N doping: progress in development and understanding

Anna Grassellino
Cavity Test and Performance Group Leader, SRF Development Department, TD

SRF conference, September 2015, Whistler, BC
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 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 $Q > 2.7 \times 10^{10}$ @16MV/m, 2K

$\langle Q \rangle = 3.5 \times 10^{10}$

$\langle E_{\text{max}} \rangle = 22.2$ MV/m

$E_{\text{max}}$ 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)
N doped nine cell cavities performance post He vessel dressing

- 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 cryomodule
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)

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
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 800°C for 2 min with N₂ + 6 min annealing

Flat Nb sample baked at 800°C for 20 min with N₂ + 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 (Nb₂N 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

Nitrides
Interstitial nitrogen in Nb
Doped
Non-doped

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

SIMS measurements show concentration of N one-two order of magnitude larger than background
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. 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 $R_S$?

**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

- EP 120 um + BCP 10 um finish
- EP 120 um
- EP 120 um + 120C bake
- Nitrogen treatment

\( mfp \sim 2 \text{ nm at the surface, increasing deeper} \)

\( mfp > 40 \text{ nm} \)

\( mfp \sim 40 \text{ nm} \)

Optimal mfp = N doping

Dirty limit (120C bake) Clean limit (EP, BCP)

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

Ba = 25 mT
Progress in N doping understanding: what is the optimal N doping recipe?
Parameters in play for recipe optimization: overdoped vs underdoped regime

- **R\text{BCS} (Bpk > 60 mT)**
  - This is the most robust parameter; \(R\text{BCS}\) is low for a very wide range of N concentration at the surface (> ~50 ppm)
  - Below (underdoped regime), \(R\text{BCS}\) gradually returns to that of standard treatments

- **R\text{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 \(R\text{BCS}\)

- **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

- 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 \( \sim 0.5 \) nOhm / mGauss
  - EP \( \sim 0.7 \)
  - N dope (best) \( \sim 0.9 \)
Recipe optimization: $R_{\text{BCS}}$ 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

**Graphs:**

- **Recipe 2/6**
  - FNAL/Jlab
  - \(<Q>=3.6e10\)
  - \(E_{\text{max}}>=22.2 \text{ MV/m}\)
  - \(E_{\text{max}}\) median=22.8 MV/m
- **Recipe 20/30**
  - Cornell/Jlab/FNAL
  - \(<Q>=3.24e10\)
  - \(E_{\text{max}}>=16.3 \text{ MV/m}\)
  - \(E_{\text{max}}\) median=16.5 MV/m
New insights on quench in N doped cavities – magnetic peak field driven

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

M. Checchin et al, MOPB022

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?