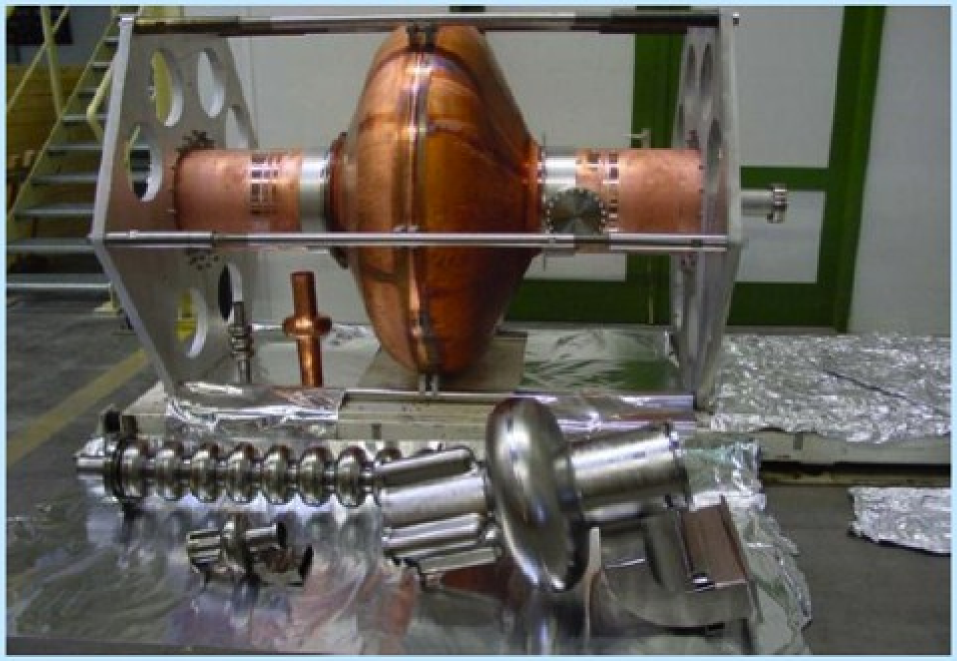
Superconducting RF cavities: extending knowledge boundaries

A. Romanenko

Outline

- What are SRF cavities
- Why study SRF cavities
- Main scientific problems
- Ways of addressing
- Recent findings
- Future plans

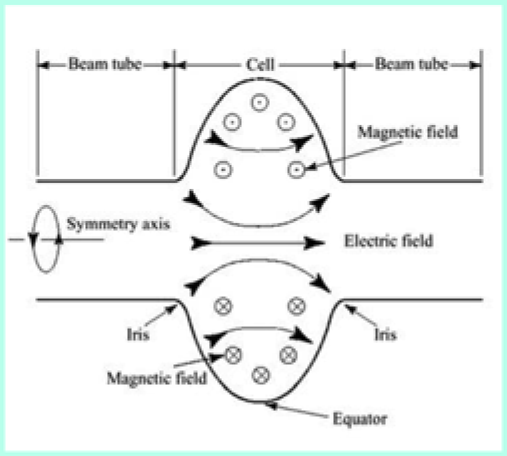
Superconducting RF cavities



SRF high beta cavities of different frequencies

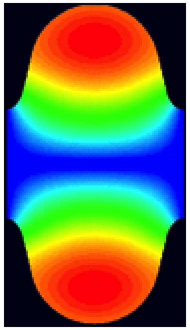
ILC 9-cell elliptical cavity

Technology of choice for: ILC, Project X, NGLS, Cornell ERL, CEBAF, XFEL, SNS and many other accelerators

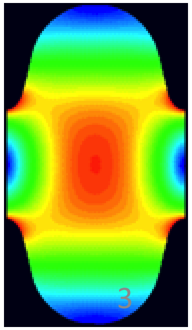


TM_{010} mode

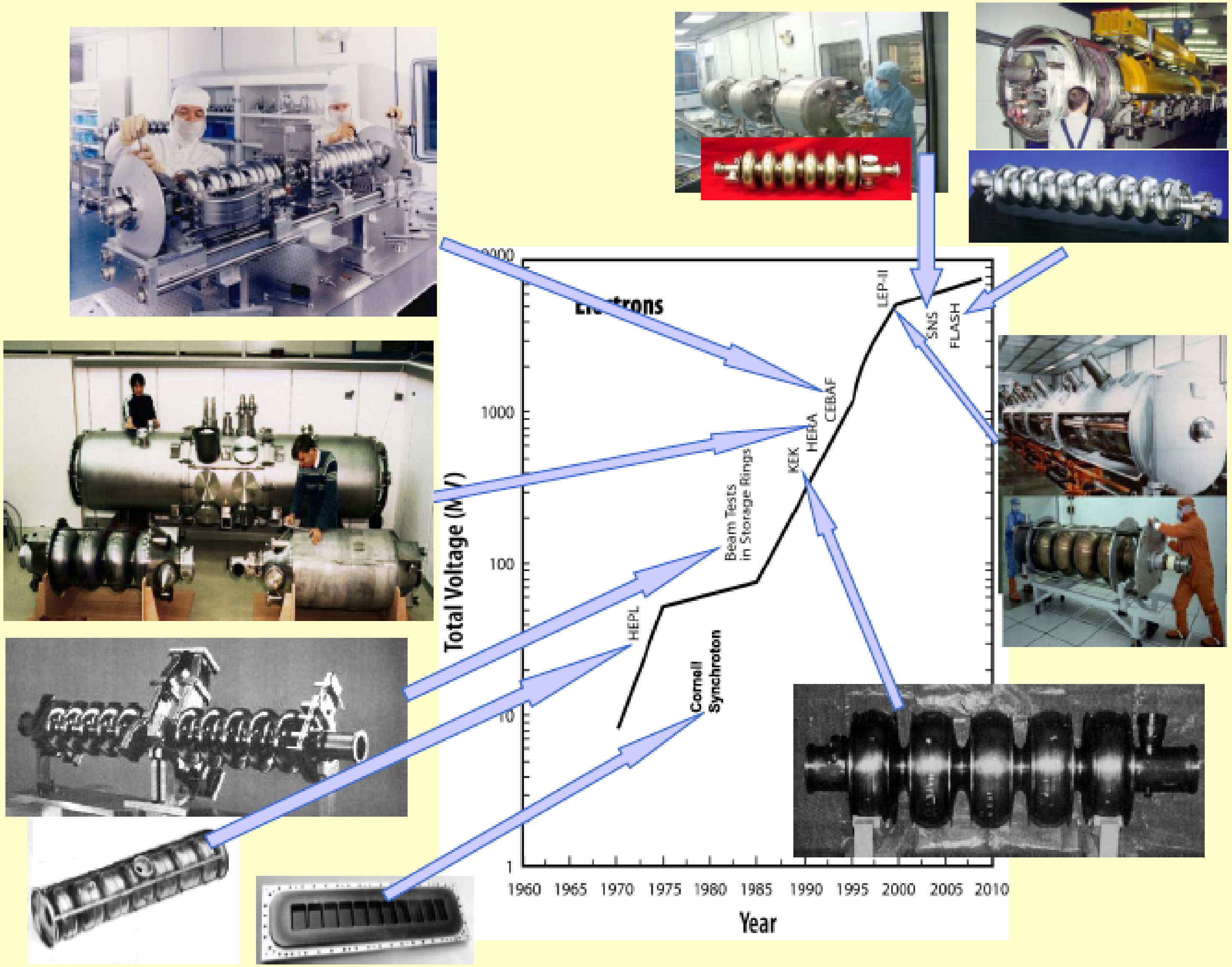
H



E



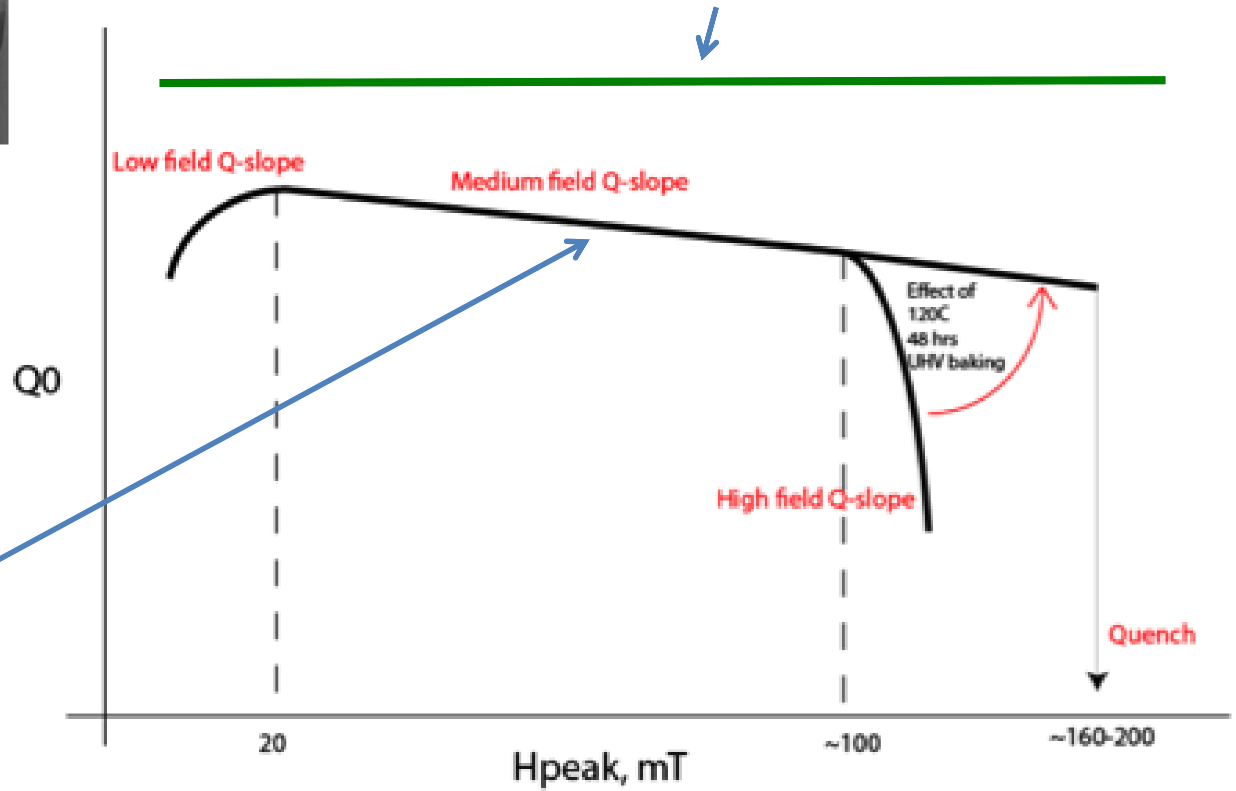
Total Installation > 1000 m, > 7 GV



Why study SRF cavities

Elliptical TESLA shape 1.3 GHz cavity

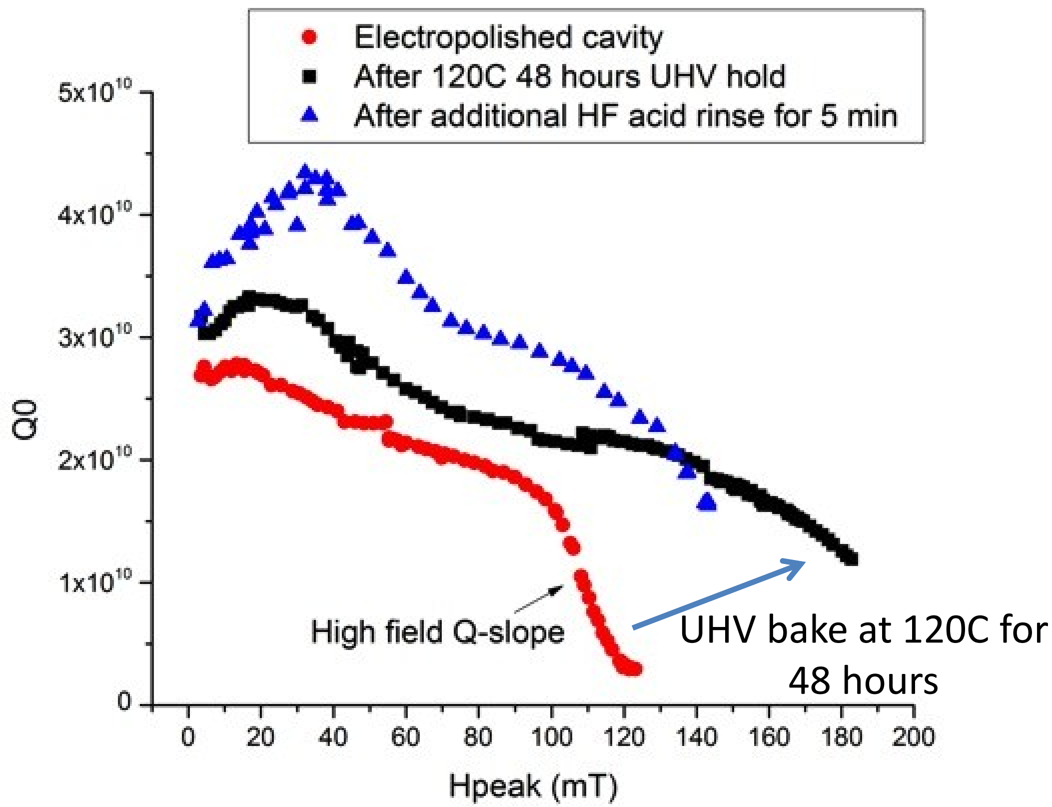
Should be constant Q_0 at all fields for the constant surface resistance (neglecting thermal effects)!



- History of success – multipacting, thermal breakdown, Q-disease , field emission – mechanisms understood and countermeasures found
- Currently – lack of clear physical understanding of why Q(H) has 3 distinct slopes and why localized quench happens

Practical Q_0(H) curves

Understanding the shape of the Q(H) curve and learning how to control it – primary practical objective

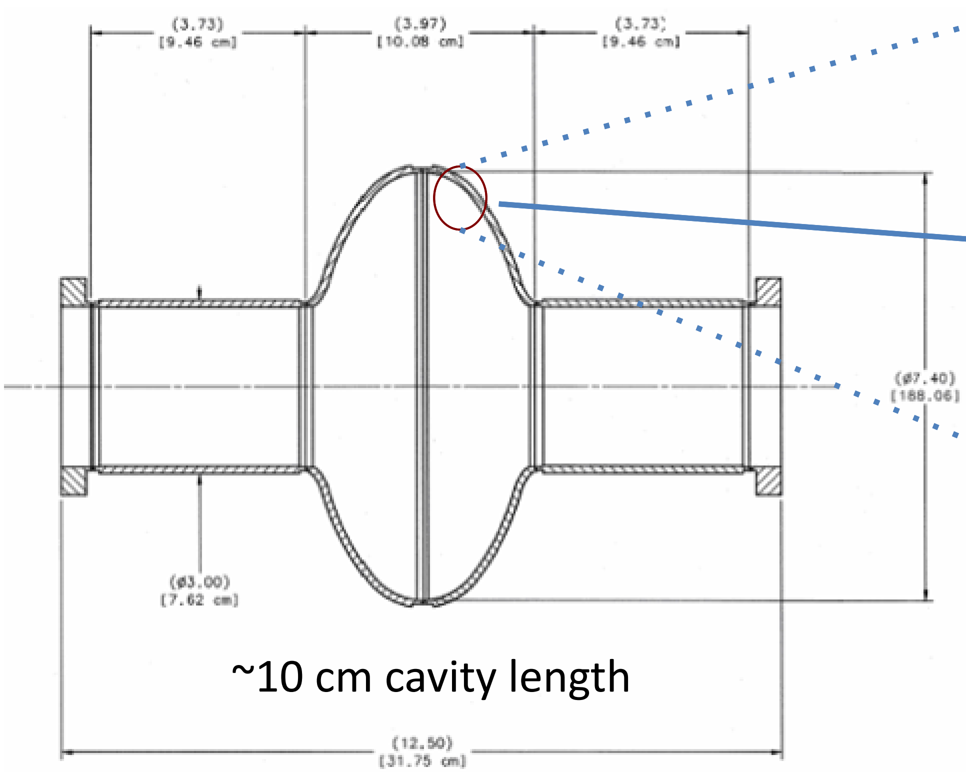


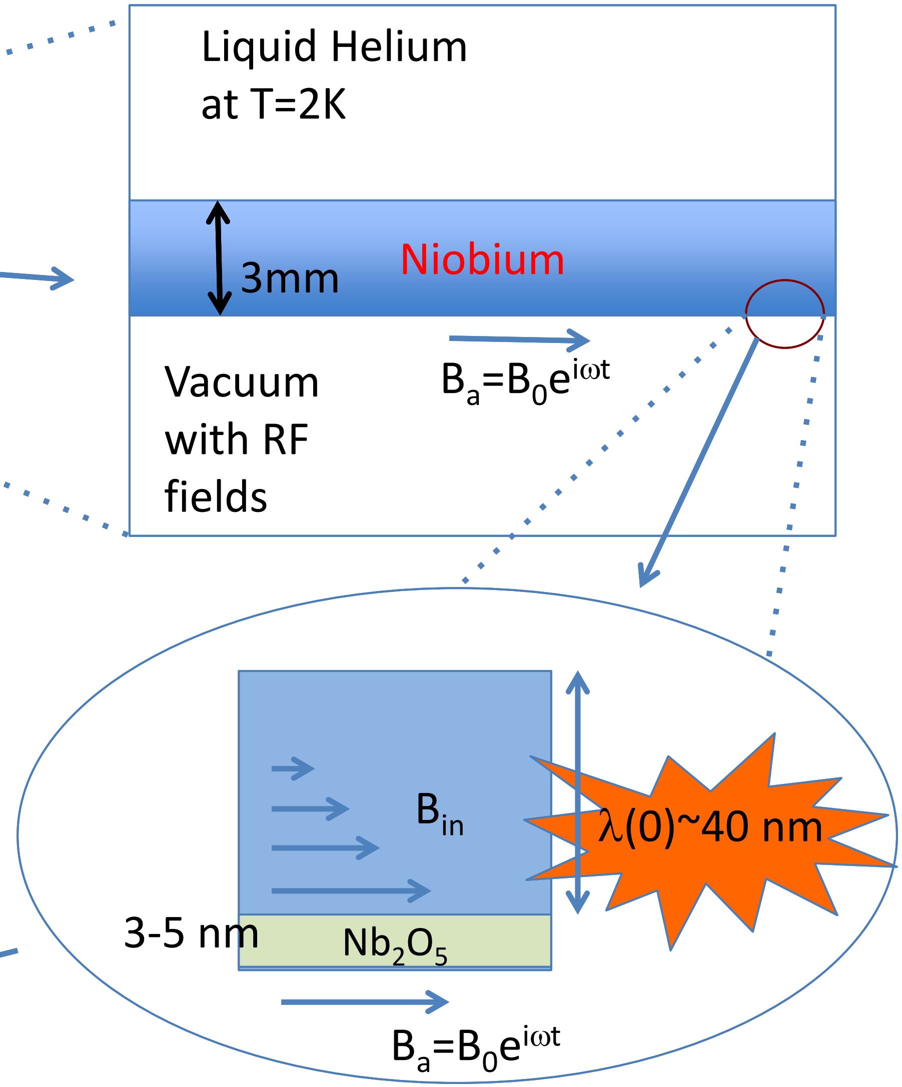
1.3 GHz bulk niobium cavity

$$Q_0 = \frac{\omega U}{P_{diss}}$$

- The most dramatic effect - high field Q-slope removed by mild baking – UHV in situ annealing at 120C for 48 hours

Only surface ~40 nm matter





Inner surface nanostructure within $\lambda \sim 40$nm completely determines RF losses in the cavity

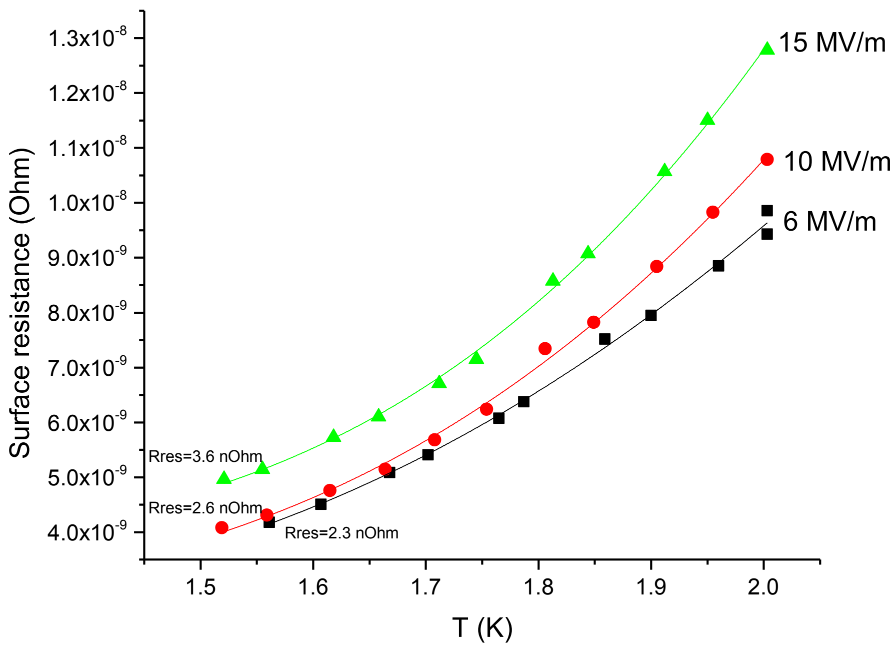
Surface resistance

$$Q_0 = \frac{\omega U}{P_{diss}} \propto \frac{1}{R_s}$$

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

Thermally excited quasiparticles

$$R_{BCS} \approx \frac{1}{2}\omega^2\mu_0^2\lambda_L^3 = \frac{A}{2}\omega^2\mu_0^2\left(\lambda_{L0}\sqrt{1+\frac{\xi_{BCS}}{l}}\right)\frac{RRR}{\rho_n(300K)}e^{\left\{-\frac{\Delta(0)}{k_B T_c}\frac{T_c}{T}\right\}}$$

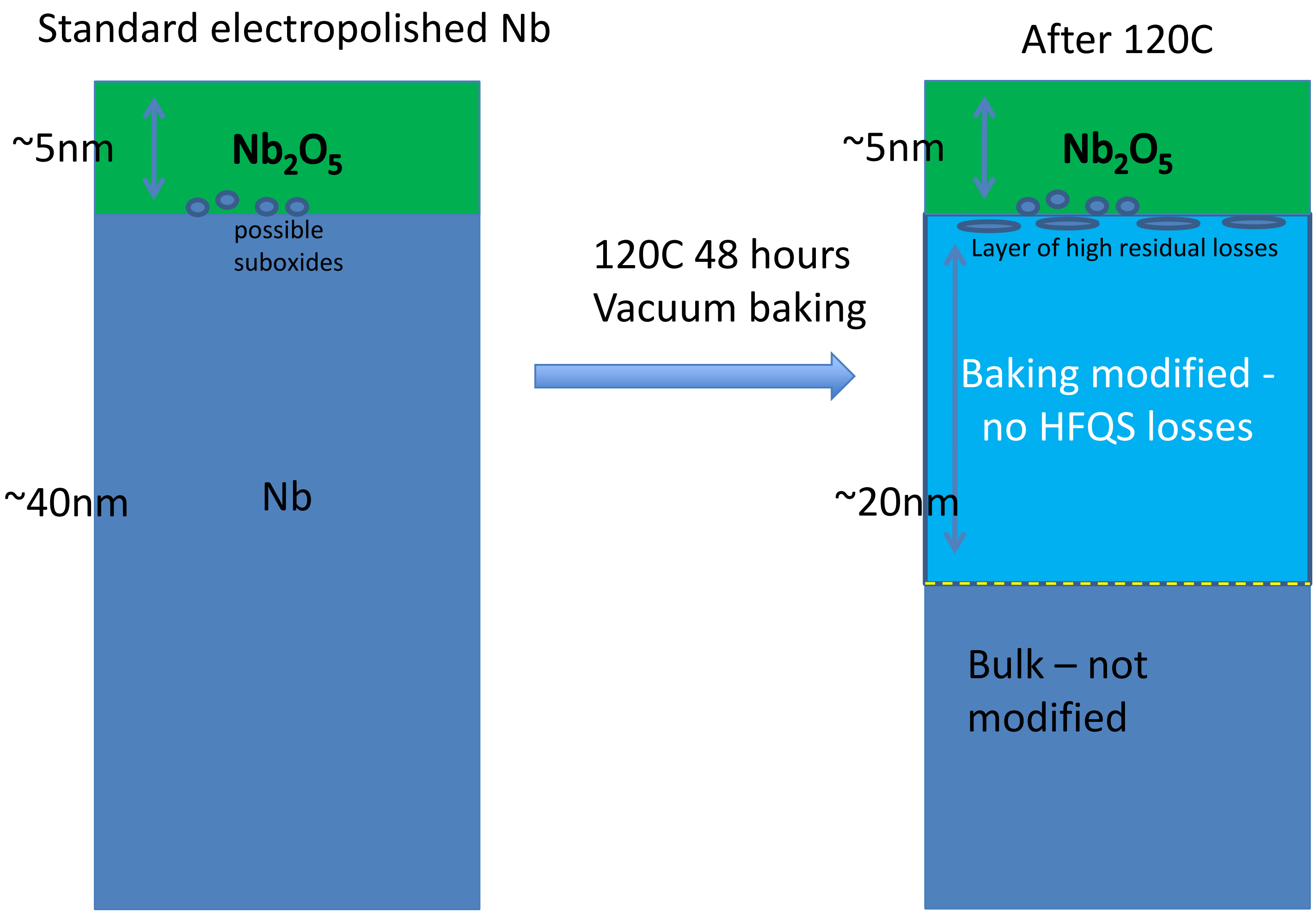


To fit numerically the $R_s(T)$ curve we need 6 parameters:

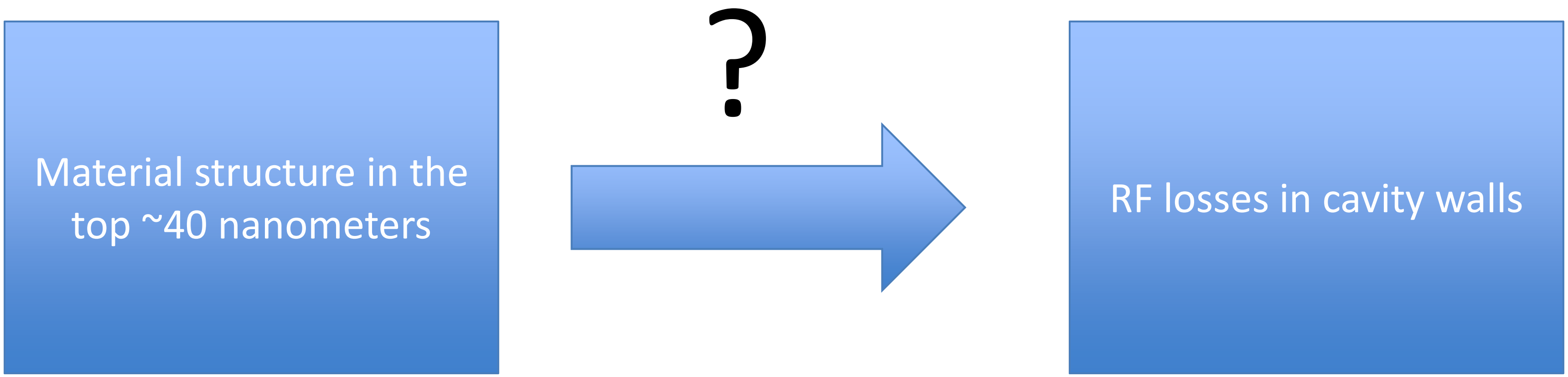
T_c, $\Delta(0)$, λ_0, ξ_0, l, R_{res}

Need to have independent measurements of as many of these as possible

Existing knowledge about near-surface layer



What needs to be understood

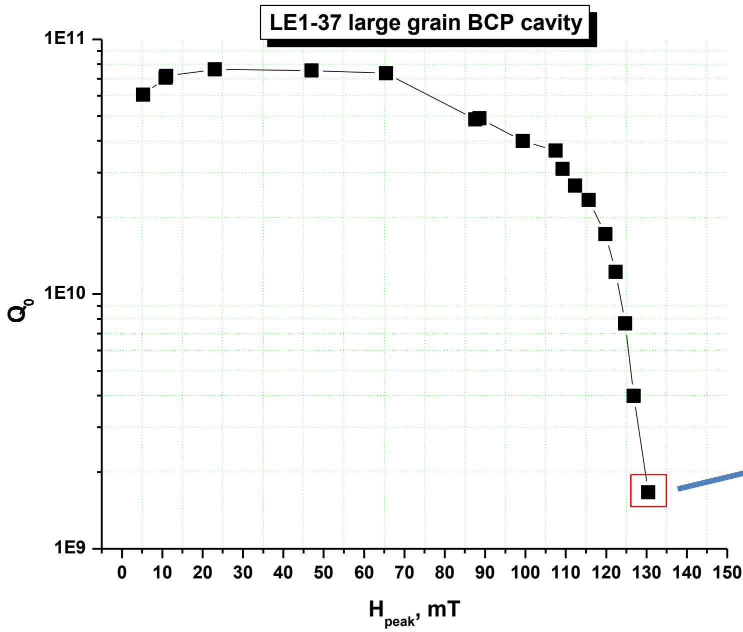


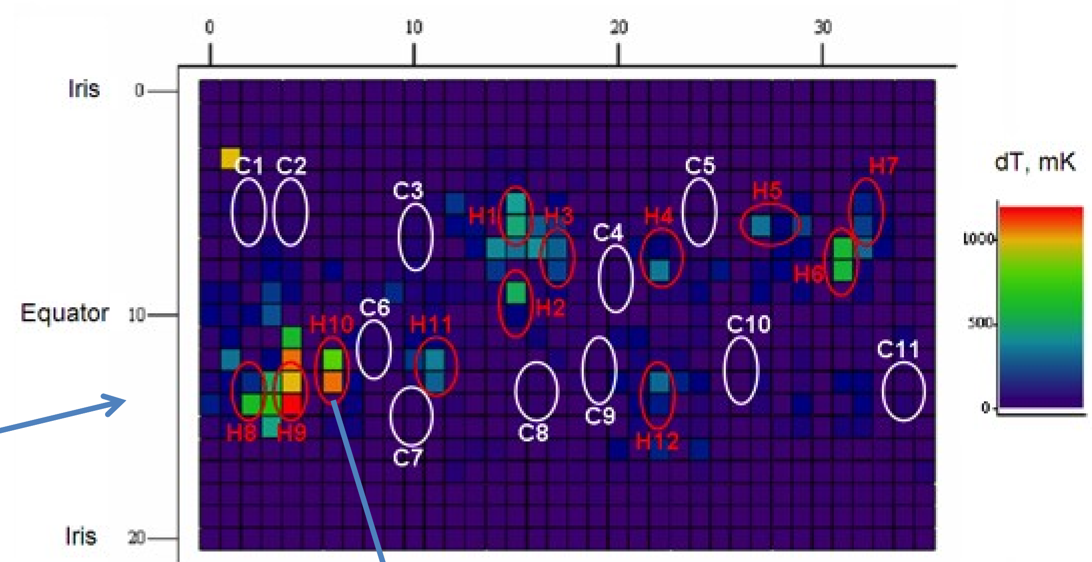
?

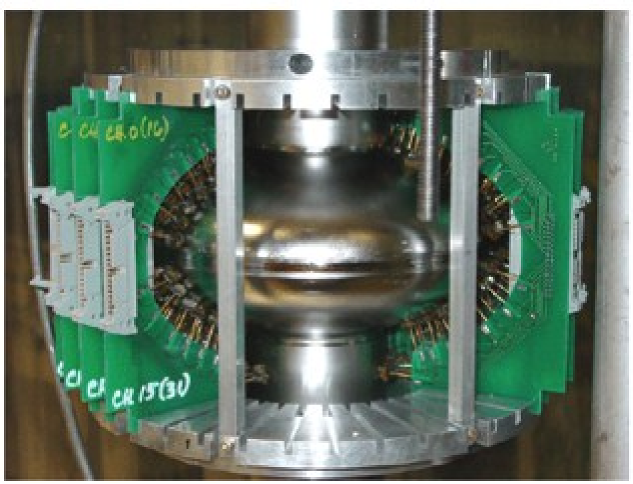
- Subtle details of the material structure
    - Dislocations
    - Vacancies
    - Precipitates (hydrides, oxides)
- What changes upon cooling to 2K!

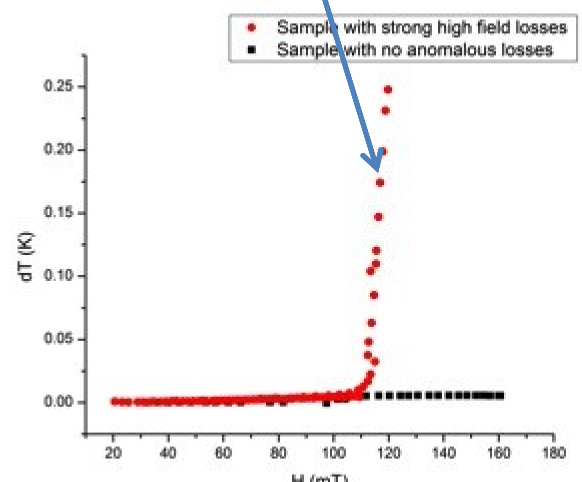
- A lot of “production” data available
    - Less useful – always the same treatments, no temperature mapping
- Much to explore with T-mapping (to be commissioned)
    - Especially low and medium field Q-slopes

Best approach - thermometry and cutout



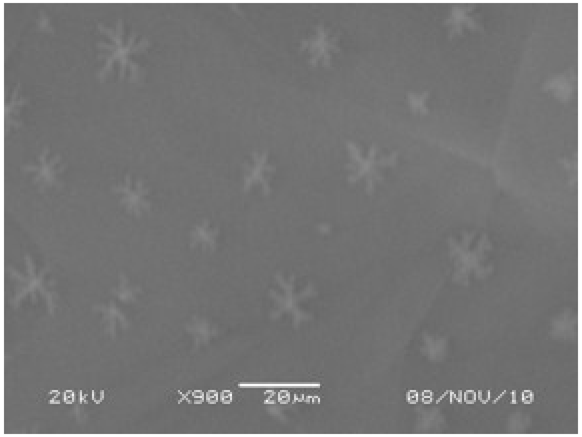


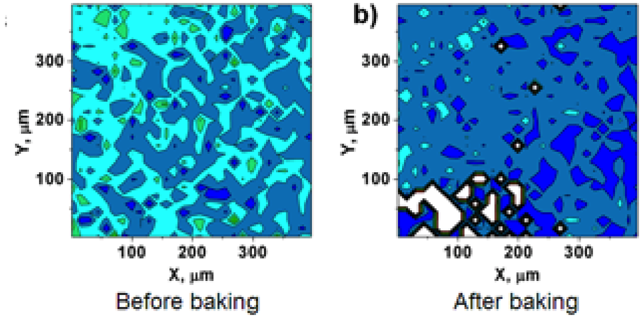


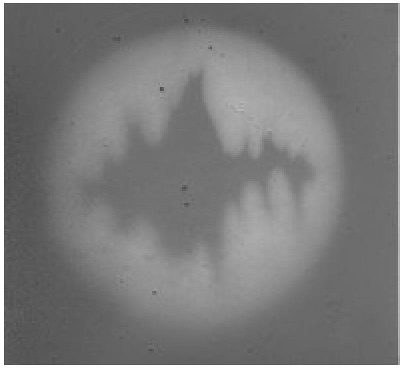


Detailed surface studies

- SEM/EDS, XPS
- Laser confocal scanning microscopy
- Elastic Recoil Detection for hydrogen profiling
- Positron annihilation studies – vacancy depth profiling
- Electron Backscattered Diffraction – dislocation density mapping
- FIB preparation of cross-sectional samples for defect structure observation in TEM and EELS analysis
- Local magnetization using single and arrays of microHall probes
- Magneto optical imaging
- Muon spin rotation
  - Bulk (TRIUMF)
  - Surface (Paul Scherer Institute)

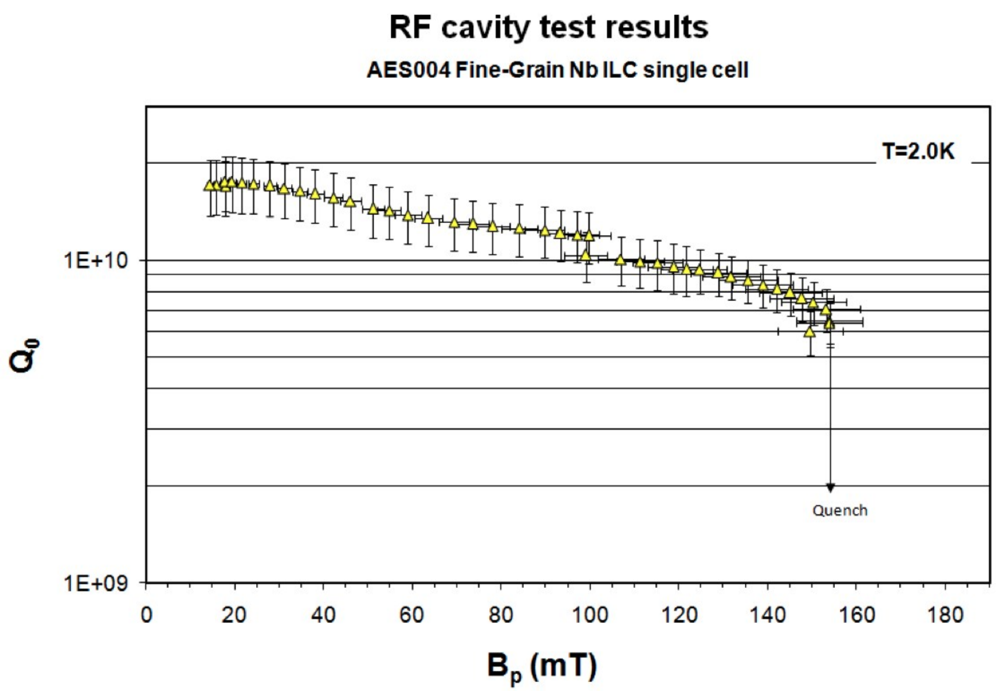


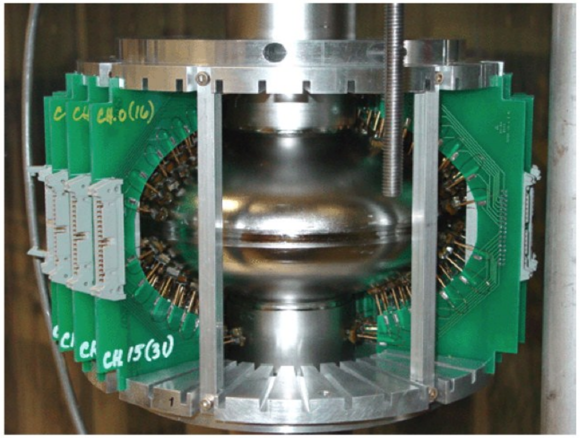




Results - high field quench and post-baking losses

- 1.3 GHz fine grain single cell
  - Electropolishing+120C bake at ANL/FNAL
  - RF tested at JLab with thermometry – we don't have temperature mapping

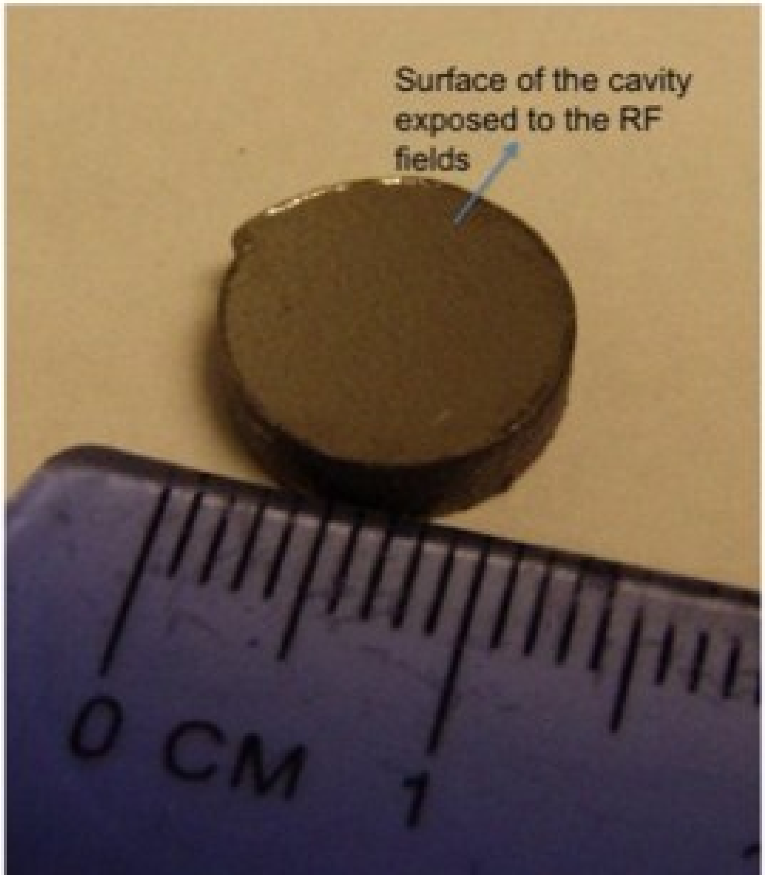




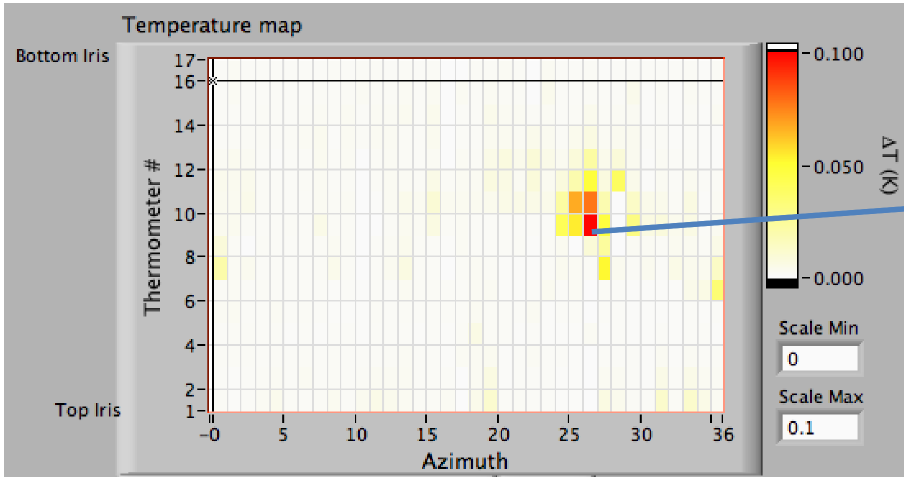
Thermometry system attached to outside cavity walls

A. Romanenko, G. Wu, L. D. Cooley, G. Ciovati, Proceedings of SRF'11, THPO008

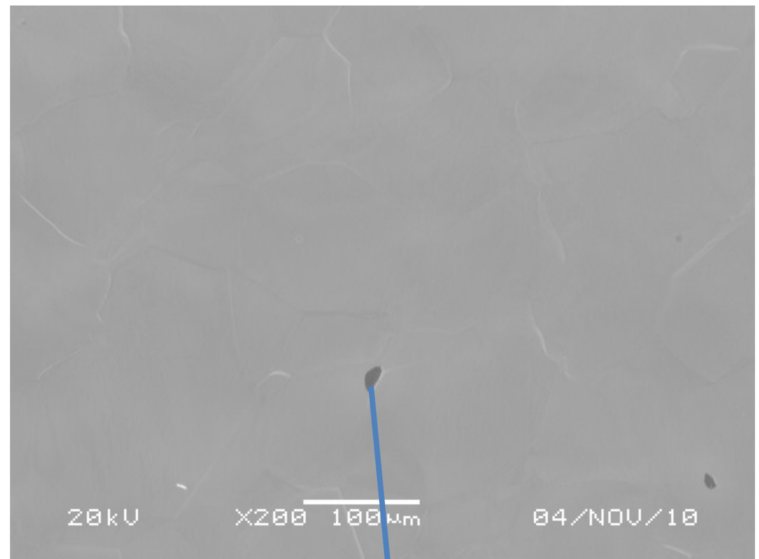
Extract areas of interest

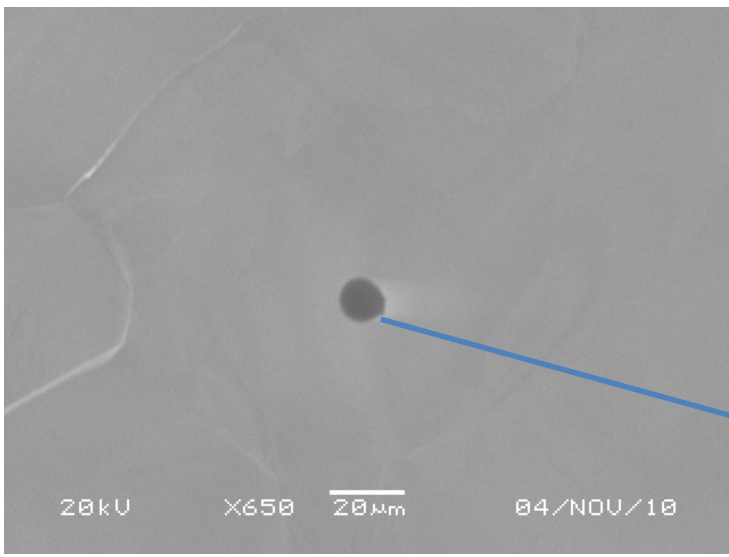


Quench



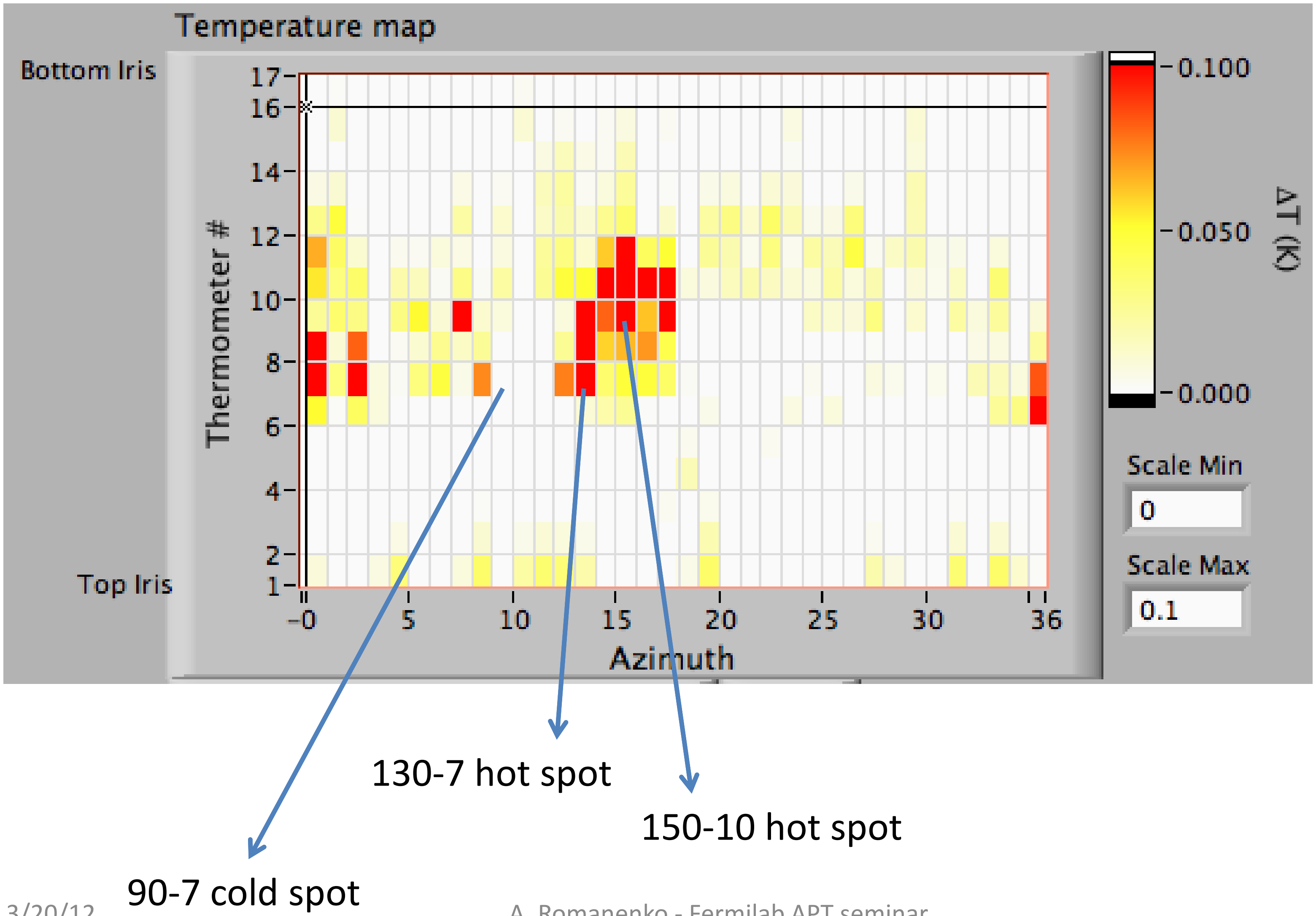
Quench at 160 mT
Site localized and cut out



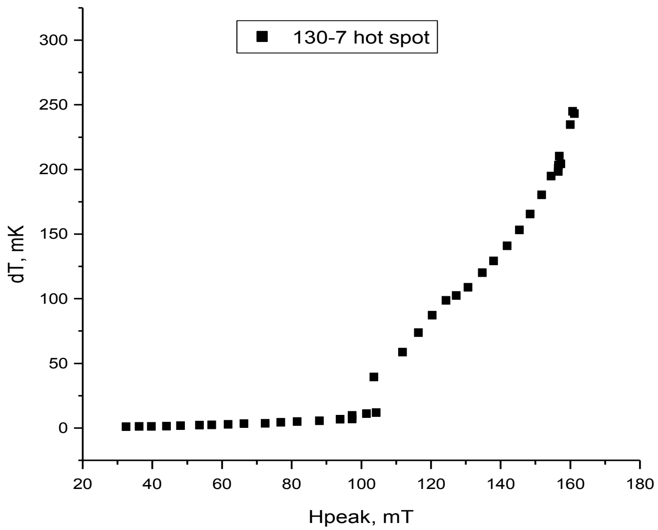


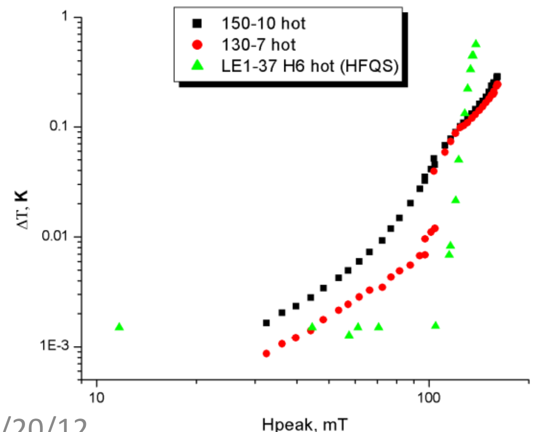
Carbon-rich spots are the only features found – niobium carbides?

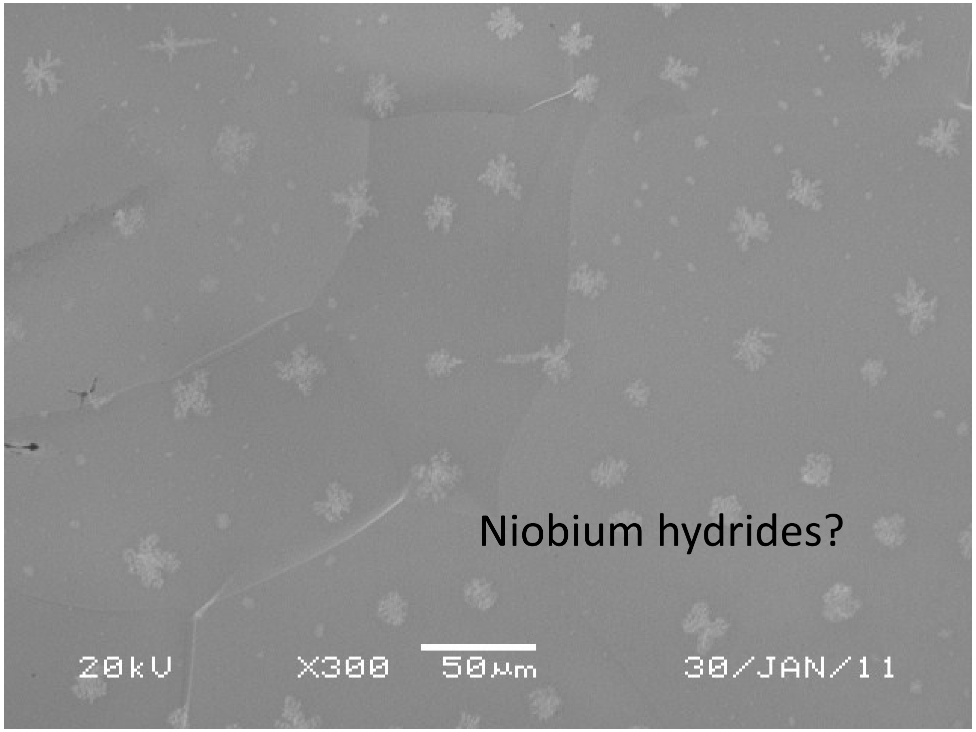
Lossy areas


Temperature map
Bottom Iris
Top Iris
Thermometer #
17
16
14
12
10
8
6
4
2
1
0
5
10
15
20
25
30
36
Azimuth
0.100
0.050
0.000
ΔT (K)
Scale Min
0
Scale Max
0.1
130-7 hot spot
150-10 hot spot
90-7 cold spot

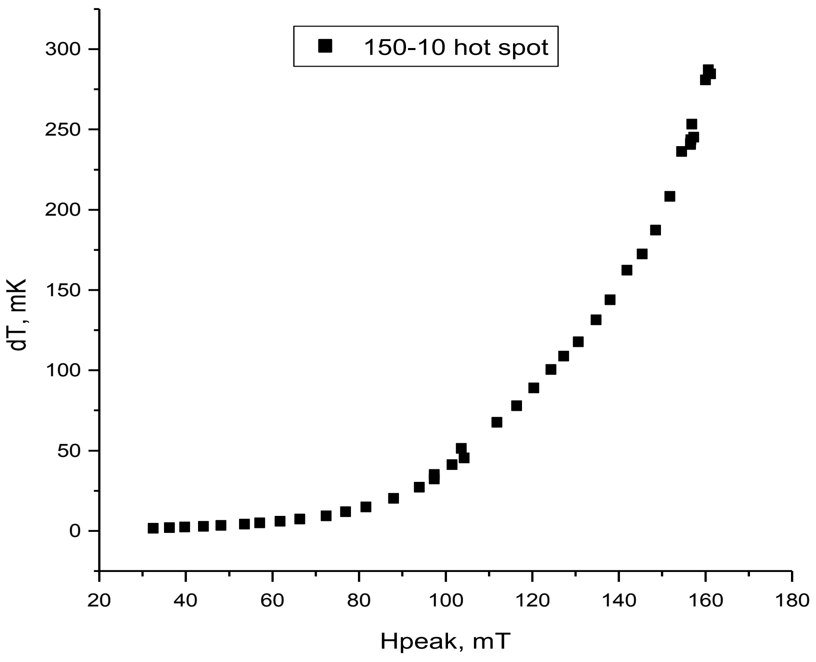
130-7 hot spot

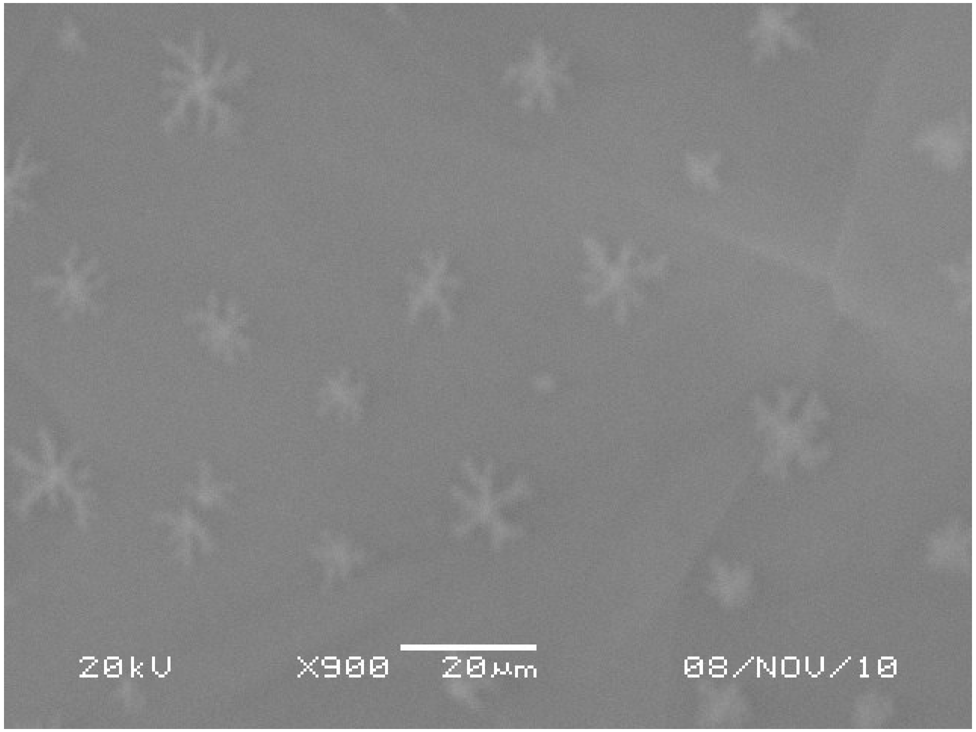




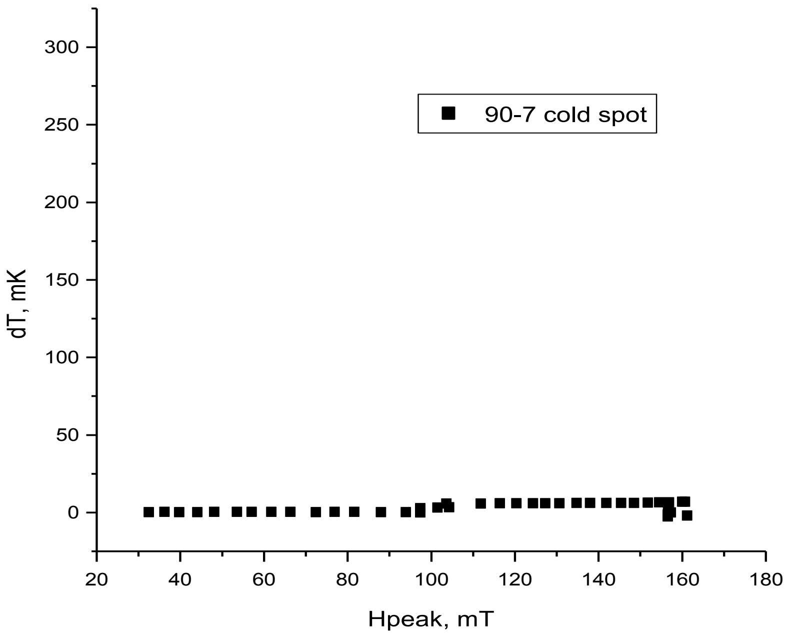


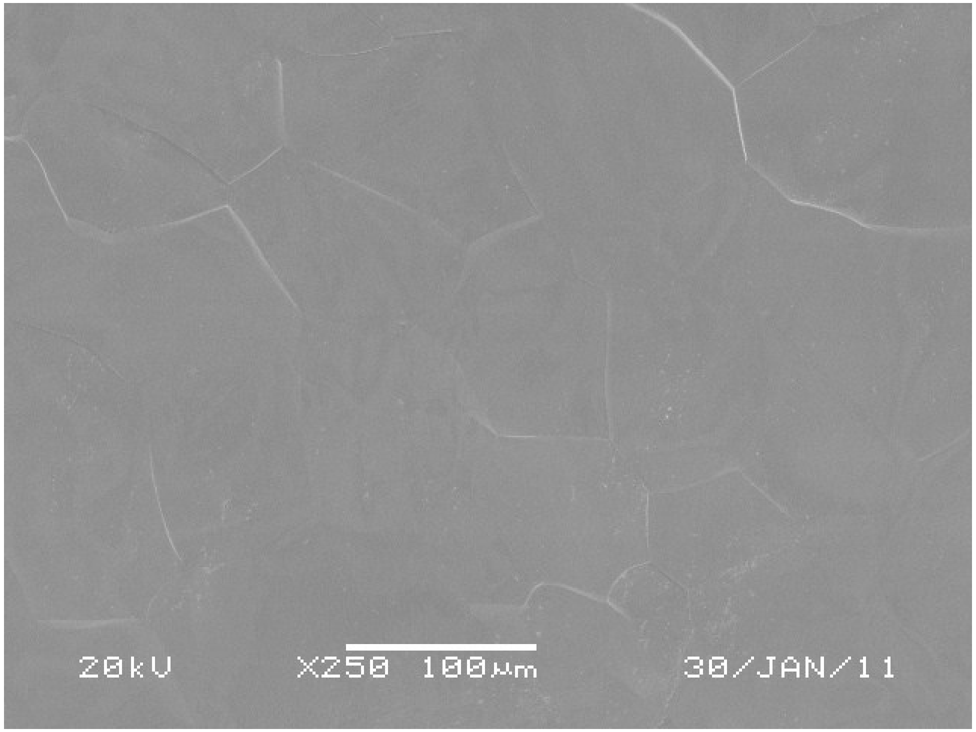
150-10 hot spot





90-7 cold spot

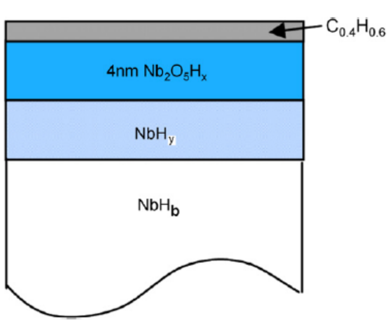


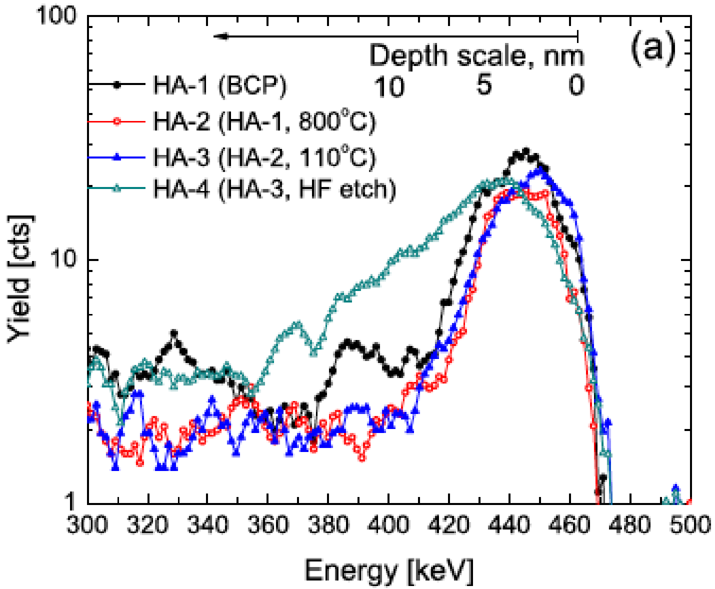


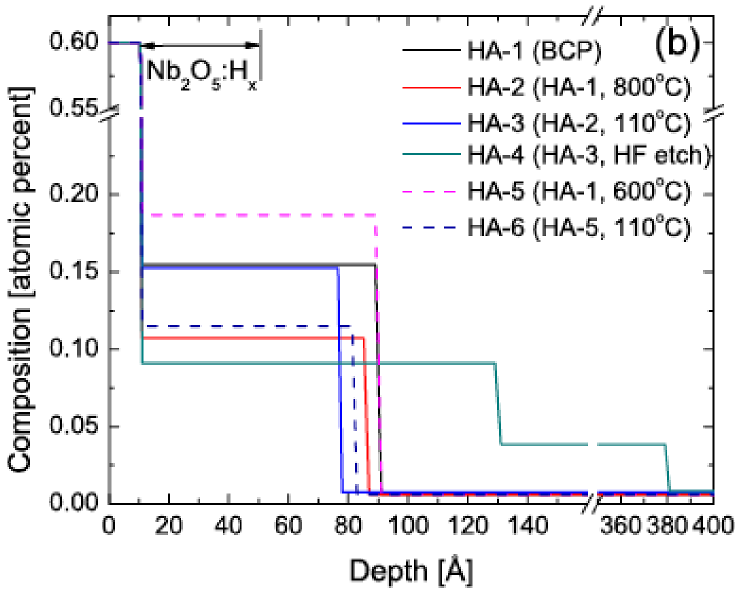
Elastic recoil detection in collaboration with Univ. of Western Ontario – near-surface hydrogen

A. Romanenko and L.V. Goncharova, 2011 Supercond. Sci. Technol. 24 105017

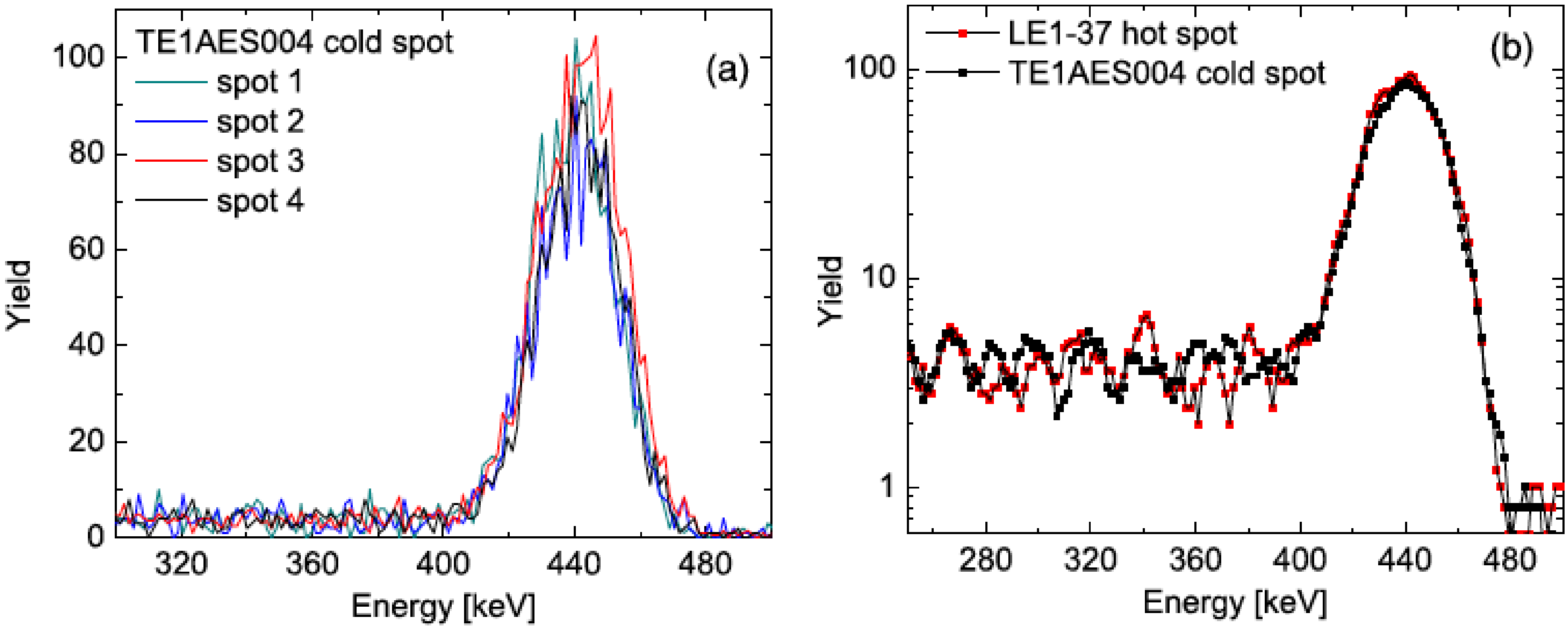
Sample	Treatment	Enriched layer (nm)	*x*	*y*	*b*
HA-1	BCP 150 μm	4	0.15	0.15	0.008
HA-2	BCP 150 μm + 800 °C 4 h	3.6	0.11	0.11	0.006
HA-3	BCP 150 μm + 800 °C 4 h + 110 °C 74 h	2.7	0.15	0.15	0.008
HA-4	BCP 150 μm + 800 °C 4 h + 110 °C 74 h + HF rinsing 20 min	8/25	0.09	0.09/0.04	0.008
HA-5	BCP 150 μm + 600 °C 10 h	4	0.19	0.19	0.006
HA-6	BCP 150 μm + 600 °C 10 h +110 °C 54 h	4	0.11	0.11	0.006
LE1-37 hot spot	BCP 200 μm	0.7	0.16	0.16	0.006
TE1AES004 cold spot	EP 120 μm + 120 °C 48 h	0.7	0.16	0.16	0.006







Hot/cold spot cutouts – same hydrogen content



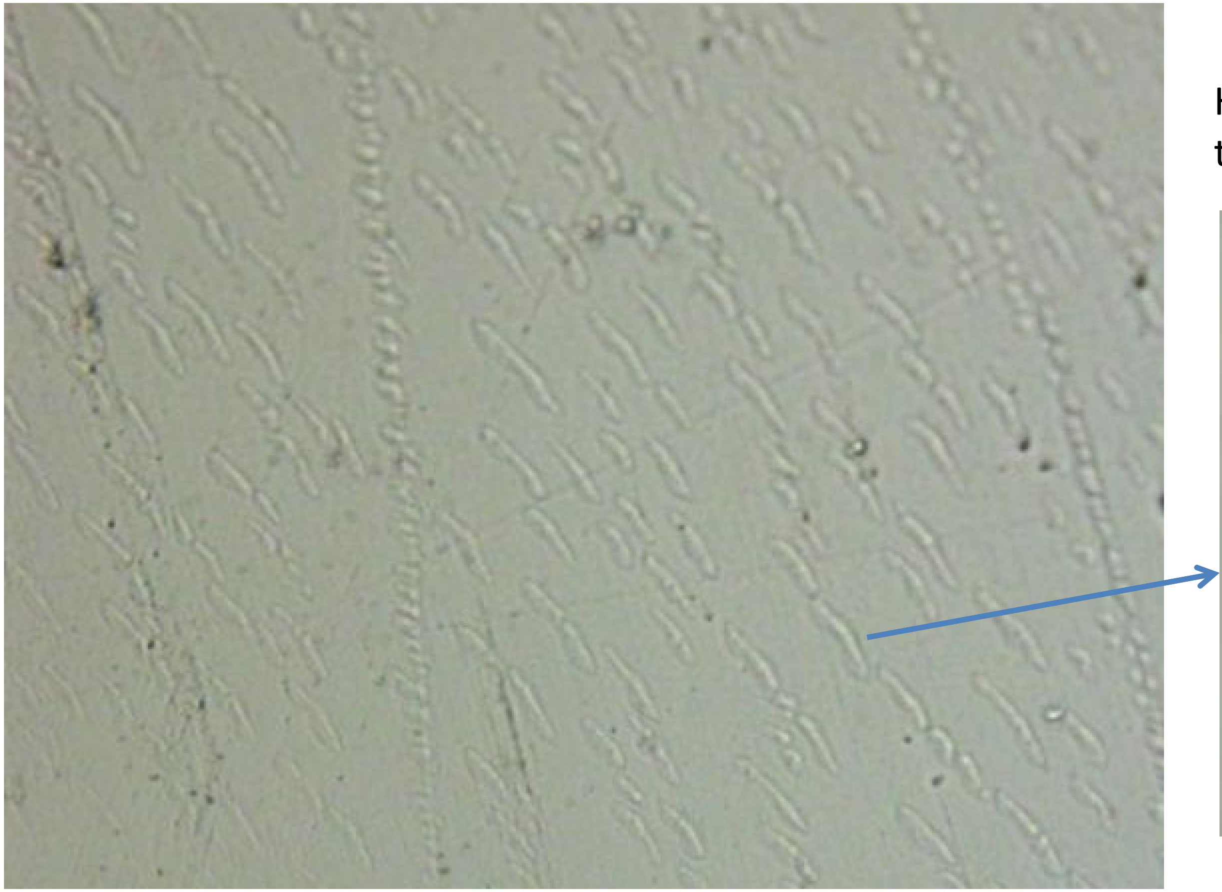
A. Romanenko and L.V. Goncharova, 2011 Supercond. Sci. Technol. 24 105017

Hydrides – what do we know in SRF

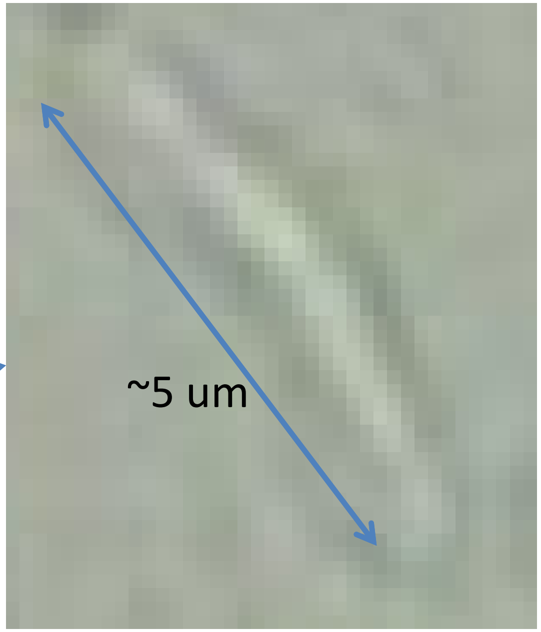
- First came to the spotlight due to the occurrence of "Q-disease" in 1989-1991
- Hydrides formed during cooldown accepted as a cause
  - Remedies quickly found
    - 800C vacuum anneal for 2 hours to eliminate bulk hydrogen
    - Fast cooldown through the 150-70 K range where hydrides form
- BUT - never studied in detail – what these hydrides are, is it a layer or islands etc – we decided to explore!

NEW - surface relief due to hydrides on single grain cavity-grade niobium (mechanically polished)

After 77K hold



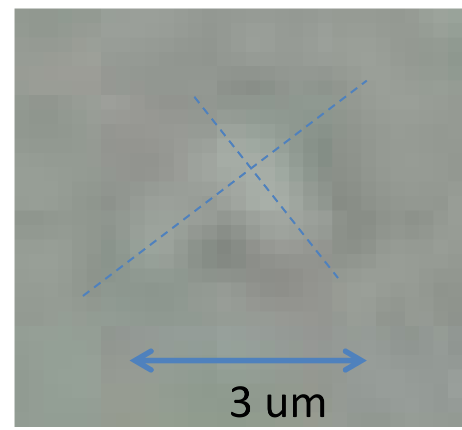
Hydride morphology depends on the crystallographic orientation



NEW - surface relief due to hydrides on fine grain cavity-grade niobium (mechanically polished)

After 77K hold

Hydride morphology depends on the crystallographic orientation



After 800C treatment

- No hydride surface relief present after hold at 77 and 150 K
- QUESTION – Are hydrides not present or are they too small to produce any observable surface relief in the optical microscope?
  - Need techniques with sensitivity for such precipitates

Advanced Photon Source SAXS studies – directly look for small hydrides

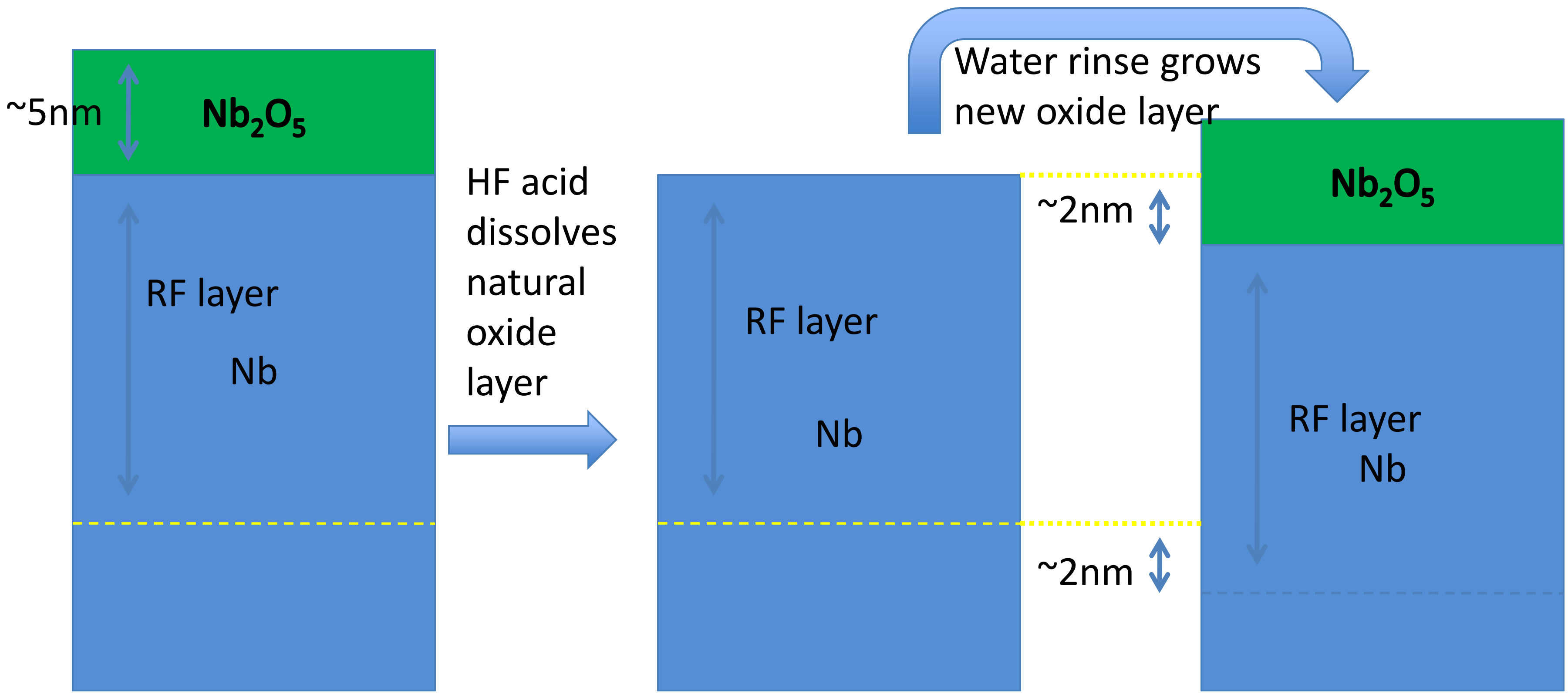
- Collaboration with Prof. Heuser (UIUC)
- Use small angle X-ray scattering at APS/ANL to look for near-surface hydrides on cavity cutout samples at T~10K
  - Study their volume density and size distribution
- Proposal submitted on Mar 9, 2012

Cavity "HF rinsing" experiments

- Purpose: explore the distribution of losses within the RF layer (~40 nm)
- Means:
  - Hydrofluoric acid rinsing as a "nanostripping" method - ~2 nm/step
  - Cavity Q(H) measurements after each HF rinse

A. Romanenko and J. Ozelis, Proceedings of SRF'11, ThPO022
A. Romanenko, TTC Meeting 2011

Hydrofluoric acid rinse – "nanostripping"



Each HF/water rinse step consumes about 2 nm of niobium from the top of the RF layer determining the surface resistance and moves deeper into the bulk – depth profiling of the losses is possible

HF rinse procedure

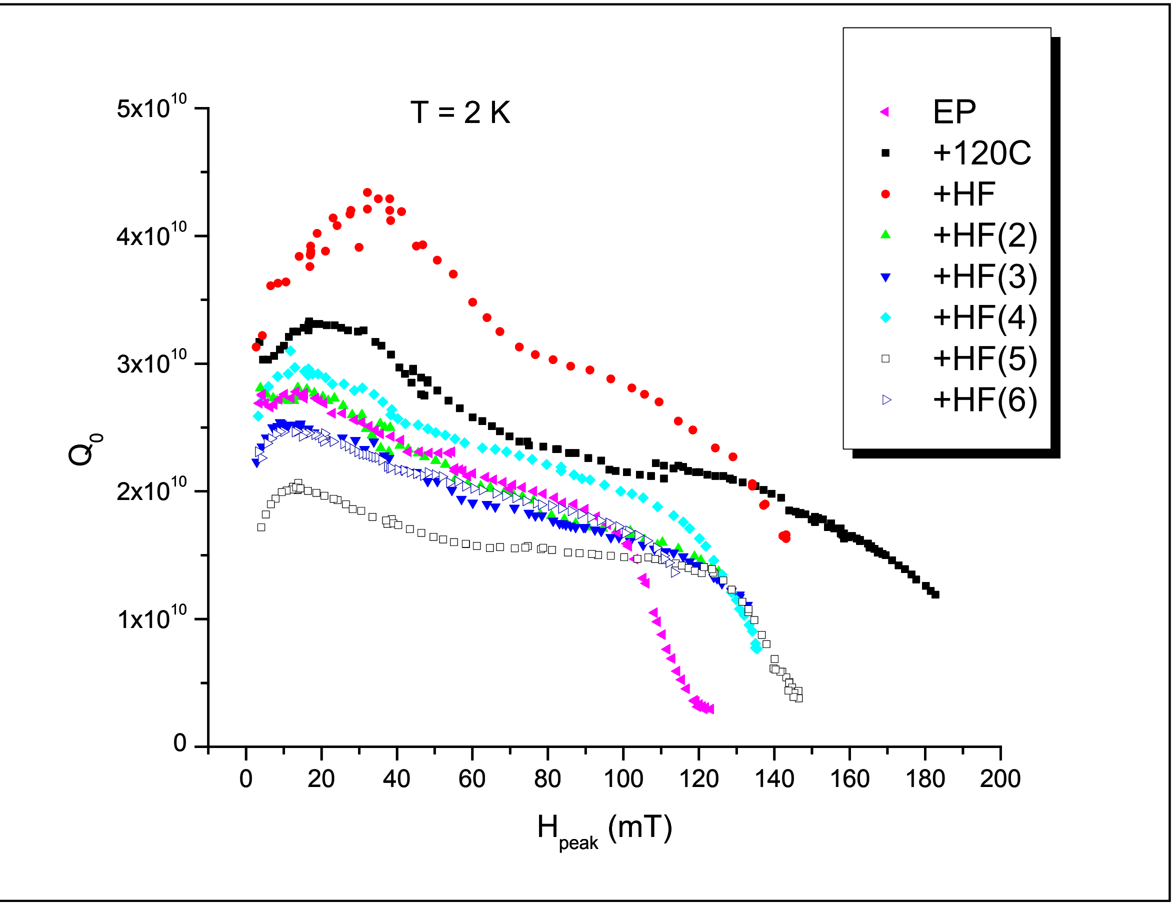
Filling with HF

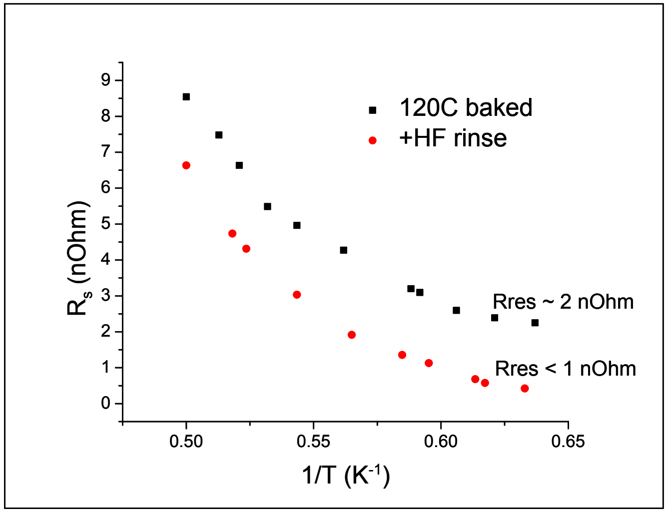
5 minutes hold

HF dumping

DI water rinse

Electropolished fine grain tumbled cavity

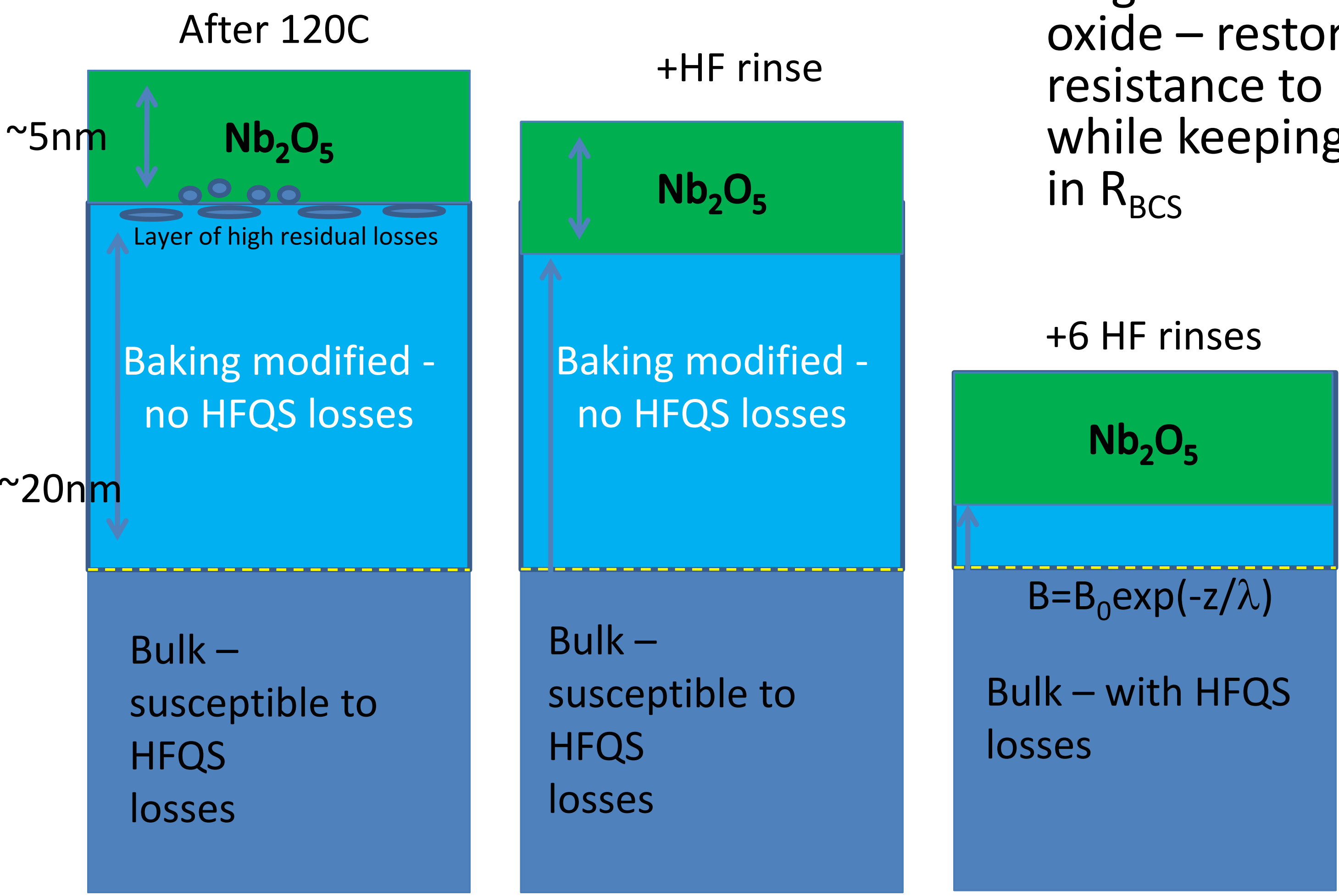




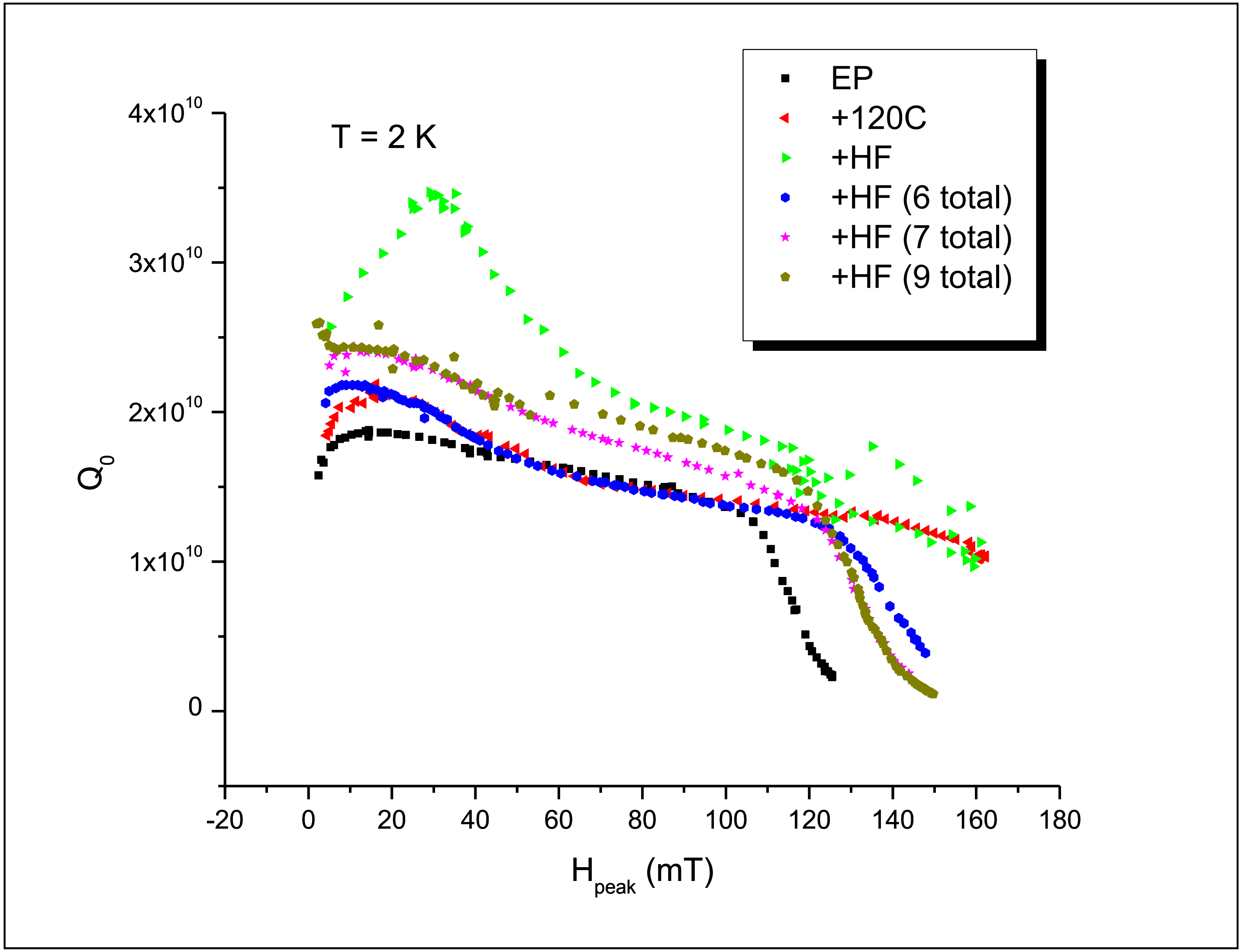
- ✓ Single HF rinse after mild baking significantly improves medium field Q0
- ✓ Multiple HF rinse cycles do bring the high field Q-slope back – but with higher onset!

Possible interpretation

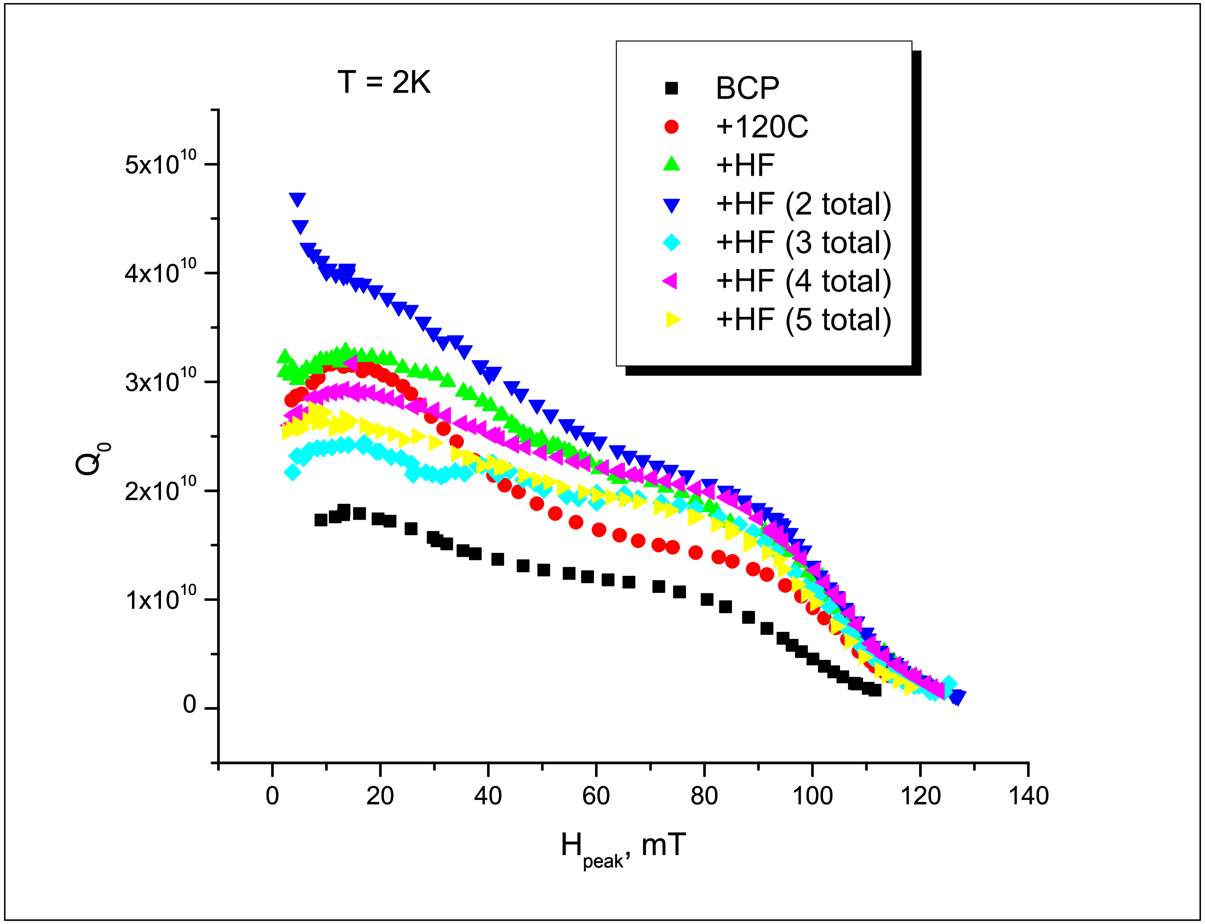
- Literature – 120C enhances residual resistance; possibly due to suboxide formation
- Single HF rinsing and regrowing oxide – restores residual resistance to pre-bake state while keeping the improvement in R_{BCS}



Electropolished fine grain cavity

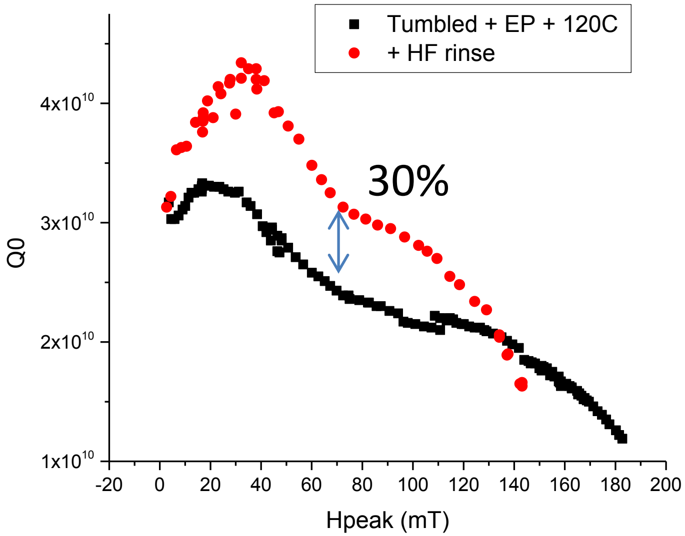


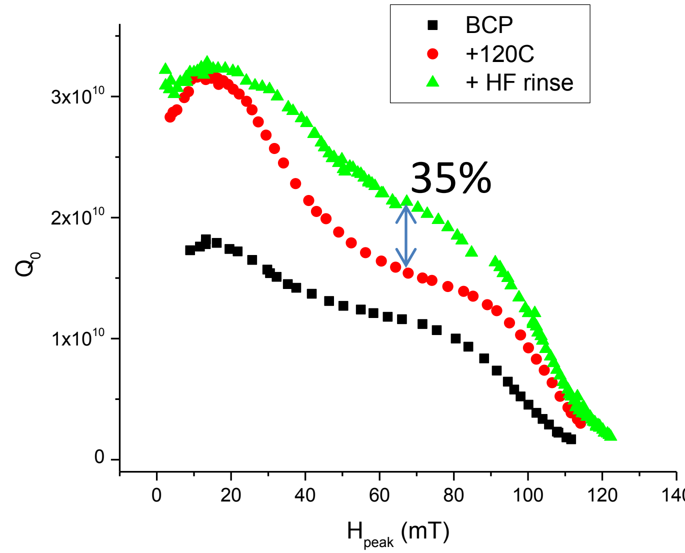
Results on BCP fine grain cavity

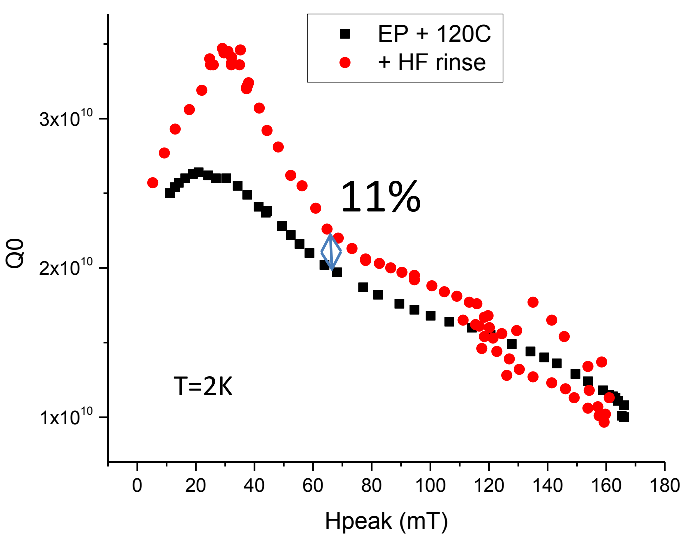


- ✓ Single and double HF rinse cycles significantly improve medium field Q0
- ✓ High field Q-slope is present after mild baking (typical of fine grain BCP)

Simple higher Q_0 recipe



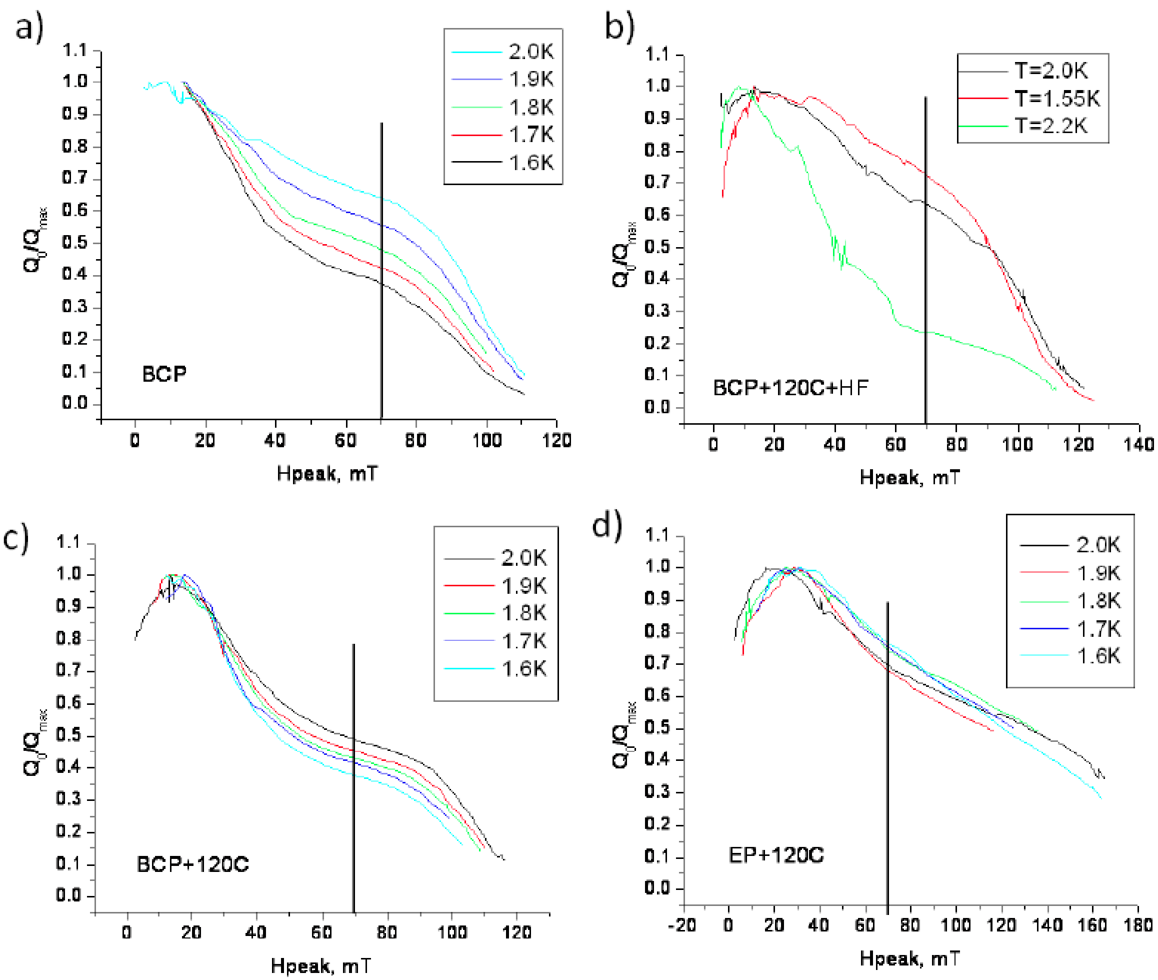


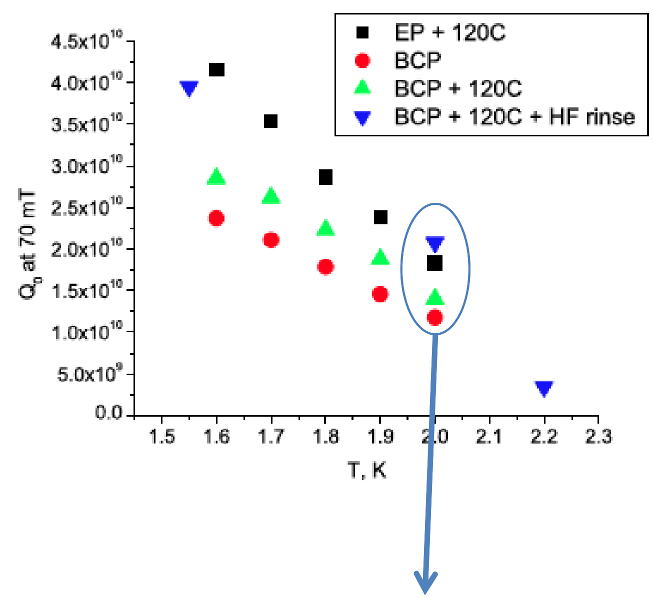


- Single HF rinse (5 min) followed by water rinse is beneficial for the medium field Q value – gains of up to 35% measured at 70 mT

Medium field Q studies

Range of Q-slopes for different surface treatments





BCP may be good enough for Project X?

A. Romanenko et al, Proceedings of PAC'11, TUP085

Brief summary

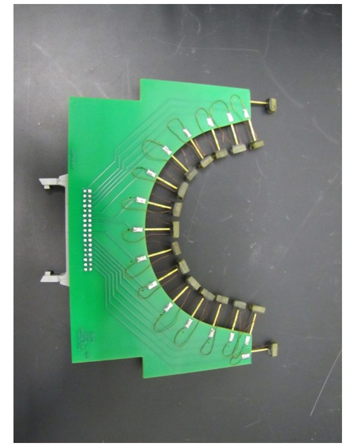
- Near-surface hydrogen enrichment found
  – Previously thought 800C removes all H
- Niobium hydrides artificially created on cavity-grade niobium, properties studied
- Simple way to increase Q_0 of existing cavities at medium fields up to 35% developed – HF rinse
- Carbon-rich inclusions found on the high field quench spot
- Preliminary optimization of medium field Q using existing treatments

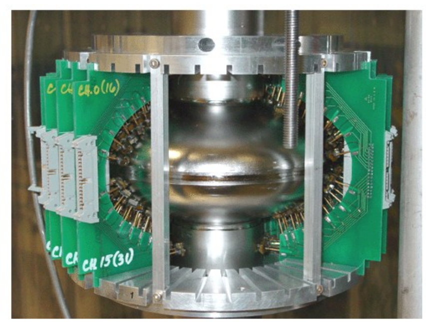
Future plans

- Continue systematic exploration of the near-surface structure/superconducting properties of niobium coupled with cavity experiments
  - DOE Early Career Award - 2.5M$ over 5 years
- Develop best recipe for the highest Q_0 in cavities for CW machines – i.e. Project X, NGLS

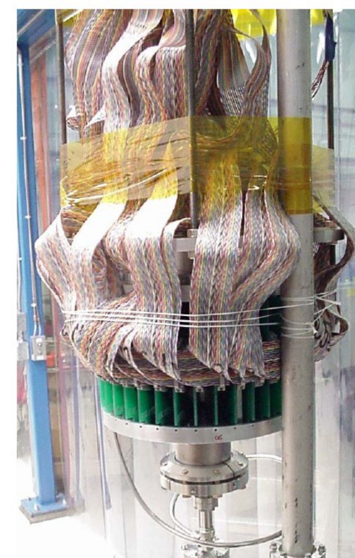
Brand new T-mapping system

- A new 1.3 GHz single cell T-mapping system built based on JLab design
  - 576 custom-made sensors based on Allan-Bradley carbon resistors
  - <~1 mK resolution at 2K
- We vitally needed one for all basic SRF research – will give us a strong boost!



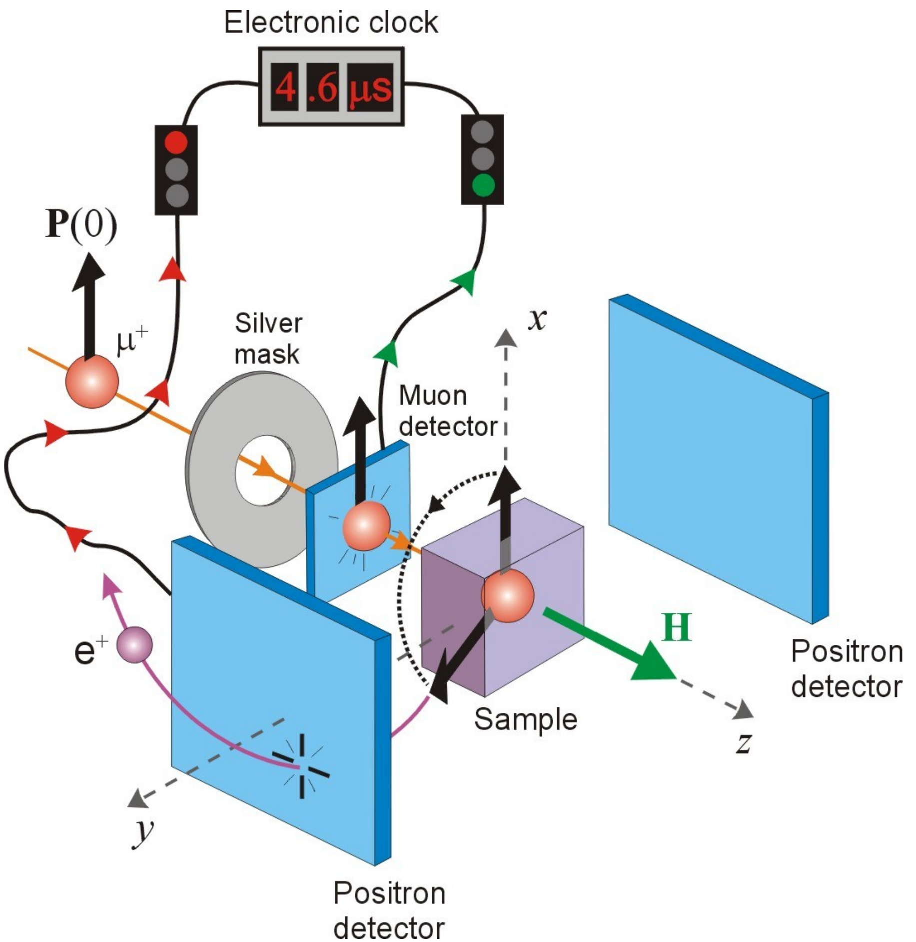


a)



b)

Muon Spin Rotation (muSR)

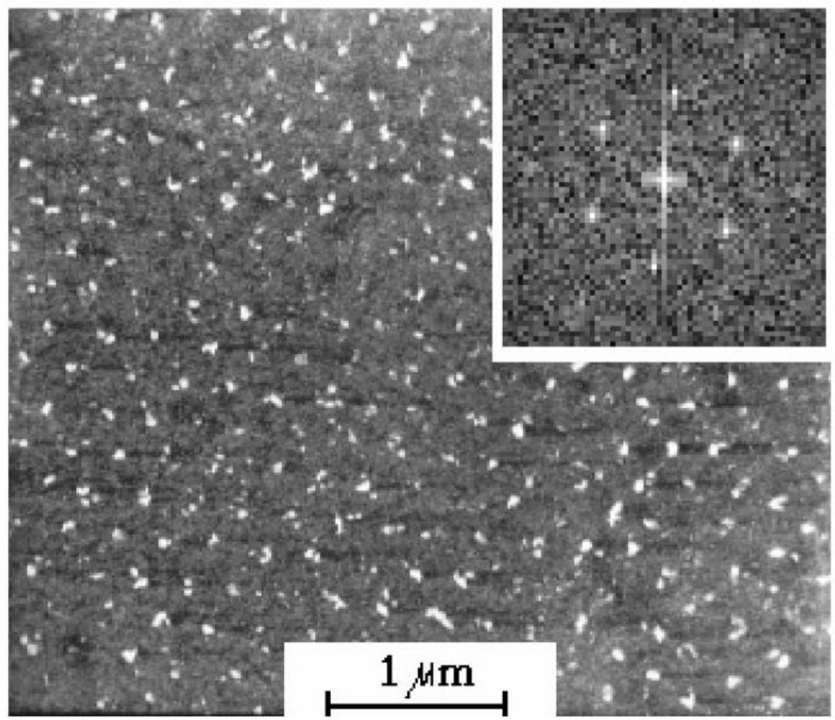


- Directly measure superconducting properties INSIDE cavity cutouts using bulk (TRIUMF) and surface (PSI) muSR
- TRIUMF – proposal approved Dec, 2010, waiting for beam time
- Paul Scherer Institute – technical study approved, measurements early June, 2012

Bitter decoration at ISSP, Russia

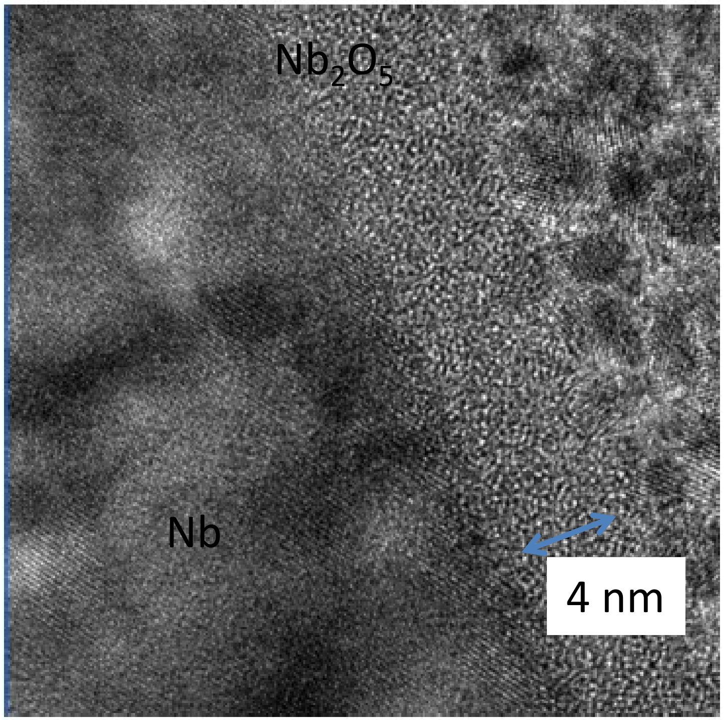
- Measurements to be performed in April-May, 2012

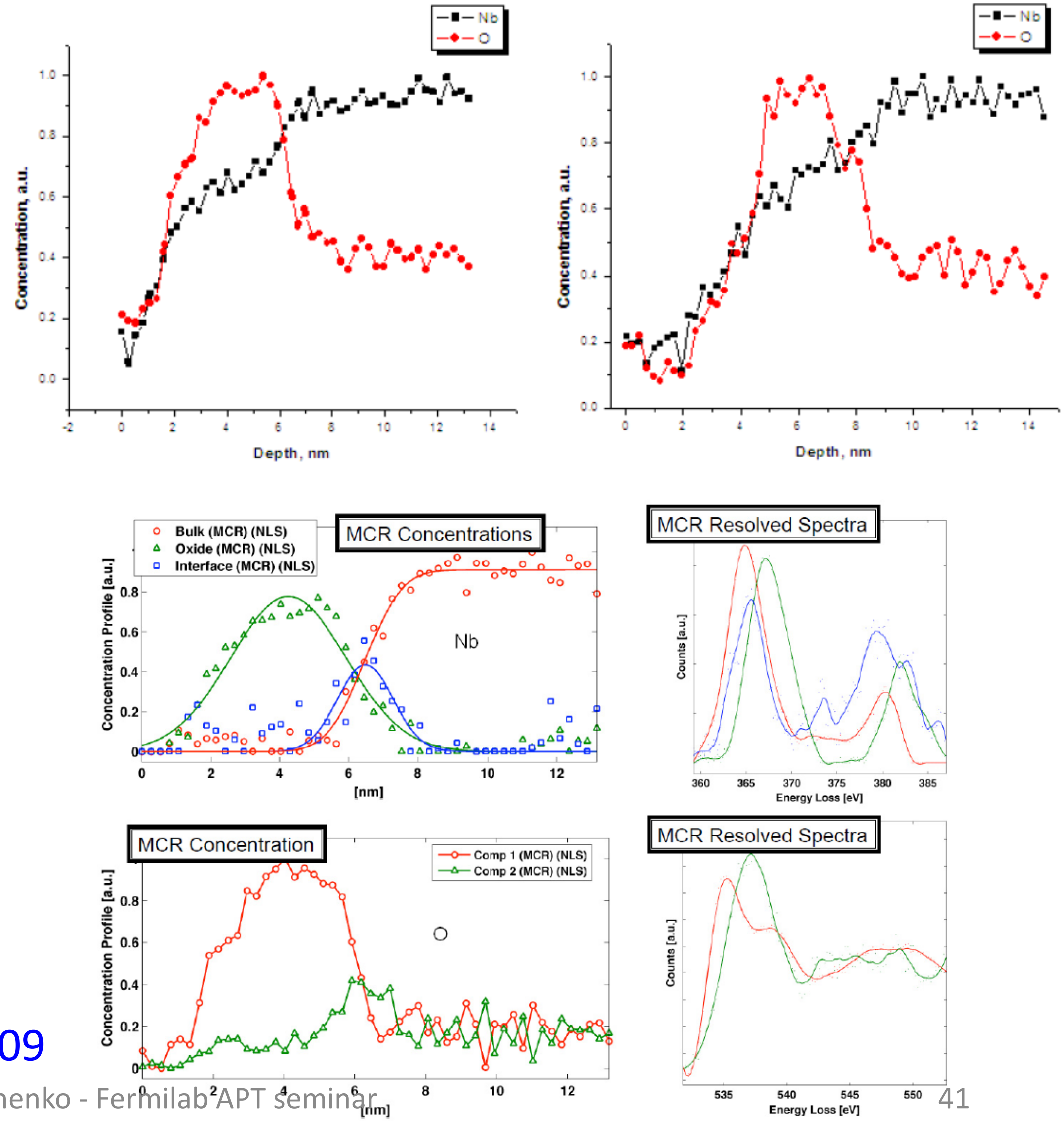
Visualize magnetic vortex lattice on the surface by ferromagnetic nanoparticles – what is the difference between cutout samples with different RF losses?



F. L. Barkov et al, Phys. Rev. B 64, 024504 (2001)

(S)TEM/EELS – material structure details needed after all surface treatments





No evidence for difference in oxide/oxygen structure

A. Romanenko et al, Proceedings of SRF'09

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