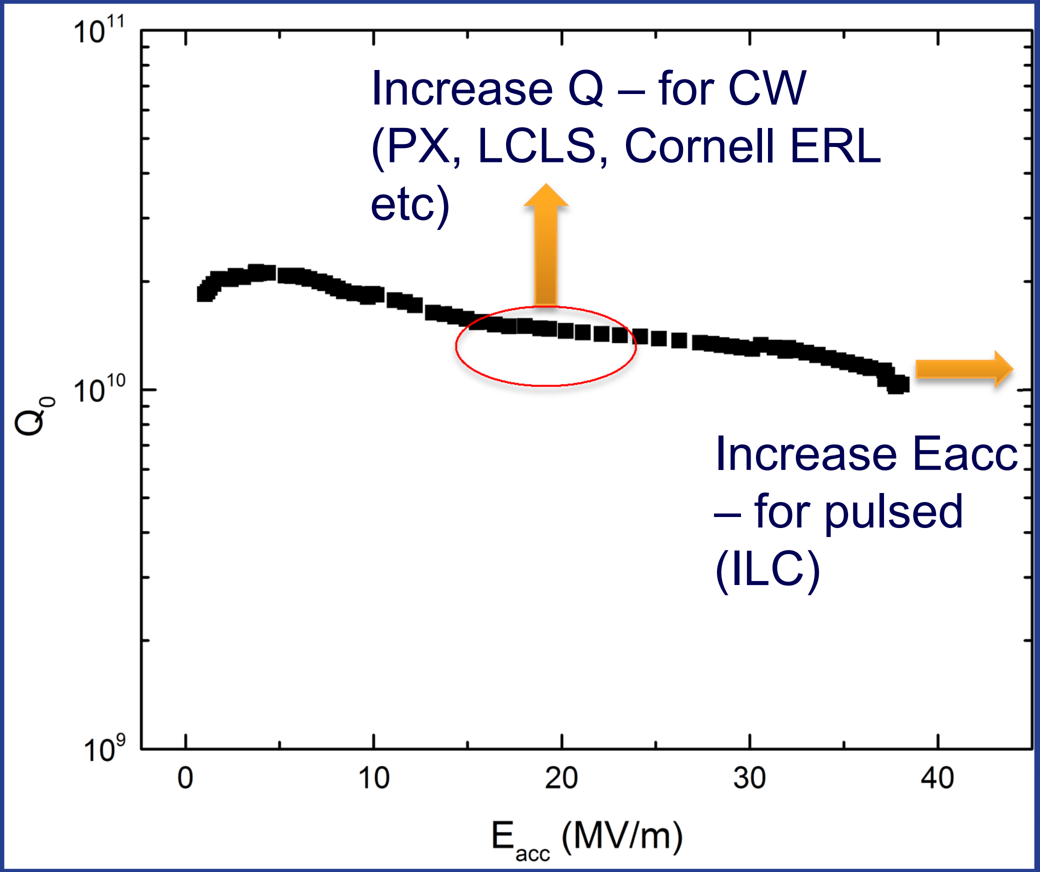
- Low energy nuclear physics, for nuclear shape, spin, vibration... – Heavy ion linacs
- Medium energy nuclear physics, structure of nucleus, quark-gluon physics
  - Recirculating linac
- Nuclear astrophysics, for understanding the creation of elements
  - Facility for rare isotope beams (FRIB)
- X-Ray Light Sources for life science, materials science & engineering
  - Storage rings, free electron lasers, energy recovery linacs
- Spallation neutron source for materials science and engineering, life science, biotechnology, condensed matter physics, chemistry
  - High intensity proton linac
- Future High Intensity Proton Sources for
  - Nuclear waste transmutation, energy amplifier, power generation from Thorium
- High energy physics for fundamental nature of matter, space-time
  - Electron-positron storage ring colliders, linear collider, proton linacs for neutrinos

Need for higher Q

$$Q_0 = \frac{\omega_0 \mu_0 \int_V |\mathbf{H}|^2 dv}{R_s \int_S |\mathbf{H}|^2 ds}.$$

$$Q_0 = \frac{G}{R_s},$$

$$G = \frac{\omega_0 \mu_0 \int_V |\mathbf{H}|^2 dv}{\int_S |\mathbf{H}|^2 ds}$$



- Increasing Q of cavities – very important for high duty factor accelerators – virtually all planned superconducting machines (e.g. Project X, LCLS-II, ERLs…)
- Capital and operational costs scale with dissipated power ~ 1/Q

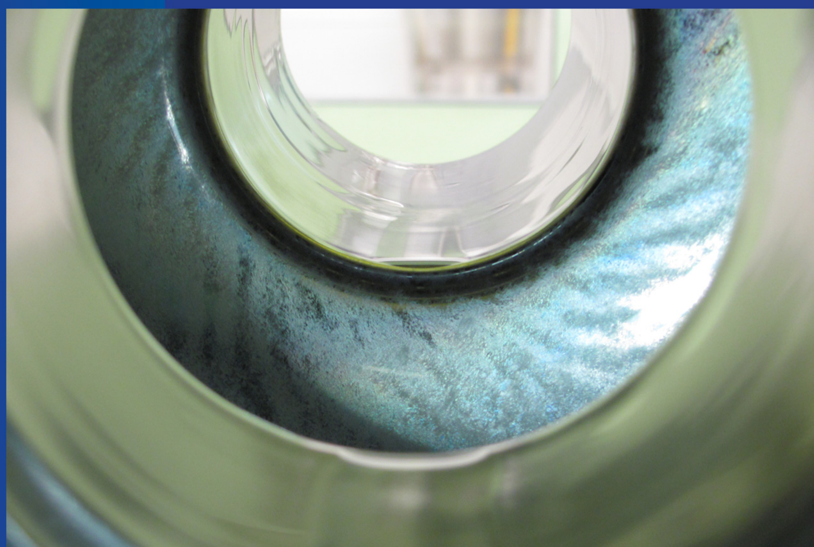
How to approach the problem?

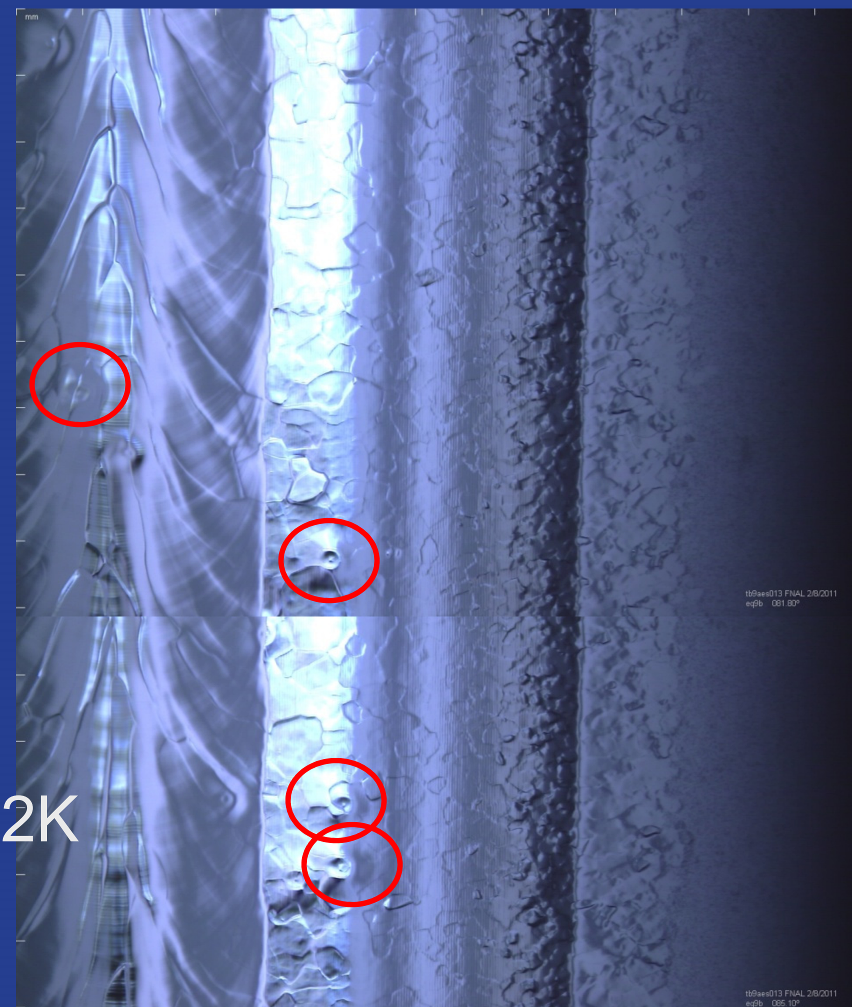
What to look for?

The ‘macroscopic’ does not always matter

Typical surface processing sequence:

100-200 µm EP/BCP + 800°C + light EP/BCP + 120°C

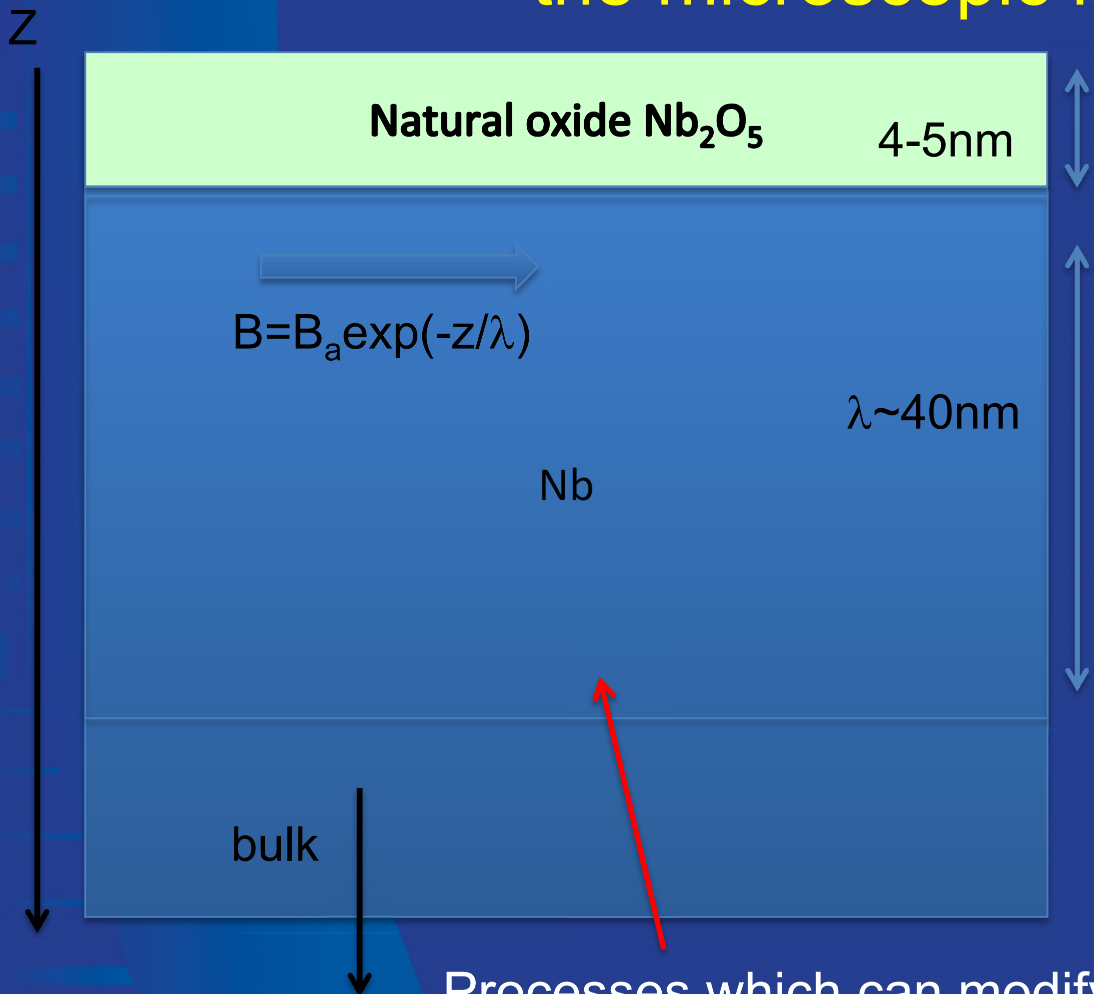




Bad looking surfaces, normal performance:

- Swirl cavity, Q above 2e10 @ 2K
- Pits cavity, 38 MV/m

RF surface resistance of a superconductor: the microscopic is what mostly matters



- Supercurrents flow in the thin London layer to screen the SC bulk from magnetic field
- In DC case currents flow with zero resistance but in RF case- due to the inertia of the Cooper pairs – electric field is present in the London layer causing losses
- Recent studies (Romanenko et al – **Phys. Rev. ST Accel. Beams 16, 012001 (2013)**) show that the first few nanometers strongly affect the Q value!

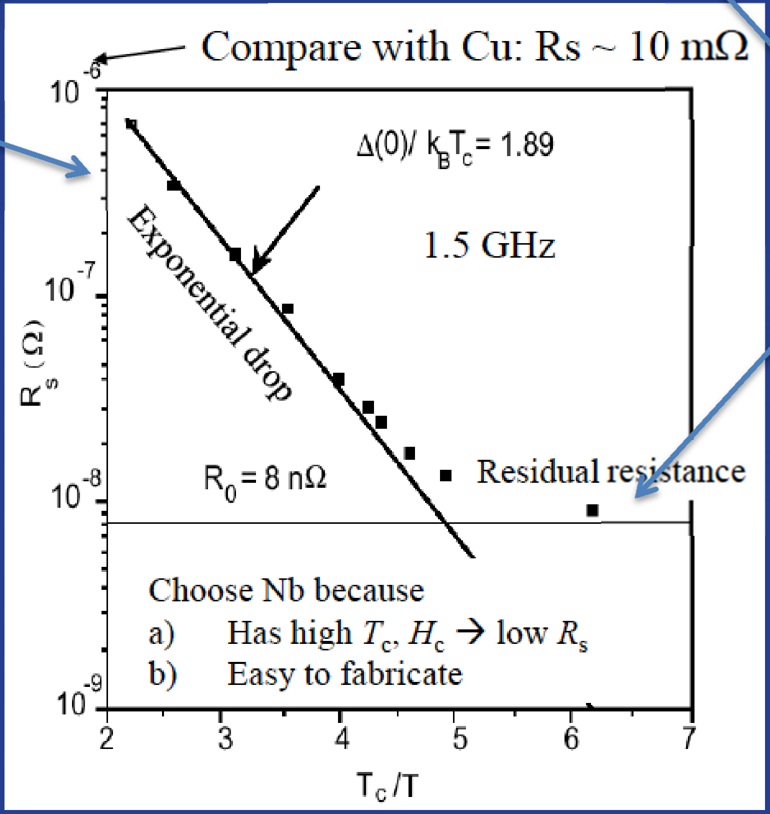
Processes which can modify this layer in a controlled manner are of special interest

Nb microwave surface resistance

$$R_s = R_{BCS}(T) + R_0$$

<u>BCS resistance:</u>
'unpaired' electrons at a finite T:

- Scales as f^2
- Depends on mean free path, gap, critical T, several microscopic parameters (London depth, coherence length)



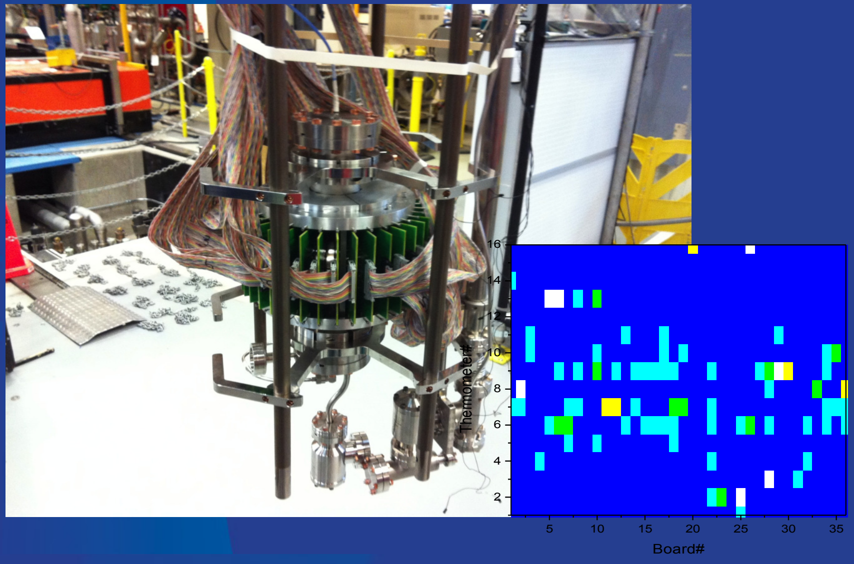
<u>Residual resistance:</u>
T independent component, known and unknown contributions:

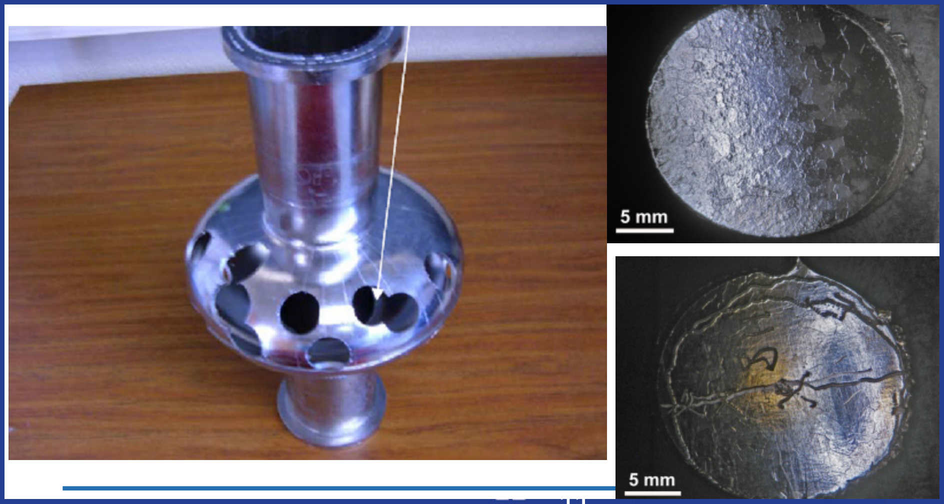
- Scales as sqrt(f)
- Trapped flux
- Hydrides

New insights on understanding of origin and causes of RF losses

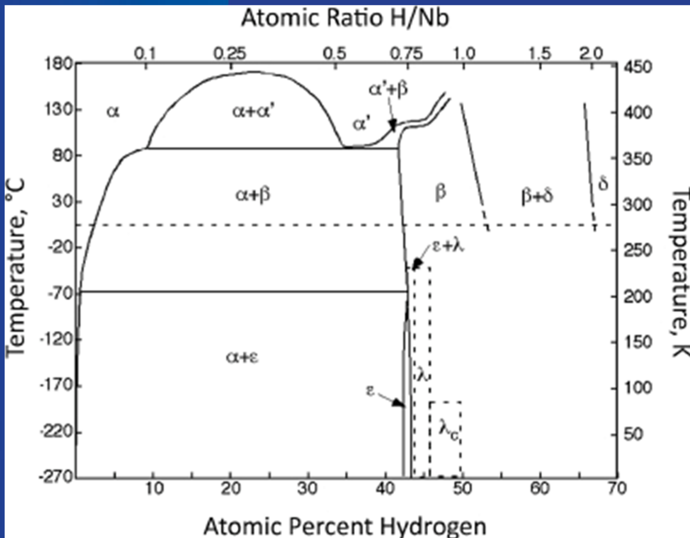
Techniques employed to gain understanding of origin of RF losses

- Experiments on cavities – eg $R_s(B)$ deconvolution as a function of surface treatments, T-mapping…
- Elemental and microstructural investigations: SIMS, XPS, XRD, PAS, ERD, cryogenic laser confocal microscopy…
- Superconducting properties studies: magnetization, muon spin rotation, Bitter decoration, magneto optical imaging, point contact tunneling…

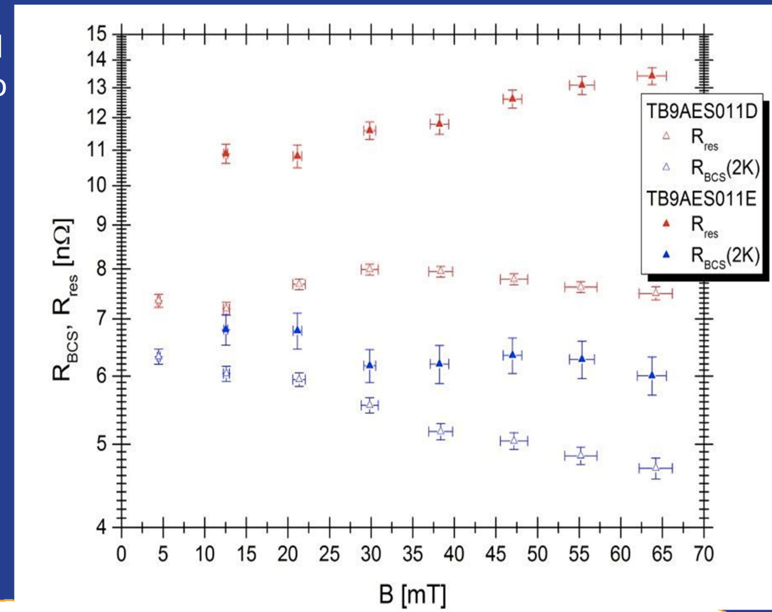




Causes of RF losses: hydrides



M. Checchin and A. Grassellino, to be published



E_{acc} (MV/m)

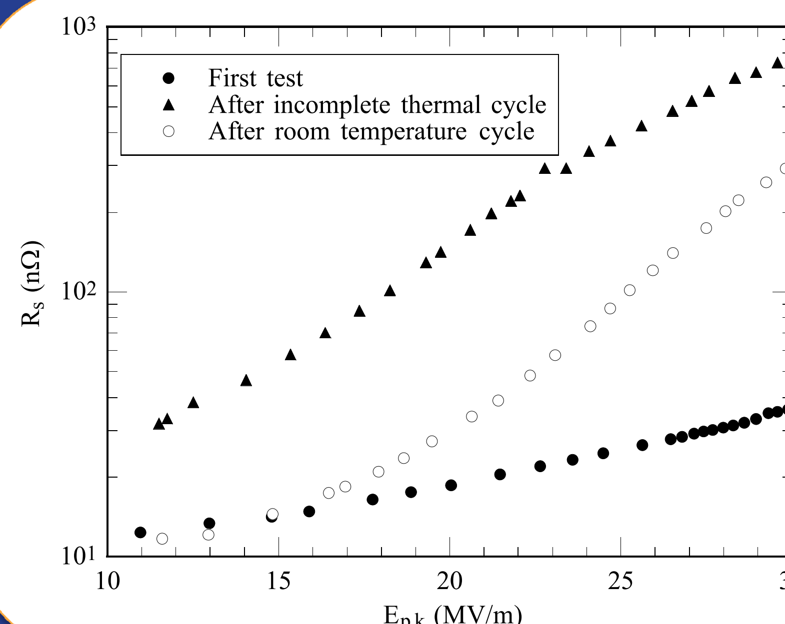
FIGURE 5. Q_0 curves of a cavity, once measured after a fast cooldown and once after a slow cooldown[11].

1980's, reactor-grade material (RRR = 40) had been used. Then there was a strong push to improve the quality of as-delivered niobium and to post-purify cavities during a 1400-°C bakeout combined with solid-state gettering[8, 9, 10]. In that manner RRR values were increased up to 500 and, as predicted, achievable gradients were also improved substantially[2]. However, the use of high-purity niobium also lead to the discovery of a new anomalous loss mechanism—the so-called "*Q* disease."

THE Q DISEASE

Discovery

A significant advantage of a vertical test stand as in Figure 2 lies in the ability to



Knobloch and Padamsee, 8th Workshop on RF Superconductivity, Padova, Italy. SRF 981012-12

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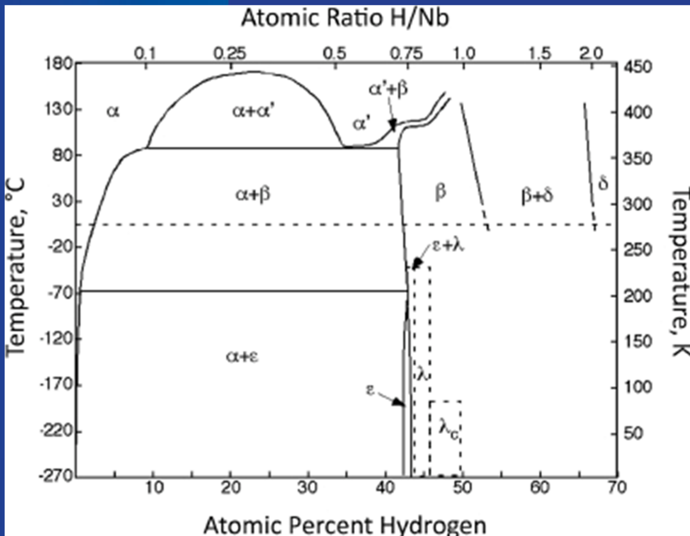

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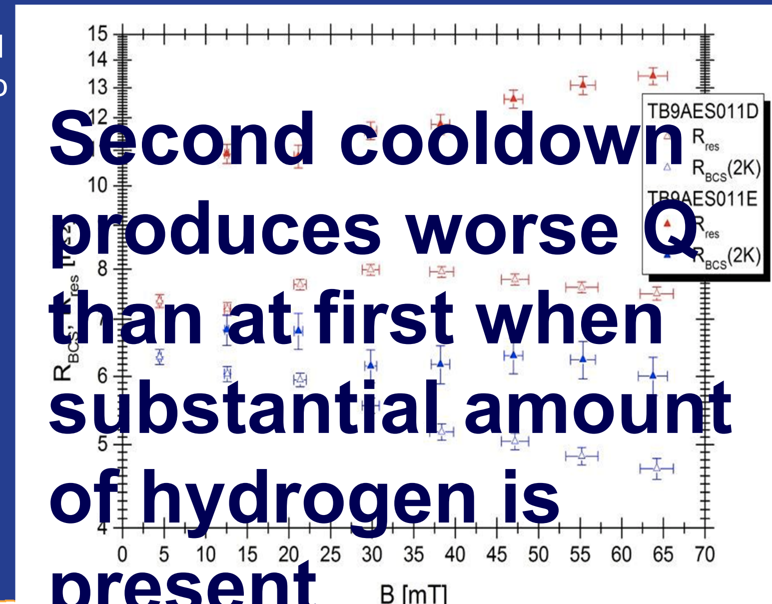

Second cooldown produces worse Q than at first when substantial amount of hydrogen is present

E$_{acc}$ (MV/m)

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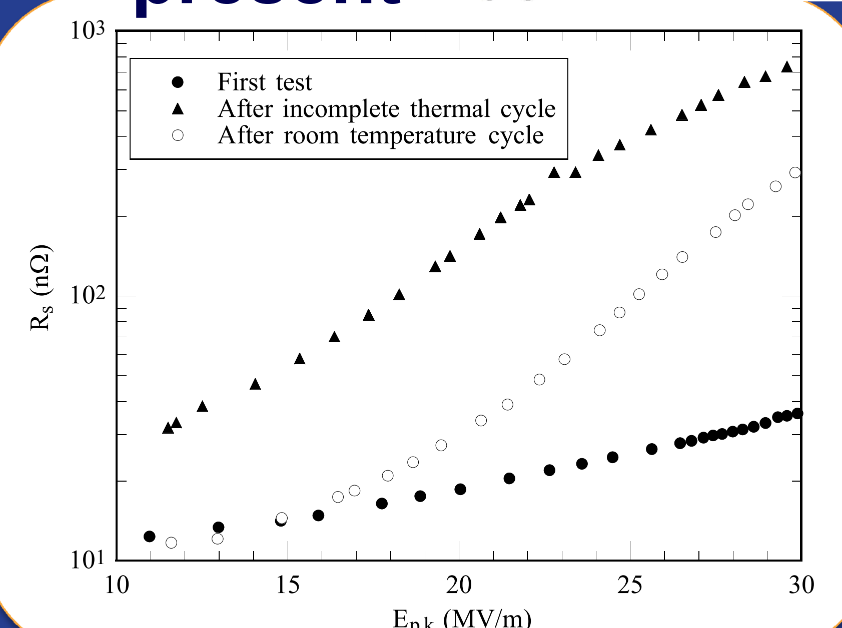

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Cryogenic Laser Confocal Microscopy by A. Romanenko et al: First cooldown

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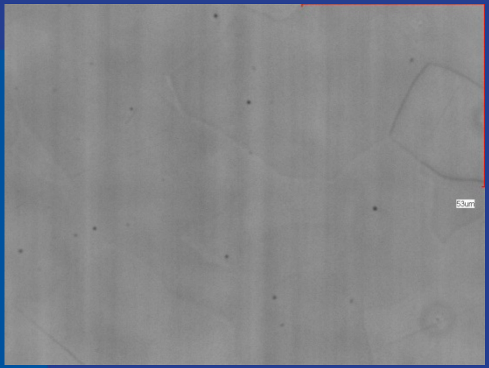

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F. Barkov, A. Romanenko, and A. Grassellino,
Phys. Rev. ST Accel. Beams, 15 122001 (2012)
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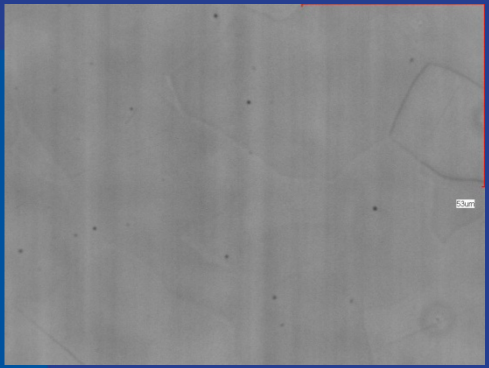

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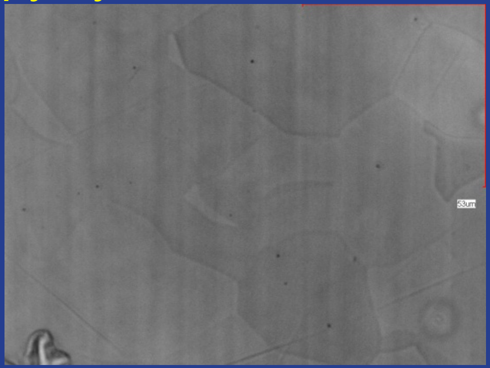

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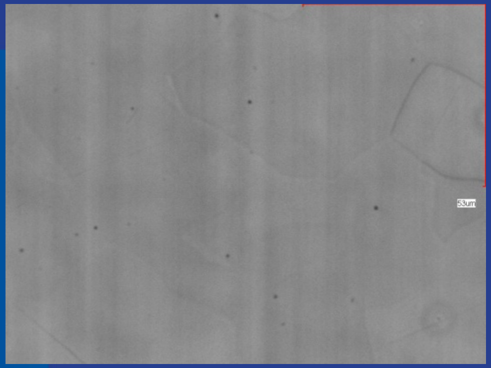

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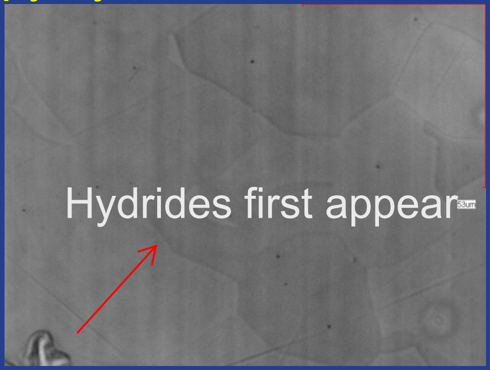

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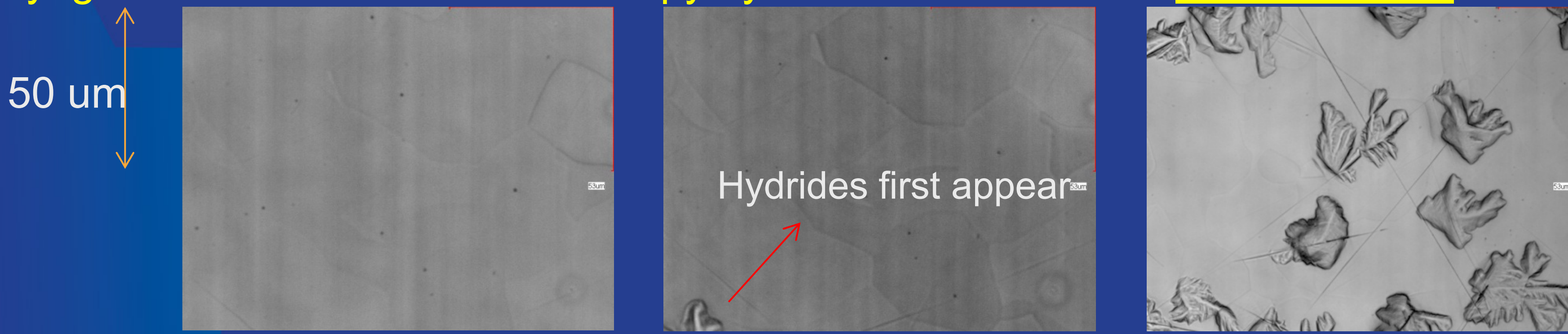

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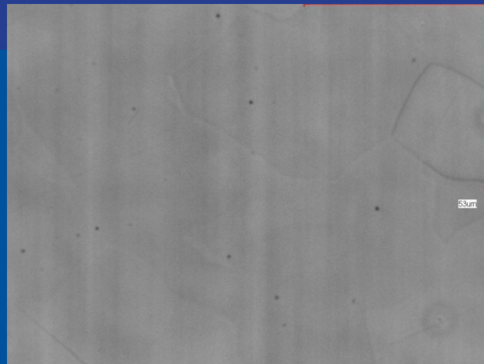

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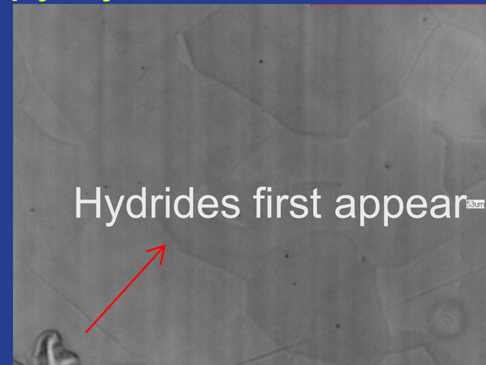

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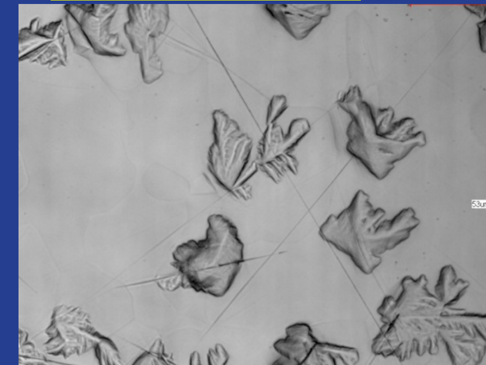

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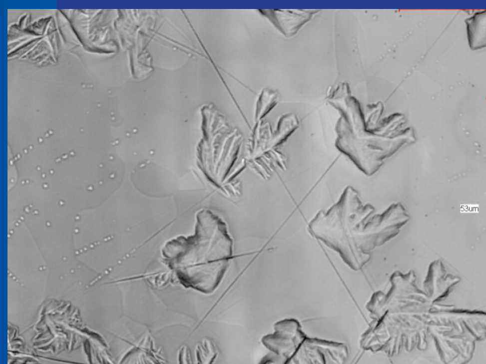

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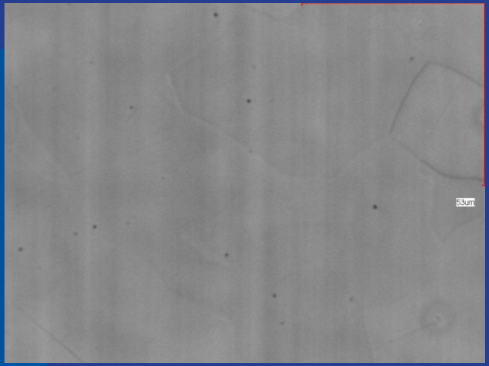

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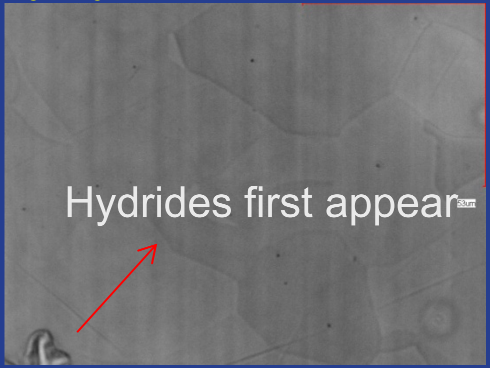

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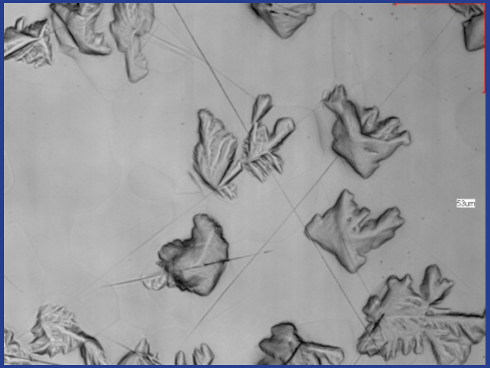

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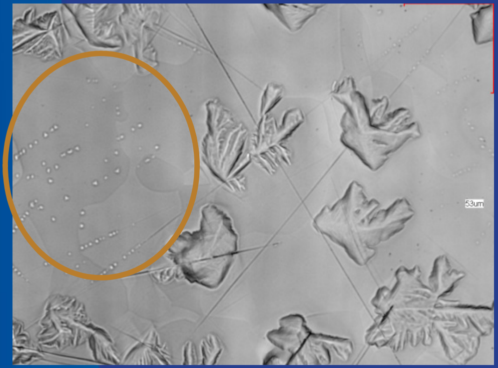
Second (smaller) phase of hydride forms



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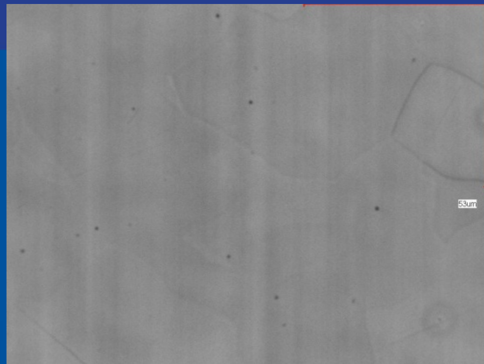

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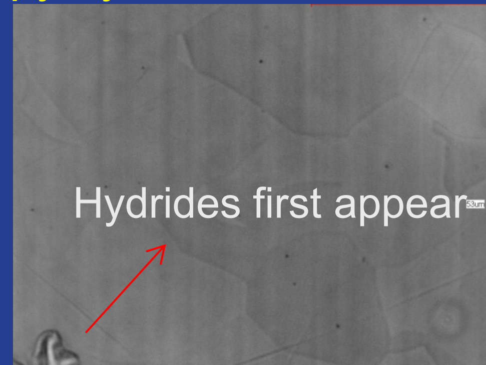

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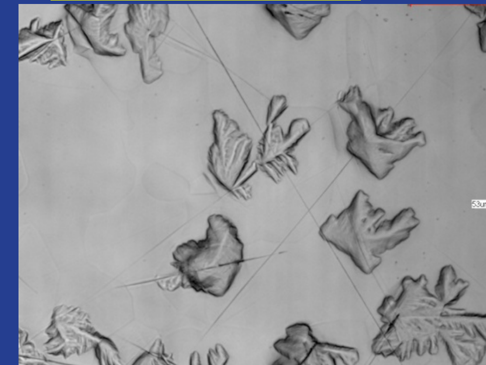

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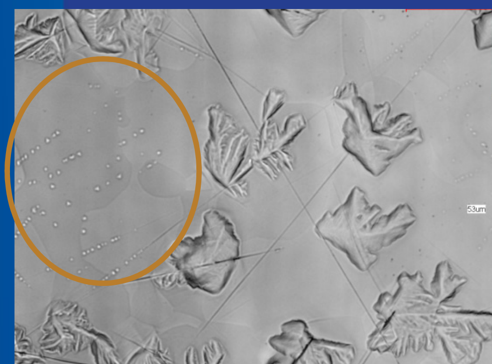

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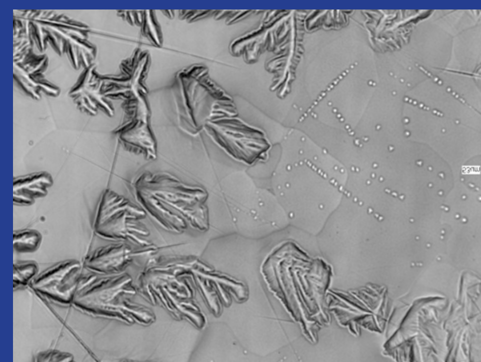

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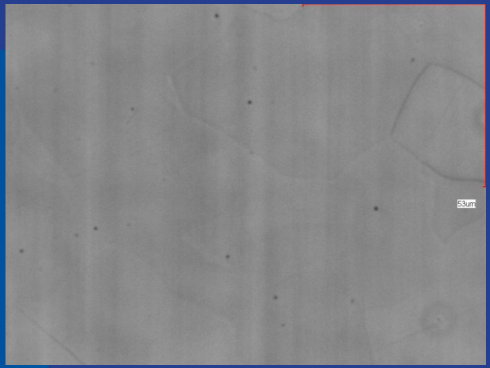

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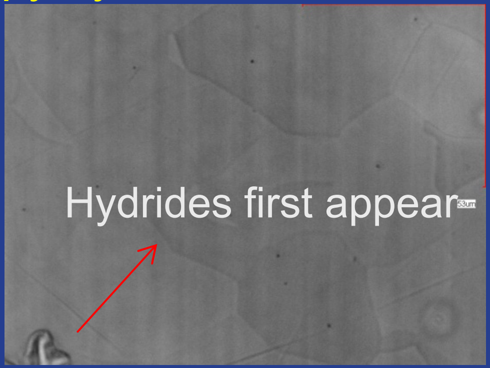

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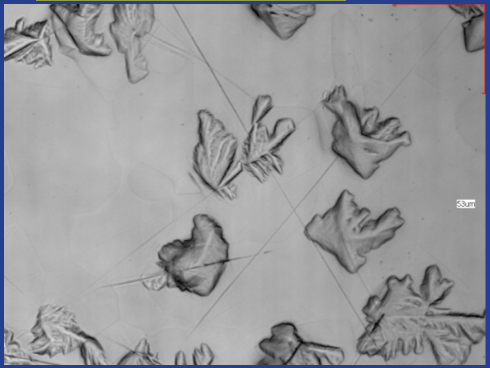

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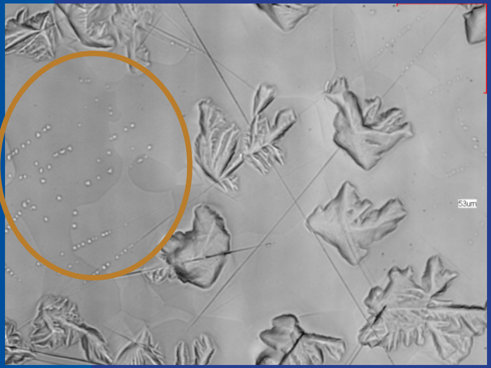

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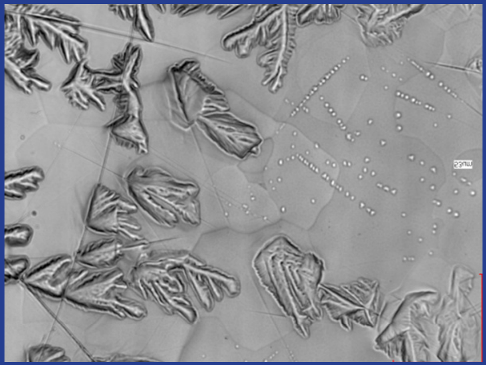

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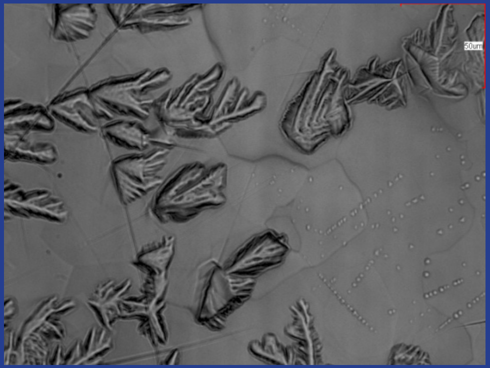

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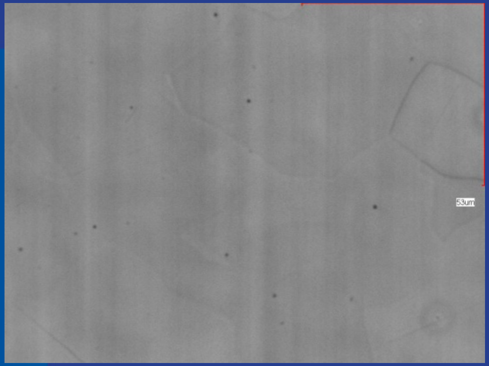

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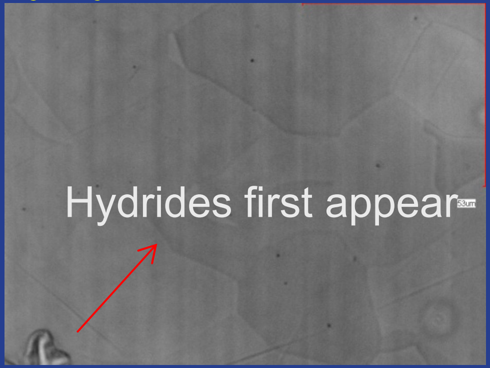

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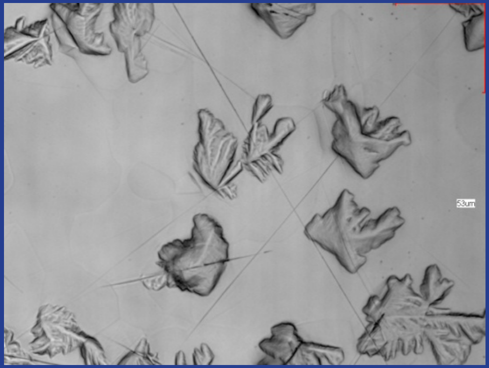

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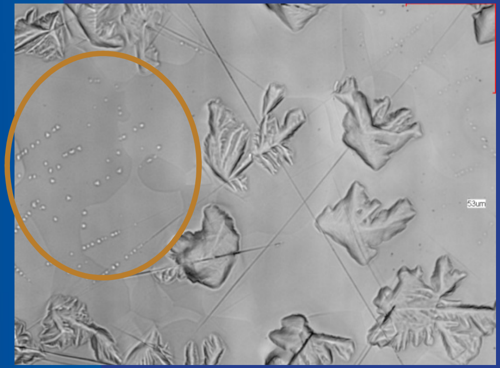

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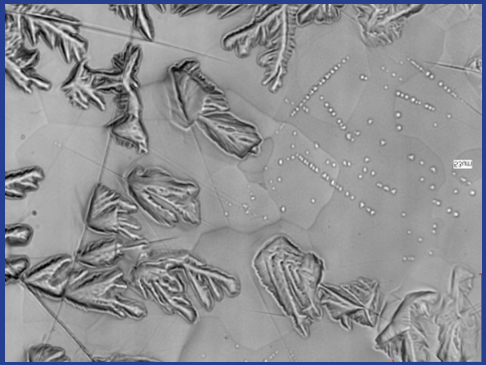

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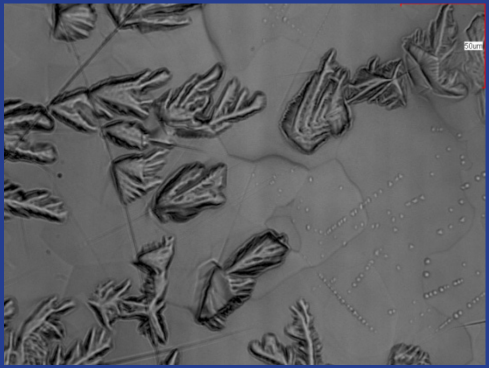

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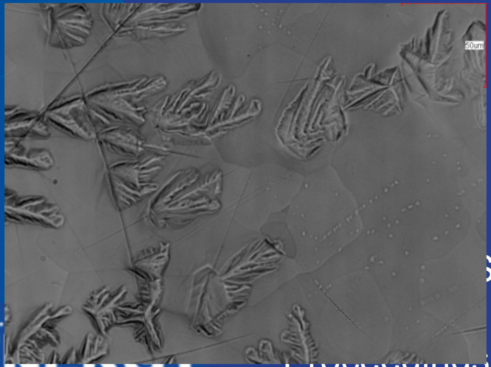

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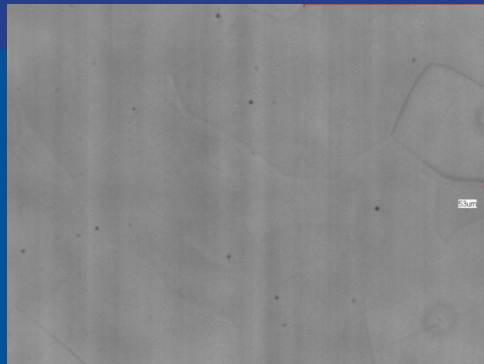

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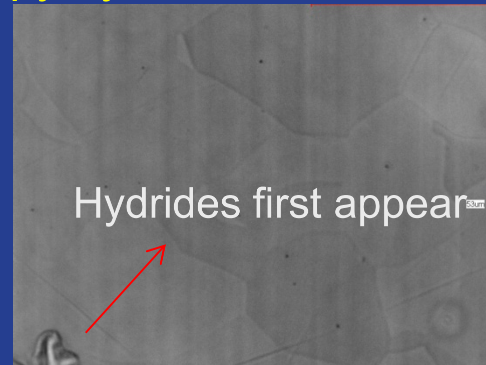

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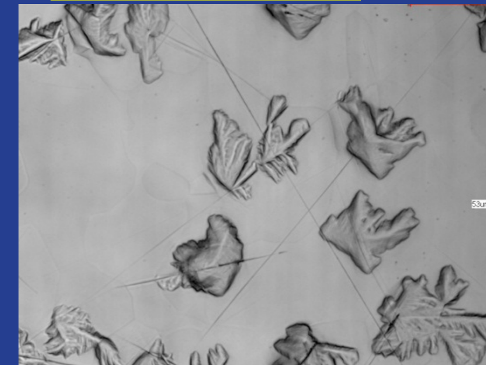

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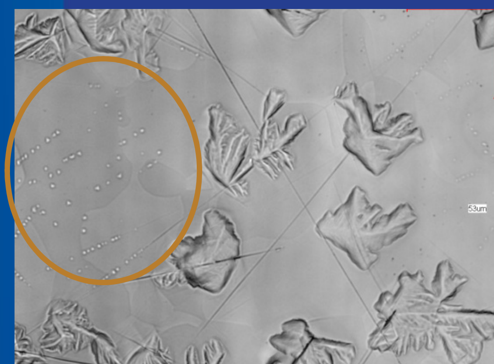
Second (smaller) phase of hydride forms



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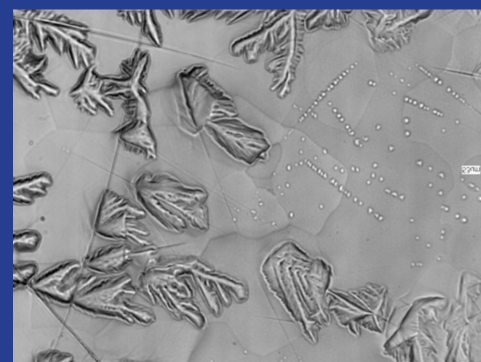

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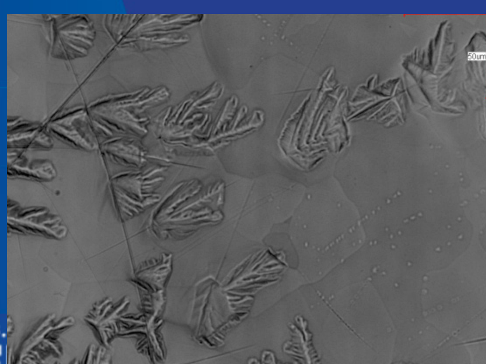
T=180K

Large phase starts to dissolve

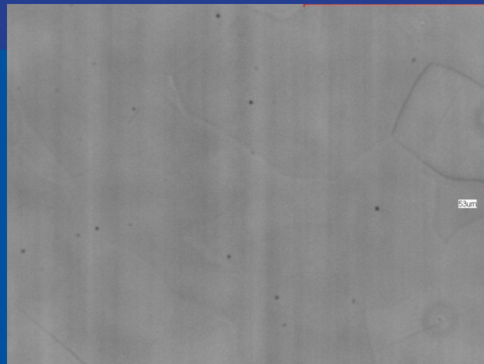


T=210K

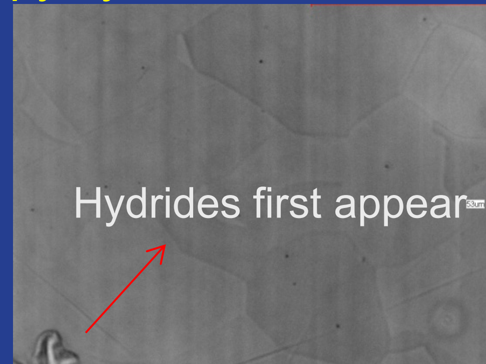
Romanenko, and A. Grassellino,
ST Accel. Beams, 15 122001 (2012)
Romanenko, A. Grassellino,
of SRF'2013, TUP014

Cryogenic Laser Confocal Microscopy by A. Romanenko et al: First cooldown

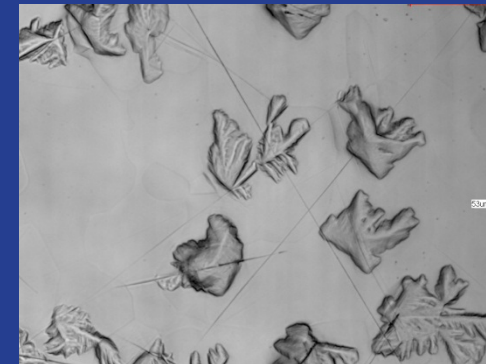
50 um



T=300K

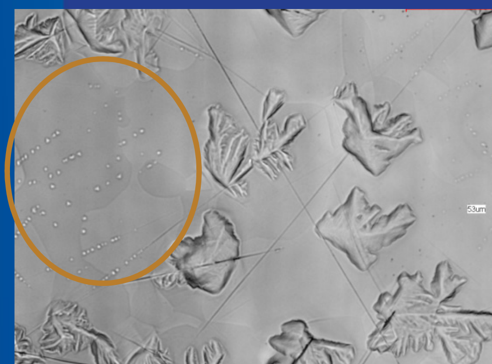


T=160K

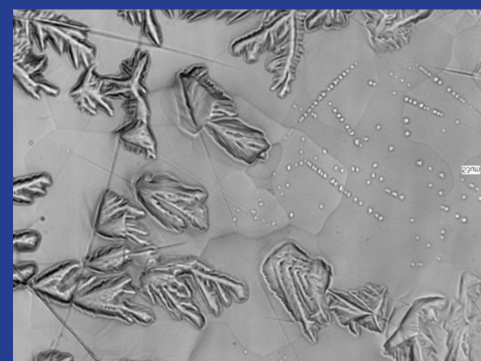


T=140K

Second (smaller) phase of hydride forms



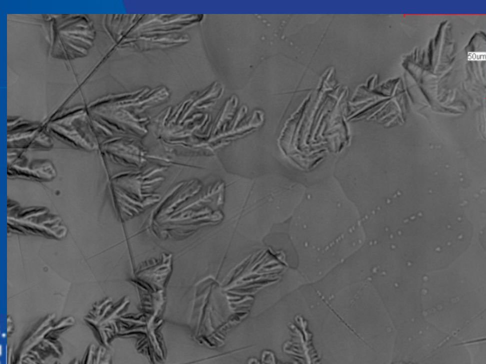
T=100K



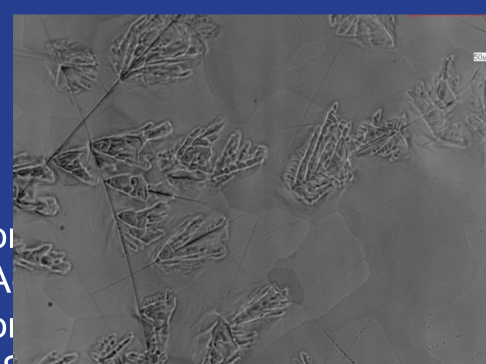
T=6K

T=180K

Large phase starts to dissolve



T=210K

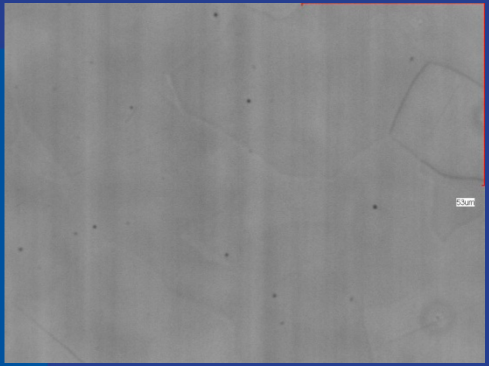


T=260K

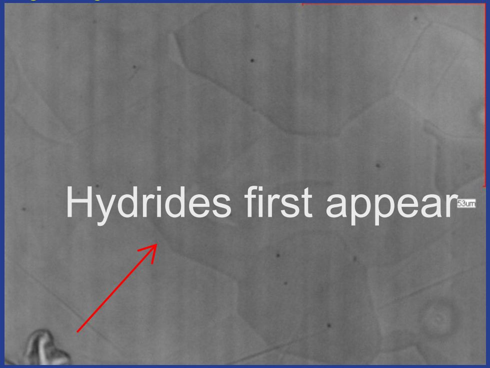
Fermilab

Cryogenic Laser Confocal Microscopy by A. Romanenko et al: <u>First cooldown</u>

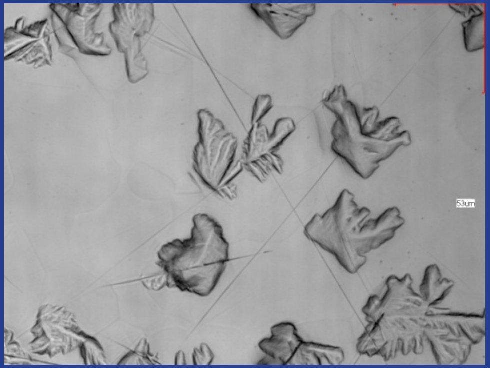
50 um



T=300K

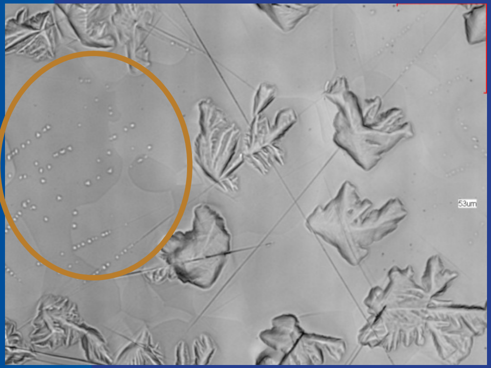


T=160K

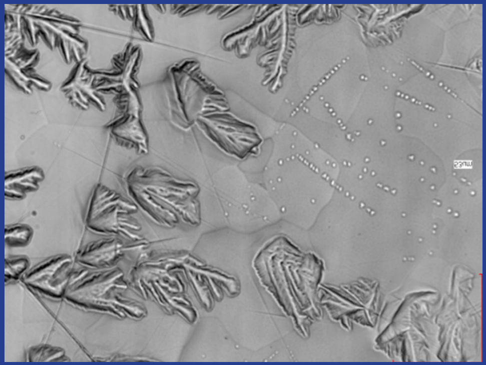


T=140K

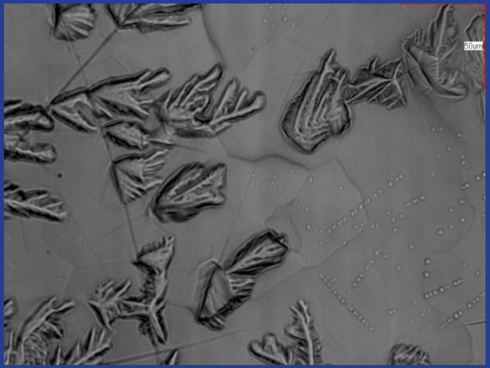
Second (smaller) phase of hydride forms



T=100K

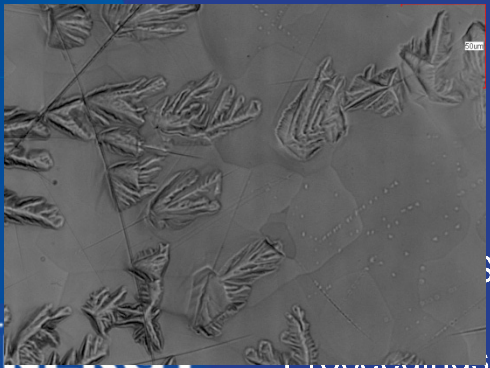


T=6K

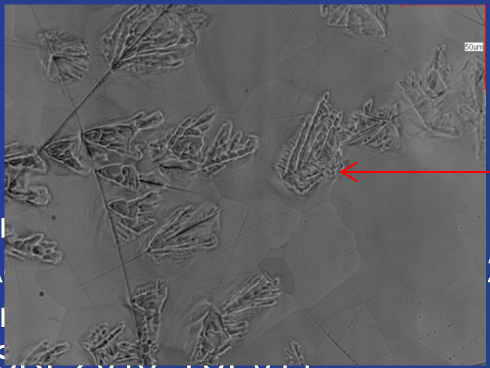


T=180K

Large phase starts to dissolve



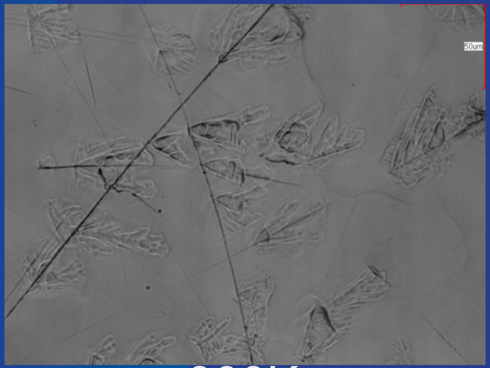
T=210K



T=260K

Hydrides gone, dislocation skeleton (deformation) remains on the surface

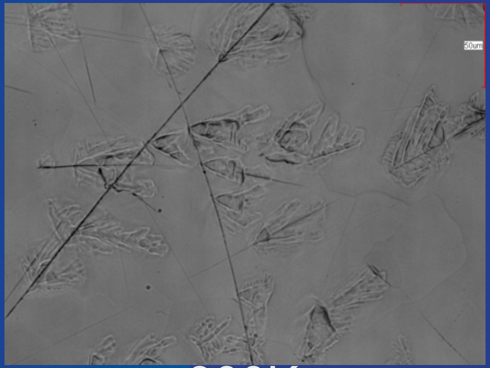
Cryogenic Laser Confocal Microscopy by A. Romanenko et al : <u>Second cooldown</u>



300K

F. Barkov, A. Romanenko, and A. Grassellino,
Phys. Rev. ST Accel. Beams, 15 122001 (2012)
F. Barkov, A. Romanenko, A. Grassellino,
Proceedings of SRF'2013, TUP014

Cryogenic Laser Confocal Microscopy by A. Romanenko et al : Second cooldown



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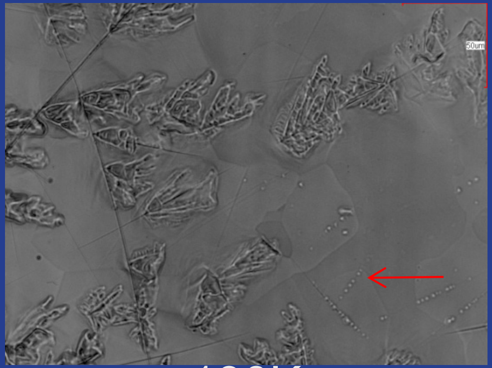

190K

F. Barkov, A. Romanenko, and A. Grassellino,
Phys. Rev. ST Accel. Beams, 15 122001 (2012)
F. Barkov, A. Romanenko, A. Grassellino,
Proceedings of SRF'2013, TUP014

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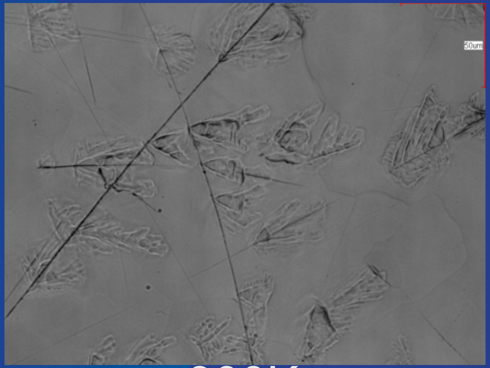
Cryogenic Laser Confocal Microscopy by A. Romanenko et al : Second cooldown



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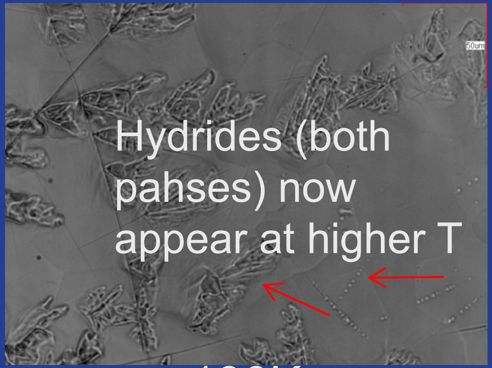

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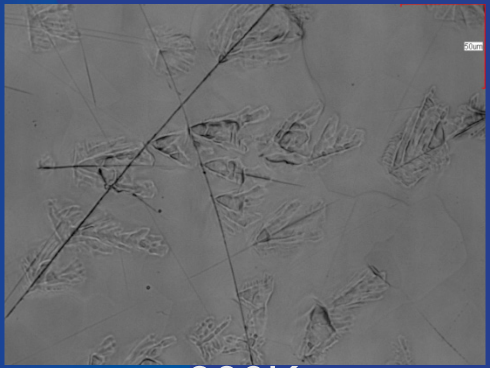
F. Barkov, A. Romanenko, and A. Grassellino, Phys. Rev. ST Accel. Beams, 15 122001 (2012)
F. Barkov, A. Romanenko, A. Grassellino, Proceedings of SRF'2013, TUP014

Cryogenic Laser Confocal Microscopy by A. Romanenko et al : Second cooldown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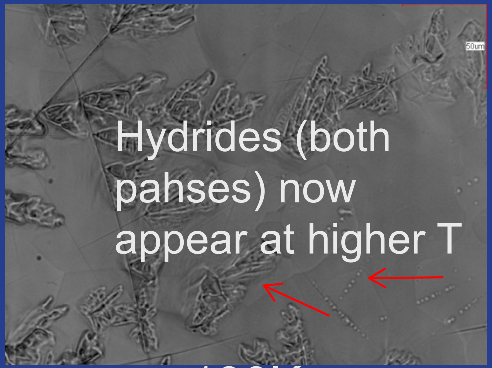

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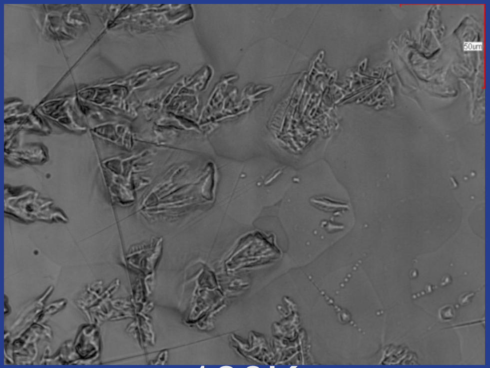
180K

F. Barkov, A. Romanenko, and A. Grassellino, Phys. Rev. ST Accel. Beams, 15 122001 (2012)
F. Barkov, A. Romanenko, A. Grassellino, Proceedings of SRF'2013, TUP014

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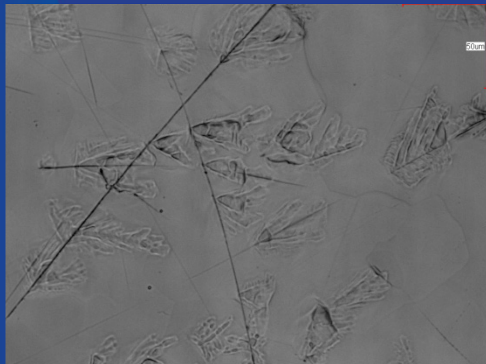
Cryogenic Laser Confocal Microscopy by A. Romanenko et al : <u>Second cooldown</u>



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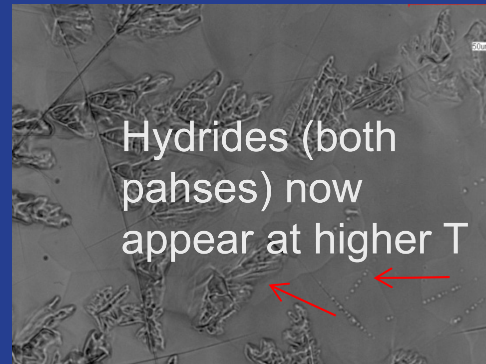

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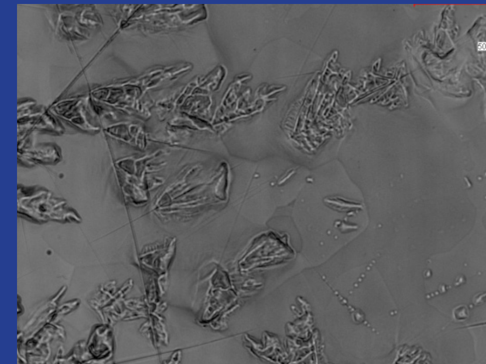

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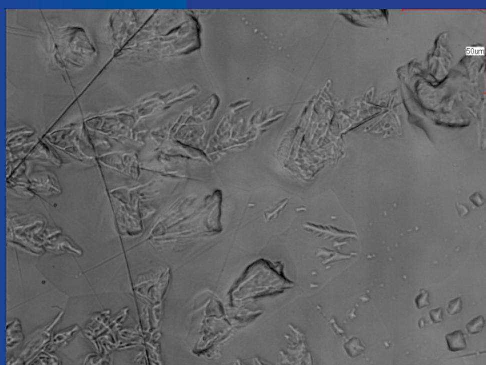
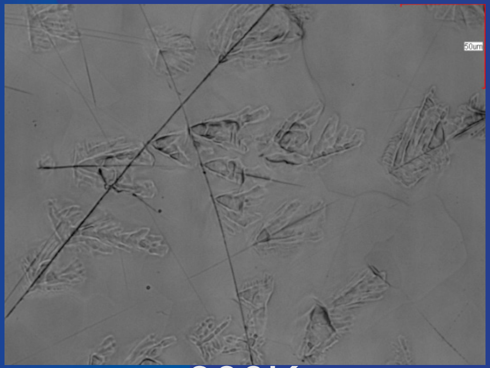


160K

F. Barkov, A. Romanenko, and A. Grassellino, Phys. Rev. ST Accel. Beams, 15 122001 (2012)
F. Barkov, A. Romanenko, A. Grassellino, Proceedings of SRF'2013, TUP014

Cryogenic Laser Confocal Microscopy by A. Romanenko et al : <u>Second cooldown</u>



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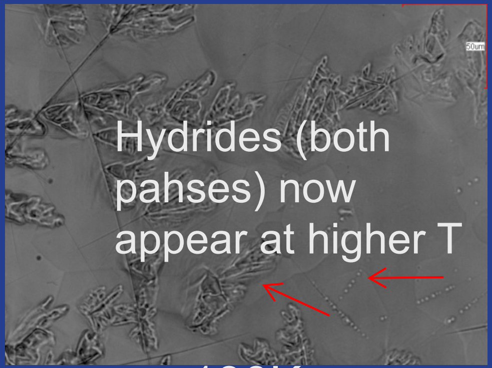

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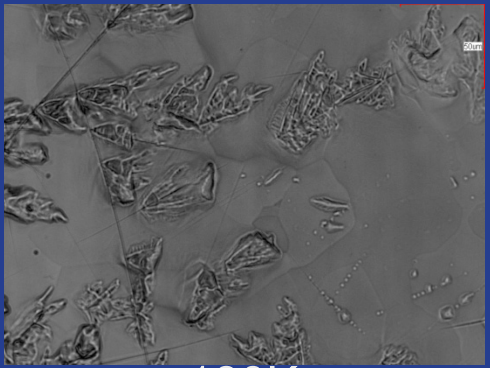

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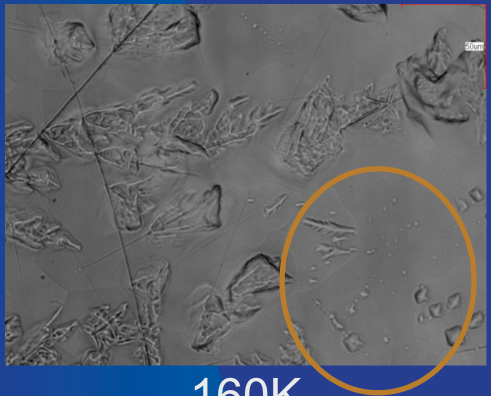

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F. Barkov, A. Romanenko, and A. Grassellino, Phys. Rev. ST Accel. Beams, 15 122001 (2012)
F. Barkov, A. Romanenko, A. Grassellino, Proceedings of SRF'2013, TUP014

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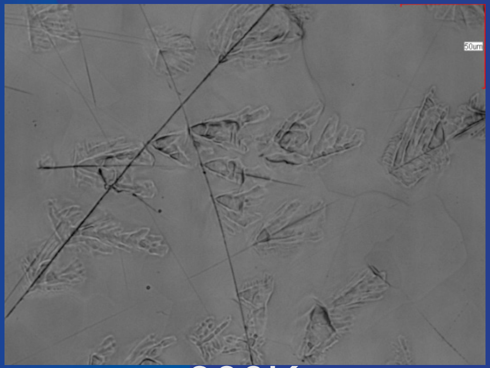
Cryogenic Laser Confocal Microscopy by A. Romanenko et al : <u>Second cooldown</u>



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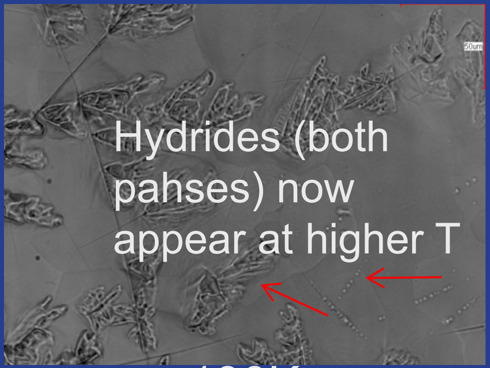

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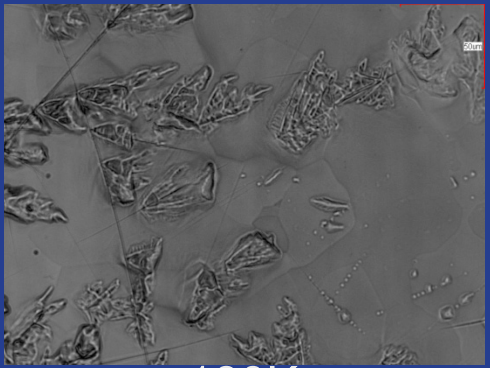

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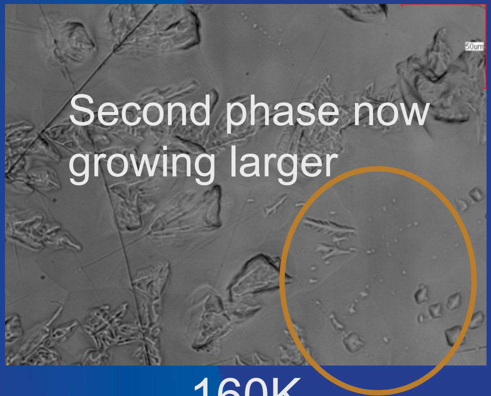

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F. Barkov, A. Romanenko, and A. Grassellino, Phys. Rev. ST Accel. Beams, 15 122001 (2012)
F. Barkov, A. Romanenko, A. Grassellino, Proceedings of SRF'2013, TUP014

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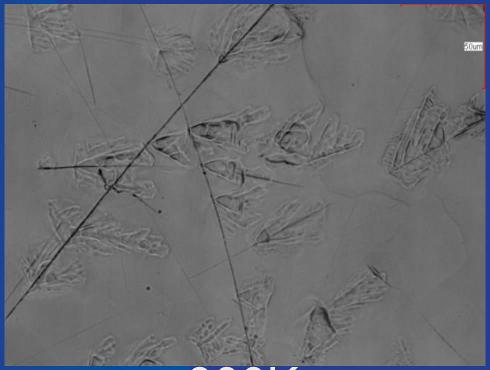
Cryogenic Laser Confocal Microscopy by A. Romanenko et al : <u>Second cooldown</u>



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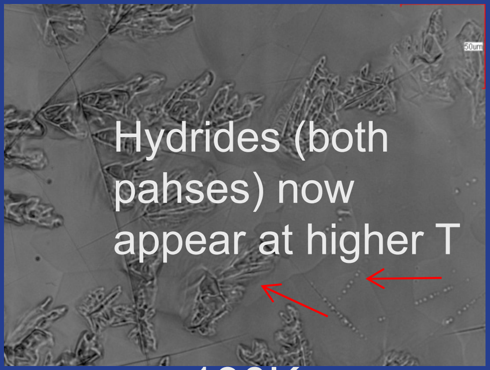

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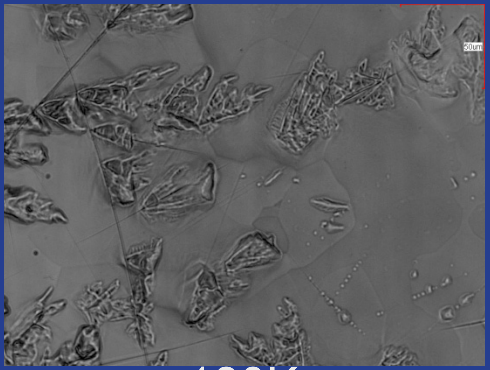

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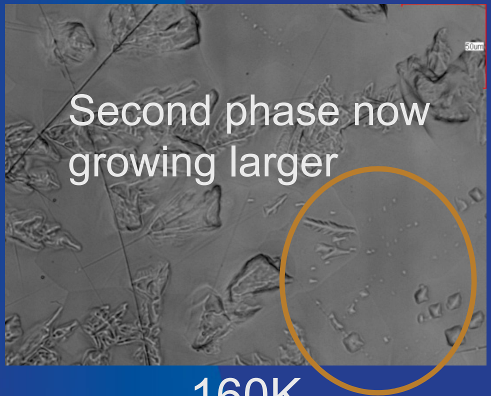

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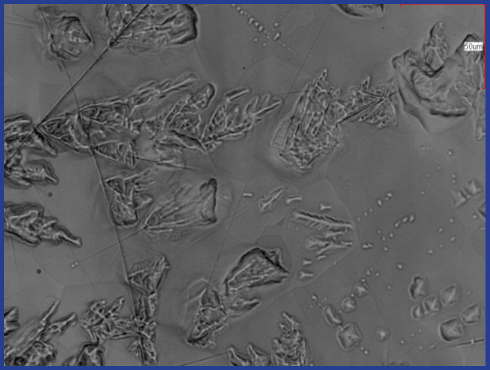

140K

F. Barkov, A. Romanenko, and A. Grassellino, Phys. Rev. ST Accel. Beams, 15 122001 (2012)
F. Barkov, A. Romanenko, A. Grassellino, Proceedings of SRF'2013, TUP014

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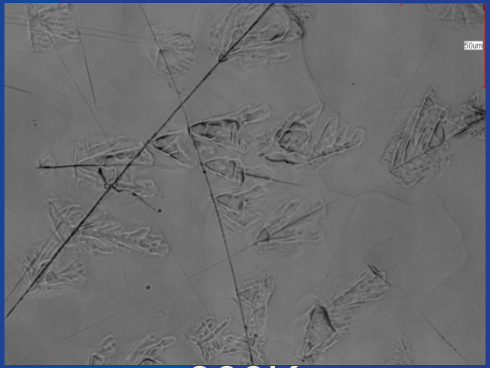
Cryogenic Laser Confocal Microscopy by A. Romanenko et al : <u>Second cooldown</u>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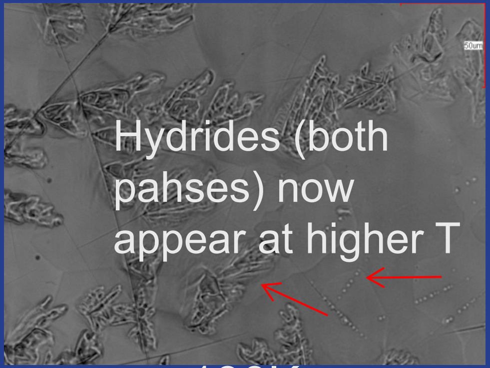

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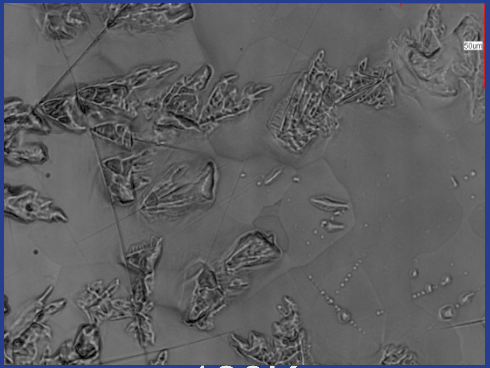
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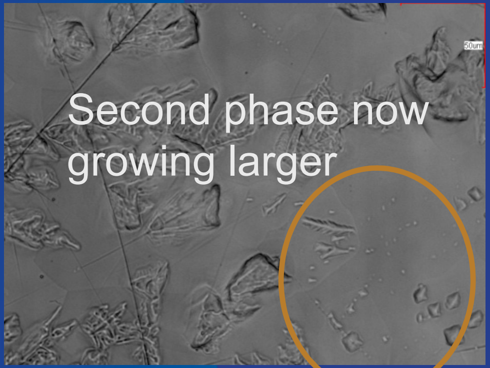

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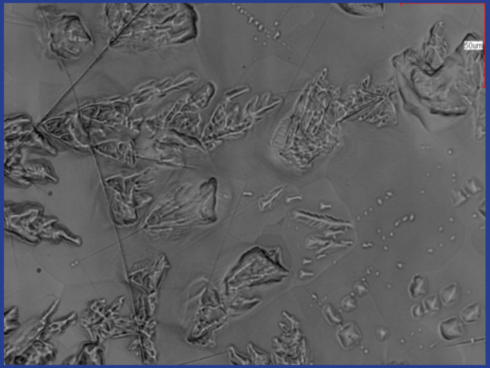
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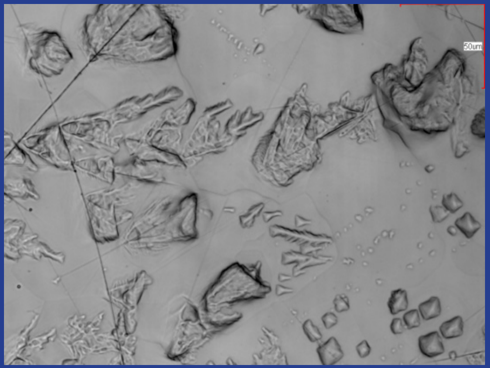
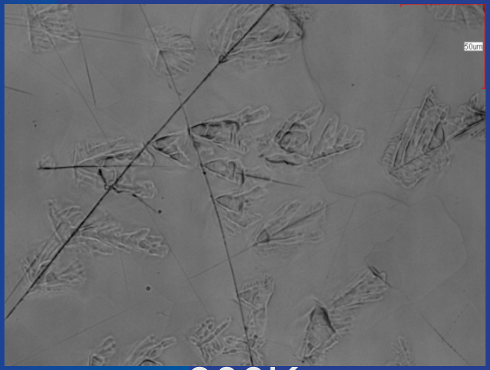

100K

F. Barkov, A. Romanenko, and A. Grassellino, Phys. Rev. ST Accel. Beams, 15 122001 (2012)
F. Barkov, A. Romanenko, A. Grassellino, Proceedings of SRF'2013, TUP014

Cryogenic Laser Confocal Microscopy by A. Romanenko et al : Second cooldown



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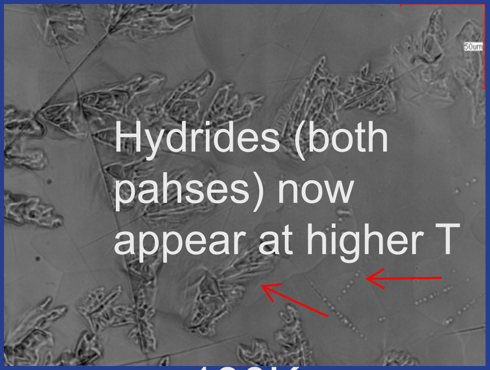

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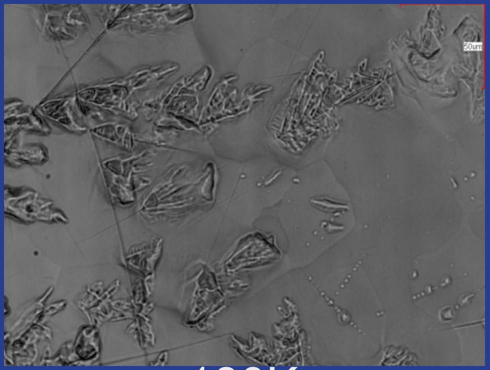

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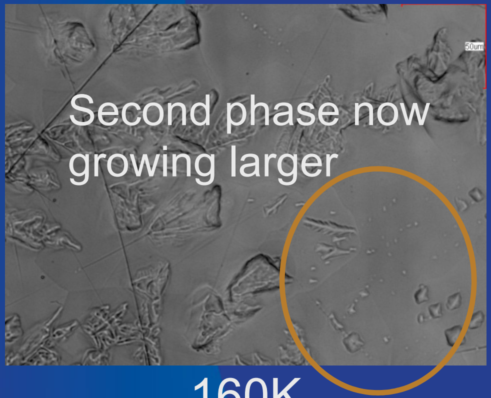

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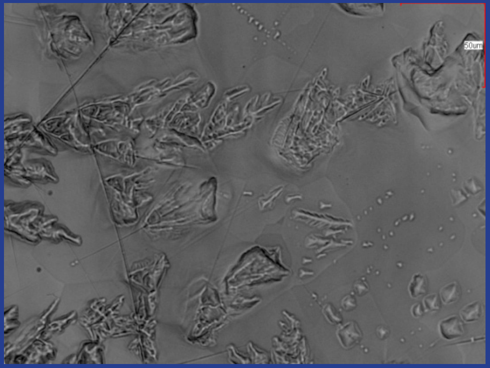

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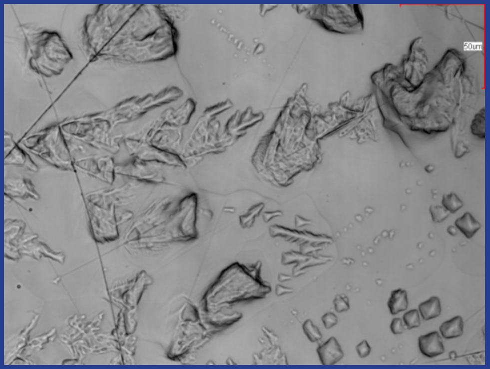

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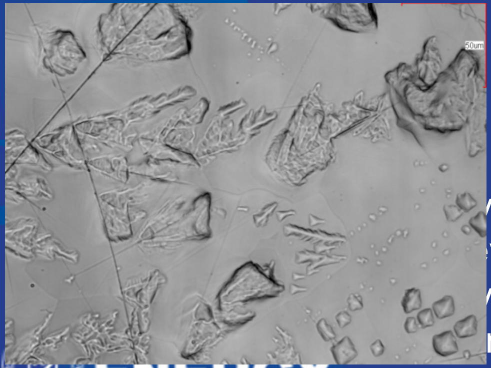
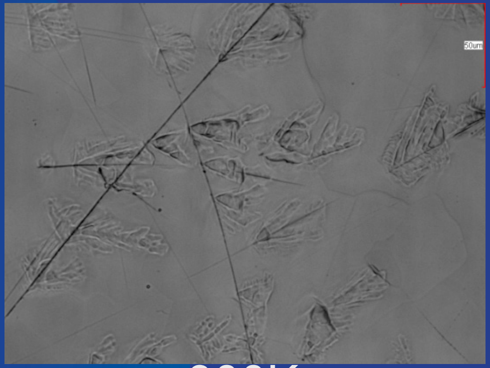


6K

, A. Romanenko, and A. Grassellino,
v. ST Accel. Beams, 15 122001 (2012)
, A. Romanenko, A. Grassellino,
ngs of SRF'2013, TUP014

Cryogenic Laser Confocal Microscopy by A. Romanenko et al : Second cooldown



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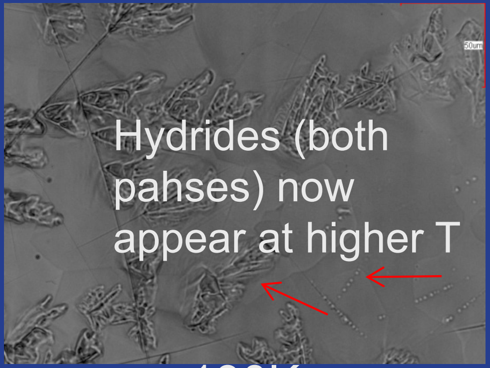

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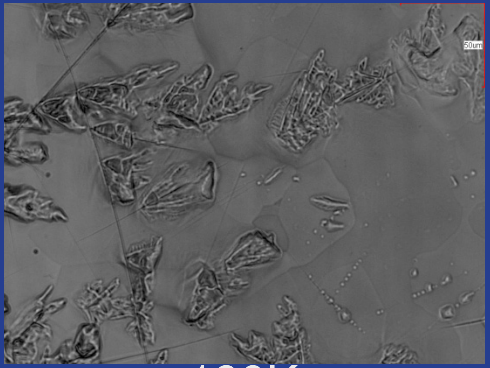

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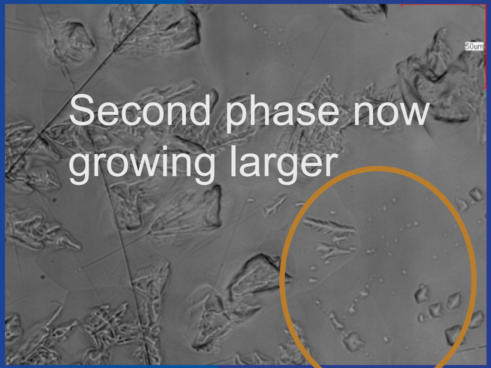

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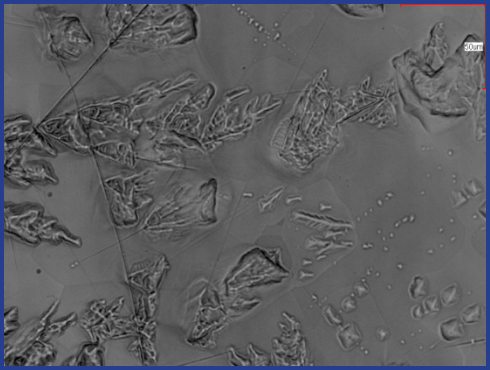

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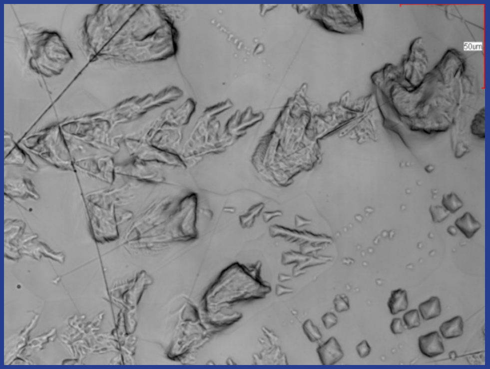

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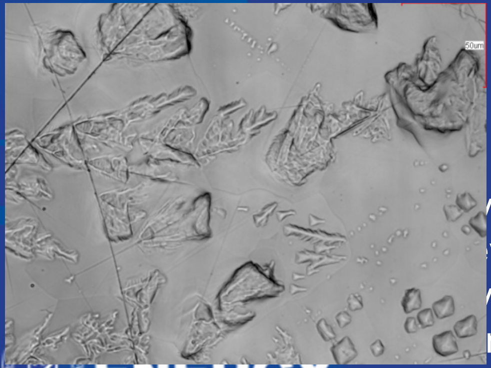

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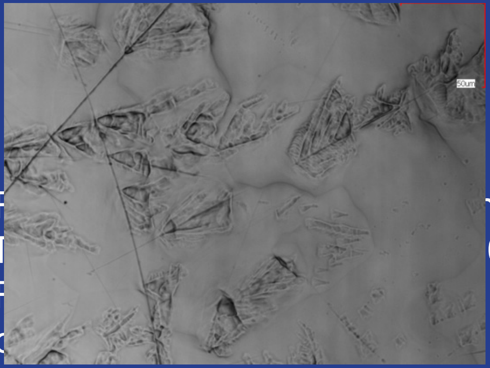

300K

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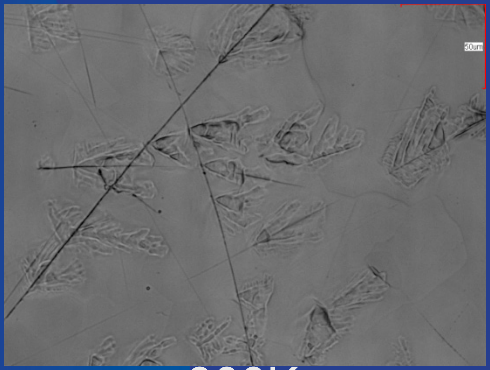
v. ST … 012)
, A. F
ngs c

Cryogenic Laser Confocal Microscopy by A. Romanenko et al : Second cooldown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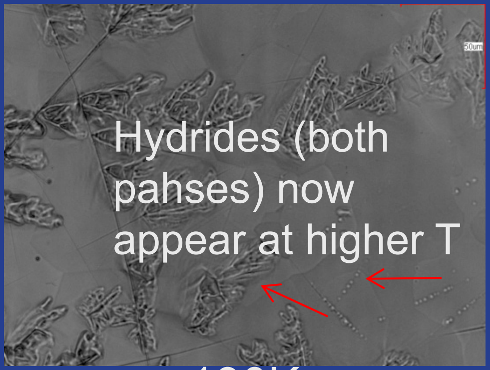

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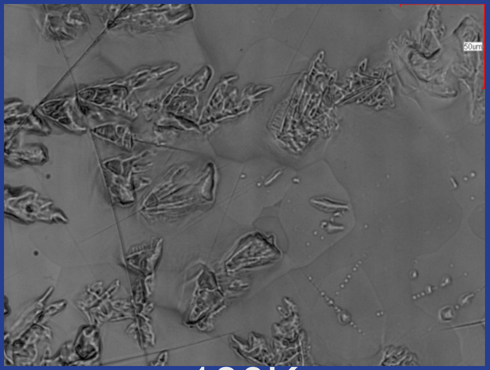
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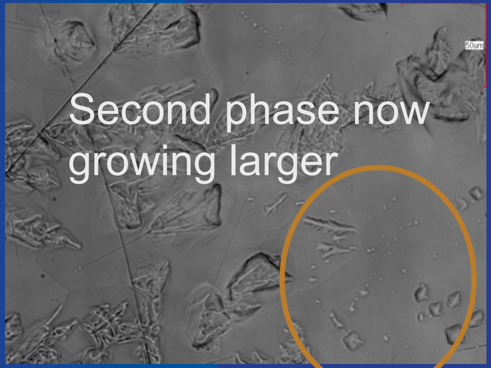

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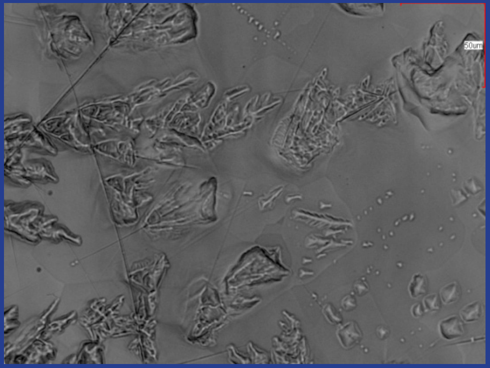
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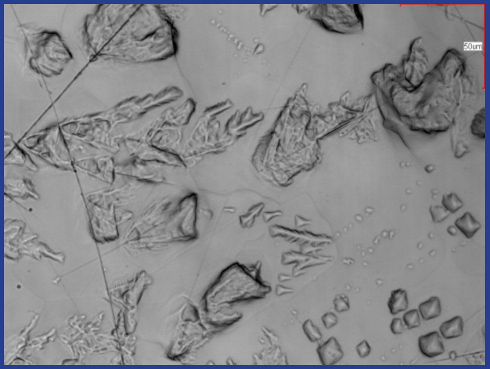
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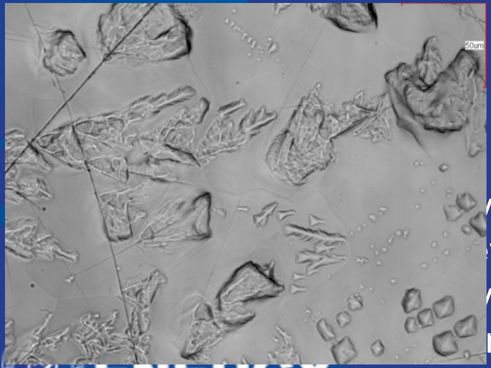
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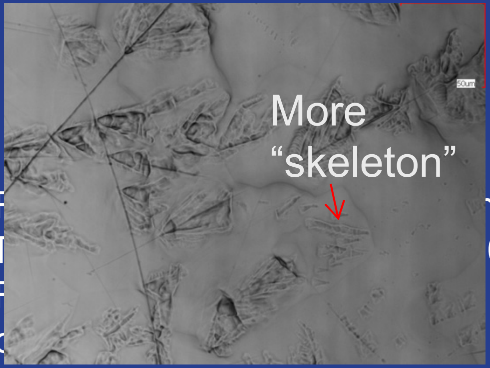

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ENERGY

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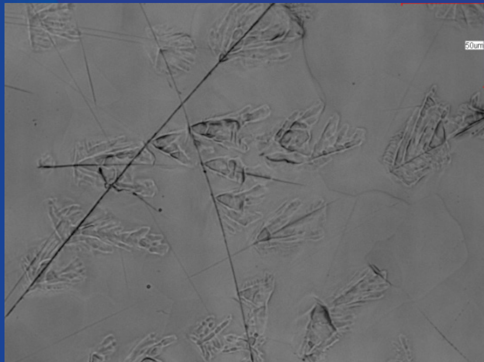
Cryogenic Laser Confocal Microscopy by A. Romanenko et al : <u>Second cooldown</u>



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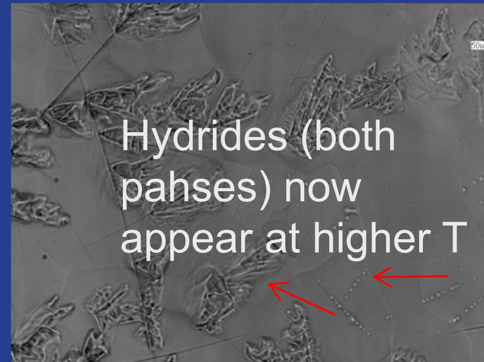

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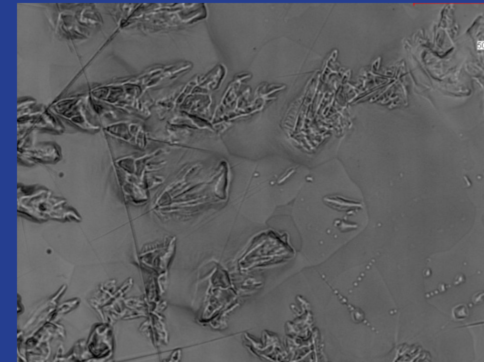

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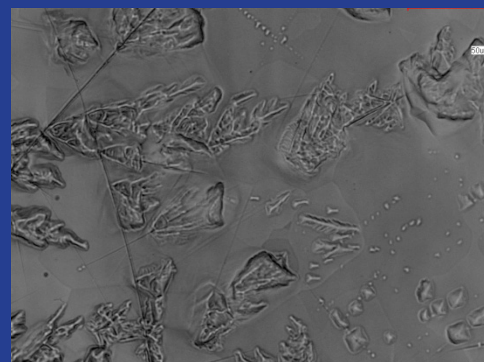

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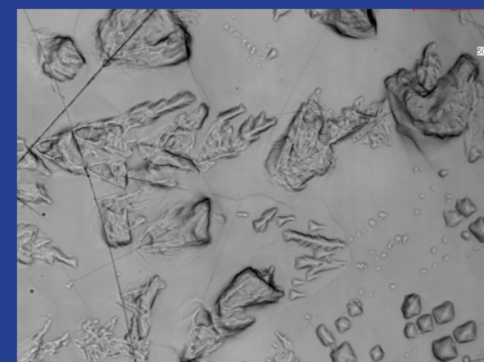

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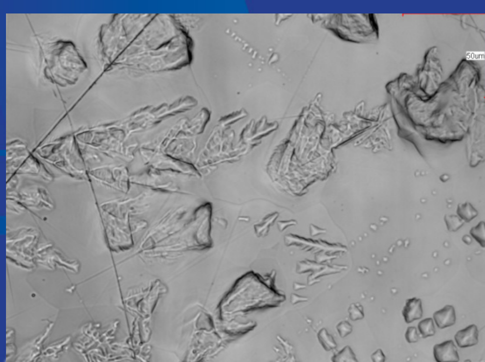

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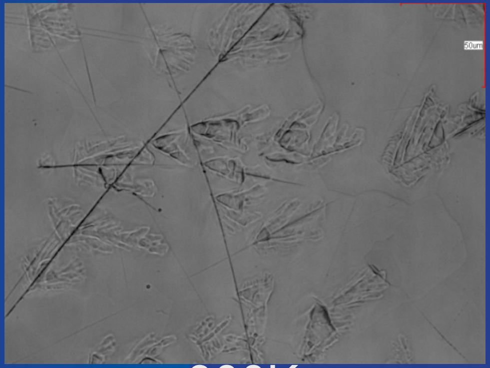
300K

Hydrides form much easier and at a higher temperature at both the “skeleton” left behind in the first cryocycle and at the locations of the second phase => cannot avoid Q-disease

Fermilab

Cryogenic Laser Confocal Microscopy by A. Romanenko et al : Second cooldown



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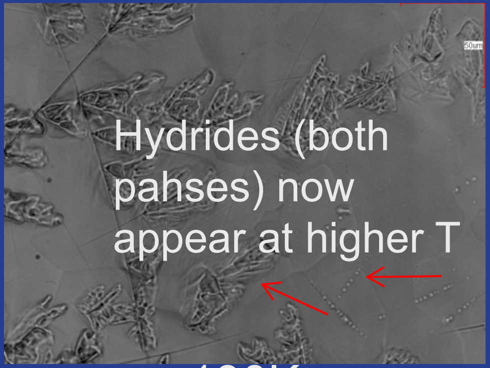

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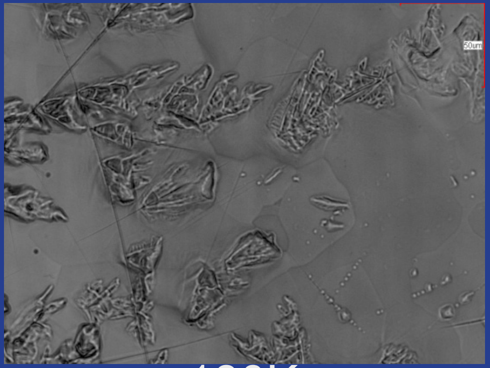

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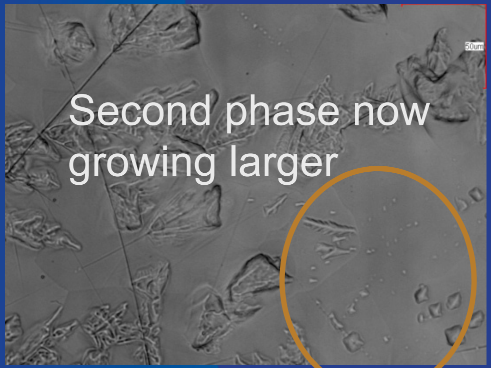

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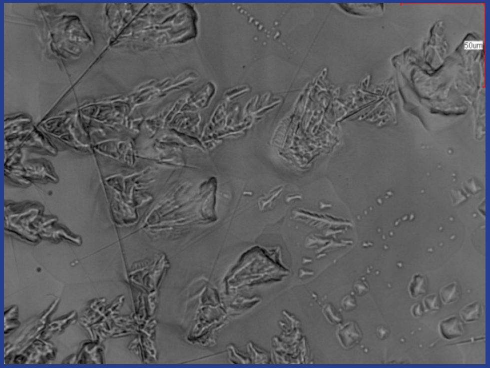

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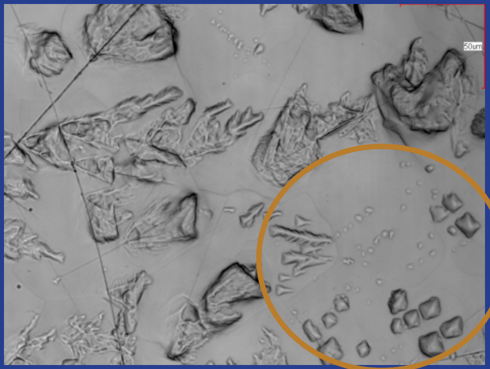

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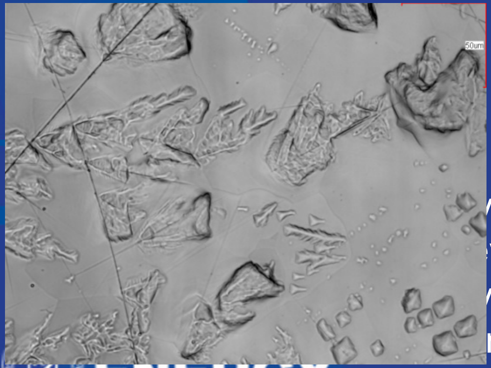

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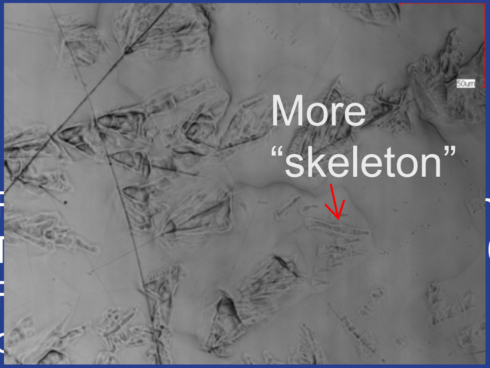

300K

Hydrides form much easier and at a higher temperature at both the “skeleton” left behind in the first cryocycle and at the locations of the second phase => cannot avoid Q-disease

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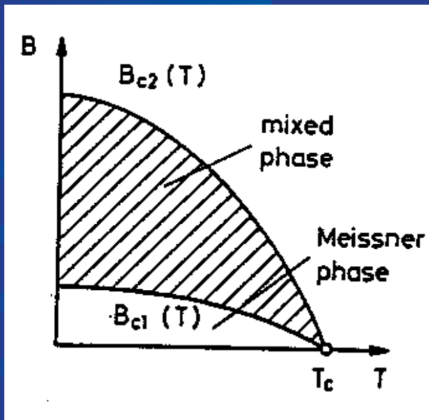
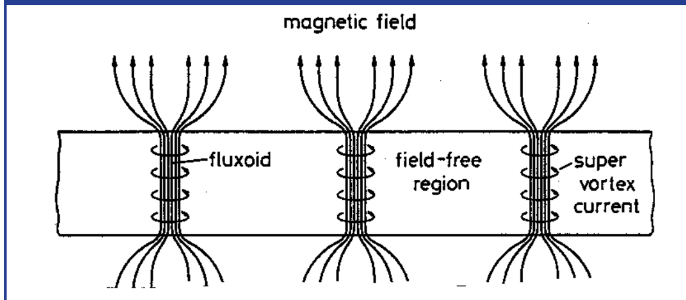
Causes of RF losses: Trapped flux





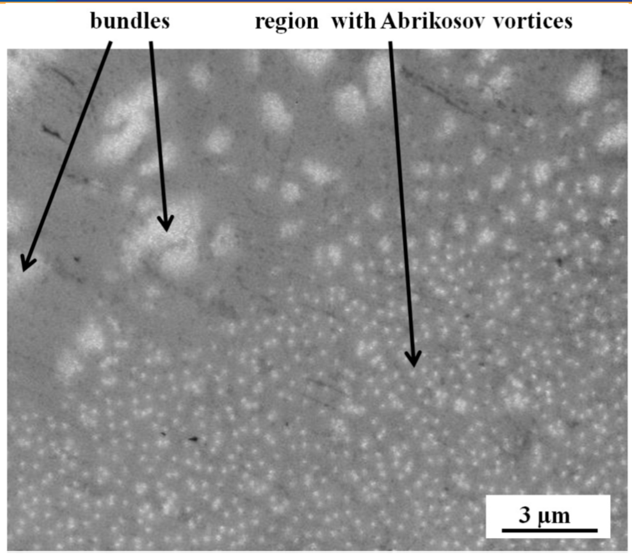


Figure 4: Decoration pattern for a flat sample at the magnetic field 8 mT reveals coexistence of regions with bundles and Abrikosov vortices.

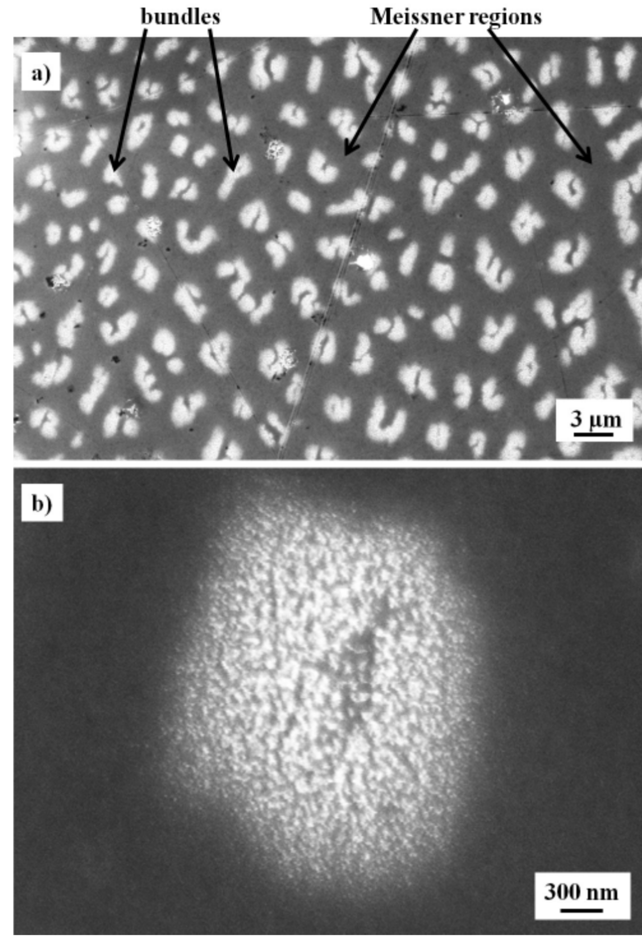


Figure 1: a) Decoration pattern at the magnetic field 10 mT reveals coexistence of "bundles" and Meissner regions. Each bundle carries 80 magnetic flux quanta in average; b) zoom-in of a single bundle.

Origin of RF losses: Field Dependence of Surface Resistance for typical treatments

- Crucial question – how does *medium field Q-slope* emerge from its components R_{BCS} (B) and R_0 (B)?
- Answering allows:
  - Obtain *R_s(B,T) predictions for any standard treatment* (EP, BCP, mild bake, anneal…) to design accelerators -> missing input for optimization
  - *Baseline for comparison* with new, innovative treatments
  - *Fundamental understanding* of “Q-slopes”

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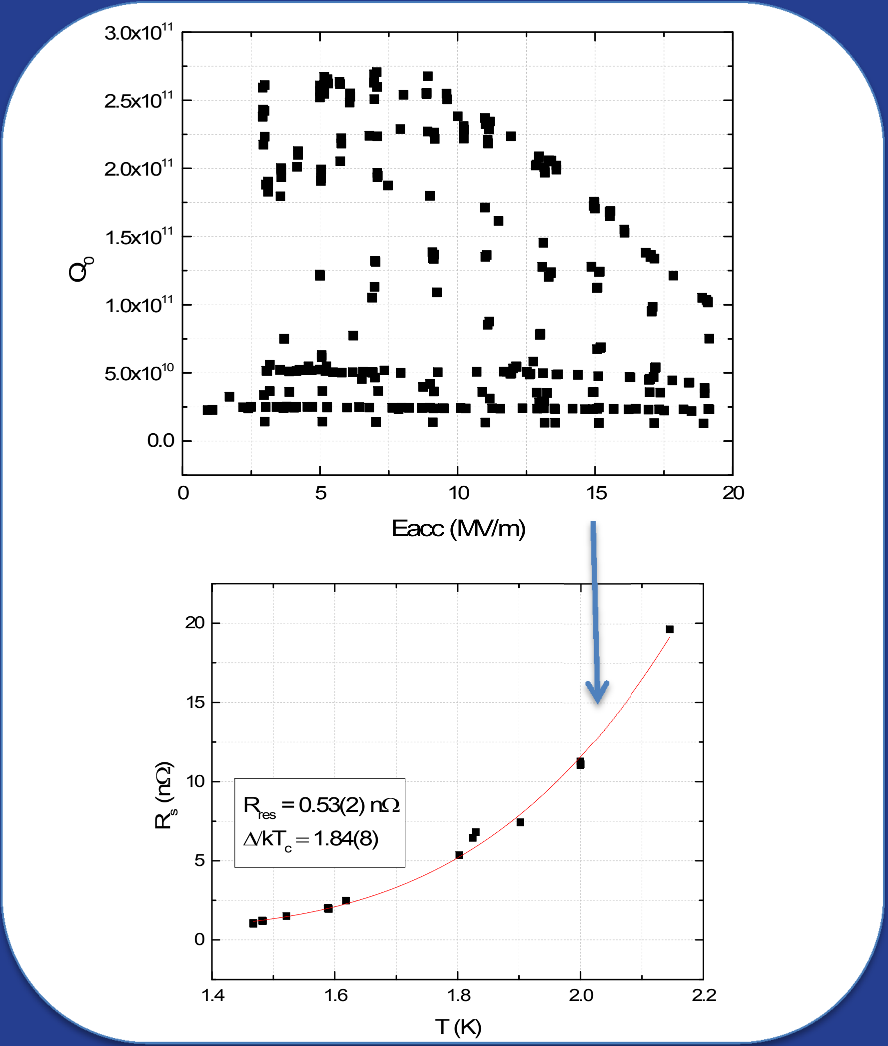
Approach

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

- Obtain as many Q(B,T) measurements as practical at *ALL fields* (not only at a single low field as is customary)

- At each fixed field fit corresponding Q(T) to extract Rres
  - Also gives Rbcs(T) = Rs(T)-Rres



Bath temperature

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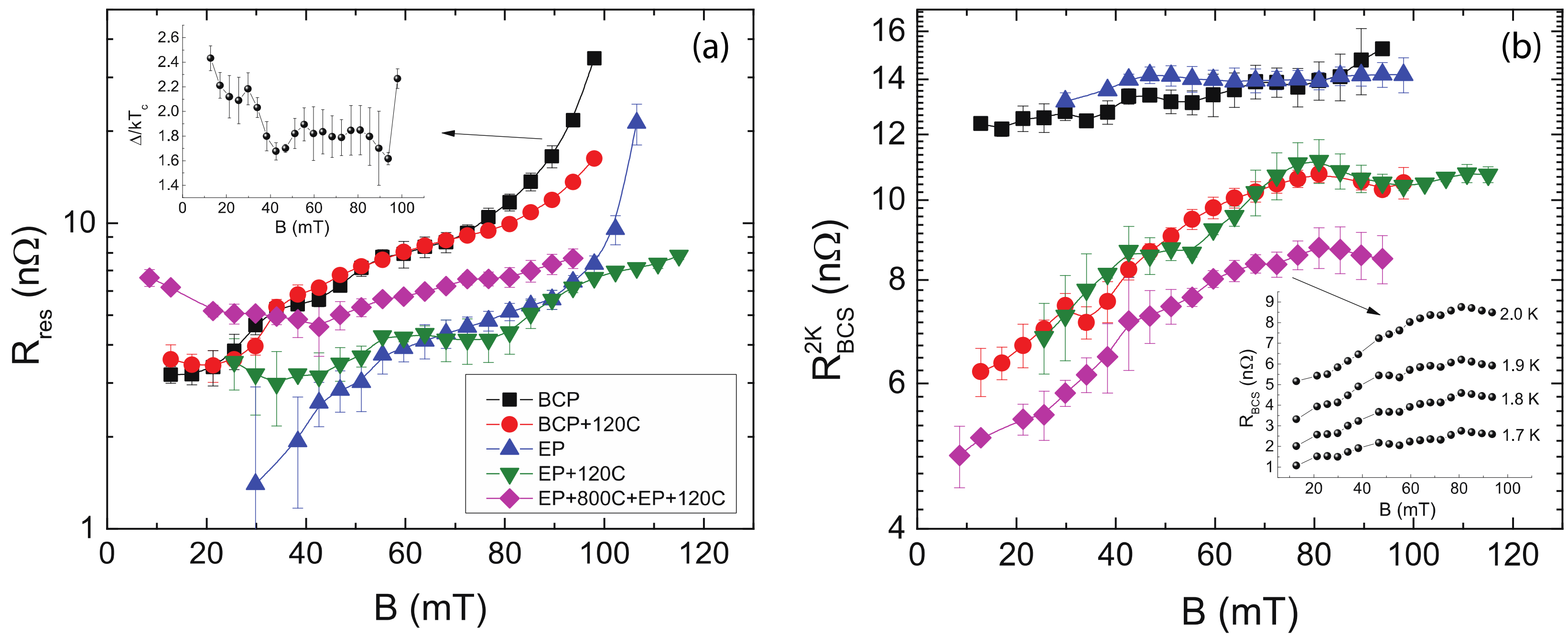
A. Romanenko and A.Grassellino
Appl. Phys. Lett. **102**, 252603 (2013)

Results (1.3 GHz)



- Temperature dependent component uniquely determined by surface processing
- Both R_{BCS} and R_0 field dependence is determined by the surface processing
- R_{BCS} decreases but becomes *strongly field dependent after 120C*
- Medium field Q slope is *NOT due to thermal feedback,* stronger R_0(B) for *BCP vs EP*

New surface processing techniques for high Q

Attack strategy based on fundamental understanding of causes of RF losses

Ideas to minimize BCS resistance:

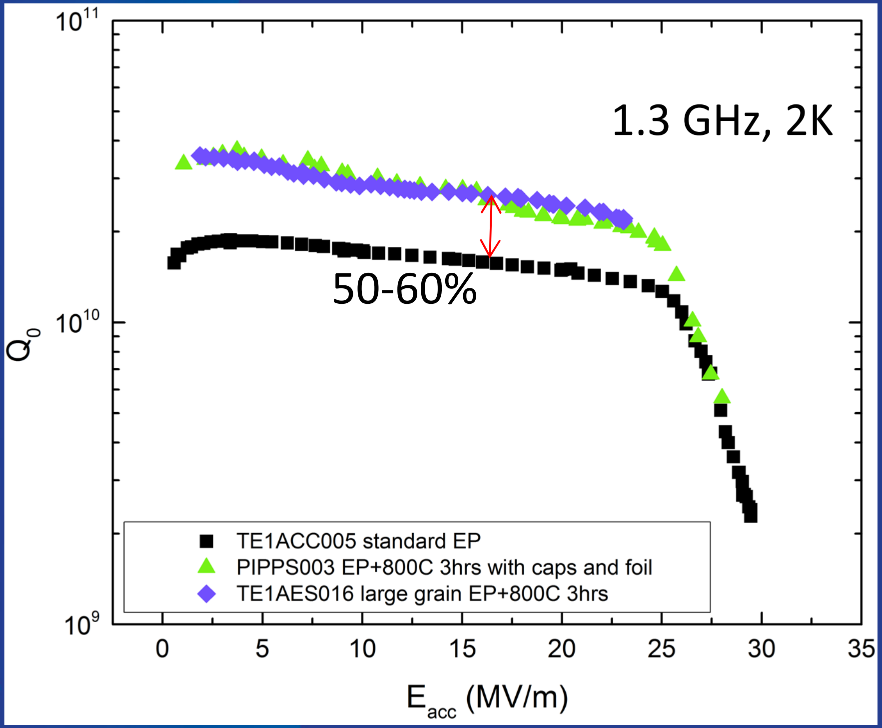
- Modify mfp, penetration depth → *doping* with interstitials
- Modify gap →eliminate sources of gap suppression (precipitates), create *higher Tc* compound (NbN, Nb_3Sn…)

See talk by Sam Posen!

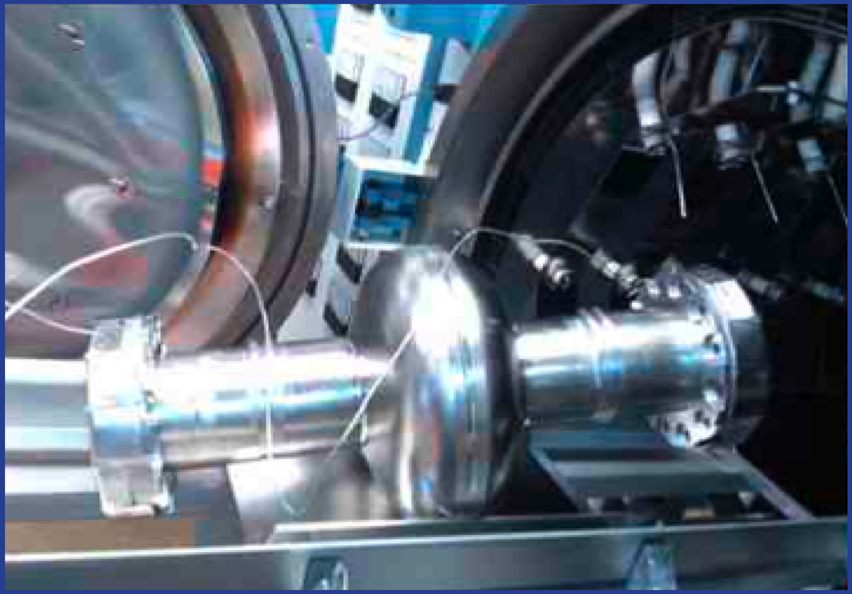
Ideas to minimize residual resistance:

- Minimize trapped flux → eliminate *trapping centers*
- Avoid precipitates (e.g. hydrides) → minimize *nucleation centers*, minimize *hydrogen reabsorbed*, neutralize hydrogen via doping

Annealing as a last processing step



A.Grassellino et al, http://arxiv.org/abs/1305.2182



- *EP + 800C 2 hrs + 20-40 micron EP + 120C*
- *Systematically low R_0 ~ 1nΩ*
- *Extra cost savings from skipping the post furnace chemical processing*

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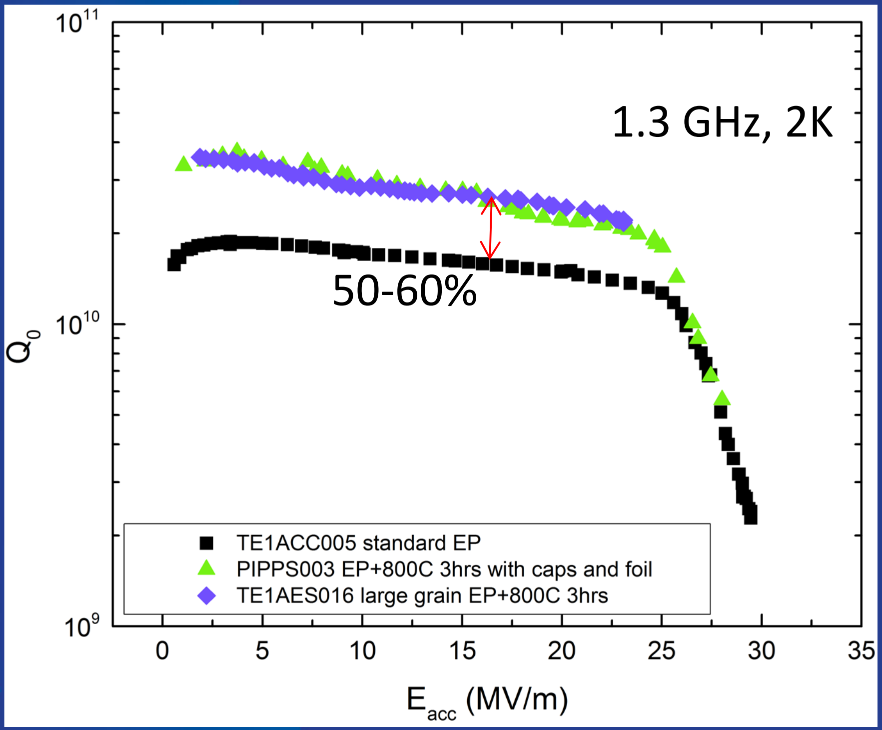
Annealing as a last processing step



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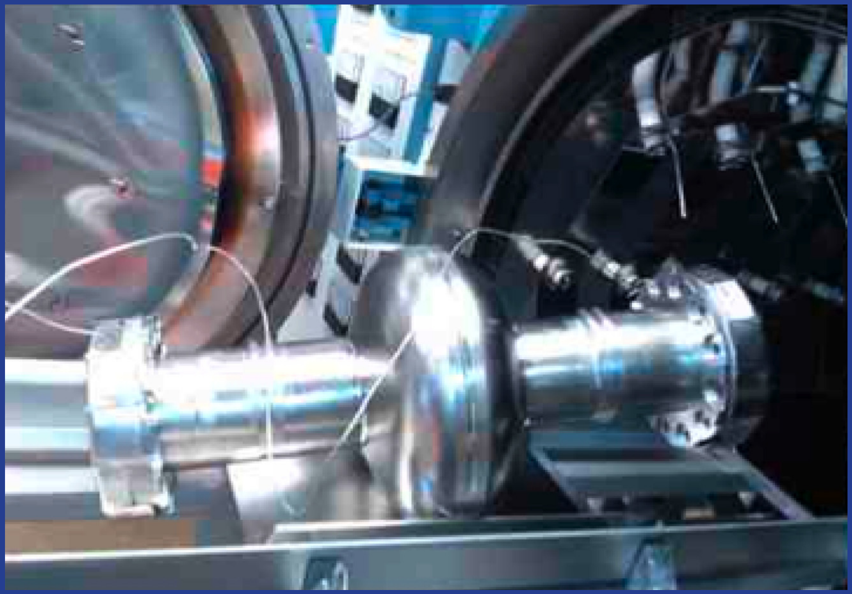
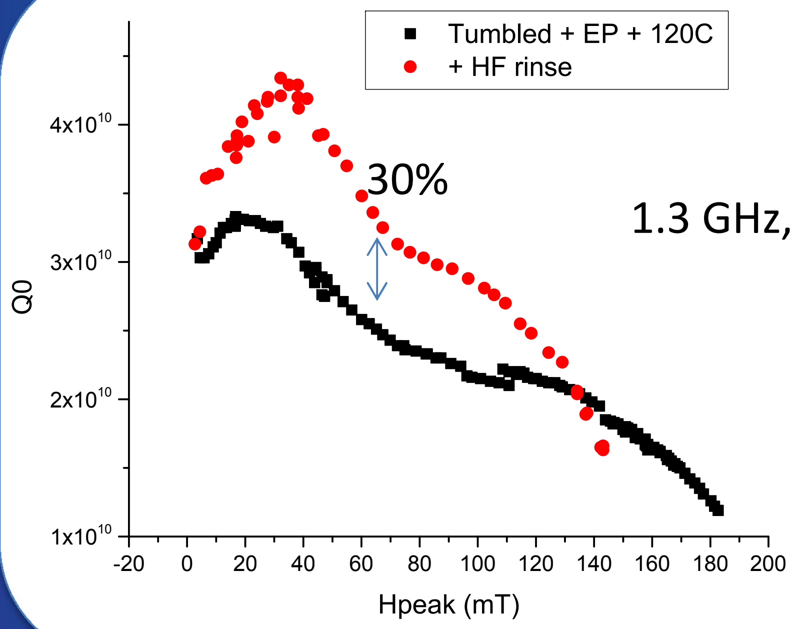
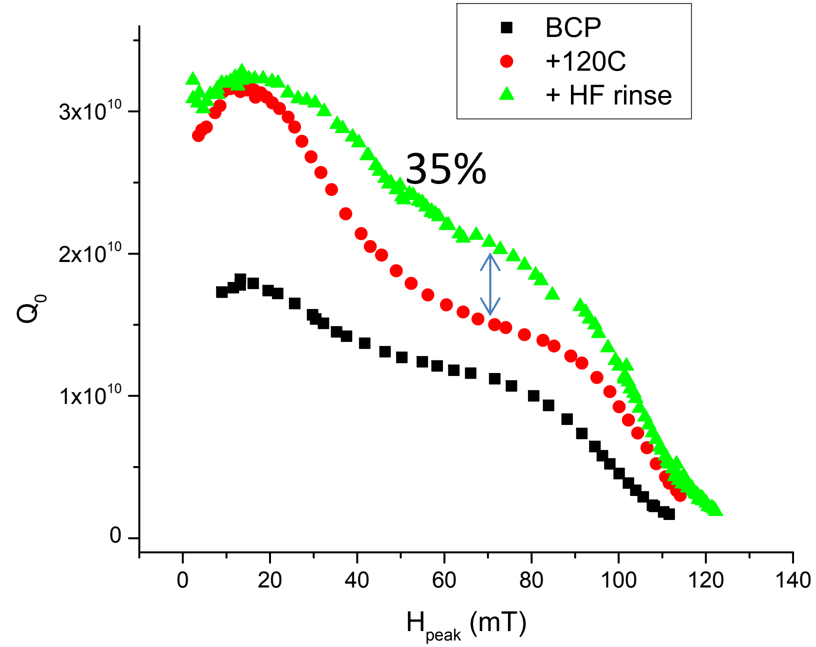


- *EP + 800C 2 hrs + 20… micron EP + …C* → *higher Q*
- *Systematically low R_0 ~ 1nΩ*
- *Extra cost savings from skipping the post furnace chemical processing*

Simple higher Q_0 recipe: 120C bake +1 HF rinse





- Single HF rinse (5 min) followed by water rinse is beneficial for the medium field Q value – gains of up to 35% measured at 70 mT, 2K, up to 100% at 1.8K
- Cornell already implemented successfully on several multicell cavities

A. Romanenko et al, Phys.Rev.ST Accel.Beams 16 (2013) 012001

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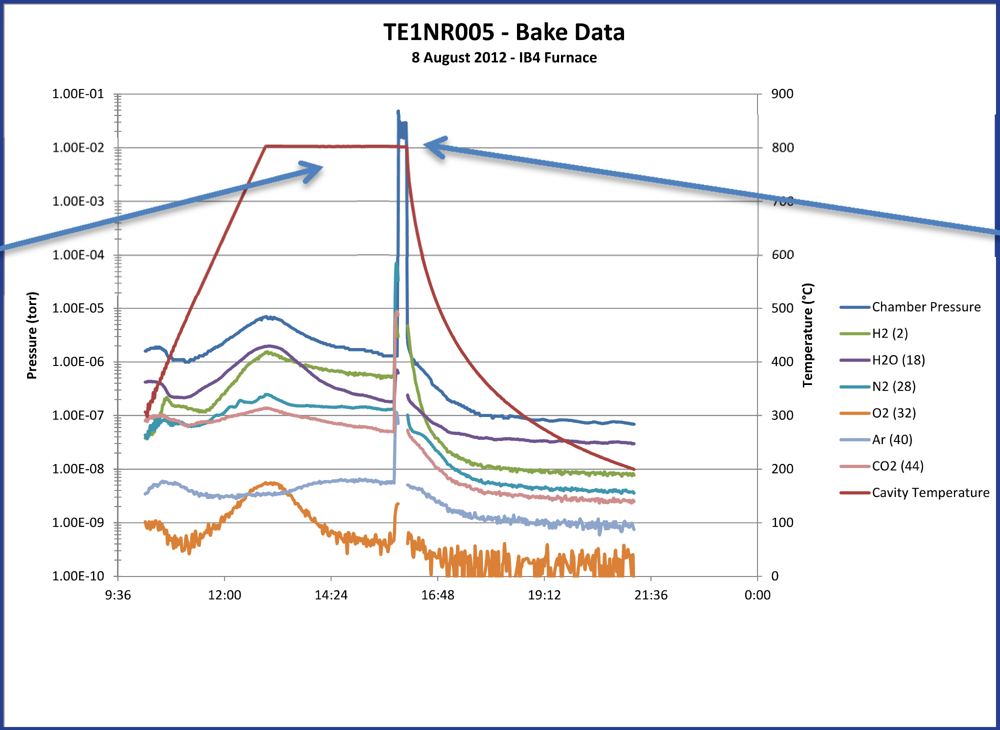
NEW- FNAL: High T bake in nitrogen gas

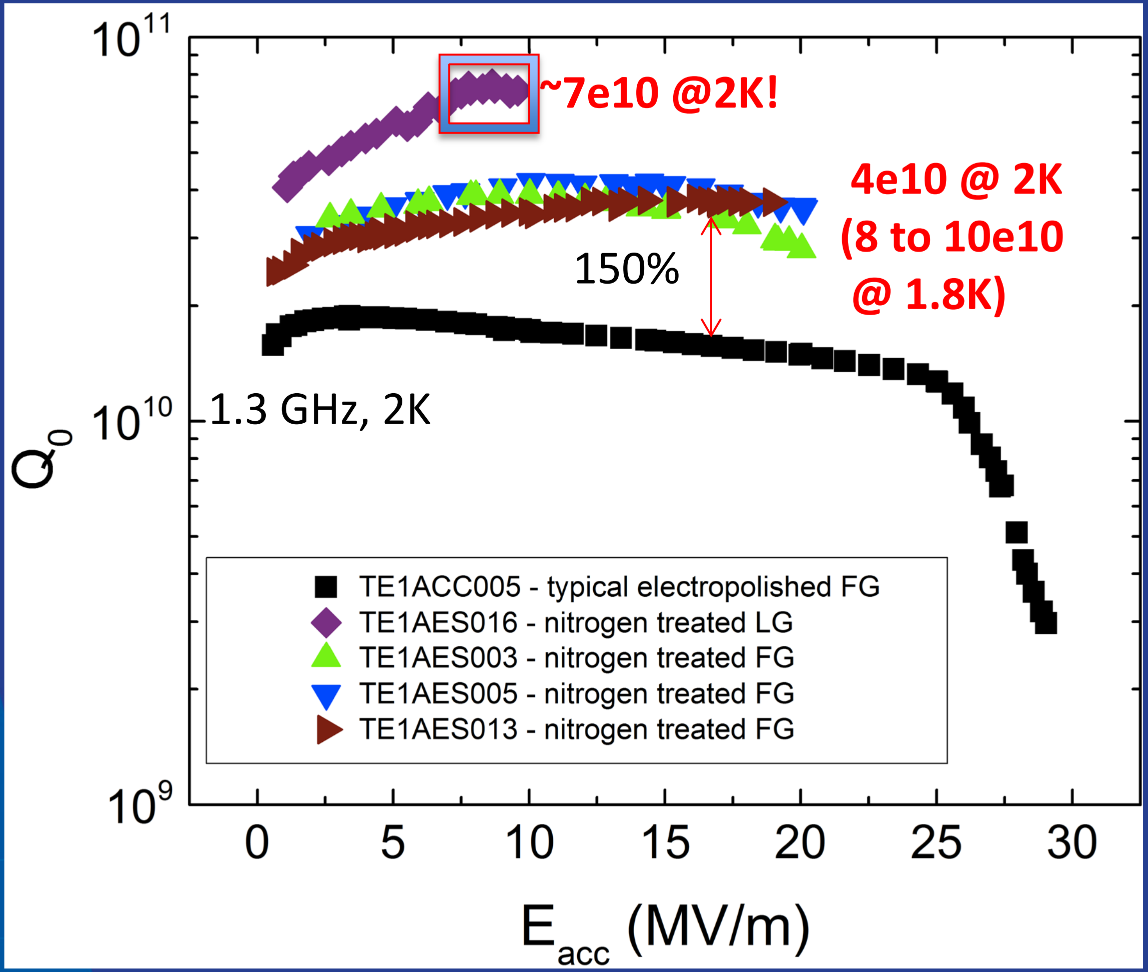
Standard 800C degassing cycle



Gas injection, ~10 min

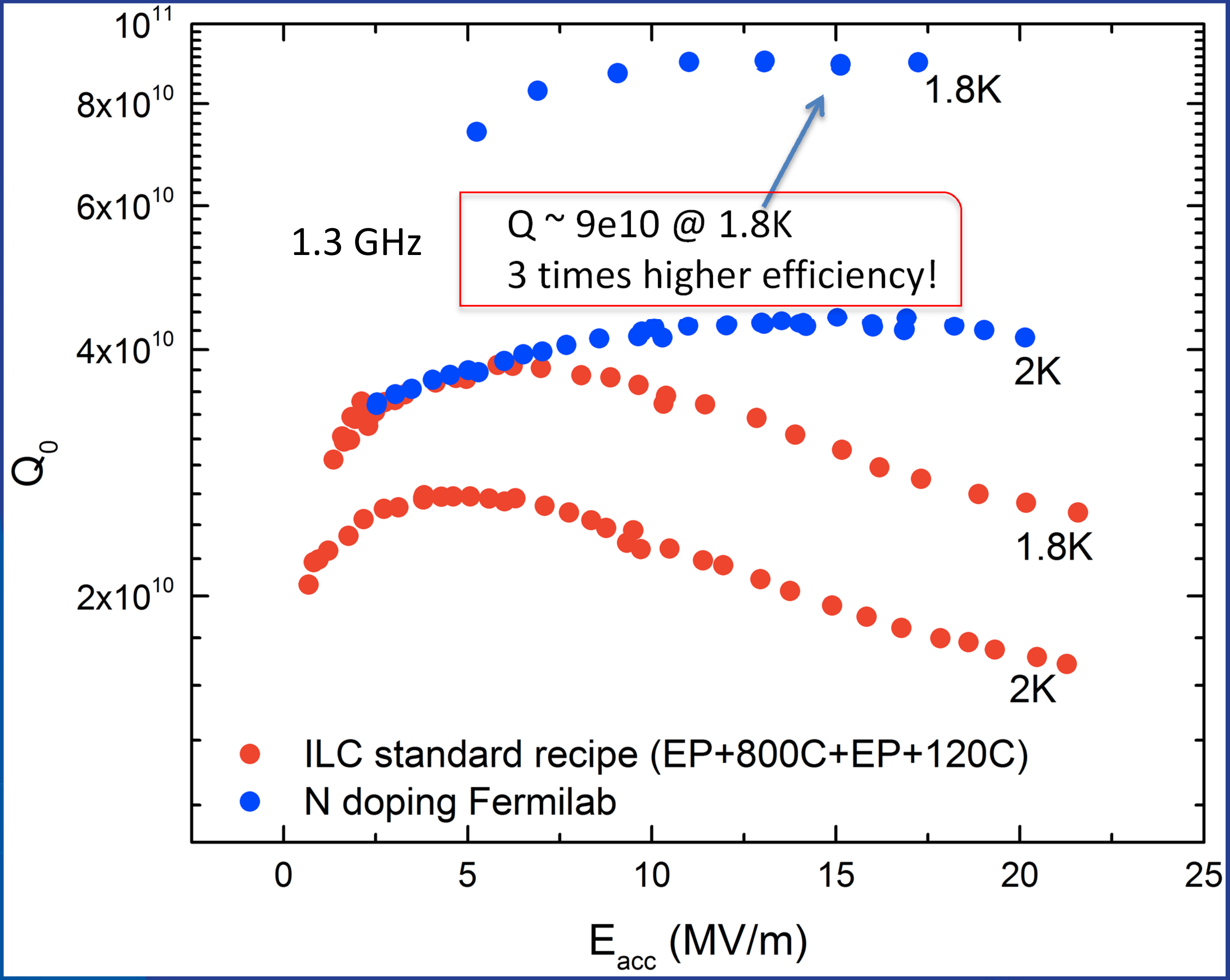
- Several cavities treated with nitrogen at different T: 600C, 800C and 1000C for different duration
- Q all extremely poor after treatment ~ 10^7-10^9
- Then, we removed a certain amount of material via electropolishing

Record Quality Factors obtained via impurity doping - beyond the expected BCS limit for Nb

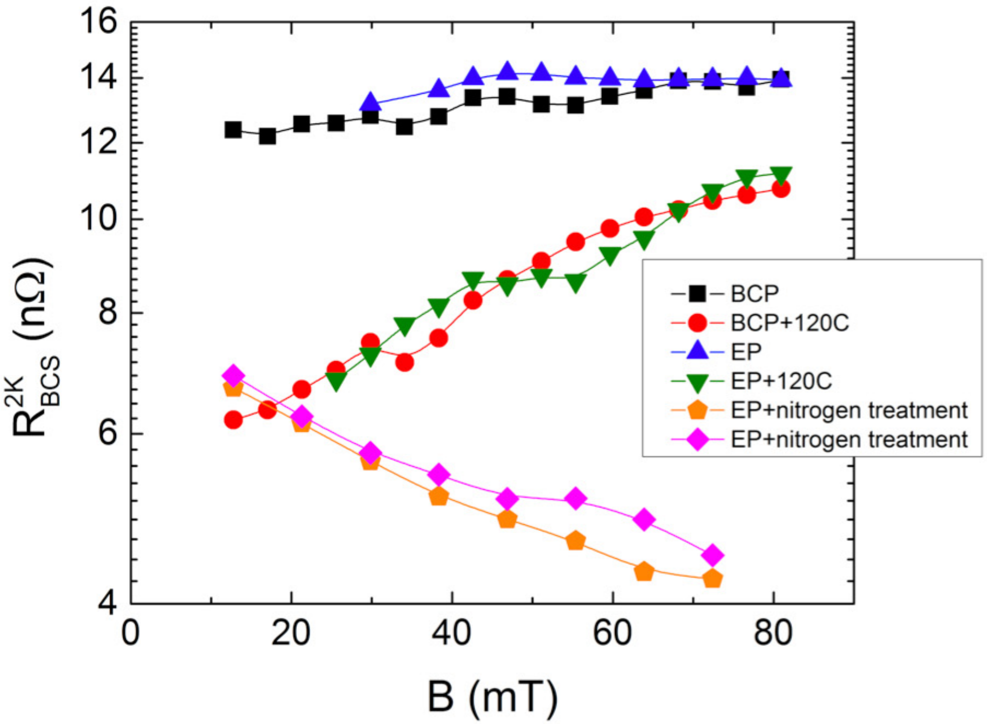


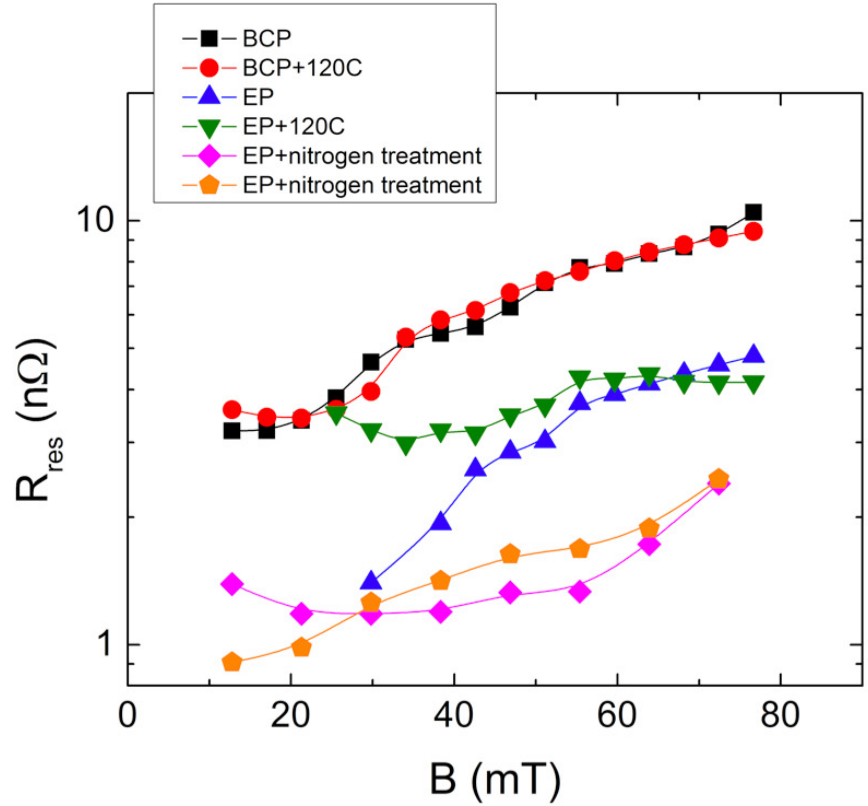
A.Grassellino et al, 2013 *Supercond. Sci. Technol.* 26 102001

Comparing nitrogen treated to standard ILC processing at 2 and 1.8K



Where does the improvement originate? The reversal of $R_{BCS}(B)$





Previously unseen phenomenon!

A.Grassellino et al, 2013 *Supercond. Sci. Technol.* 26 102001

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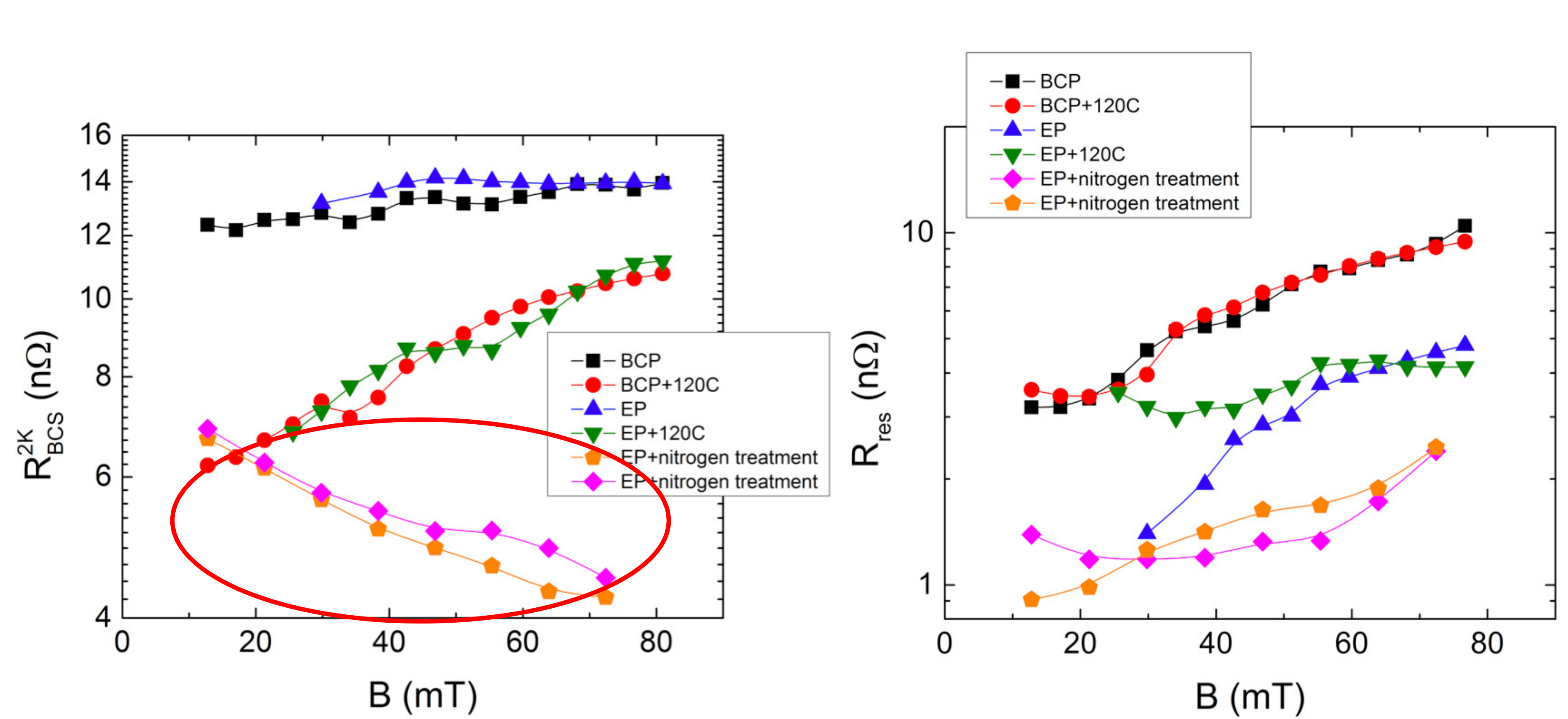

Previously unseen phenomenon!

A.Grassellino et al, 2013 *Supercond. Sci. Technol.* 26 102001

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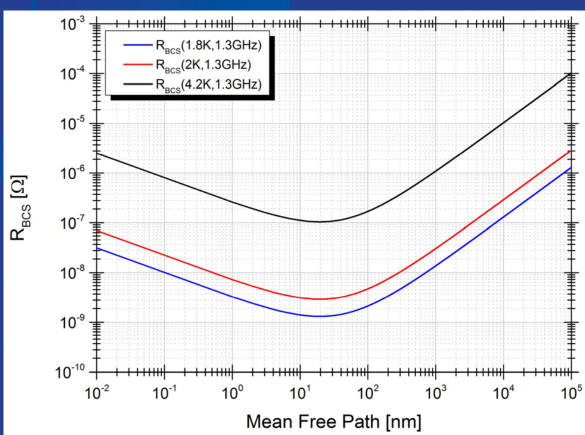
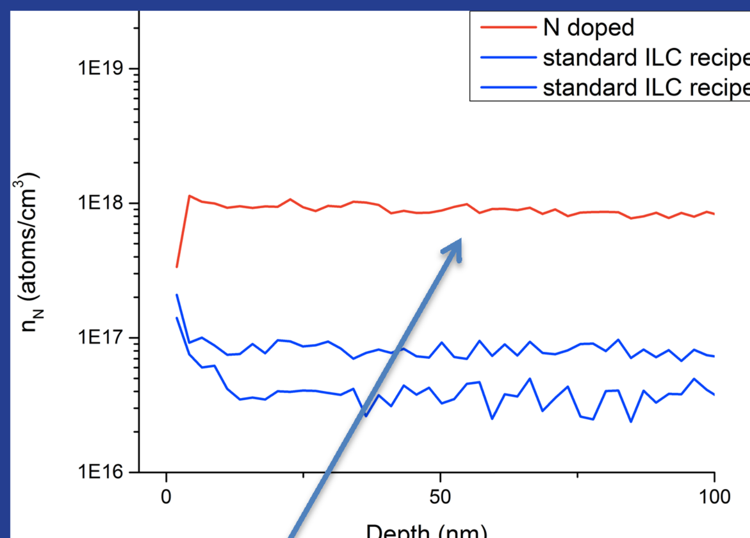
So far, our understanding of it

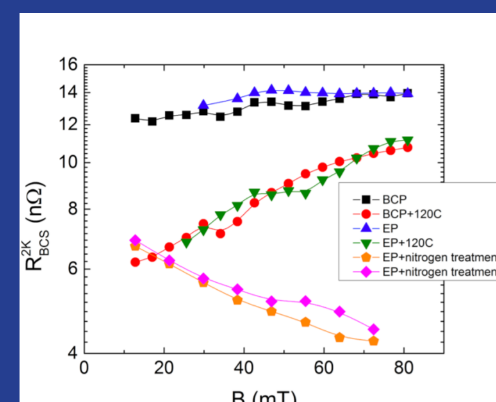
-BCS is lowered with lower mean free path:

- EP, BCP → clean limit, high BCS, little to no field dependence
- In the 120C bake case mfp near surface ~ 2nm (→ lower BCS at low field, BUT dirty limit, field dependence of the gap causes slope
- Nitrogen/Argon treated: intermediate purity! Near surface ~ 40 nm → minimum of BCS at low field, but reverse field dependence unclear, maybe intrinsic?



M. Checchin, calculated in two fluid model approx





SIMS results showing 10 times higher than typical nitrogen concentration

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Q ‘preservation’ in a real machine

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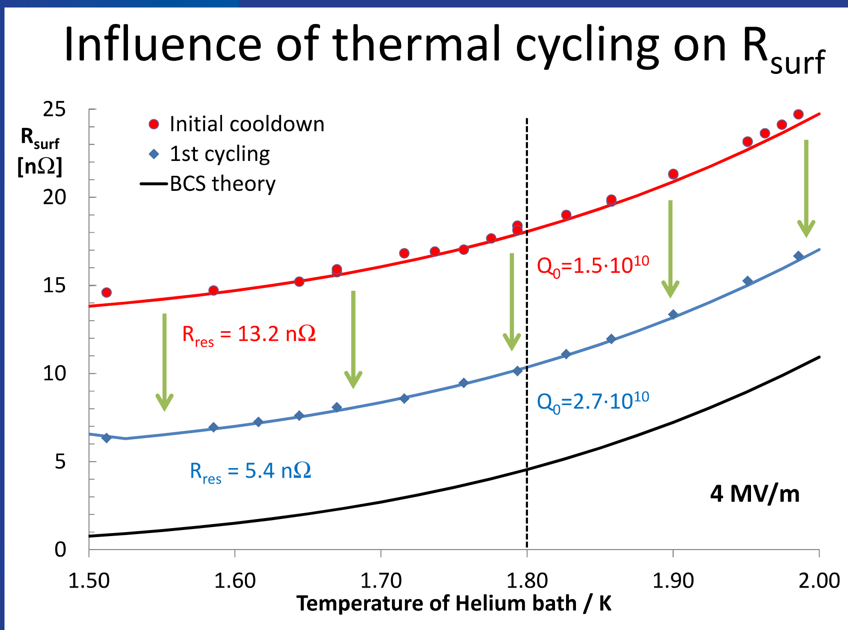
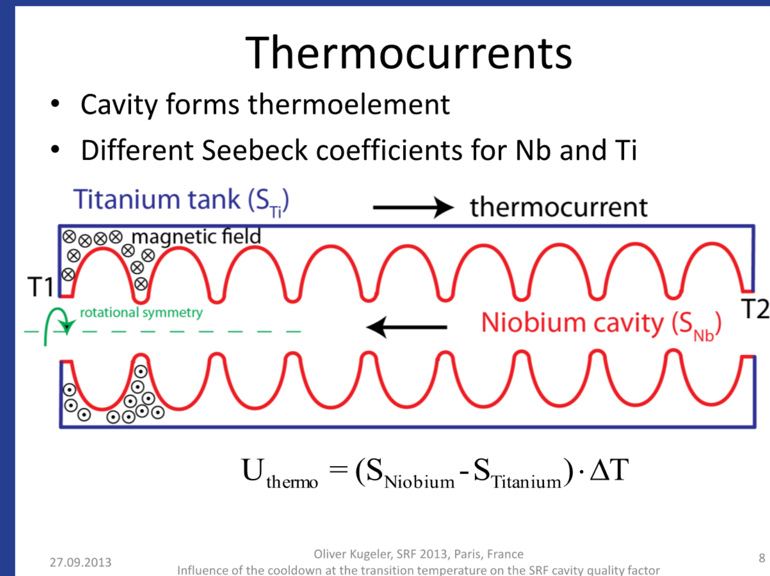
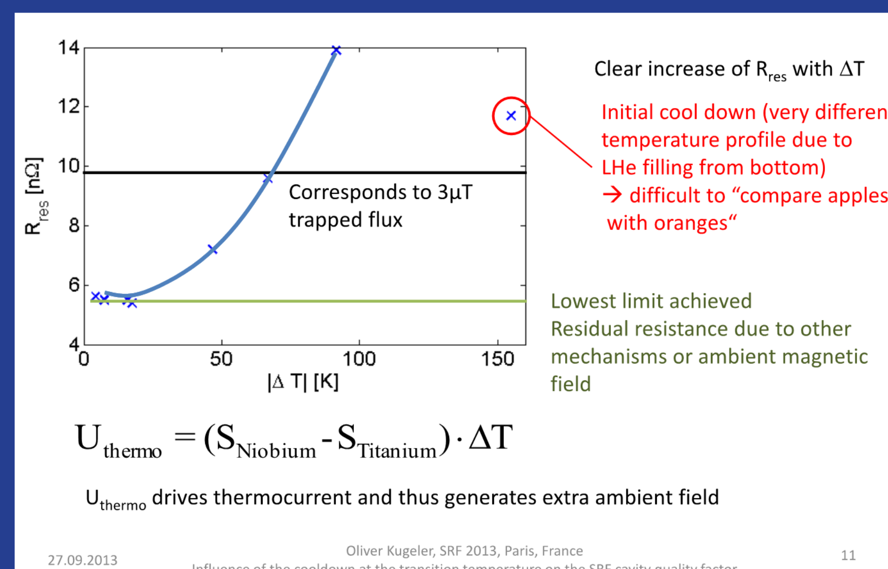
HZB studies of trapped flux due to thermocurrents



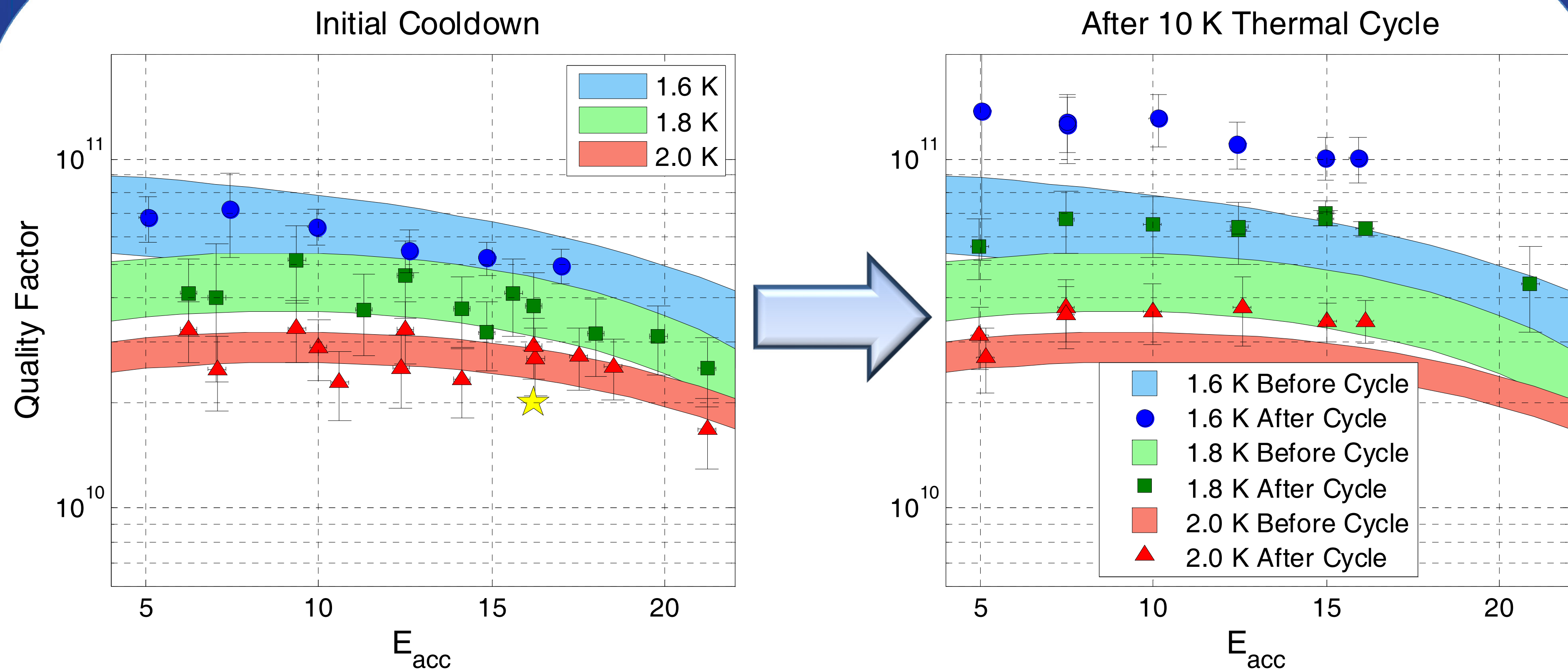


Kugeler et al, talk presented at SRF 2013



Cornell studies of minimization of trapped flux in cryomodule

N. Valles – High Q Cavity Operation in the Cornell HTC – TTC Topical Meeting on CW-SRF 2013



Initial Cooldown at 16.2 MV/m

Q(2.0 K) = 2.5 x 10^{10}

Q(1.8 K) = 3.5 x 10^{10}

Q(1.6 K) = 5.0 x 10^{10}

10 K thermal cycle at 16.2 MV/m

Q(2.0 K) = 3.5 x 10^{10}

Q(1.8 K) = 6.0 x 10^{10}

Q(1.6 K) = 10.0 x 10^{10}

57

Conclusions

- Tremendous progress in understanding and finding of new cures in the last two years, since high Q effort started
- The doping with interstitials discovery shows that Nb is NOT at the end of the road! And that new exciting horizons are open for the SRF technology!
- R&D largely pays off, with relatively small effort we have already produced results which translate into huge savings for SRF based accelerators planned worldwide

The FNAL work presented comes from a team effort:

A.Grassellino, A.Romanenko, A.Rowe, O.Melnychuk, A.Crawford, M. Checchin, D.Sergatskov, T.Khabiboulline, A. Sukhanov, Y.Trenikhina, F.Barkov, M.Wong, D.Bice, B.Stone, C.Baker, Y. Pischalnikov

Thanks to R.D.Kephart and V.Yakovlev for their strong support of the high Q program at FNAL