Raising Medium Field Q_0: Ways to Proceed

A. Romanenko

Outline

- Importance of Q_o for CW applications
- State of the art in SRF niobium cavities
- Contributors to medium field Qo
  - Proposed models and recent developments
- Possible ways to increase Q_o
- Proposed research effort

Project X (CW): Q_0 is crucial

$Q_o = \omega U/P_{diss} = G/R_s$

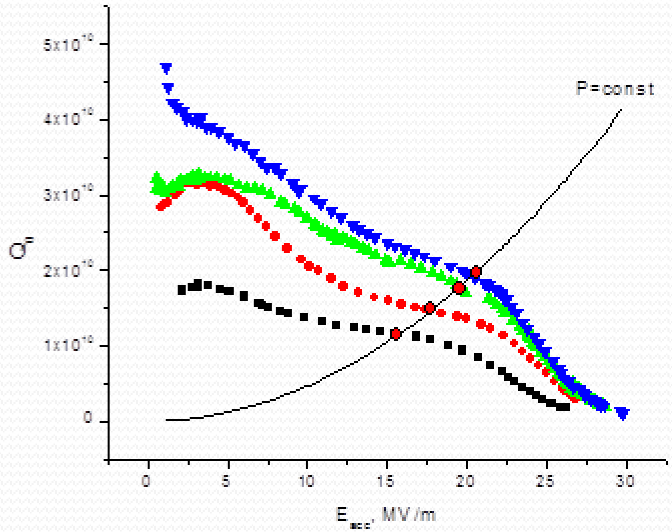
Surface resistance

Q-slopes

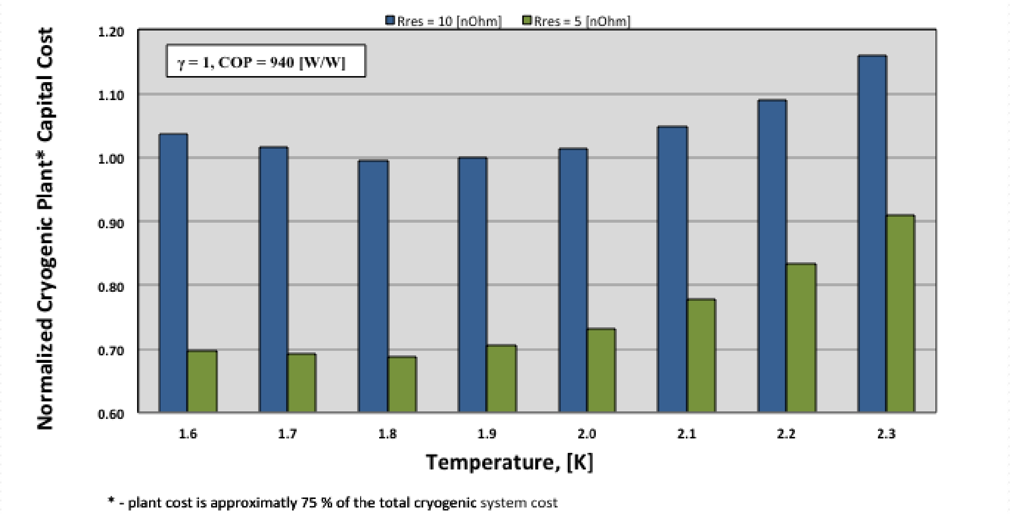
$R_s = (R_{BCS}(T) + R_{res})*f(H)$

[Equality only holds for $R_s(H)$ = const]

Power dissipated in cavity walls P_{diss} => determines dynamic
heat load => requirements for cryogenic power plant

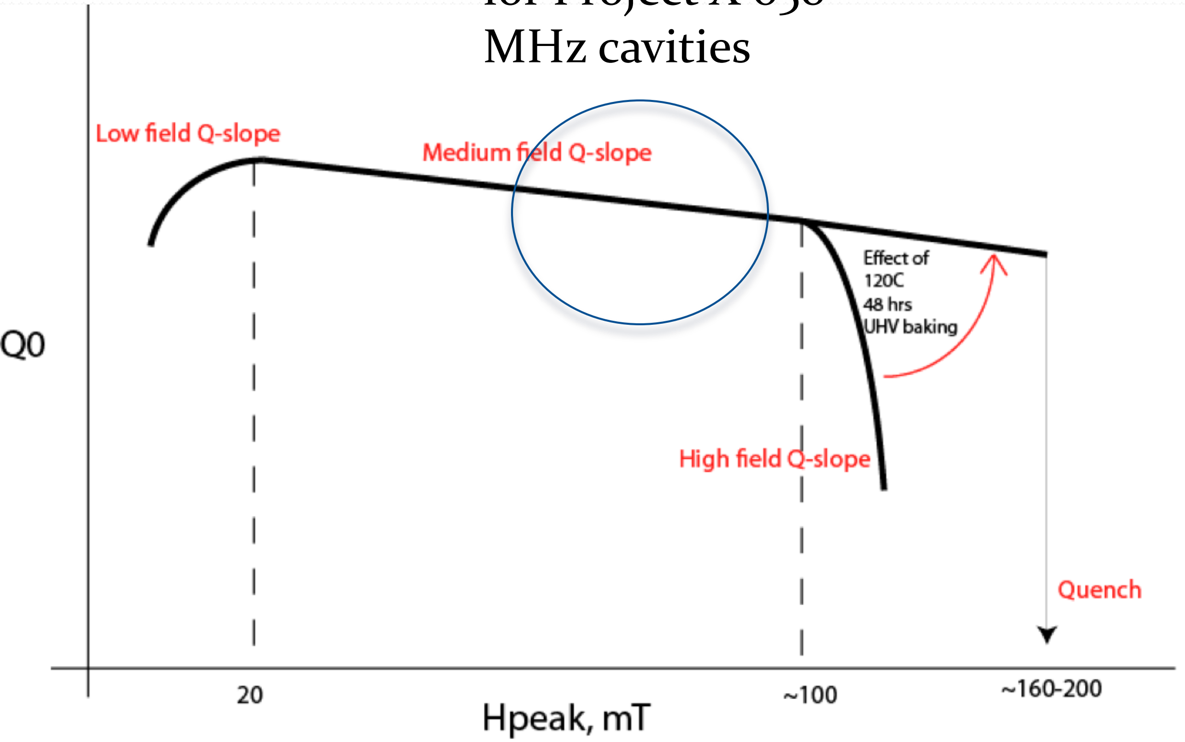


Project X cryoplant cost – determined by Q_o
[A. Klebaner et al, PX 2011 Collab. Meeting]



Excitation curve $Q(H_{peak})$

Operational gradients for Project X 650 MHz cavities



- Three distinct regions of the Q-curve – low, medium, and high field Q-slope
- Respond differently to heat and chemical treatments
  - Most likely different origin
- ILC standard processing – EP+120C to overcome high field Q-slope to reach highest gradient
- THERE IS NO OPTIMIZED RECIPE FOR MEDIUM FIELD Q YET
  - Interest has grown only recently, nobody really worked on it

Factors affecting Q_0

- Many phenomena understood and controlled
  - Multipacting
  - Field emission
  - Hydrogen Q-disease
- Main problem – lack of clear understanding and control of remaining ones
  - Residual resistance
  - Low, medium, high field Q-slopes

Residual resistance

A few mechanisms have been identified:

- Trapped flux due to residual magnetic field on cooling
  - Minimized by shielding
    - Is there more we can do? Maybe modifying things from the material point of view? Like decreasing pinning or maybe increasing depending on what the dissipation mechanism is
- Niobium hydrides
  - More on this later
- Condensed gases
- All contributing factors not yet uncovered – no control based on knowledge

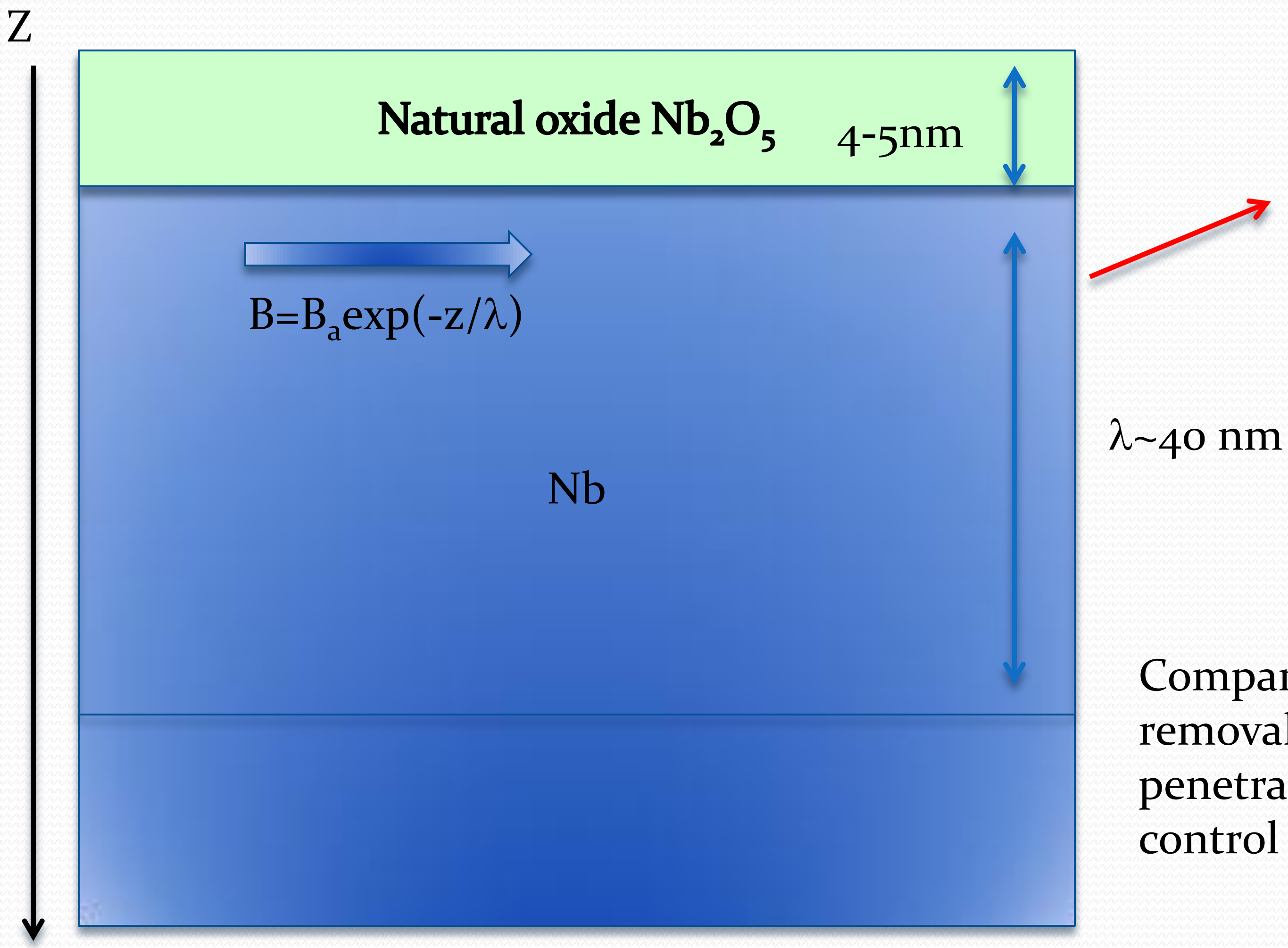
Medium field Q-slope (MFQS)

- Historically proposed mechanisms include
  - Thermal feedback
    - R_{BCS}~exp(-1/T)=>T up=> R_{BCS} up – positive feedback
    - Problem – underestimates the slope, not the only player
  - Hysteretic losses due to Josephson fluxons penetrating at "weak links" (came from the observation that often MFQS has linear component in it)
    - $R_s=R_{so}(1+b^*H/H_c)$
  - Non-linear BCS
    - $\Delta(v_s) = \Delta - p_f|v_s|$=> decreased gap => $R_s = R_{so}(1+C(\Delta/T)^2(H_o/H_c)^2)$
    - Problem – overestimates the slope

Newer findings

- Hydrides might actually ALWAYS be present – strong effect on medium field Q via R_{res}, may also be $R_{res}=R_{res}(H)$
  - A lot of hydrogen in all samples near surface (ERDA studies, Romanenko, Goncharova, SRF'2011, submitted to PRSTAB)
  - Hydride precipitates identified and directly observed for the first time in a single cell (Cutout studies, Romanenko et al, SRF'2011)

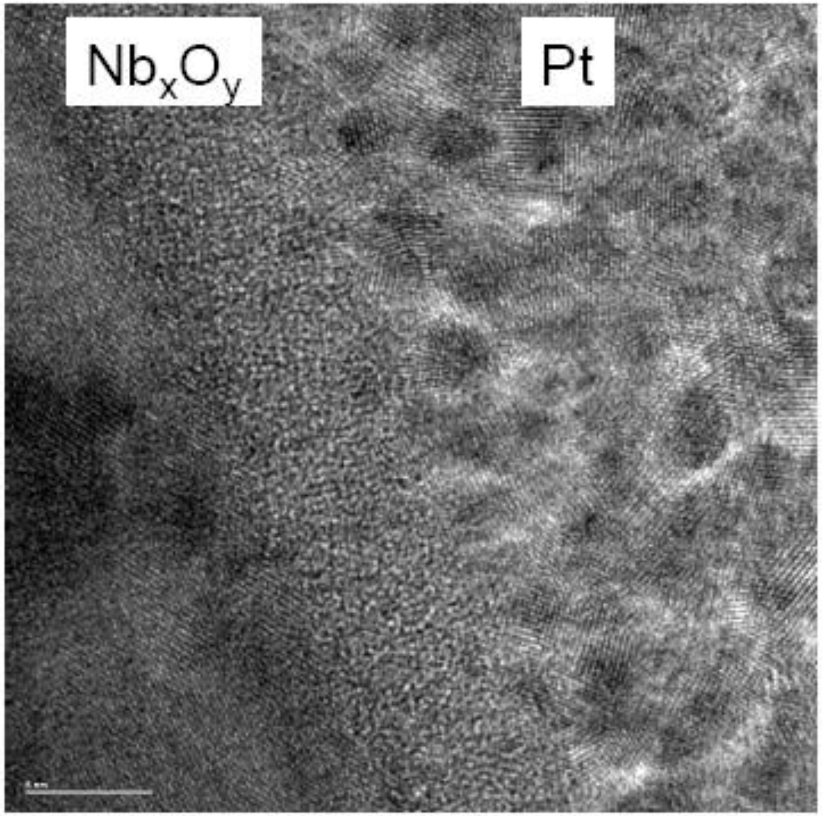
Cavity surface

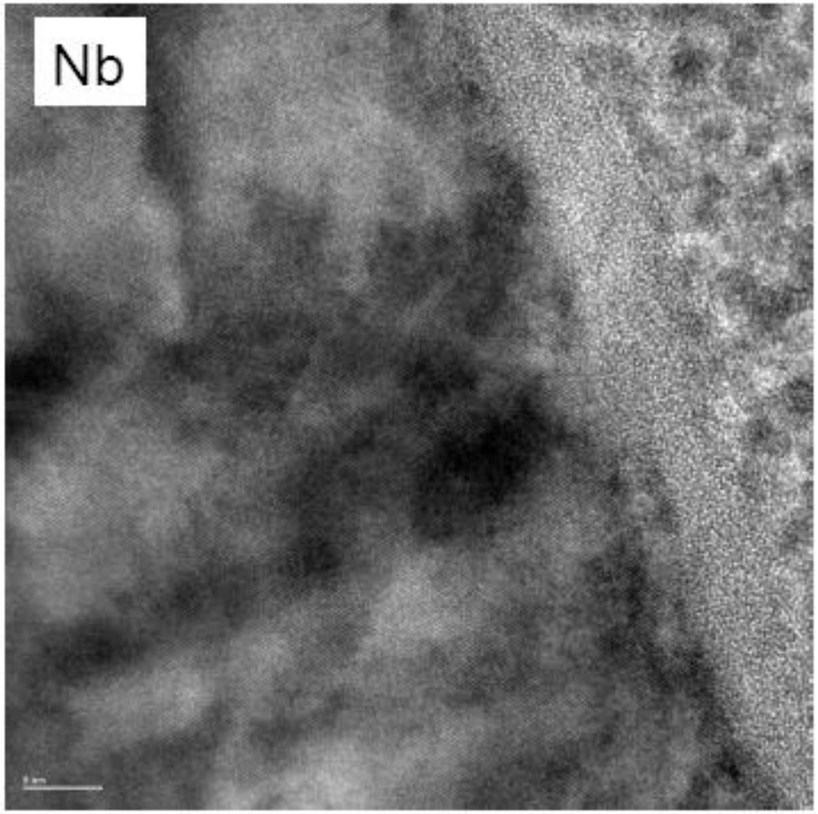


Processes, which can modify this layer in a controlled manner are of special interest

Compare: “Light EP” or 20 um removal = approximately 500 penetration depths – no control

TEM images of Nb near-surface

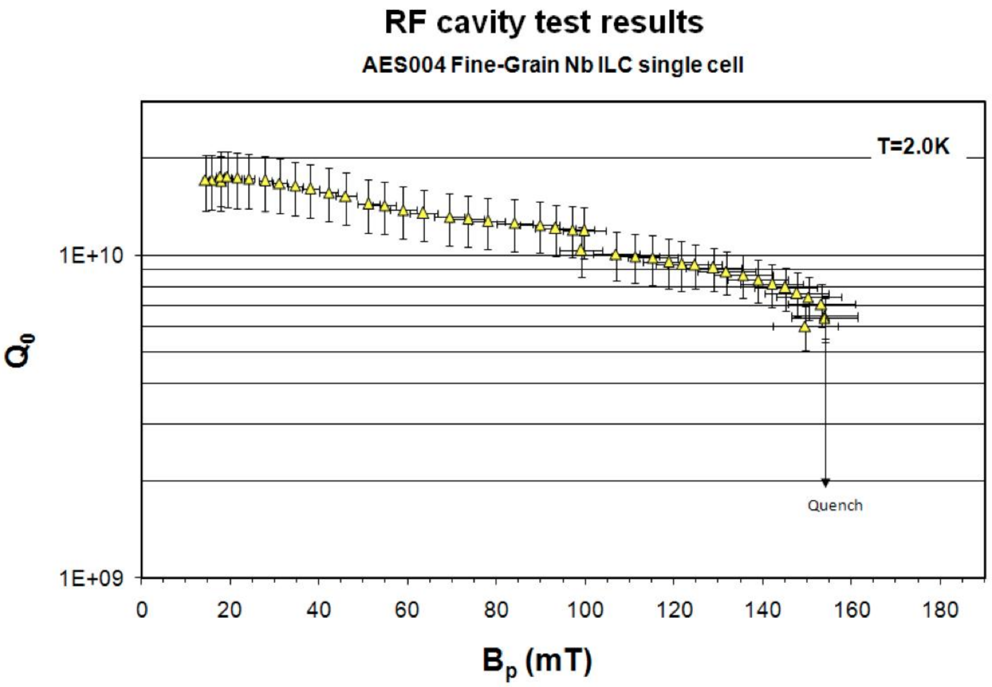


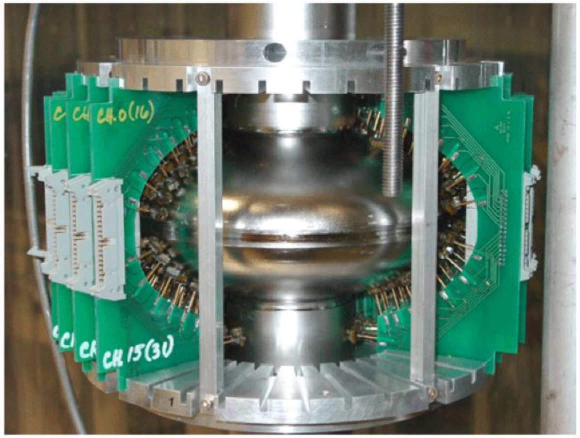


[Romanenko et al, SRF'2009, TuOAAU02]

Unexpected finding - HYDRIDES

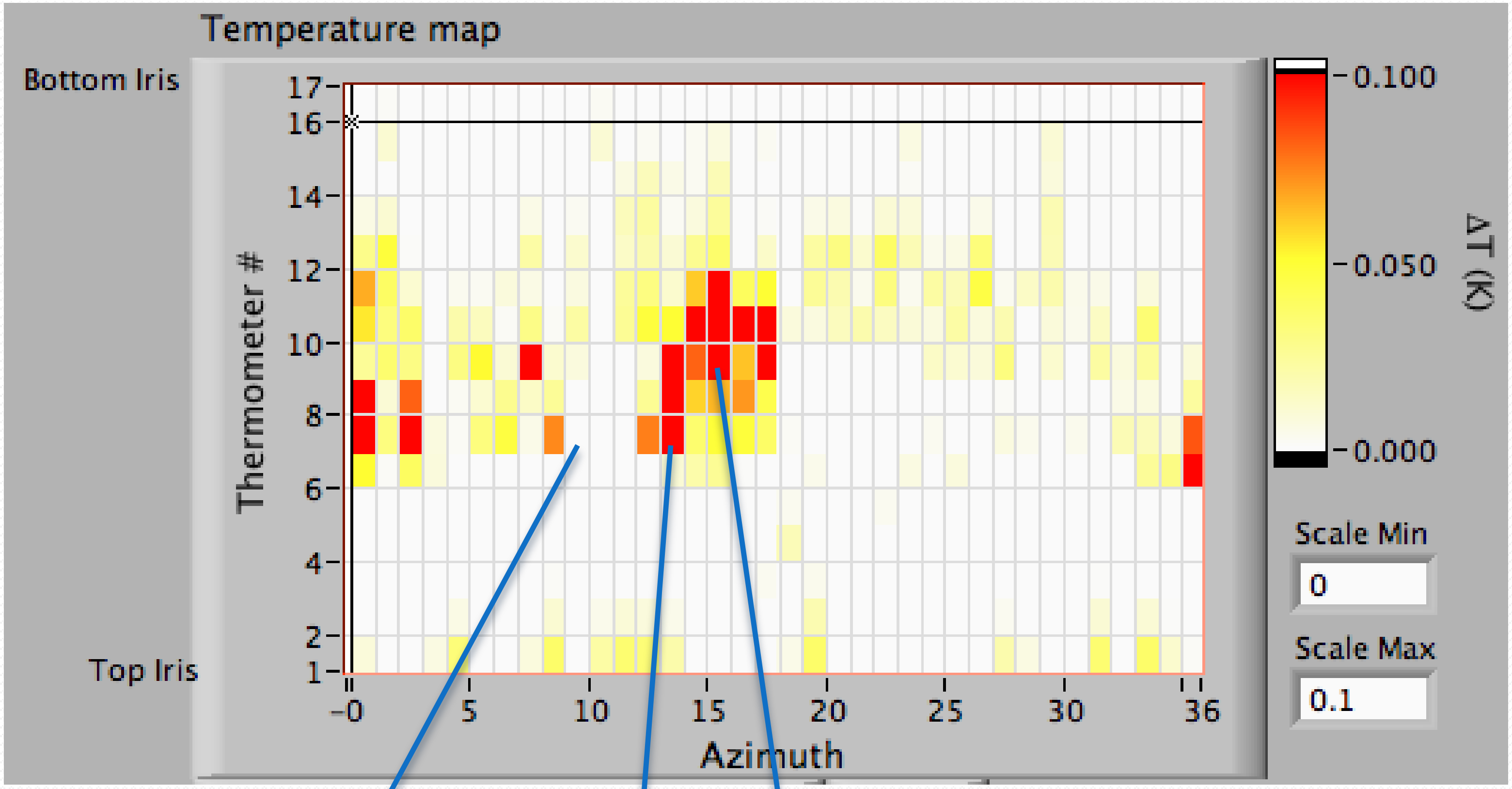
- 1.3 GHz fine grain single cell
  - EP+120C bake at ANL/FNAL
  - RF tested at JLab with thermometry last year (collaboration with G. Ciovati)





Thermometry system attached to outside cavity walls

Lossy areas AFTER mild baking

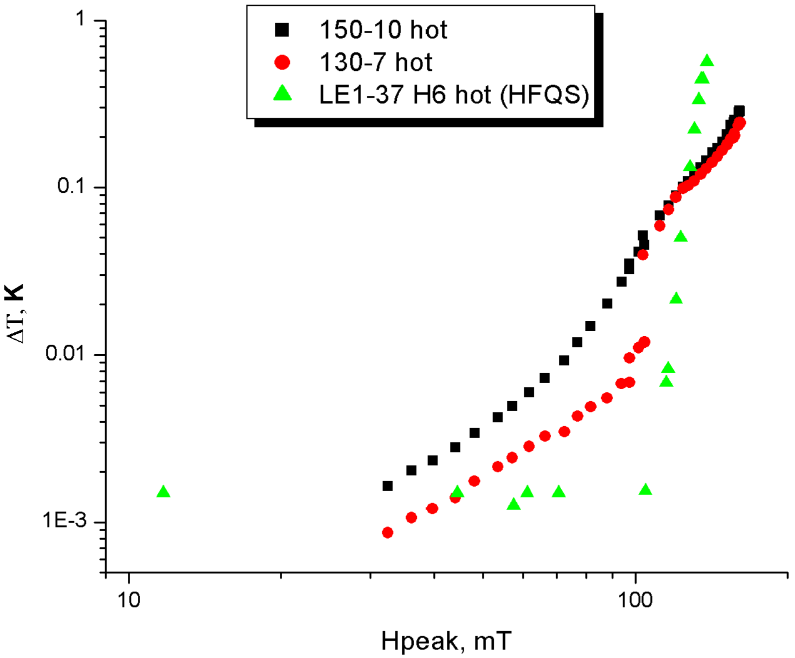


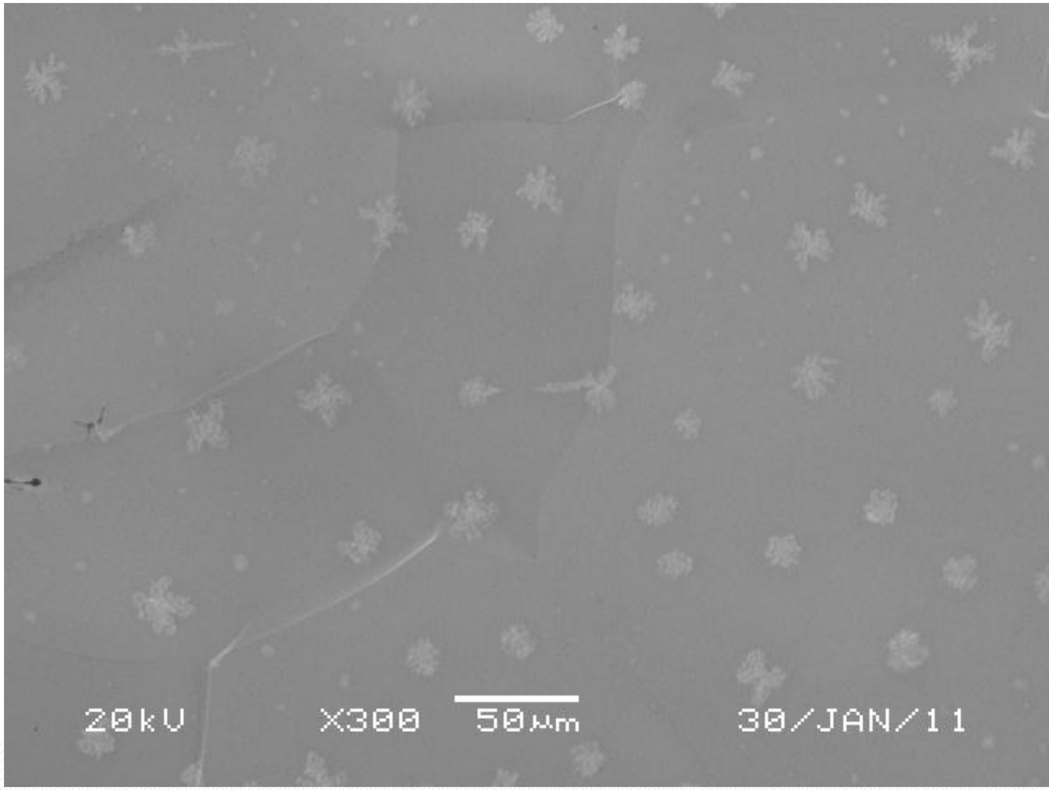
130-7 hot spot

150-10 hot spot

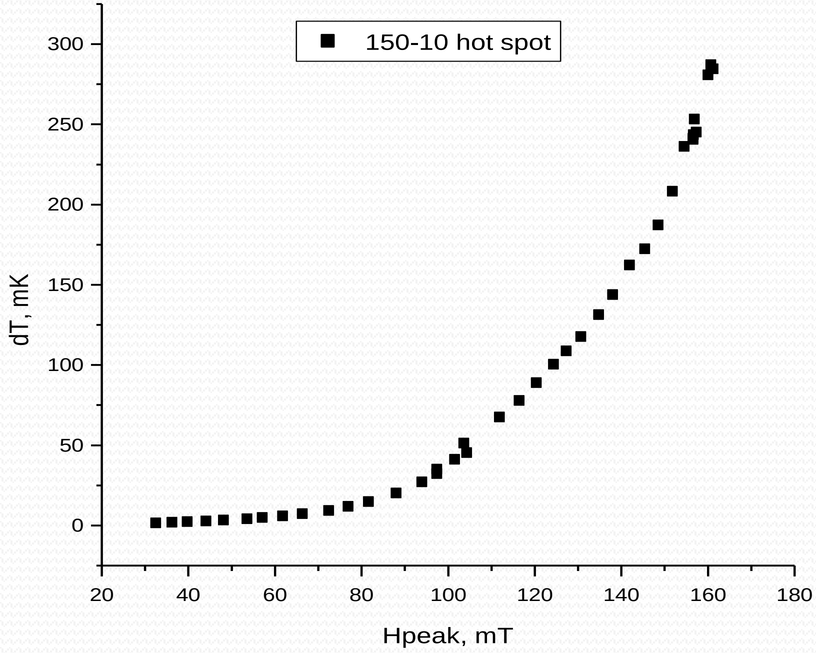
90-7 cold spot

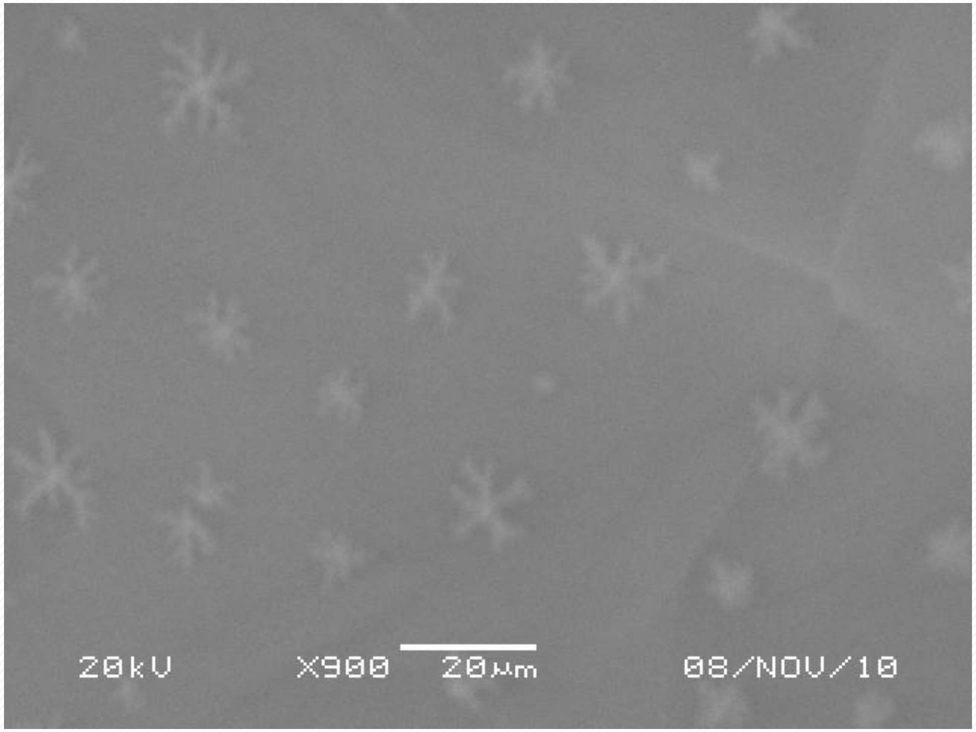
130-7 hot spot



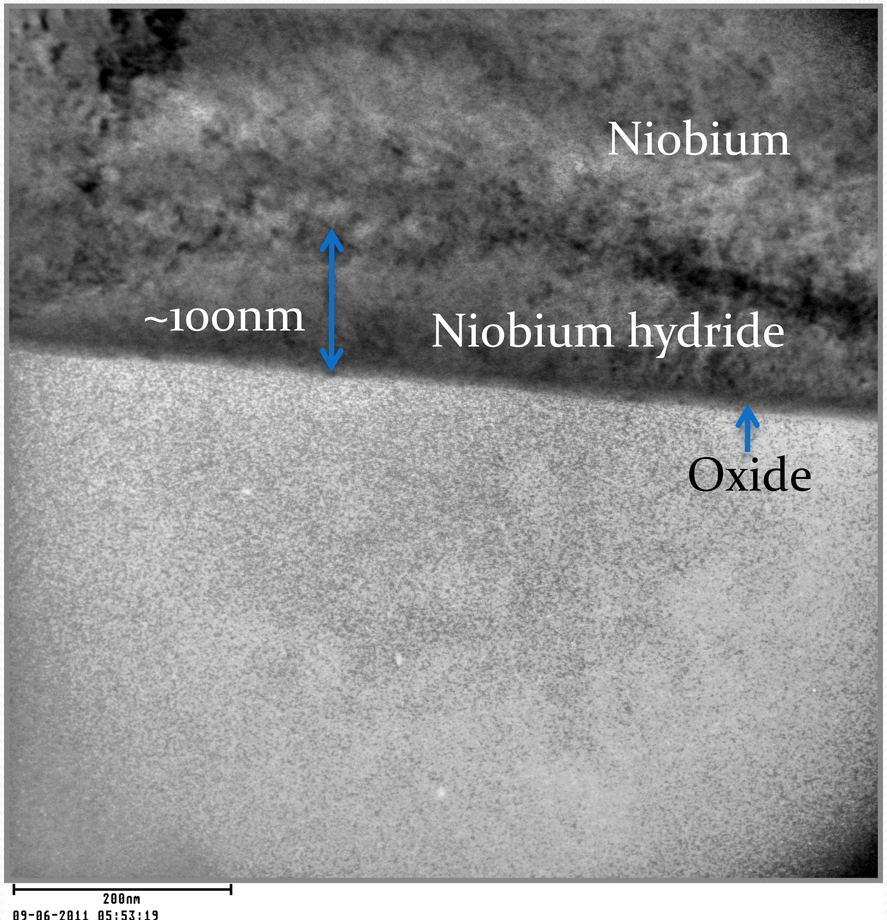


150-10 hot spot

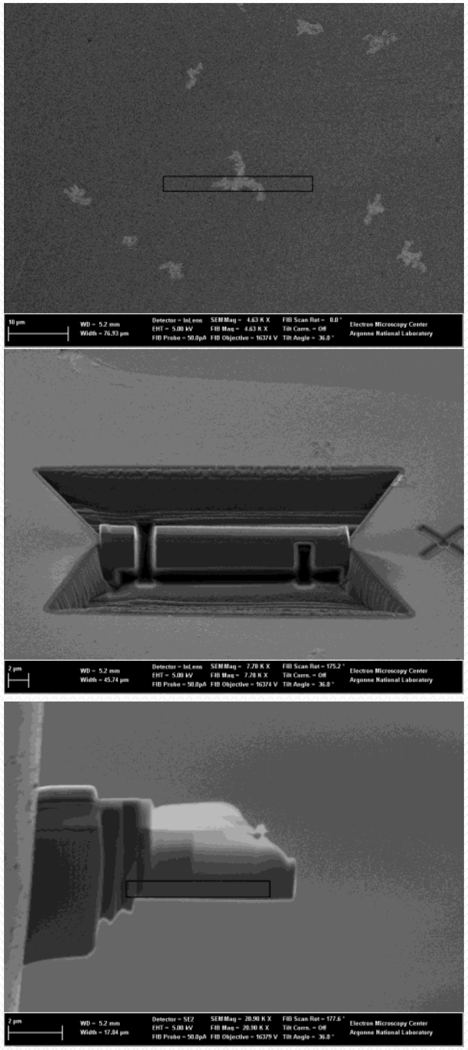




TEM: detailed structure of “stars”



TEM image

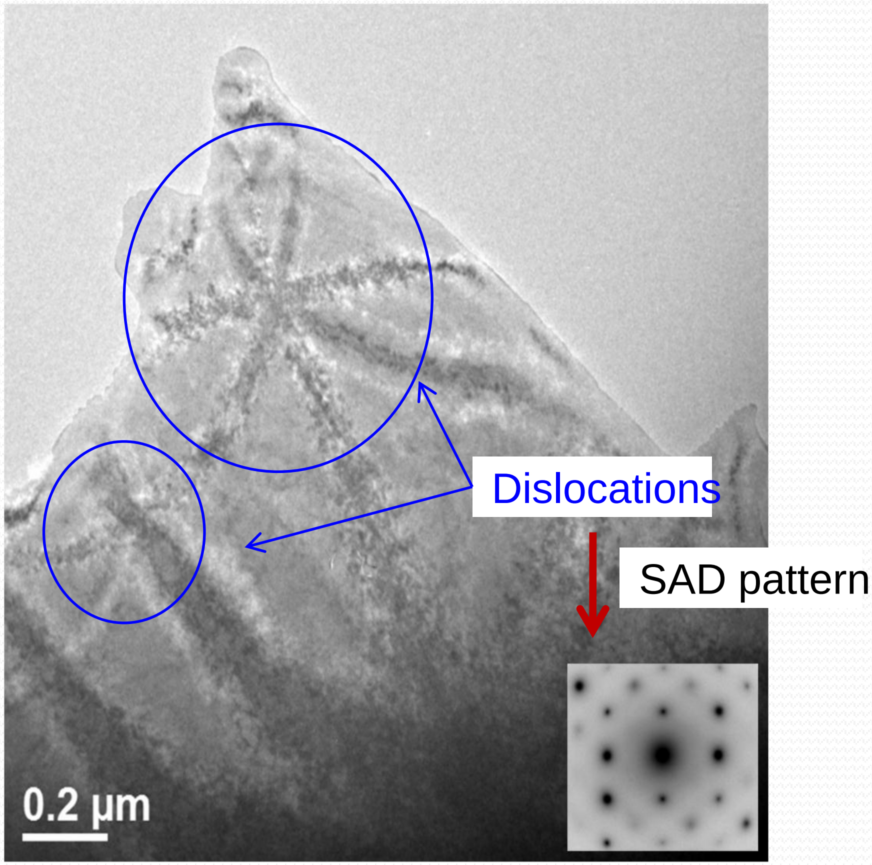


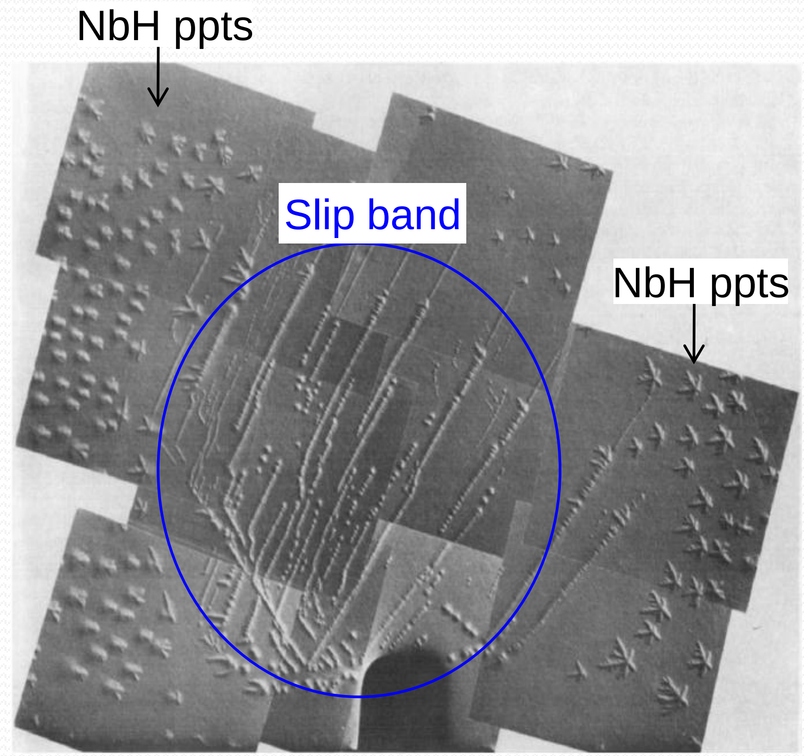
Making TEM sample from “star” by FIB

❑ TEM – Pure Nb

Y. Kim, D. Seidman – Northwestern Uni

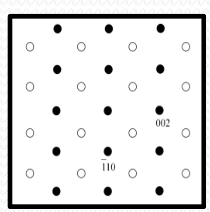
- NbH precipitates near dendritically shaped dislocations





Grossbeck, Birnbaum , Acta Metall. 25 (1977) pp. 135

Nb 110 zone
Simulated SAD
pattern

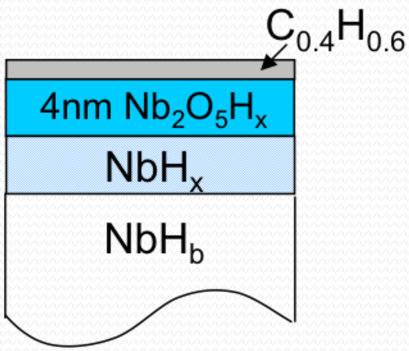


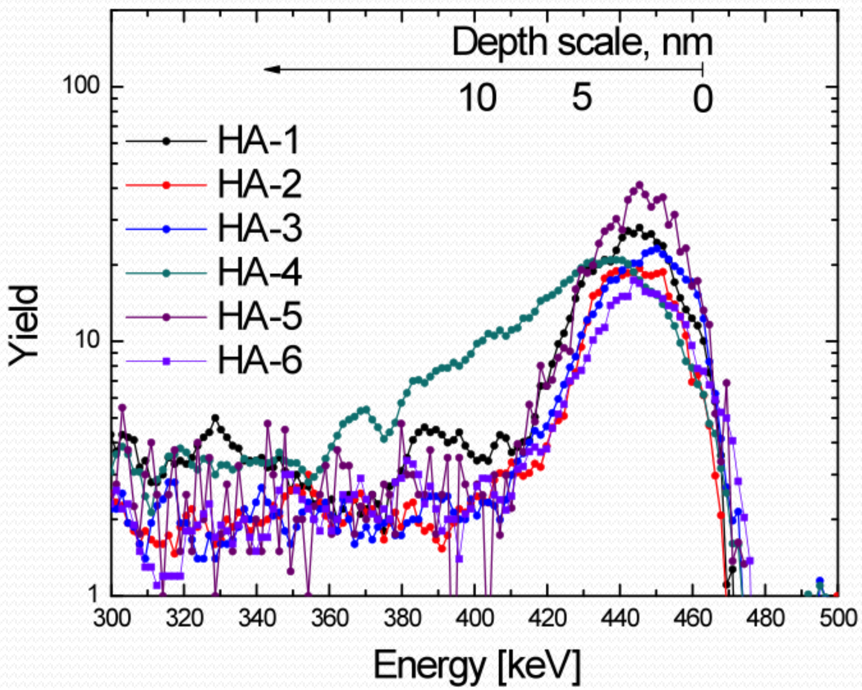
● Nb ○ H sublattice

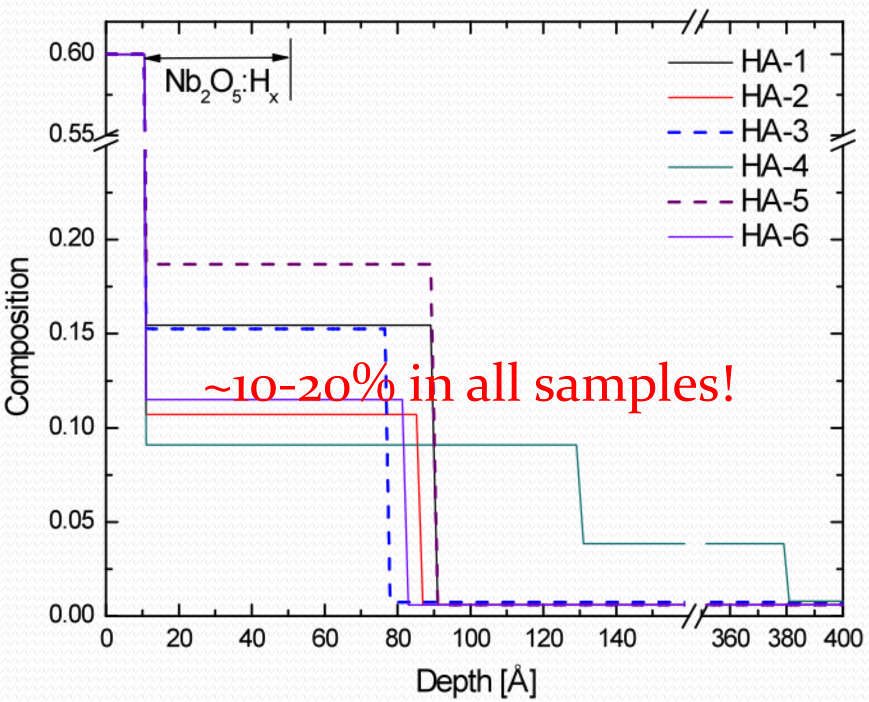
Hydrogen near-surface enrichment

HA-1->BCP
HA-2->+800C
HA-3->+120C
HA-4->+HF
HA-5->BCP+600C
HA-6->+120C

Elastic recoil detection shows hydrogen enrichment in all samples







Hydrides – major player in R_{res} and MFQS?

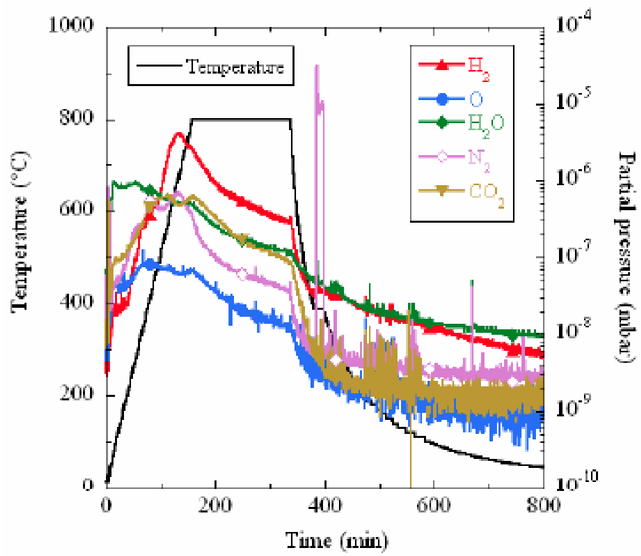
- A lot of hydrogen in the near surface
  - Must precipitate on cooldown
    - Form of precipitation depends on the process and presence of nucleation centers
- Beta phase of NbH_x normal conducting T>1.3K
  - May become superconducting by proximity effect depending on the size of precipitates at higher T if surrounded by SC Nb

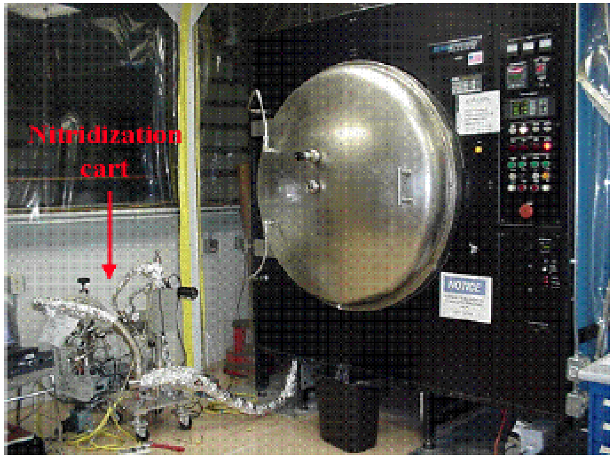
Q_0 R&D – other labs

- Only JLab has related R&D plans (to the extent of my knowledge)
- Jlab Plan: exploration of heat treatment/nitride passivation with the dedicated furnace
  - Anneal at 800+C to remove interstitial impurities and lattice defects in the near-surface layer
  - Prevent defects/interstitials from reforming on cooldown by "capping" with niobium nitride at intermediate temperature (400C)
- Preliminary results reported at SRF Materials Workshop 2010, Tallahassee by G. Ciovati
- Spiral 2 has huge improvement in MFQS at 120C baking, this seems to be true for many low beta cavities – importance of low T heat treatments systematic studies in looking for the best recipe

Heat treatment procedure

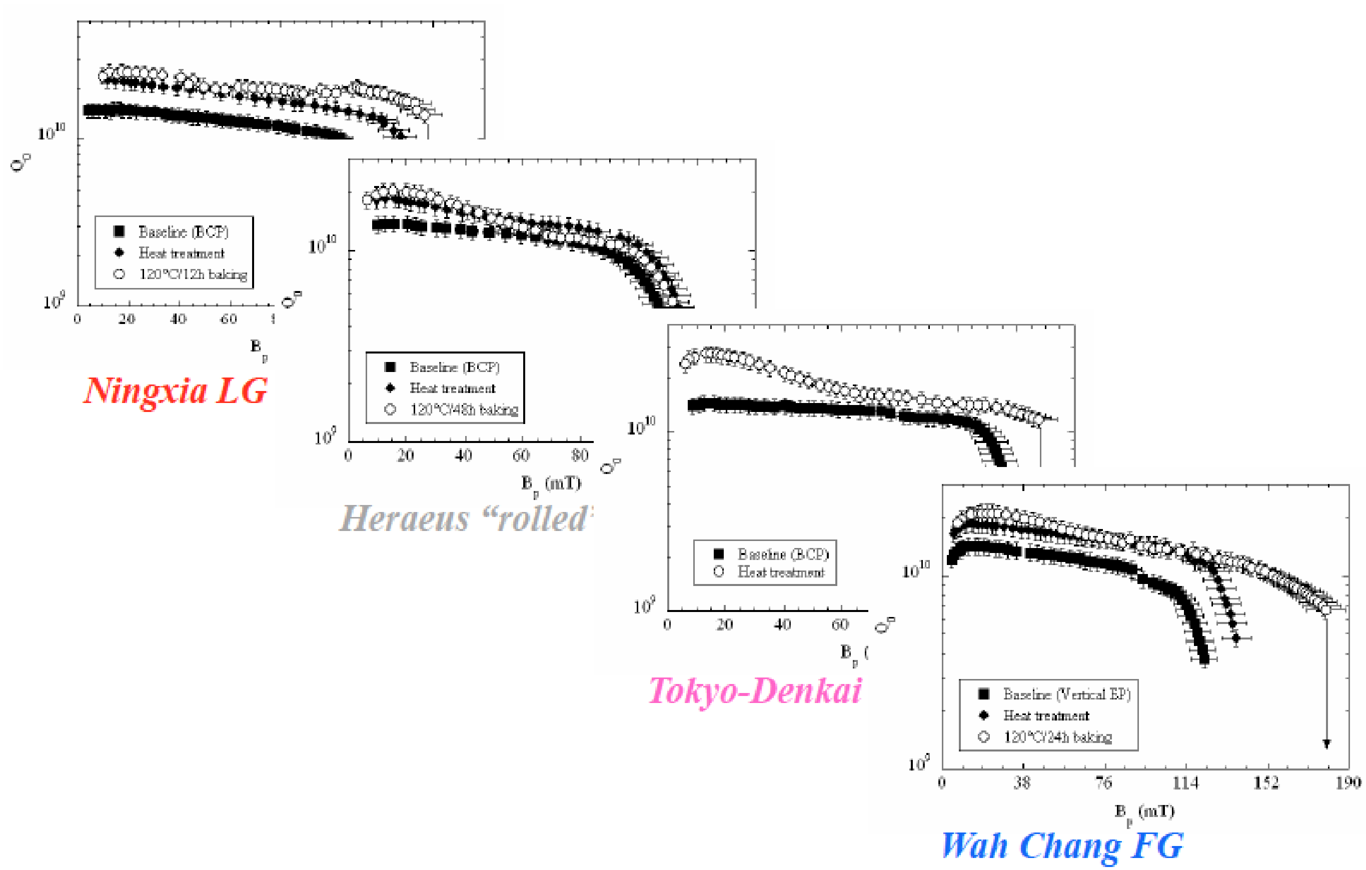
- UHV Heat treatment at 800 °C/3h
- Rapid cooling to 400 °C, admit ~ 5×10^{-6} Torr N_2 for 15 min
- Cool to 120 °C and hold for 12 h (optional)
- No chemical etching afterwards!!! Just degreasing and HPR





G. Ciovati, SRF Materials Workshop, 2010

Some $Q_0(B_p)$ data plots



Jefferson Lab

Thomas Jefferson National Accelerator Facility

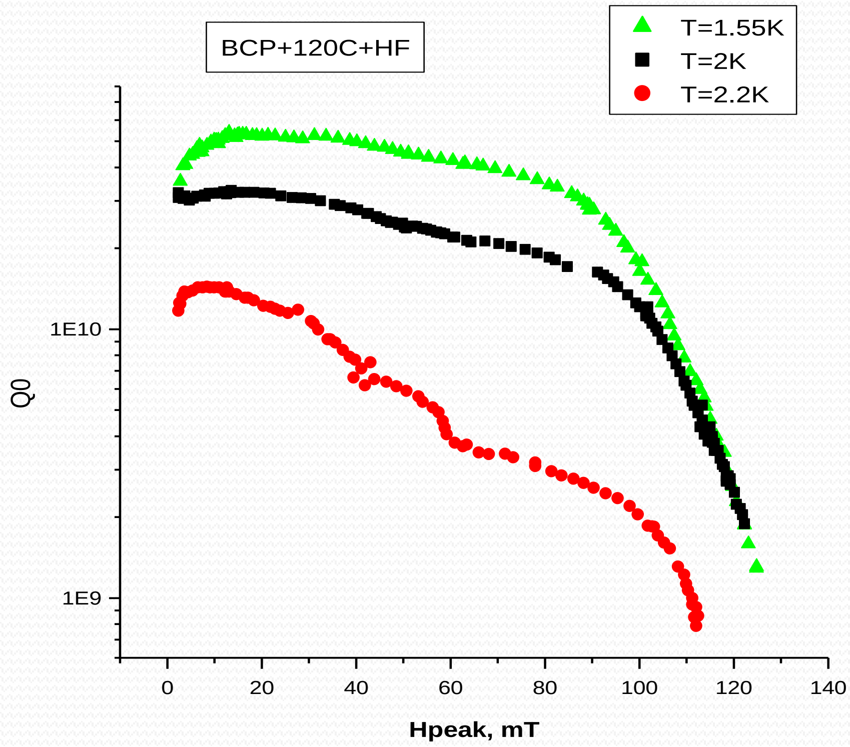
JSA

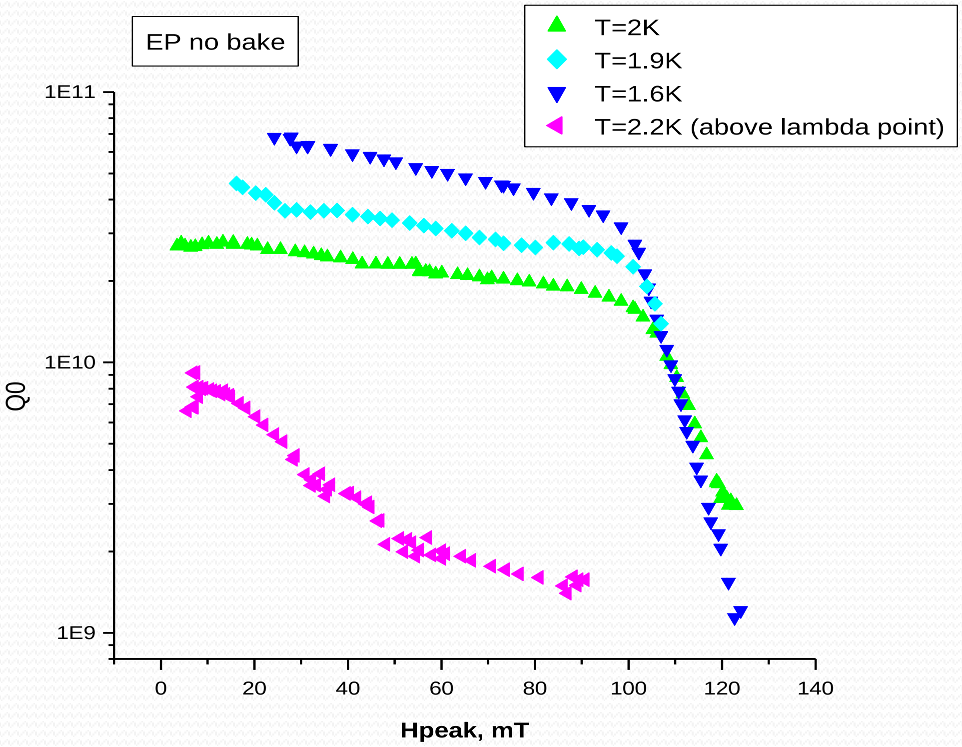
G. Ciovati, SRF Materials Workshop, 2010

Recent effort at FNAL

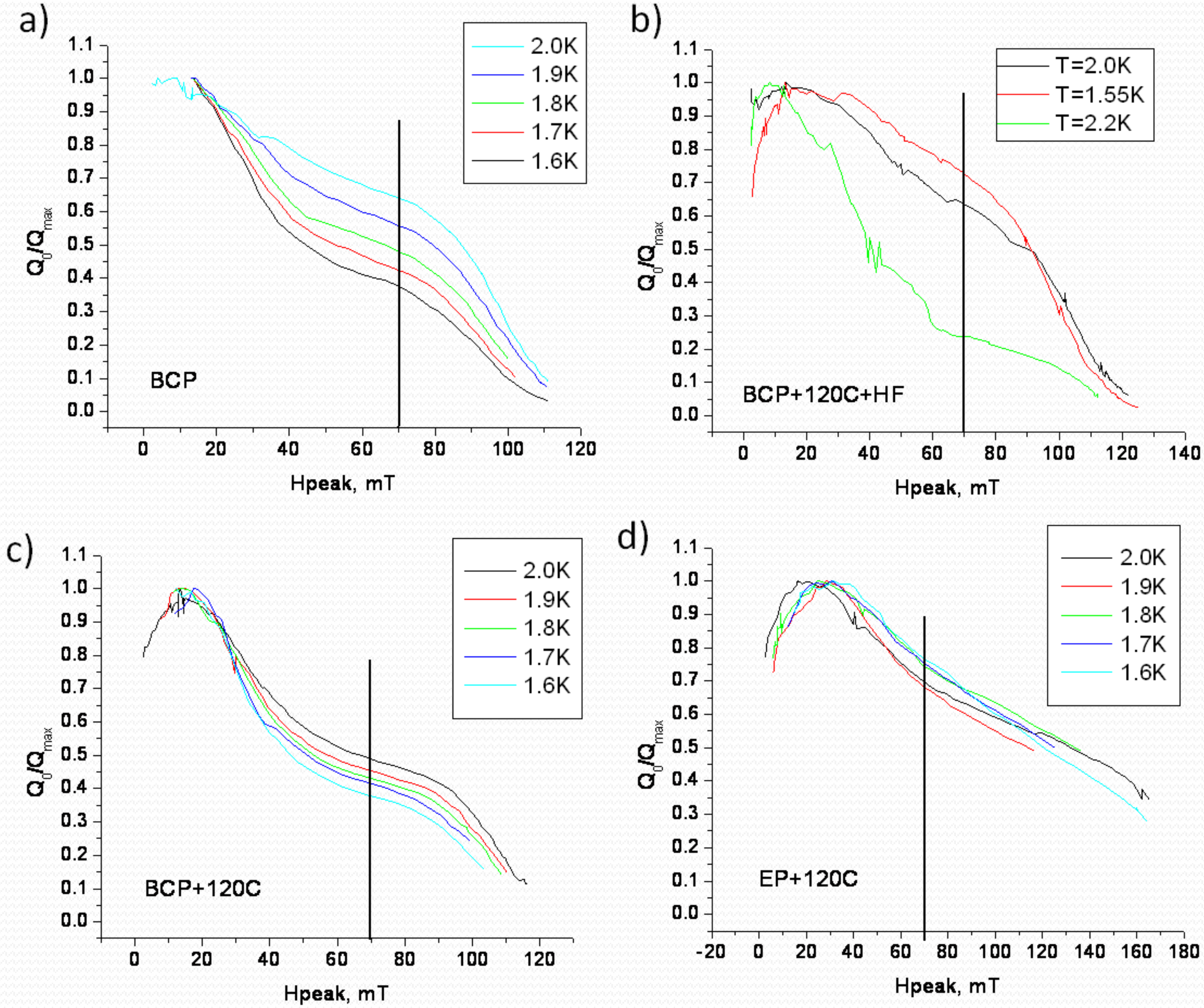
- Bath temperature (1.6-2.2 K) and available surface treatments (BCP, EP, tumbling) effect on the medium field Q before/after mild baking [PAC'11 – Romanenko et al, TuP085; SRF'11 – Romanenko, Ozelis, Wu]
- Tumbling improvement of Q_0 in some cavities (C. Cooper)
- "Depth profiling of losses" via HF rinsing
  - Improvement in the low and medium field range – spin-off

Confirmed T>2.17K not practical

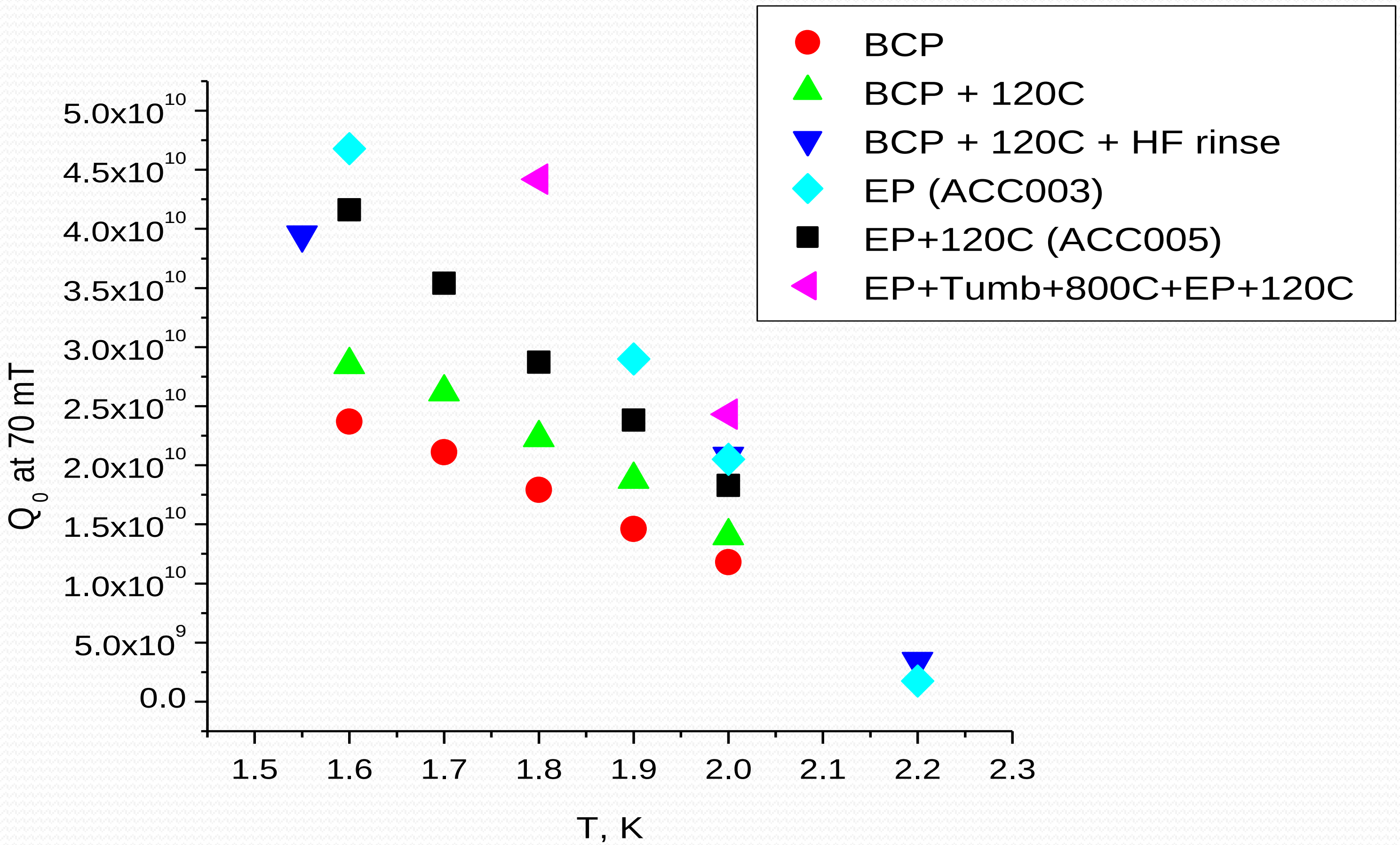




Medium field Q-slope variation with treatments/bath temp

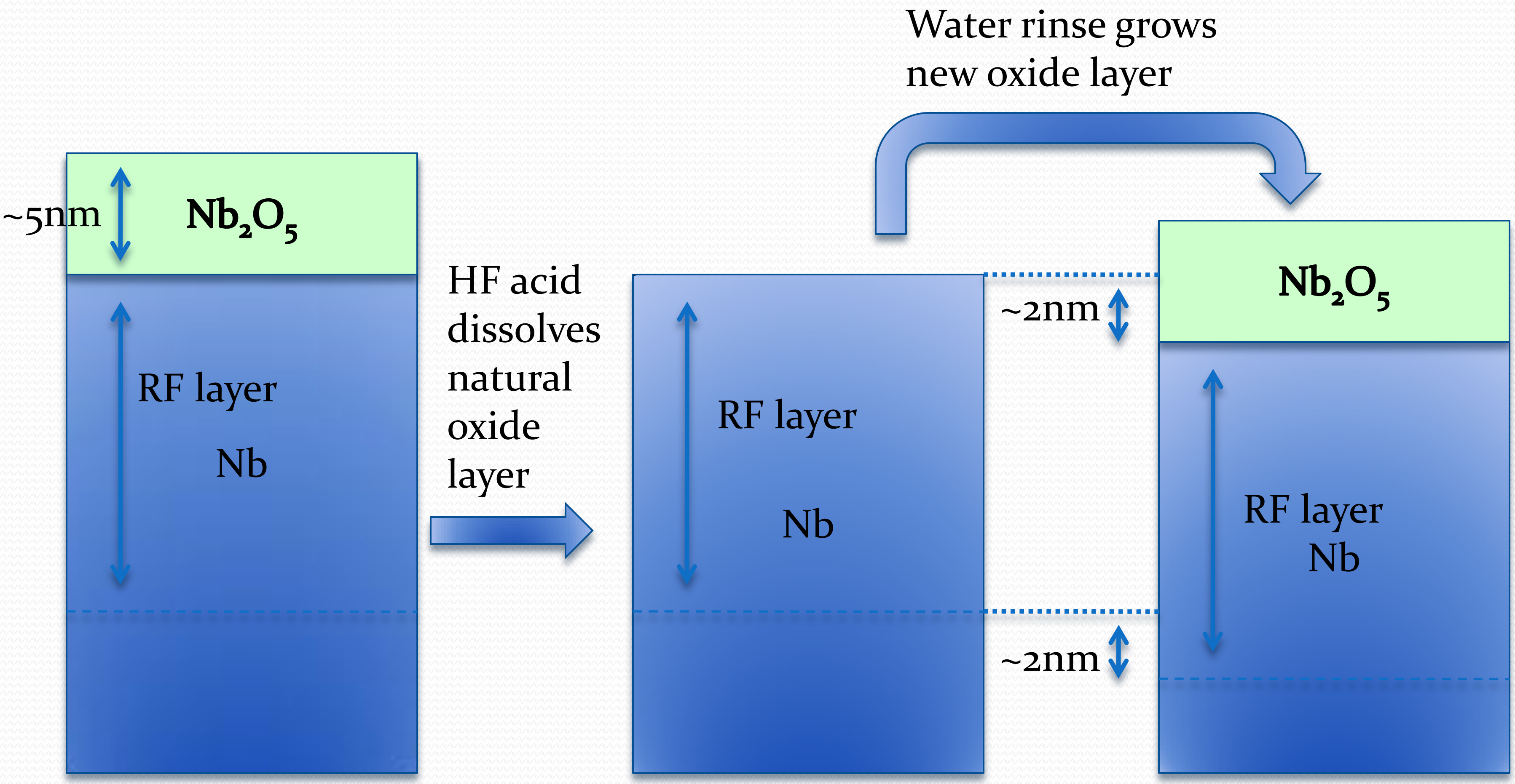


Q_0 at 70 mT



BCP
BCP + 120C
BCP + 120C + HF rinse
EP (ACC003)
EP+120C (ACC005)
EP+Tumb+800C+EP+120C
Q0 at 70 mT
5.0x10^10
4.5x10^10
4.0x10^10
3.5x10^10
3.0x10^10
2.5x10^10
2.0x10^10
1.5x10^10
1.0x10^10
5.0x10^9
0.0
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
2.3
T, K

"Depth profiling of losses"

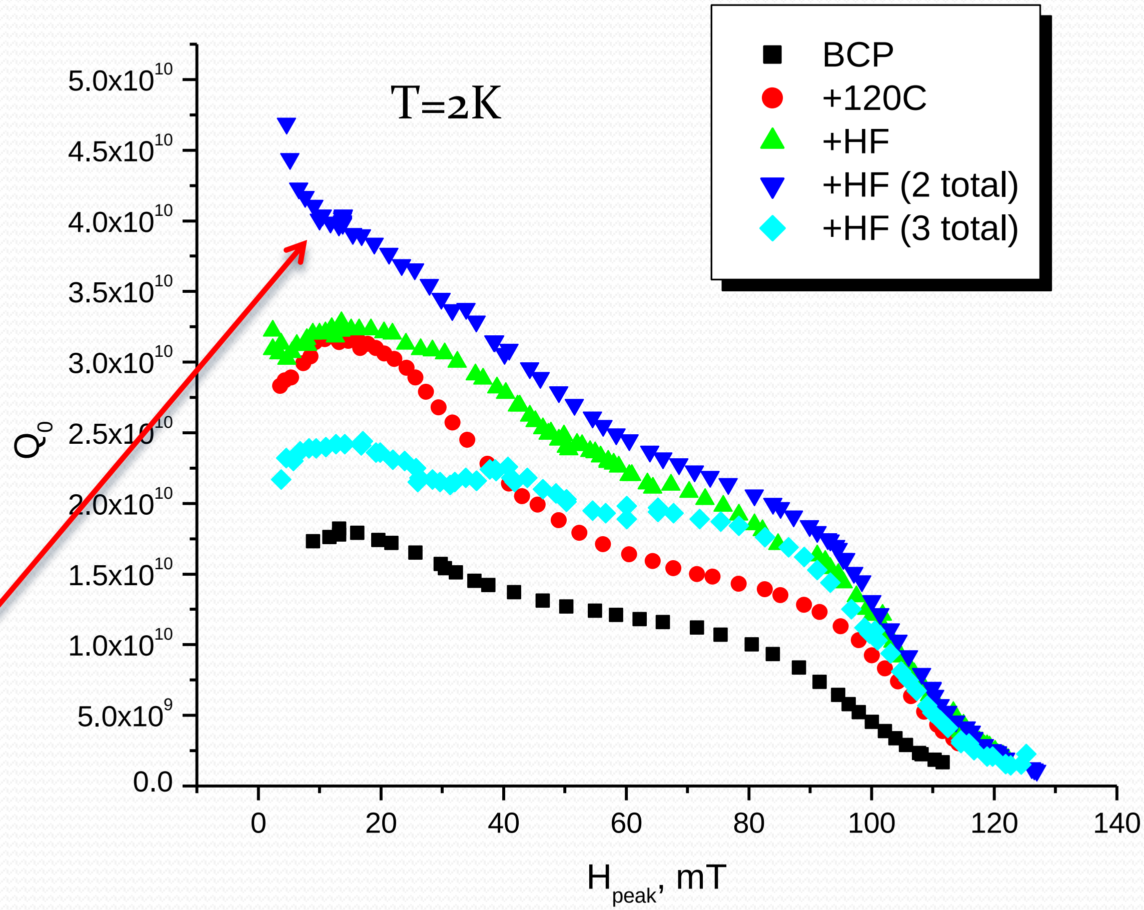


Each HF/water rinse step consumes about 2 nm of niobium from the top of the RF layer determining the surface resistance and moves deeper into the bulk – depth profiling of the losses

RF layer profiling by HF acid rinsing

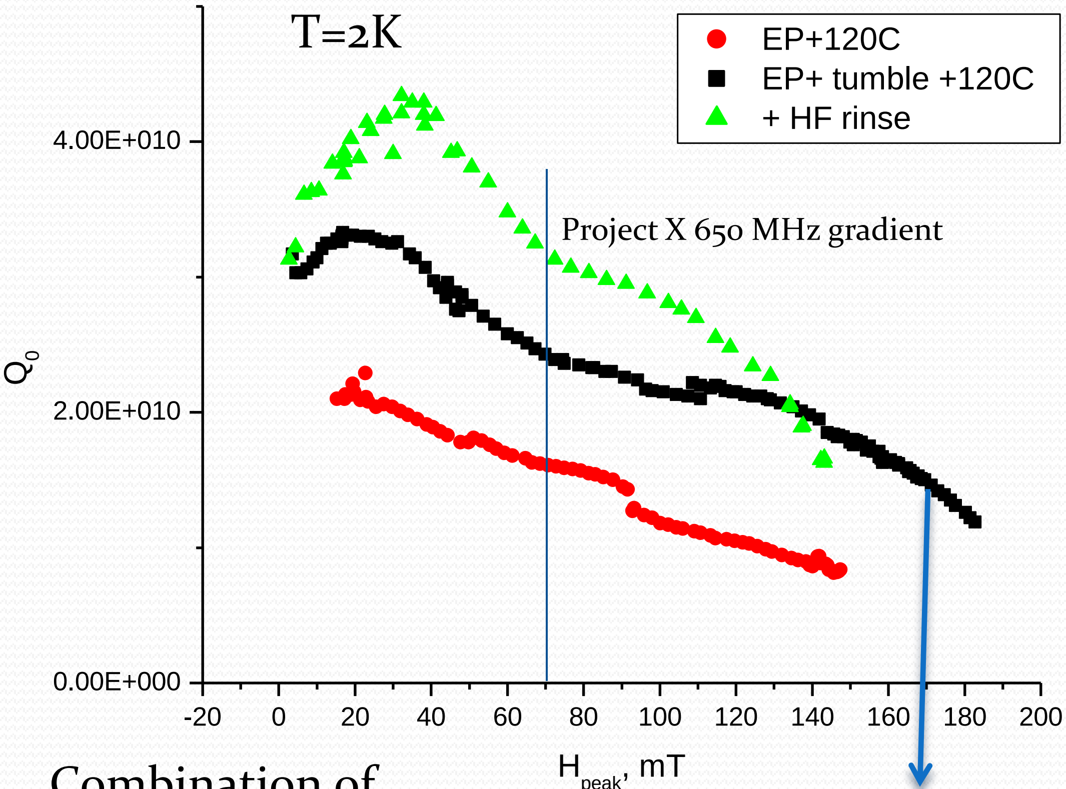
The goal of experiment: what layer(s) determine what regions of Q(H) curve?

- Anodizing experiments indicated about 20 nm of mild baking modified layer (Eremeev et al, SRF'2005 ,TuAO8; Ciovati et al, PRST AB 10, 062002 (2007)) – ~expect 10 HF rinses to get everything back to original curve
- Highest Q_0 at low and medium fields after 2 rinses



Preliminary – first ~4 nm underneath oxide most important for medium field Q

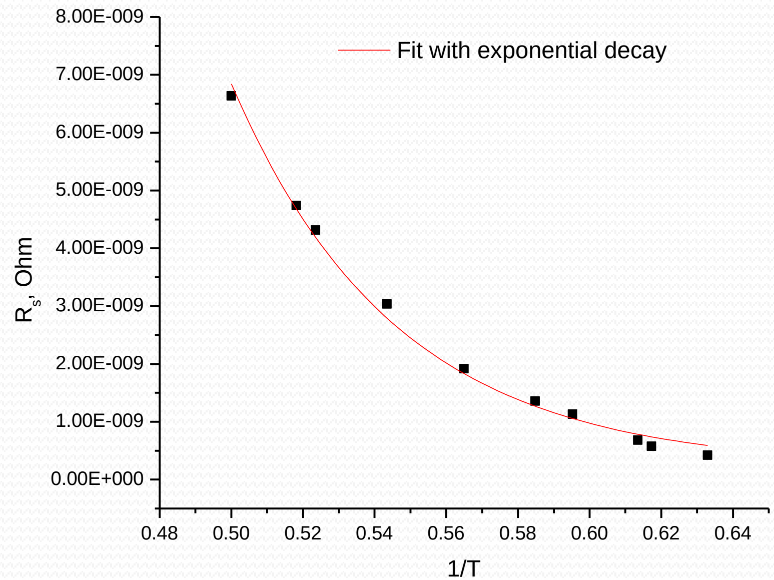
HF rinsing improvement on tumbled cavity



Combination of smoothening and removal of ~4nm of Nb underneath oxide

Best tumbled single cell
(C. Cooper research – mirror finish)

Surface resistance estimate for EP+tumble+800C+light EP+120C+HF



R^2 0.99488

Parameter	Value	Error
y0	2.25492E-10	1.81174E-10
A1	3.56644E-4	3.34983E-4
t1	0.04589	0.004

Residual resistance <0.4 nOhm

Where do our findings lead us?

- After standard treatments
  - “Select” the RF layer with minimal medium field RF losses by sequential HF rinsing
- Alternative heat treatments
  - Explore temperature/duration range
- Correlate findings with samples investigation

Initial research plan (1)

- Experiments to be performed on
  - 1.3 GHz single cells
    - With temperature mapping after the system construction is completed
  - Later- single spoke resonators (325 MHz)
    - Different baseline treatment, even bigger possible margin of improvement

- Find the optimal number of HF rinsing steps for existing BCP, EP, tumbled cavities to maximize Q_0 at fields of interest ~ 30 processes/RF tests
  - Confirm findings with different “nanoremoval” – anodizing ~ 10 processes/tests
  - Repeat the same with the large grain cavity ~ 10 processes/tests

Initial research plan (2)

- Explore heat treatments to modify first 40 nm (eliminate hydrogen, other interstitials and lattice defects) ~ 30 treatments/processes/tests
  - With/without passivation to avoid recontamination
  - With/without chemistry afterwards
  - Different temperatures: 100-1000C
  - Different durations
- "Witness" samples processed with cavities and analyzed using appropriate surface analytical tools
  - TEM – nanoscale imaging of the near-surface (~100 nm) structure
  - ERDA – nanoscale near-surface elemental distribution (especially H)
- **TOTAL = 80 processes/tests**

Resources needed

- Manpower
  - Scientist(s)/postdoc(s)/student(s) with SRF expertise
    - 1 FTE – HF rinsing/anodizing experiments
    - 1 FTE – Heat treatment experiments
    - 1 FTE – surface studies on samples following the same treatments
- Facilities time
  - ANL/FNAL processing facility
  - FNAL furnace
  - Vertical test stand (VTS)

Project constraints

- Competing for the same ANL/FNAL processing time
  - 9-cell 1.3 GHz CM production cavities – main project
  - 1-cell 1.3 GHz – ~1 cavity/week on average
    - ILC-related high field quench
    - High field Q-slope R&D
    - Tumbling
    - Vendor qualification
    - ARRA-funded initiatives (Cabot, Faraday)
    - Laser remelting
- ~ 80 tests/1 (test/week)=80 weeks (1.5 years) total time with 100% use of all available time for single cells
  - Subtract time for all other single-cell projects => ~10 years for the proposed project
- Manpower
  - 3 FTE total required

Conclusions

- Qo at medium fields -> direct impact on Project X costs (cryogenic plant)
- Feasible research program to investigate medium field Qo improvement
  - Manpower and facility time needed

Extended research plans

- Explore atomic layer deposition (ALD) or chemical vapor deposition (CVD) of some (yet to be determined) passivation layer – i.e. Al_2O_3
  - Collaboration with ANL or build on-site