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Performance of nitrogen doped cavities

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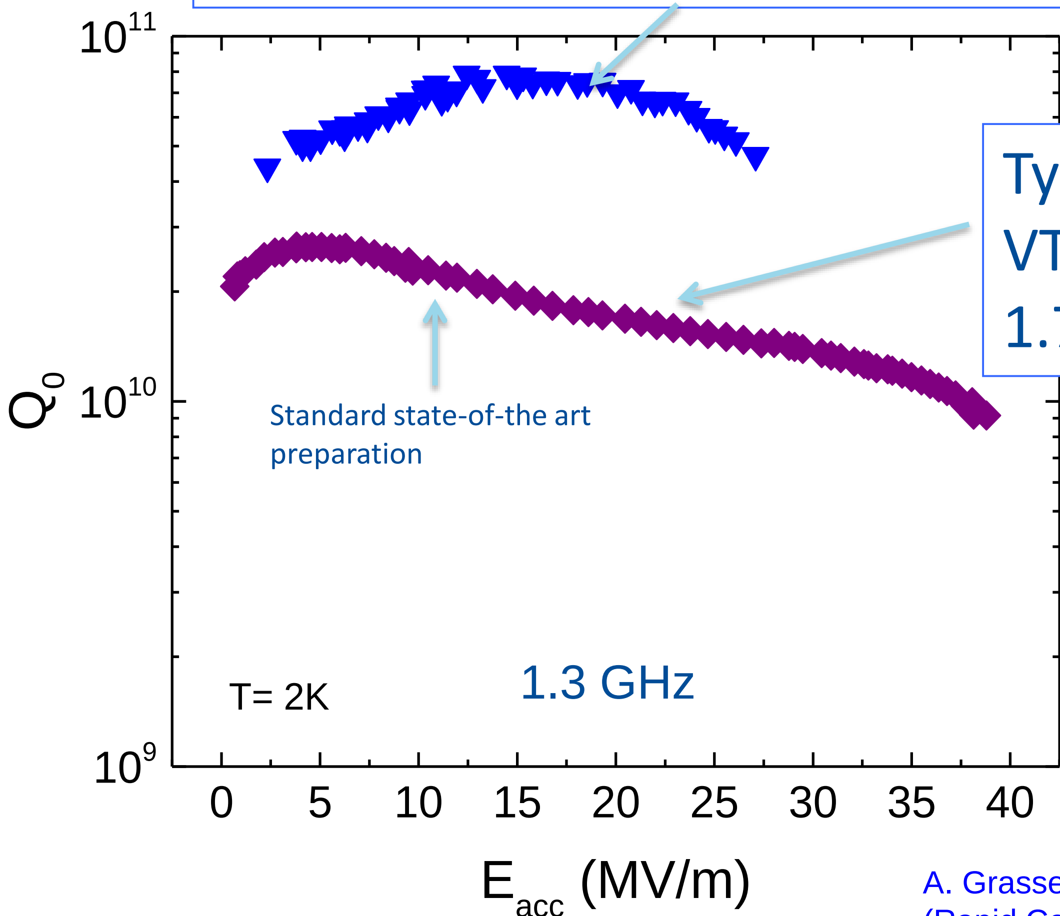
LHeC Workshop June 24-26, 2015 Geneva

Nitrogen Doping: a breakthrough in Q

Record after nitrogen doping – up to 4 times higher Q! Average values obtained on nine cell Q(2K, 16MV/m)~ 3.5e10



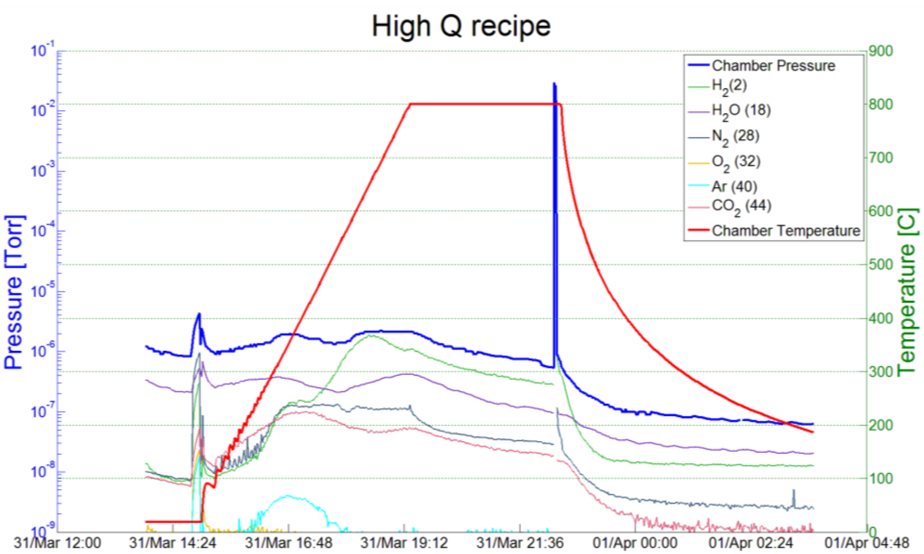
Typical Q obtained in VTS with 120C bake ~ 1.7e10 at 2K, 16 MV/m

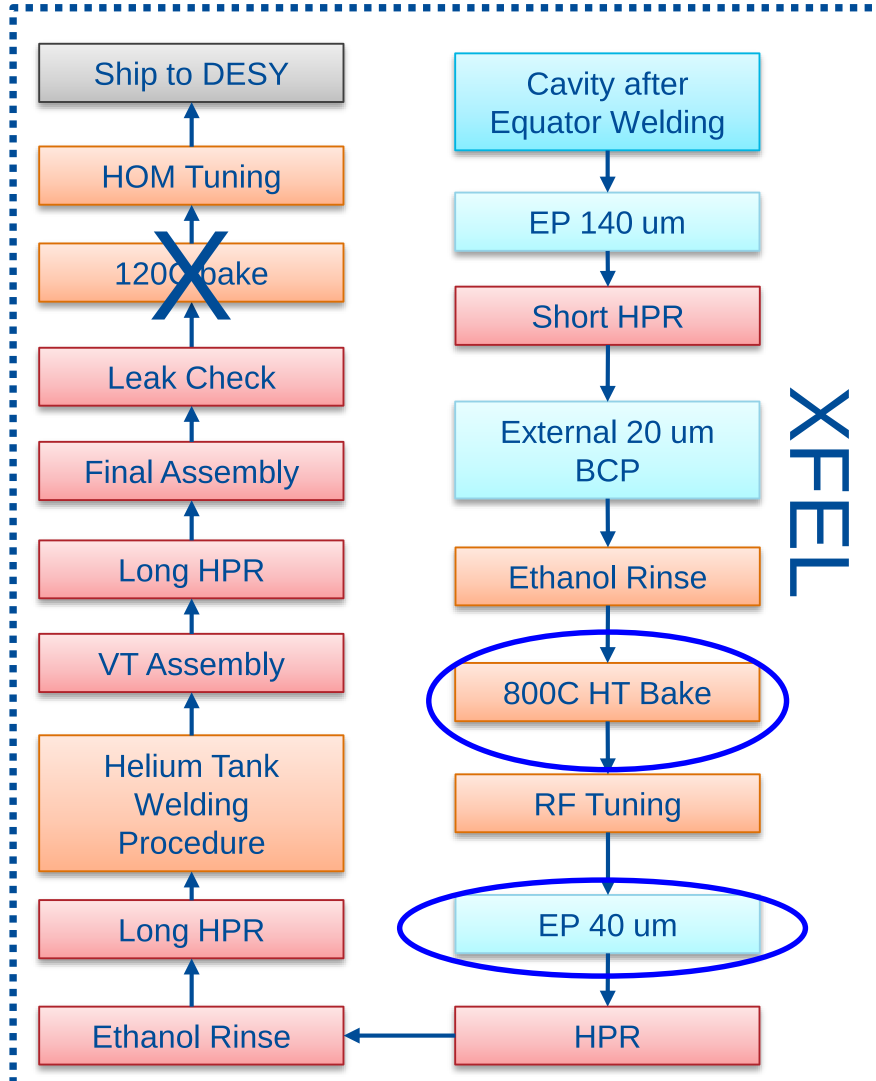
A. Grassellino et al, 2013 Supercond. Sci. Technol. **26** 102001 (Rapid Communication)

Doping Treatment: small variation from standard protocol, large difference in performance

Example from a doping process developed for LCLS-2:

- Bulk EP
- 800 C anneal for 3 hours in vacuum
- 2 minutes @ 800C nitrogen diffusion
- 800 C for 6 minutes in vacuum
- Vacuum cooling
- 5 microns EP



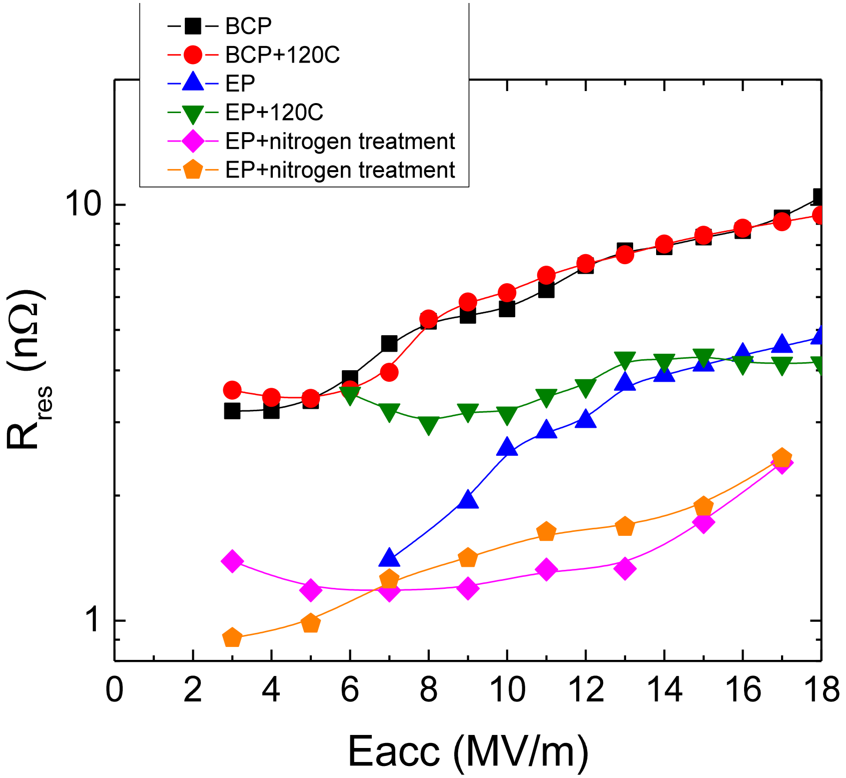


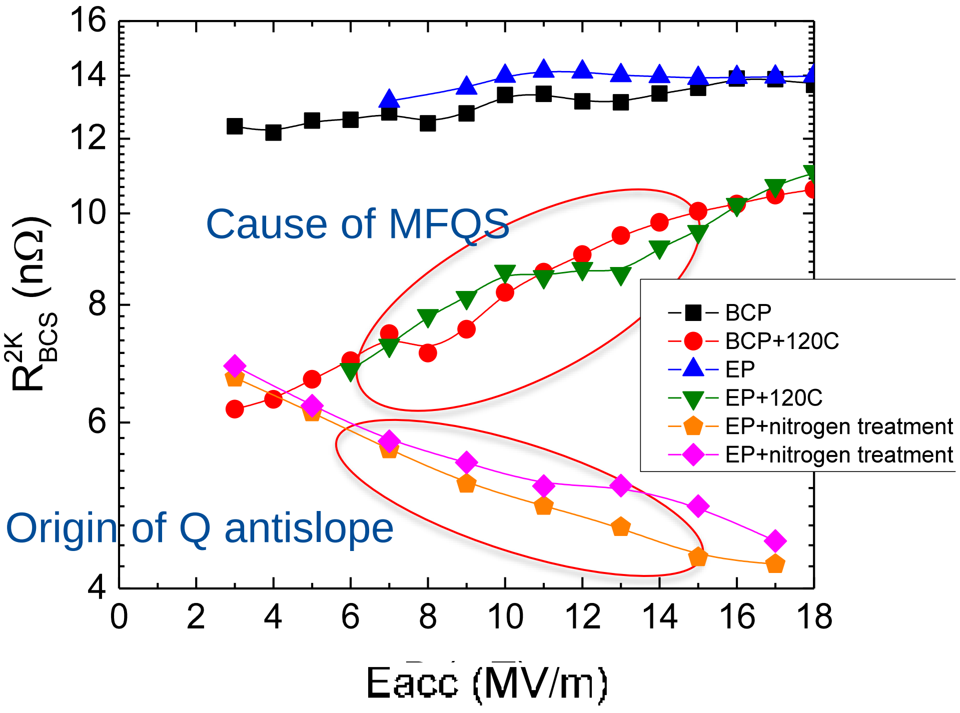
A bit of history about N doping

- Discovered at FNAL in 2012 on single cells treated with nitrogen in high temperature furnace
- During the first two years FNAL focused on understanding root of improvement and making process controllable and reproducible on single cells
- Different doping recipes were designed based on simple diffusion models and implemented/tested; went from one step diffusion to two step diffusion to create flatter, deeper nitrogen concentration – this improved robustness and quench fields
- In 2014 LCLS-2 decided to invest on this technology to go from wide demonstration on single cell to production ready nine cell; three partner labs working together FNAL-Cornell-Jlab
- More than 100 N doped cavity tests with 16 nine cell qualified for the two LCLS-2 prototype cryomodules
- Vendors RI and Zanon currently being qualified for N doping production process for LCLS-2
- R&D continues for further understanding and improvements (quench, B sensitivity)

Origin of the Q improvement

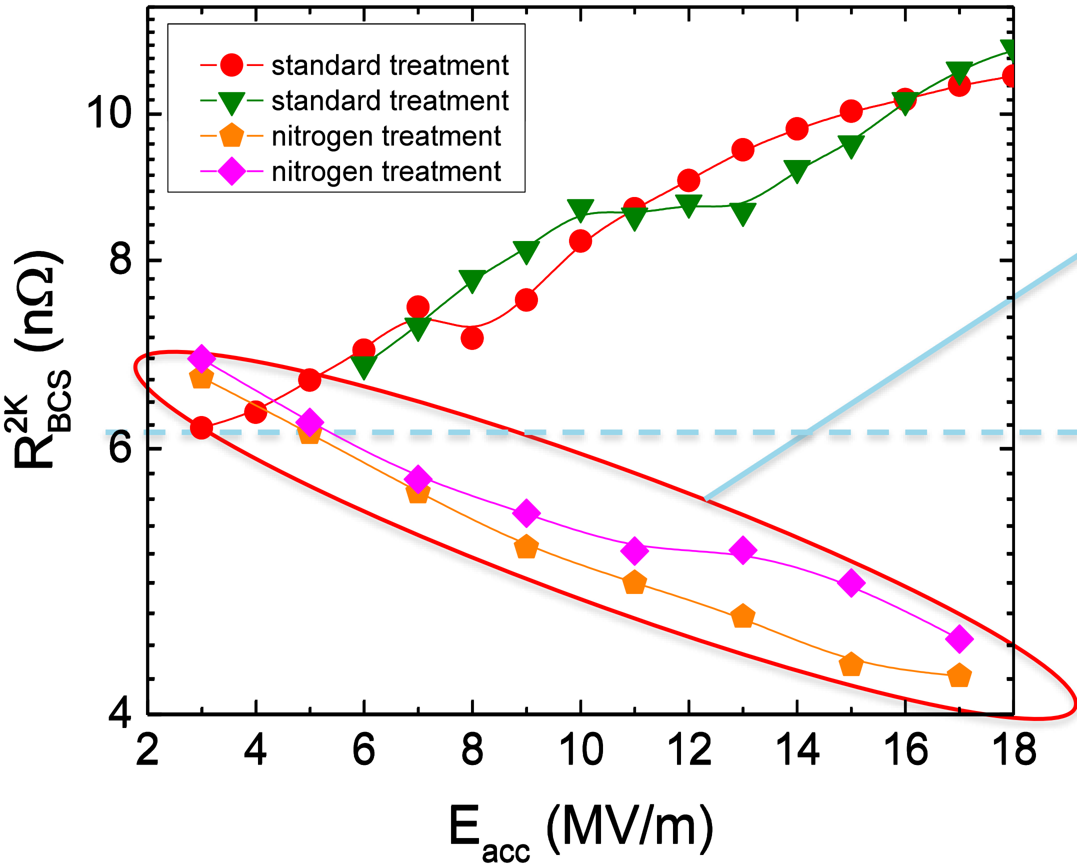
- Reverse field dependence of the BCS surface resistance component → lowest R_{BCS}
- Lower than typical residual resistances (seems to zero all contributions but trapped flux)





A.Grassellino et al, 2013 *Supercond. Sci. Technol.* 26 102001
A. Romanenko, A Grassellino, Appl. Phys. Lett. 102, 252603 (2013)

Physics – perceived BCS limit has been overcome



Anti-Q-slope emerges from the BCS surface resistance decreasing with field

This is what BCS theory predicted to be the lowest possible surface resistance

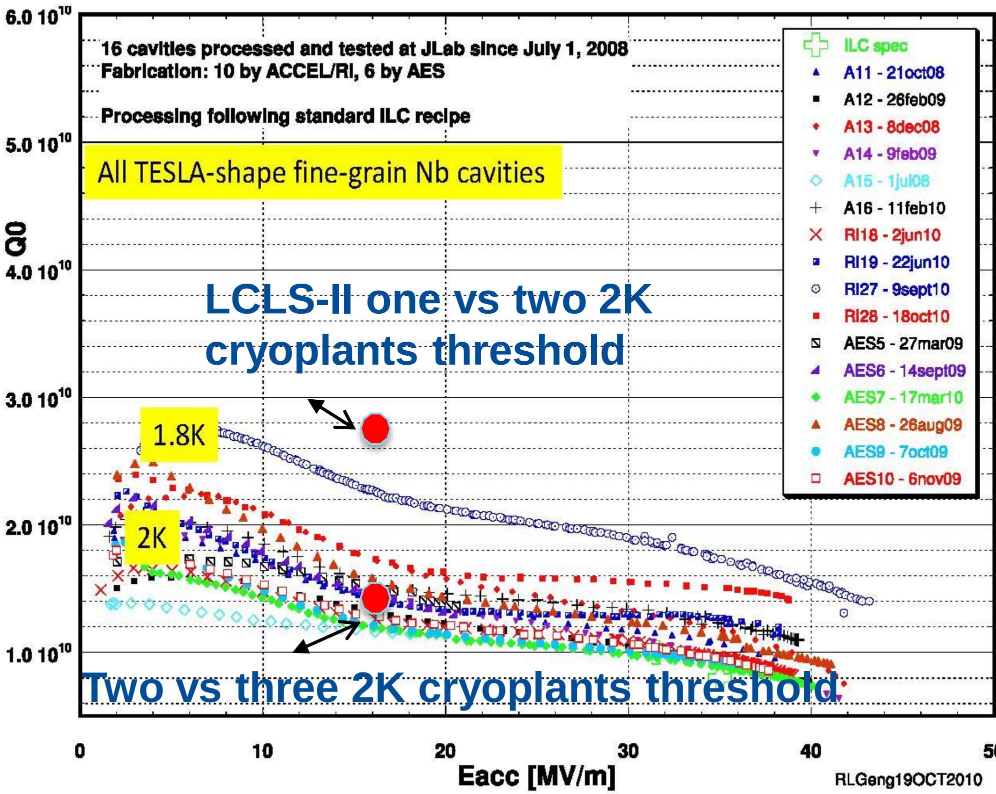
The increasing Q with field allows to run at higher gradient with lower cryo-cost

A. Grassellino et al, 2013 Supercond. Sci. Technol. **26** 102001 (Rapid Communication)
A. Romanenko and A. Grassellino, Appl. Phys. Lett. **102**, 252603 (2013)

The importance of a high Q technology – the case of the CW machine LCLS-2

Example of 120C baked (standard ILC/XFEL technology)

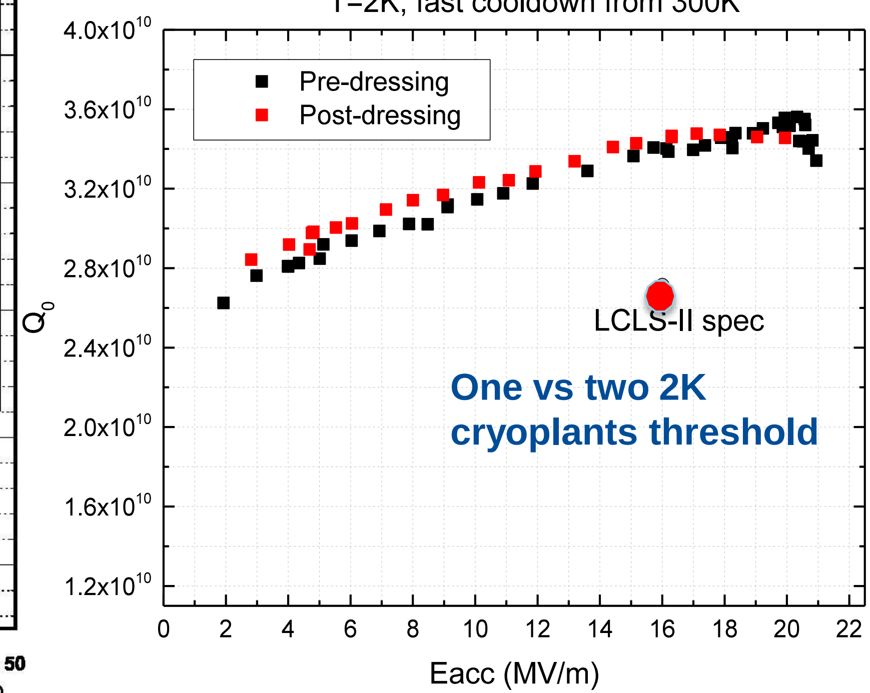
Would possibly require > 2 full cryoplants



Example of N doped

Dressed cavity for LCLS-2

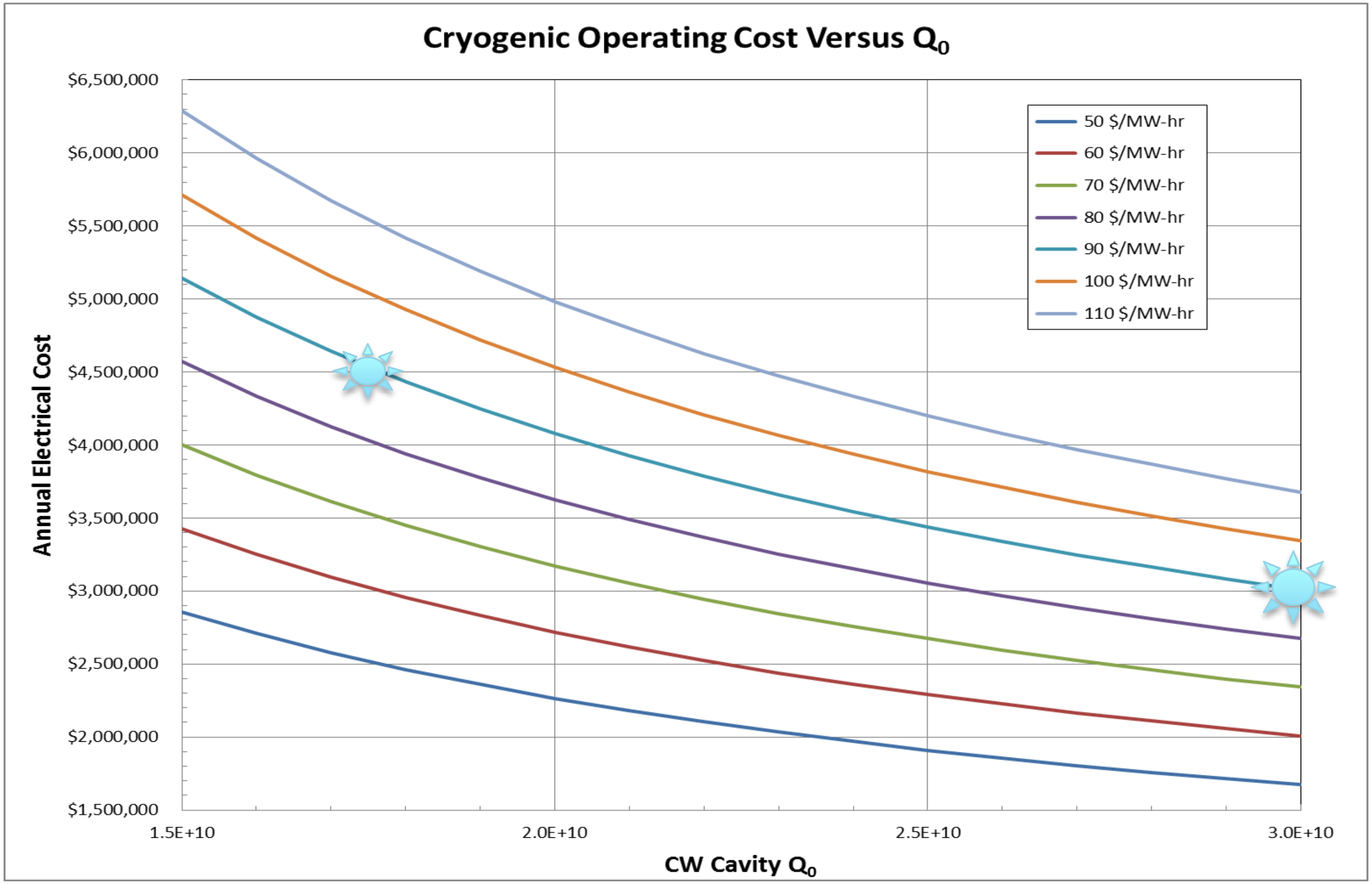
Below the one cryoplant threshold



- N doping technology allows significantly lower refrigeration costs (capital, operating)
- Larger margin and possibility for an energy upgrade for same refrigeration cost

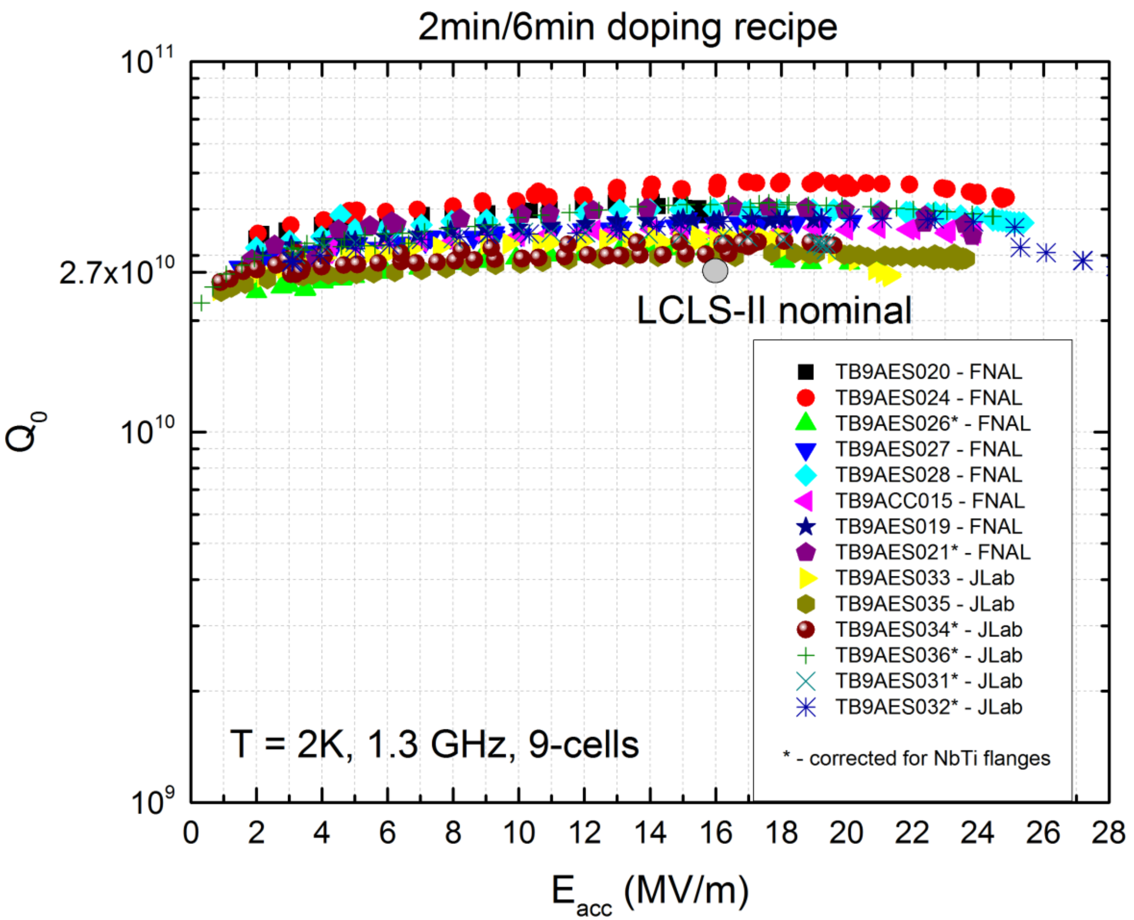
Fermilab

The importance of a high Q technology – the case of the CW machine LCLS-2



- Higher Q ~ 3e10 compared to 1.7e10 will translate into ~1.5 millions saving per year in operating costs
- Capital cost savings go in thresholds of several tens of millions (LCLS-2)

From single cell R&D to cryomodule ready technology: the two LCLS-II prototype cryomodules (FNAL and Jlab)

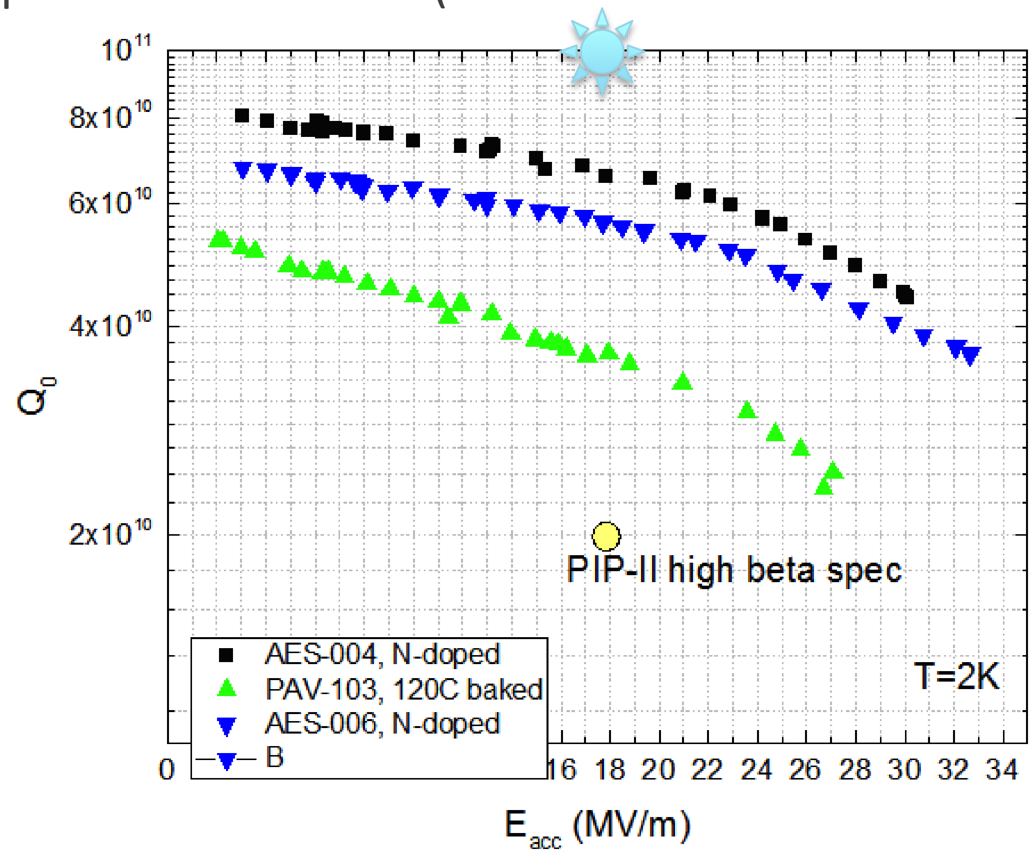


<Q>=3.6e10
$<E_{max}>$=22.2 MV/m
E_{max}median=22.8MV/m

It is the highest average Q ever demonstrated in vertical test for 1.3 GHz nine cells at 2K, 16 MV/m in the history of SRF (larger than a factor of two the state of the art)

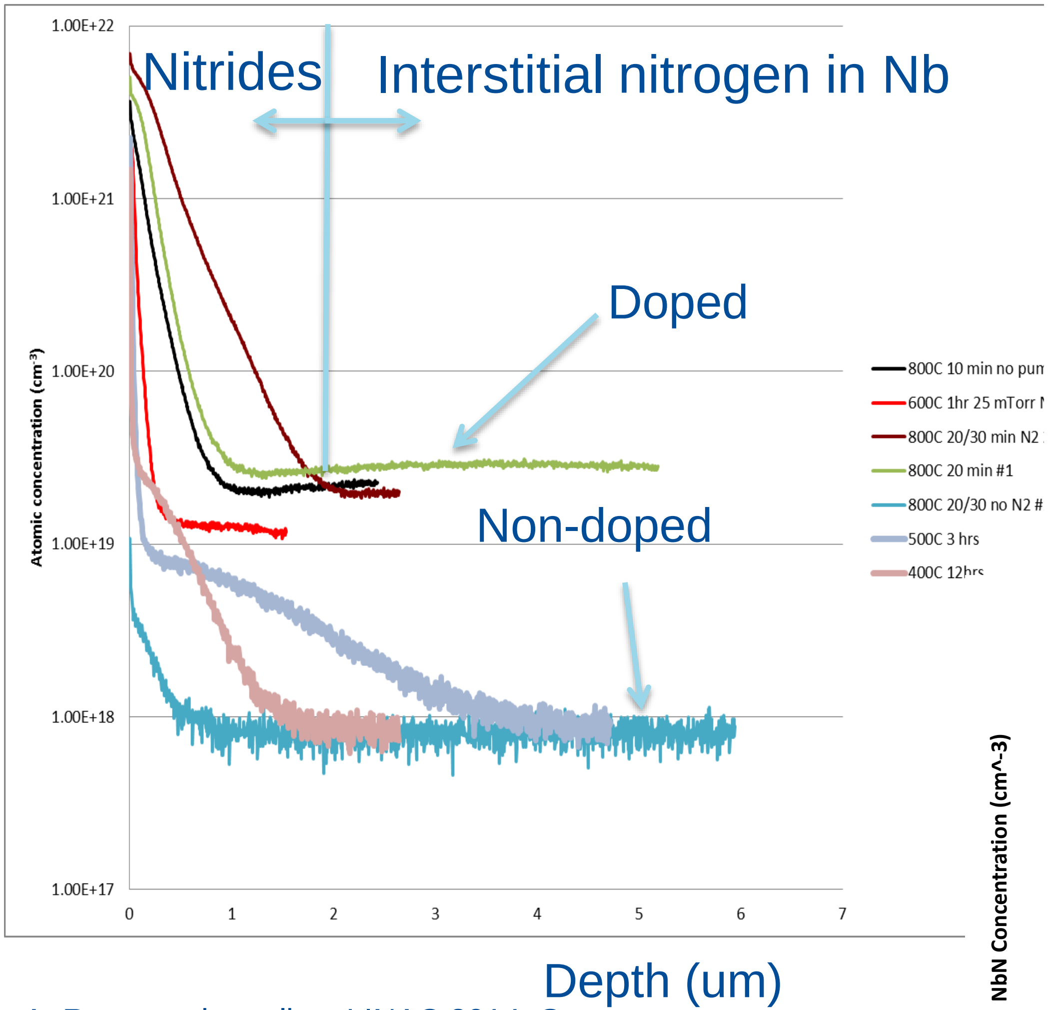
N doping applied to 650 MHz cavities at FNAL
Q~ 7e10 at 2K, 17 MV/m – record at this frequency!

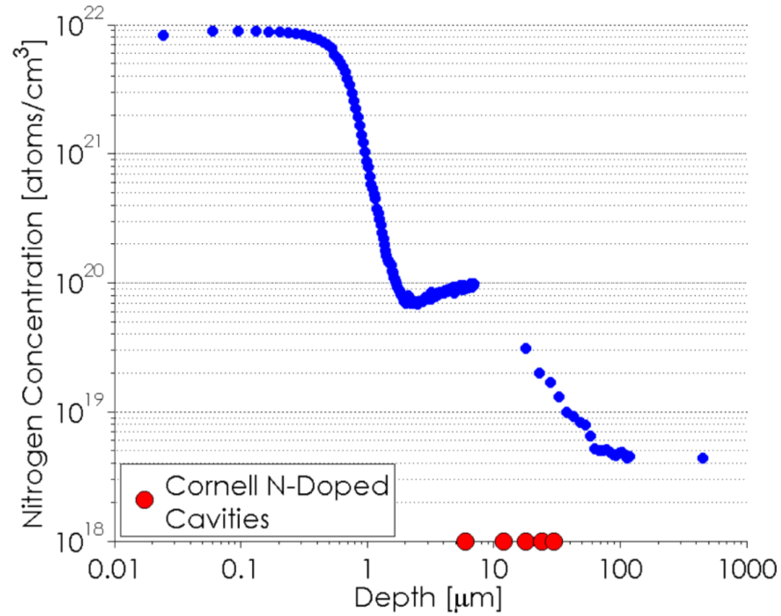
Applying N doping to 650 MHz (beta=0.9) leads to double Q compared to 120C bake (standard surface treatment ILC/XFEL)

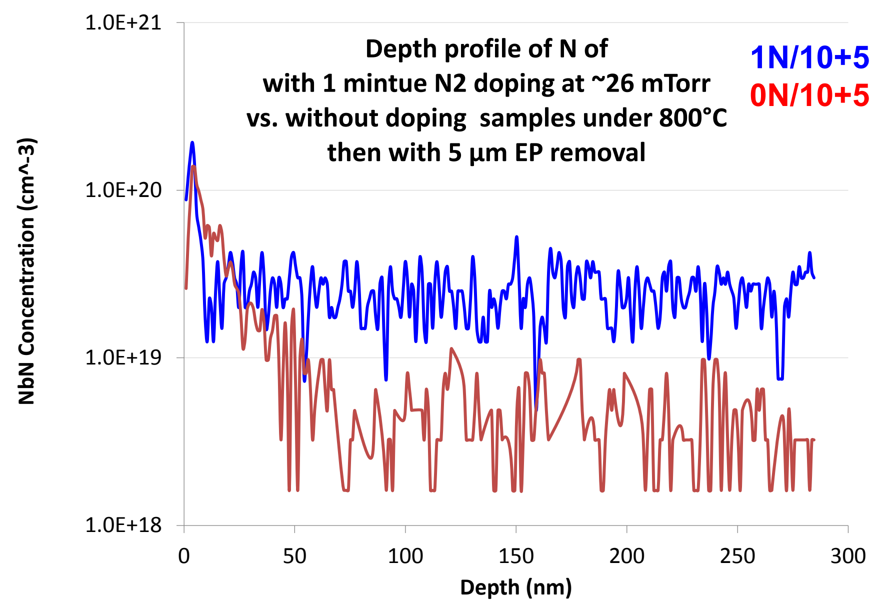


But from frequency scaling from 1.3GHz, with ideal recipe the projected Q value is ~1e11 at 17 MV/m, 2K! Need to optimize doping recipe at lower freq

What does the N treatment do? N doping profiles via SIMS



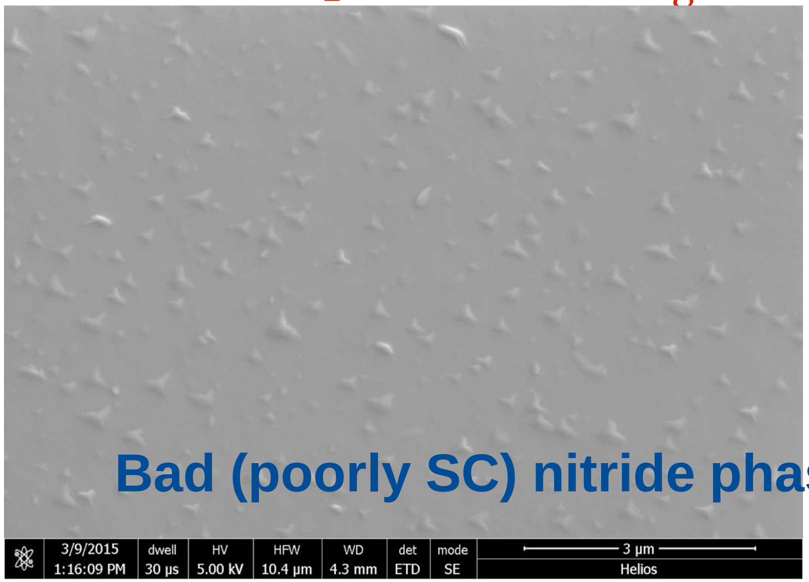


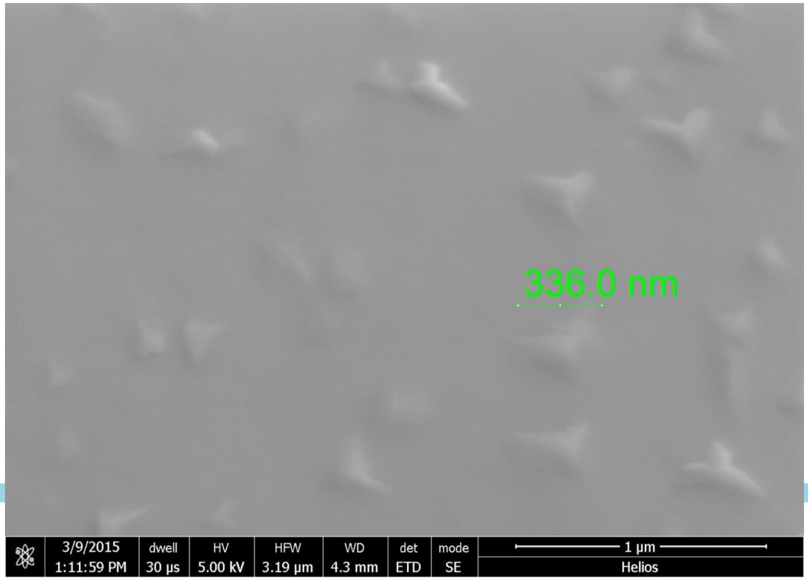


A. Romanenko, talk at LINAC 2014, Geneva
And D. Gonnella et al, LINAC 2014, Geneva
C. Reece et al, **WEPWI026**

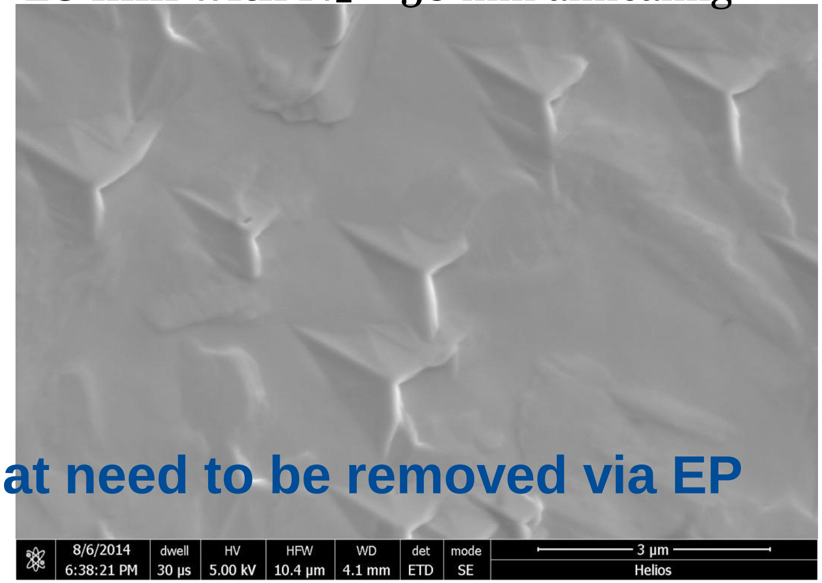
Surface Nitrides (post bake, pre-EP) – imaged by SEM

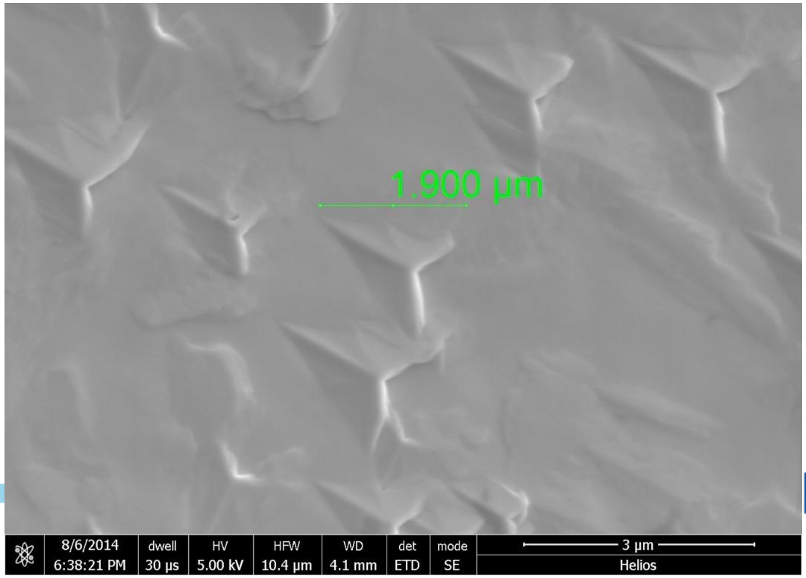
Flat Nb sample baked at 800C°
for **2 min with N_2** + 6 min annealing





Flat Nb sample baked at 800C° for
20 min with N_2 + 30 min annealing

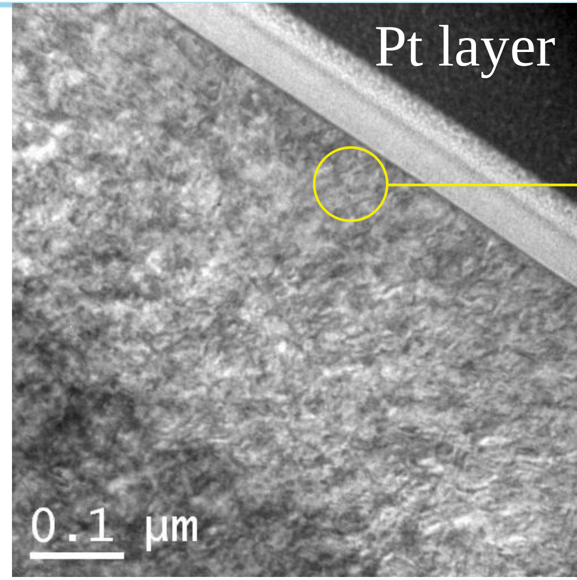


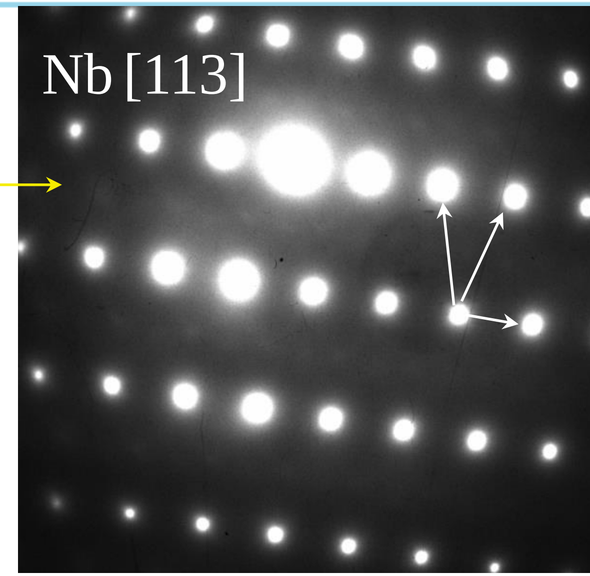


Bad (poorly SC) nitride phases that need to be removed via EP

Room T TEM on post gas bake, pre-EP surface (2/6 recipe)

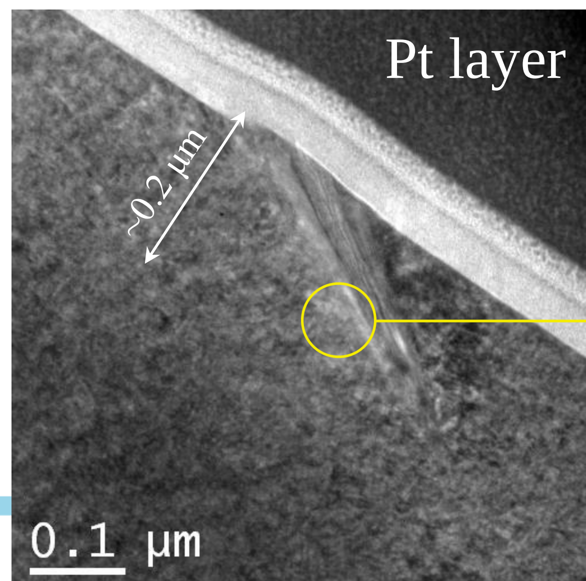
a) μm-sized areas of "uniform" contrast in near-surface show only Nb reflections

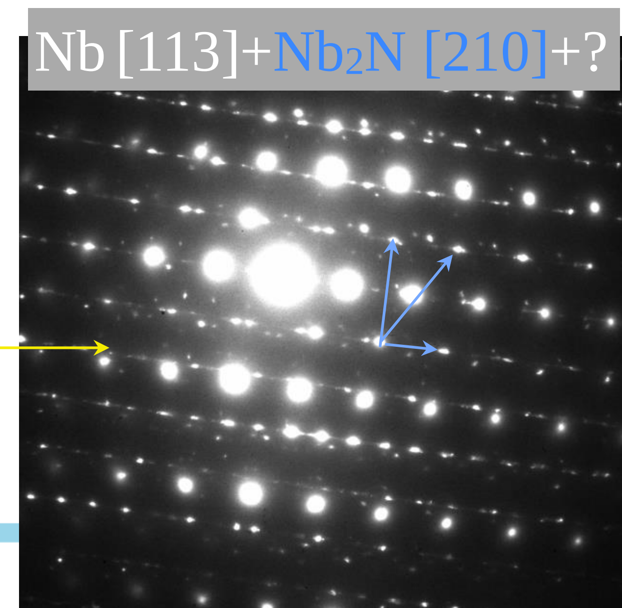




Courtesy of Y. Trenhikina, FNAL

b) few Nb nitrides-features (Nb_2N reflections) in Nb near-surface. Nitride "teeth" go ~0.2 μm deep

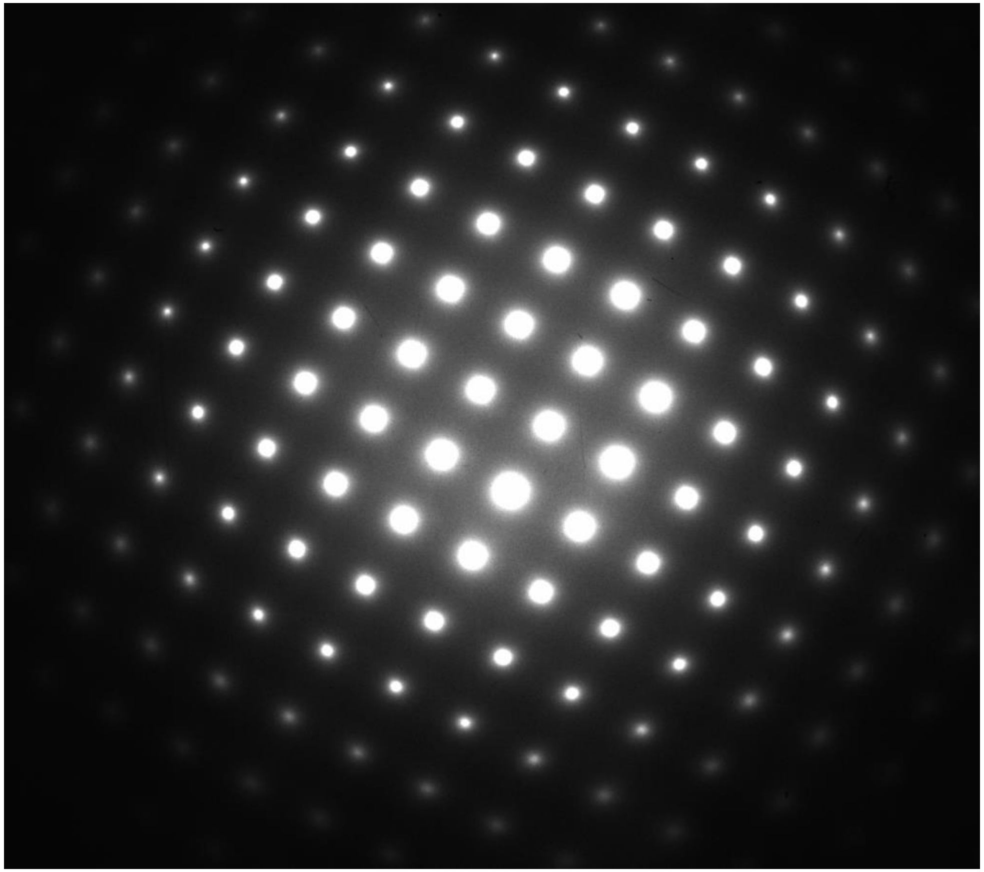




Room T TEM on N doped surface AFTER EP

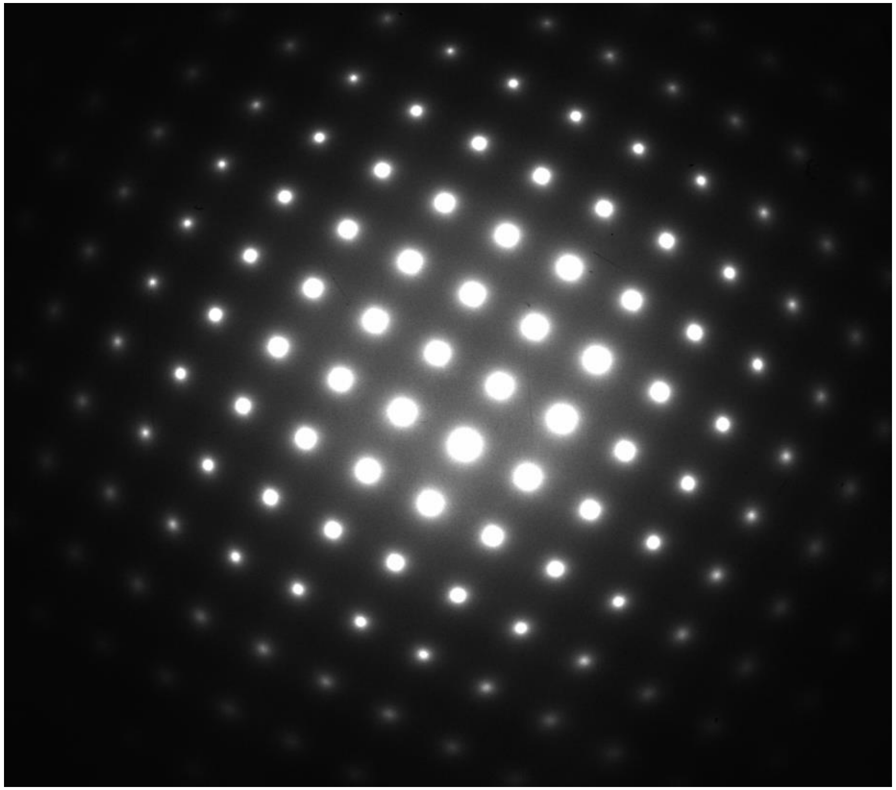
- Preliminary: <u>no</u> visible Nb nitrides-teeth in near-surface show only Nb reflections

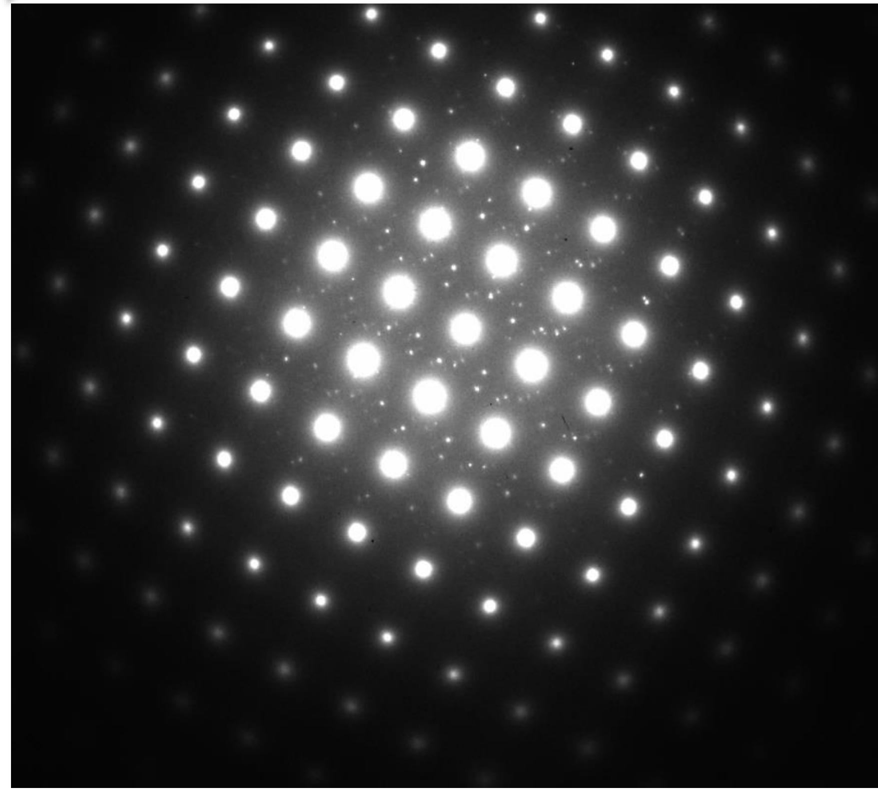
- Confirms that root of improvement is from nitrogen as interstitial in the lattice



Cryogenic TEM on N doped surface AFTER EP

ROOM T → 90K





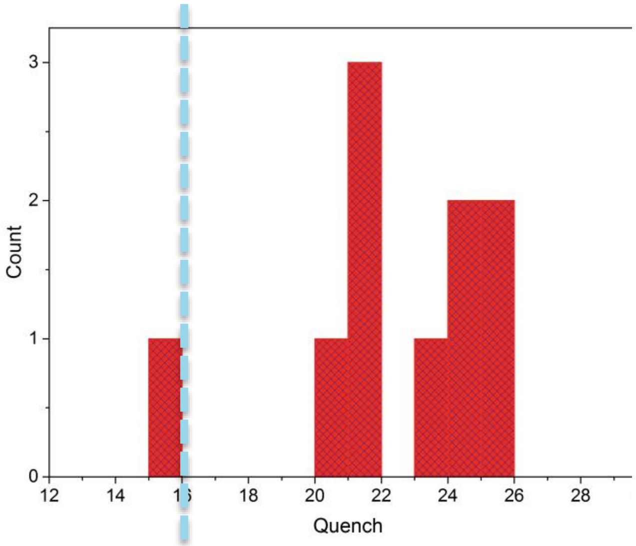
Preliminary: large near-surface area is affected by Nb nanohydride precipitation!
But different than typical: closely spaced, very small/thin Nb hydrides.

Nanohydrides in standardly treated samples: Trenikhina et. al. J. of Appl. Phys., 117, 154507 (2015).

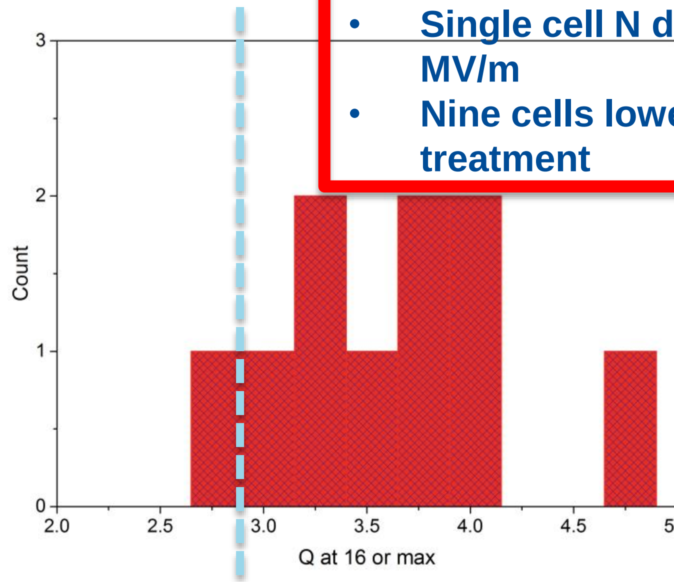
Open questions: nature of premature quench in N doped

- Heavier doping levels result in premature quench
- Single cell N doped demonstrated up to 39 MV/m
- Nine cells lower than single cell for same treatment

16 MV/m



2.7e10

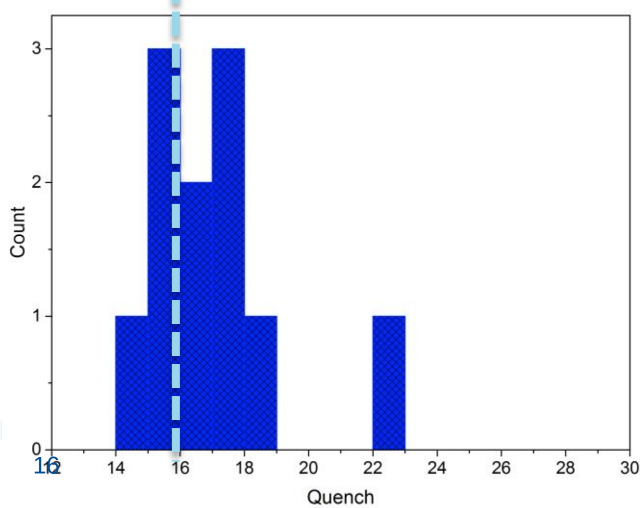


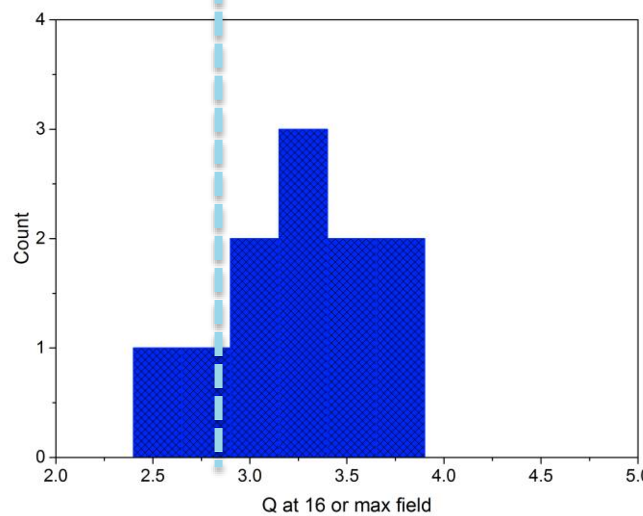
Recipe 2/6 "light doping"

$<Q>=3.6e10$

$<E_{max}>=22.2$ MV/m

E_{max}median=22.8MV/m





Recipe 20/30 "heavy doping"

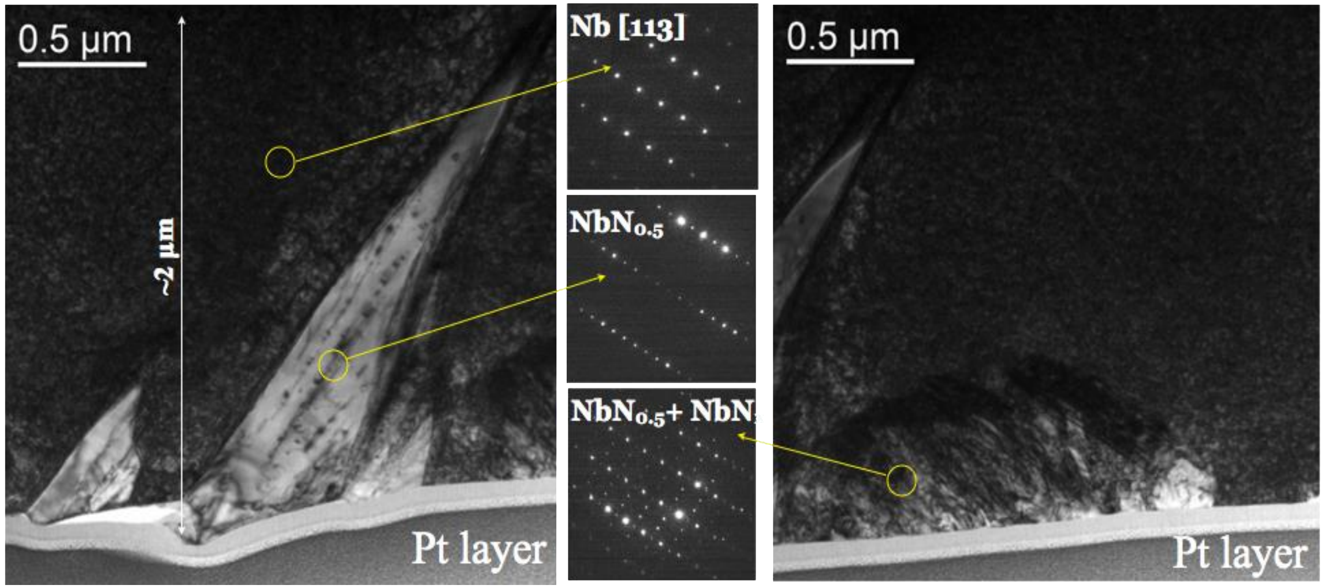
$<Q>=3.24e10$

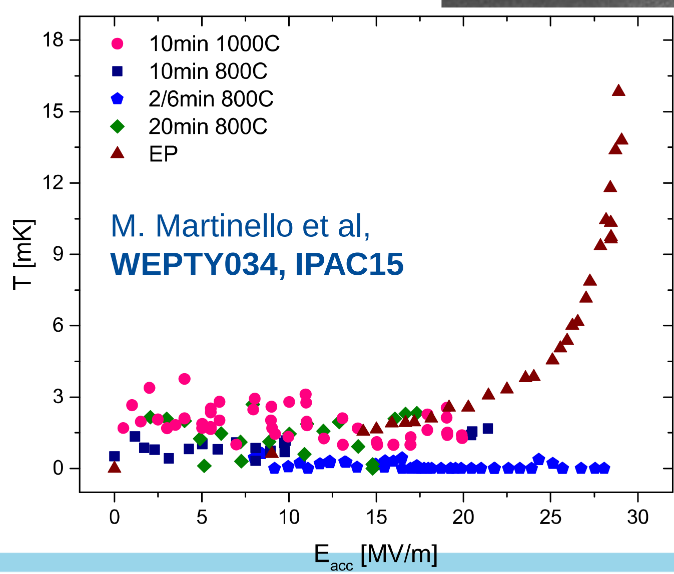
$<E_{max}>=16.3$ MV/m

E_{max}median=16.5MV/m

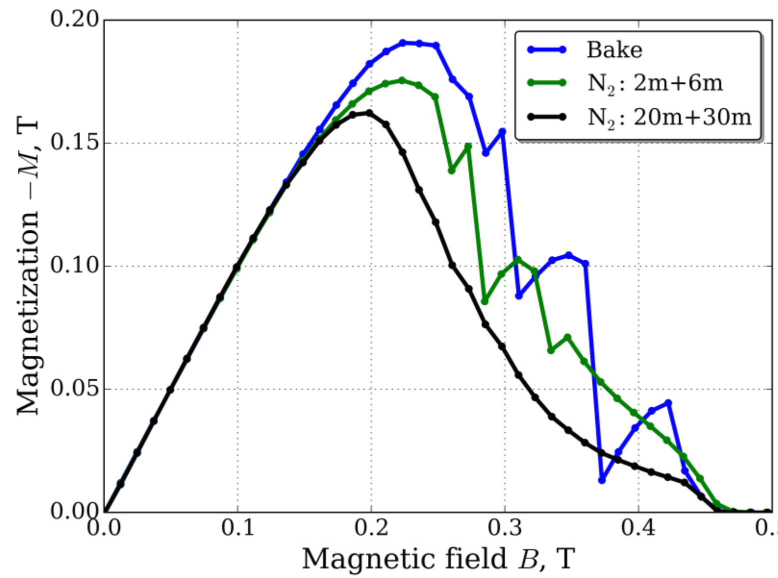
New insights on quench in N doped cavities – magnetic peak field driven

Nitride teeth…residual nanonitrides post EP?





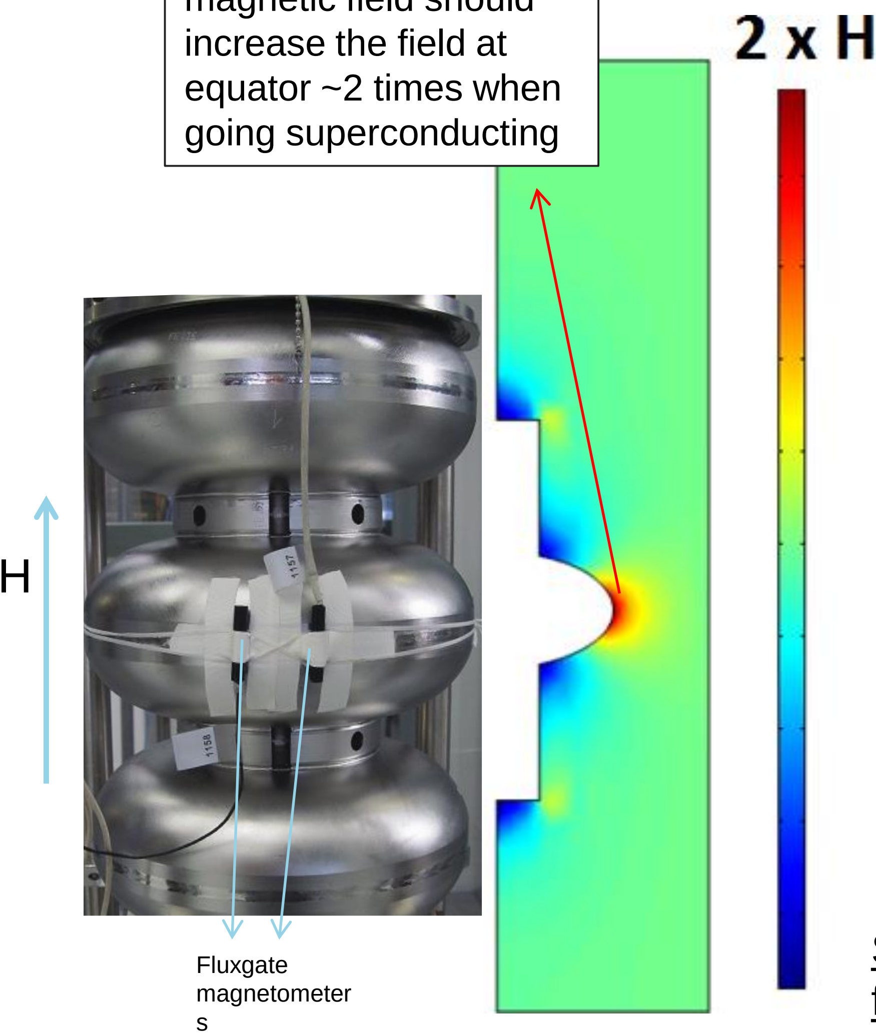
M. Martinello et al, **WEPTY034, IPAC15**



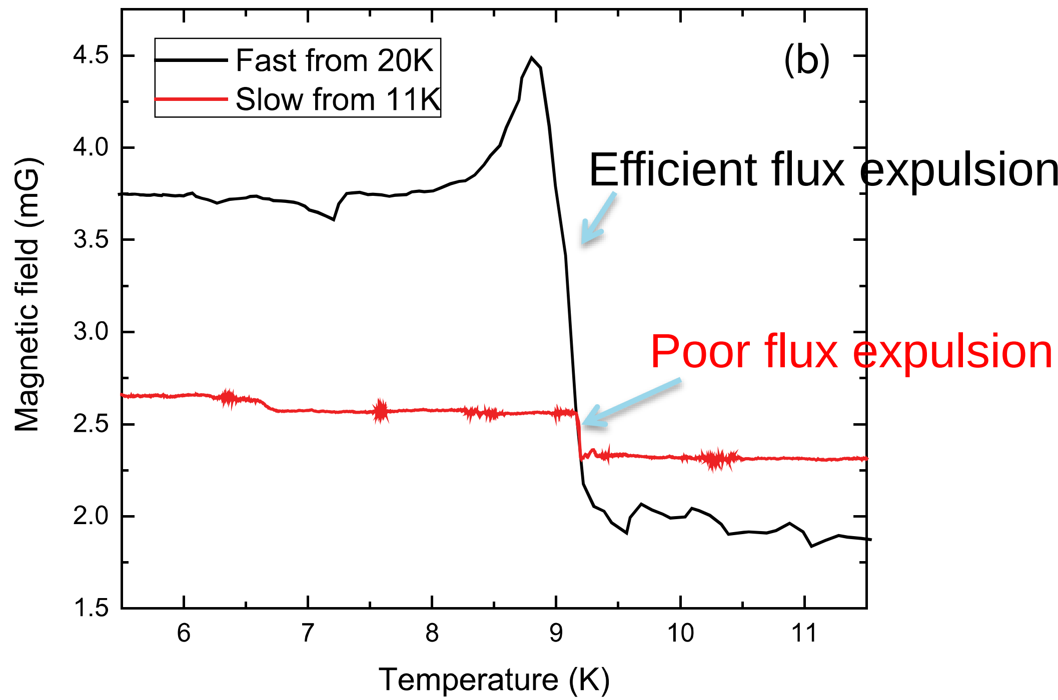
A. Vostrikov et al, **WEPTY022, IPAC15**

High Q discovery 2 – efficient flux expulsion

Full expulsion of the magnetic field should increase the field at equator ~2 times when going superconducting

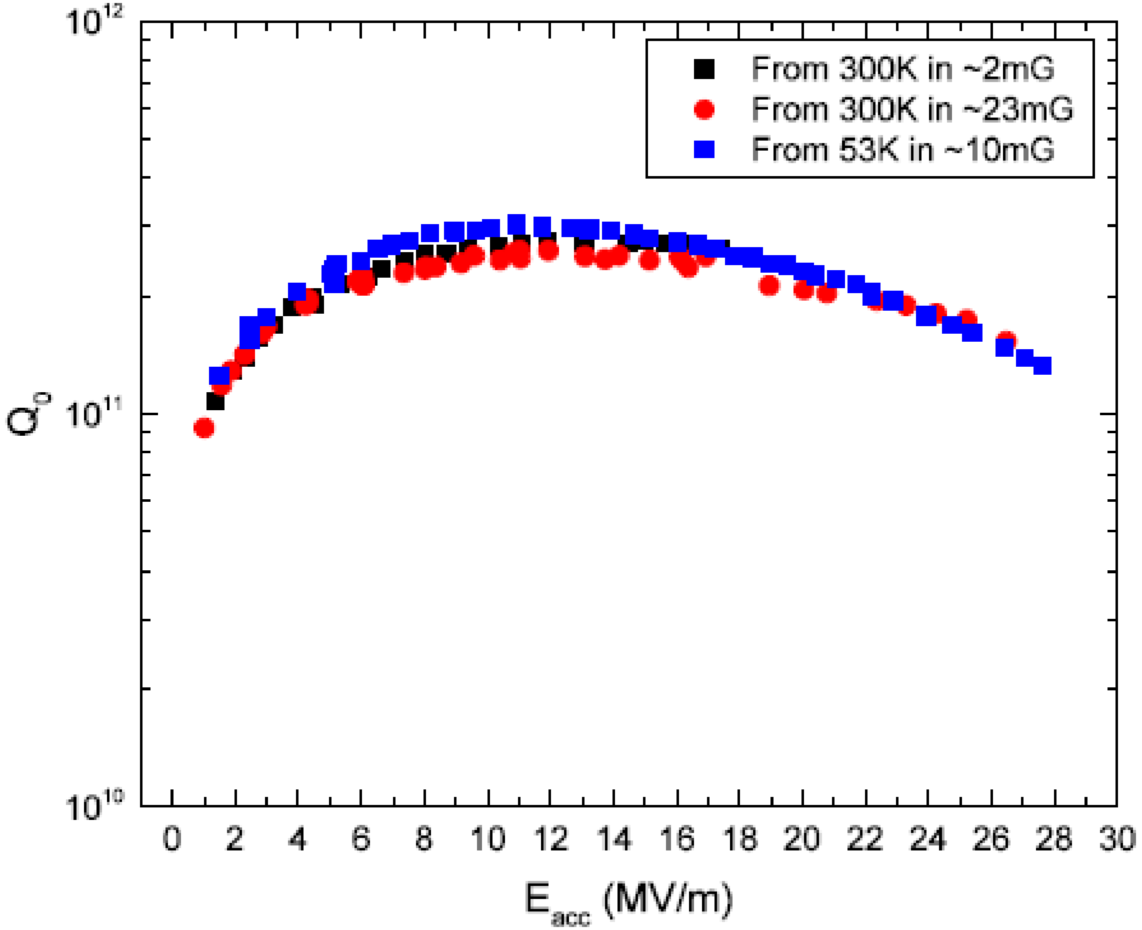


It turns out the expulsion efficiency can be controlled by the cooldown procedure through Tc=9.2K (fast/slow, uniform or not)



<u>Same Meissner behavior for EP, EP+120C, N doping, fine/single grain, cooling is what matters</u>

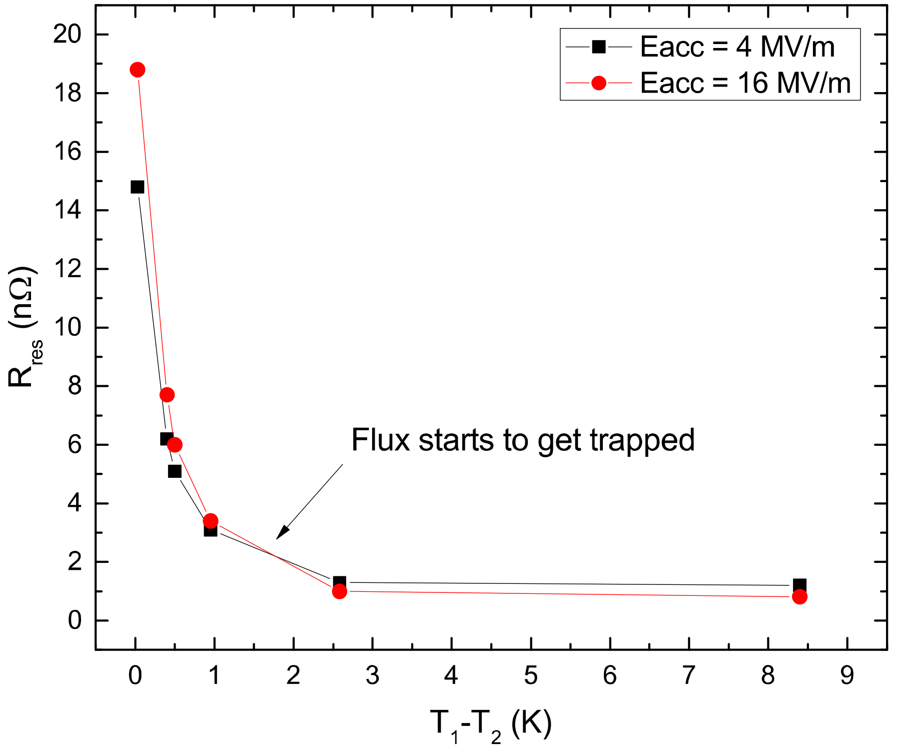
Record Q up to the highest fields combining N doping and efficient flux expulsion

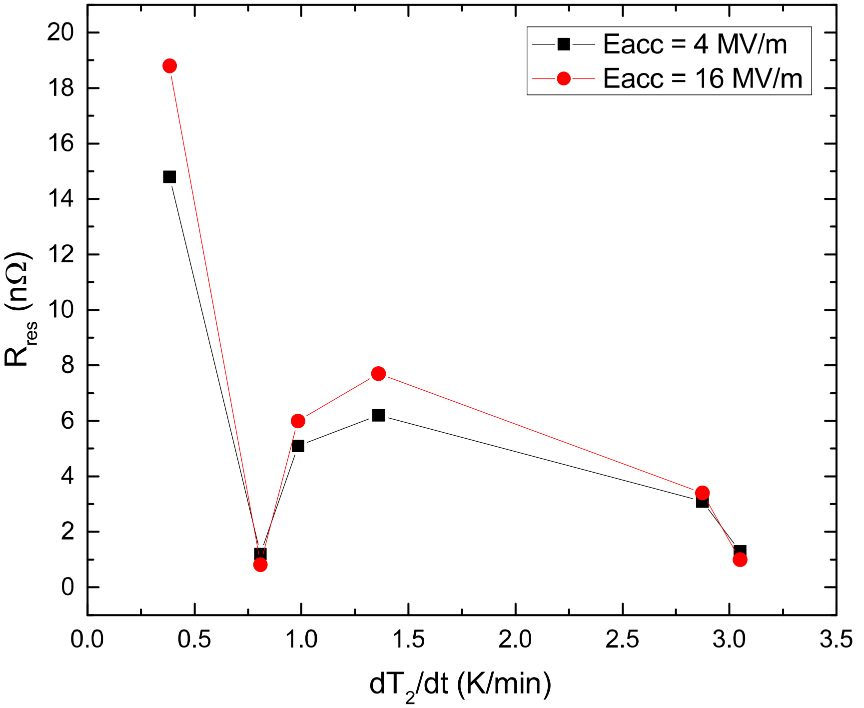


- High thermal gradient provides depinning force allowing efficient magnetic field expulsion
- Ultra-high Q_0 even in 190mG

A. Romanenko, A. Grassellino et al. J. Appl. Phys. 115, 184903 (2014)
A. Romanenko, A. Grassellino et al. Appl. Phys. Lett. 105, 234103 (2014)

It's a matter of thermogradient along the cell (at the phase front) – and geometry of the problem has an effect, too…



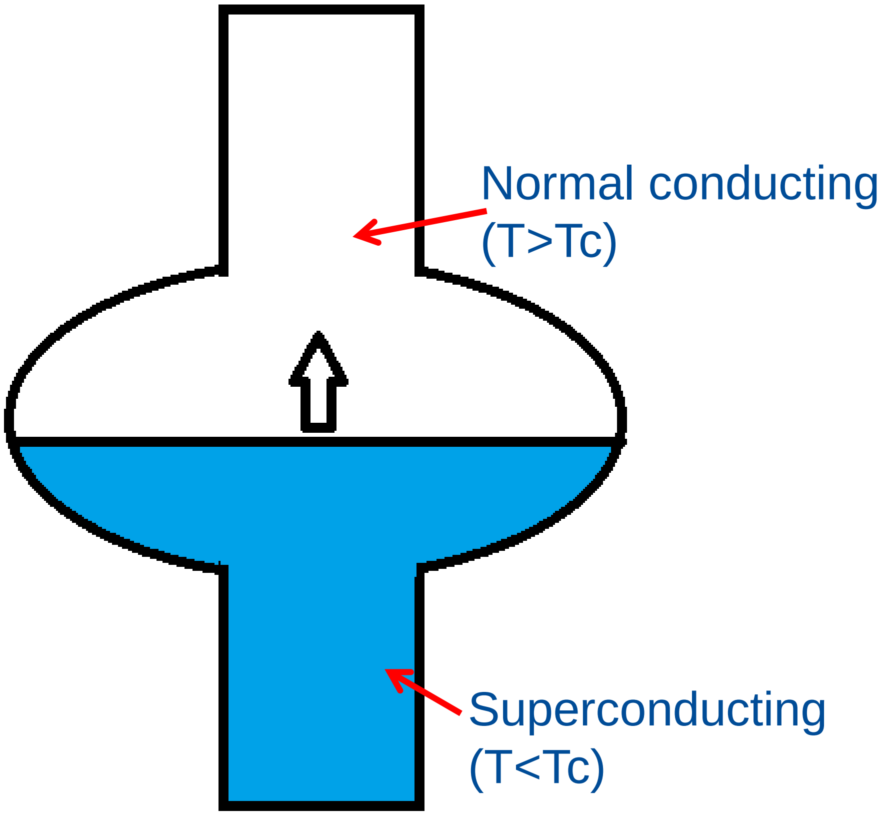


A. Romanenko, A. Grassellino, A.Crawford, D. A. Sergatskov, Appl. Phys. Lett. 105, 234103 (2014)

M. Martinello et al, **arXiv:1502.07291**

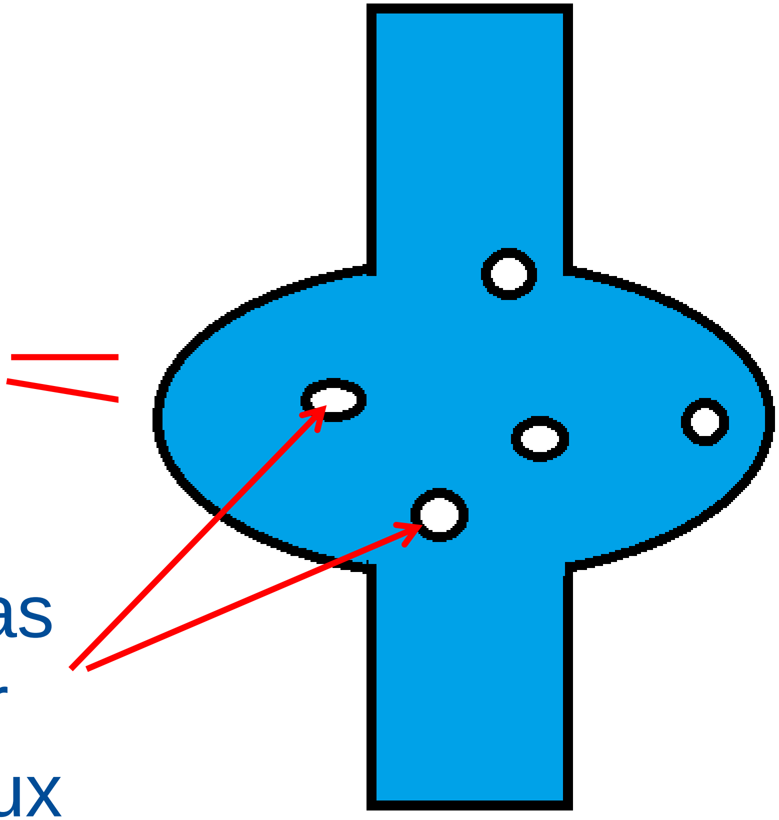
Details of superconductivity nucleation matter

Fast cooldown – well-defined superconducting/normal boundary is moving from bottom to the top => <u>no energy barrier</u> for flux to be expelled



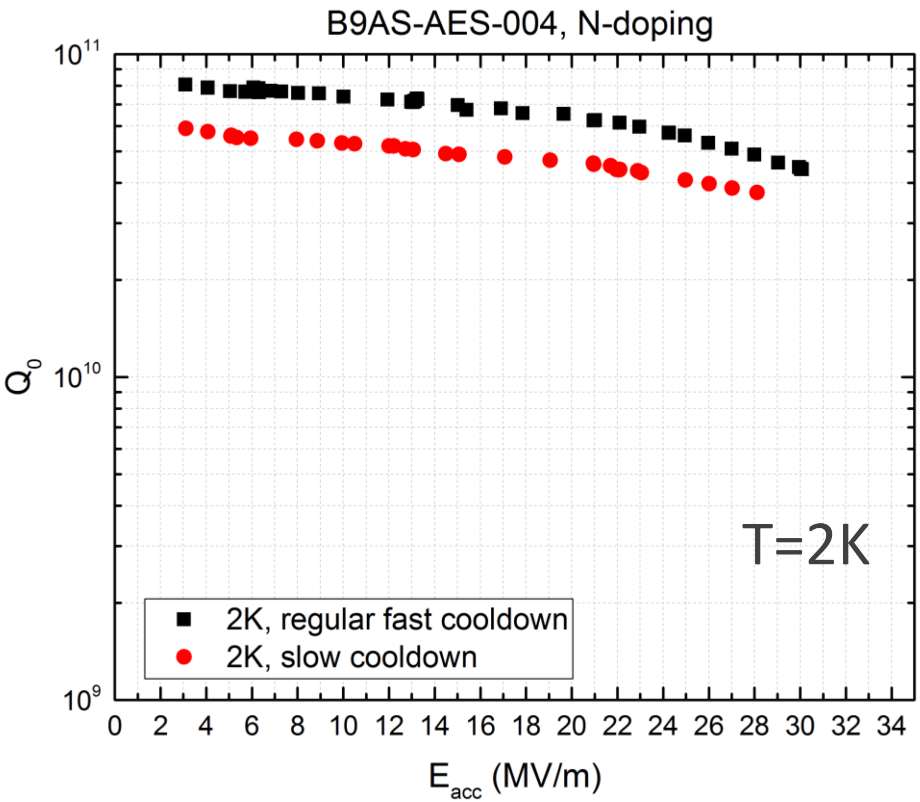
Details of superconductivity nucleation matter

Slow uniform cooldown – superconductivity is nucleated at multiple spots which reach T<Tc



Flux surrounded by superconducting areas has an energy barrier for escape=> more flux trapping is possible

Results on 650MHz – cooling studies – fast vs slow cooling

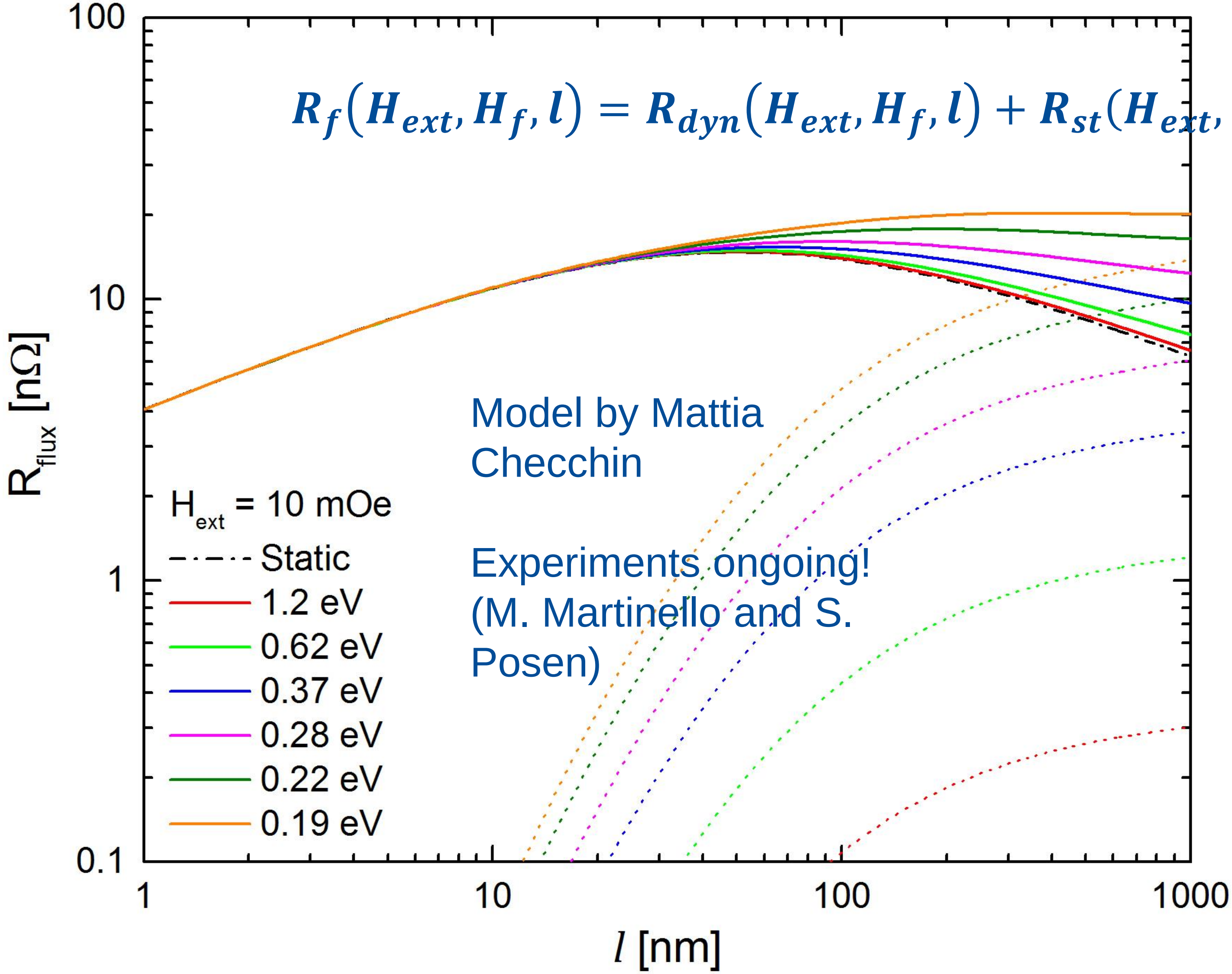


- Cooling details have been shown to play an important role in Q retention
- Slow cooling through Tc shown to severely deteriorate Q for 1.3 GHz cavities
- At 650 MHz we find a much weaker effect, likely due to smaller impact of trapped flux at lower frequency
- Very promising for Q retention in cryomodule

A. Romanenko, A. Grassellino, O. Melnychuk, D. A. Sergatskov, J. Appl. Phys. ***115****, 184903 (2014)*
A. Romanenko, A. Grassellino, A.Crawford, D. A. Sergatskov, Appl. Phys. Lett. 105, 234103 (2014)

R&D on trapped flux dependence as a function of mfp

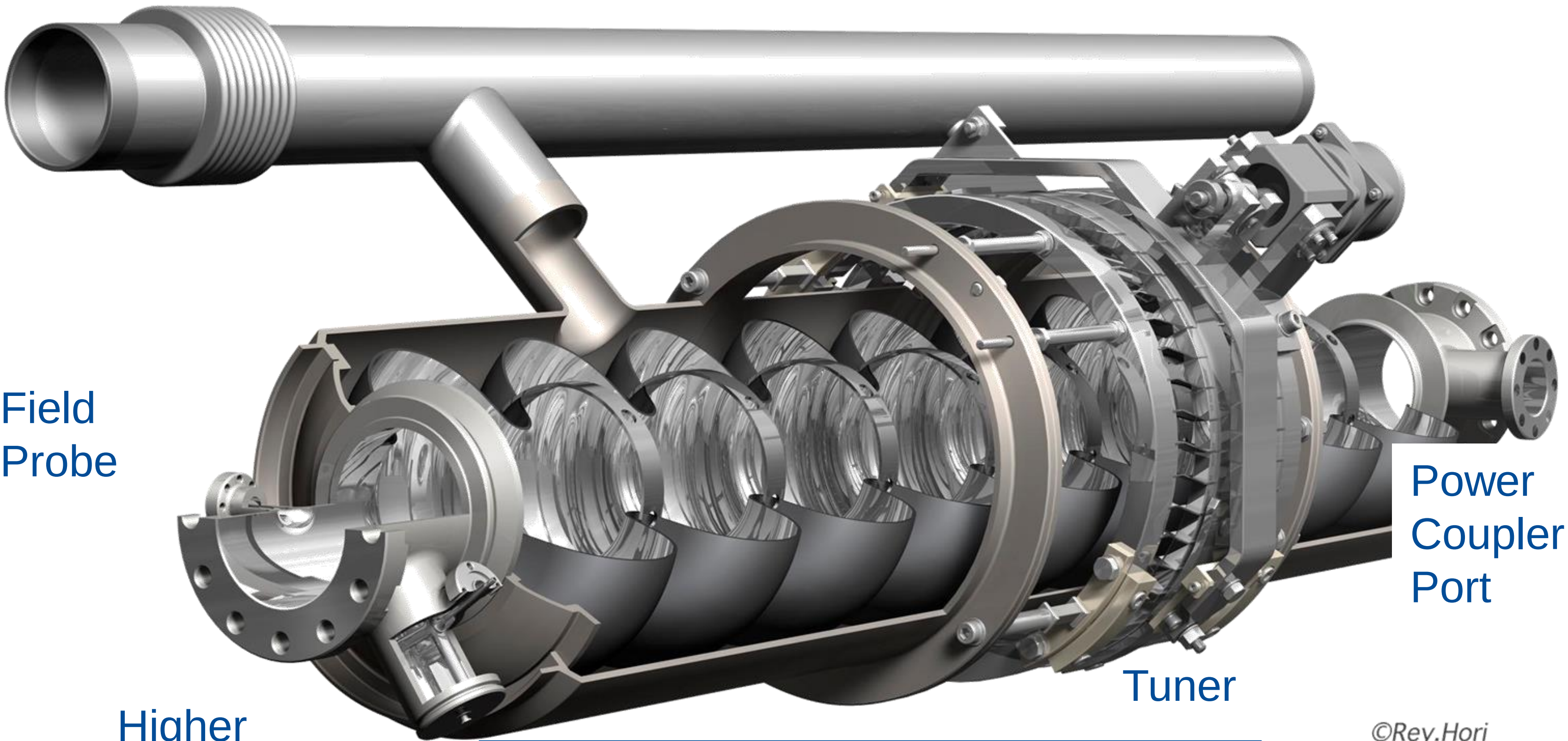
$$R_f(H_{ext}, H_f, l) = R_{dyn}(H_{ext}, H_f, l) + R_{st}(H_{ext}, l)$$



Model by Mattia Checchin

Experiments ongoing!
(M. Martinello and S. Posen)

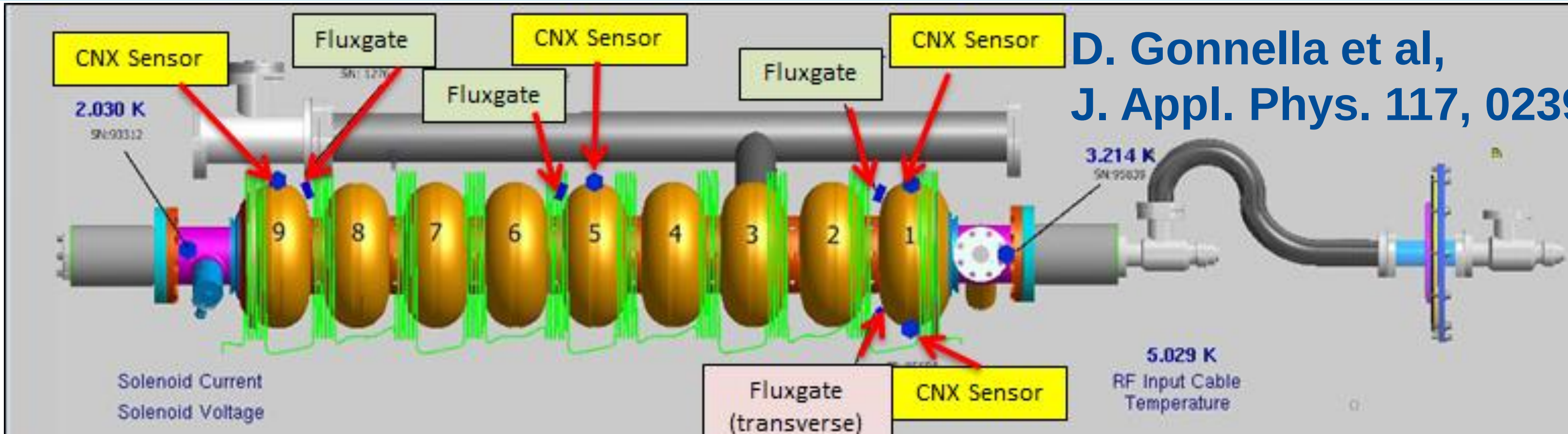
SRF cavity in its liquid helium filled tank: operating at 2 degrees above absolute zero (-456 deg F)

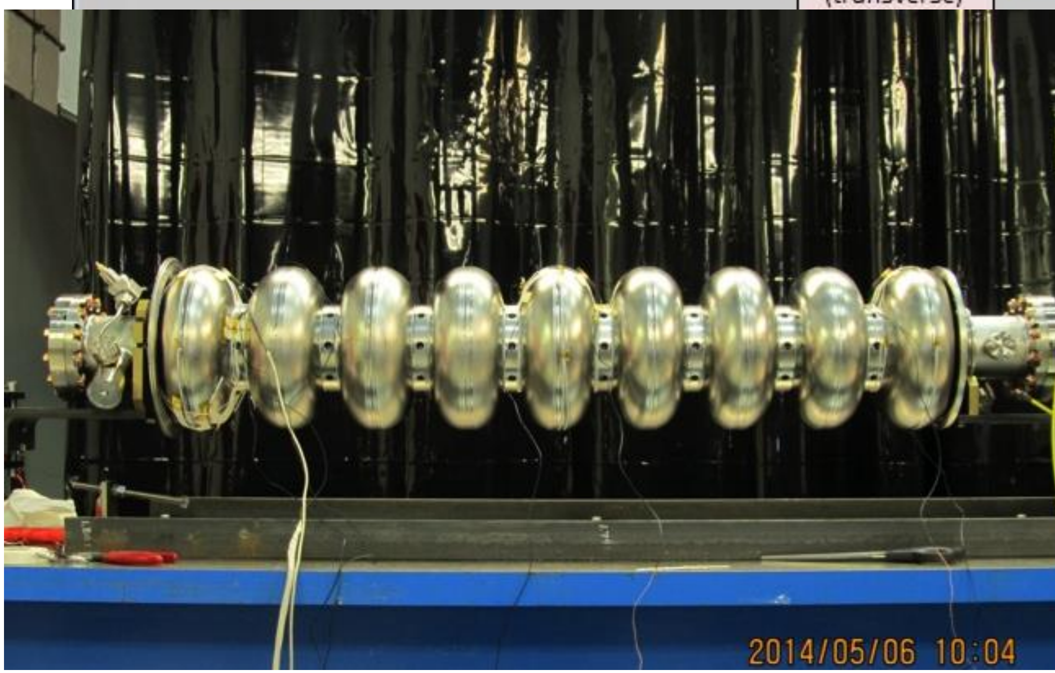


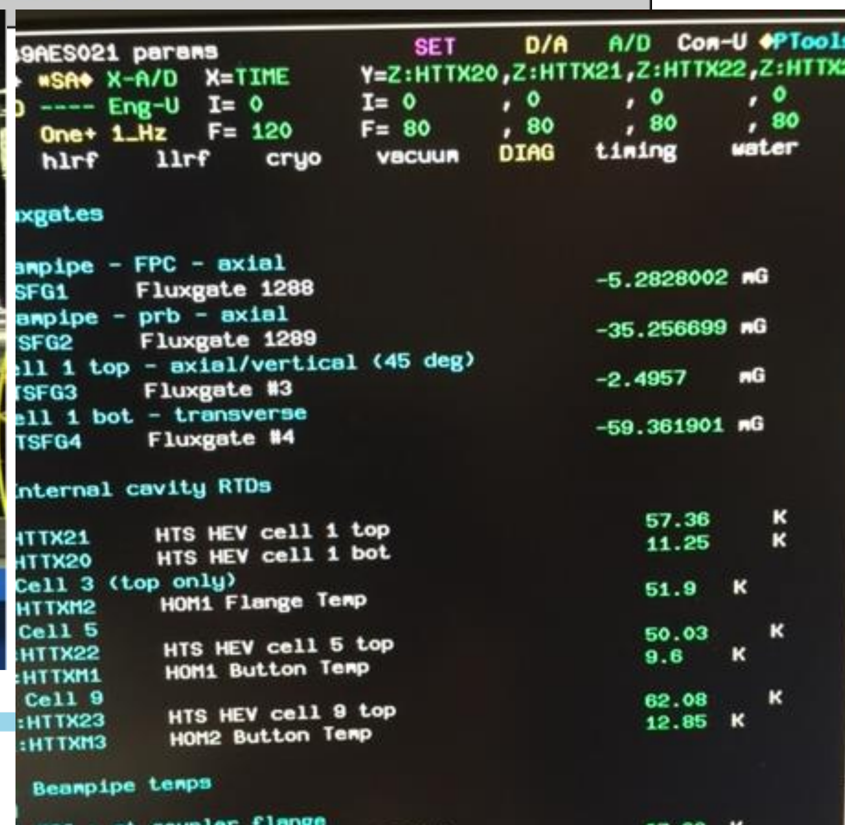
- Ports:
  - Beam in /out
  - Bring in power
  - Monitor field
  - Extract un-wanted frequencies

LCLS-2 cavities dressed with instrumentation inside vessel

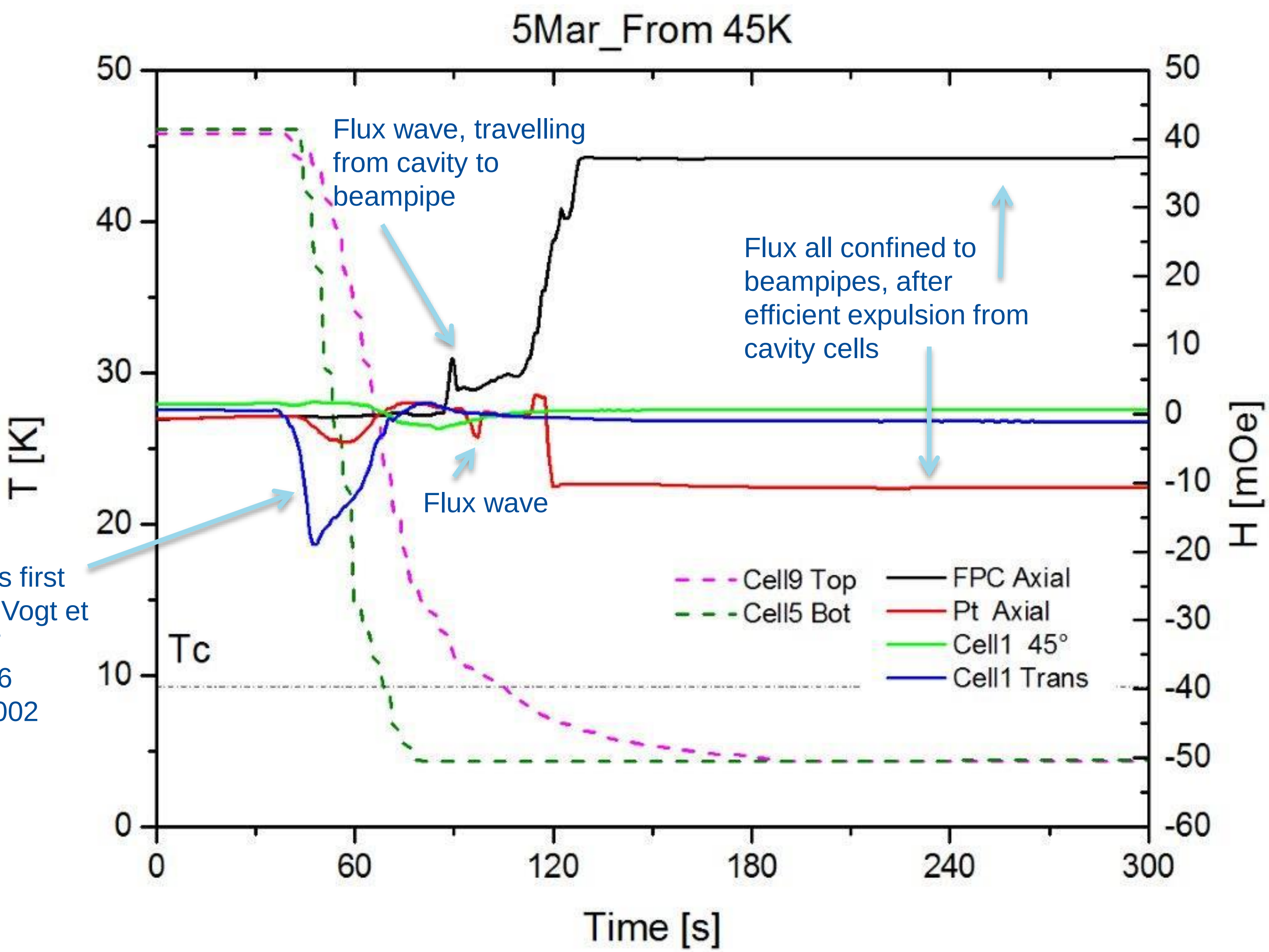
D. Gonnella et al,
J. Appl. Phys. 117, 023908 (2015







Sweeping the flux into the beampipes via fast cooling



Thermoelectric induced field, as first discussed in J. Vogt et al Phys.Rev.ST Accel.Beams 16 (2013) 10, 102002

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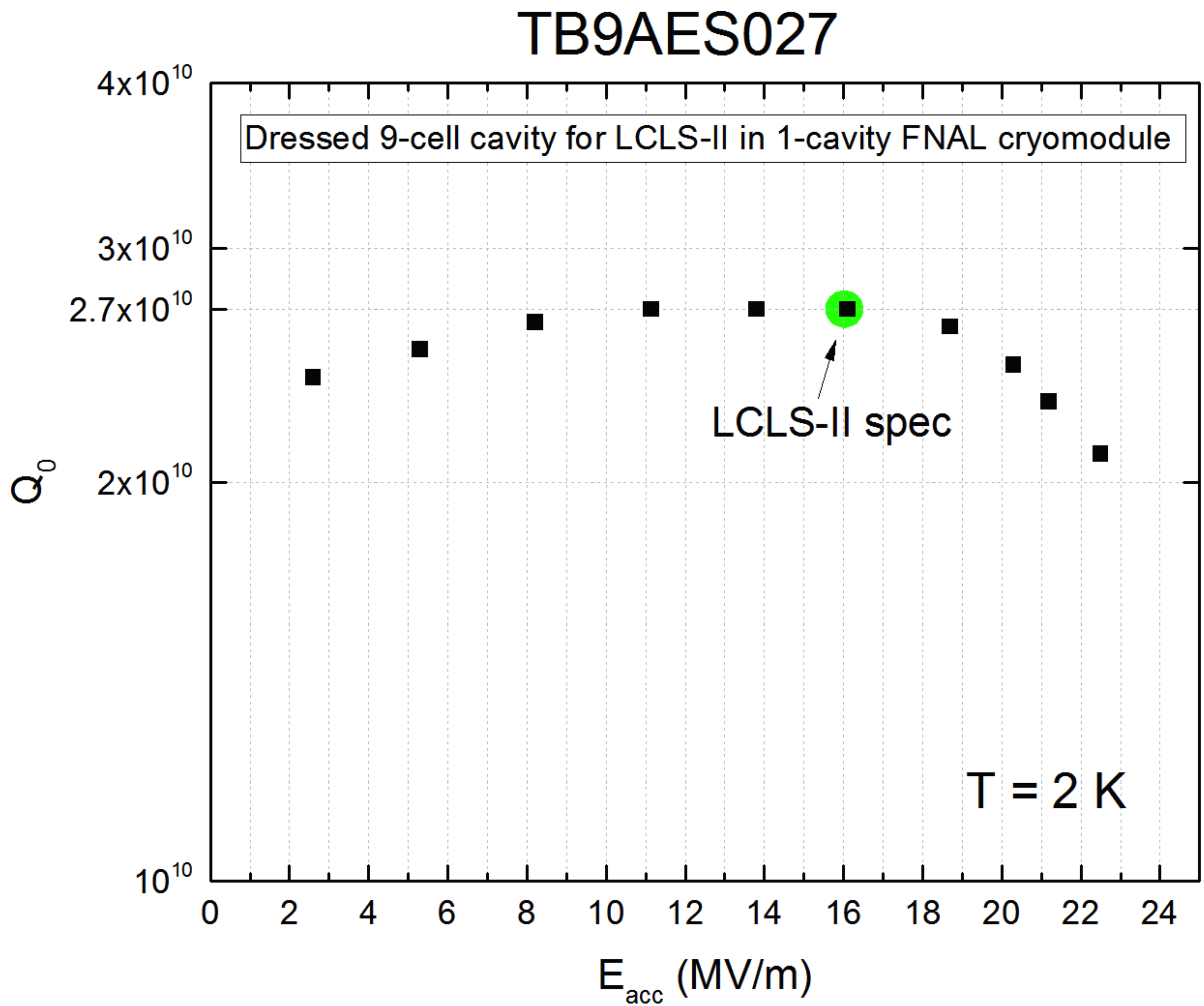
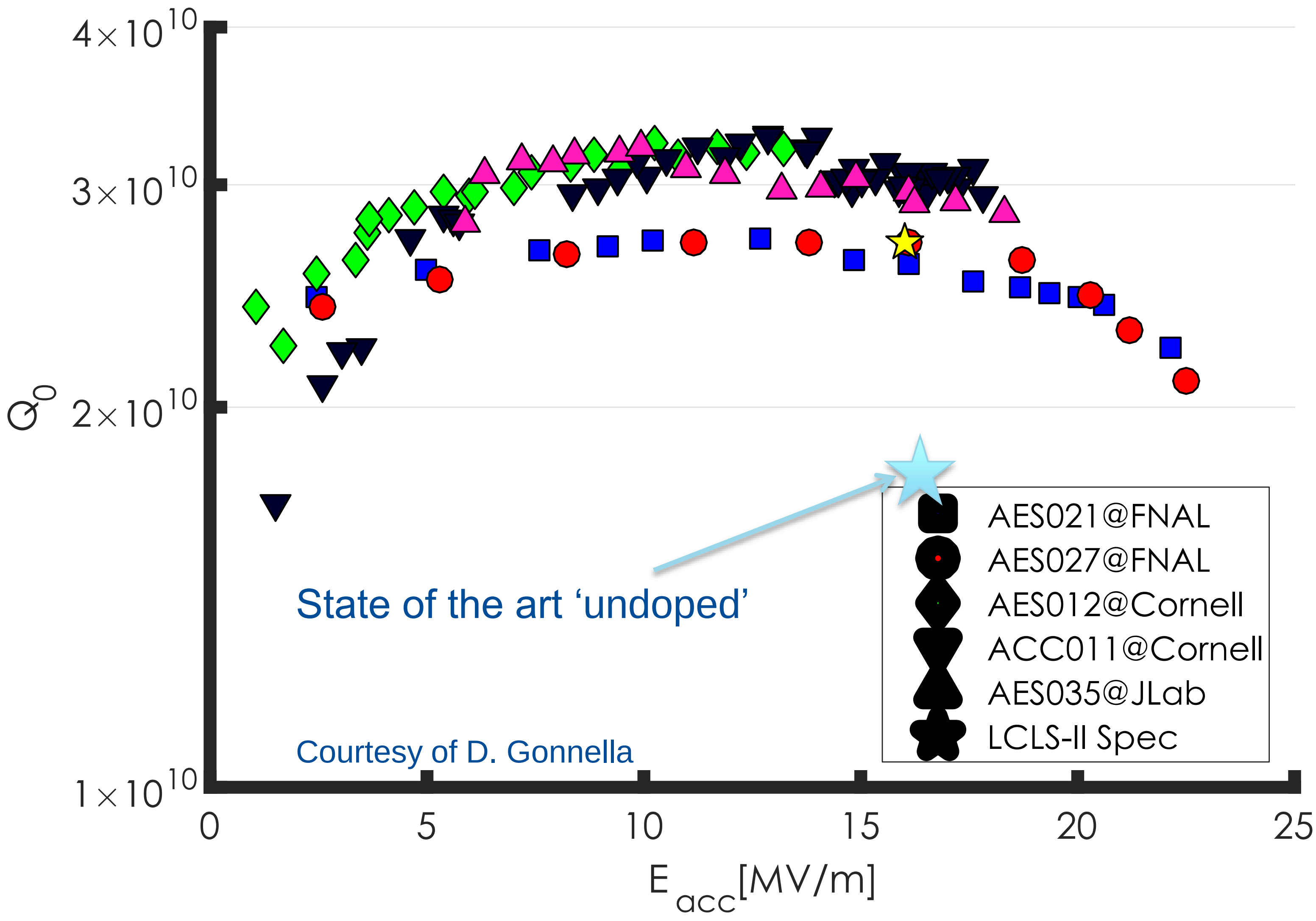


TB9AES027
Dressed 9-cell cavity for LCLS-II in 1-cavity FNAL cryomodule
4x10^10
3x10^10
2.7x10^10
2x10^10
10^10
Q_0
LCLS-II spec
T = 2 K
0
2
4
6
8
10
12
14
16
18
20
22
24
E_acc (MV/m)

Horizontal dressed cavity tests at FNAL, Cornell, Jlab Meeting final LCLS-2 specs in cryomodule environment!



Fermilab

Conclusions

- Tremendous progress in the past two years in understanding of contributors to RF surface resistance
- Record Q achieved from bare cavity tests all the way down to cryomodule environment, by implementing N doping and understanding of flux expulsion via efficient cooling through Tc
- High Q at high gradient via doping is the frontier to be explored, exciting R&D ongoing
- Flux trapping/detrapping and losses due to trapped flux for different surface processing is also a very interesting R&D path currently being pursued
- Lower frequency N doping (~700 MHz) already doubled Q of standard treatment, and promises Q ~ 1e11 at 2K mid field – R&D ongoing