Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

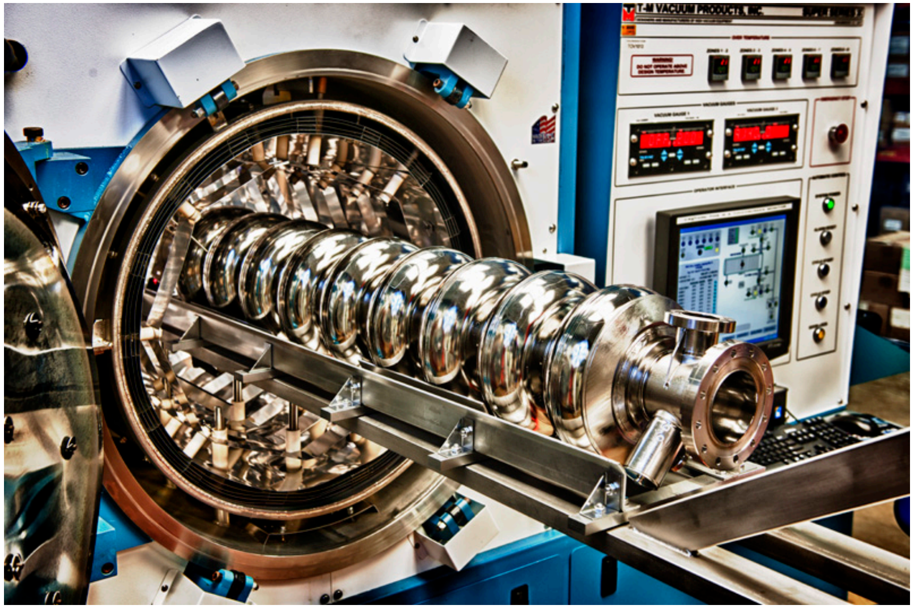
ILC Accelerator
(SRF R&D under US-Japan)

Anna Grassellino

US Japan 40th Symposium

April 15th, 2019

University of Hawaii



SRF activities towards ILC -FY19

- ILC Cost Reduction– focuses on cost cut based on cavity performance improvement (and cavity processing optimization)
  - Led by Fermilab, in collaboration with Cornell University and Jlab
  - Activities aligned with KEK ILC cost reduction scope
  - Also in collaboration with DESY
  - Main research directions: Increasing achievable accelerating gradients and Q at high gradients via innovative surface processing techniques and field emission abatement

- US-Japan SRF R&D (Advanced Accelerator Technology)
  - Fermilab (electroplating Nb_3Sn), Cornell (Nb3Sn), Jlab (Low Surface Field cavities)

Funding profile

ILC Cost Reduction

	US	Japan
FY17/18	$1M	$1M
FY18/19	$500K*	$1M
FY19/20	---	$1M

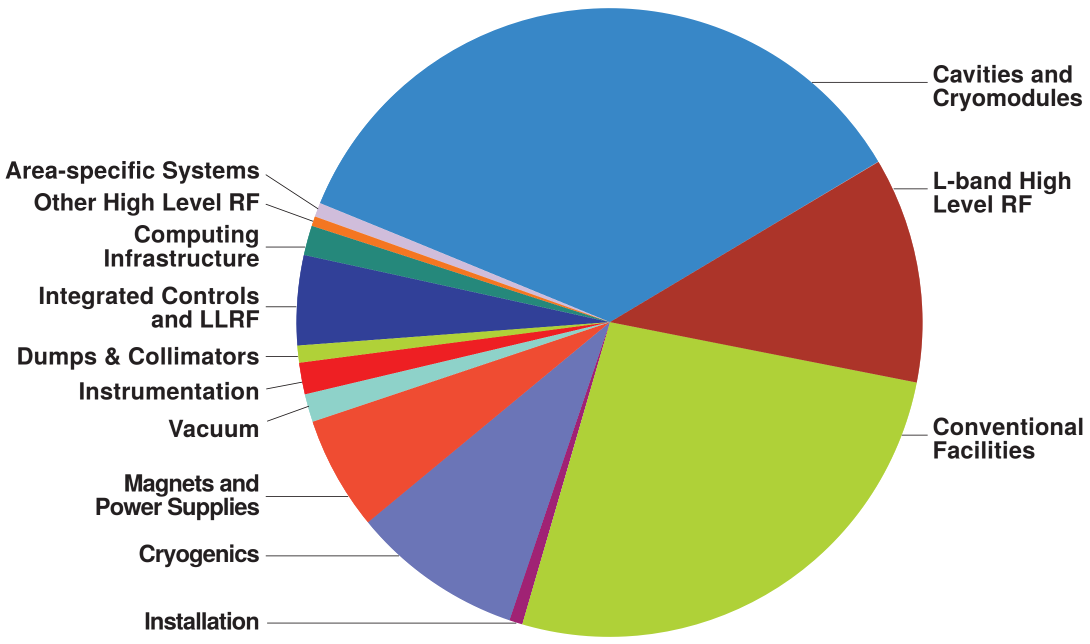
*half funded, though December 2018

US-Japan Advanced Accel Technology

	US	Japan
FY17/18	$400K	$1.2M
FY18/19	$400K	$1.2M
FY19/20	---	---

Approach to the ILC cost reduction

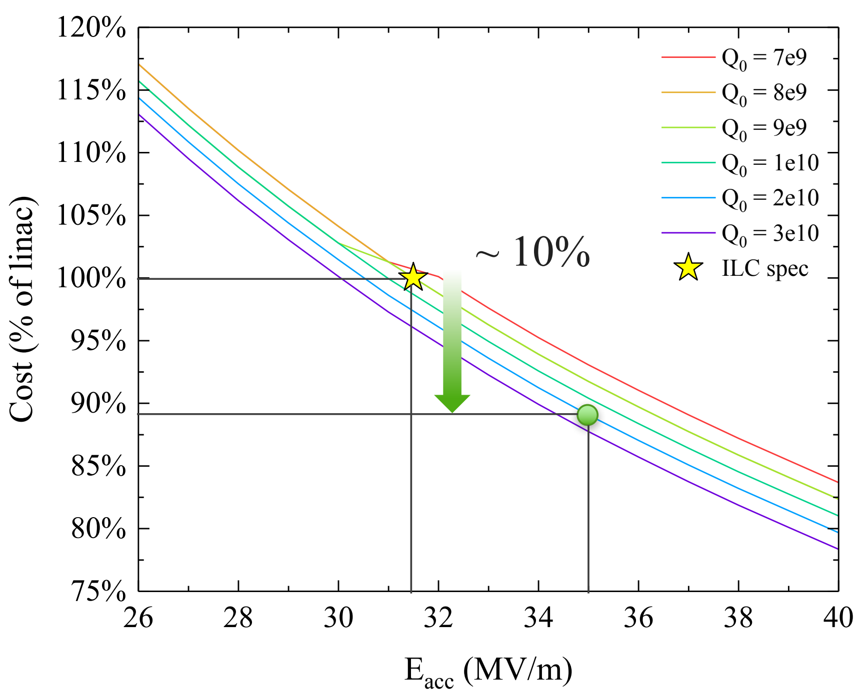
- From the ILC TDR: "[the cost] is dominated by the SRF components and related systems, together with the conventional facilities. These two elements account for 73% of the total. The main linac itself corresponds to 67% of the total project."
- Investing in a carefully selected main linac R&D should be most efficient in bringing the ILC cost down.

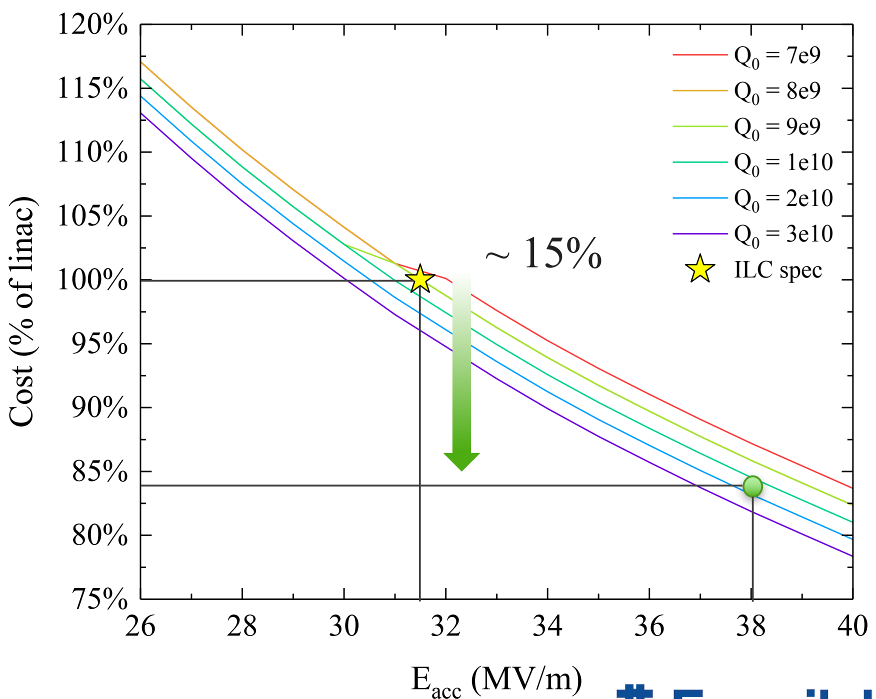


Main Linac Cost Breakdown from ILC TDR

ILC cost reduction – cost model and R&D pathways

- A cost model has been developed based on the ILC TDR and new progress in the SRF technology on cavity achievable efficiency (Q) and acceleration (E_{acc})
- Achievable cavity Q and acceleration are among the main cost drivers
- Improving simultaneously Q and gradient can give substantial cost cut >10% of the total linac cost with current ILC parameters
- **If ILC is to be re-designed or upgraded to achieve higher luminosity, higher energy, Q and Eacc will have a even more dramatic impact on cost (enabling)**



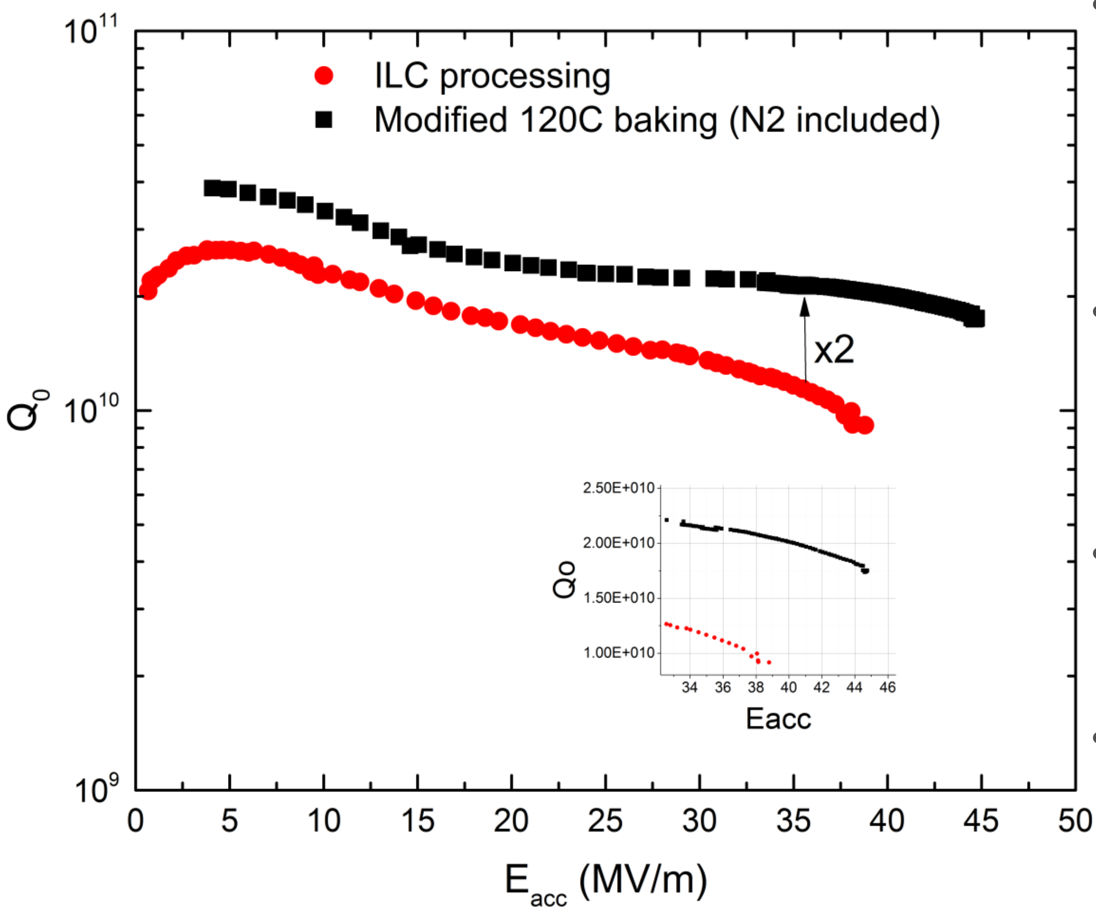


ILC cost reduction – SRF R&D timeline in US (FNAL, Jlab, Cornell)

1. Demonstrate increase in Q at 31-35 MV/m via flux expulsion **{FY18}** ✔
2. Install high power klystron at FNAL Vertical test Facility to study field emission reduction via HPP **{FY18-19}- 90% complete**
3. In parallel continue to push single cell R&D for high Q at high gradient via doping/infusion – FNAL, Jlab, Cornell (transfer to KEK) **{FY18-19}** ✔
4. Apply best High Q/high gradient recipe to nine cells – FNAL, Jlab (KEK) **{FY19}** **50% complete**
5. Dress best nine cell cavity and demonstrate high Q at 35 MV/m in cryomodule configuration (horizontal test stand, **and KEK ATF**) **{FY19}**
6. **Build a cryomodule (CM) with high Q/high G cavities for final demonstration of CM - ready technology- FNAL, {FY20}**

Highlights of 2018-2019 High Q at high gradients via Nitrogen Doping/Infusion and other low T treatments

Cavity performance progress at FNAL: "standard" vs "N infused" cavity surface treatment

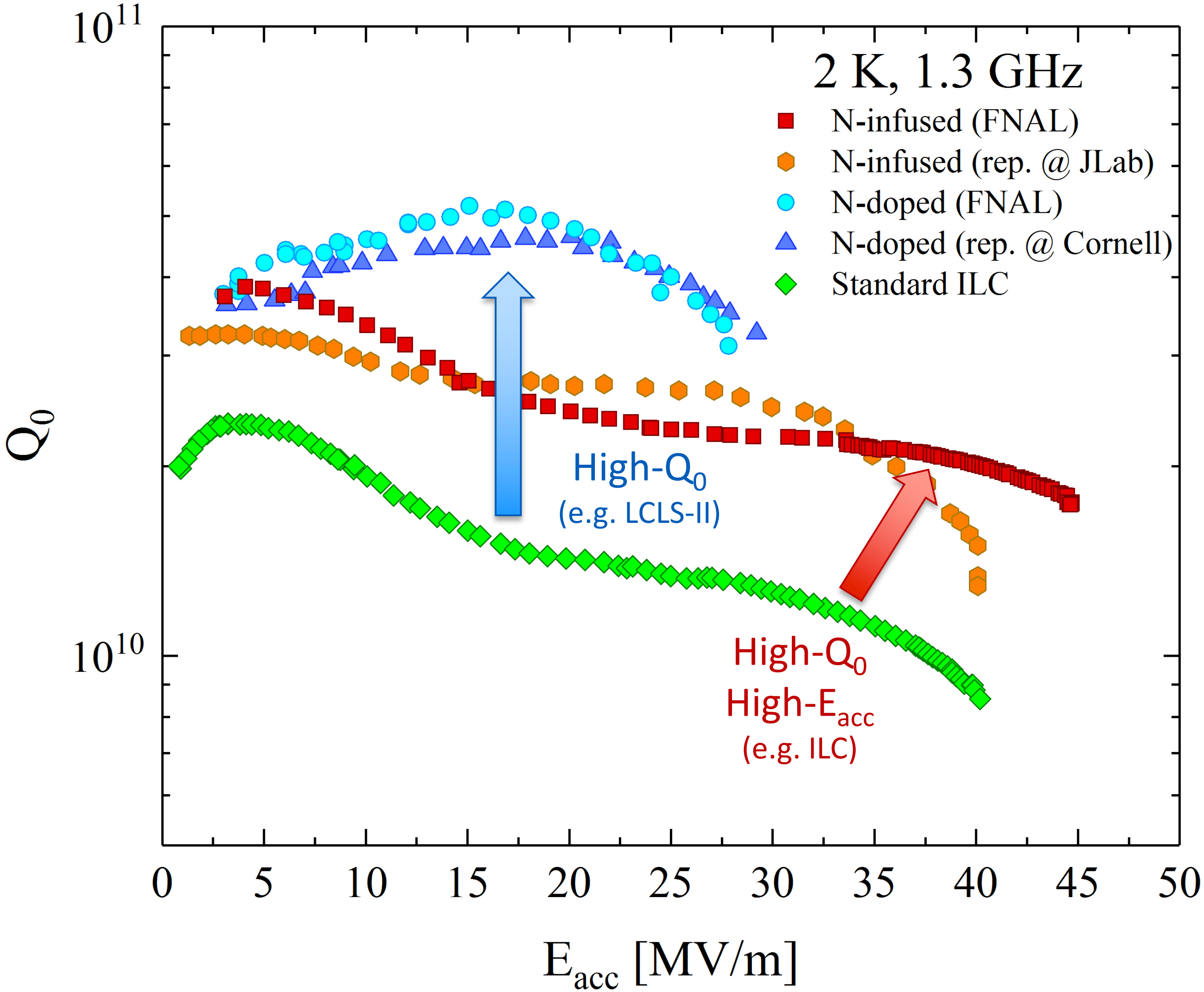


Increase in Q by > a factor of two
Increase in gradient ~15%

A Grassellino *et al* 2017 *Supercond. Sci. Technol.* **30** 094004

- FNAL has demonstrated in 2017 a new treatment, which utilizes "nitrogen infusion", achieving
  45.6 MV/m → 194 mT
  with Q ~ $2x10^{10}$
- The idea is to nano-engineer the surface with a nitrogen enriched layer of some optimal depth (5-100nm)
- Jlab, has reproduced similar results on single cell cavities with Q >2e10 at 35 MV/m
- R&D work towards:
  - Best recipe for higher Q at high gradient
  - Robustness of process

Potential for very high Q at very high gradients

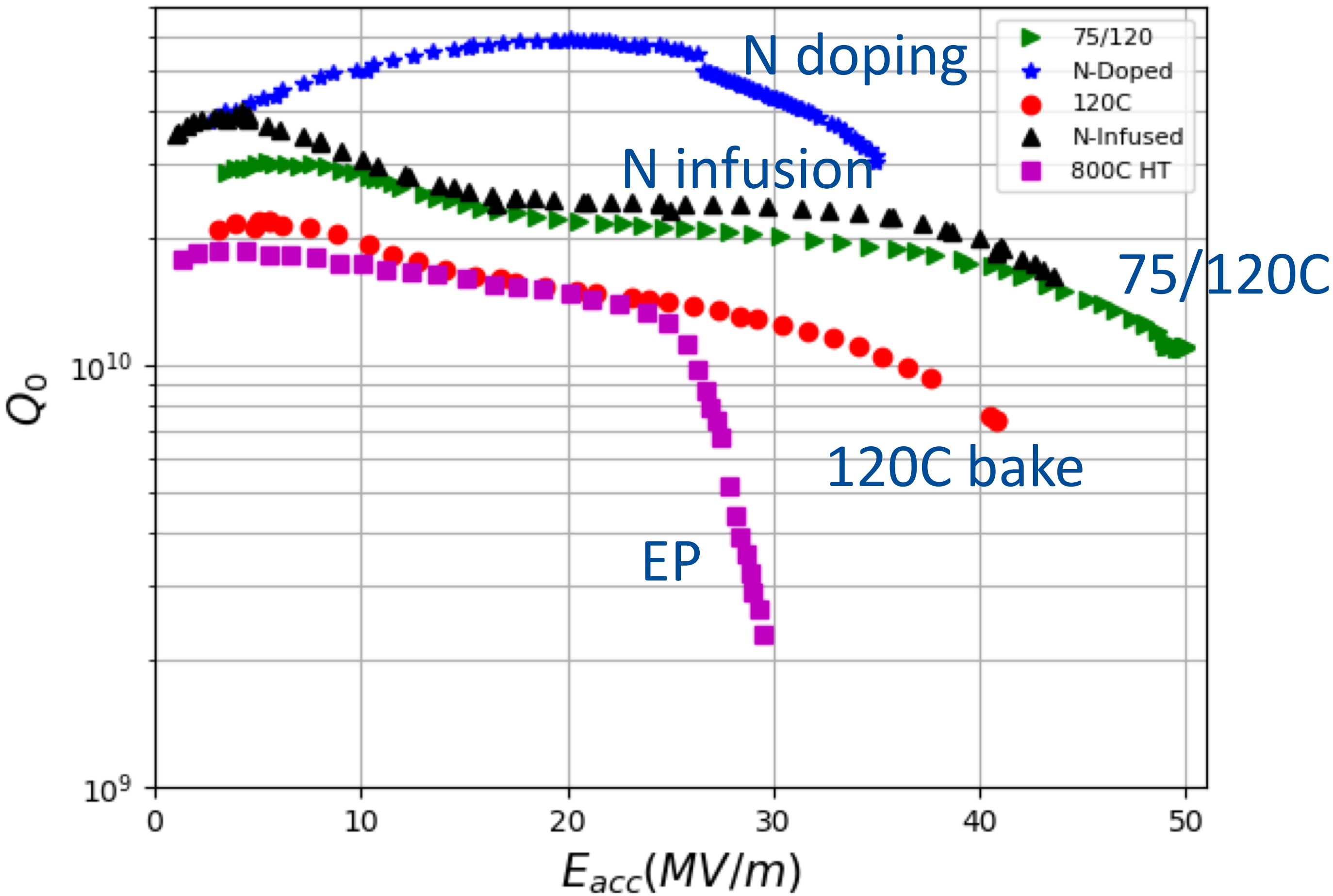


ILC Cost Reduction R&D global effort will explore doping parameter space to extend high Q at the highest gradients

Currently working on this R&D direction: FNAL, KEK, Jlab, Cornell, DESY

Summarizing the progress in high Q and high G (1.3 GHz, 2K)

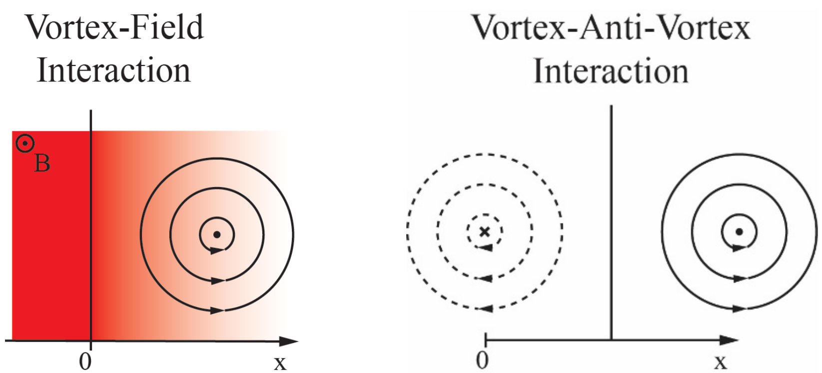
- Q>3e10 @35 MV/m with N doping
- Q >1e10 at 50 MV/m with 75/120C bake

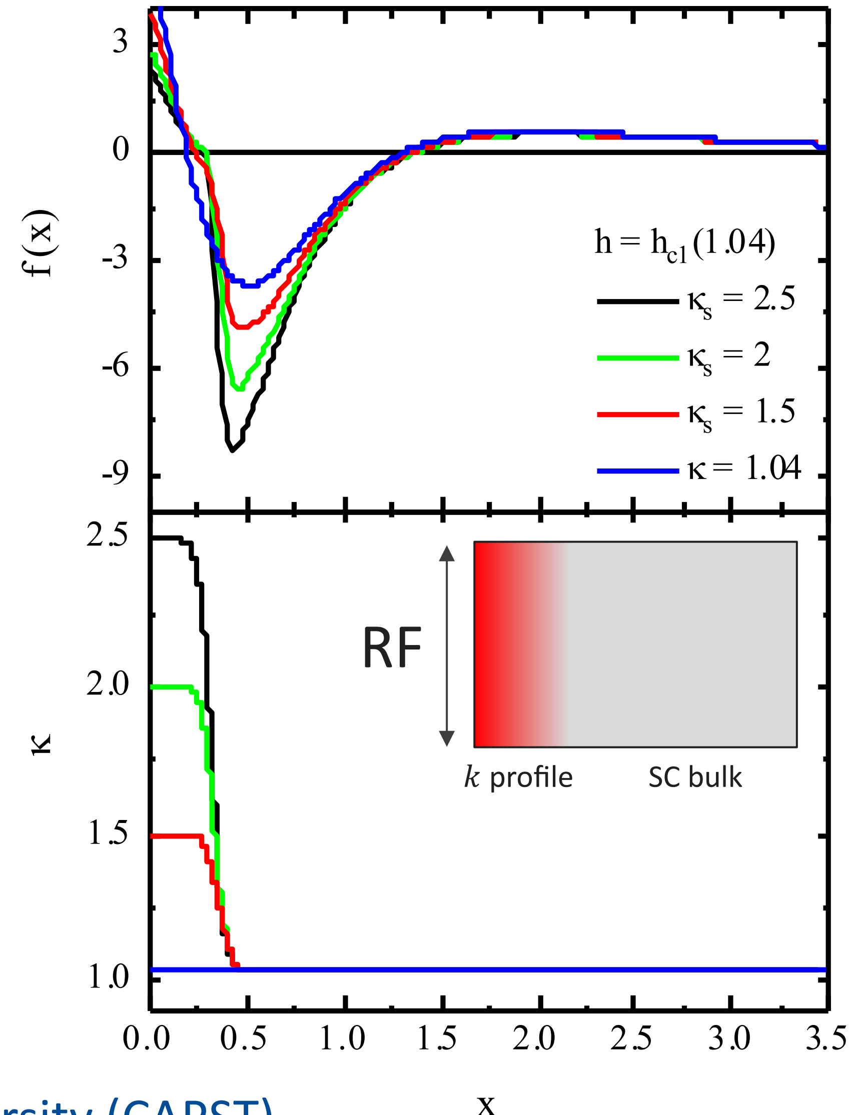


Theoretical Understanding -Impurity profile: high gradients

Numerical calculation of Bean-Livingston barrier from GL equations predicts:

- ***High κ layers*** at the surface ***delay vortex penetration***
- Higher force pushing vortices out of the superconductor





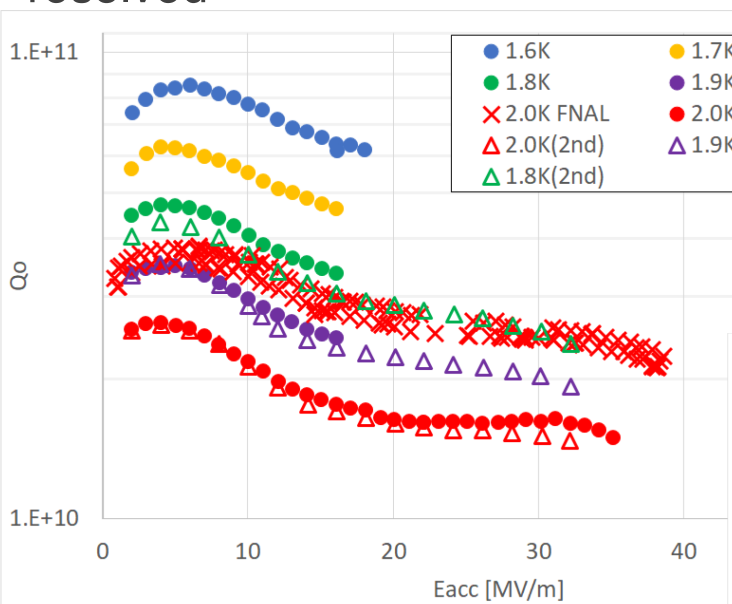
M. Checchin, FNAL, Ph.D. Thesis (2016)
T. Kubo, Supercond. Sci. Technol. 30, 023001 (2017)
W. Ngampruetikorn, arXiv:1809.04057
Koshelev, arXiv:1901.05584

Work in partnership with Northwestern University (CAPST)

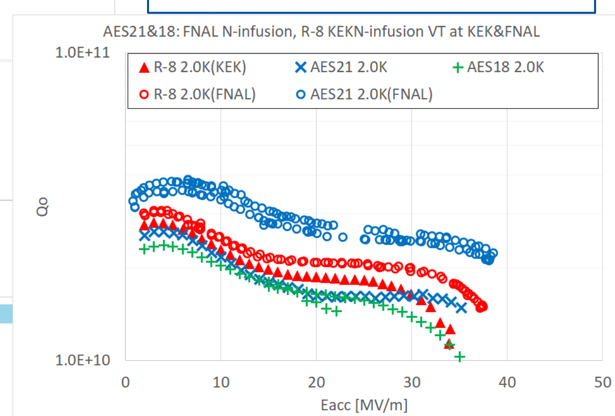
Progress with N infusion in 2018/19 – KEK cavity exchange

- We have been performing N infused cavity exchanges between FNAL and KEK to verify that first of all – measurements methods are consistent
- KEK infused cavity tested at FNAL, FNAL cavities at KEK
- The process has been very useful, along with visits exchange between research personnel at KEK→ FNAL and viceversa
- Highlighted some differences in sensors calibrations and cryo-controls which had led to mismatch in results; issues being resolved

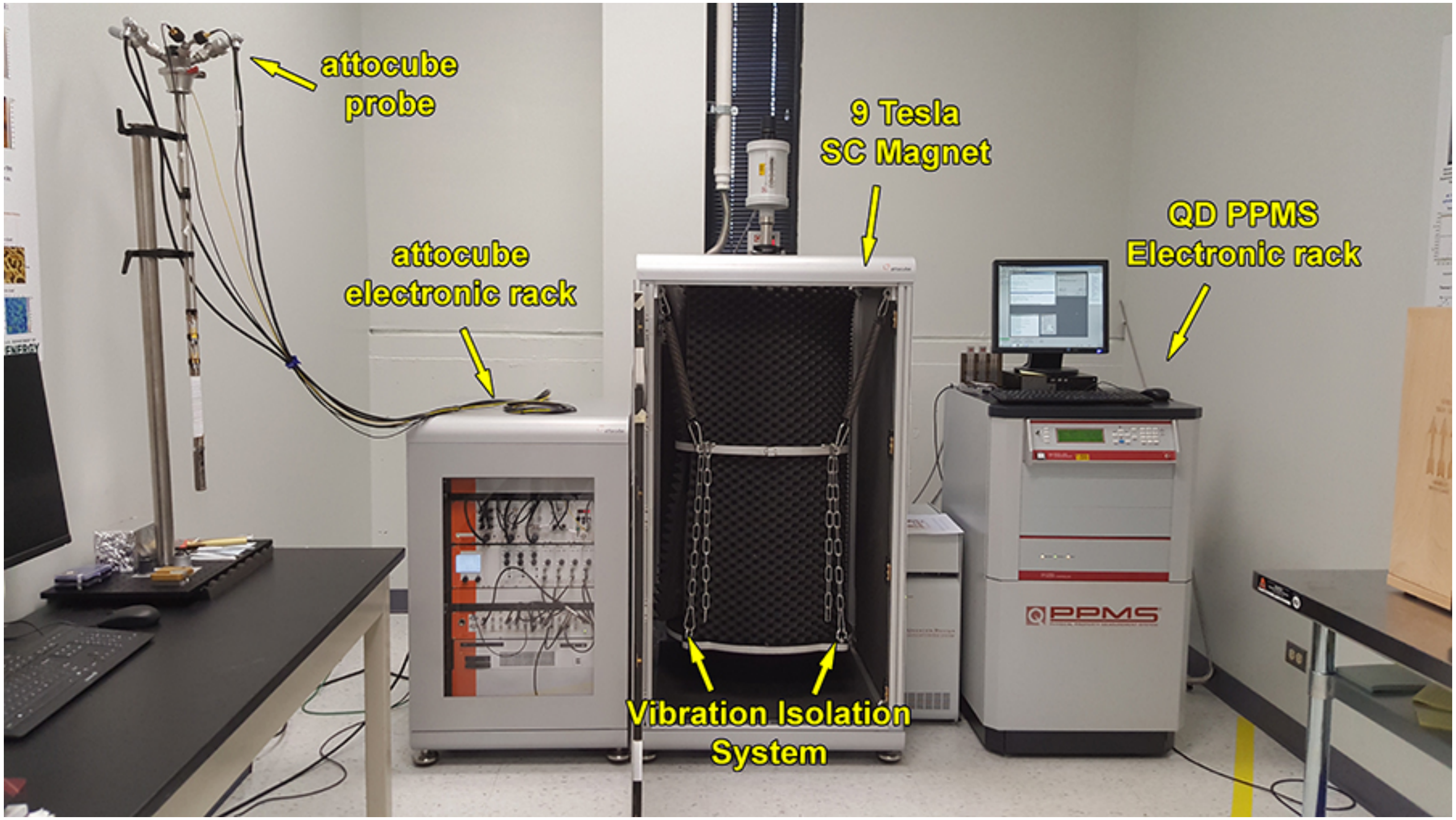
Next: FNAL to send more cavities to KEK with flawless substrate to apply high Q/G treatments at KEK



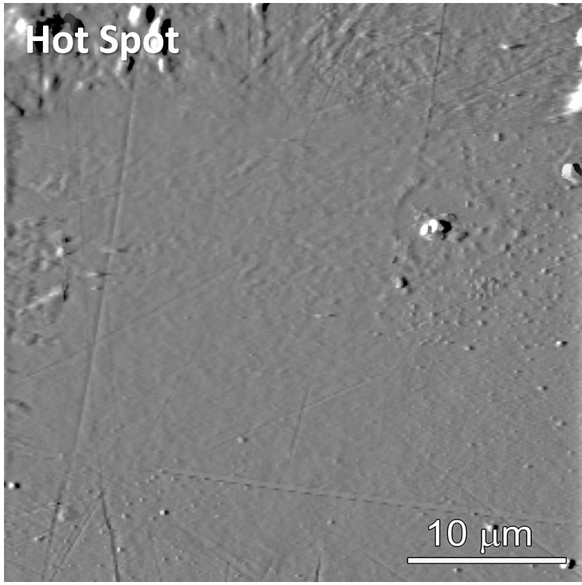
- Eacc is 10% lower at KEK
- Qo is > 50% lower at 2.0K
- Differences understood

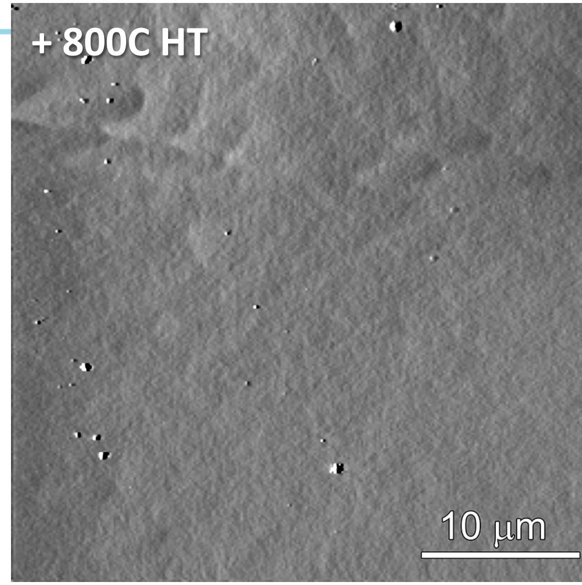


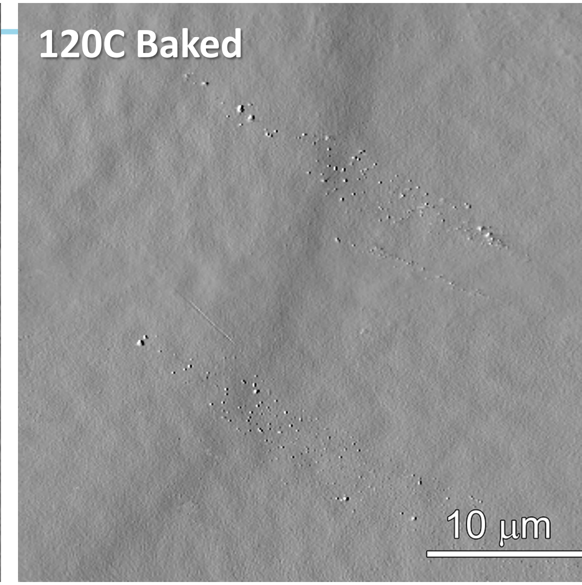
Progress with N infusion in 2019 – nanohydrides studies

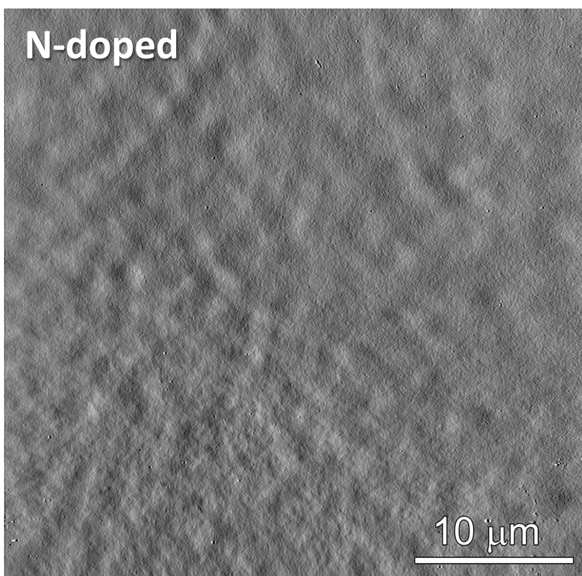


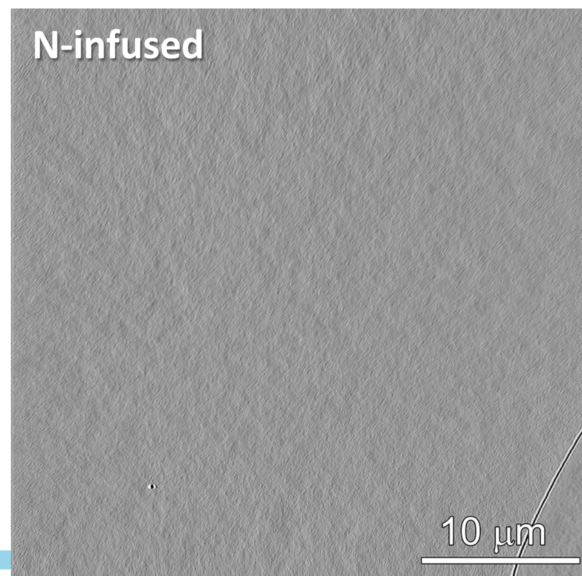
300K Surface features on cavity cut-out samples

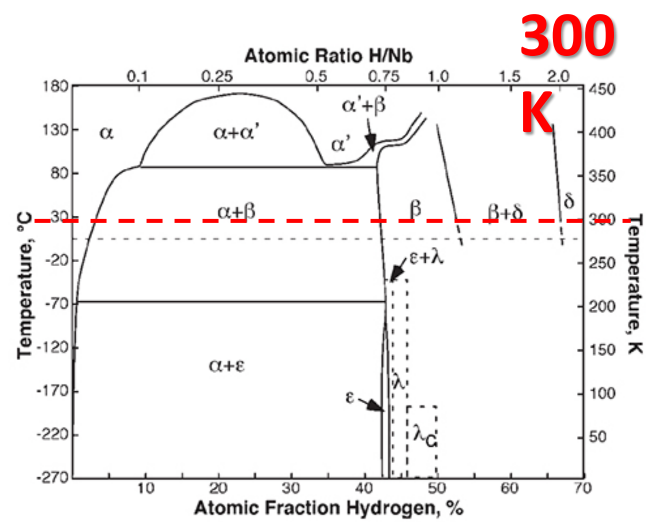




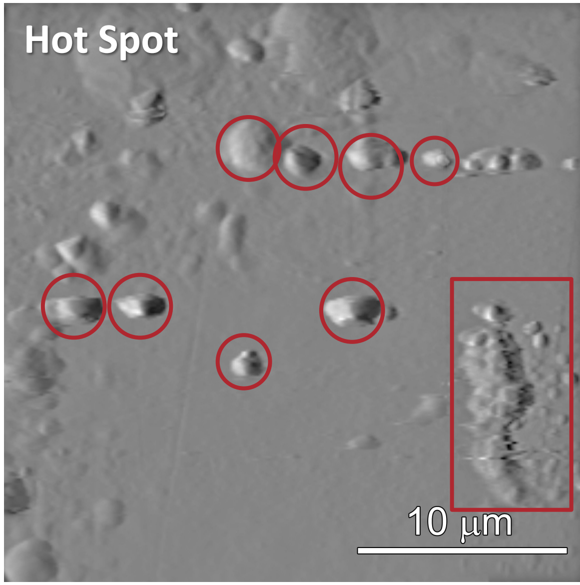


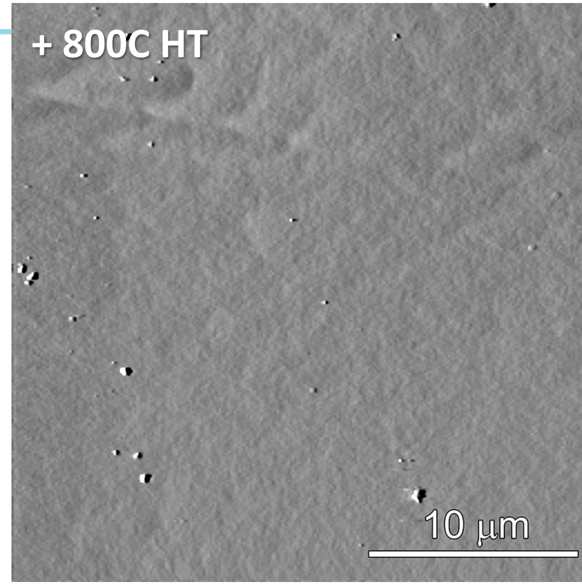


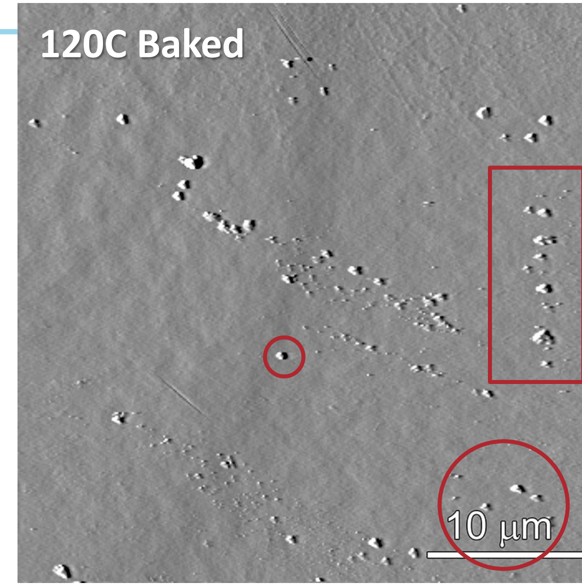


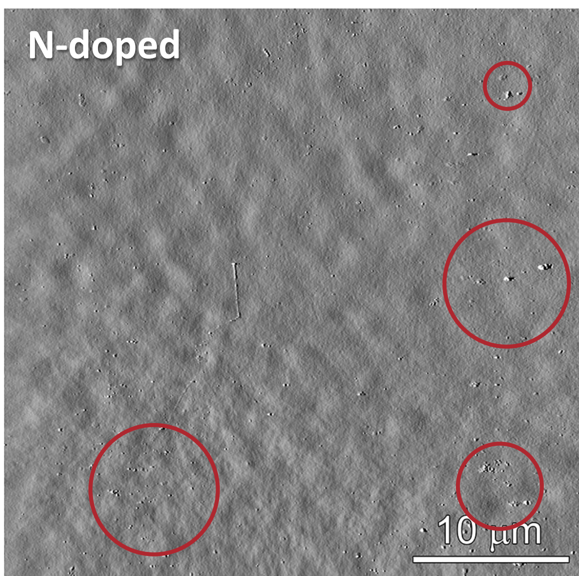


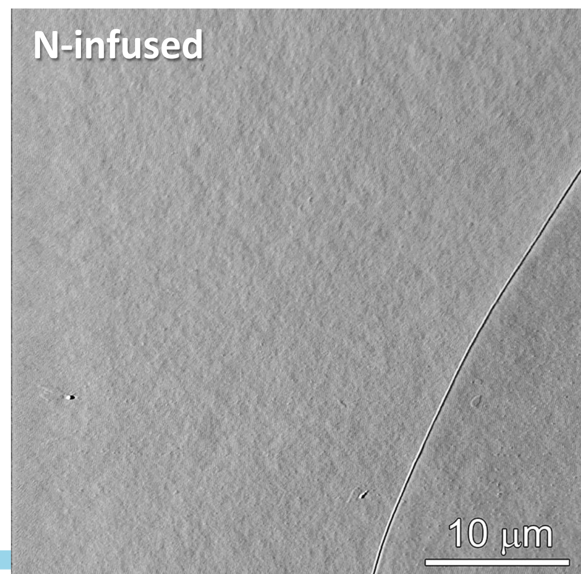
300-200K Surface features on cavity cut-out samples

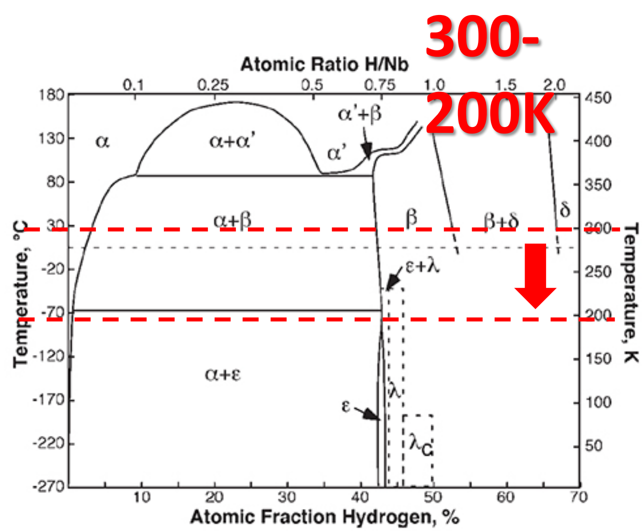




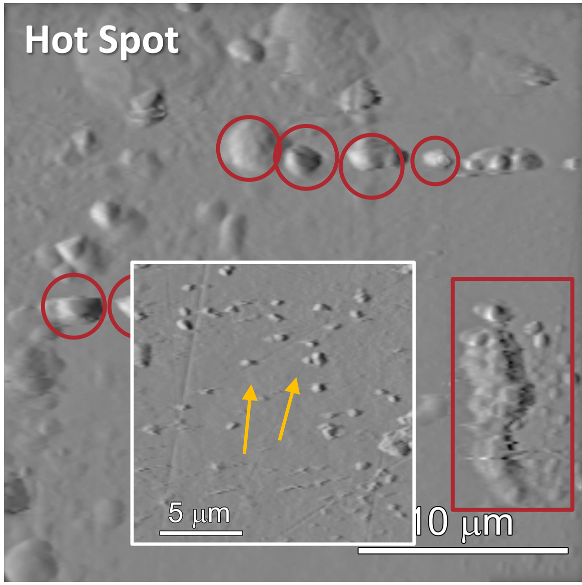


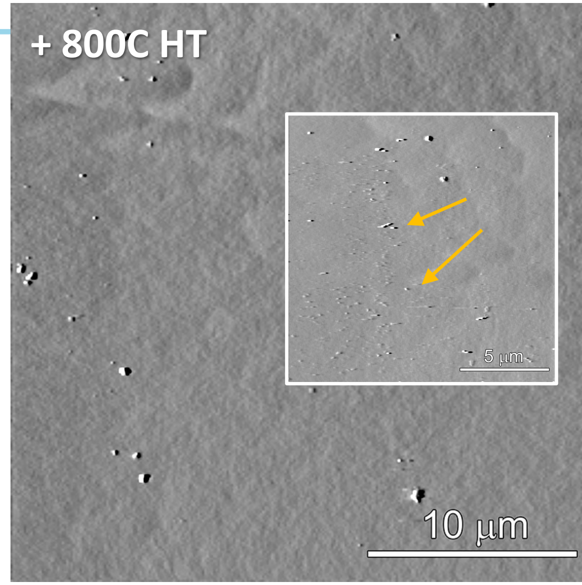


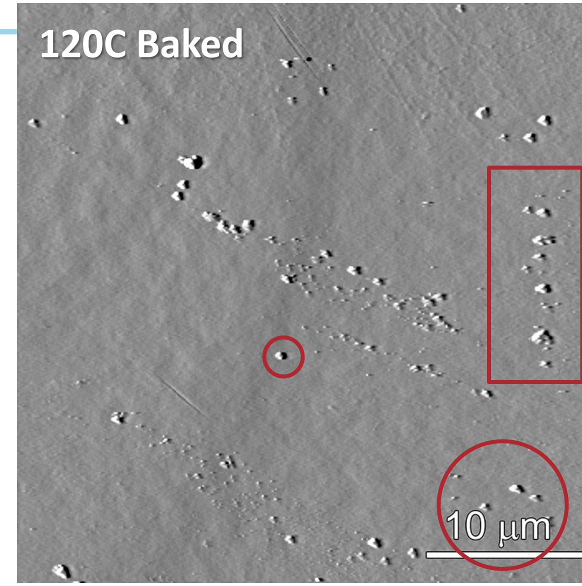


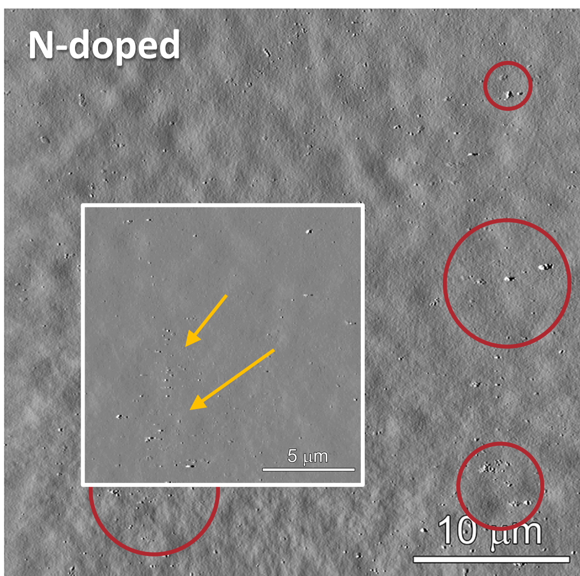


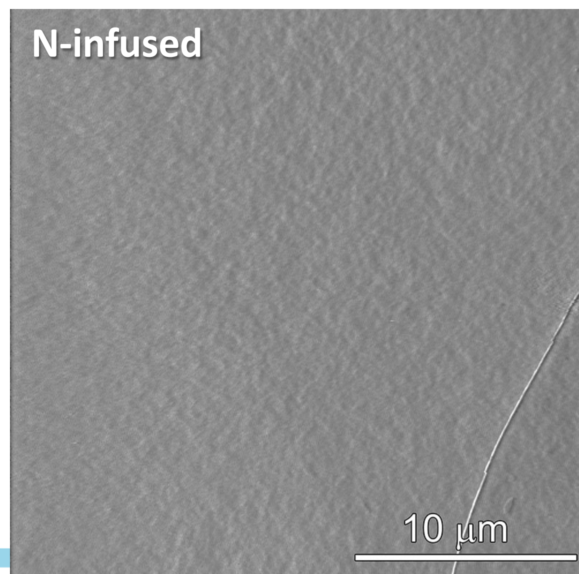
200-100K Surface features on cavity cut-out samples

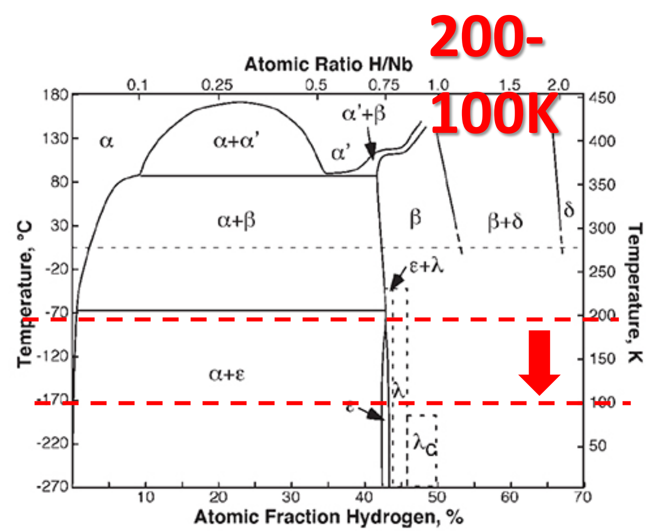




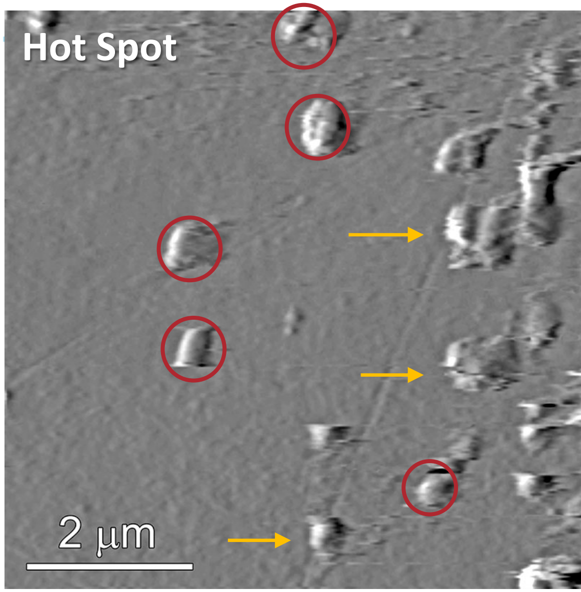


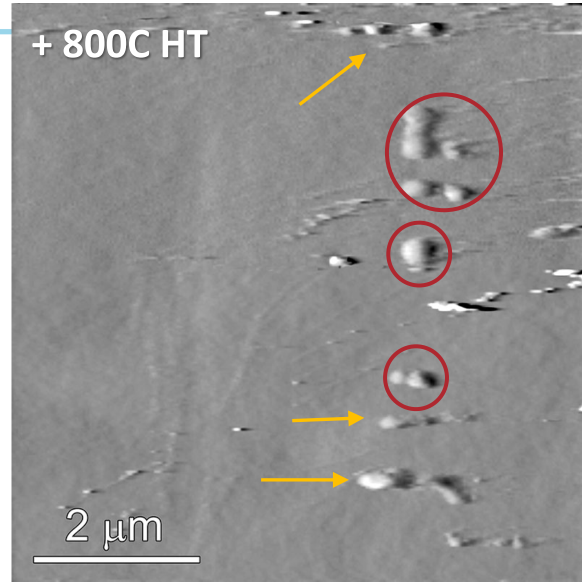


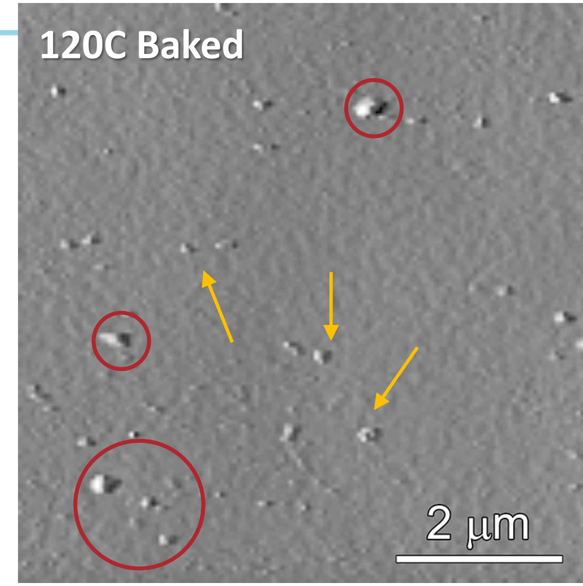


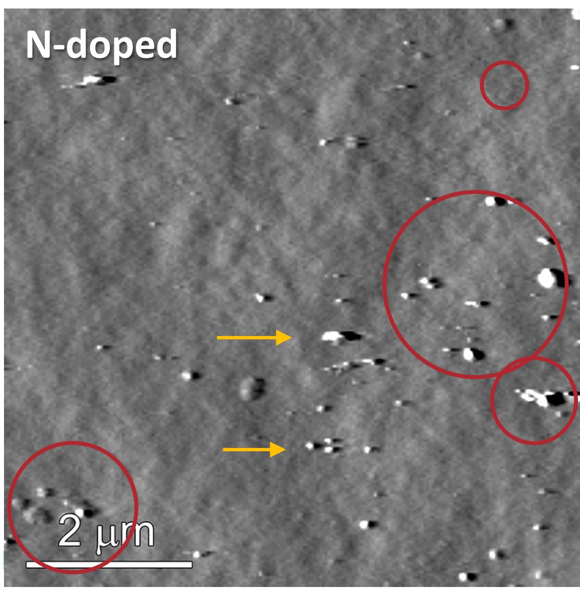


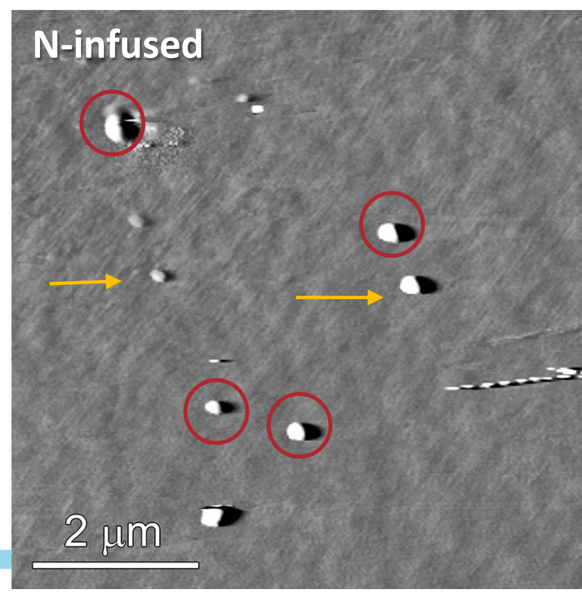
100-10K Surface features on cavity cut-out samples

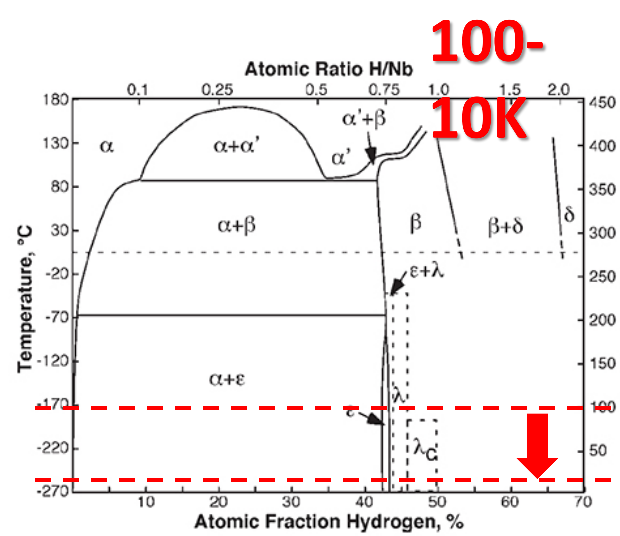






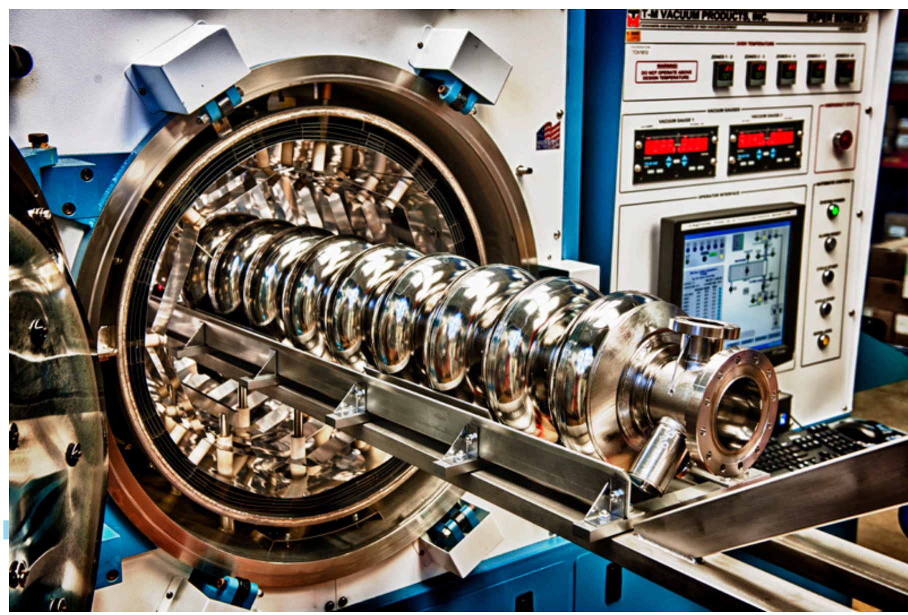




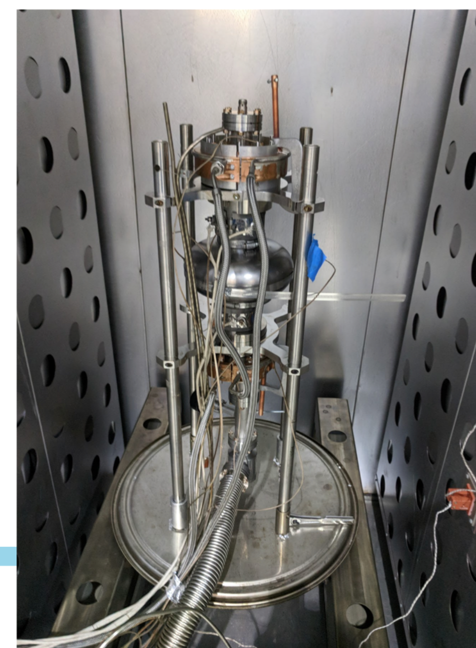


Progress with N infusion @FNAL in 2019 -

- Standard method to diffuse nitrogen in surface layer is to utilize a very clean high temperature furnace
- At FNAL, **more than 40 successful nitrogen infusion cycles/tests** have been carried out; KEK and other labs have struggled with variability in performance depending on furnace contamination background
- So we are developing a new method for N-infusion in a low T oven, keeping cavity always under vacuum, never to see the heating chamber
- This new method involves in situ removal of the Niobium surface oxide, leaving the surface ‘naked’ and to be doped/infused; method was developed also for SRF quantum computing, see A. Romanenko, S. Posen, and A. Grassellino, “Methods and system for treatment of SRF cavities to minimize TLS losses,” US patent pending, Serial No.: 62/742,328.



High T furnace ←

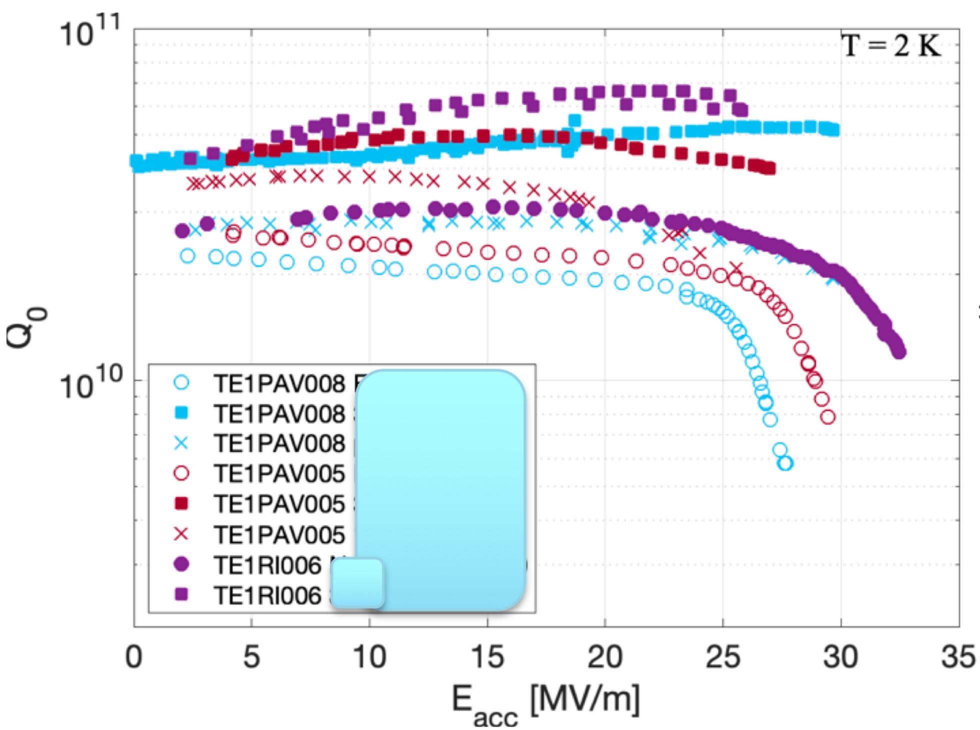


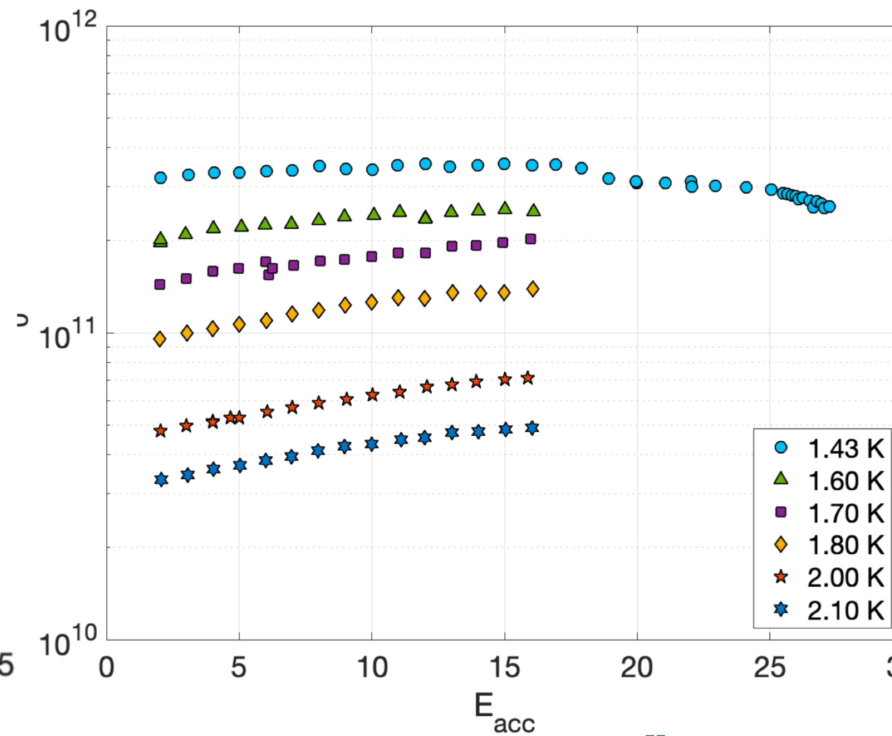
Low T oven ←

Progress with N infusion @FNAL in 2019

- World record Q values at all temperatures below 2K
- Currently we have achieved a nitrogen layer > 60nm (studied in SIMS) ; work is ongoing to study performance changes as a function of nano-surface removal; as N layer thins down, Eacc should go up

Plots courtesy of S. Posen; Manuscript in preparation

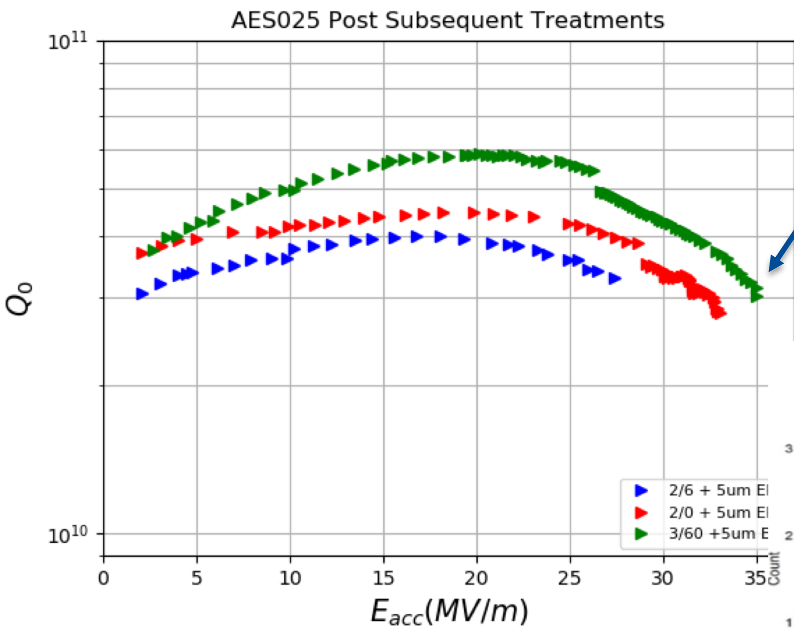




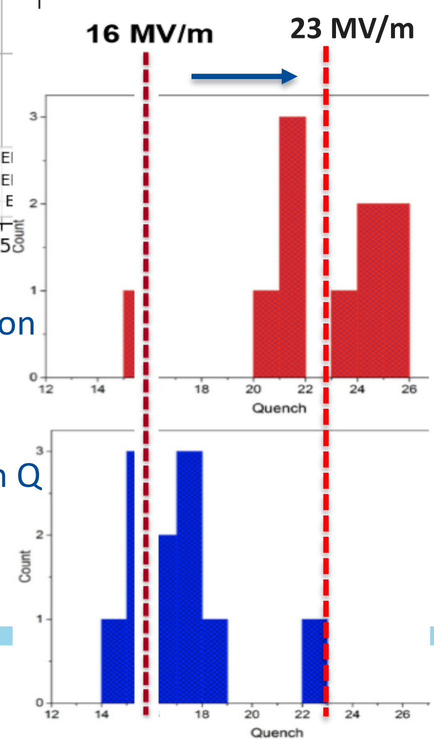
Progress with high gradient N doping in 2019

- Work in synergy with LCLS-2 HE R&D , to push high temperature doping to higher quench fields

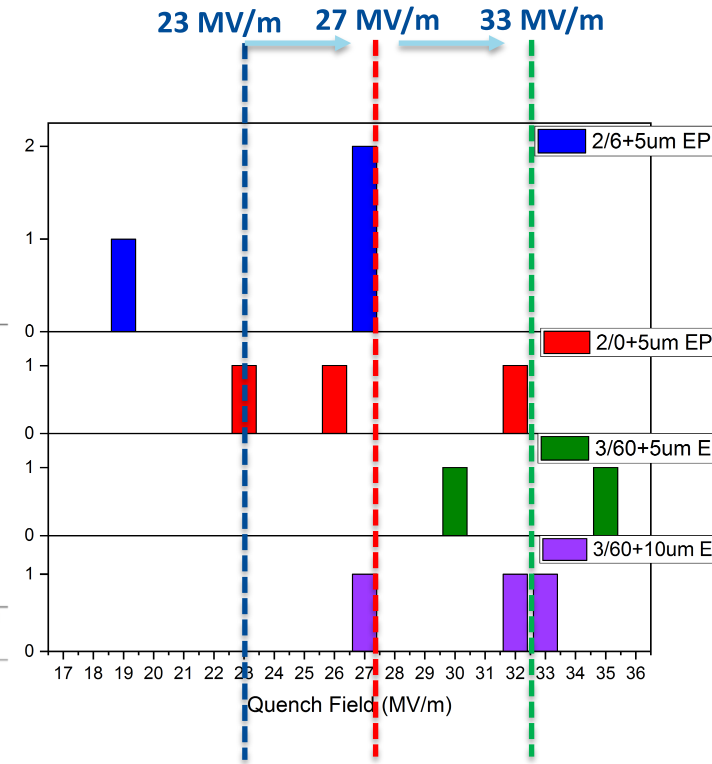
Q~3e10 at ILC spec (35 MV/m)



Plots courtesy of D. Bafia; Manuscript in preparation



LCLS-2 High Q R&D 2015



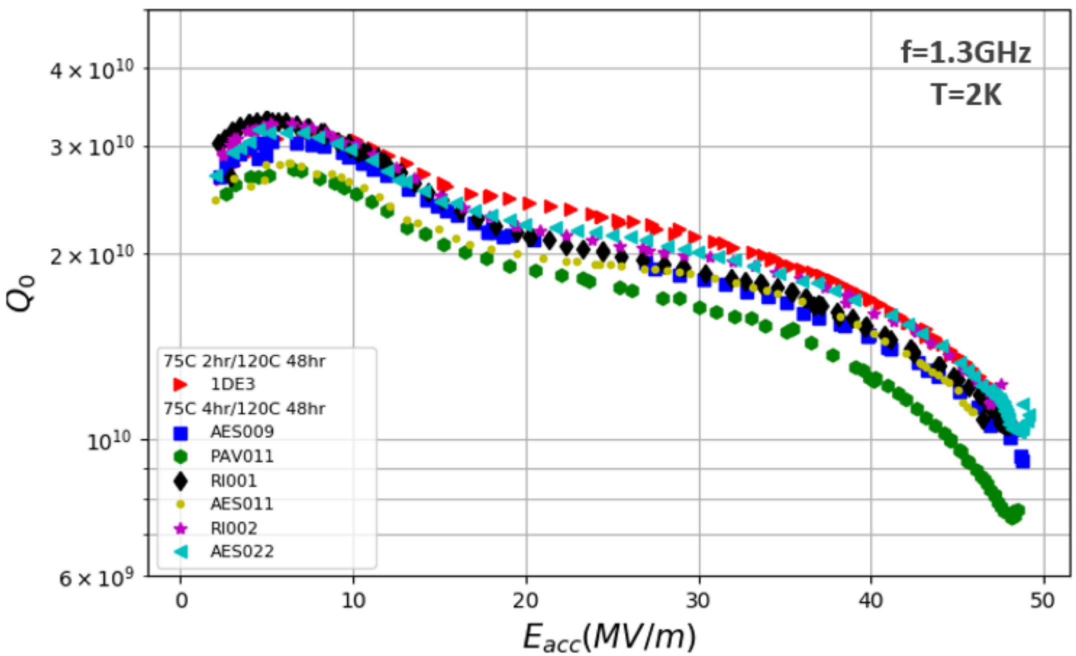
Progress with the ”modified bake” in 2019

- Last year we reported of a newly found low T treatment (no nitrogen involved) which led to unprecedented E_{acc} up to 50 MV/m in TESLA shaped cavities (~220 mT) with good Q

- Since discovery, we have moved forward on three fronts:
  A. Reproducibility, statistics
  B. Fundamental understanding – material/surface science
  C. Cross checking/cavity exchange with Jlab, Cornell, DESY, (KEK is next)

The new 75/120C findings - reproducibility

- We have recently focused our attention to the unexpected finding that a pre-120C bake step of ~4 hours at 75C seem to lead consistently to unprecedented accelerating gradients ~50 MV/m (220 mT, TESLA shape)
- However, under the ILC cost reduction effort, as we study more and more cavities, and exchange cavities worldwide, some new interesting findings are emerging in terms of Q and achievable accelerating gradient cooldown dependence



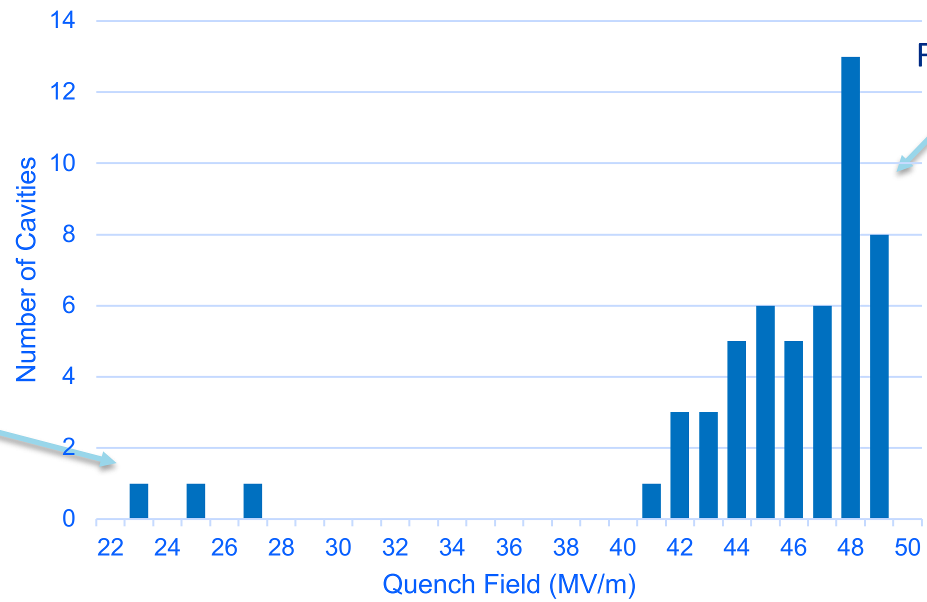
75/120C bake cavities

See Grassellino et al arXiv:1806.09824

Quench Field Histogram

- More than a dozen different cavities tested; multiple tests for several cavities
  - Consistently achieve excellent cavity performance
- Material : WC, TD, NX, Hareaus; cavities from AES, RI, DESY, KEK

KEK cavities (TD material): optical inspection indicates some potential surface flaws?

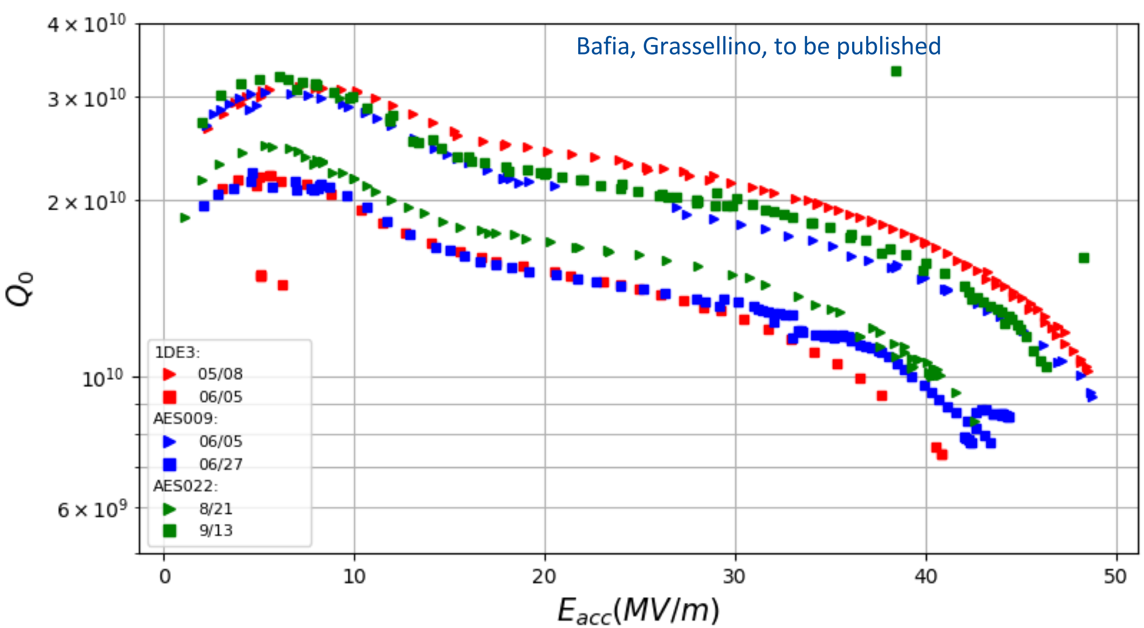


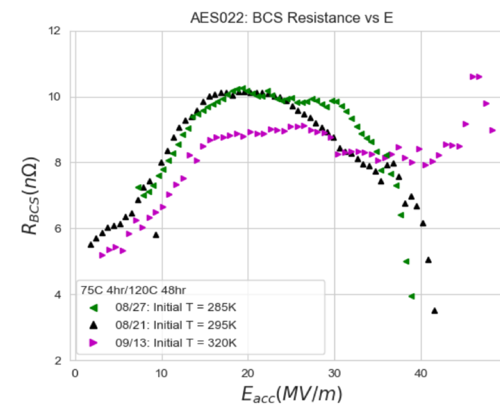
FNAL, DESY: TD, NX, WC, H

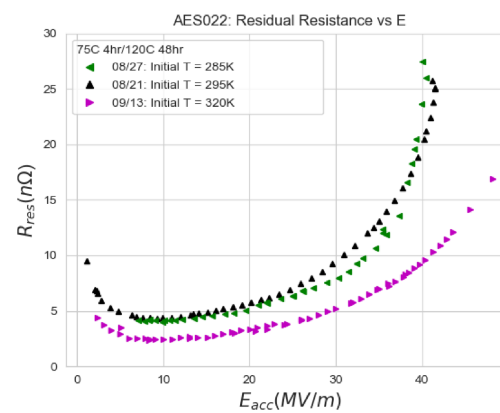
"Bunching up" of quench field observed: (45MV/m vs 48MV/m)

Finding 1: the strange ‘branching’ performance for 75/120C

- On dozens of tests and several cavities now, we see switch in performance for same cavity with no retreatment in between (always under vacuum)
- Effects of magnetic fields, dewars, cables, top plates have been excluded
- Some correlation has been found with cooldown speed near room T and starting T ~320-340K
- See **Daniel Bafia poster** for many details on this study

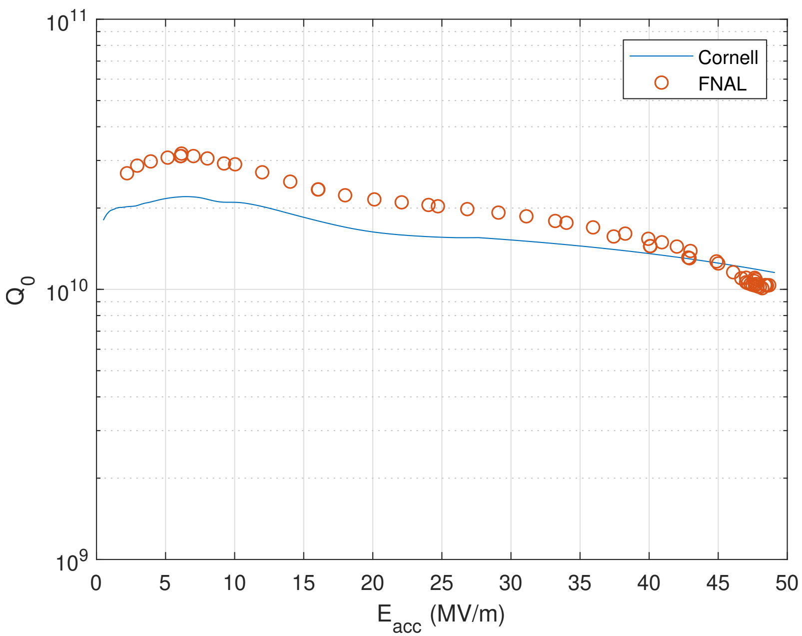




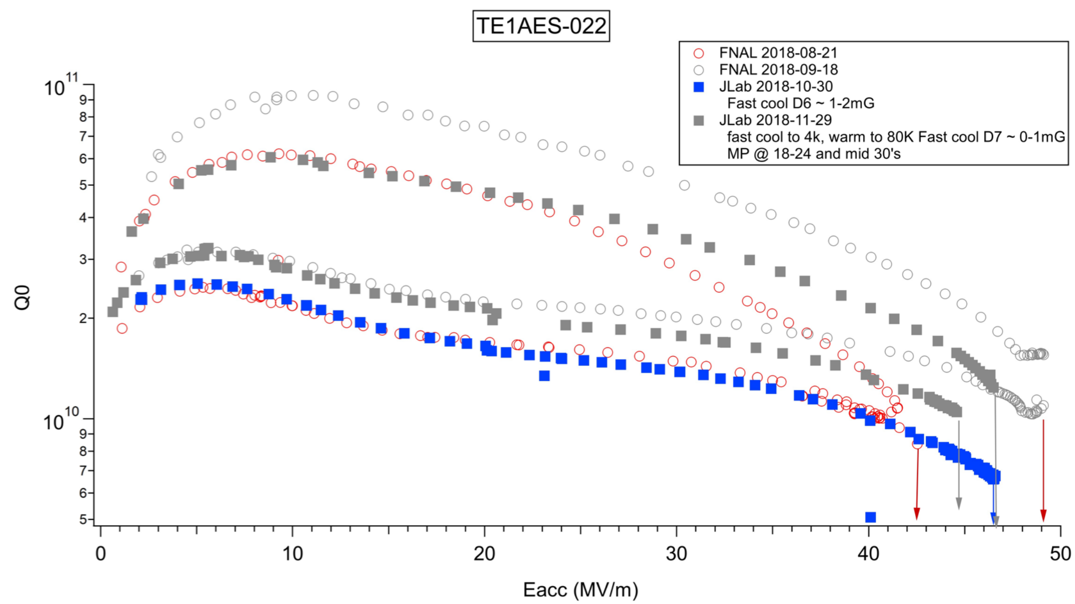


Two 75/120C cavities sent from FNAL to Jlab and Cornell

- Cornell gradient matches our 49 MV/m
- Jlab reproduced exactly the upper/lower branching behavior in two separate cooldowns
- Same cavity to DESY, then to KEK

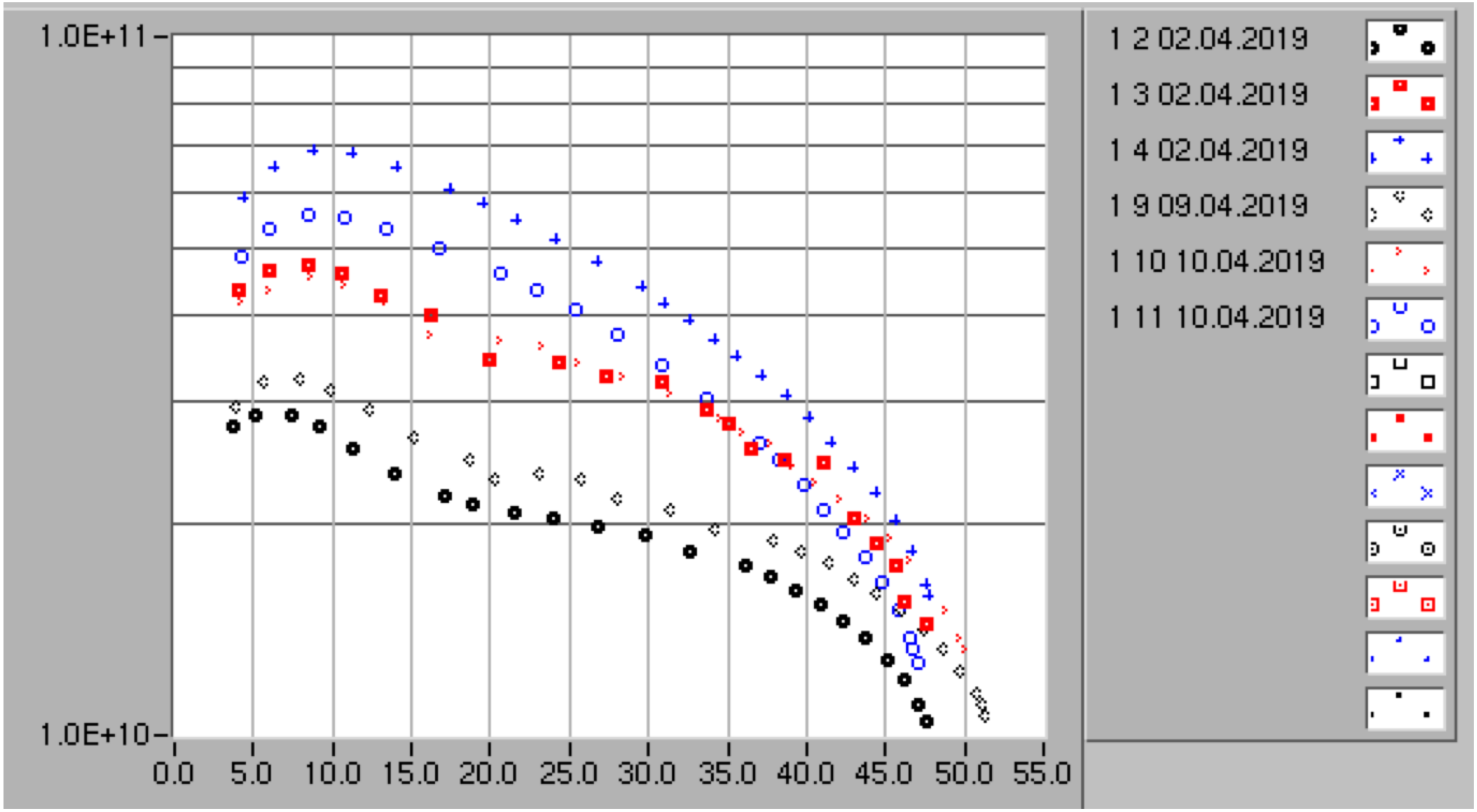


Courtesy of Liepe, Maniscalco, **Cornell**



Courtesy of Palczewski, **Jlab**

Results of 75/120C FNAL cavity at DESY



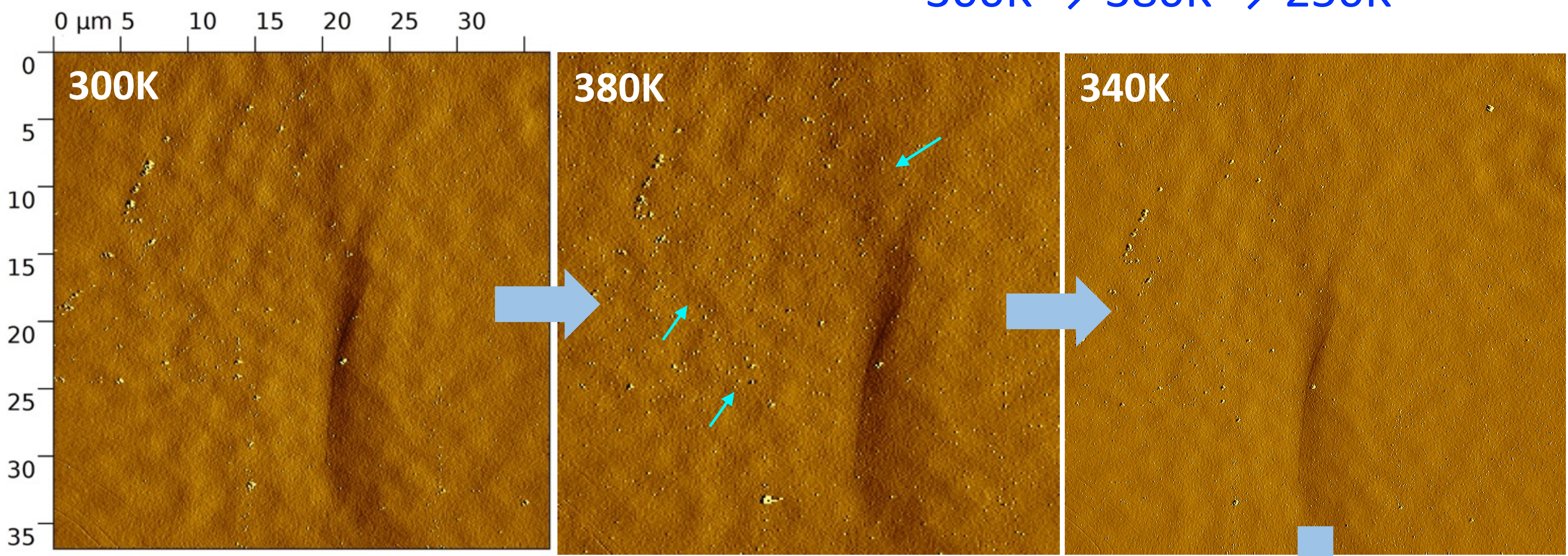
First cooldown reached 47 MV/m; second cooldown reached ~52 MV/m!

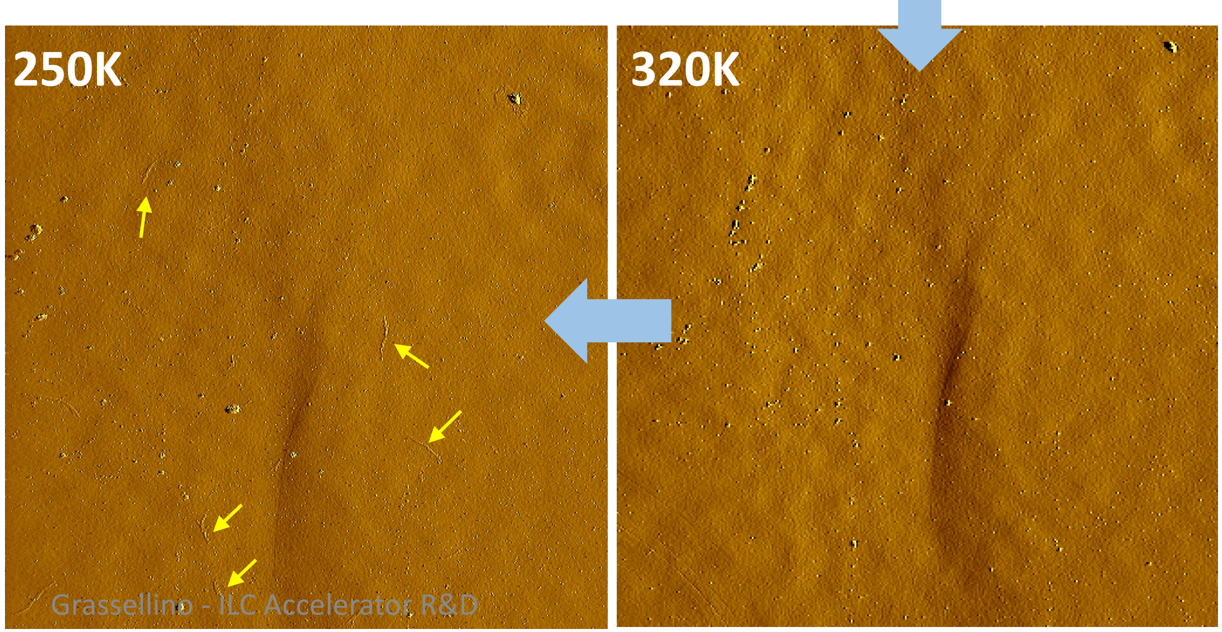
Studies ongoing; Results courtesy of D. Reschke (DESY);

Next: cavity will be sent for measurements at KEK

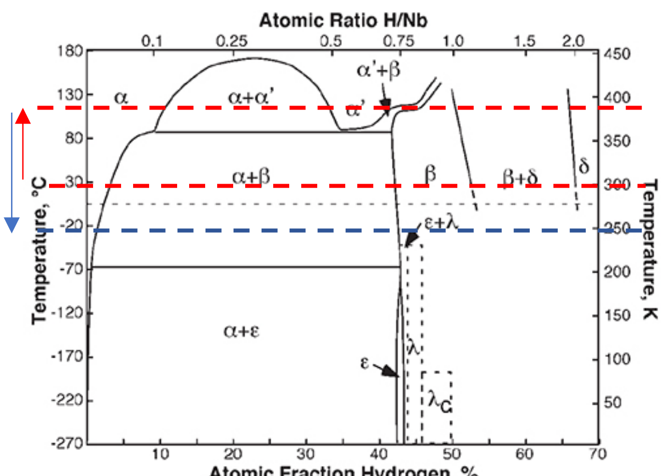
All non-contact (tapping) AFM mode images

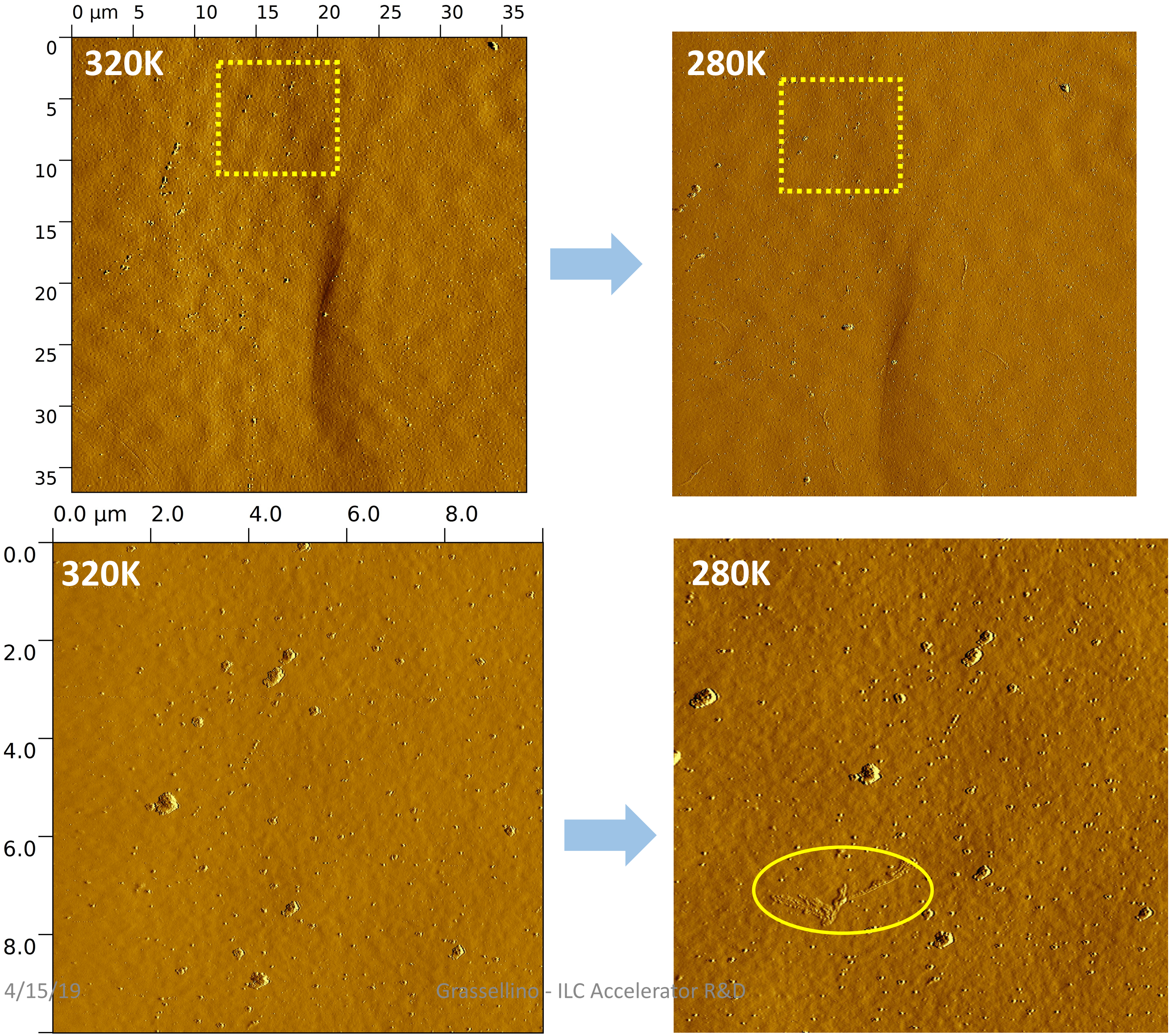
300K → 380K → 250K





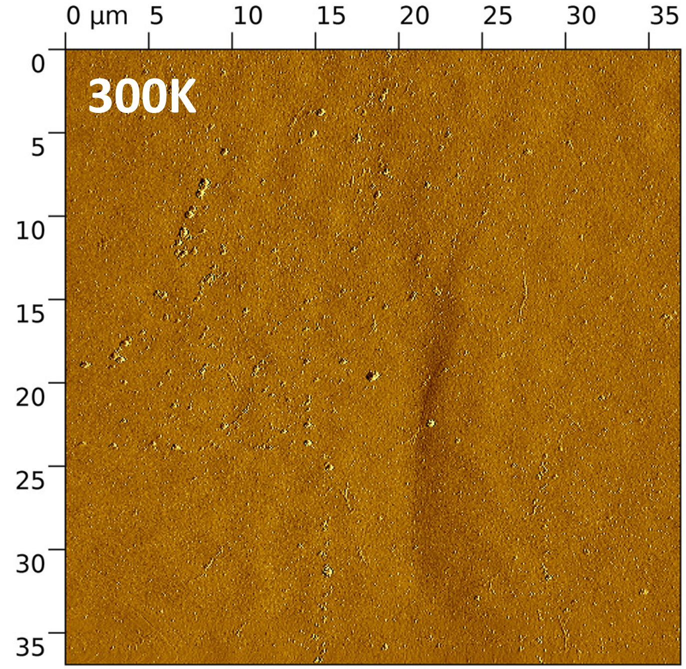
300 K



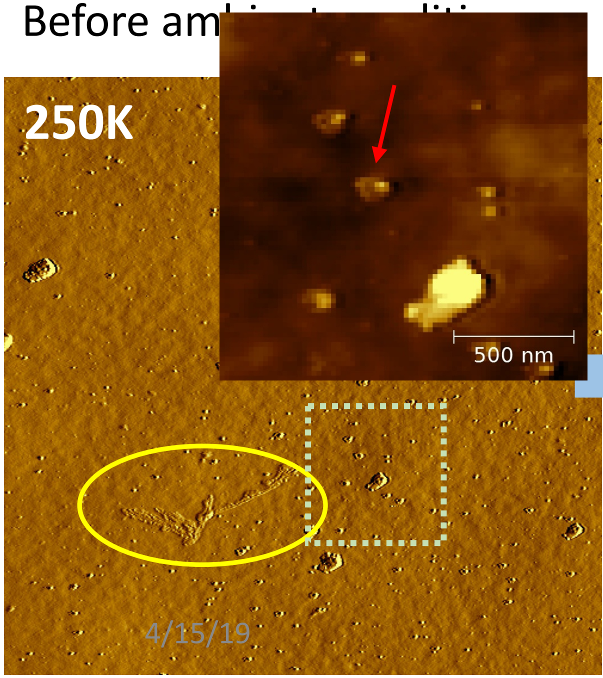


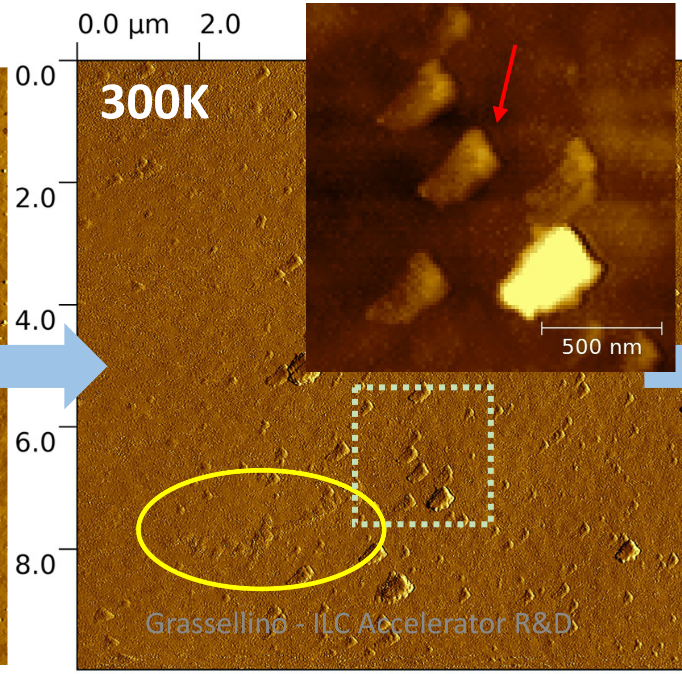
0 µm
5
10
15
20
25
30
35
0
320K
280K
0.0 µm
2.0
4.0
6.0
8.0
0.0
320K
280K

After 9 days 17 hours ambient condition

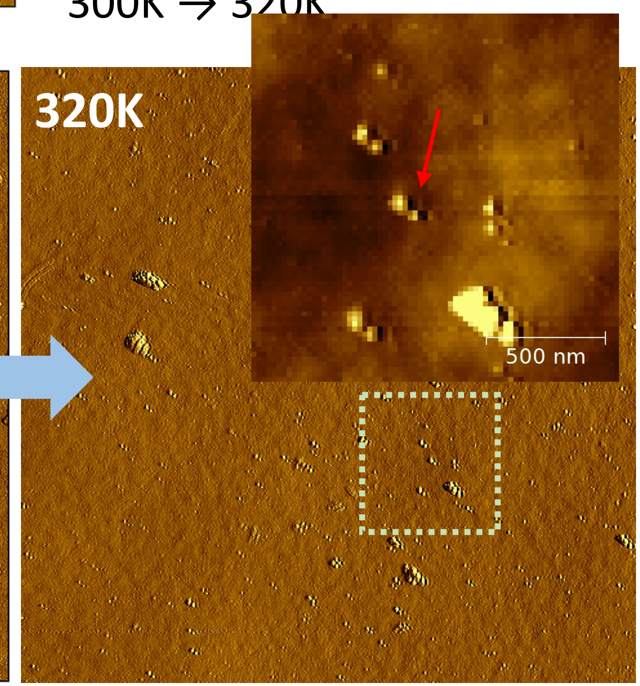


Before ambient condition

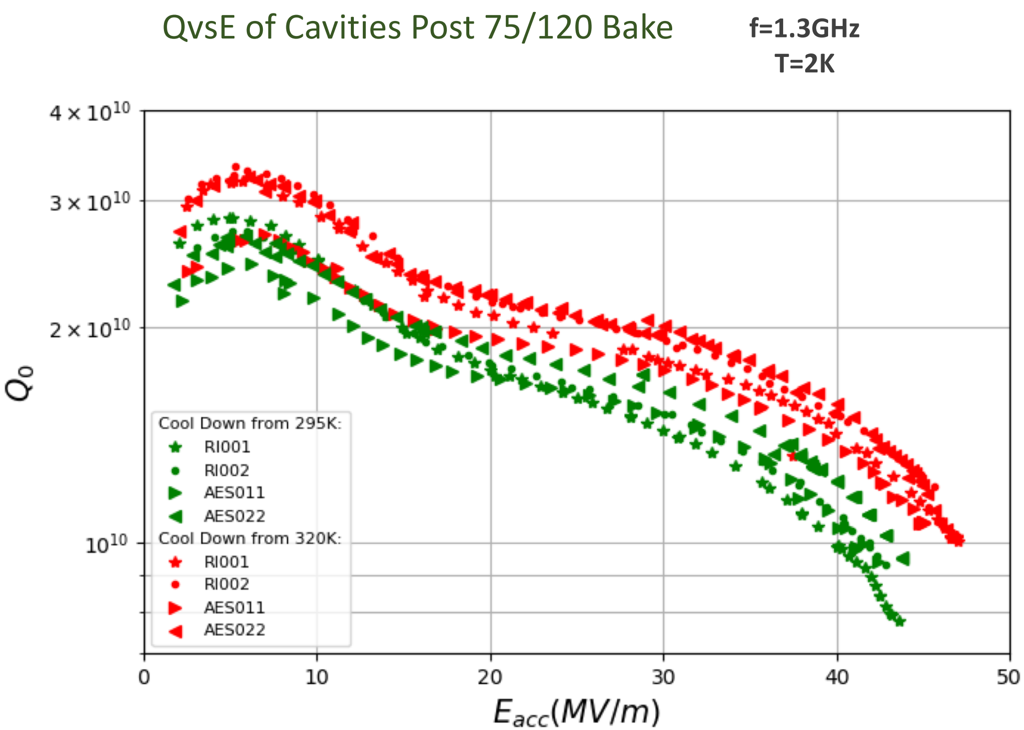


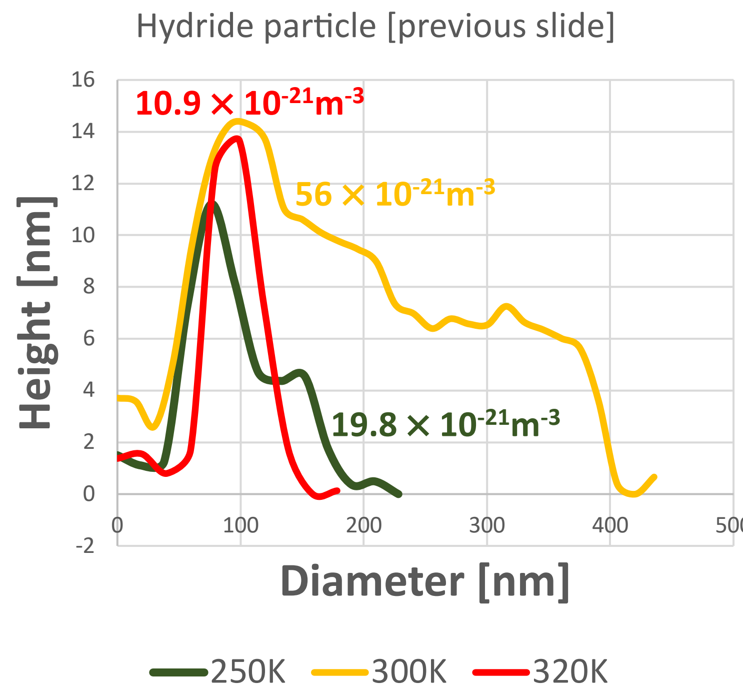


300K → 320K



Comparison of 75/120 Bake Cavities Cooled From 295K vs 320K





**** Number = Volume of particle***

See Daniel Bafia poster

- Cooling cavities from 320K shows consistently higher quench field and Q_0 at high fields for cavities post 75/120 bake when compared to cooling from 295K.
- In-situ 320K may be dissociating non-superconducting niobium hydrides

Summary

- ILC Cost Reduction activities proceeding at full speed
- US partners work in alignment with international collaborators, periodic meetings: FNAL, Jlab, Cornell, KEK, DESY
- Progress in KEK – FNAL results alignment
- Research and lessons learnt via US-DOE GARD program and LCLS-2 paved the way for cavity performance improvement for ILC
- Unprecedented Q and E_{acc} > 50 MV/m, steady progress with niobium
- Measurements of world record cavity worldwide agree within 2%
- Performance differences as a function of cooldown possibly revealing new insights on cavity performance limiting mechanisms → key to move forward

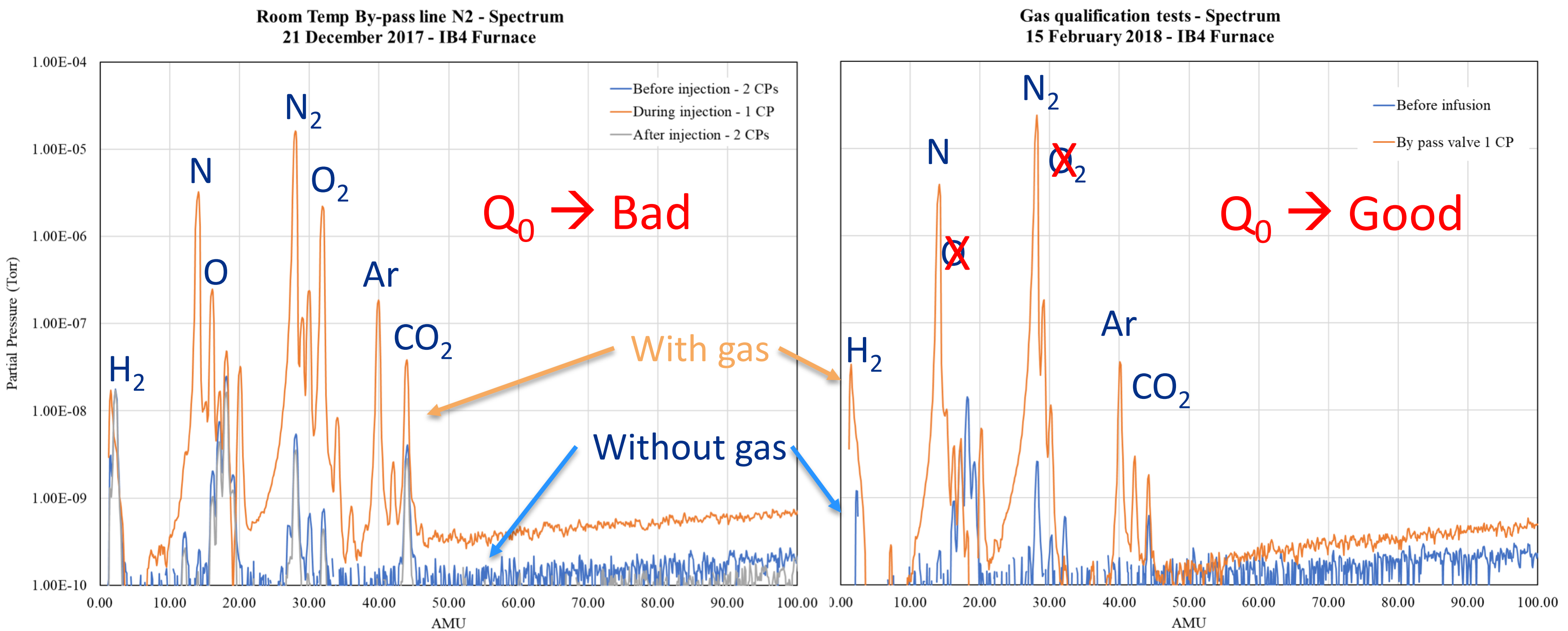
Backup slides

N Infusion (and going up to doping)– summary and update

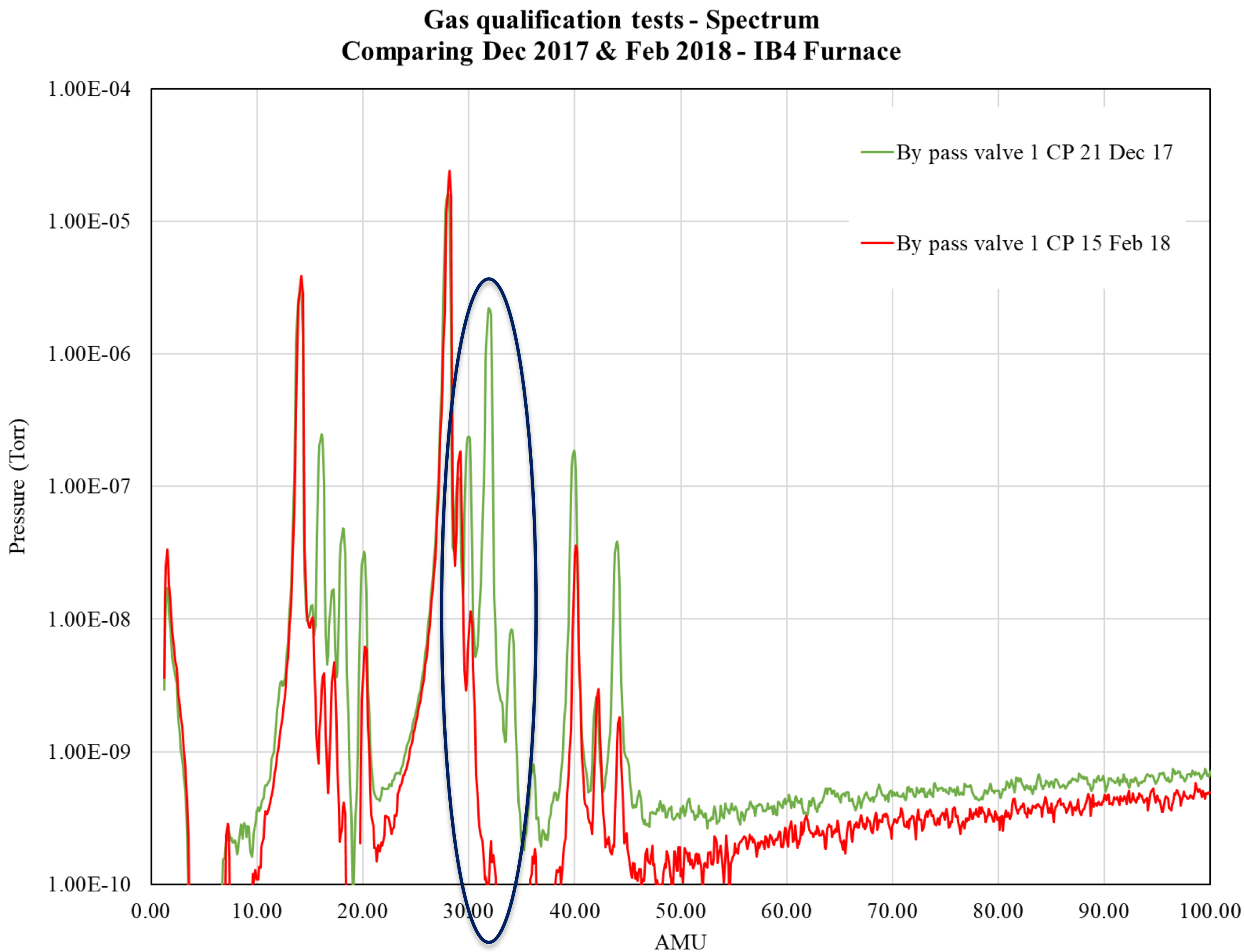
Temperature	Duration of N_2 injection (@25 mTorr)	E_{acc} max, average	Q @ 21 MV/m -2K	Q@ 35 MV/m - 2K	Limitation	Average on # single cell cavities
120°C	24 hrs	38 MV/m	2.5e10	1.7e10	Q slope @30	1
120°C	48 hrs	43 MV/m (max 45.6)	2.5e10	2.3e10	Quench	>20
120°C	48 hrs w/o N_2	36 MV/m	2.5e10	1e9	Q slope @30	2
120°C	60 hrs	43 MV/m (max 44.5)	3e10	2.5e10	Quench	3
120°C	60 hours (BCP)	33 MV/m	2.7e10	~2e10 @30	Q slope @28	1
120°C **	90 hrs	42 MV/m	2.3e10	2e10	Quench/slope	2 ** (non well annealed NX)
140°C	48 hrs	35 MV/m	2.5e10	2.2e10	Quench	2
160°C	48 hrs	36 MV/m	3e10	1e10	Q slope@30	1
160°C	48 hrs with N_2/48 wo	35 MV/m	4e10	2.5e10	Q slope@25	1
160°C	48 hrs with N_2/96 wo	34 MV/m	3e10	8e9	Q slope@25	1
170°C	48 hrs with N_2/48 wo	27 MV/m	4e10	--	Quench/Q slope @25	2
200°C	48 hrs	28 MV/m	3.5e10	--	Q slope @15	1
300°C	4 hrs with N_2/48 wo	28 MV/m	2e10	--	Quench, MFQS	1
400°C	30 mins	--	1e8	--	Nitrides	1

Experimental Progress with N infusion: degradation issue resolved

- Oct   Q degradation observed
- Nov   Extensive traditional leak checks performed
- Dec   Innovative gas qualification method resulted in observing signs of air in infusion gas line
- Jan/Feb   Further tests on the line revealed valve problematic
  - Replaced valve & Initial cavity Q improved & per expectations
- Degradation attributed to excessive O_2

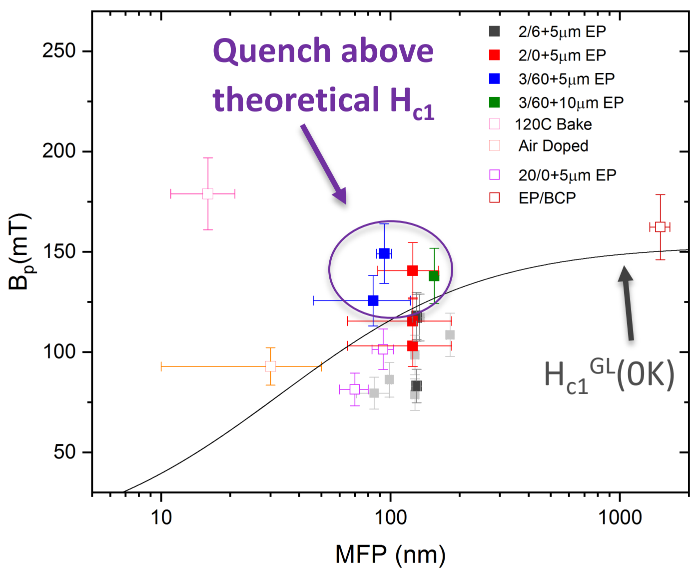


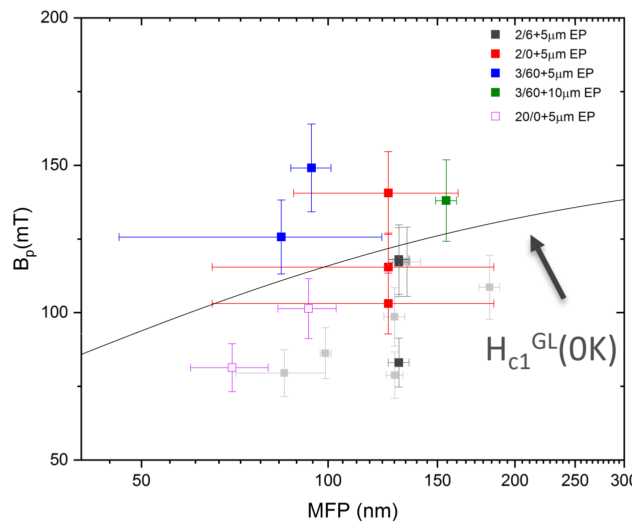
RGA scans – before & after

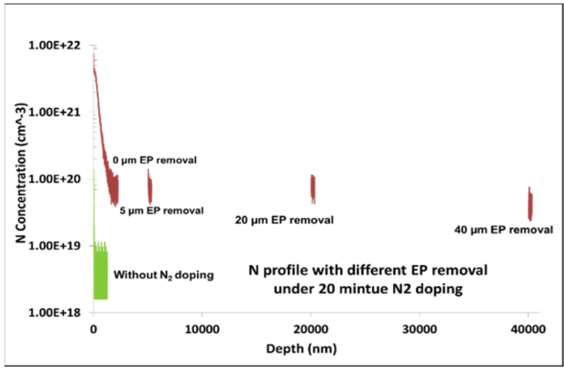


Role of mean free path/nitrogen concentration?

- One of the leading thoughts on quench in N doped cavities has been that higher concentration/lower mfp could reduce the quench field (corroborated by the fact that lighter doping or deeper EP typically yield higher gradients)
- In reality, data does not show a clear correlation with mean free path
- More detailed SIMS studies ongoing to systematically relate surface N concentration to achievable field



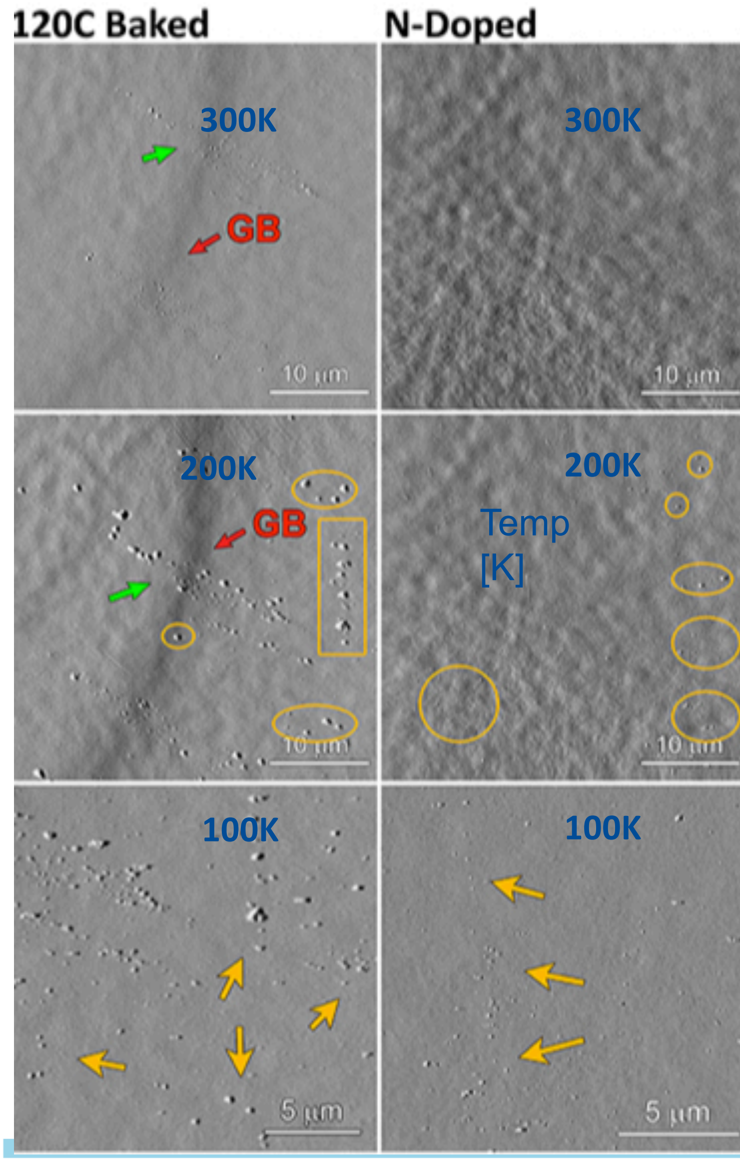




Palczewski, Reece MOPB039 Proceedings of SRF2015, Whistler, BC, Canada

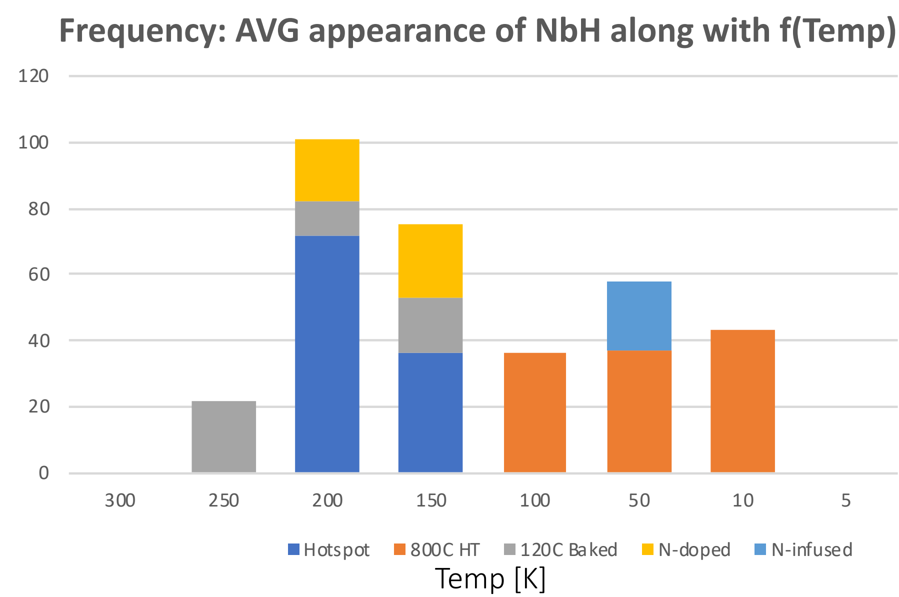
Open squares data points from M. Checchin talk @TTC RIKEN 2017, new data from D. Bafia in solid colour, presented at TTC ARIES @CERN

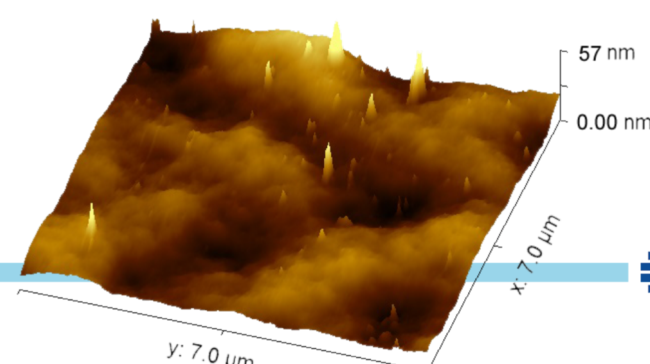
Nano-Hydrides in N doped cavity cutouts (Romanenko/Sung)



See Z. Sung (FNAL) breakout talk

Nanohydrides form in the range 200-100K, fewer than other treatments and size ~30-50 nm

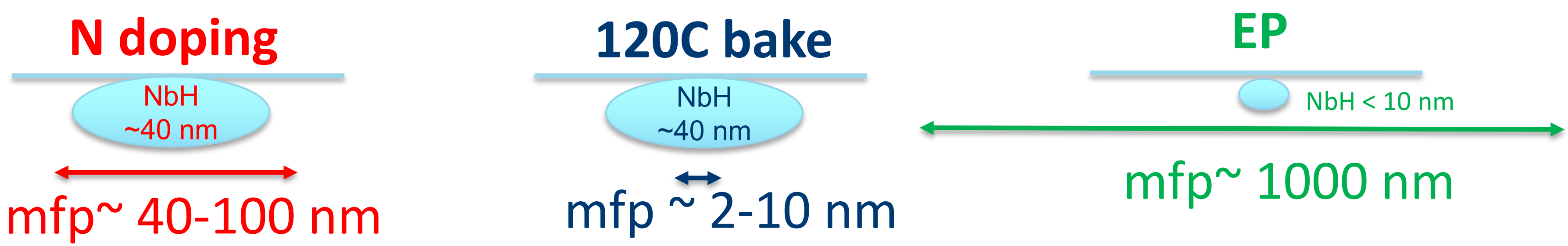




Fermilab

A proposed model to explain quench in N doped cavities

- Field of first vortex entry will depend on size of superficial defects compared to coherence length
- Doping recipe and final N level modifies the coherence length (mfp) but also size of hydrides
- Think of hydrides as surface 'defects' that will lower field of first entry
- Possible that **N doping brings the coherence to unfavorable point** compared to other treatments, **coherence length comparable to size of the hydrides** (which is exactly the case)
- Possible pathway forward: decouple coherence from hydrides size (move to dirtier or cleaner or longer second step outgassing cycles e.g. 3/60min to reduce hydrides size)



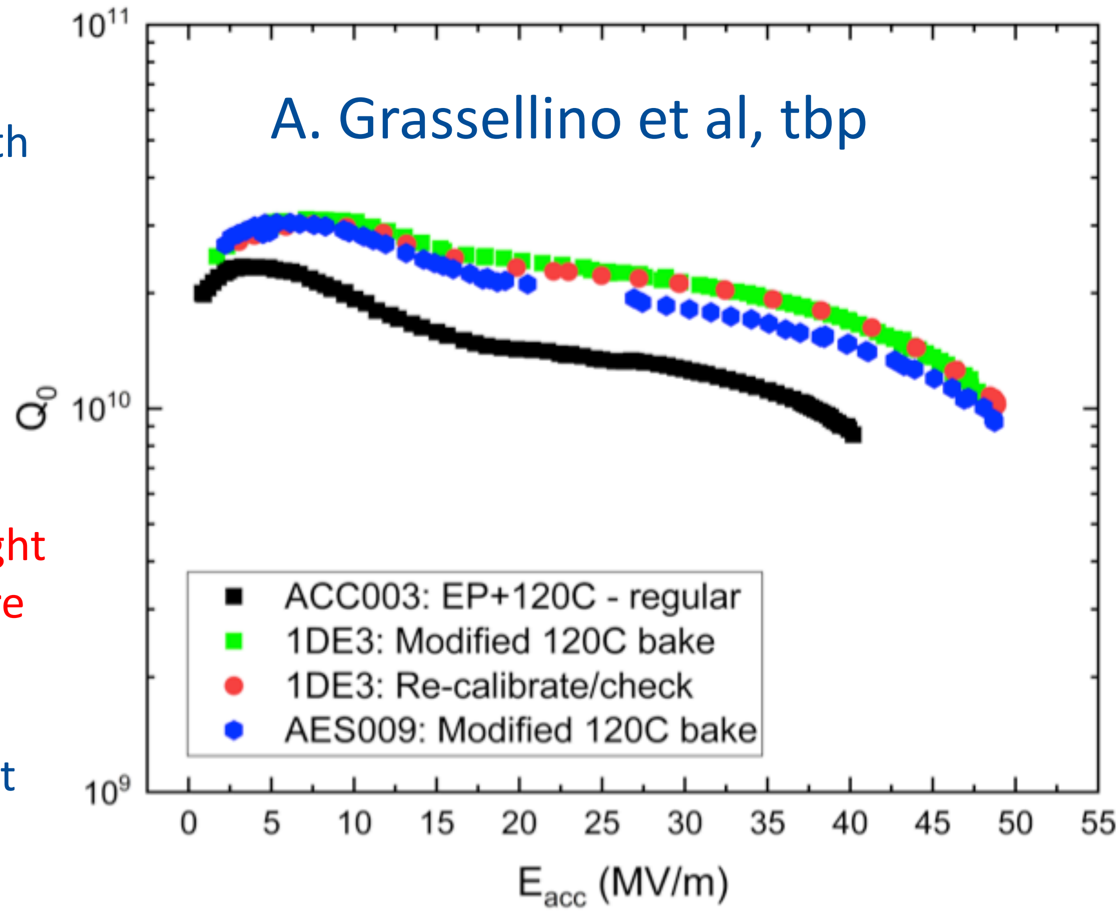
Model under development, Grassellino and Sauls (Northwestern U, CAPST)

TABLE II. Vortex entry field H_{en} for various inclusion defects .

Defect size	$1\xi \times 1\xi$	$2\xi \times 2\xi$	$3\xi \times 3\xi$	$4\xi \times 4\xi$	$6\xi \times 6\xi$	$8\xi \times 8\xi$
H^I_{en}/H_{c2}	0.38	0.30	0.27	0.28	0.28	0.28

NEW: Breakthrough in gradient for Tesla shape – 49 MV/m

- New results showing reproducibly ***unprecedented*** accelerating gradients for TESLA shape 1.3 GHz cavities: 49MV/m (B_{pk}=210 mT), with higher Q
- Highest ever measured for Tesla shape cavities was 45 MV/m (very rare)
- New surface treatment involves slight modification of the low temperature bake (120C bake), **no nitrogen**
- Q ~1.5e10 @ 40MV/m and ~1e10 at 49 MV/m
- More details in my TTC talk next week, arXiv paper out soon



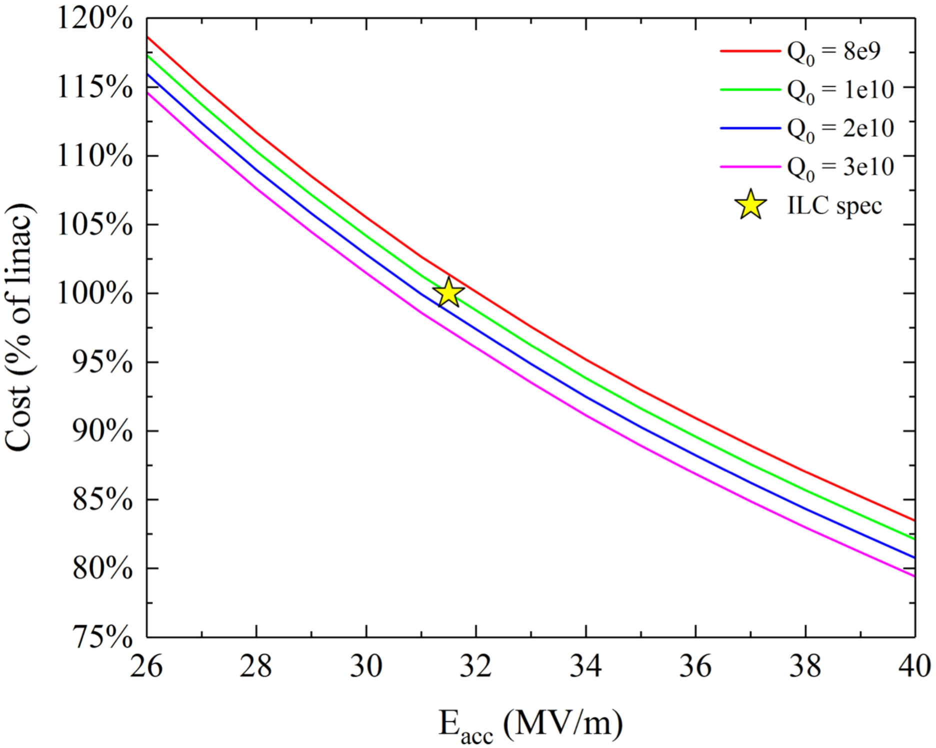
Very Large Potential impact for ILC

- If verified with sufficient statistics, could allow to raise ILC operating point to >40 MV/m

- Impact:
  - Reach 250 GeV with cost reduction of the SRF linac >20%

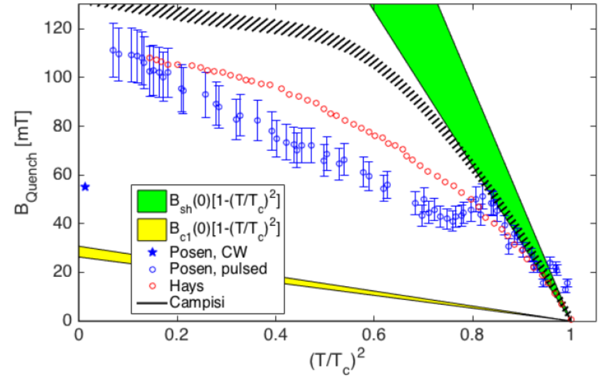
    Or

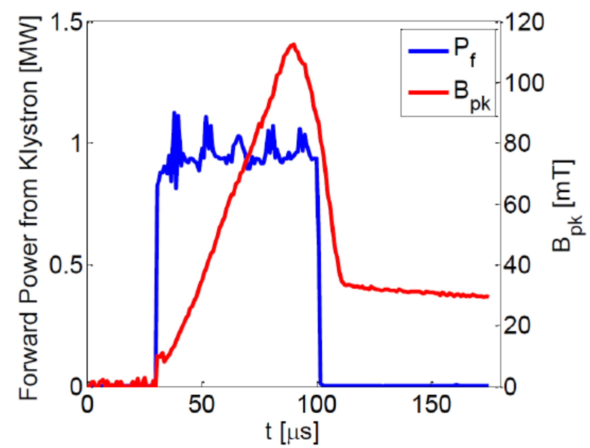
  - Raise energy from 250 GeV to >300GeV



New VTS Capability at FNAL: High Power Pulsed RF

- RF station under development at FNAL
- **~3 MW**, up to 100s of μs pulses at ~1 Hz rep rate to vertical test stand
- Quickly raise fields in cavity (tens of μs)
  - Push through and reduce **field emission**
  - Outpace many **thermal effects**, reach closer to fundamental limit of material
- Benefits to many programs:
  - Field emission – study HPP for use in CM
  - Nb_3Sn, Nb/Cu, new materials – bypass small defects to study fundamental limits
  - N-infusion – investigate possible increase of superheating field





S. Posen, N. Valles, and M. Liepe, ***Phys. Rev. Lett.*** 115, 047001 (2015)

New Klystron at FNAL-VTS