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Update on N doping at Fermilab

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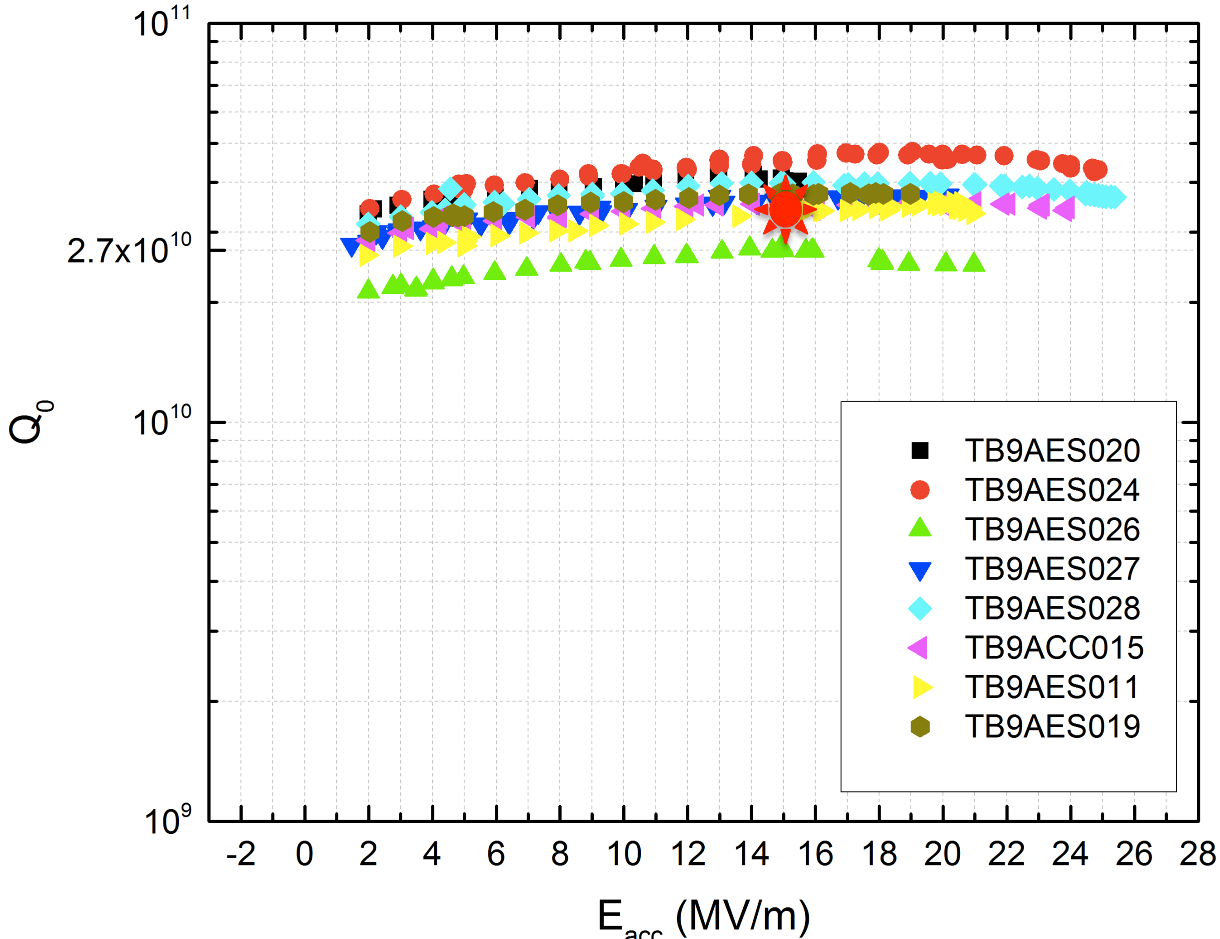
For the FNAL high Q group

Summary of ongoing effort

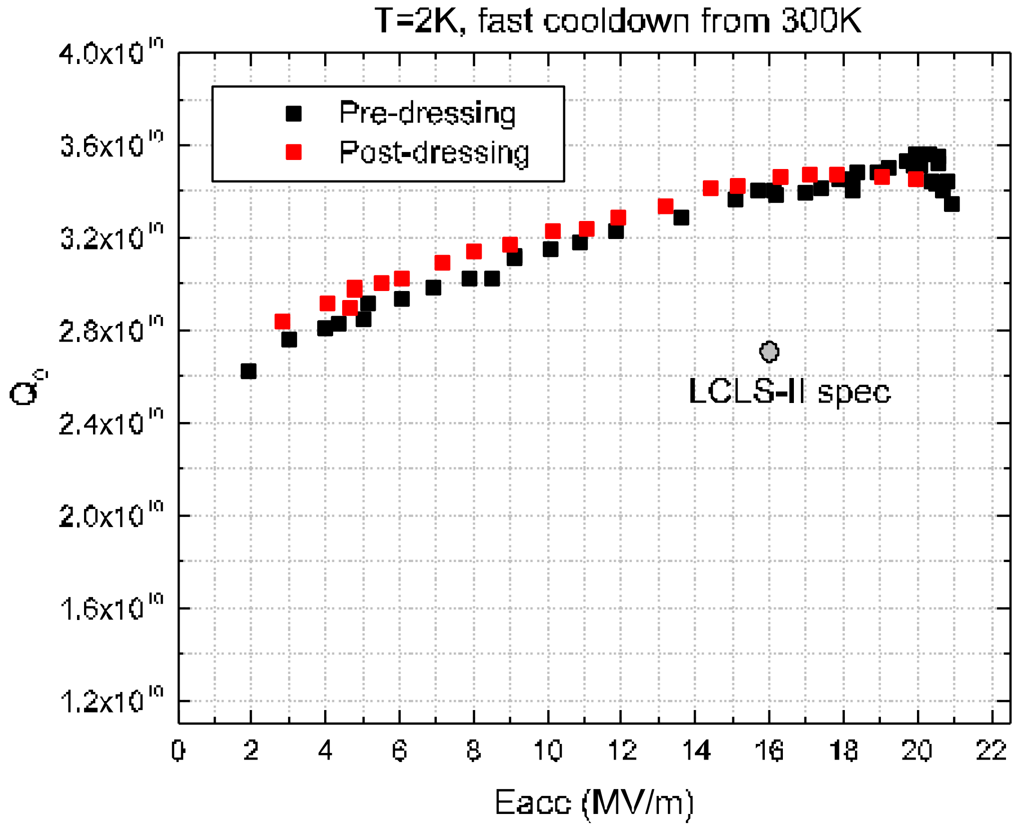
- Building a LCLS-II prototype cryomodule with N doped cavities, to reach target Q(2K, 16 MV/m, 1.3 GHz) = 2.7e10
  - Developed several doping formulas to obtain the ideal nitrogen concentration for high Q and good gradients in a large enough surface layer (10-15 microns)
  - At FNAL, more than 50 single cells processed and tested with high Q, and one full cryomodule milestone of eight nine cell cavities qualified for LCLS-II with an average Q~3.75e10 and Eacc~22 MV/m, some dressed and ready for string assembly
- Pursue fundamental understanding of the N doping mechanism via cavity and sample studies (Tmap, SIMS, muSR, SEM..)
- Extend the N doping to other frequencies: 650 MHz for PIP-2, 3.9 GHz for LCLS-II, and study 4.2K for the different frequencies

One cryomodule milestone – avg Q (2K, 16 MV/m)~3.75e10, avg quench field ~22 MV/m



Best N doping recipe so far (high Q and highest gradients achieved on nine cells) is the one known as "Fermilab 2/6": 800C 3 hrs in HV, then 2 min @ 800C with ~ 25 mTorr N2, then 6 min @ 800C in HV + 5 microns EP

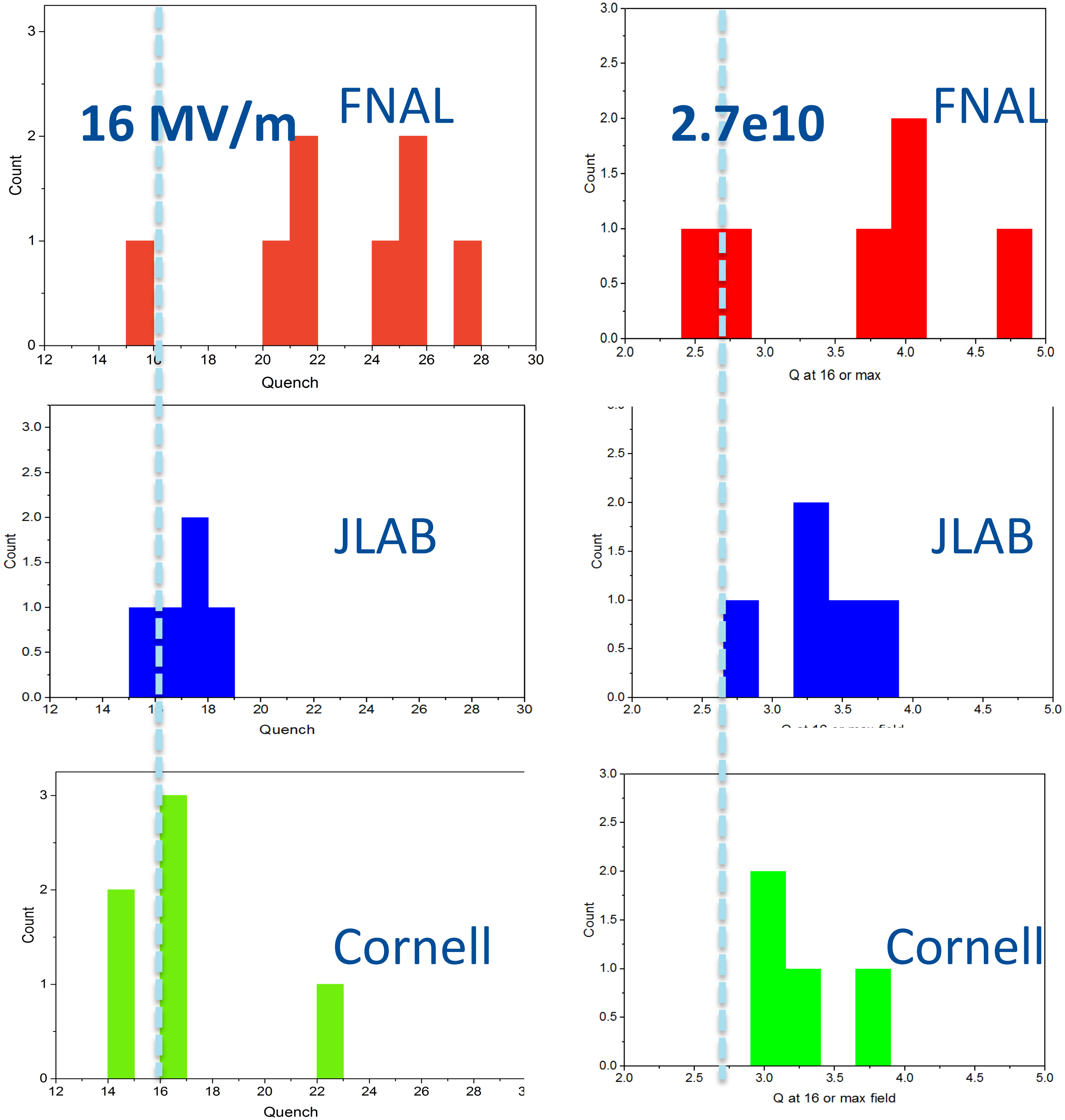
One cryomodule milestone – avg Q (2K, 16 MV/m)~3.75e10, avg quench field ~22 MV/m – status of cavities



- Two cavities dressed in ILC vessel (for R&D/cooling studies)
- Two cavities dressed in LCLS-II prototype CM vessel and fully instrumented for Q preservation studies in HTS/cryomodule
- Performance of N doped unchanged after dressing
- All cavities will be dressed by February; string assembly begins in April

Recipe optimization towards improved gradients

- So far best performing high Q nine cell has ~ 25.5 MV/m quench
- But several proof of principle high gradient N doped single cells exist up to 35 MV/m
- N doping appears to have a very interesting effect of making quench systematically around a value based on surface N concentration (see next slide)
- Also, we observe an interesting effect of quench field reduction passing from single to nine cell: some doping formulas that produce up to 30 MV/m on single cell become quench limited at ~ 17 MV/m on nine cell
- ‘Light’ doping to be preferred to ‘heavy’ doping for quench improvement – we are currently developing nine cell doping formulas to increase gradients higher than 25 MV/m
- Early quench may be an effect of residual tiny nitrides left behind



Recipe 1 (2/6, light doping)+ 5 microns EP

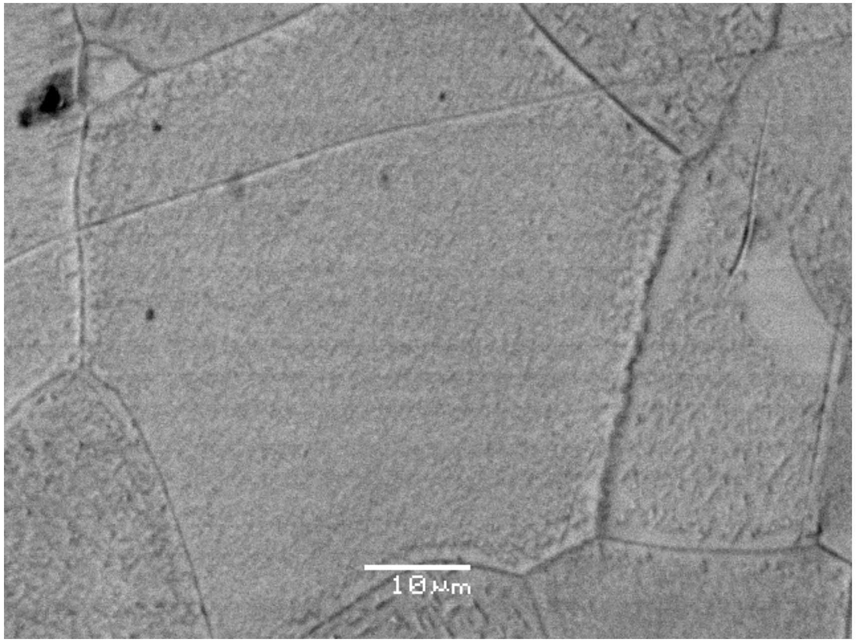
Q and quench field distribution for the two recipes

Recipe 2 (20/30, heavy doping) + 15-20 microns EP

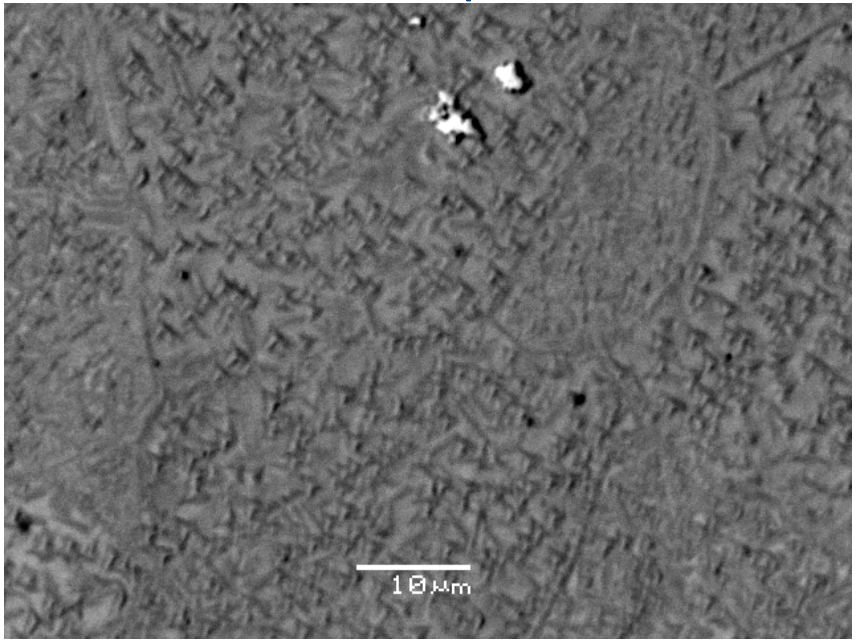
The two steps diffusion causes nitrides to grow larger

- In 2013 FNAL proposed doping via two steps diffusion (step 1: injection, step 2: anneal) to create a flatter N concentration at the surface
- A flatter concentration is achieved, however sample studies show that the anneal step post injection causes nitrides to grow larger
- This may be the cause of quench limitation for 20/30 – residual tiny nitrides left behind

20 min N2

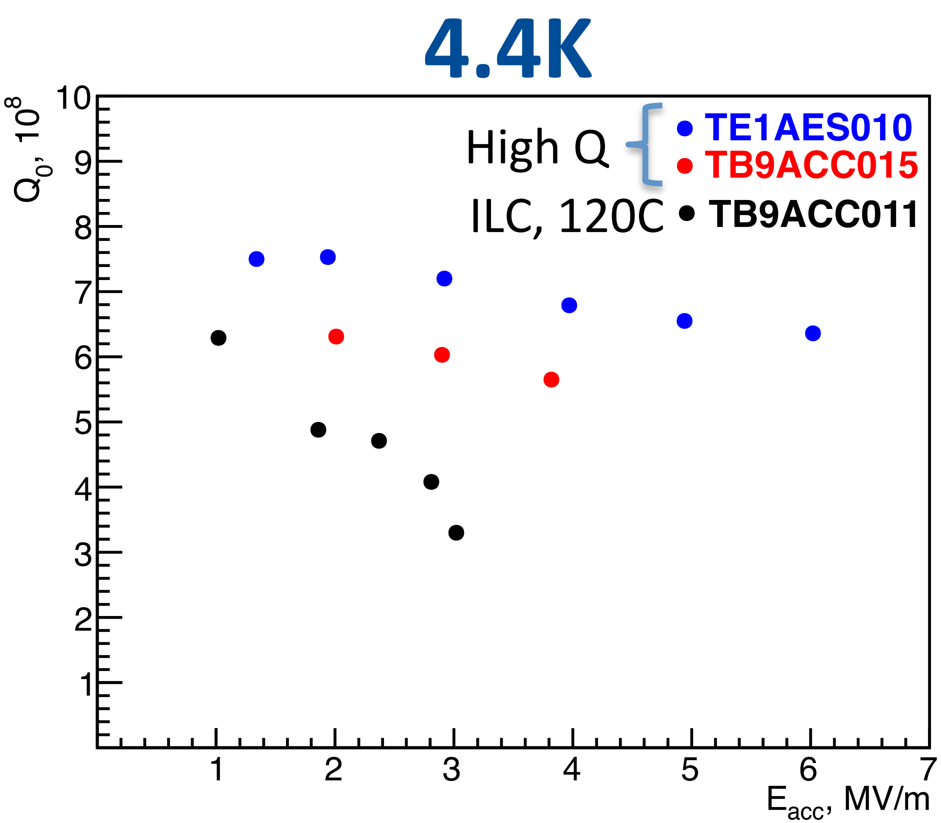


20 min N2/30 min no N2



Fermilab

Comparison of High Q and ILC cavity at 4.4K



- Compare 4.4K Q vs E curves for:
  - two Nitrogen doped 1.3GHz cavities (9-cell and 1-cell)
  - ILC recipe treated cavity (9-cell)
- Nitrogen doped cavities hold Q better with field increase at 4.4K
  - effect of thermal feedback is weakened in N doped cavities because of the lower BCS resistance at higher field
  - Promising for 4.2K operation of lower frequencies?

Conclusions

- In little over two years, N doping has made important milestones:
  - Confirmed/replicated at different laboratories
  - From single cell R&D to nine cell production for LCLS-II
  - Systematically making cavities two-three times more efficient at 1.3 GHz, 2K, with practical potential to save a full cryoplant (plus yearly operating costs) for LCLS-II
- At FNAL we are now working on realizing this large efficiency gain possible also for other frequencies (will enable PIP-2 to run at higher duty factor)
- Very interesting science behind the doping effect to be pursued

Acknowledgements

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- Thanks to the FNAL processing and testing group and TD cryo group
- Thanks to Rich Stanek, Slava Yakovlev and Hasan Padamsee for endorsing making the high Q work a high priority at FNAL

Relevant References

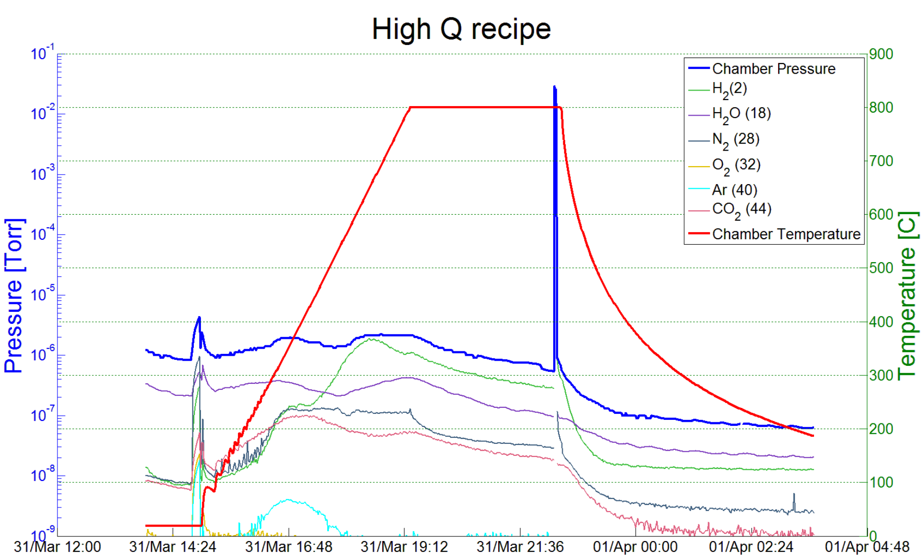
- A. Grassellino et al, Nitrogen and argon doping of niobium for superconducting radio frequency cavities: a pathway to highly efficient accelerating structures. **Superconductor Science and Technology, 26(102001), June 2013.**
- A. Crawford et al, The joint high Q0 program for LCLS---II. In **Proceedings of IPAC 14,** Dresden, Germany, June 2014, pages 2627–2630, June 2014. JACoW.
- A. Grassellino, N doping – physics and technique; LCLS---II technical note, **LCLSII---4.5---EN---0218---R0**
- A. Grassellino, High Q cavities at higher gradients, AWLC14, Fermilab
- A. Romanenko, Breakthrough Technology for Very High Quality Factors in SRF Cavities, 27th Linear Accelerator Conference (LINAC'2014)

Backup Slides

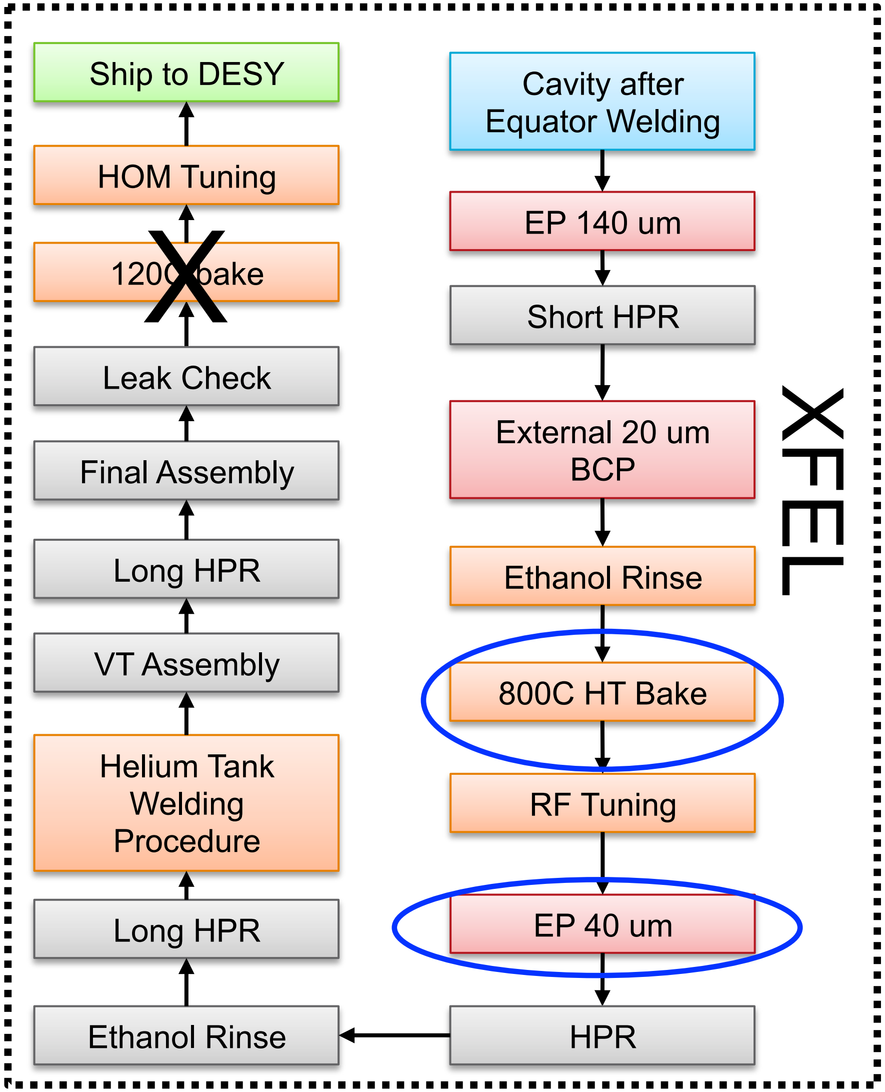
Doping treatment: small variation from standard XFEL/ILC processing recipe

Example from FNAL doping process:

- 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



Anna Grassellino, LCLS-II DOE Status Review, June 30th, 2014



Origin of the Q improvement – in numbers

Surface treatment	R_{BCS} (16 MV/m,2K) [nΩ]	R_0 (16 MV/m) (total, measured in vertical test, under low remnant fields) [nΩ]
EP + 120C (fine grain)	8-10	~4-8
EP+120C + HF rinse	8-10	<3
EP + 120C (large grain)	8-10	<3
Nitrogen bake	3.5-4.5	<3

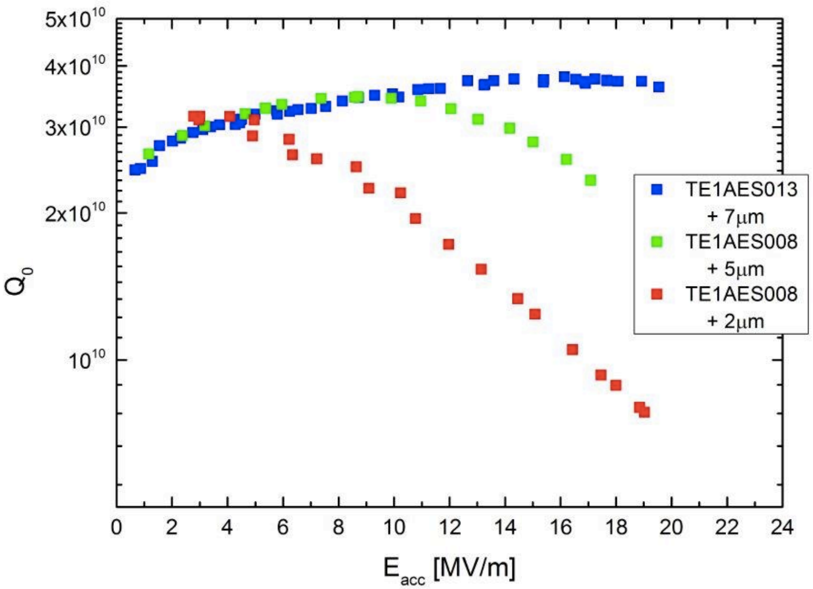
Q=G/Rs → for Q = 2.7e10 (2K) <u>max total Rs=10 nΩ</u>

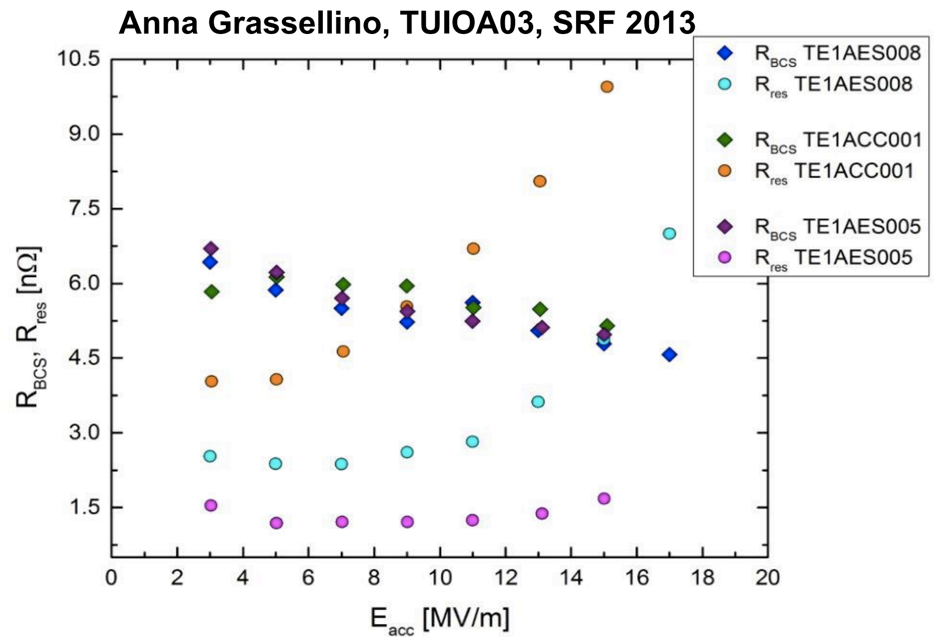
→ With any standard processing margin on residual close to ZERO
→ <u>Gas bake ONLY processing giving margin on residual to reach 2.7e10</u>

→ @ 2K : Margin on residual (with gas bake) → 5.5-6.5 nΩ

<u>Goal of the high Q work:</u>
<u>guarantee BCS ~ 4 nΩ (successful/reproducible doping) +residual < 6 nΩ in CM (trapped flux)</u>

The optimal EP removal needed post bake

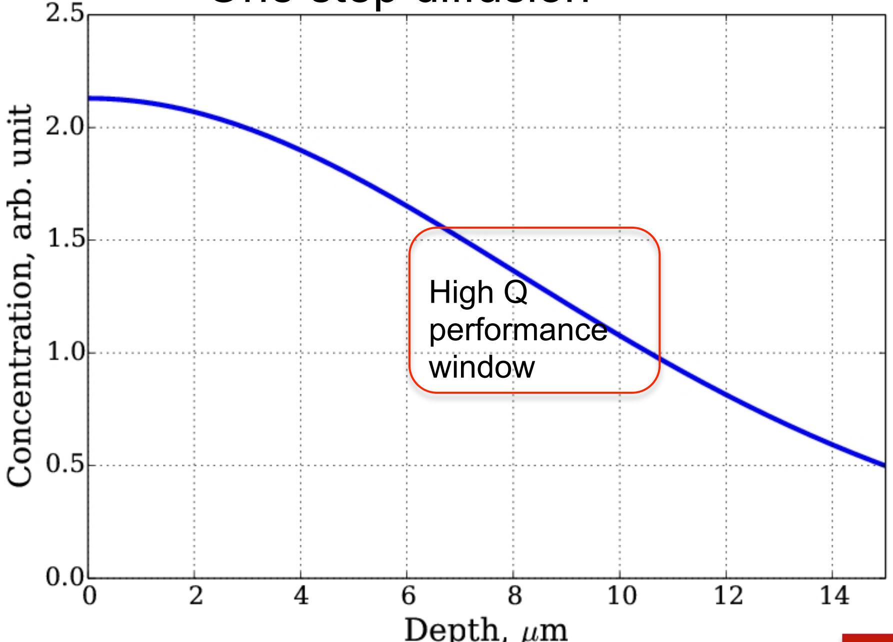




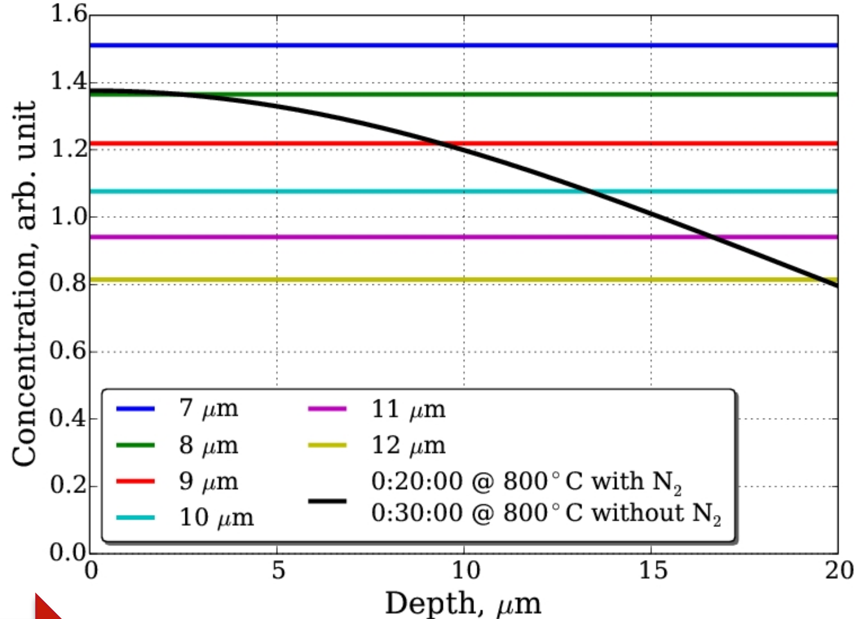
- The optimal depth of removal post gas bake arises from a field dependence of the residual component, while BCS is always low over a large range of nitrogen concentration
- → There is a window of optimal performance, <u>for both Q and quench fields</u>, that should be optimized (widened) and will give us the final ideal recipe for LCLS-II
- Collaboration focused on exploring this with single cell cavities, then move to nine cells

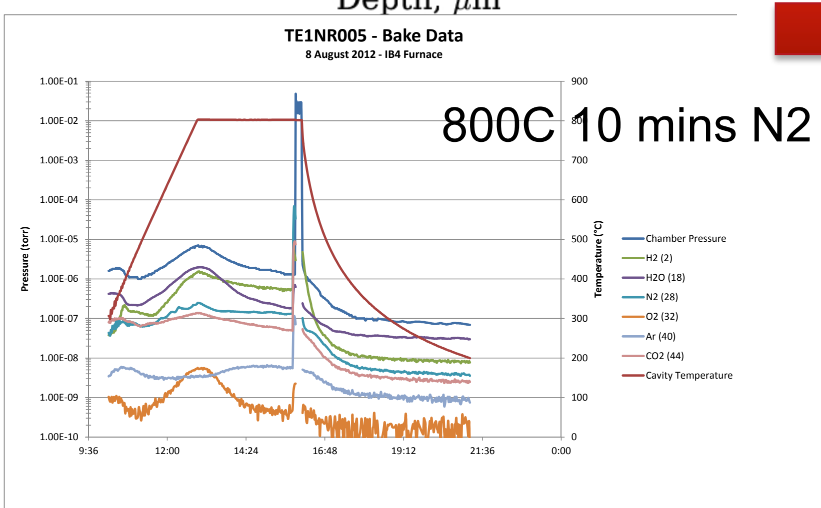
Extending the ideal nitrogen concentration over a larger depth – modeling the ideal N diffusion profile

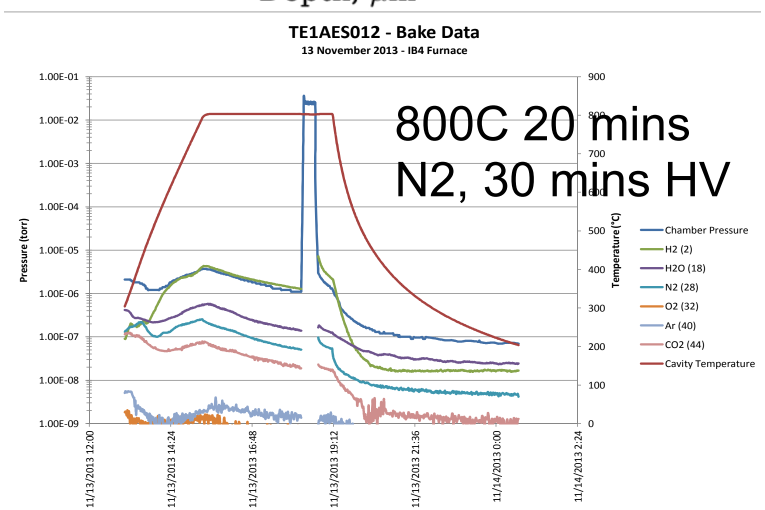
One step diffusion



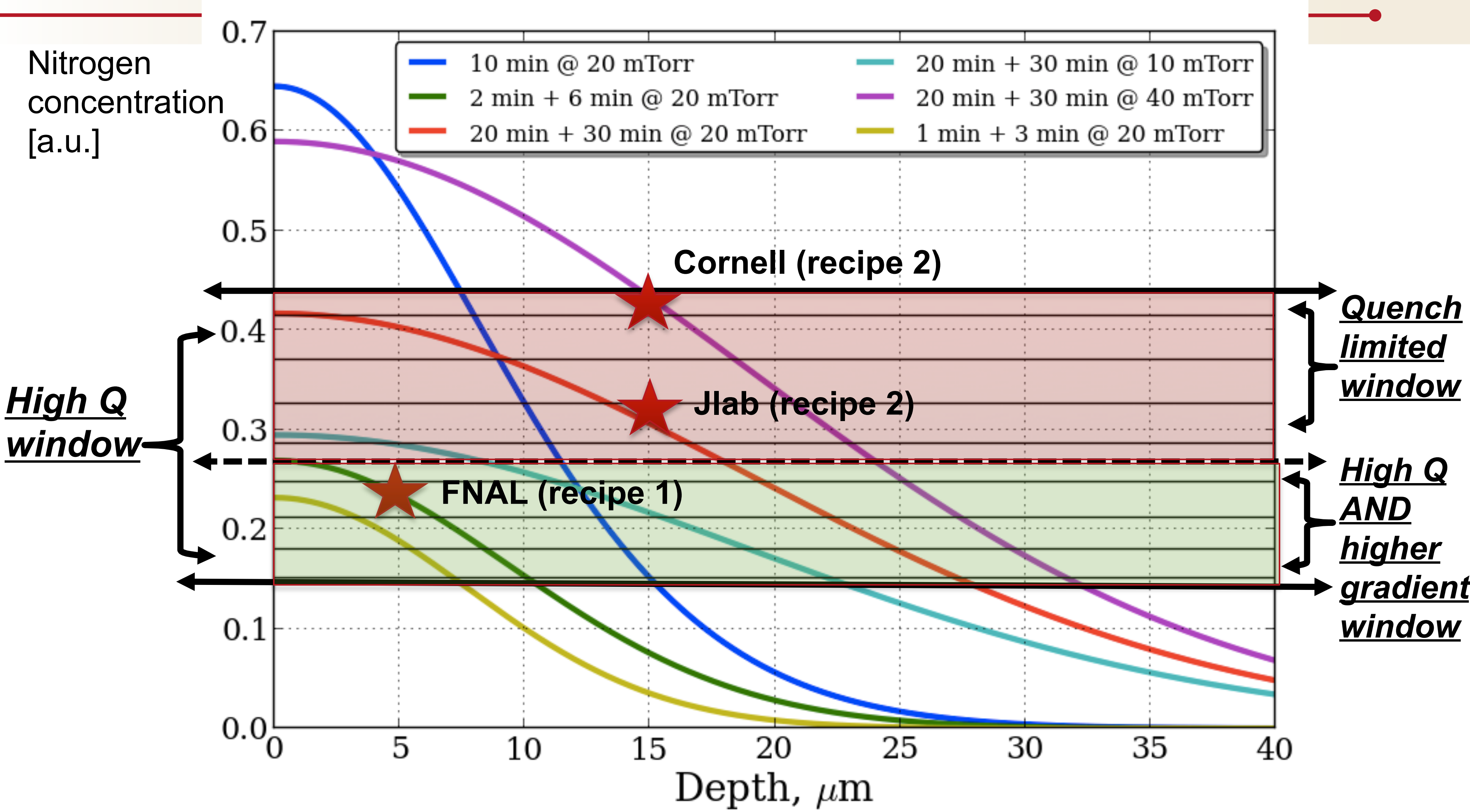
Two steps diffusion





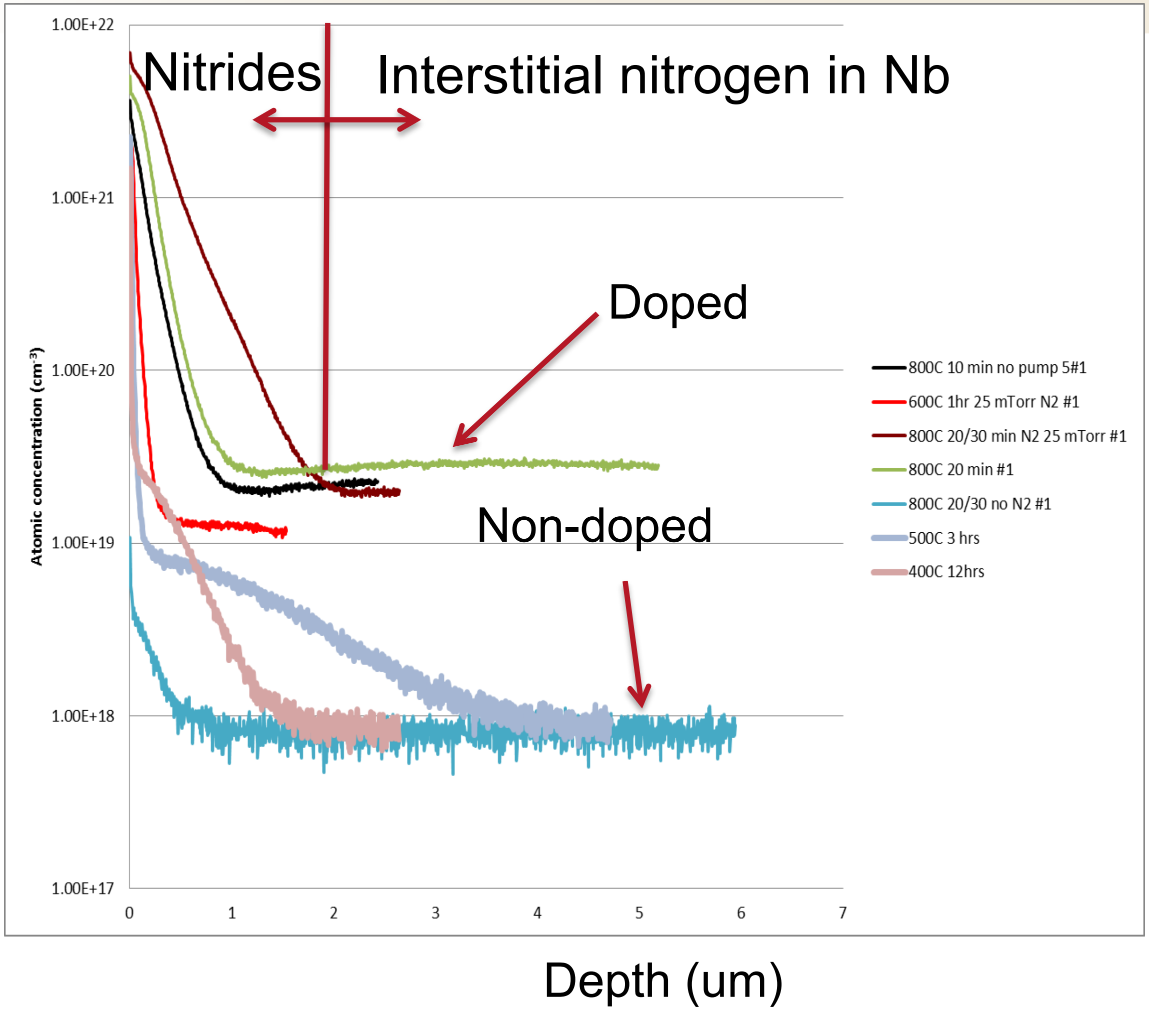


Post bake EP ideal target: High Q with higher gradients window studies at FNAL



- Final recipe needs to be in the green window to obtain high Q with the higher quench fields
- Fermilab recipe already good enough for LCLS specs
- With more work we may do even better

What does N treatment do? N depth profiles by SIMS



See A. Romanenko, talk at LINAC 2014, Geneva

FNAL PROTOTYPE CRYOMODULE-status

	First pass	Second pass	Q (2K, 16MV/m)	Quench [MV/m]	Status
TB9AES021	OK		3.35E10	24	**DRESSED – needs pressure test/leak check (next week)**
TB9AES027	OK		3.6e10	21	**DRESSED – needs TIG welding/leak check/ pressure test (next two weeks)**
TB9AES028		OK	4e10	25.5	**Lined up for dressing**
TB9AES020		Low quench	4.1e10	15.5	**Reprocessing- tumbled- awaits doping**
TB9AES024	OK		4.75e10	25	Lined up for CM
TB9AES019	OK		3.75	20	Lined up for CM (re-HPR first?)
TB9ACC015	OK	OK	3.5e10	24	Lined up for CM (needs transition rings)
TB9AES026	OK		2.75e10	21.5	Lined up for CM