N doping: progress in development and understanding

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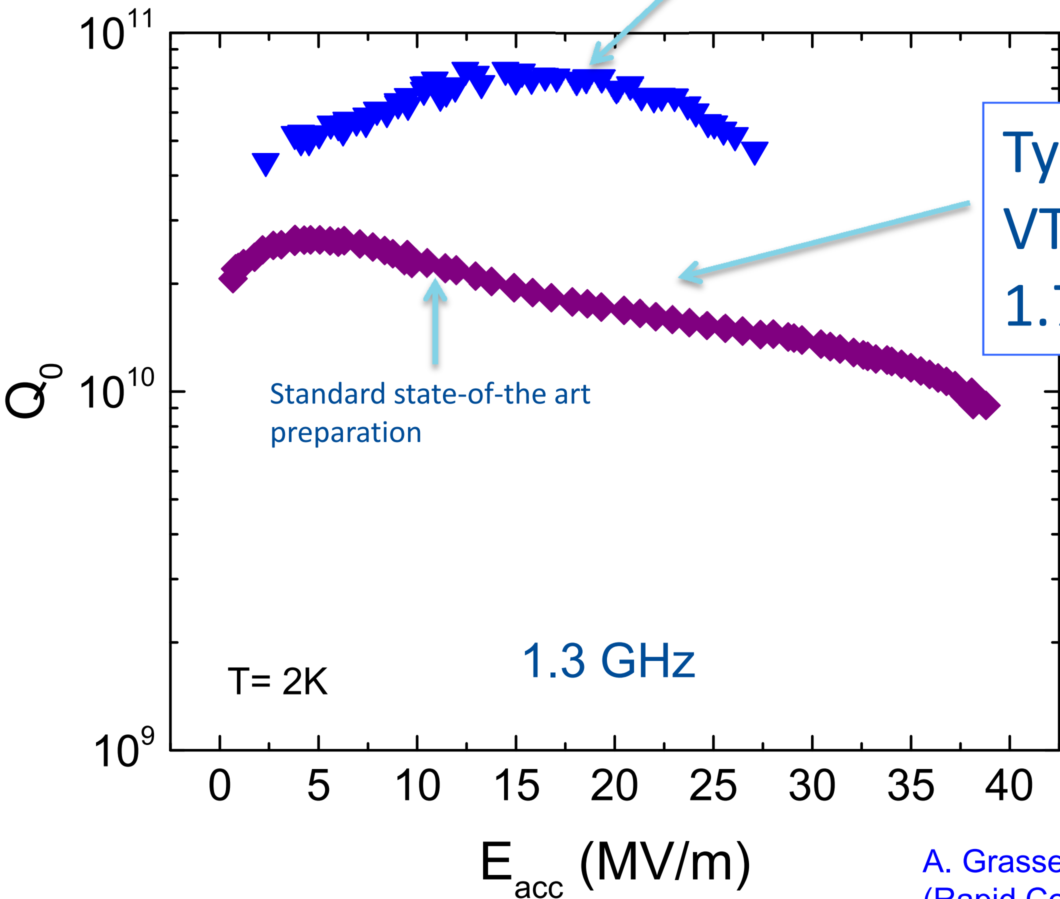
Nitrogen Doping: a breakthrough in Q

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)

A bit of history about N doping

2012

Discovery at FNAL of unprecedented Q values on single cells treated with nitrogen in high temperature furnace

2013

Developed understanding of root of Q improvement and made process controllable and reproducible

Discovered that 'light doping' improves quench fields while maintaining the benefit of high Q

2014

LCLS-2 invests in this technology, three partner labs working together FNAL-Cornell-Jlab

More than 100 N doped cavity tests with 18 nine cell qualified for the two LCLS-2 prototype cryomodules

2015

Cavity vendors currently being qualified for N doping production process for LCLS-2

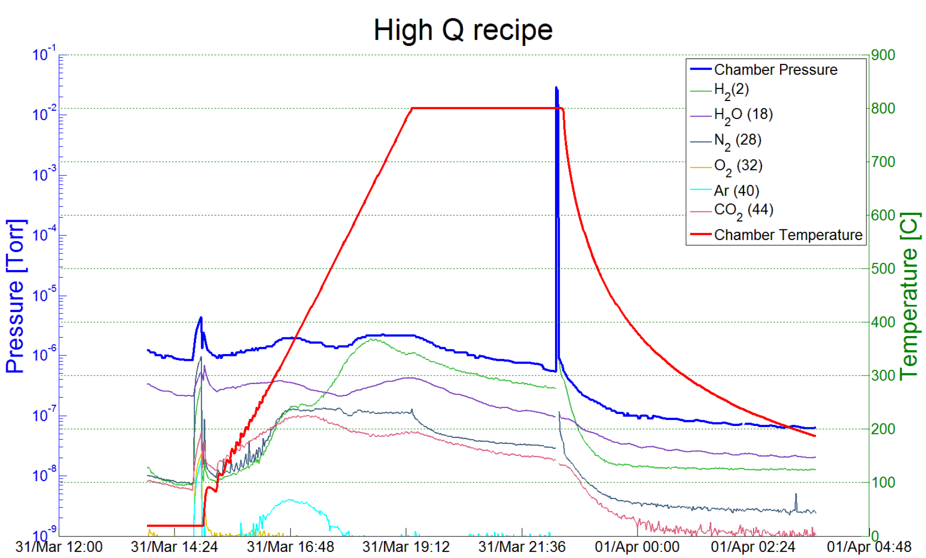
R&D continues for further understanding and improvements (quench, B sensitivity)

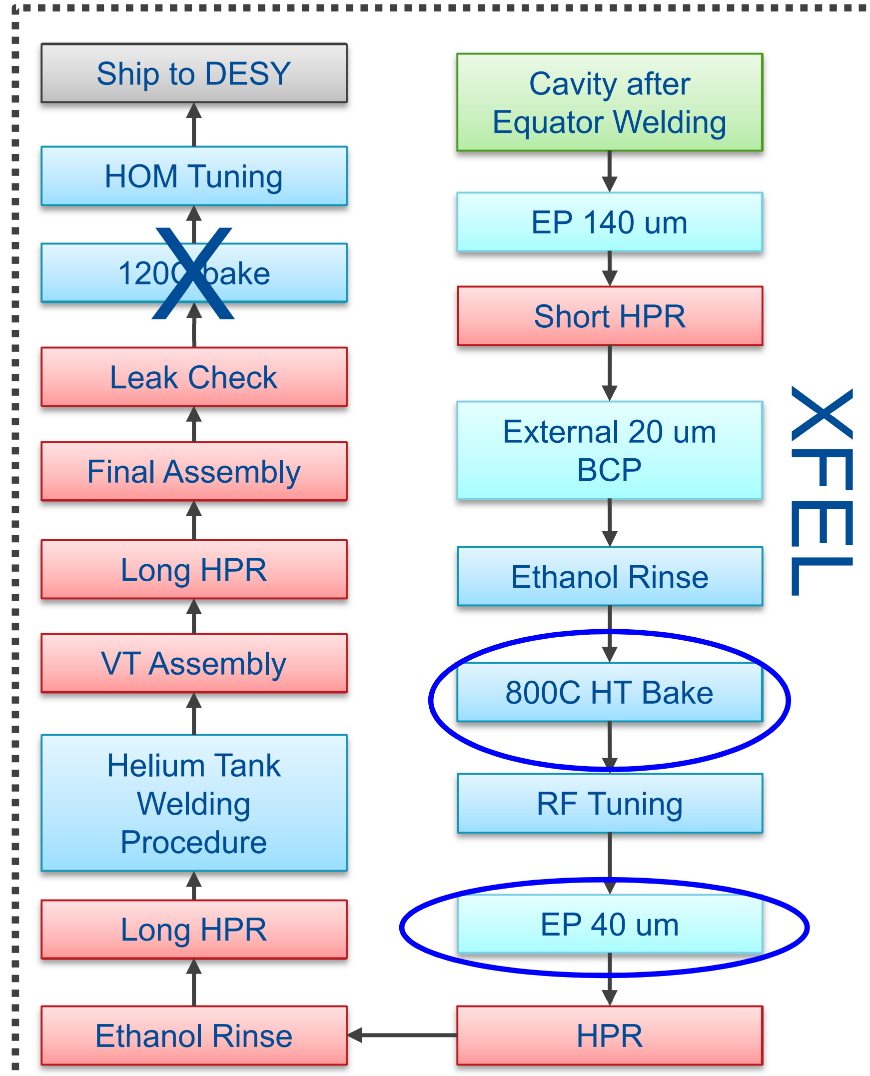
Progress in N doping development: LCLS-2 and PIP-2

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

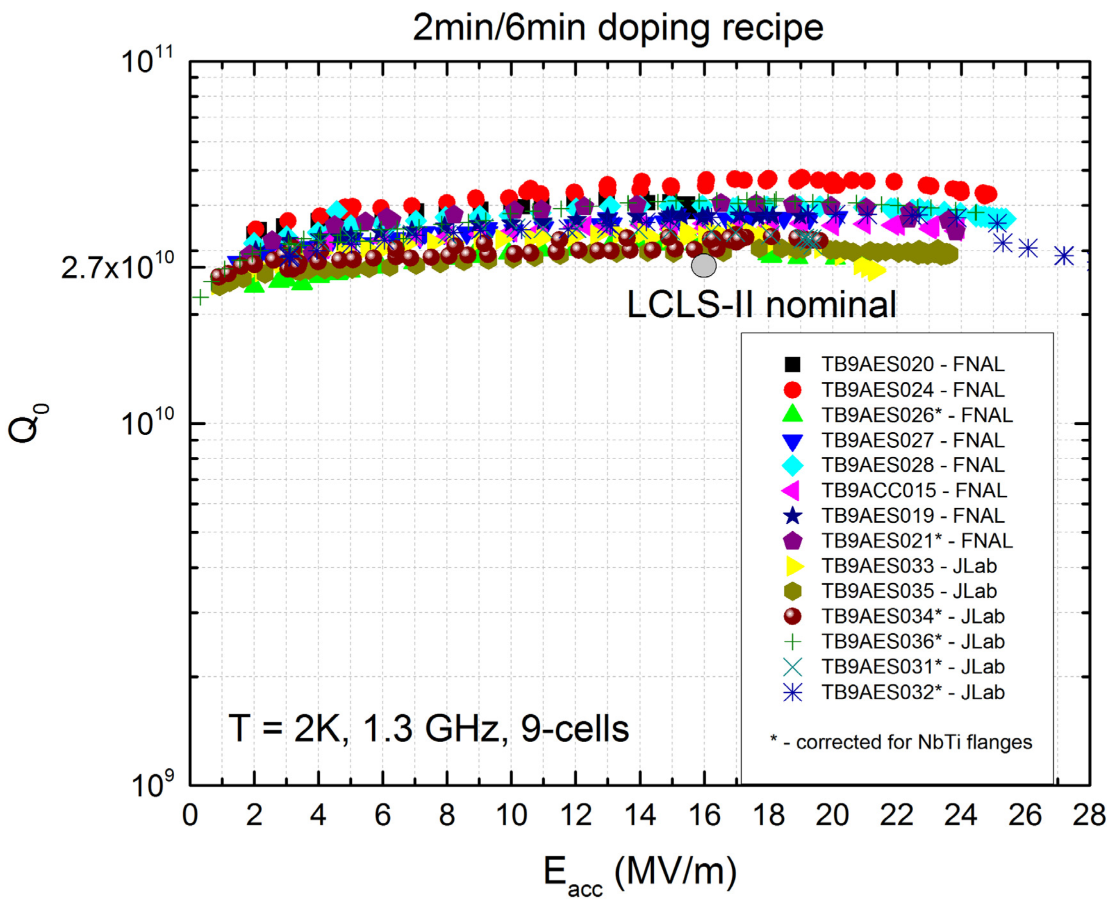
Example from a doping process developed for LCLS-2:

- 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





From single cell R&D to cryomodule ready technology:
FNAL, Jlab, Cornell, SLAC together towards record Q >2.7e10 @16MV/m, 2K



<Q>=3.5e10
$<E_{max}>$=22.2 MV/m
E_{max}median=22.8MV/m

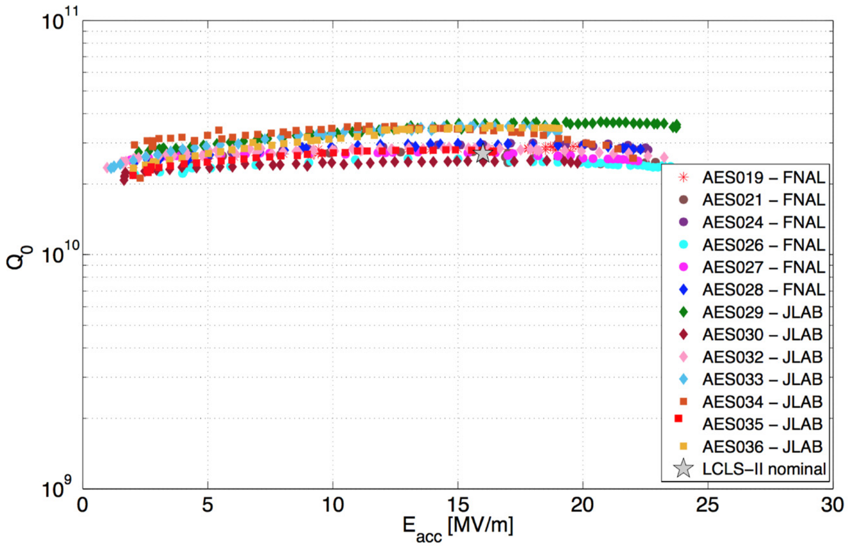
A.Grassellino et al, IPAC15

See at this conference:
MOPB033
MOPB029
MOBA07
MOBA08

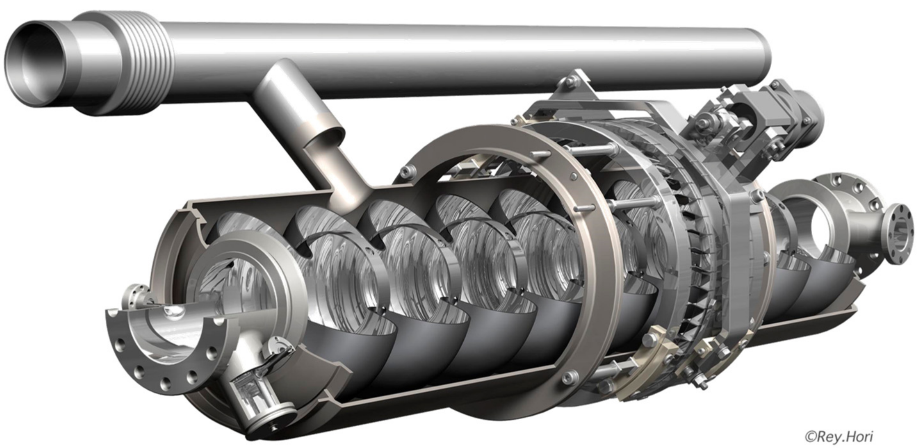
It is the highest average Q ever demonstrated in vertical test for 1.3 GHz nine cells at 2K, 16 MV/m in the history of SRF (larger than a factor of two the state of the art)

Fermilab

N doped nine cell cavities performance post He vessel dressing



MOPB033 MOPB040
MOPB028 MOPB041



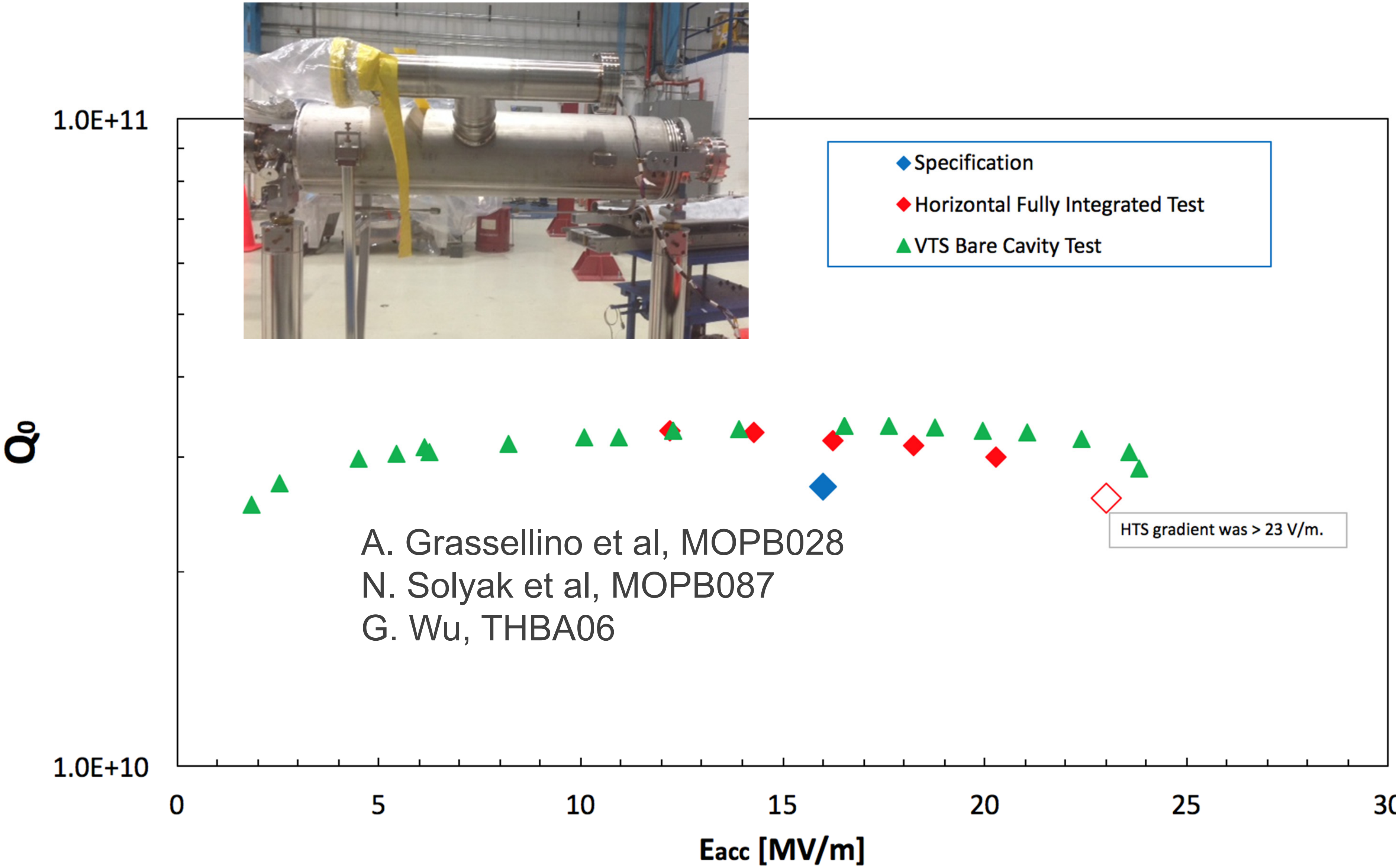
- 16 cavities dressed @ FNAL in LCLS-2 vessels ready for the prototype cryomodules – string assembly has begun, cryomodule results expected for mid 2016

- Avg VT performance still exceed >3e10 at 16 MV/m, 2K post dressing

- Four N doped nine cells horizontally tested in one cavity cryomodule (HTS) exceeding LCLS-2 specifications (for fast cooldowns from 45K)

- Fully integrated test : high power coupler, HOMs, tuner, magnetic shielding, thermal straps exceeding 3e10 @ 16MV/m, 2K – proof of principle that very high Q via N doping can be preserved all the way into cryomdoule

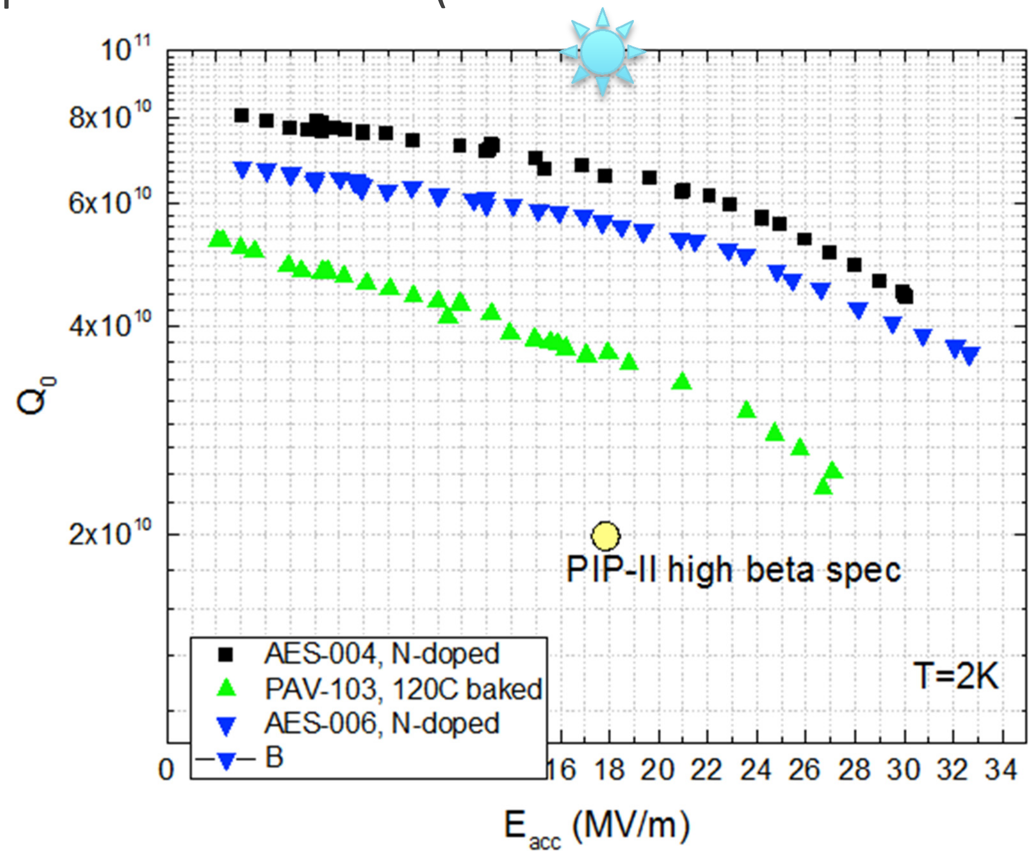
Milestone: record horizontal fully integrated test @ FNAL N doped nine cell in LCLS-2 vessel >3e10 at 16MV/m, 2K



A. Grassellino et al, MOPB028
N. Solyak et al, MOPB087
G. Wu, THBA06

N doping applied to 650 MHz cavities at FNAL
Q~ 7e10 at 2K, 17 MV/m – record values also 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)



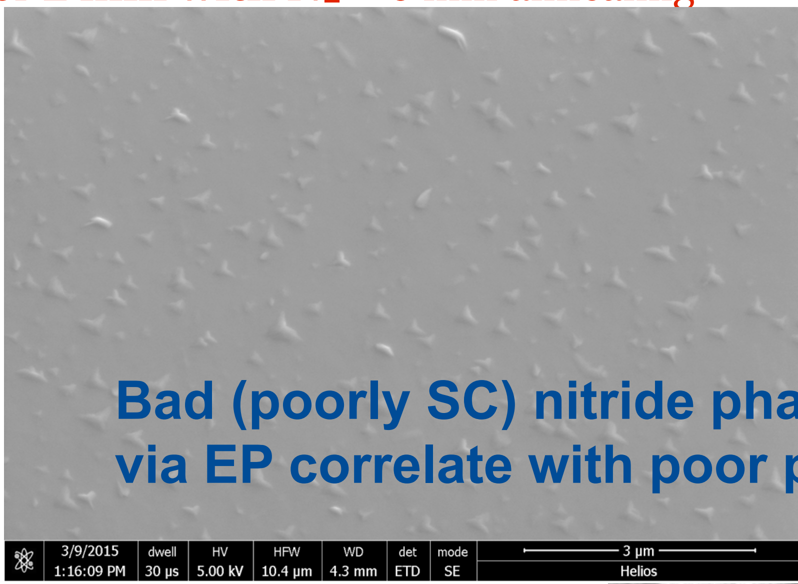
A.Grassellino, IPAC15

<u>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</u>

Progress in N doping understanding: what is the root of performance improvement?

Surface post N bake, pre-EP: poorly SC nitrides phases

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

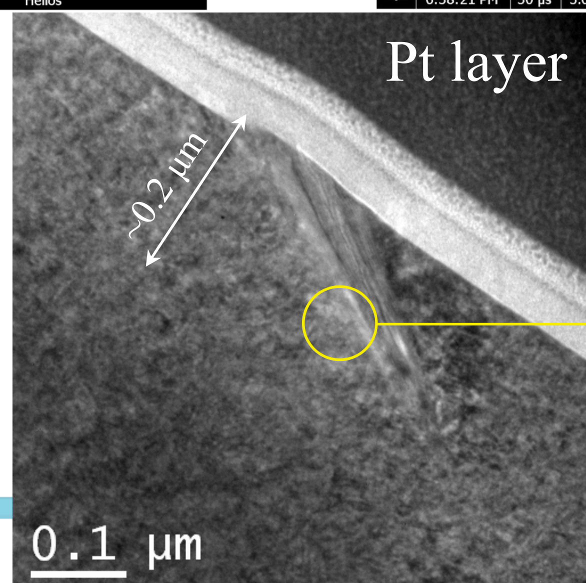


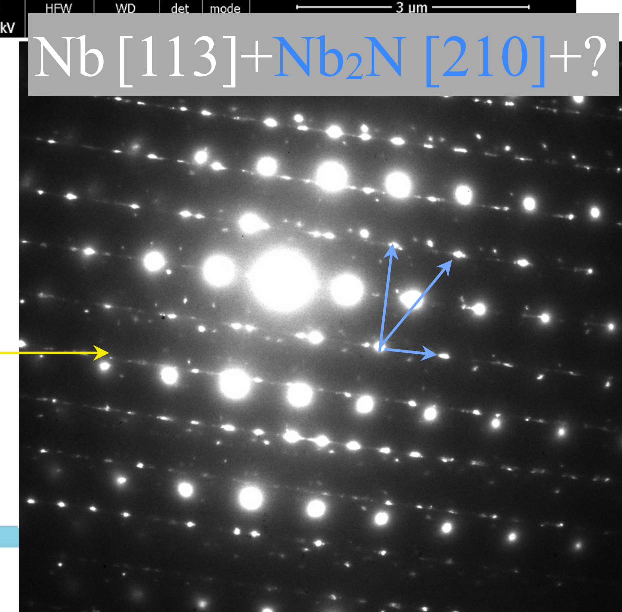
Flat Nb sample baked at 800C° for **20 min with N_2** + 30 min annealing

Bad (poorly SC) nitride phases that need to be removed via EP correlate with poor performance (pre-EP)

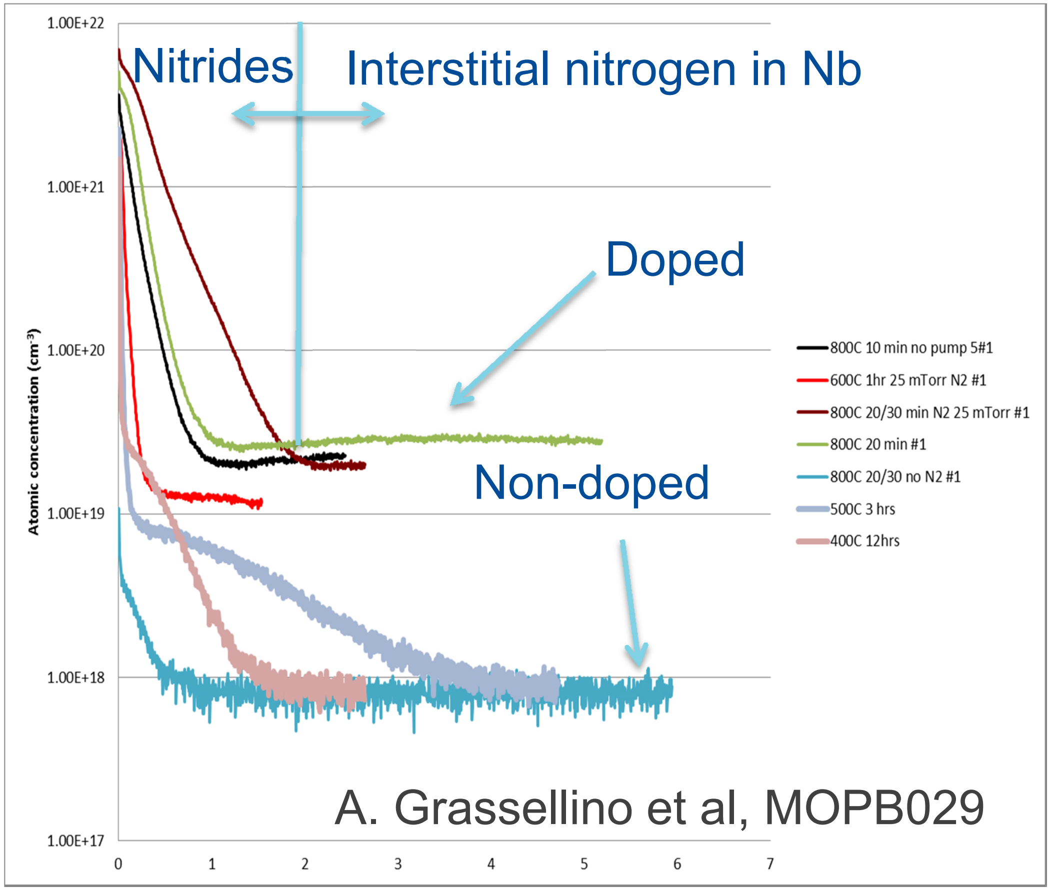
Few Nb nitrides-features (Nb_2N reflections) in Nb near-surface. Nitride "teeth" go ~0.2 µm deep

Y. Trenikhina, MOPB055



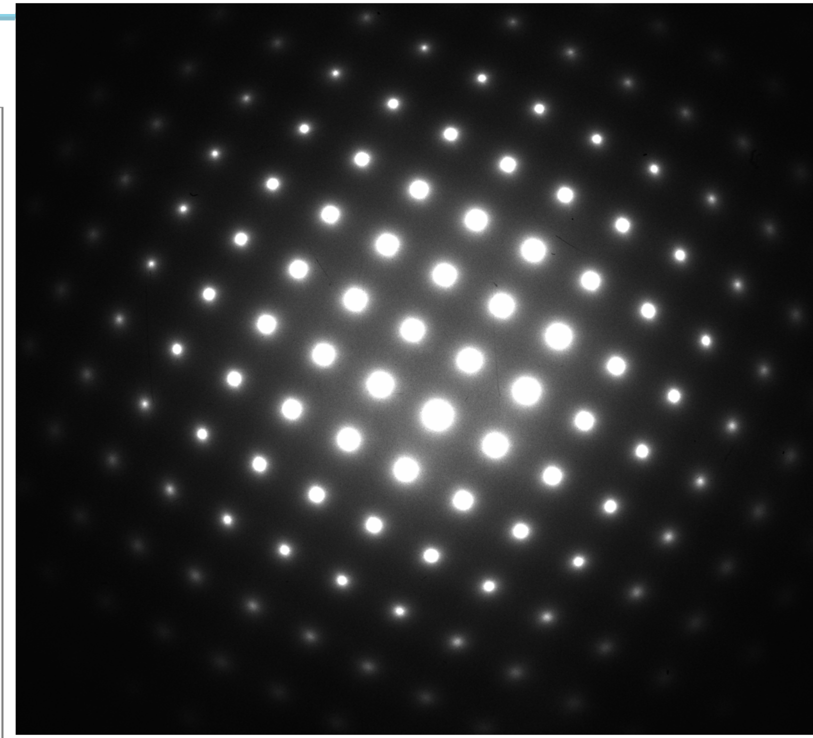


Surface post N bake + EP: only low level of interstitial N left



Depth (um)

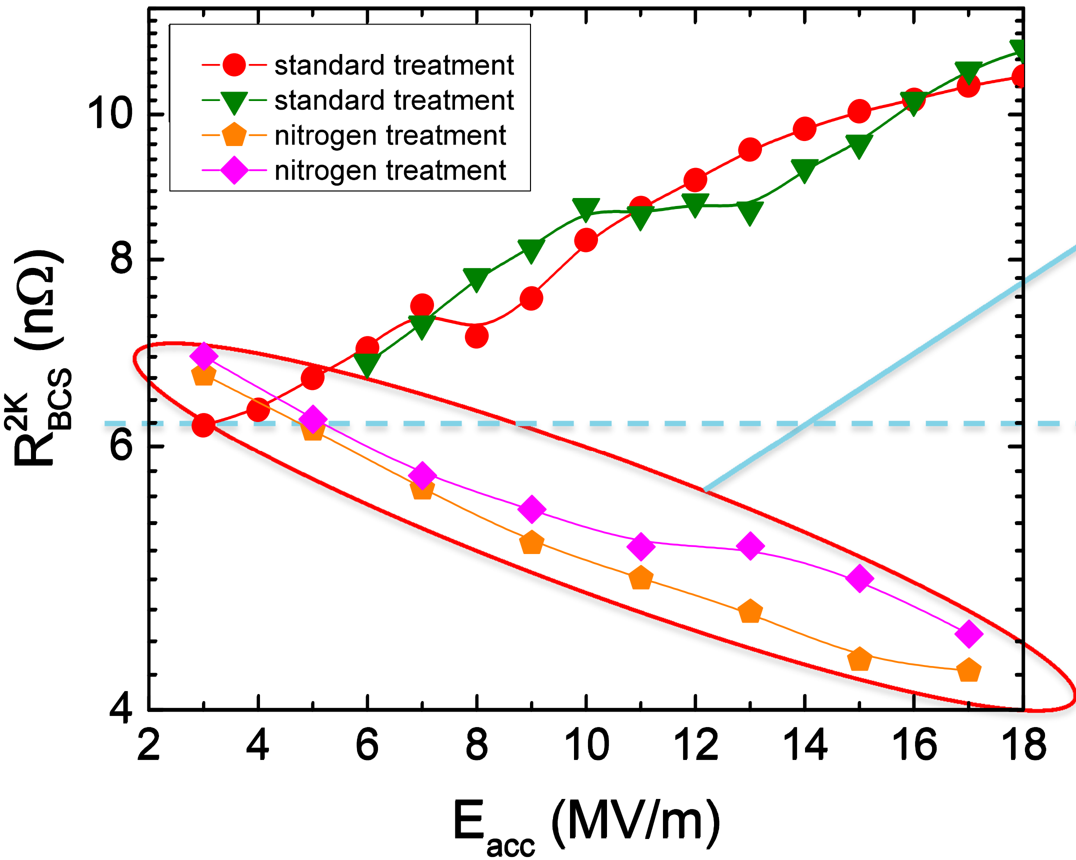
SIMS measurements show concentration of N one-two order of magnitude larger than background



No visible Nb nitrides-teeth in near-surface show only Nb reflections

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

Physics – perceived BCS limit has been overcome



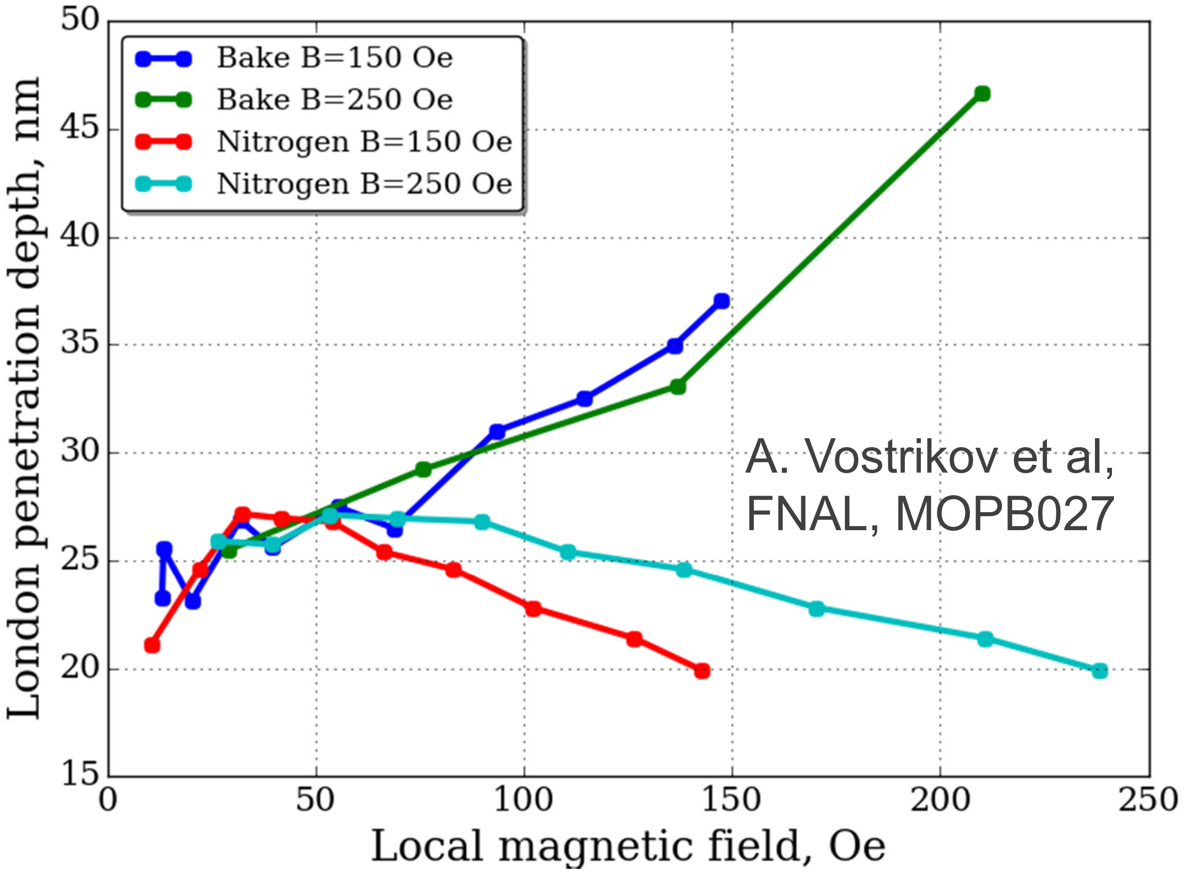
Anti-Q-slope emerges from the BCS surface resistance decreasing with field

This was thought to be the lowest possible BCS resistance

N doping brings also lower than typical residual resistance <2 nanoOhms (non trapped flux related)

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

Field dependence of the penetration depth – a possible explanation for the field dependence of BCS R_S?

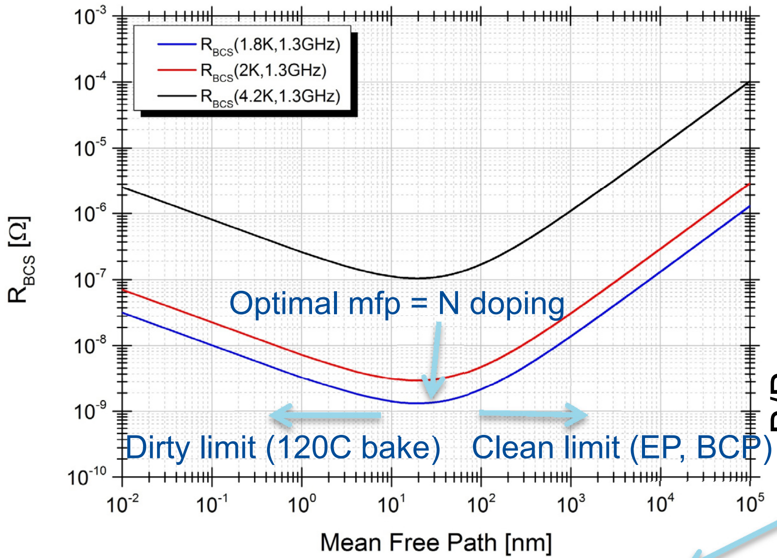


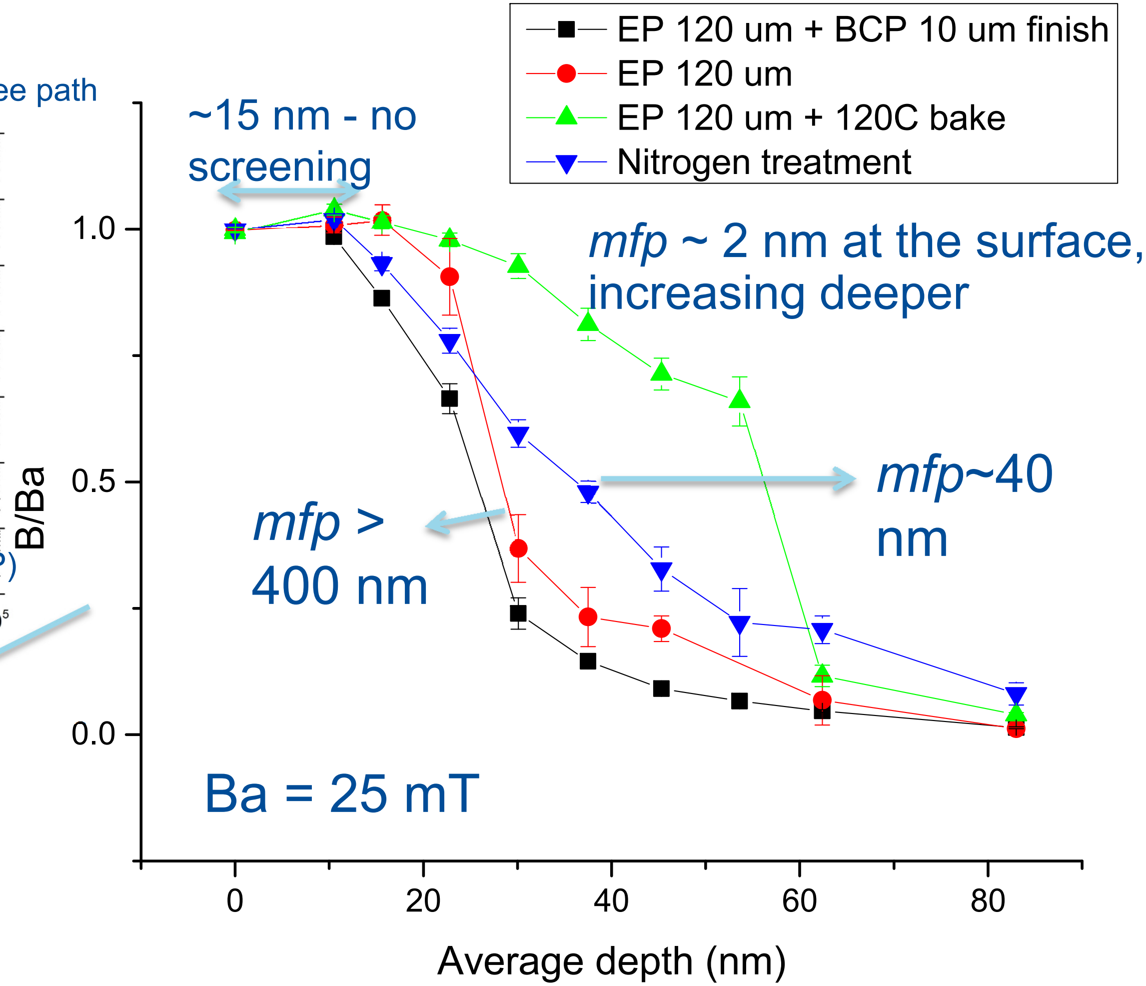
A. Vostrikov et al, FNAL, MOPB027

LEM muSR measurements on 120C bake and doped cavity cutouts revel that the penetration depth in the two cases have opposite field dependences, decreasing with field for N doping: possible origin of Q antislope?

How much nitrogen is needed for optimal performance? The intermediate mean free path

BCS surface resistance as a function of mean free path





BCP and EP unbaked -> strong screening, clean limit

EP+120C bake-> strongly suppressed m.f.p., gradient of the m.f.p. from the surface, dirty limit

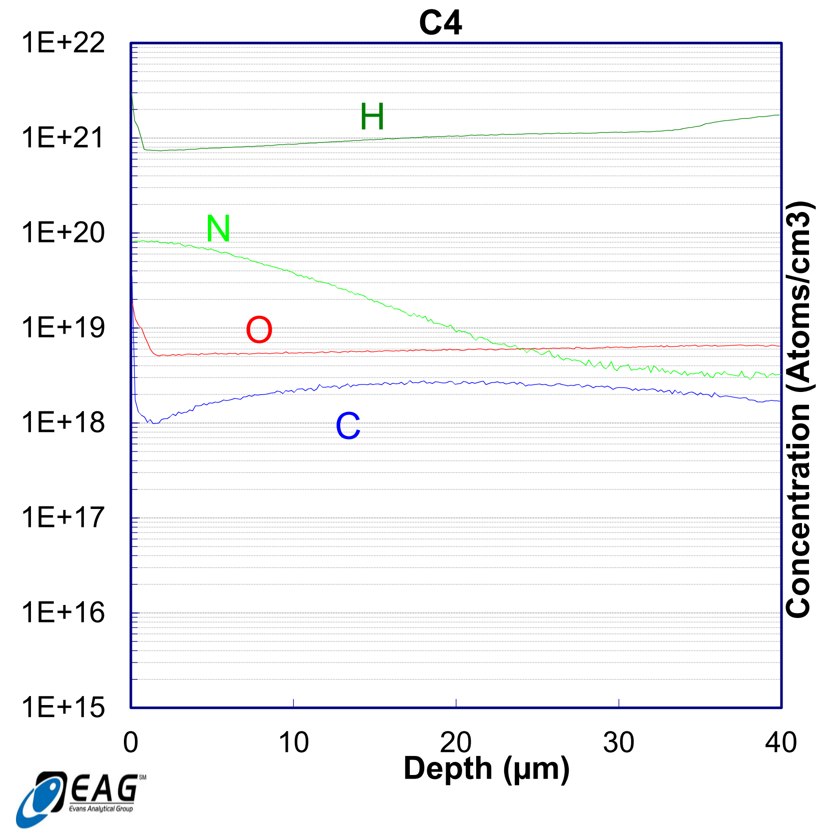
N-doped -> intermediate m.f.p., at the predicted minimum for BCS (previously unexplored)

Meissner screening profiles for differently treated cutouts (Ba magnetic field applied parallel to sample surface = 25 mT). Allows to directly extract surface mfp

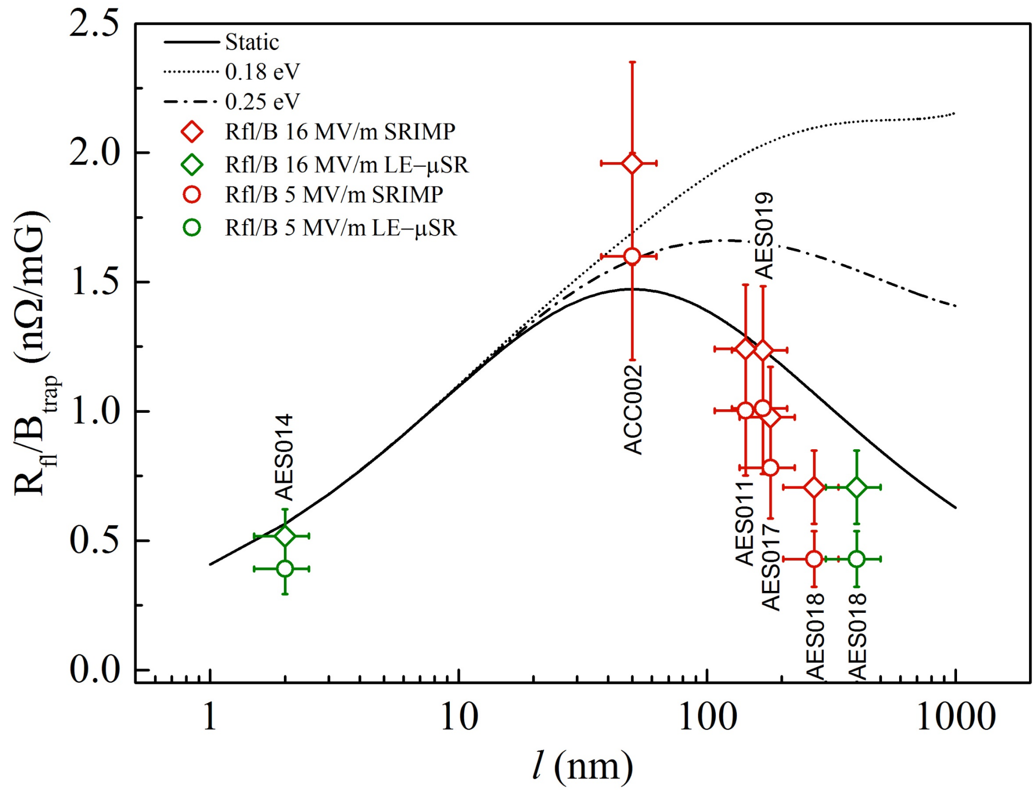
Progress in N doping understanding: what is the optimal N doping recipe?

Parameters in play for recipe optimization: overdoped vs underdoped regime

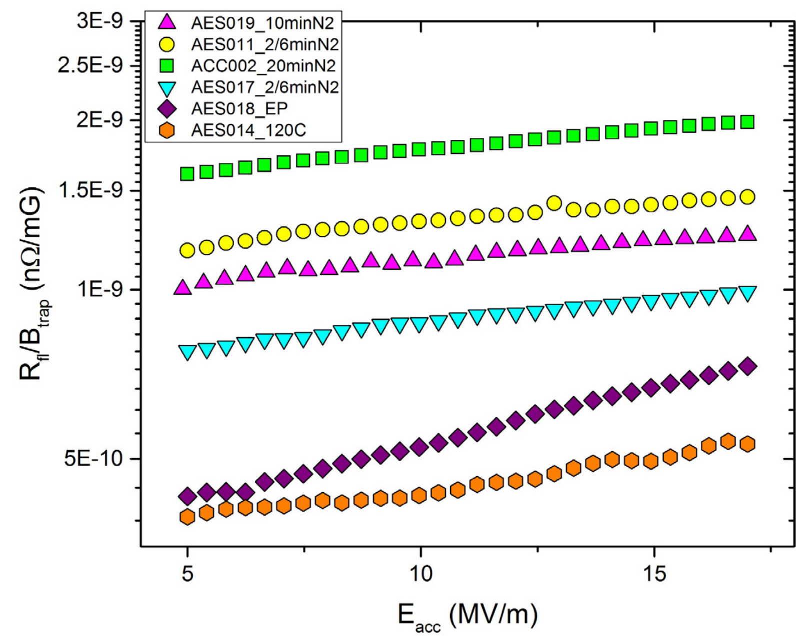
- R_{BCS} (Bpk > 60 mT)
  - This is the most robust parameter; R_{BCS} is low for a very wide range of N concentration at the surface (> ~50 ppm)
  - Below (underdoped regime), R_{BCS} gradually returns to that of standard treatments
- R_0 (non trapped flux related)
  - If “overdoped” (> ~200 ppm) a strong field dependence of the surface resistance appears
  - If “underdoped”, residual continues to stay low for a wider range than R_{BCS}
- Sensitivity to trapped magnetic flux
  - Lower doping levels lead to smaller sensitivity to trapped flux
- Maximum quench field
  - Also improves with lighter doping level



Is trapped magnetic flux sensitivity much higher for N doped cavities? Depends on the doping level -and the accelerating field

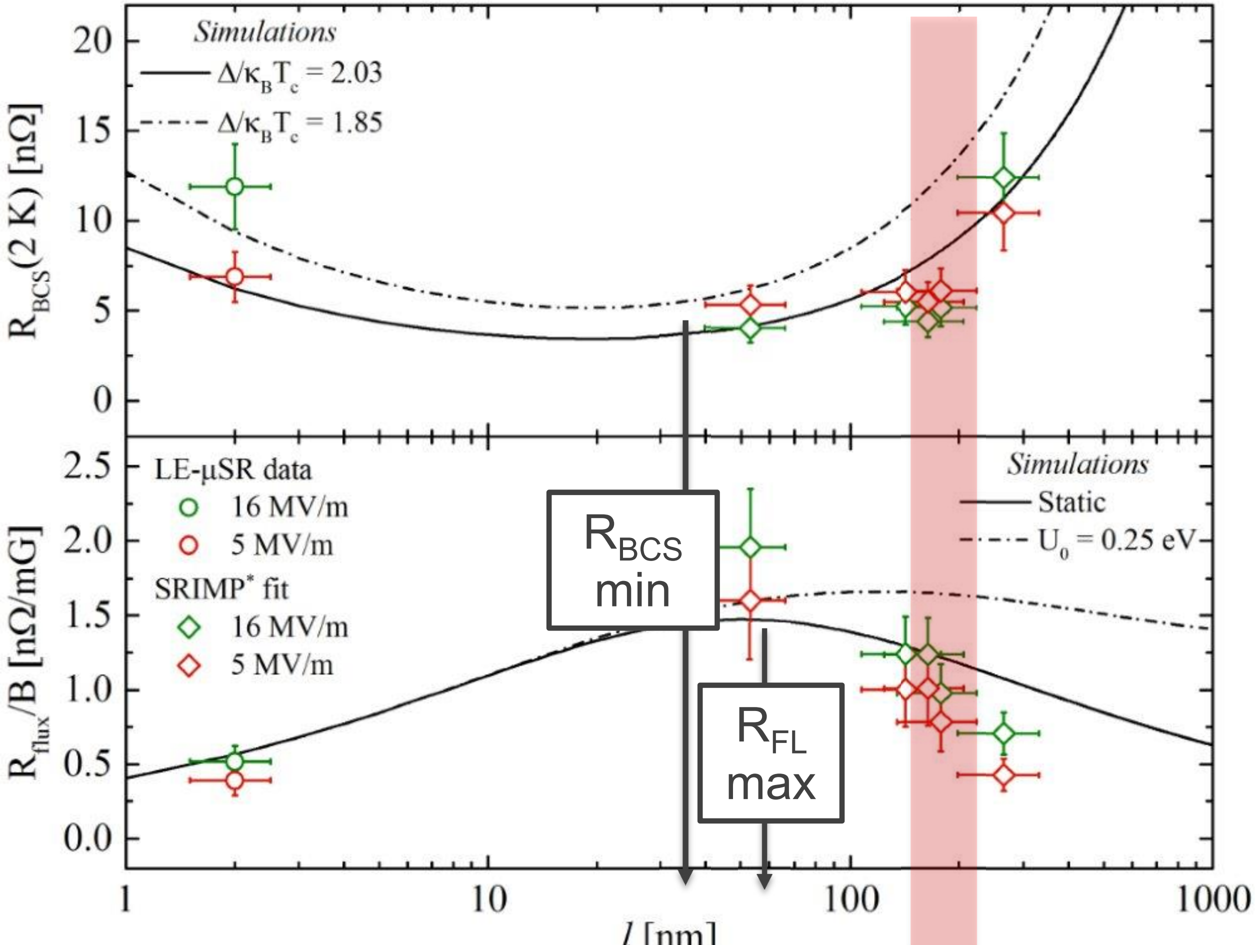


M. Martinello et al, MOPB015
M. Checchin et al, MOPB020



- Sensitivity to trapped flux for N doping improves with lighter doping (larger mfp)
- Not dramatically higher than standard (especially at higher accelerating fields):
  - 120C bake ~0.5 nOhm / mGauss
  - EP ~0.7
  - N dope (best) ~0.9

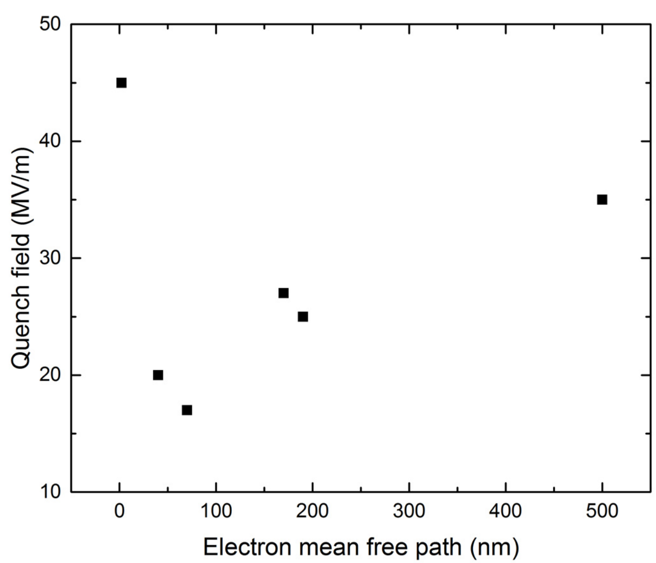
Recipe optimization: R_{BCS} vs flux sensitivity



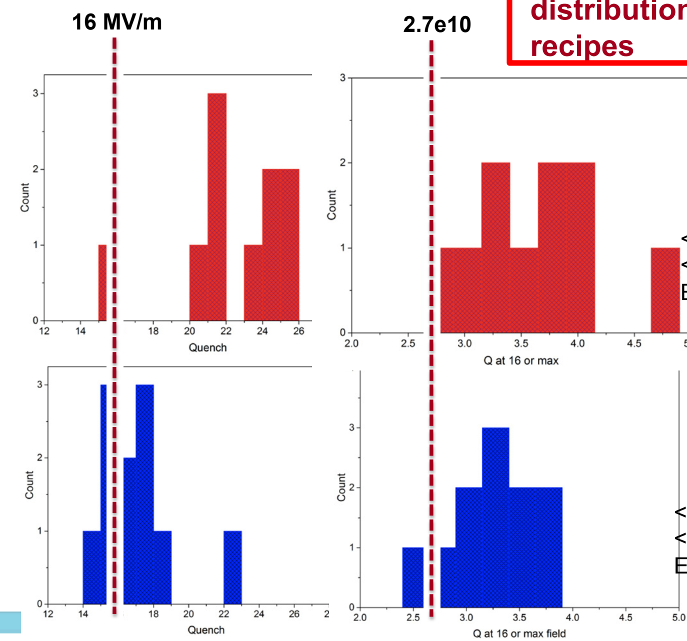
Larger mean free paths produce best performance…
But it is also interesting to notice the large windows of “unexplored”…

Recipe optimization: quench fields

- Light doping yields to higher quench field than heavy doping
- For same length of the doping step, quench field decreases with subsequent ‘anneal’ time (why?)
- For same recipe, quench fields are worse in nine cell than single cell cavities
- Quench fields are not sparse, they always ‘cluster’ around a value – different N doping levels produce different quench barriers
- More severe quench limitation > ~200 ppm concentration
- There is a trend – similar to the BCS minimum – for quench fields vs mean free path



Q and quench field distribution for the two recipes



Recipe 2/6

(FNAL/Jlab)

<Q>=3.6e10

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

E_{max}median=22.8MV/m

Recipe 20/30

(Cornell/Jlab/FNAL)

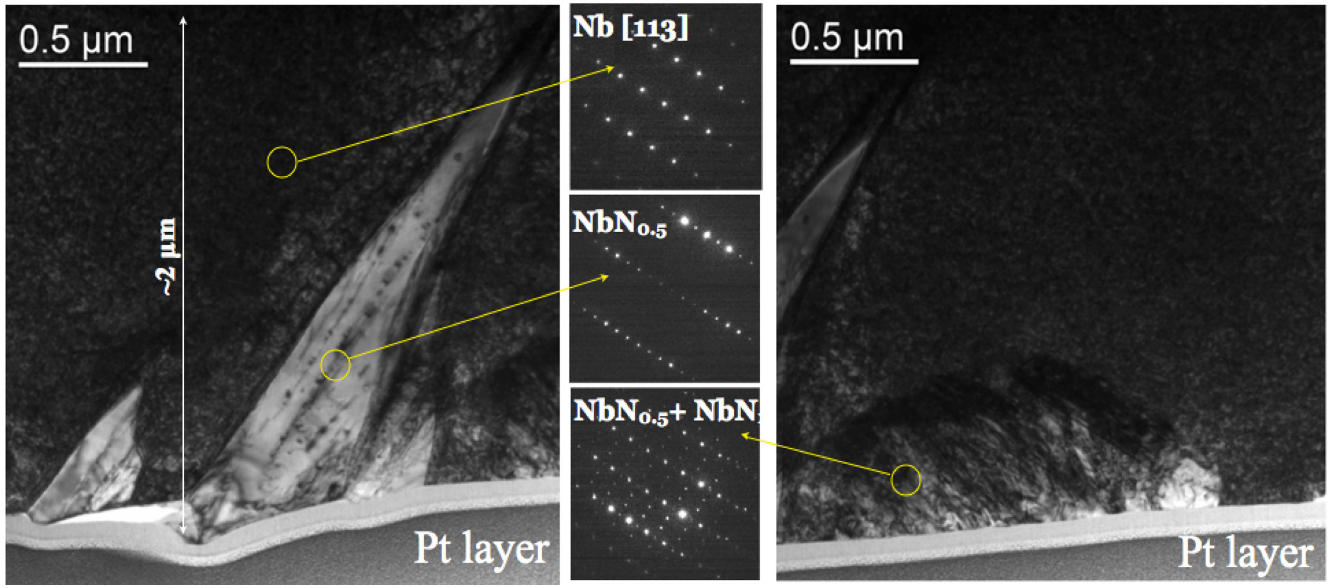
<Q>=3.24e10

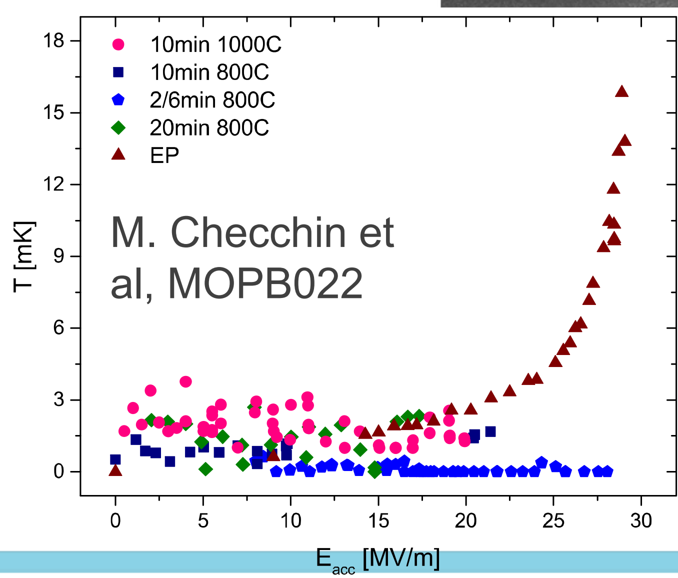
$<E_{max}>$=16.3 MV/m

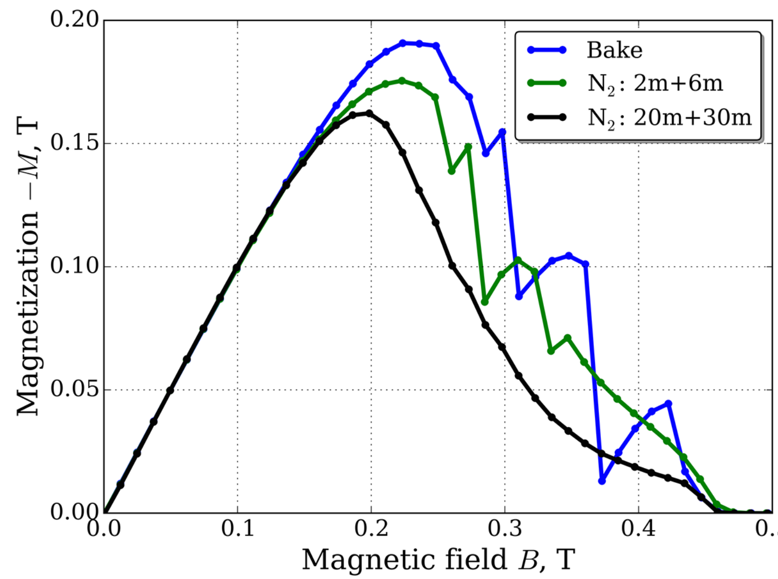
E_{max}median=16.5MV/m

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

Nitride teeth…residual nanonitrides post EP?
Or premature flux entry?







A. Vostrikov et al, MOPB027

Conclusions

- N doping has come a long way since last SRF
- Already demonstrated to systematically achieve unprecedented Q levels all the way to dressed cavities in cryomodule environment, technology ready for LCLS-2
- With their pros and cons, N doped cavities have been a new crucial tool for gaining new insights on surface resistance and its field dependence, trapped flux as a function of cooling and mean free path, and origin of quench
- What will the “yet unexplored” range of mean free paths bring?