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Overview of Progress in High Q and High Gradient in Niobium Cavities

Anna Grassellino

19th International Conference on RF Superconductivity

Dresden, July 2019

Outline

- Two main research directions to push high Q at high gradients:
  - High temperature **(> 800C**) nitrogen doping
  - Low temperature treatments (**~ 50C-200C**) with or without nitrogen
    - **NEW! With increasing importance of cooldown studies/details in the whole temperature range ~300->2K**
  - **NEW! –** “Medium” temperature in-situ bake (**200-400C**)
- Possible common matrix: nano-hydrides presence/suppression?

Key posters linked to this presentation:

Romanenko → SIMS analysis of cavity cutouts: **THP014**

Bafia → new insights in the physics of anti-Q slope, low T bake, doping: **MOP031, TUP061 TUP062 TUFUA4**

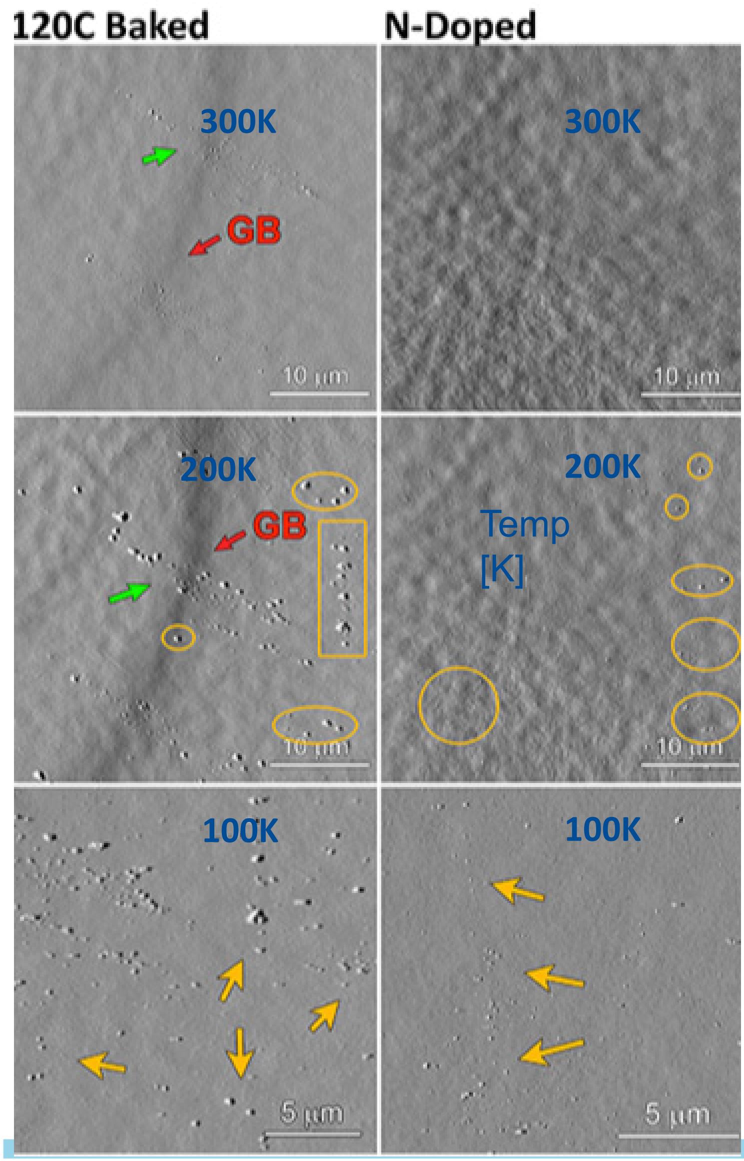
Sung → nanohydrides studies via AFM: **TUFUB1**

Posen → New “medium T bake”: **MOP043,** http://arxiv.org/abs/1907.00147

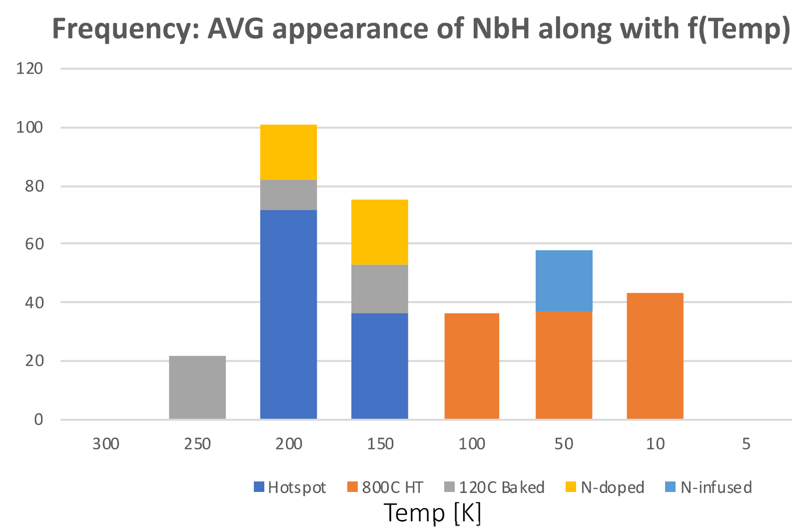
Gonnella → LCLS-2 and LCLS-2 HE cavity results: **FRCAA3**

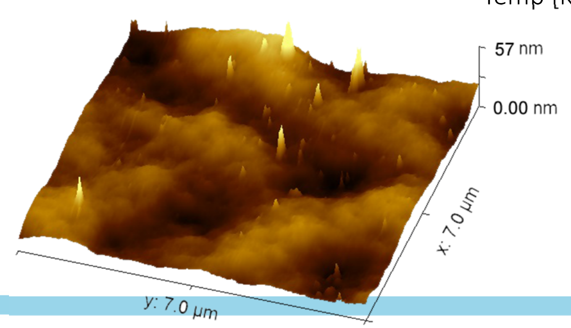
Wenskat → High G cavity around the world: **MOP026**

First nano-hydrides visualization in cavity cutouts via cryo-AFM



1. First study showing **precipitation T, size, frequency of nano-hydrides in cavity cutouts** for different surface processing
2. **N-Doped/N infused** cutouts show **fewer hydrides volume** than any other treatments
3. **120C bake** shows presence of hydrides at **room T (300K)**





See Z. Sung (FNAL) talk

Romanenko/Sung (to be published)

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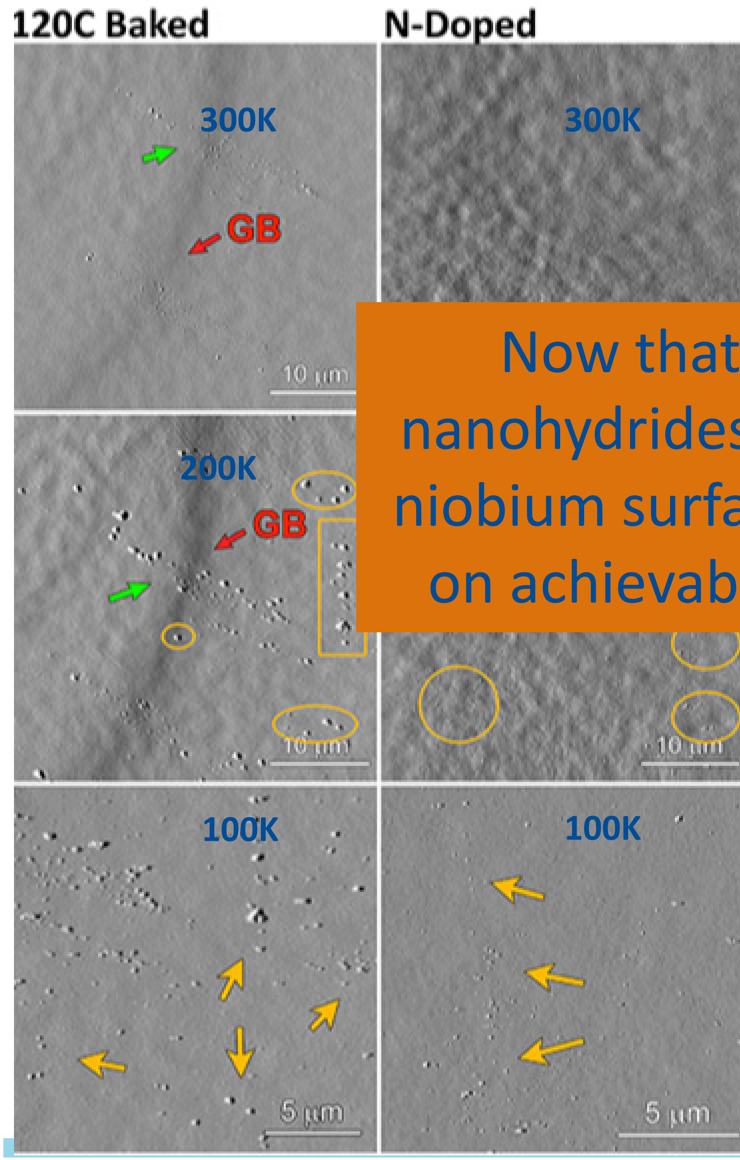

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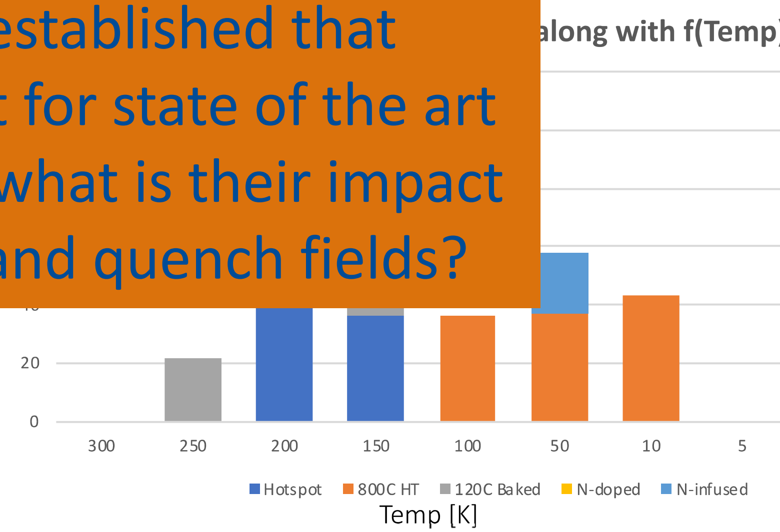
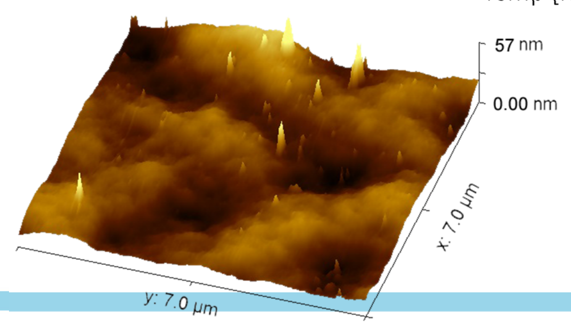
Now that it is established that nanohydrides exist for state of the art niobium surfaces, what is their impact on achievable Q and quench fields?





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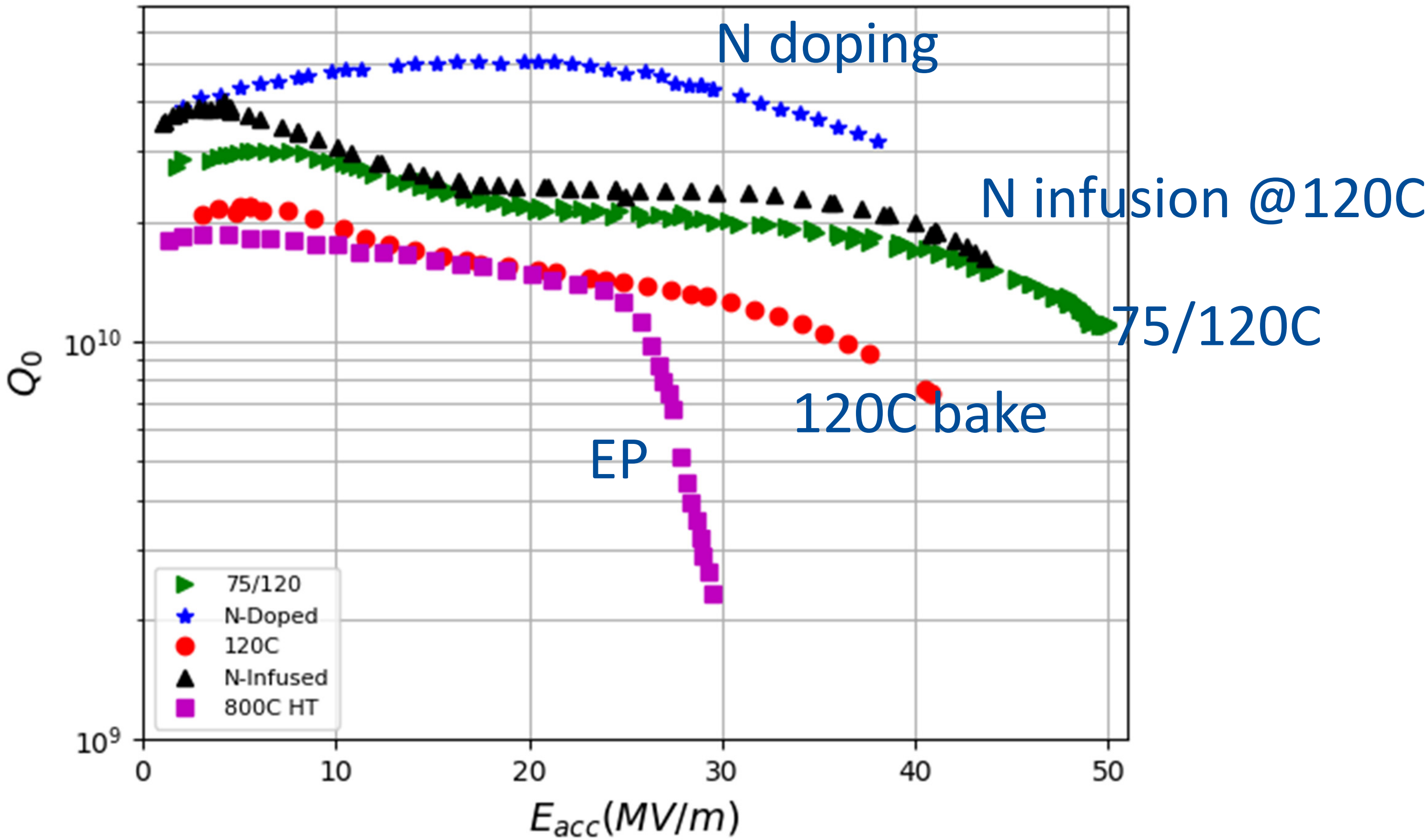
State of the art in high Q and high G (1.3 GHz, 2K)

Best Curves of 2019:

- **Q>3e10 @38 MV/m** with N doping, **> 5e10** at mid field
- Q >1e10 at **50 MV/m** (B_{pk} **~ 220 mT**) with 'modified' low T bake

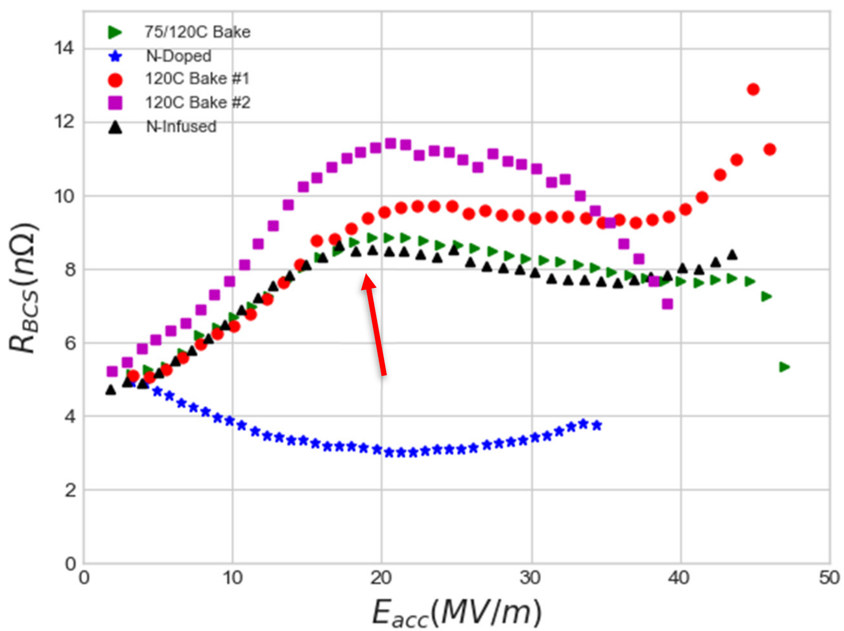


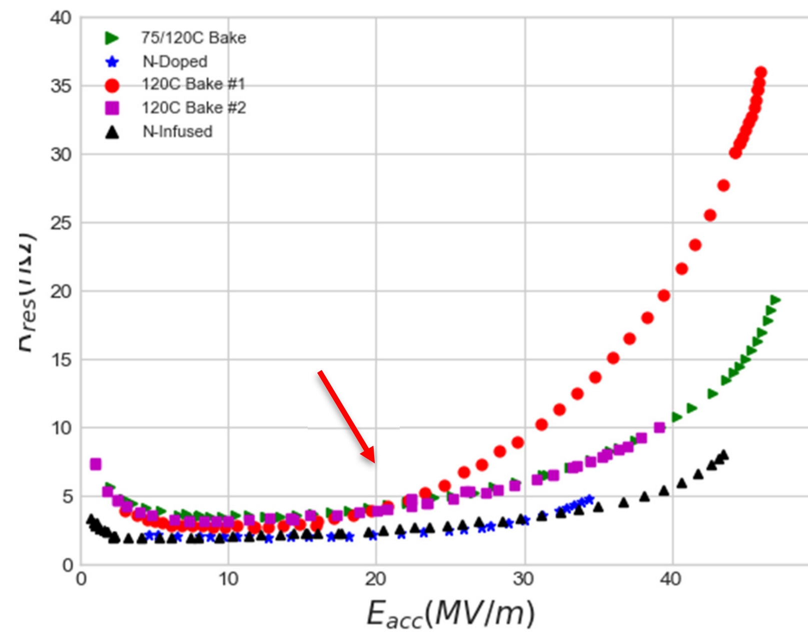
What does it mean in terms of surface resistance? R_{BCS} and R_0 field dependence for state of the art treatments

- Doping has pushed the $R_{BCS}(T)$ to as low as **3 nOhm** at 2K, 1.3GHz, ~25-30 MV/m, effectively reducing of a factor 2-4 compared to 120C bake cavities, thanks to its **reversed field dependence of $R_{BCS}(T)$**

- Residual resistance has been pushed as low as < **0.5 nOhm** for **oxide free cavities** and routinely around 1-2 nOhm for N doped cavities

- A field dependent residual resistance is limiting the Q at higher fields





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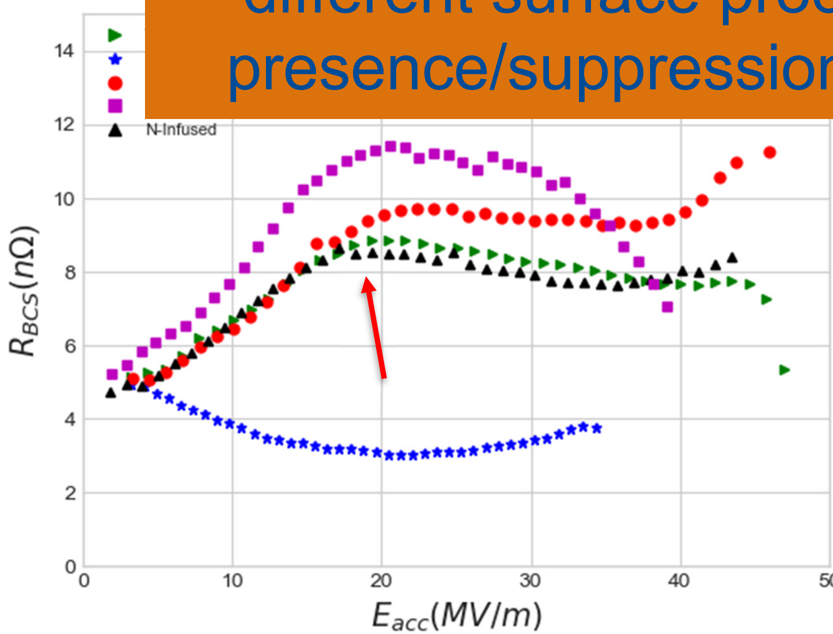
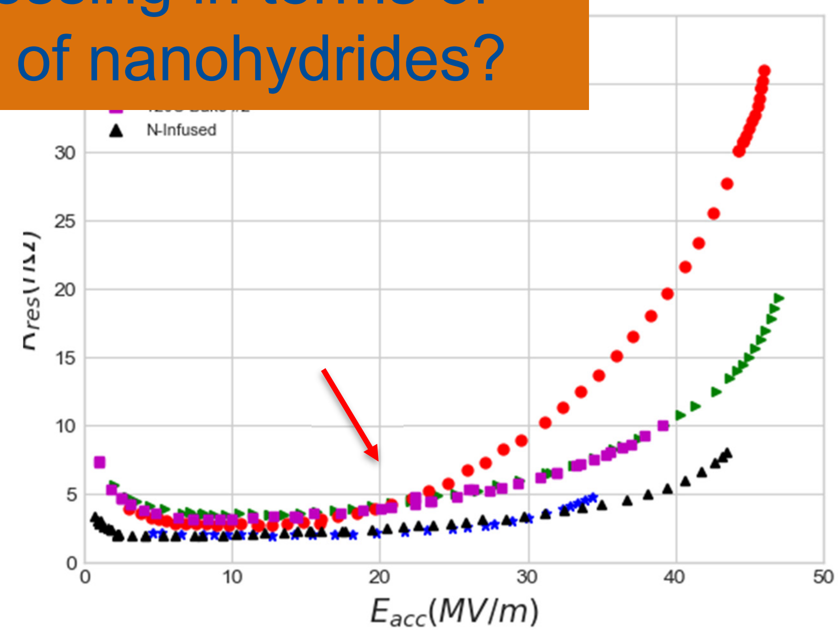
- Residu… **de free cavitie…**
- A field … s

Interestingly, the “knee” at which the residual resistance starts to increase, corresponds to a knee/decrease in $R_{BCS}(T)$: Why?

Can we interpret surface resistance for different surface processing in terms of presence/suppression of nanohydrides?

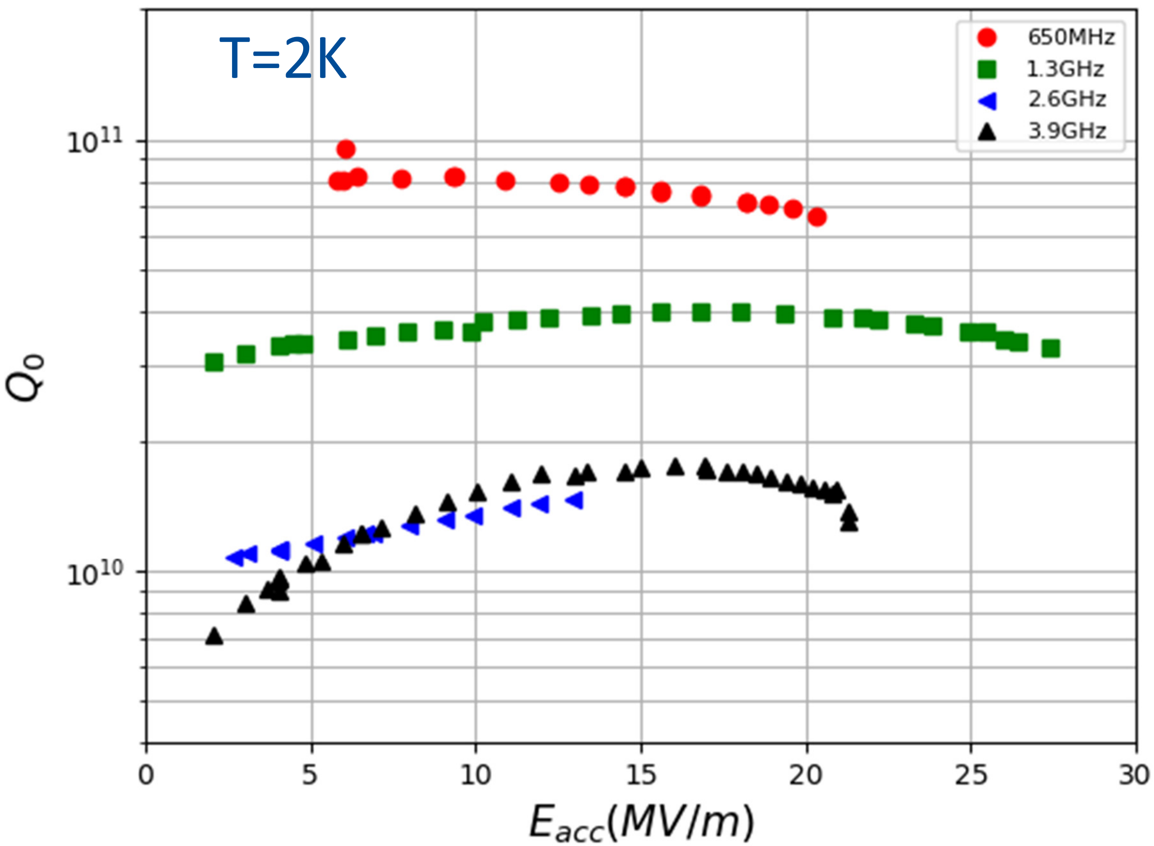




High T Doping

High Temperature Doping is key for highest Q at all frequencies in the range 650 MHz- 3.9 GHz

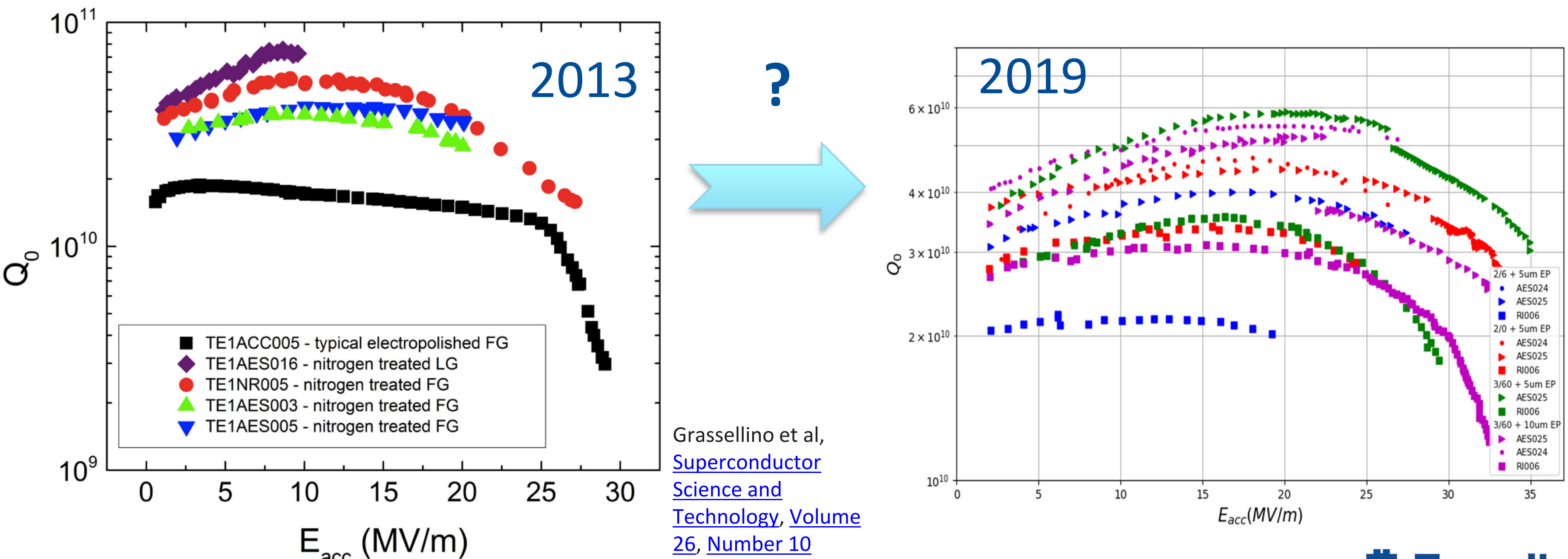
- Record Q values achieved **at all frequencies** – from 650 MHz to 1.3 GHz, 2.6 GHz, 3.9 GHz, T = 2K
- Gain factor in Q for doping vs 120C bake >2, grows for higher frequencies



	120C bake	Doping	Gain factor (2K, mid field)
650 MHz	~3.5e10	~7e10	~2
1.3 GHz	1.5e10	>3e10	>2
2.6 GHz	6e9	~2e10	>3
3.9 GHz	4e9	~2e10	>4

Where do we stand with high T N-doping quench fields?

- Achievable quench field has evolved – from being limited to **~17-20 MV/m** in earlier days to up to **30-38 MV/m** today
- What are the important steps that have led to such performance improvement in achievable gradient in doped cavities?
- What is the origin of the quench field in N-doped cavities?



Grassellino et al, Superconductor Science and Technology, Volume 26, Number 10

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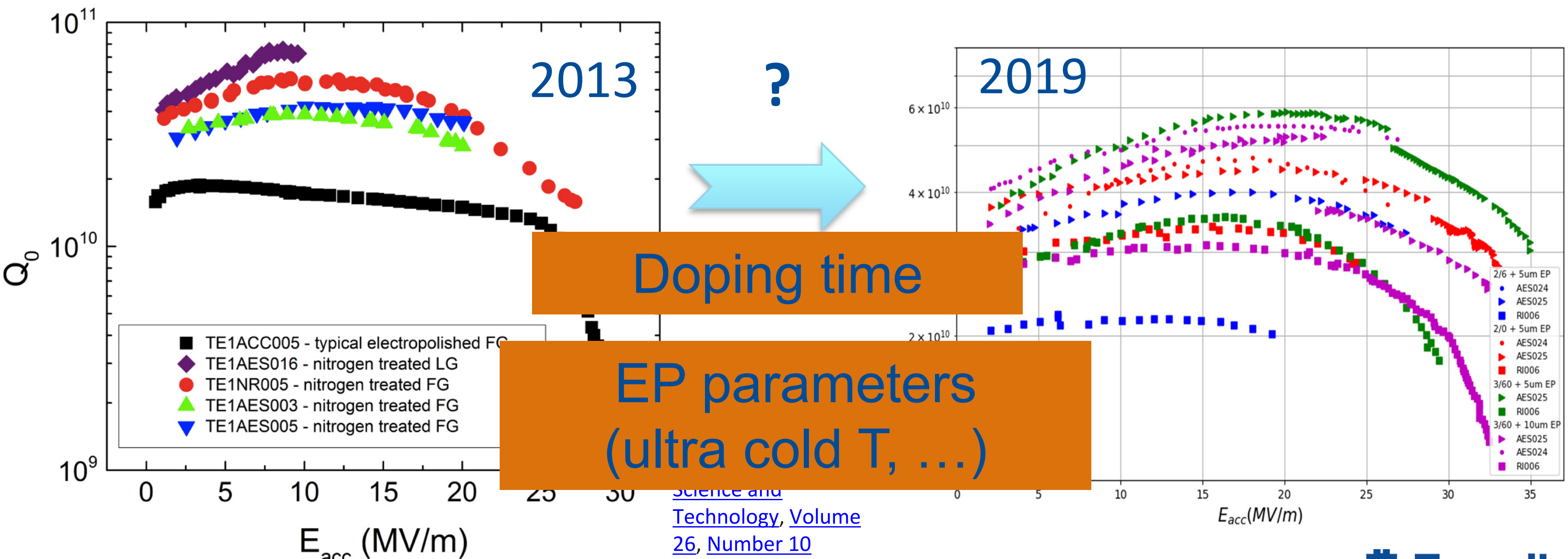
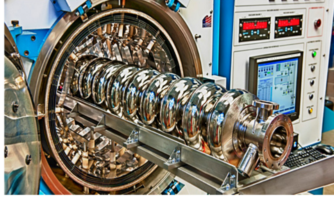


N-doping recipe changes – what are the key knobs?



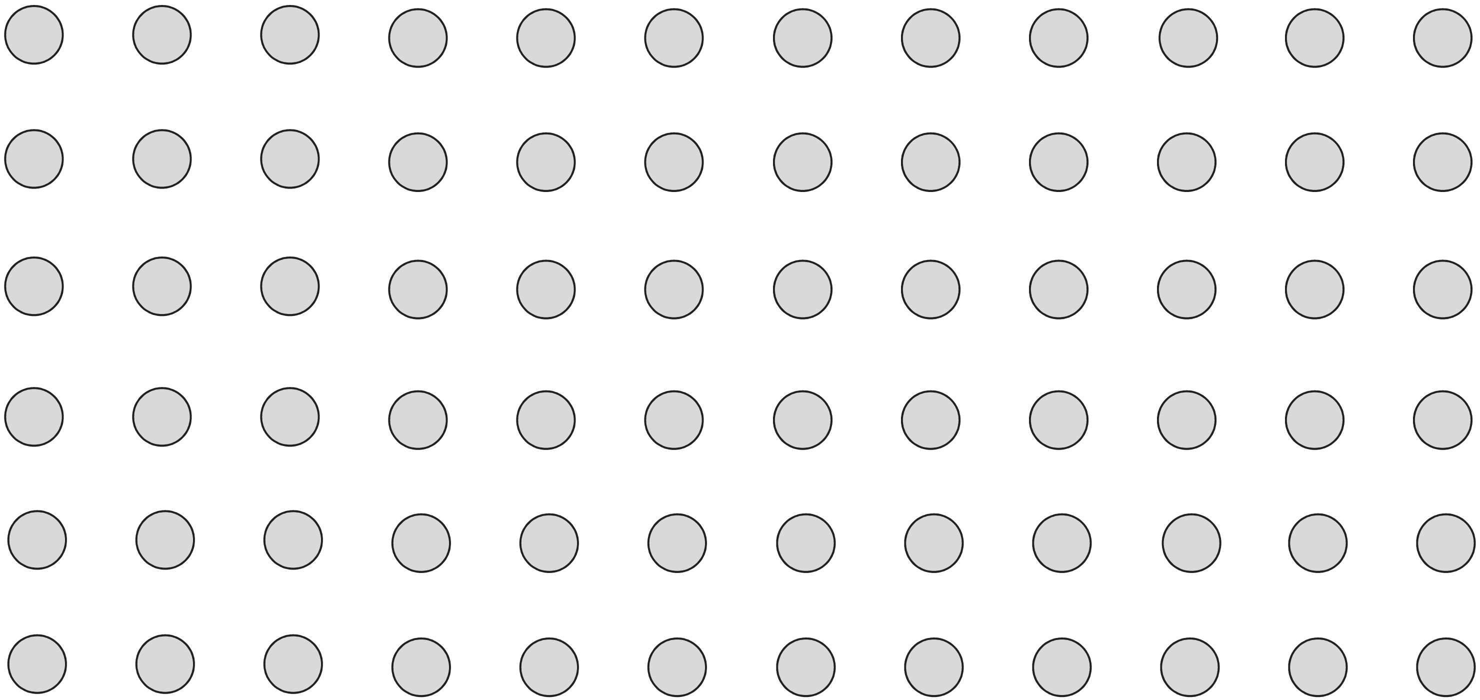
800-1000C UHV, XX hours

800C N_2 p = 25 mTorr 2 minutes

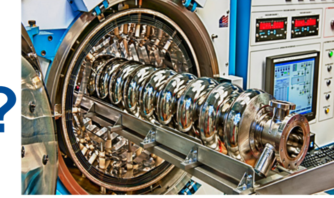
800C UHV, 6 minutes

UHV cooling

5 um EP



Slides adapted from M. Martinello



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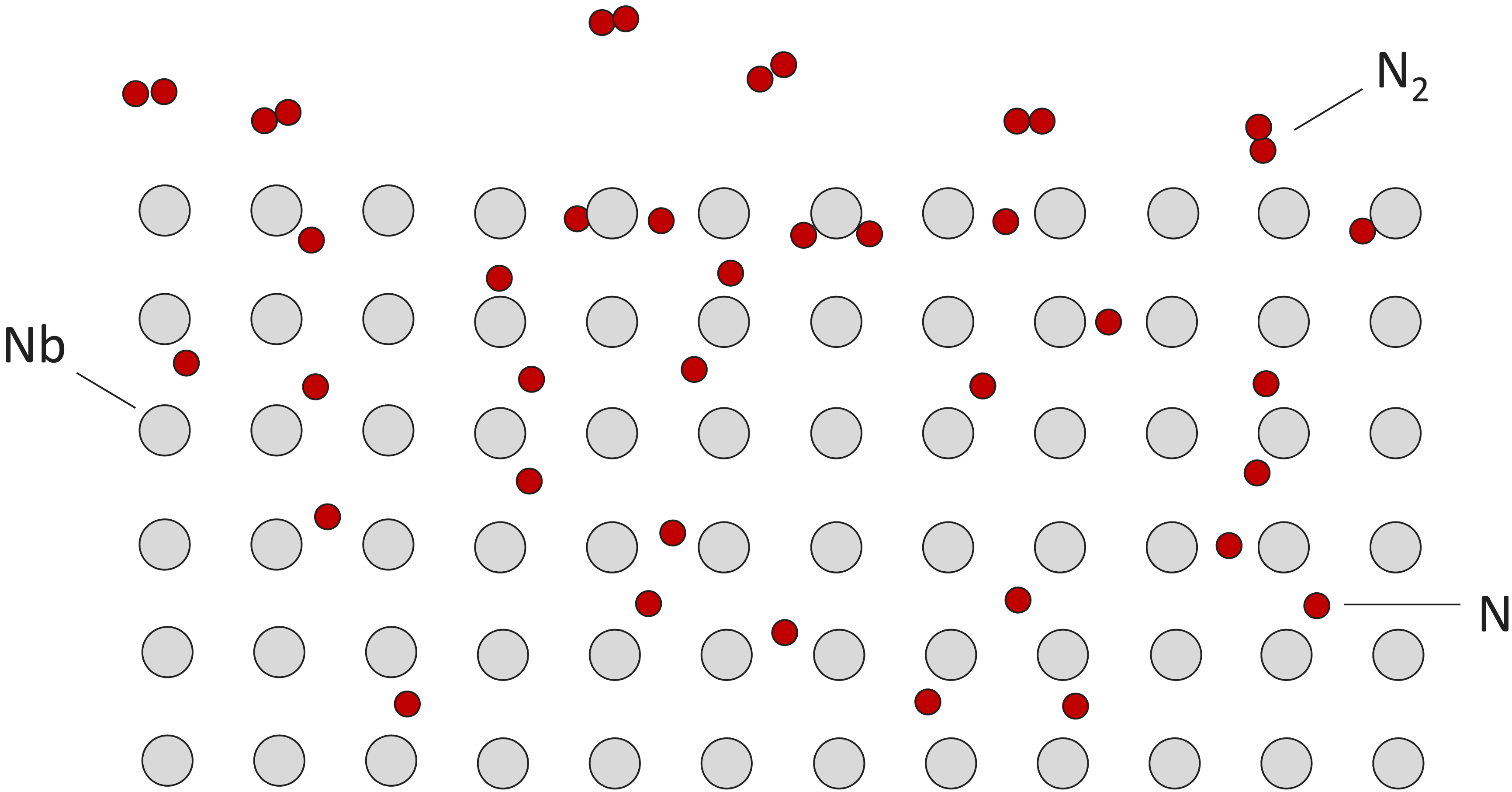

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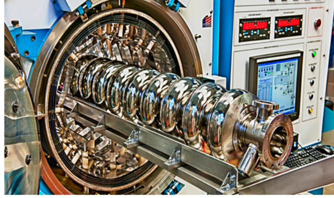

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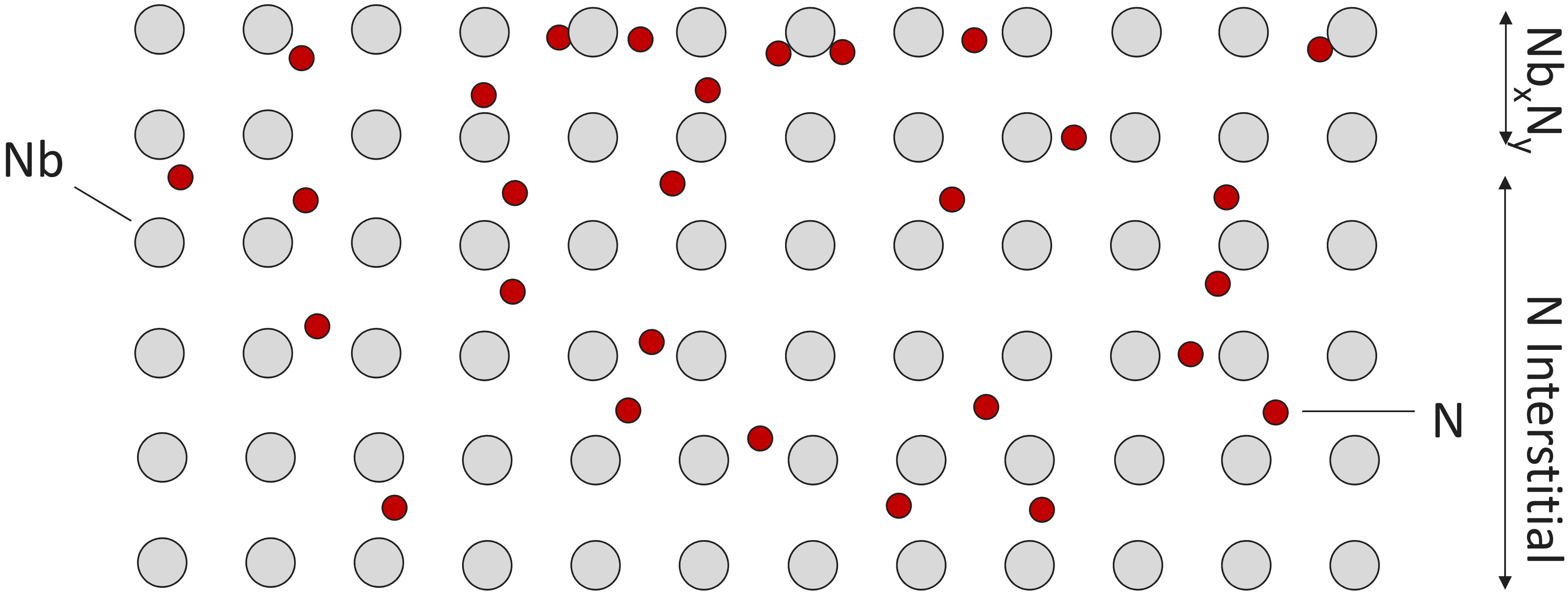

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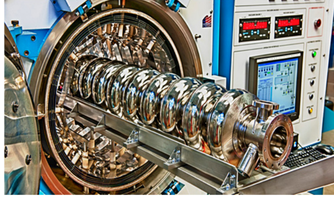

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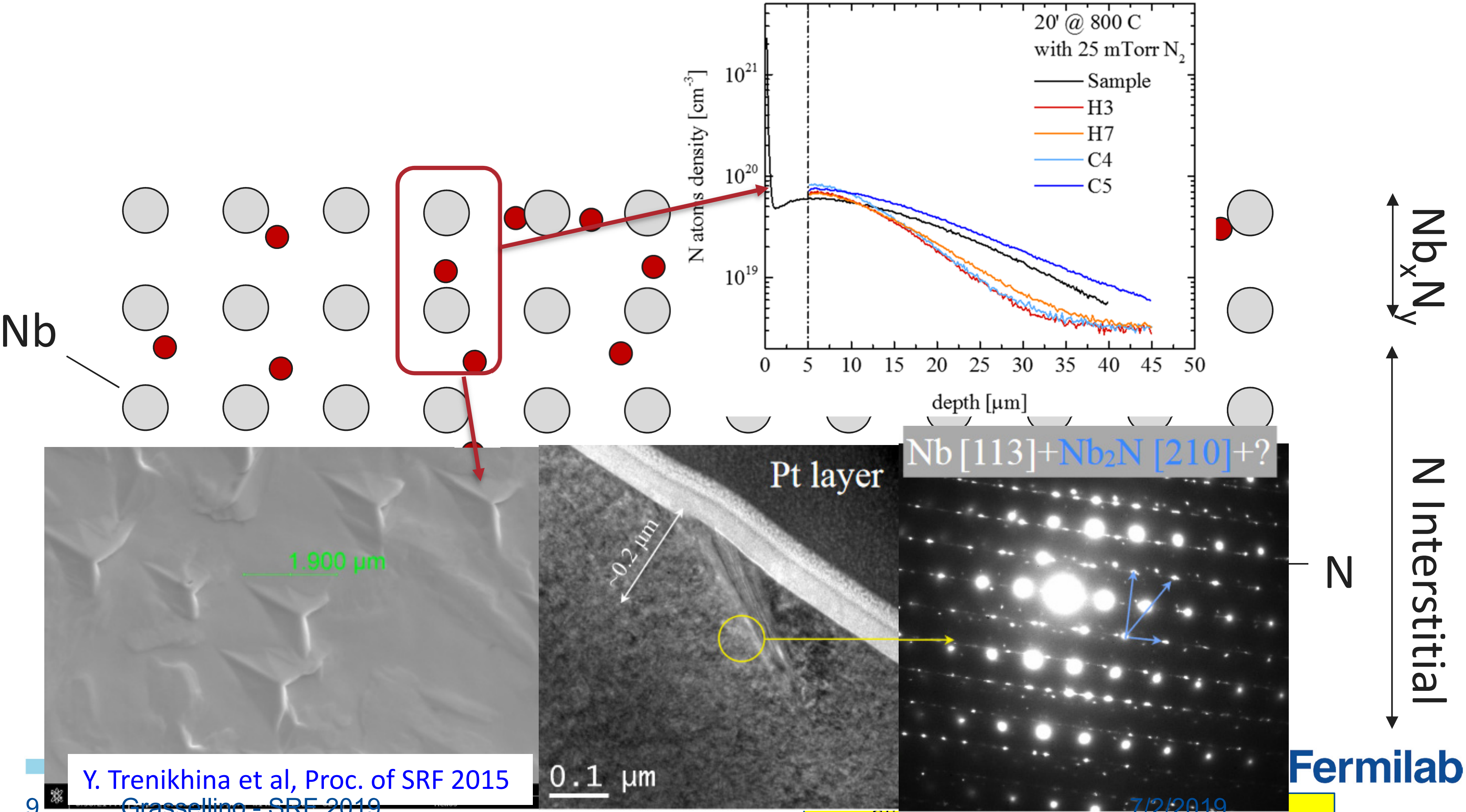

Y. Trenikhina et al, Proc. of SRF 2015

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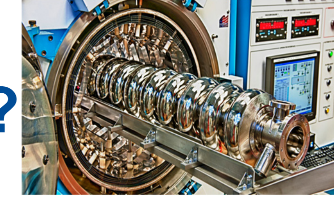

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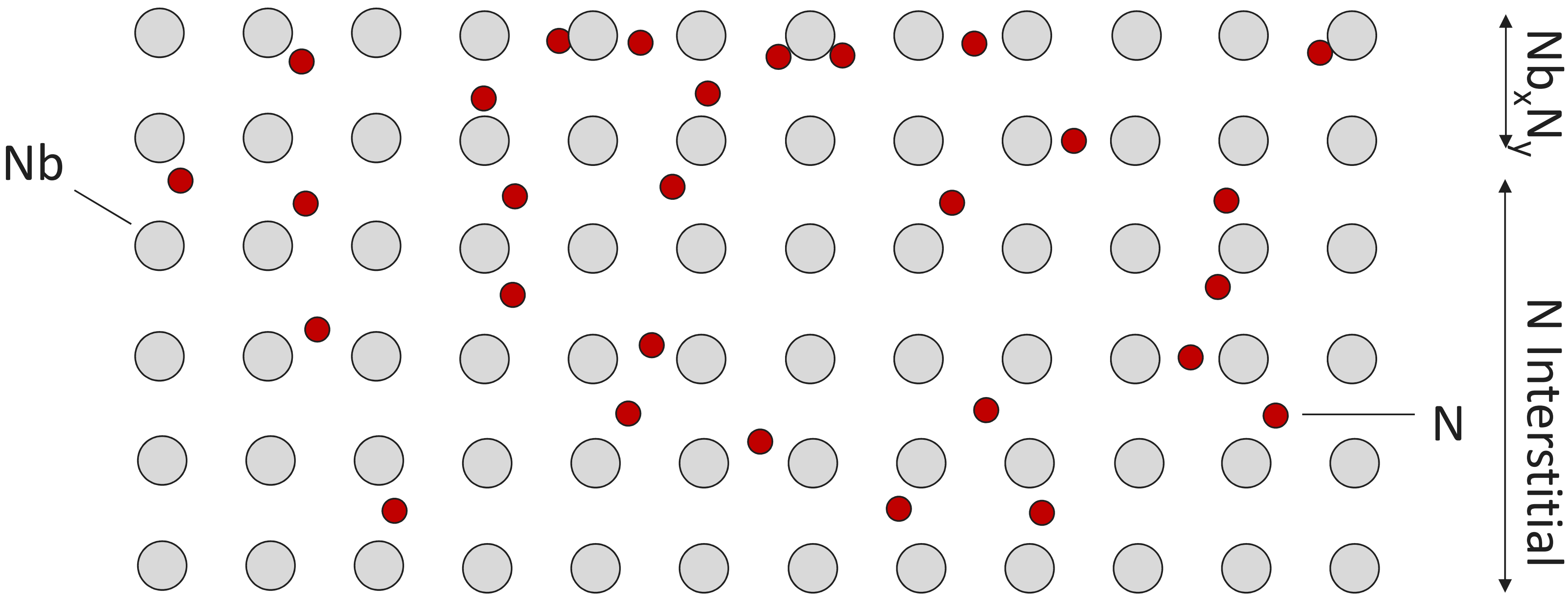

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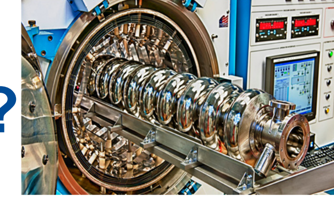

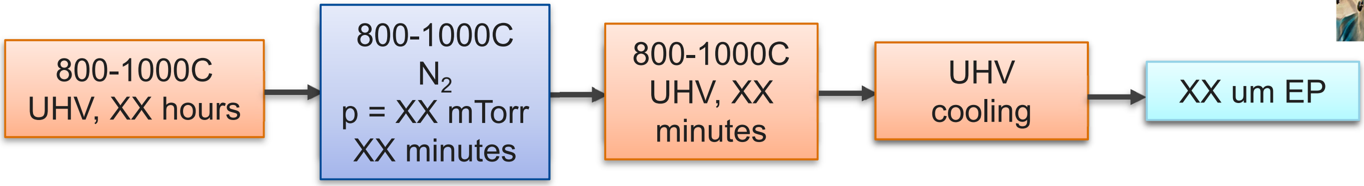

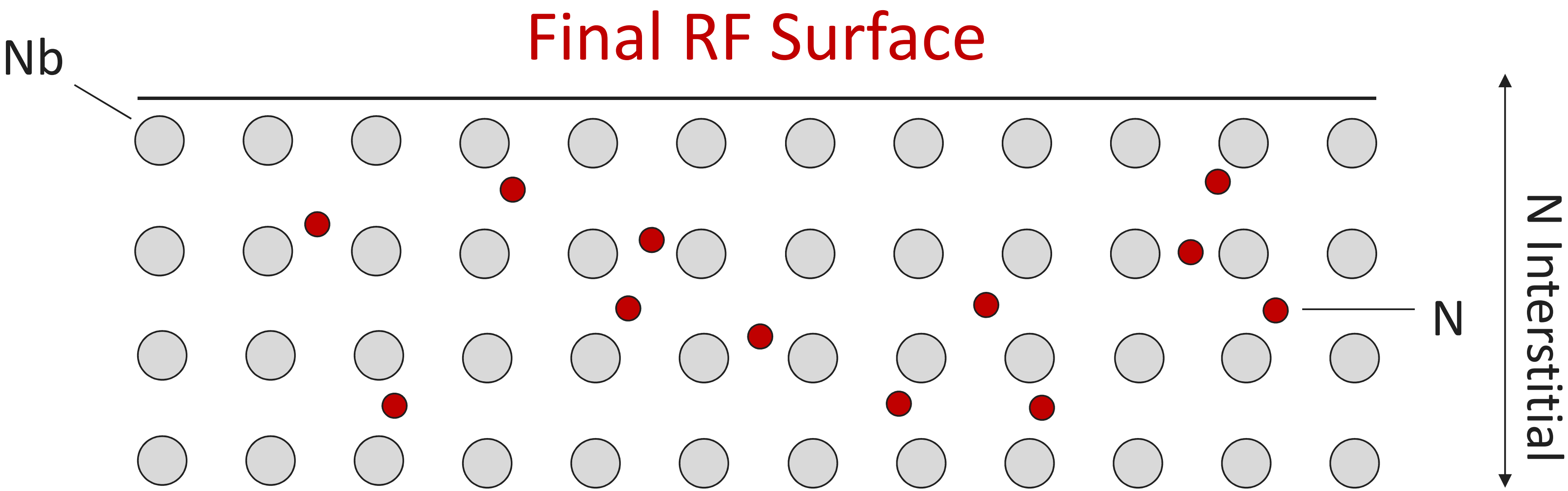

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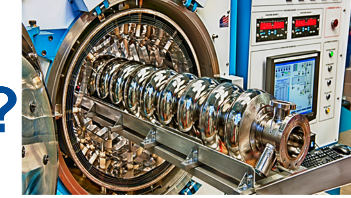

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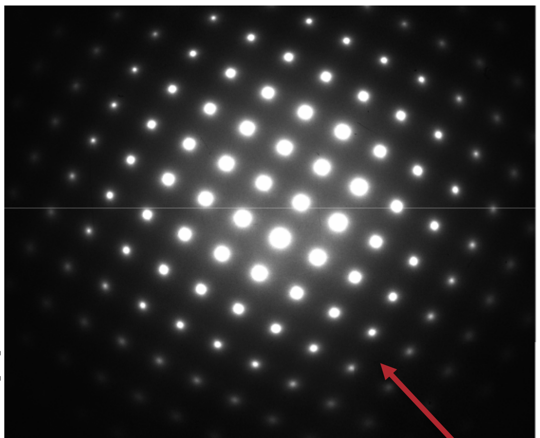
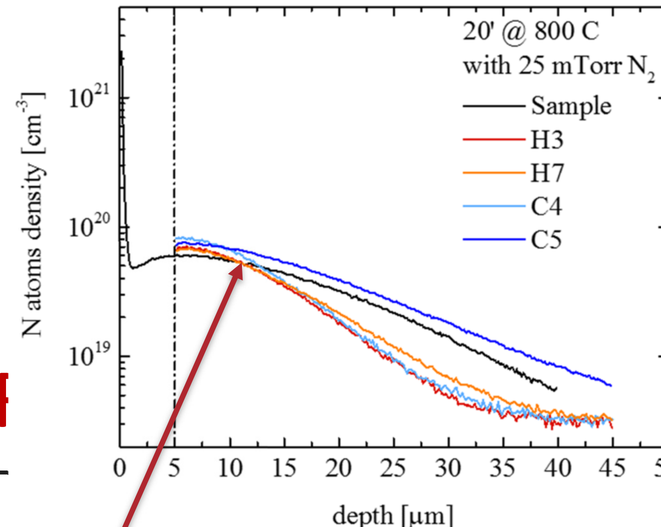
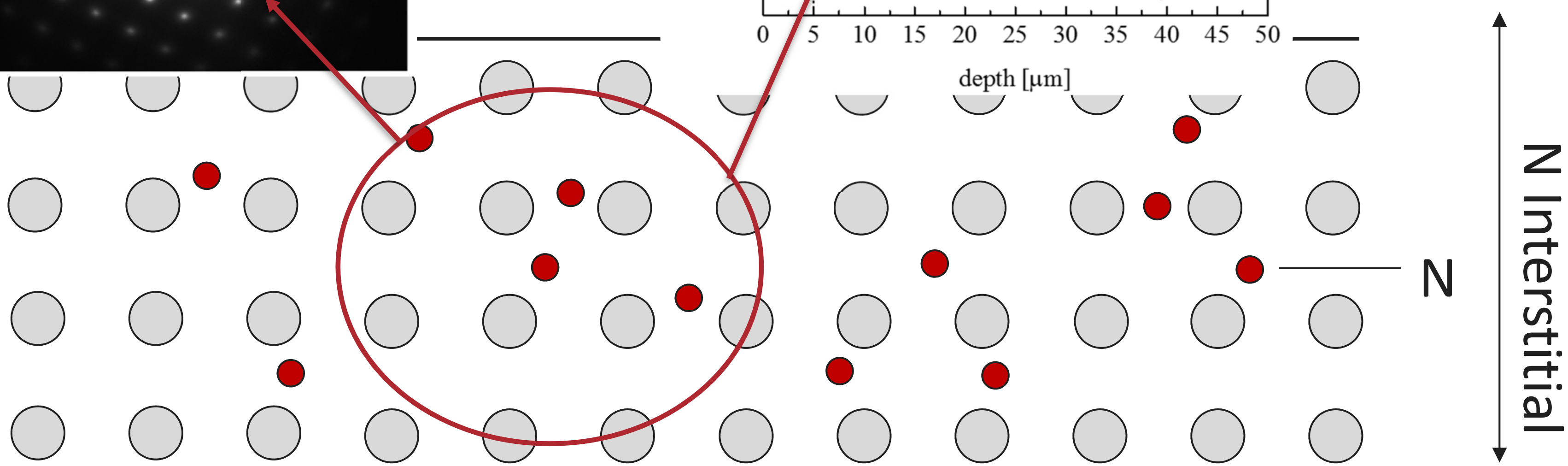






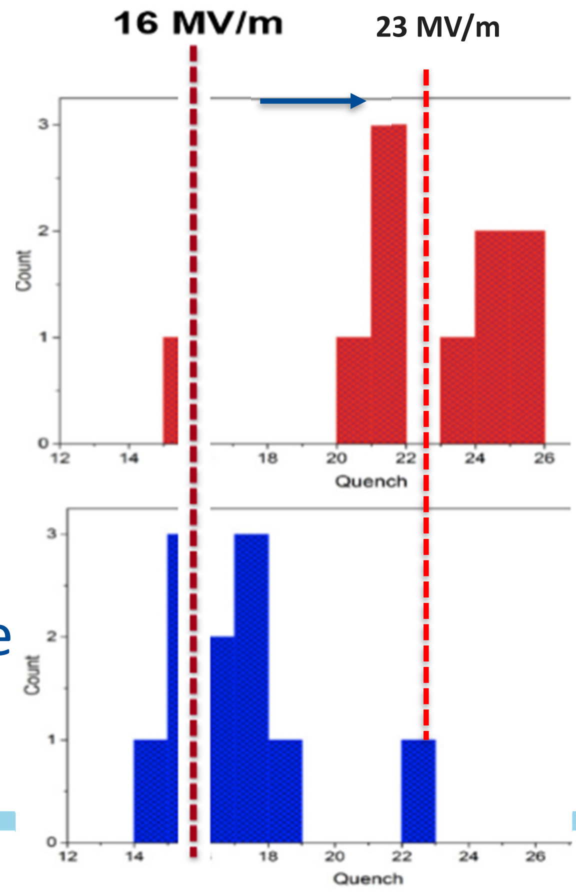
Slides adapted from M. Martinello

“Recipe” changes yielding gradient advancements

- Doping quench fields in single cell cavities **do not translate straightforwardly** into nine cell cavities
- Interesting **“clustering” effect in nine cells around a value**
- A first big improvement in nine cells in ~2014 @ FNAL was achieved moving from **longer to shorter duration** of doping (example **20/30→ 2/6**)

2/6 recipe

20/30 recipe

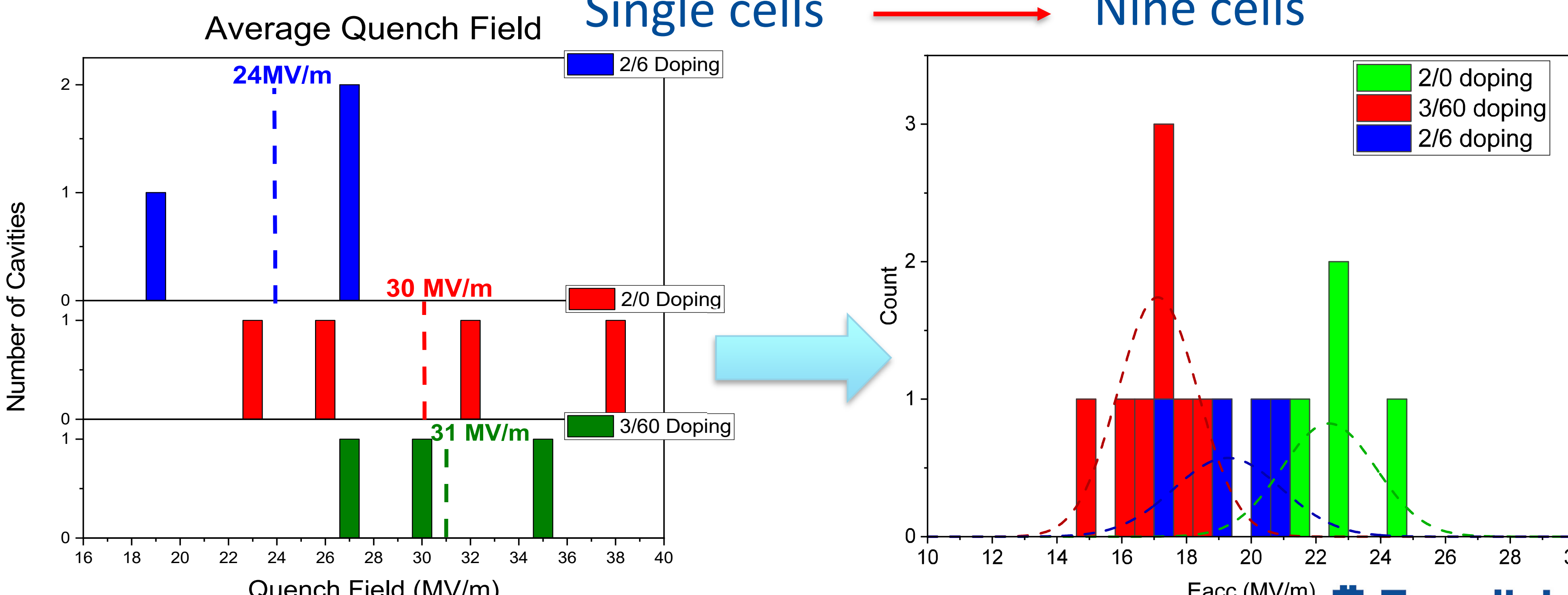


High Q R&D for LCLS-2, 2015, nine cells

“Recipe” changes yielding gradient advancements

- Recently, we are exploring new doping durations in the context of LCLS-2 HE R&D for high Q at higher gradients
- Very high gradients reached **> 30 MV/m** in single cells
- Same clustering effect observed in nine cells as in 2014, **with longer annealing times producing reduced quench fields in nine cells**

Single cells → Nine cells



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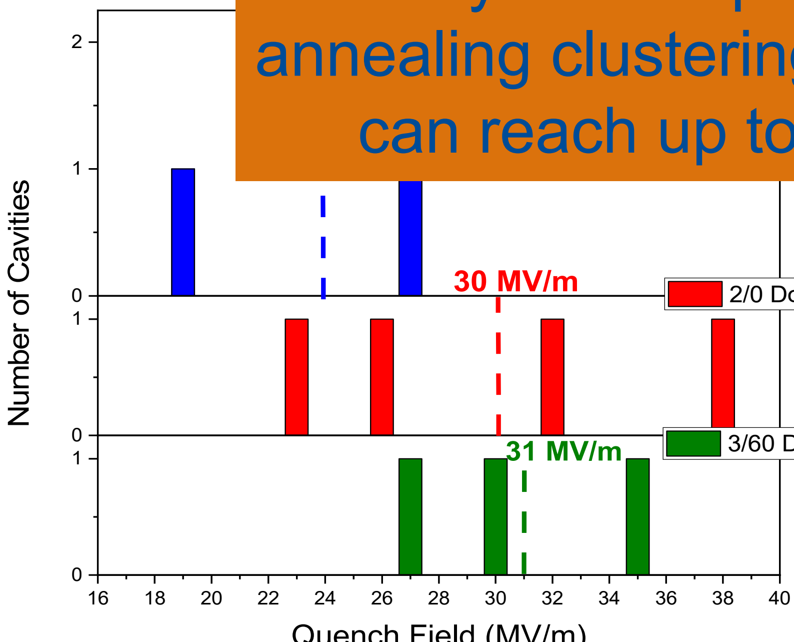
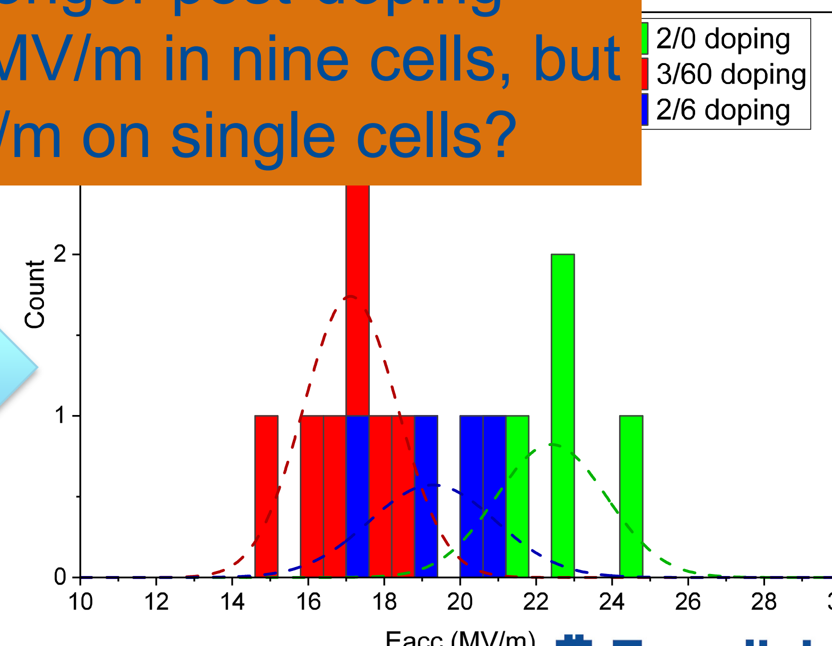
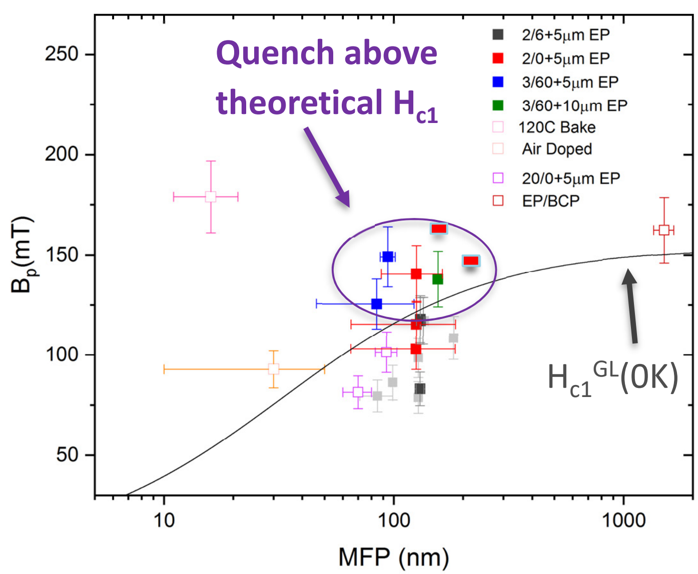
Why have doping quench fields almost doubled in single cells since 2014?
Why are recipes with longer post-doping annealing clustering ~ 17 MV/m in nine cells, but can reach up to 35 MV/m on single cells?

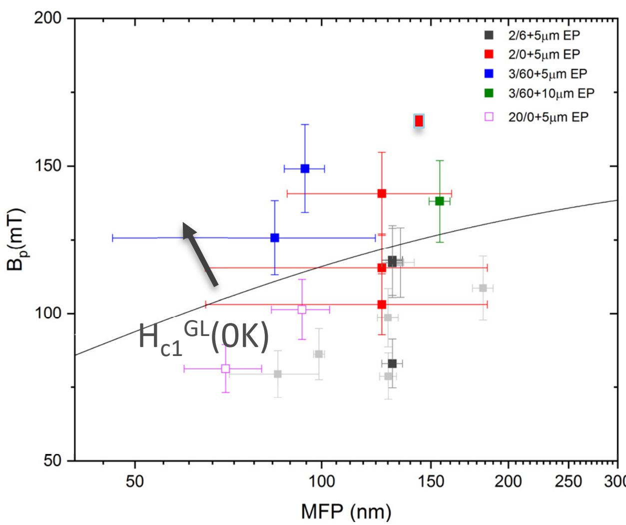




Role of mean free path/nitrogen concentration on quench?

- 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 shorter doping or deeper EP helps reaching higher gradients)
- In reality, single cell data does not show a strong clear correlation with mean free path
- More detailed SIMS studies ongoing to systematically relate surface N concentration to achievable field (see later)

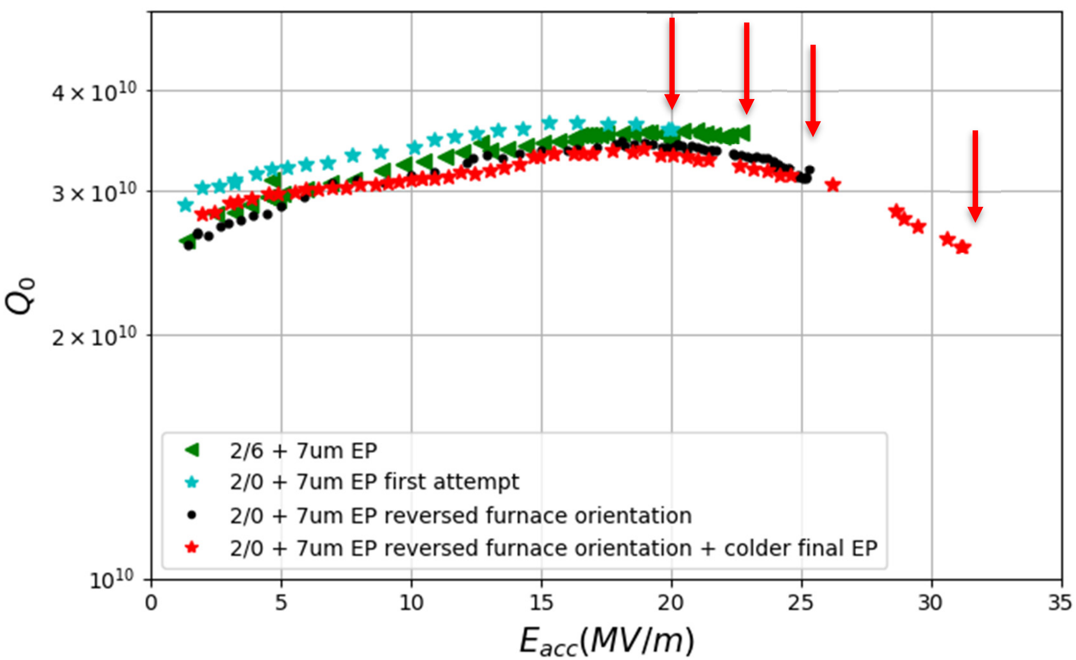




Nine cell sequential doping studies at Fermilab

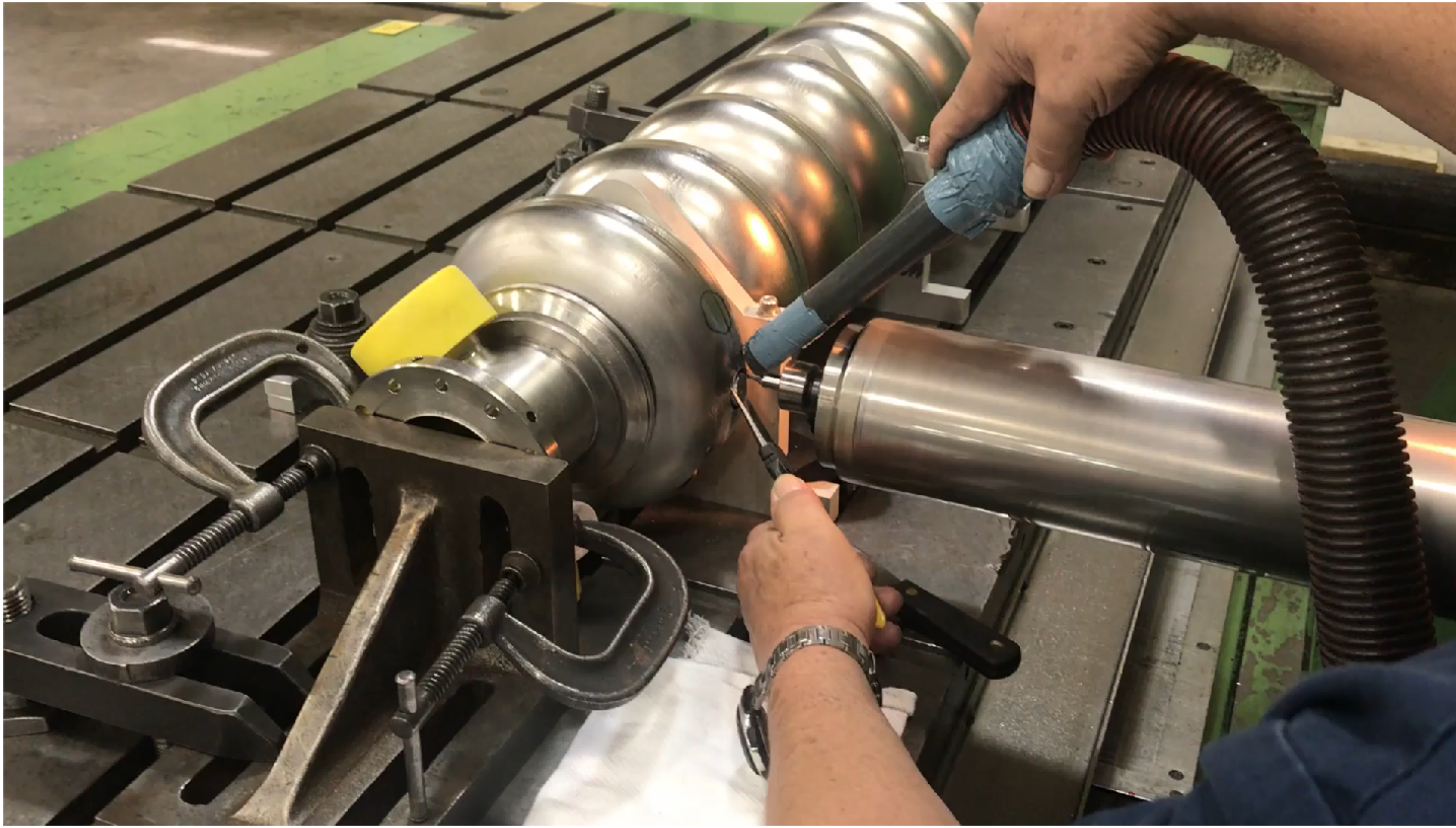
Nine cell sequential doping study

- Two nine cells from RI with 2/6 doping → **23 MV/m**
- Reset, doped at FNAL with 2/0 reached → **20 MV/m**
- Mode measurements coupled with second sound detectors for both cavities showed **quench localized in cell 1 near FPC, other cells >26 MV/m**
- One cavity was sent to be cut for sample analysis
- Other cavity orientation was reversed in furnace (**FPC facing away from nitrogen inlet**) quench field improved→ **25.5 MV/m**
- Reset, add colder final EP → **32 MV/m !!**

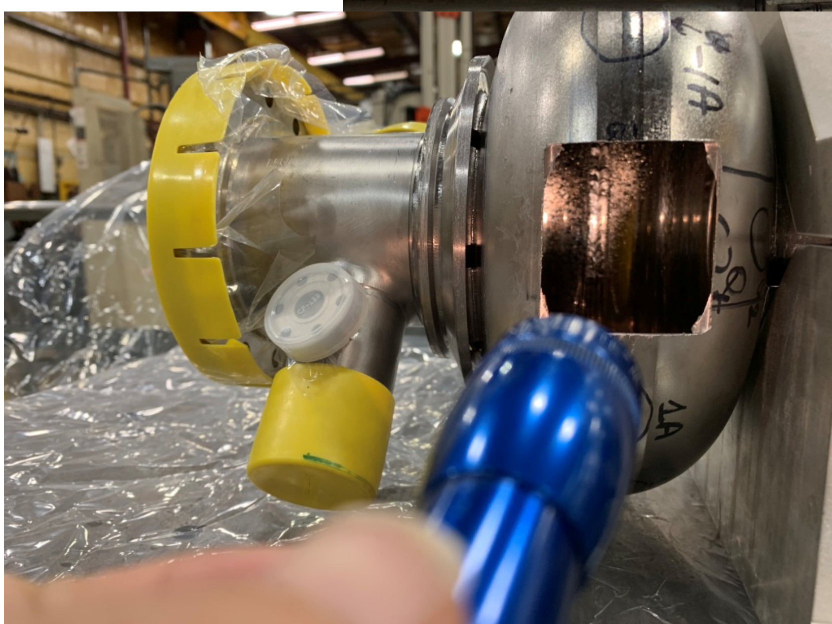


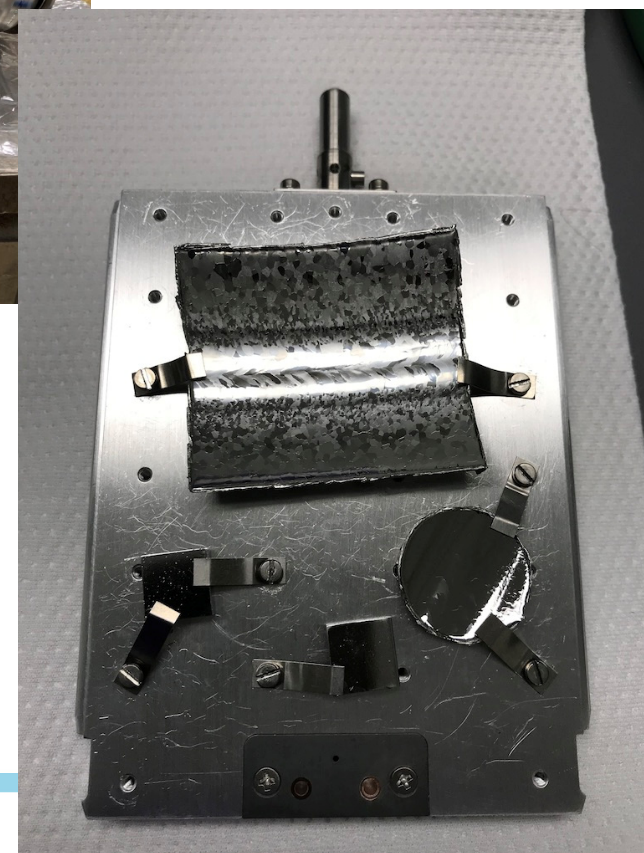
Cell #	Quench Field – FPC Faces front of Furnace (MV/m)	Quench Field - FPC Faces Rear of Furnace (MV/m)
1	20	>25.3
2	26.4	>25.3
3	>30	37.2
4	>27	>32.5
5	32.8	36.7
6	>27	>32.5
7	>30	>37
8	>26.4	>25.3
9	>26.4	25.3

CAV018 samples cut from each cell, and from irises to equators



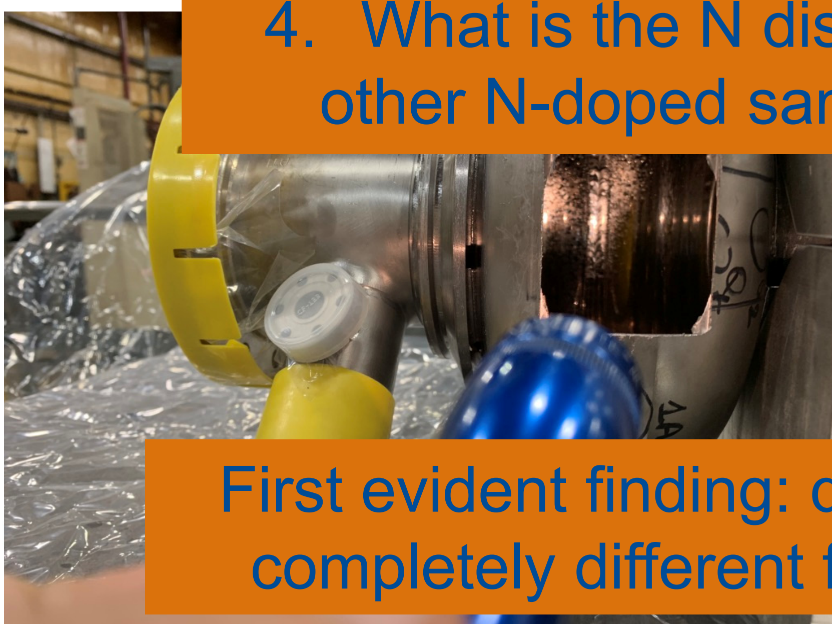
First doped nine cell cutout SIMS studies

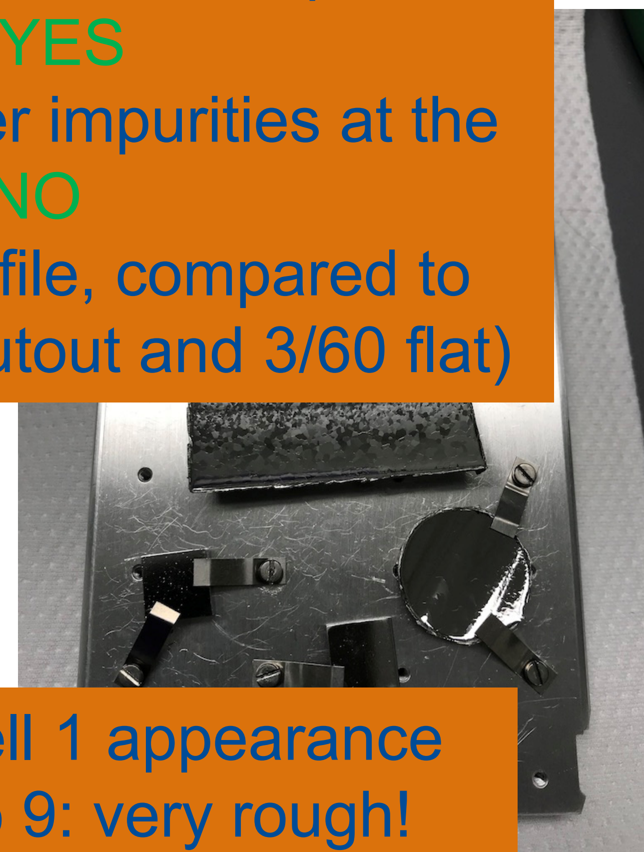




First doped nine cell cutout SIMS studies

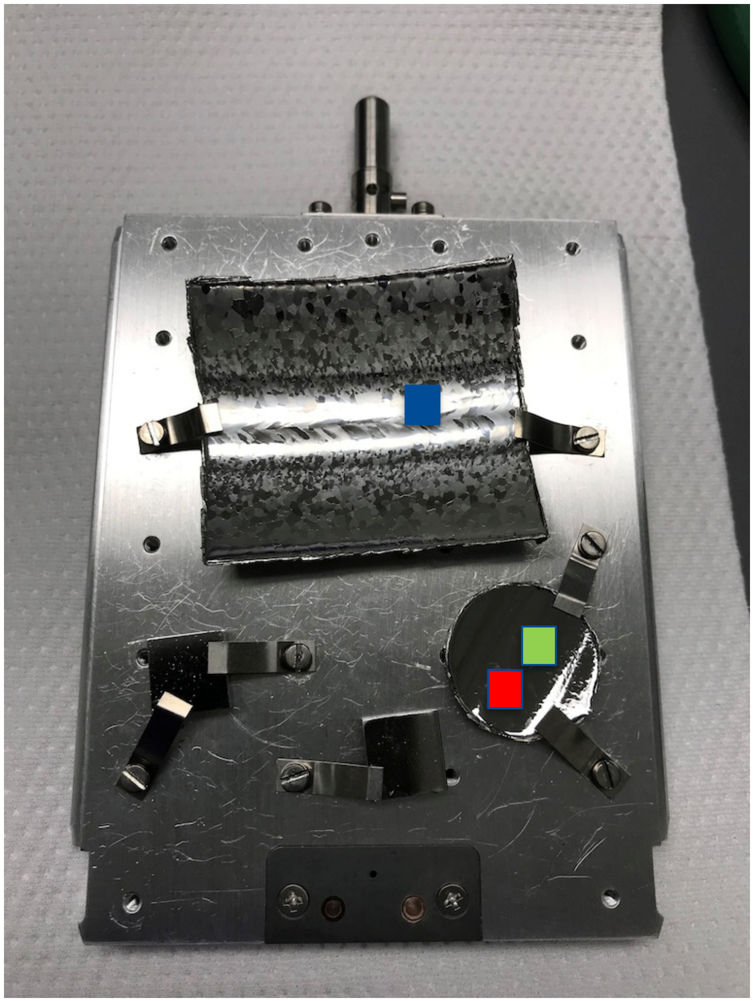
1. Is the nitrogen distribution from cell 1 to cell 9 homogenous? YES
2. Is the nitrogen distribution from iris to equator homogeneous? YES
3. Is there excess carbon or other impurities at the quench spot? NO
4. What is the N distribution profile, compared to other N-doped samples (2/6 cutout and 3/60 flat)

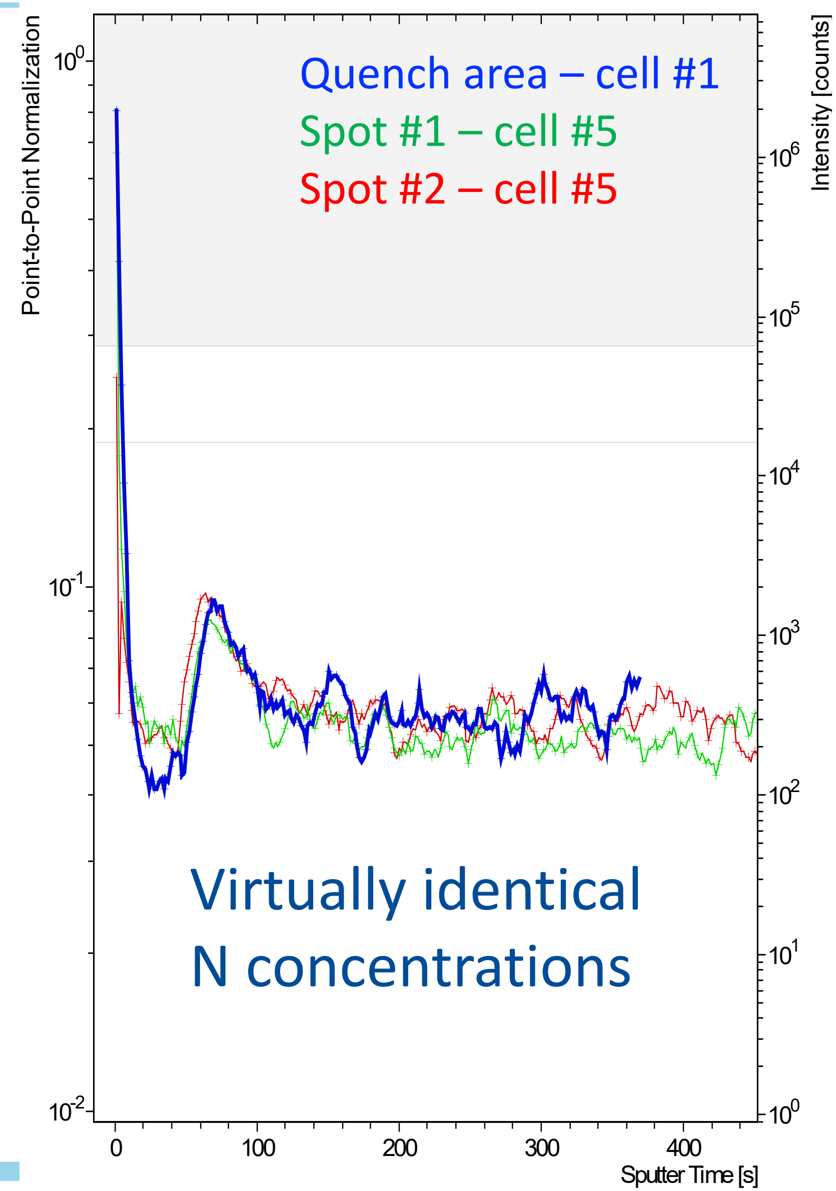




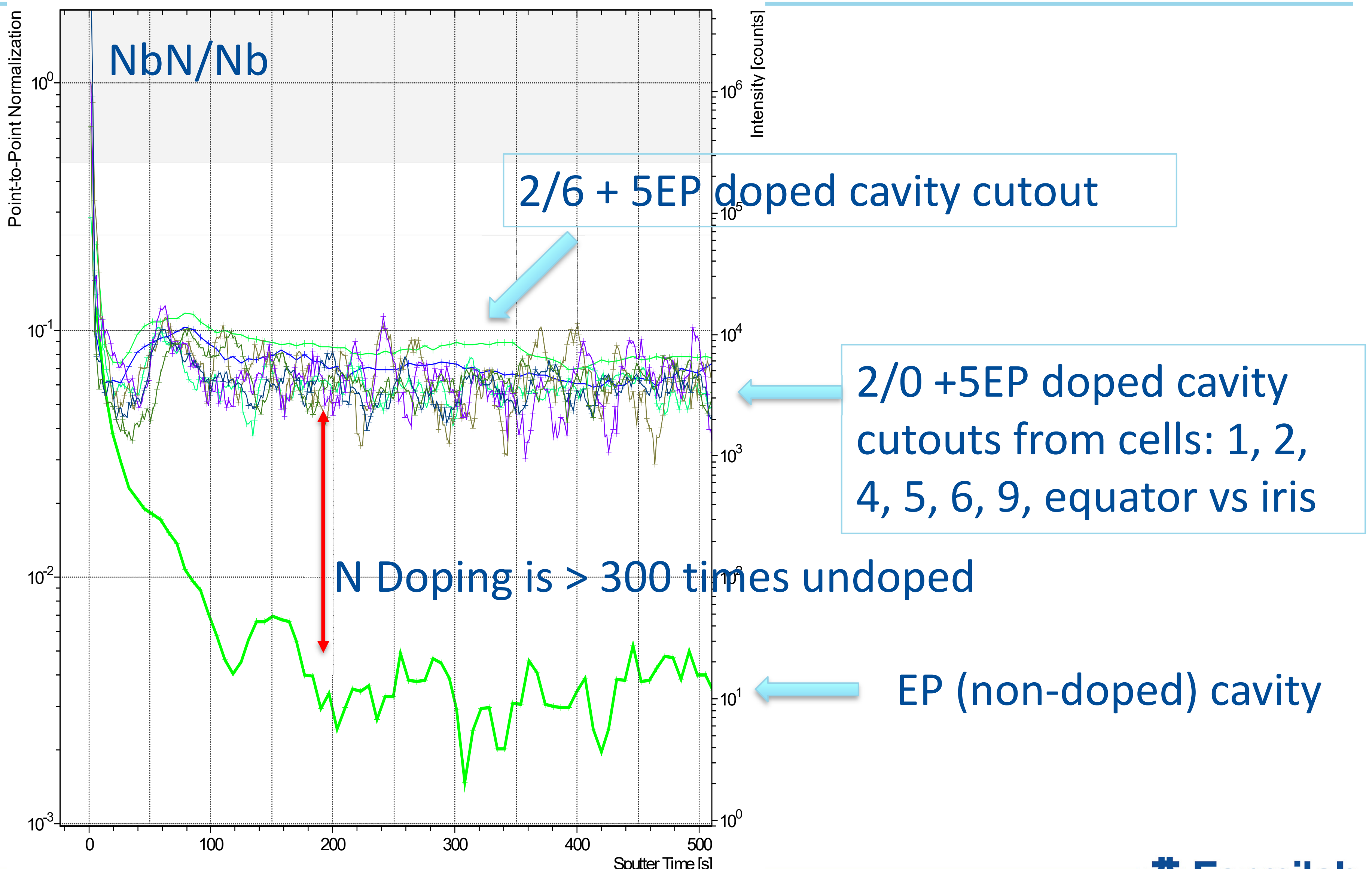
First evident finding: quenching cell 1 appearance completely different from cell 2 to 9: very rough!

NbN/Nb signal: cell 1 vs cell 5 (20 vs 32.5 MV/m)





SIMS doped vs undoped cutout studies – nitrogen homogeneity



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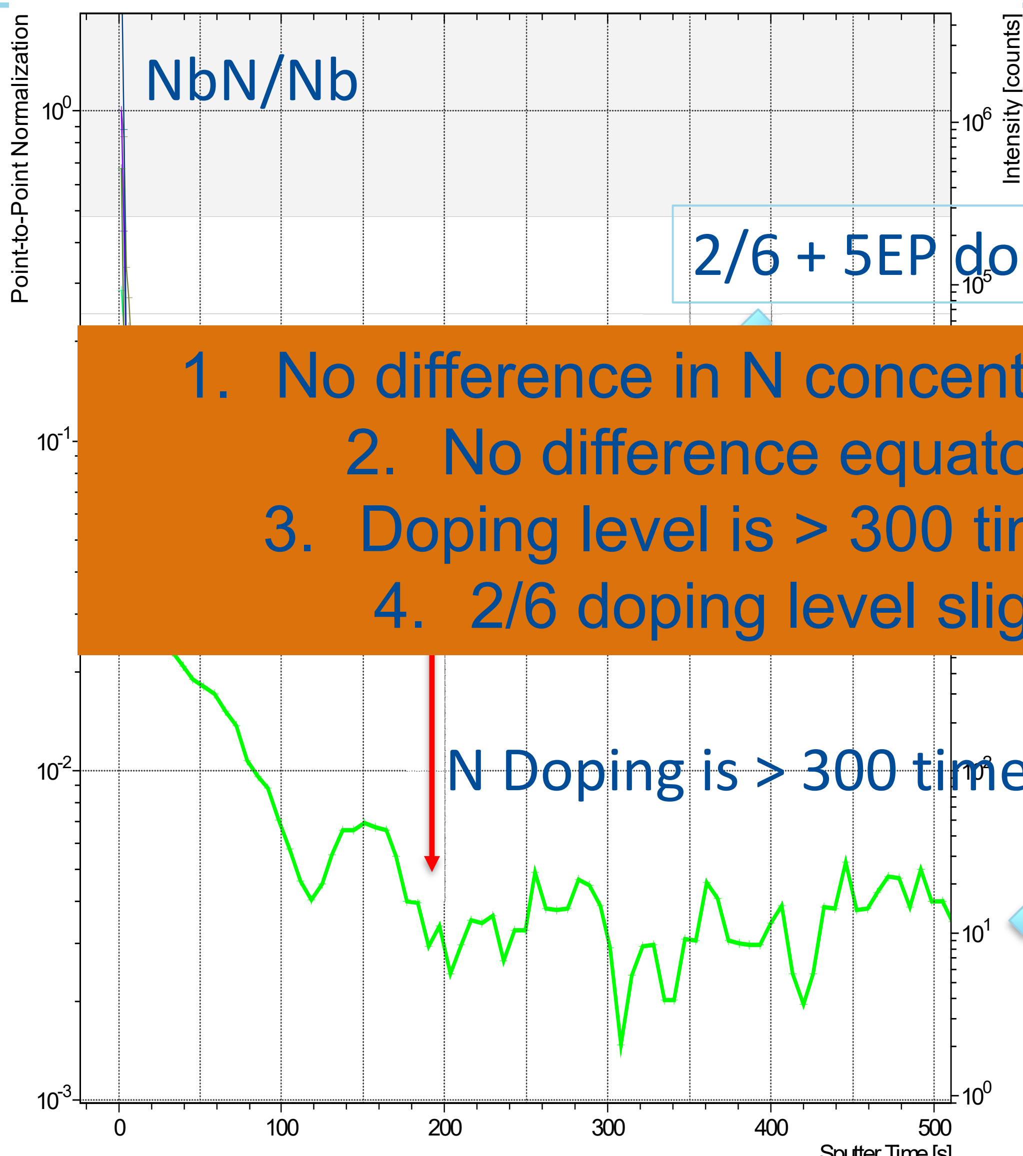

2/6 + 5EP doped cavity cutout

1. No difference in N concentration from cell 1 to 9
2. No difference equator vs off equator
3. Doping level is > 300 times undoped level
4. 2/6 doping level slightly above 2/0

4, 5, 6, 9, equator vs iris

N Doping is > 300 times undoped

EP (non-doped) cavity

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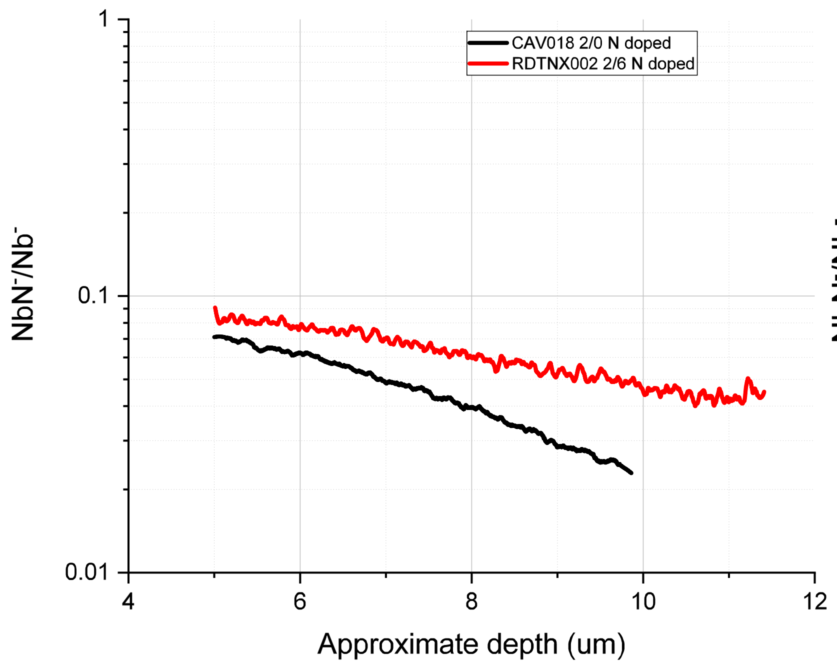
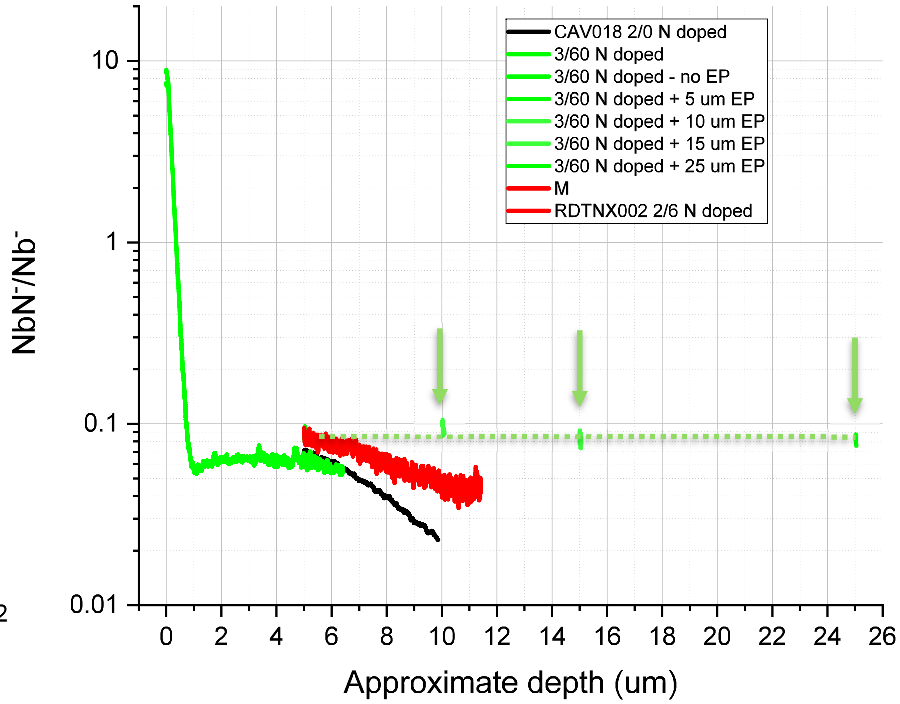
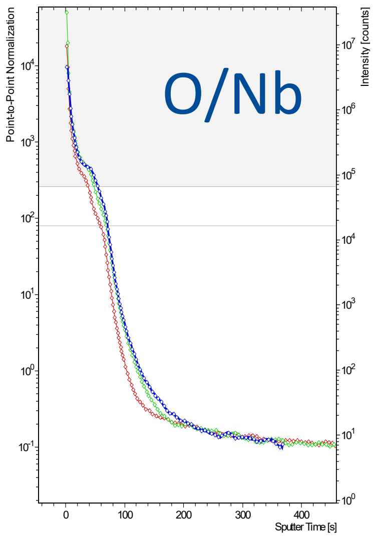
Depth profiling 2/0 vs 2/6 vs 3/60 doping

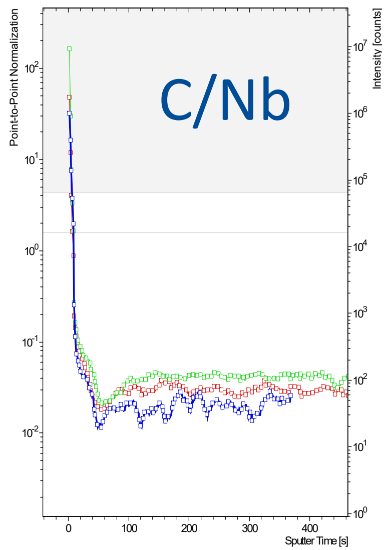
- Nitrogen depth/profile seems to be the main difference for the different recipes: 2/0 shallower, 2/6 intermediate, 3/60 deepest?
- 3/60 measurements to be repeated on actual cavity cutouts

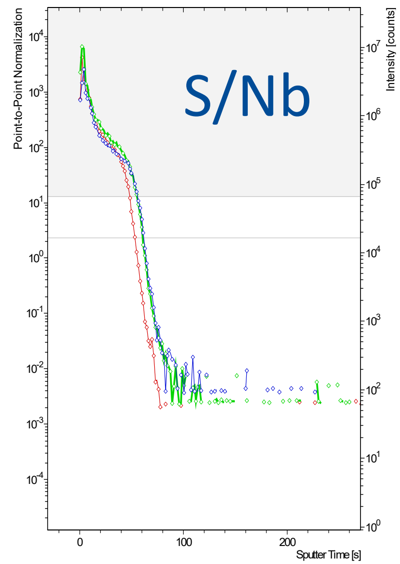


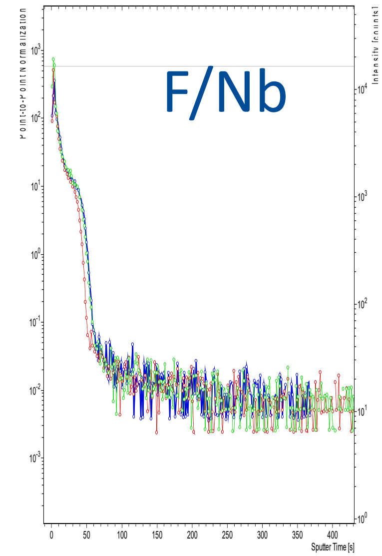


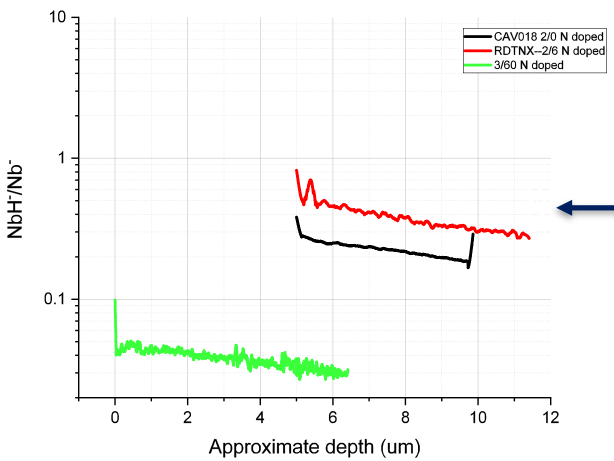
No differences in any other impurity (O, C, S, F…)









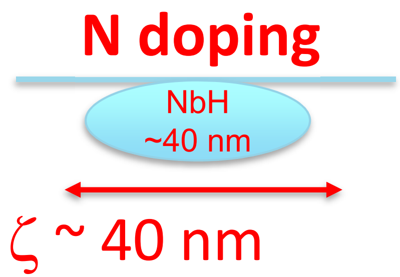


However, different NbH signal is found

Fermilab

Based on all these findings, what could the origin of quench in N doped cavities be?

- **Surface roughness/defects or nitrides pits, combined with RRR?**
  - Consistent with colder EP giving smoother surface
  - Consistent with integrated RRR of longer recipes being lower and increasing likelihood of quench
  - Consistent with quench field correlating with nitride size
- **Quantity and size of nanohydrides?**
  - Consistent with colder EP minimizing hydrogen reabsorption
  - Complex interplay between size of hydrides and coherence length?



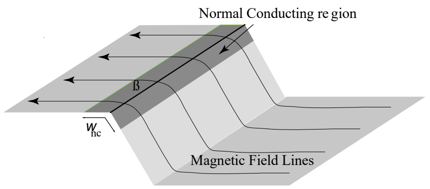
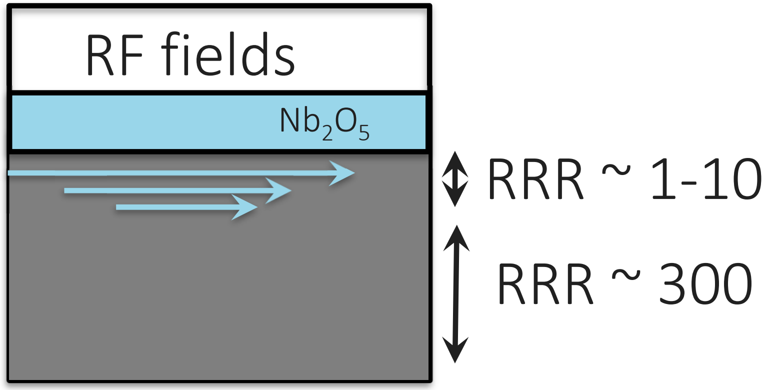
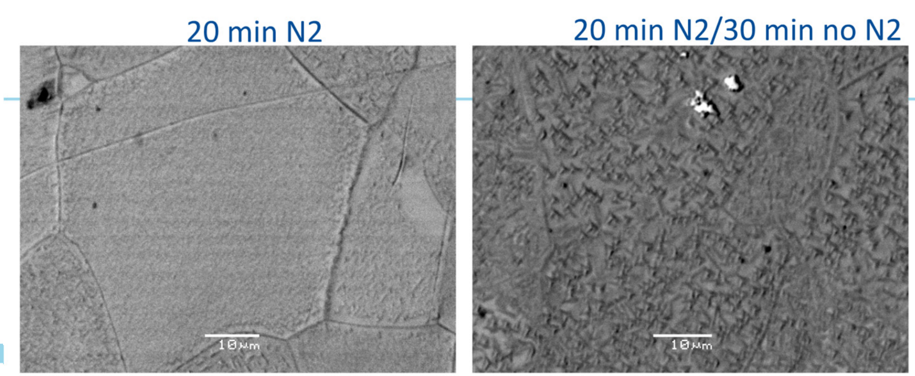


Figure 3: Schematic of a grain boundary that has quenched due to magnetic field enhancement at the grain boundary.

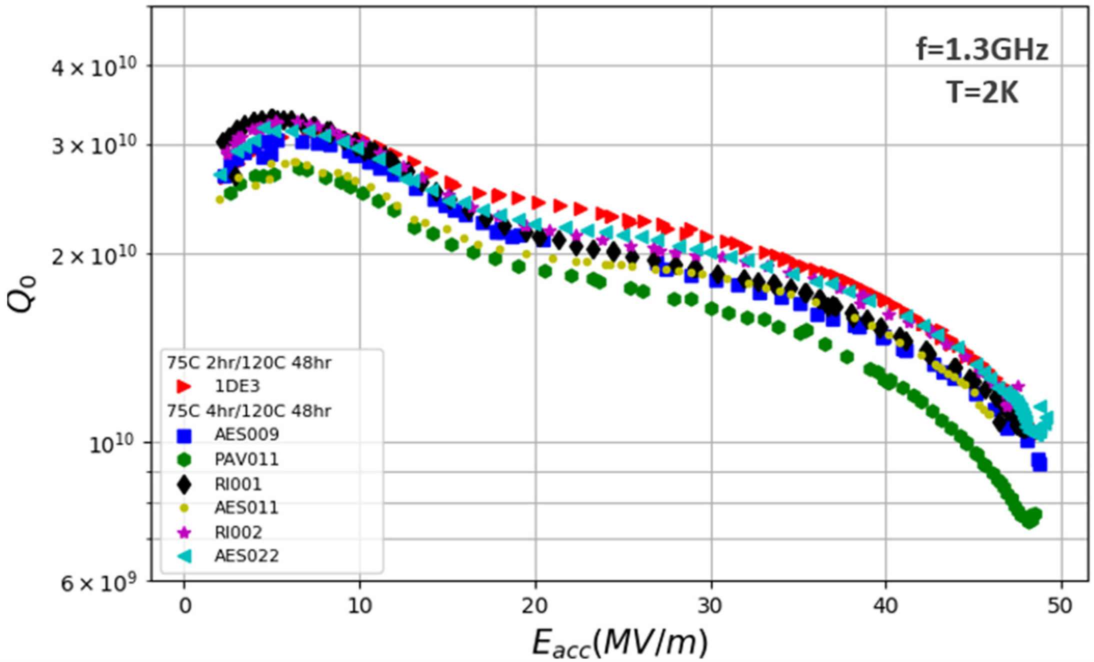




Low T treatments

New finding 1: 50 MV/ in TESLA shape cavities findings

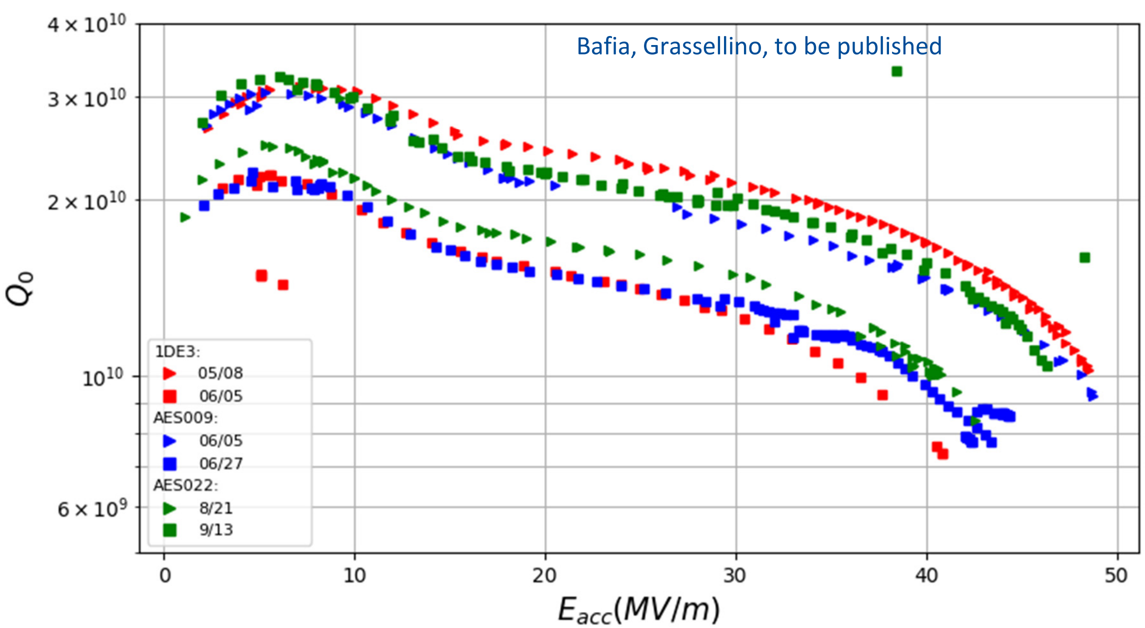
- We have recently focused our attention to the systematic achievement of unprecedented accelerating gradients ~48-50 MV/m (~ 210 mT, TESLA shape) in low temperature baked cavities
- One peculiarity of these cavities surface preparation is a pre-120C bake step at ~75C
- Another peculiarity is a surface with a very cold final EP preparation

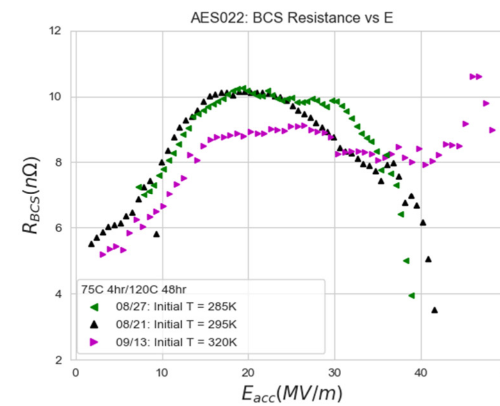


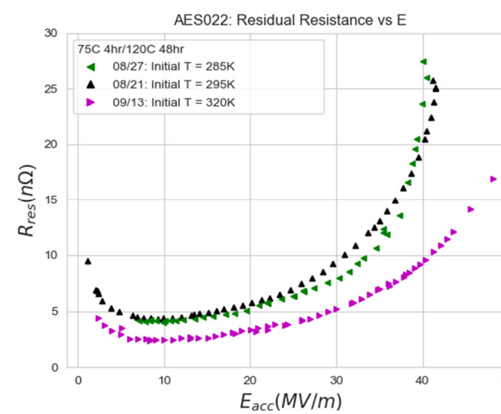
See Grassellino et al arXiv:1806.09824

Finding 2: the strange ‘branching’ performance

- On dozens of tests and several cavities now, we see switch in performance for same cavities 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 XXX for many details on this study

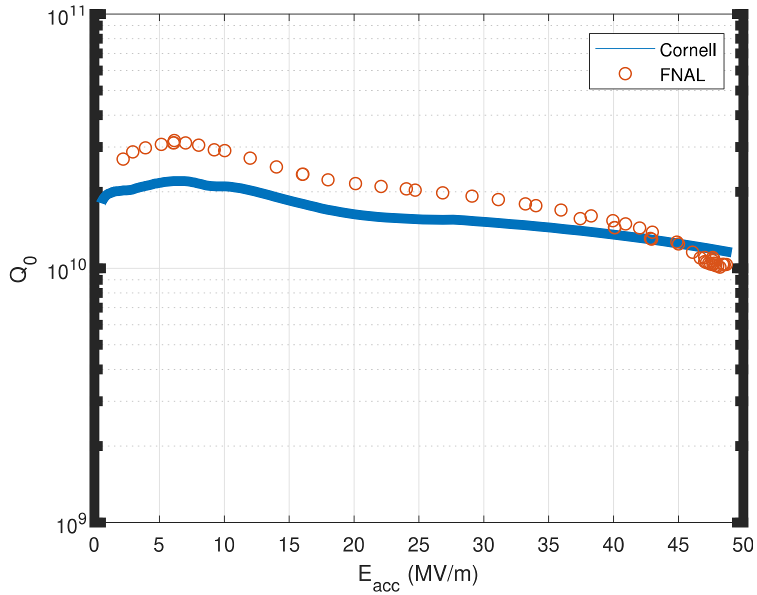




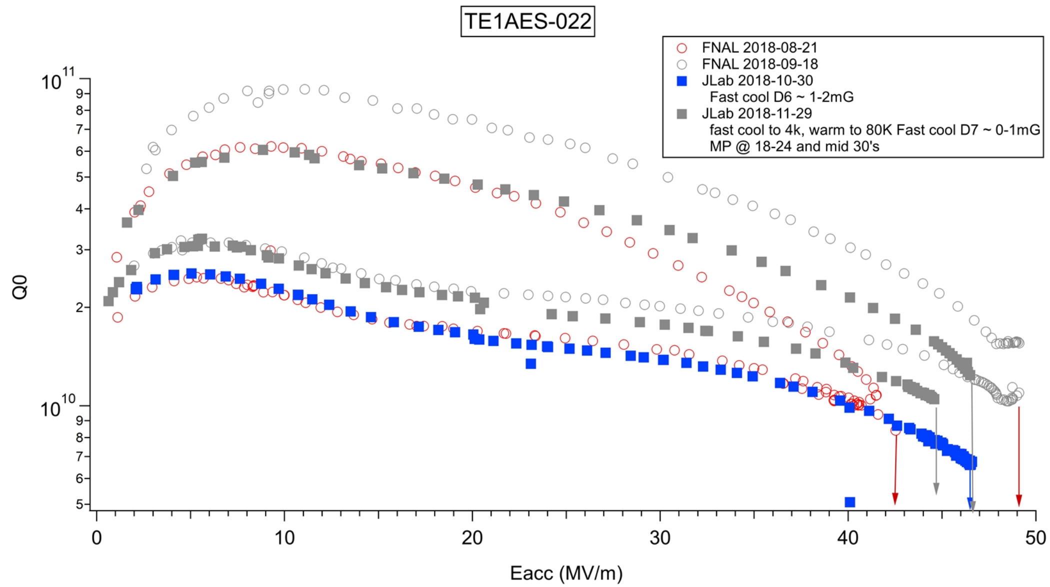


49 MV/m cavities sent around the world for verification

- Cornell gradient matches our 49 MV/m
- Jlab reproduced exactly the upper/lower branching behavior in two separate cooldowns (see Palczewski breakout talk)
- DESY also measured in range 47-50 MV/m
- Cavity now on its way to KEK



Courtesy of Liepe, Maniscalco, **Cornell**

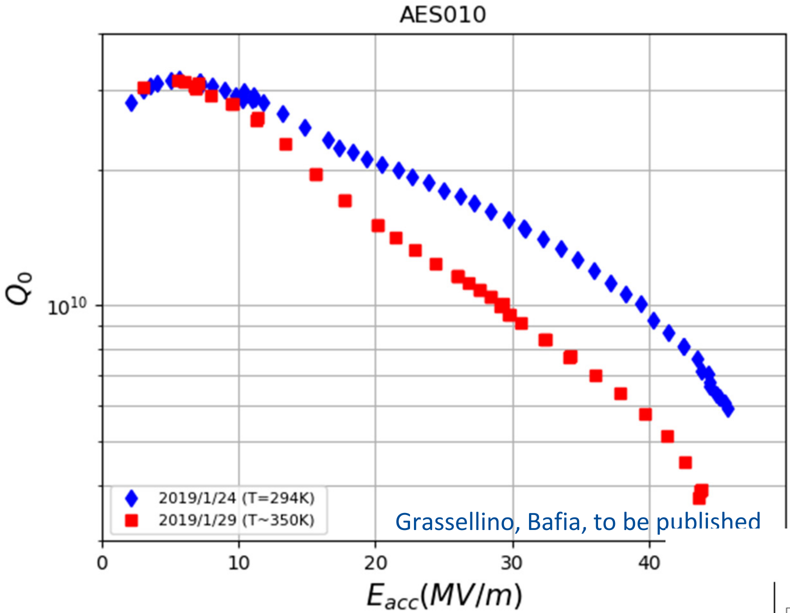


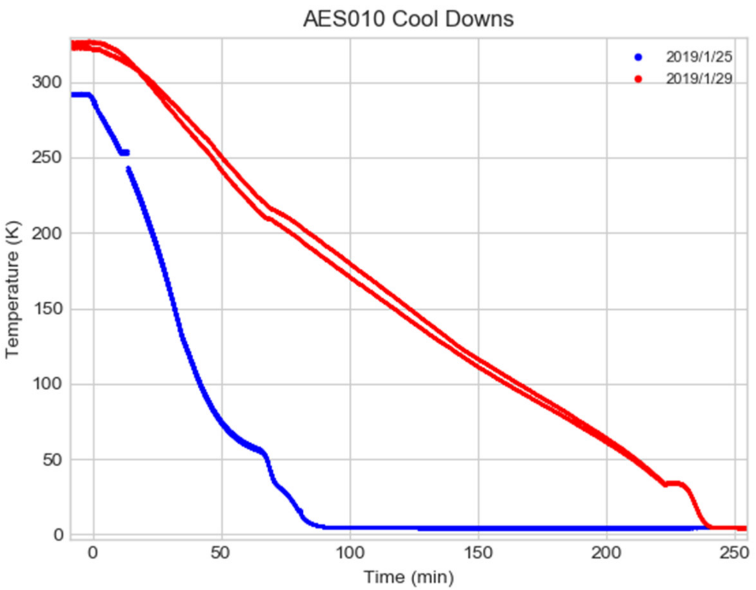
Courtesy of A. Palczewski, **Jlab**

SEE MOP043 for details

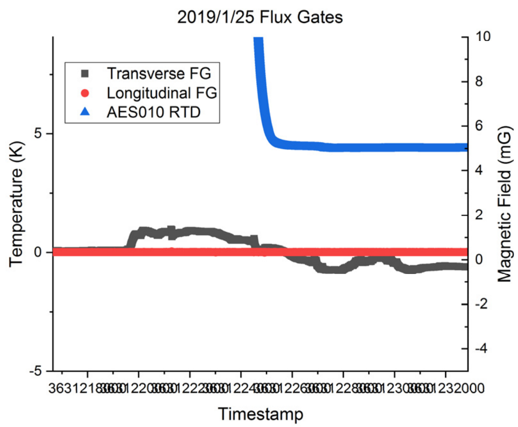
Finding 3: unequivocal performance change with cooldown (120C baked cavity)

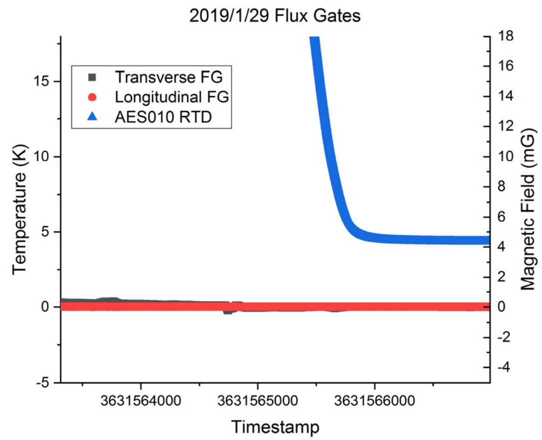
- Cooldown From 294K vs ~350K
  Cooldown from bottom vs top





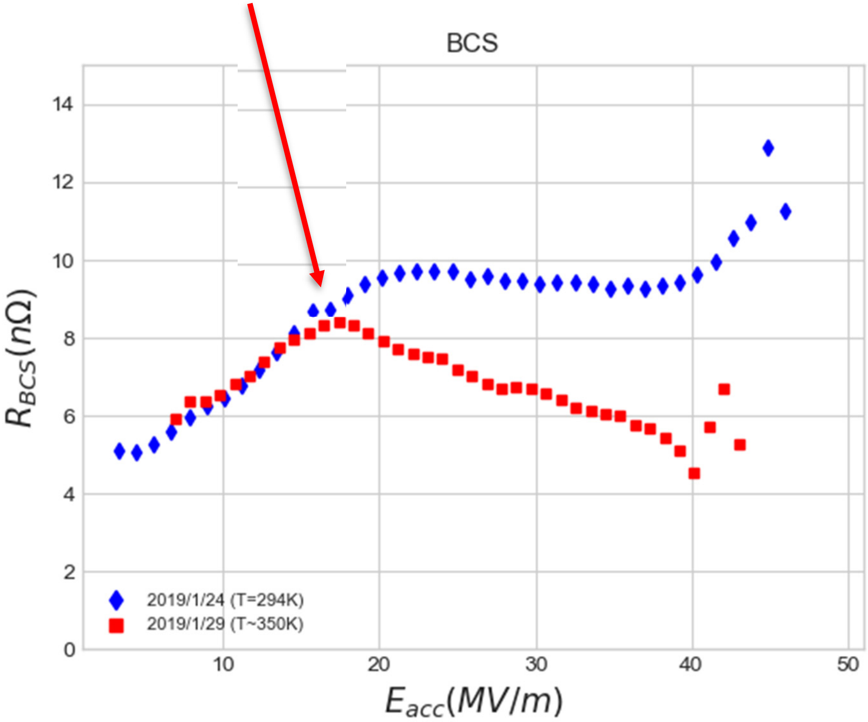
- **Compared performance for standard fast from 300K cooldown with slow from 350K**
- **Substantially lower Q and G from 350K/top cooldown**
- **ZERO compensated B field both longitudinal and transverse**



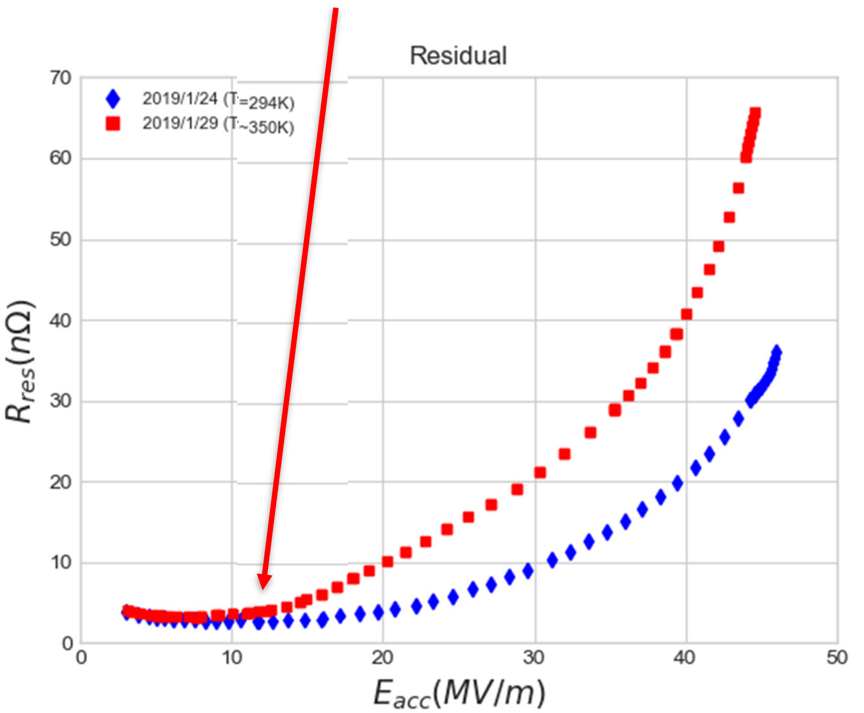


Finding 3: unequivocal performance change with cooldown

Could this be a signature of non equilibrium behavior of surface resistance shifting earlier?

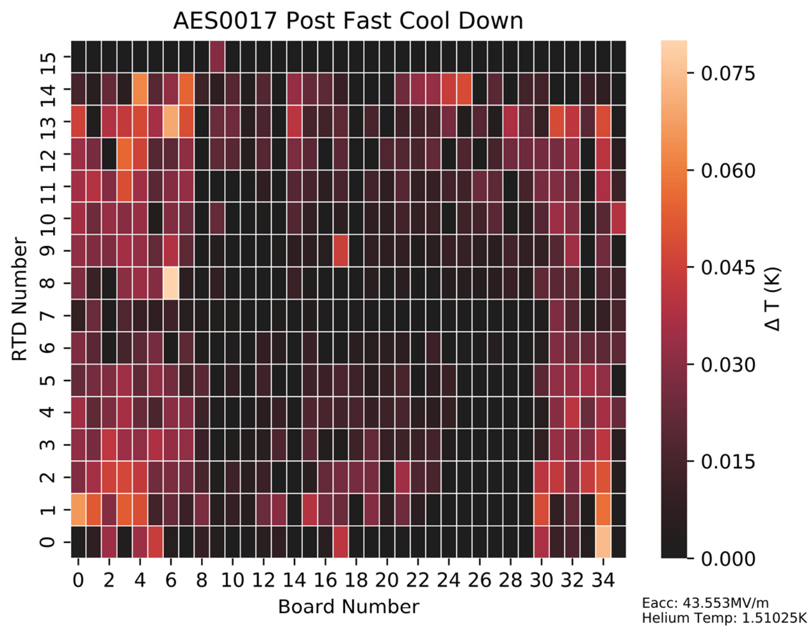


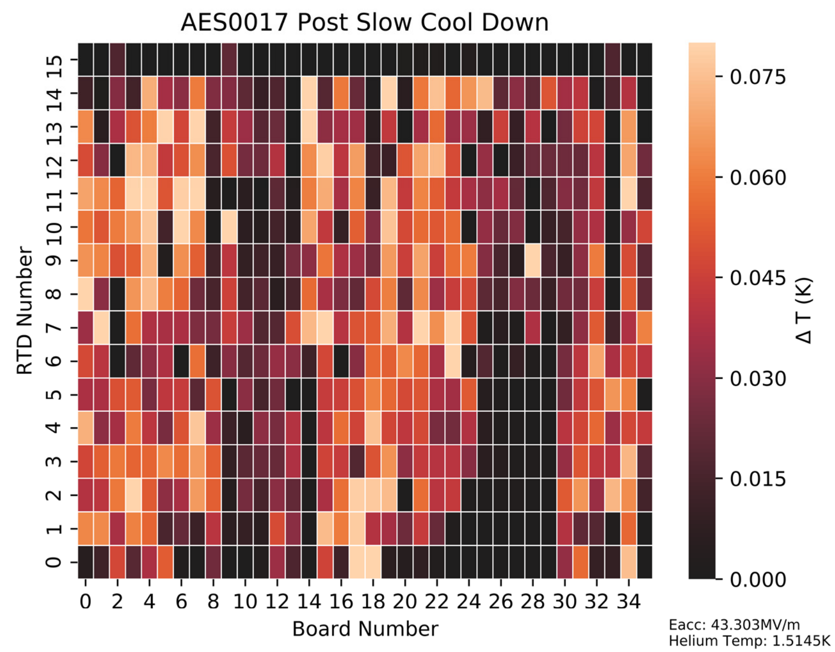
Earlier proximity breakdown of nano-hydrides?

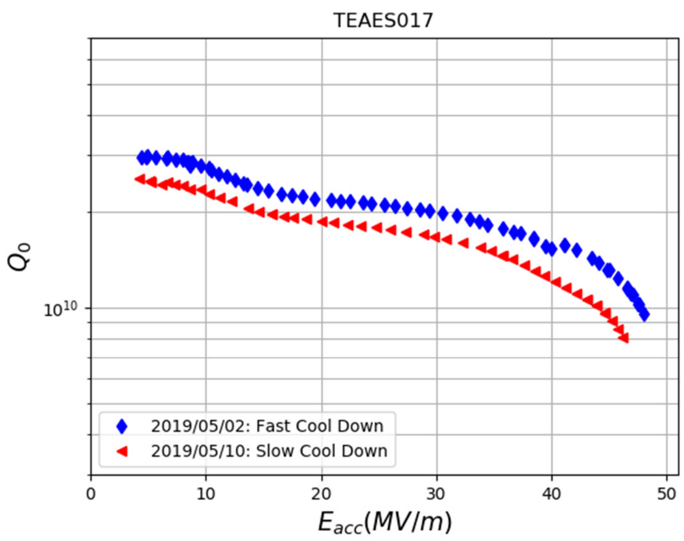


- R_{BCS} decreases, residual increases, the "knees" move at corresponding points with a 'breakdown' field compatible with the proximity effect model of nanohydrides as introduced by A. Romanenko in Superconductor Science and Technology, Volume 26, Number 3

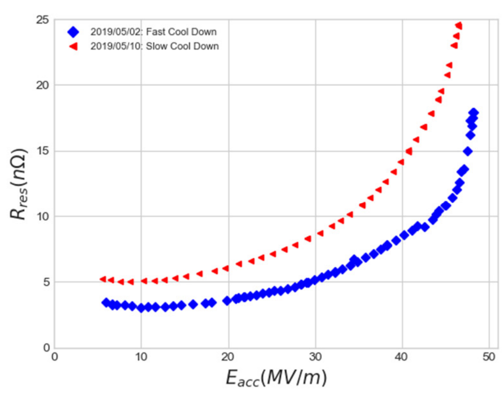
Repeat experiment with Tmap – fast vs slow cool from 300K (in zero magnetic field) shows large difference in heating

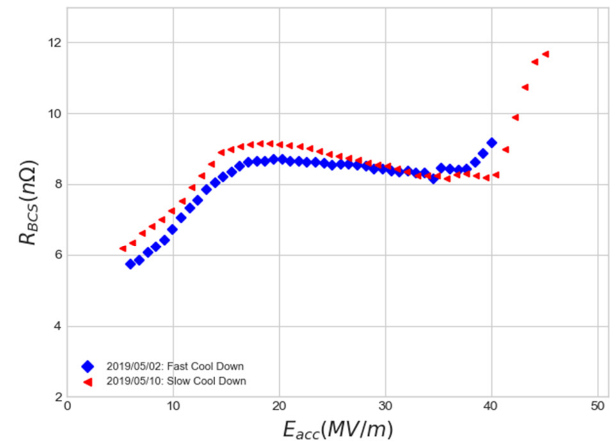






Equatorial heating turning on, signature of hydrides precipitation?



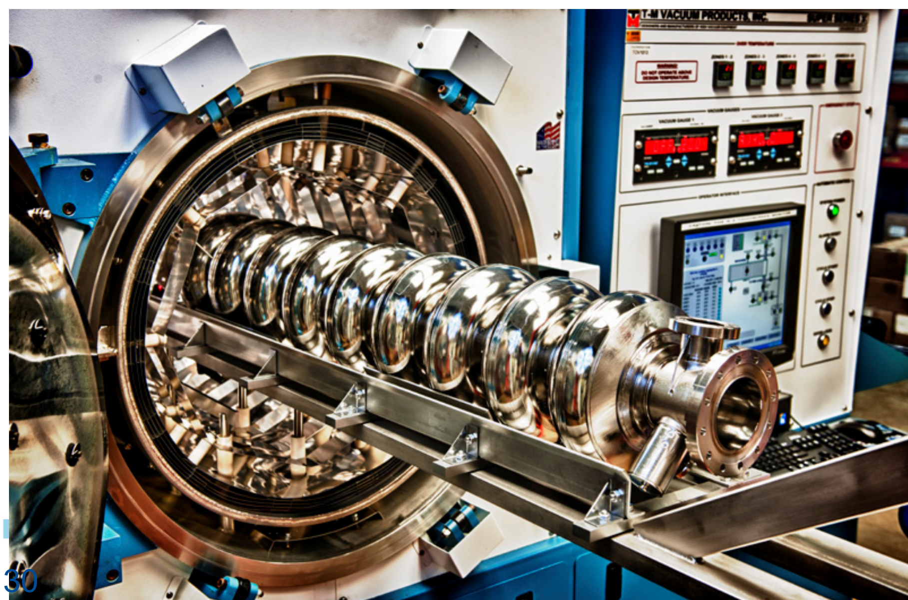


New Medium T bake

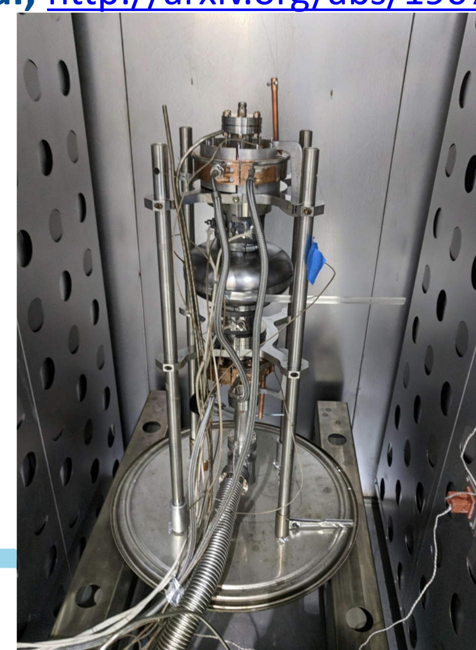
Progress with N infusion @FNAL in 2019

- 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; however other labs have seen some success and some variability in performance depending on furnace contamination background
- So we decided to develop 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

See S. Posen et al, http://arxiv.org/abs/1907.00147



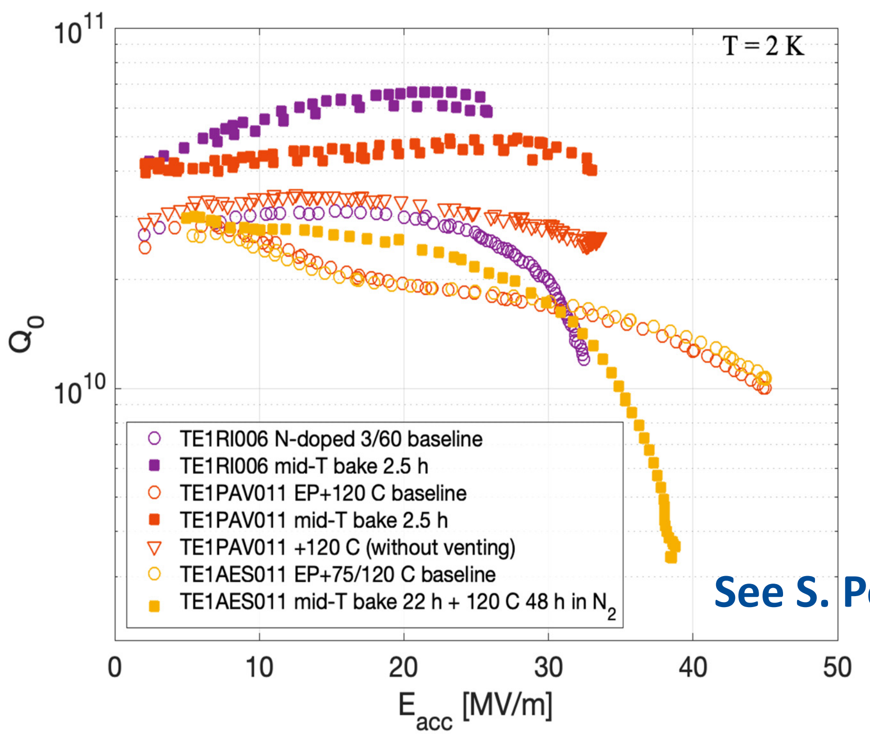
High T furnace ←

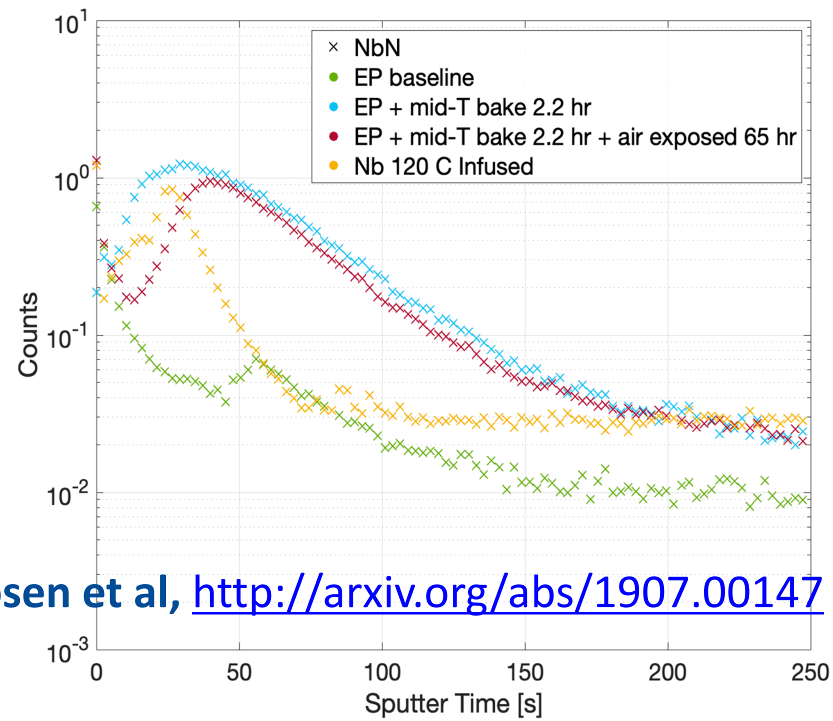


Low T oven ←

New Progress with "new N infusion/self infusion" @FNAL in 2019

- Record Q values at all temperatures below 2K
- Cavities turned into doped, without the need to inject nitrogen
- Q approaching 1e12 at low T
- "Self doped" nitrogen layer > 60nm (studied in SIMS) ; work is ongoing to study performance changes as a function of nano-surface removal;
- **KEY FOR S-S dirty layer exploration → see talk by Jim Sauls THFUB4**





See S. Posen et al, http://arxiv.org/abs/1907.00147

Method was developed also for SRF quantum systems, 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

Conclusions

- The more we do, the more we discover.
- The more we discover, the more we learn.
- The more we learn, the more we know that we don't know.
- When you combine extraordinary tools and extraordinary people, you can do extraordinary things.