Recent SRF development at FNAL

Martina Martinello

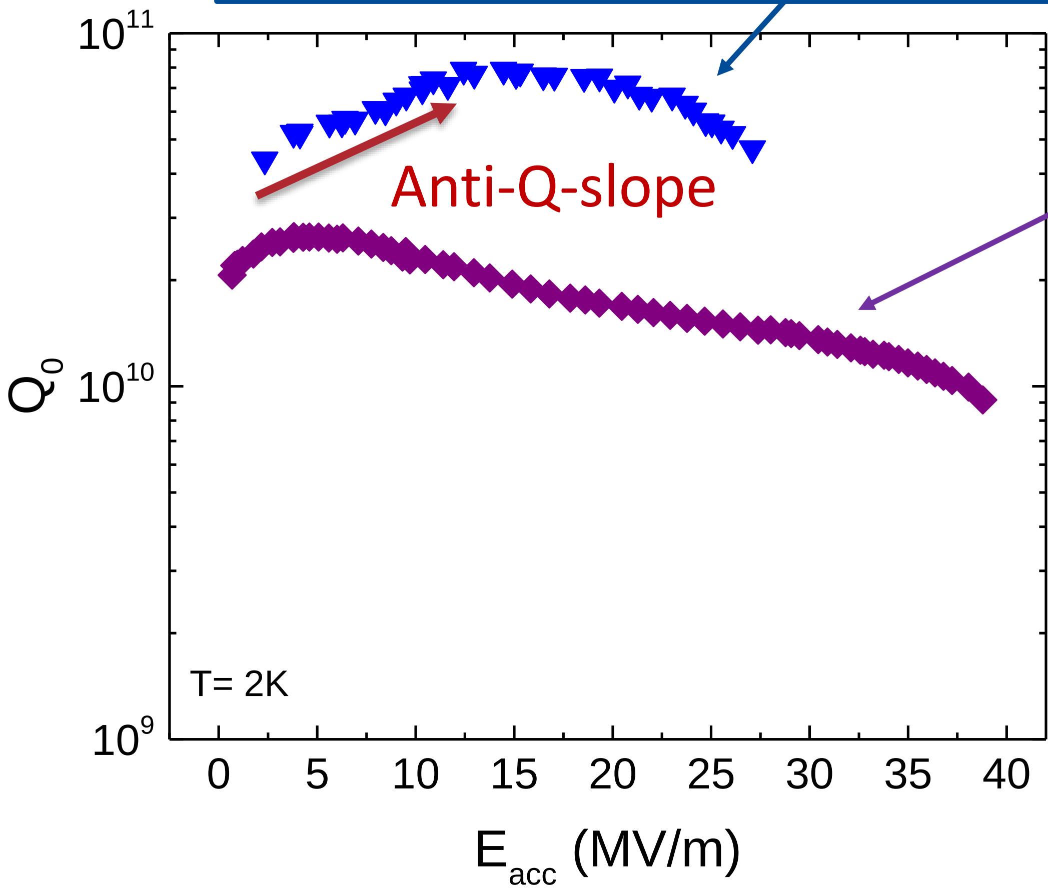
CEA Seminar, 26th Oct 2017

Outline

- N-doping R&D
- Trapped Flux in Nb cavities R&D
- LCLS-II Production Stage
- N-infusion for high-Q at high gradients
- Conclusion

The discovery of N-doping

Q-factor improvement after N-doping – up to 4 times higher Q than standard Nb cavities



Typical Q vs Eacc curve obtained with 120C baking (standard ILC treatment)

Average Q at 16MV/m:

- Standard ILC treatment:

$$\langle Q \rangle \sim 1.7 \cdot 10^{10}$$

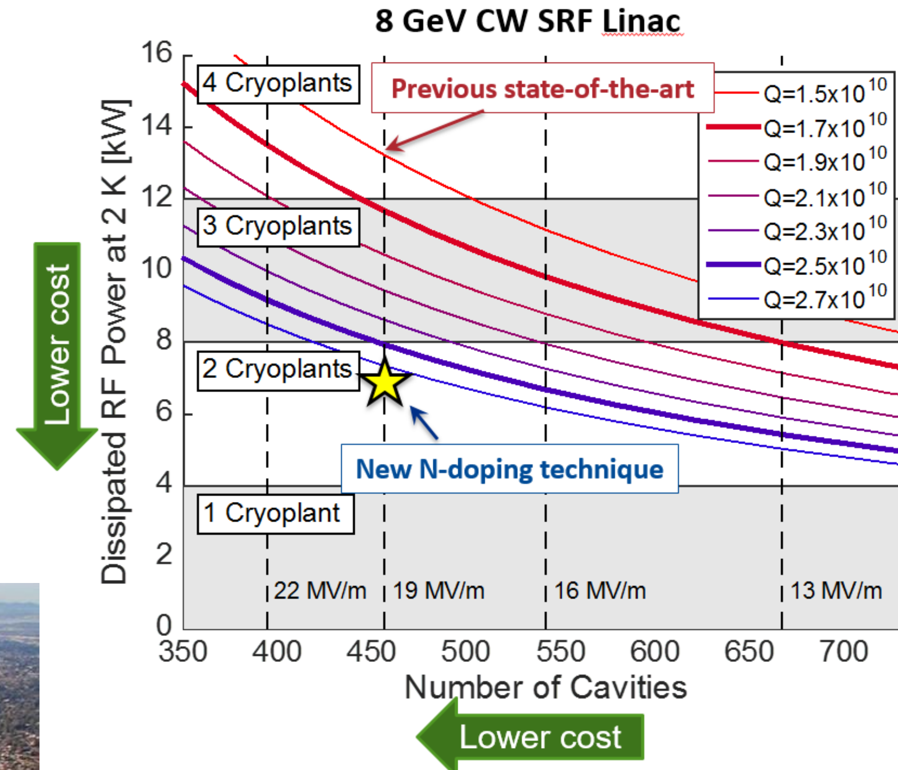
- N-doping:

$$\langle Q \rangle \sim 3.5 \cdot 10^{10}$$

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

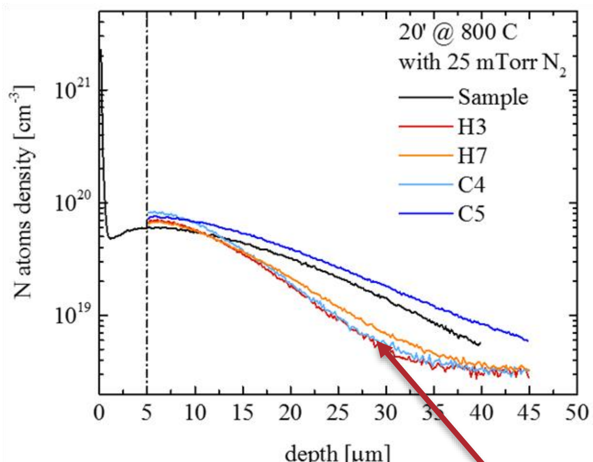
Linear Coherent Light Source-II (LCLS-II)

- $4\ GeV$, $0.3\ mA$ *CW SRF LINAC*
- 35 CM, 8 cavities/CM + 1 quad
- TESLA-type $1.3\ GHz$ 9-cells cavities
- Specs: $E_{acc} = 16\ MV/m$ with $Q_0 = 2.7 \times 10^{10}$

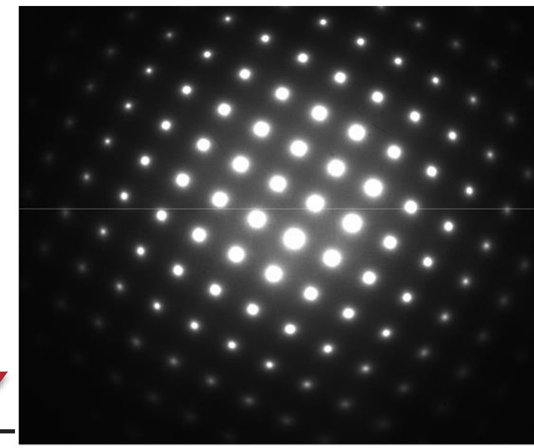


N-doping treatment (example: the “2/6 recipe”)

800C UHV, 3 hours → 800C N_2 injection p=25mTorr → 800C N_2 2 minutes → 800C UHV, 6 minutes → UHV cooling → 5 um EP

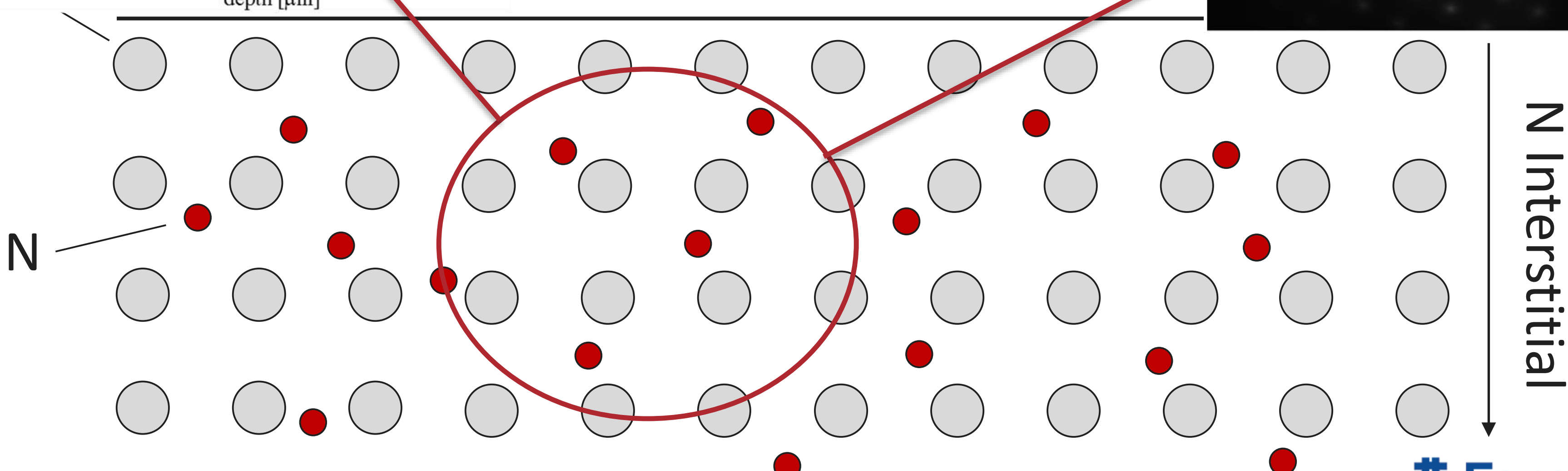


Y. Trenikhina et Al, Proc. of SRF 2015



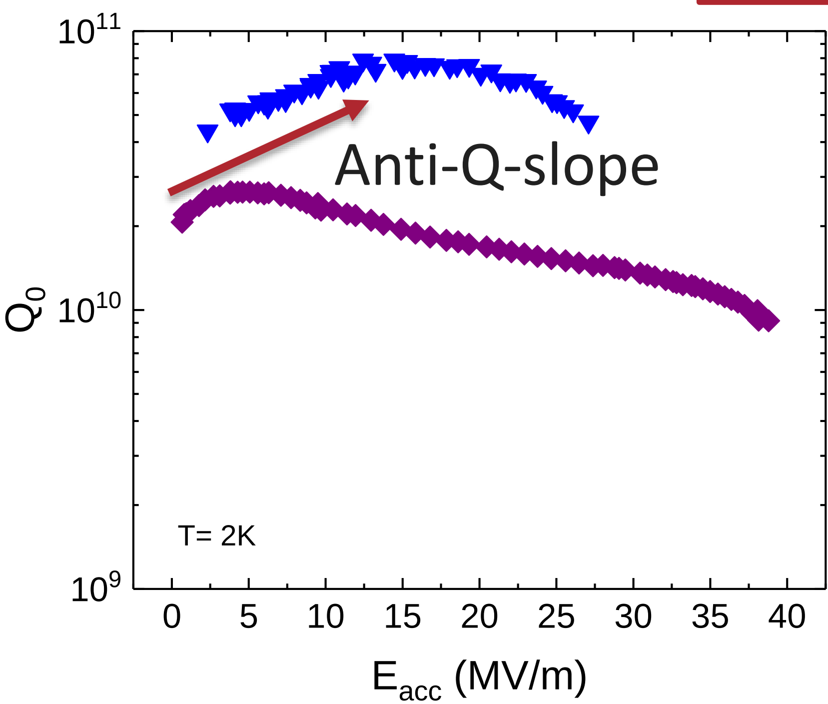
Only Nb from TEM spectra: N must be interstitial

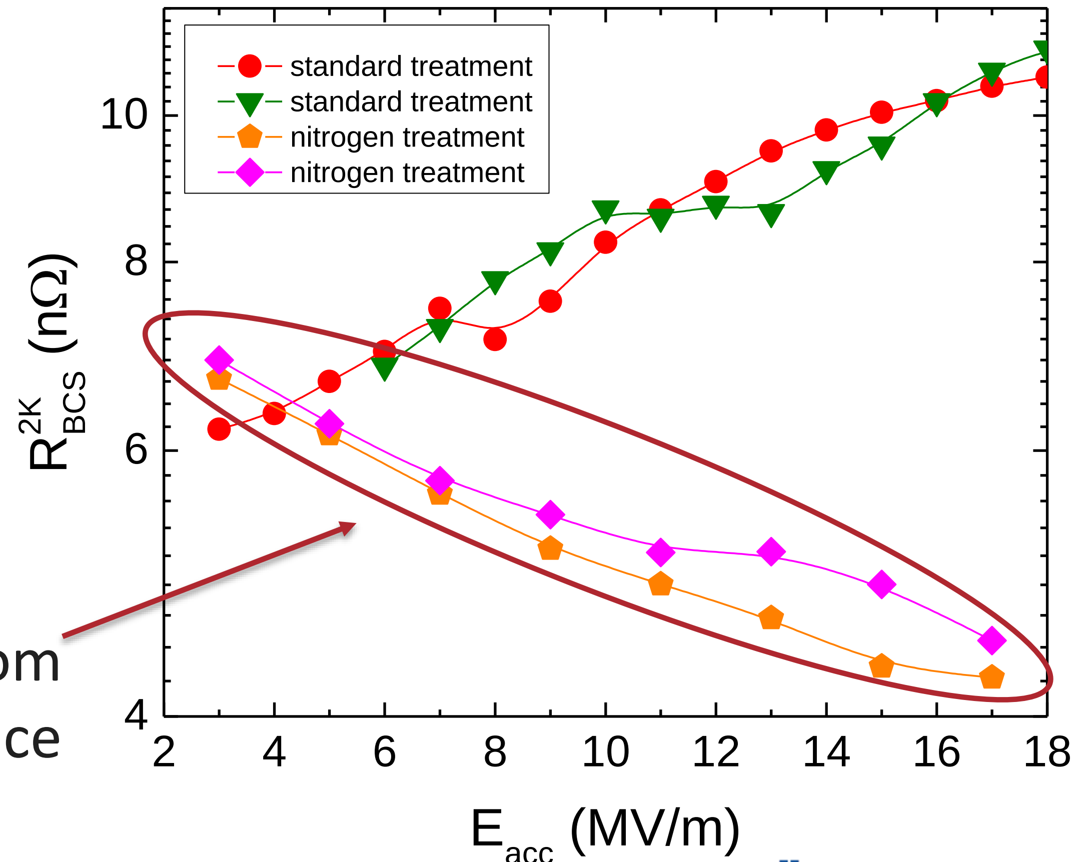
Final RF Surface



Origin of the anti-Q-slope

$$R_S\,(\,2\,K, B_{Trap}\,) = \boxed{R_{BCS}\,(\,2\,K\,)} + R_0 + R_{Fl}\,(\,B_{Trap}, l\,)$$





Anti-Q-slope emerges from the BCS surface resistance <u>decreasing</u> with field

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

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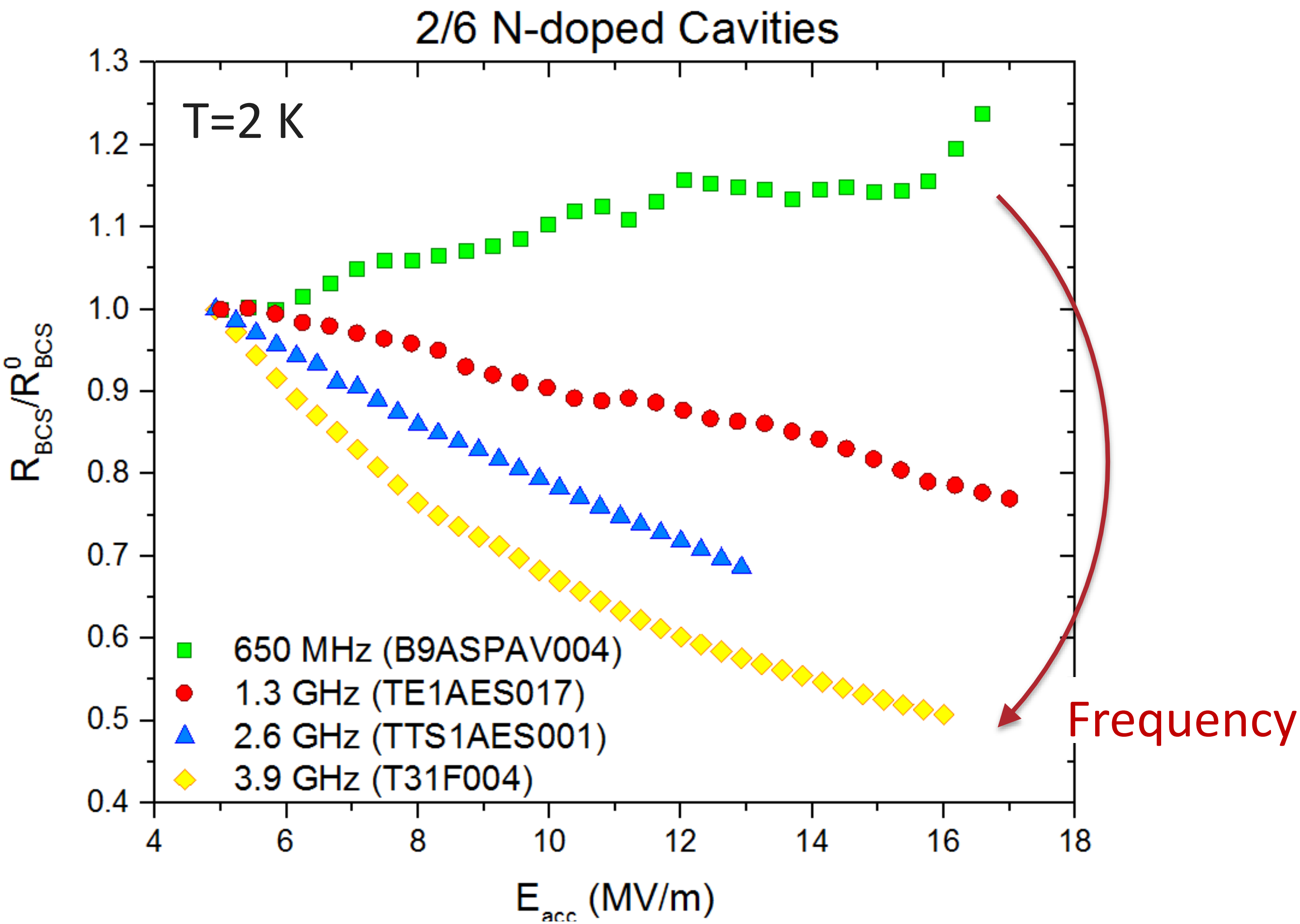
Frequency dependence of R_{BCS}(Eacc): toward a better understanding



M. Martinello et al., in Proc. of SRF 2017 (arXiv:1707.07582)

Trapped Flux in Nb Cavities R&D

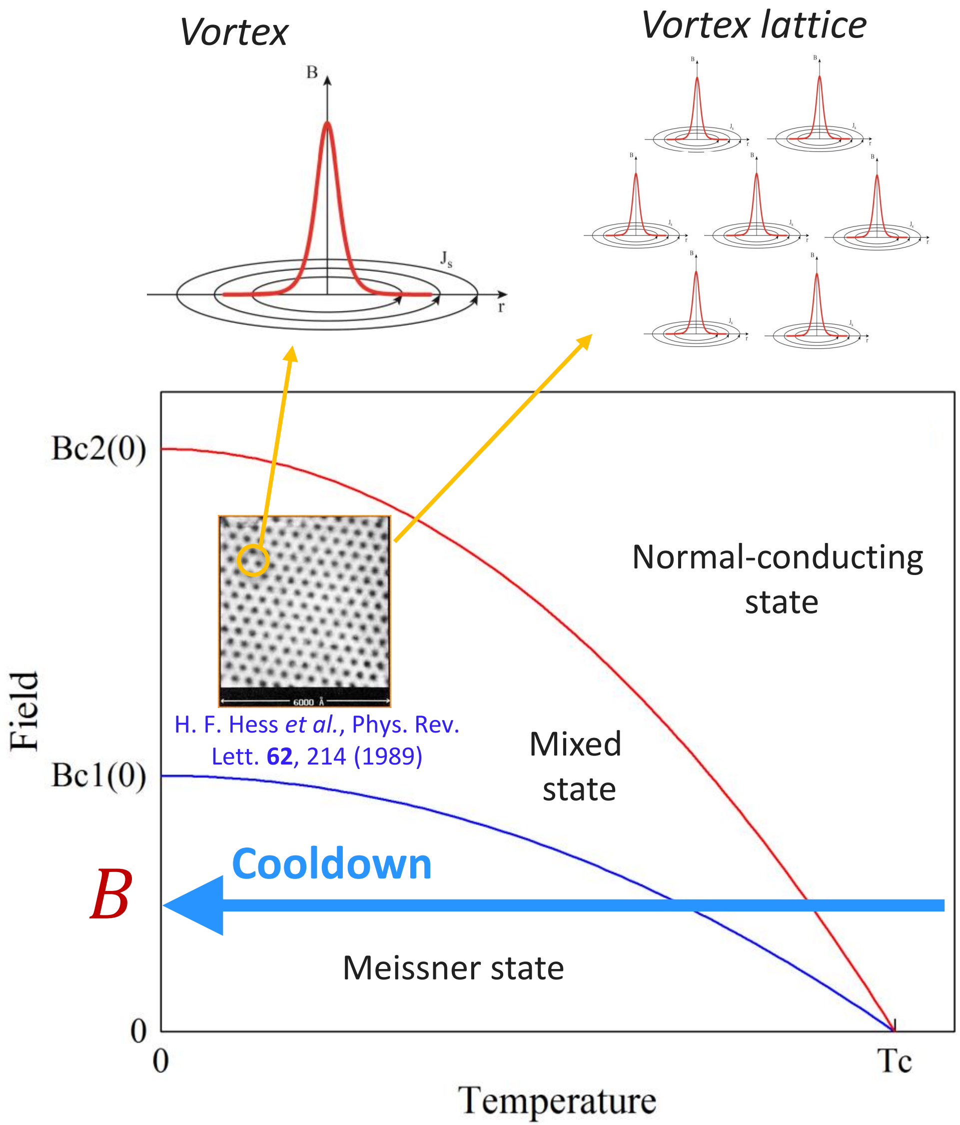
SC transition in presence of external magnetic field H

$$R_s(T) = R_{BCS}(T) + \boxed{R_{res}}$$

- In the mixed state vortices are stable in the SC
- If pinned, vortices may survive in the Meissner state introducing dissipation (R_{fl})

$$\boxed{R_{res} = R_0 + R_{fl}(B_{trap})}$$

R_0: intrinsic residual resistance
R_{fl}: trapped flux surface resistance



Trapped Flux Surface Resistance

$$R_S\,(2\,K, B_{Trap}) = R_{BCS}\,(2\,K) + R_0 + R_{Fl}$$

$$\boldsymbol{R_{Fl} = B_{ext} \cdot \eta \cdot S}$$

These losses can be reduced by minimizing these contributions:

External Magnetic Field	B_{ext}	• Magnetic shielding / hygiene improvement
Flux Trapping Efficiency	η	• Fast cooling / high T backing
Trapped Flux Sensitivity	S	• Optimizing surface treatment

Trapped Flux Surface Resistance

$$R_S\left(2\,K, B_{Trap}\right) = R_{BCS}\left(2\,K\right) + R_0 + R_{Fl}$$

$$\boldsymbol{R_{Fl} = \boxed{B_{ext}} \cdot \eta \cdot S}$$

These losses can be reduced by minimizing these contributions:

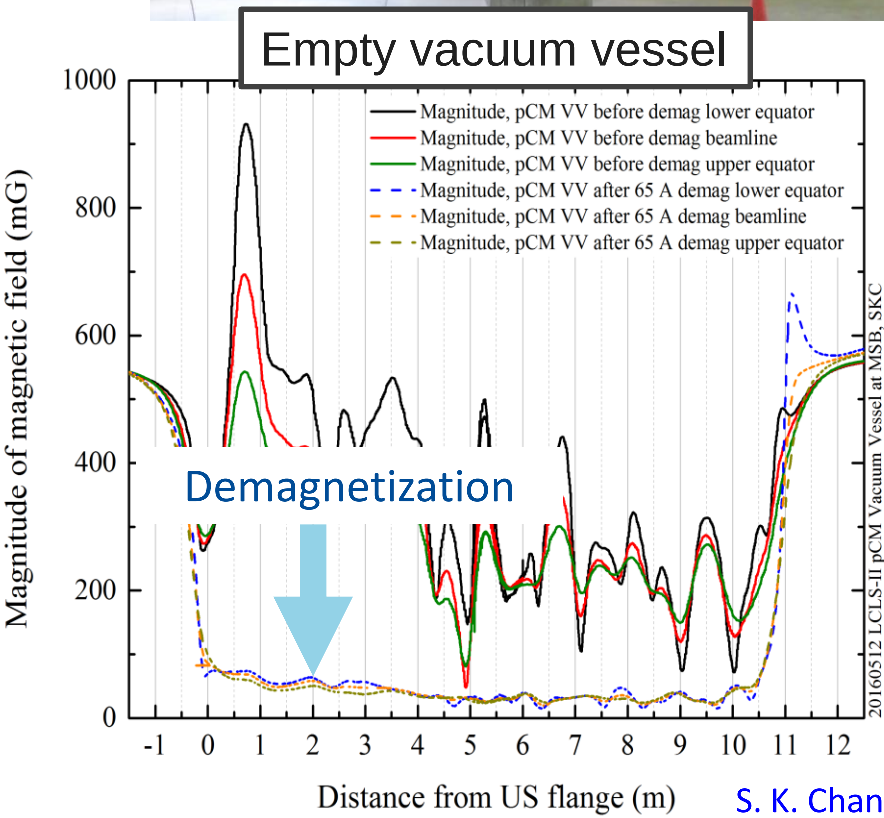
External magnetic field

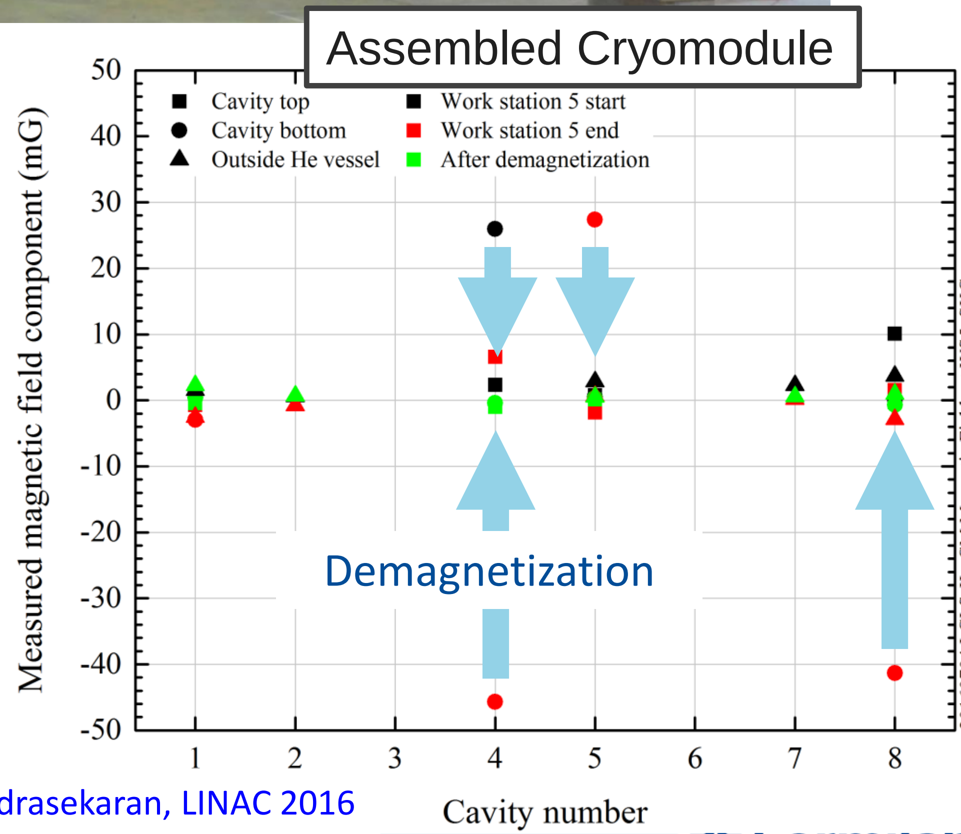
B_{ext}
- Magnetic shielding/hygiene improvement

η
- Fast Cooling
- Material Optimization

S
- Optimizing mean free path

Minimization of remnant field in the cryomodule





S. K. Chandrasekaran, LINAC 2016

Trapped Flux Surface Resistance

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These losses can be reduced by minimizing these contributions:

Flux Trapping Efficiency

- B_{ext} — Magnetic shielding / hygiene improvement
- η — Fast cooling / high T backing
- S — Optimizing surface treatment

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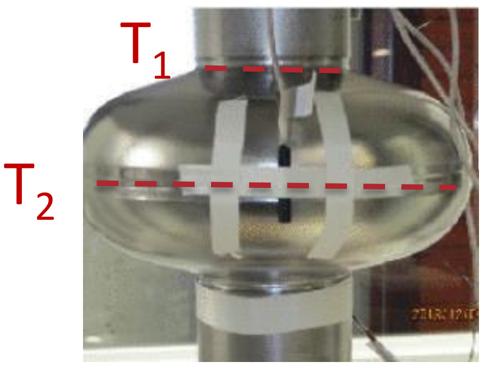
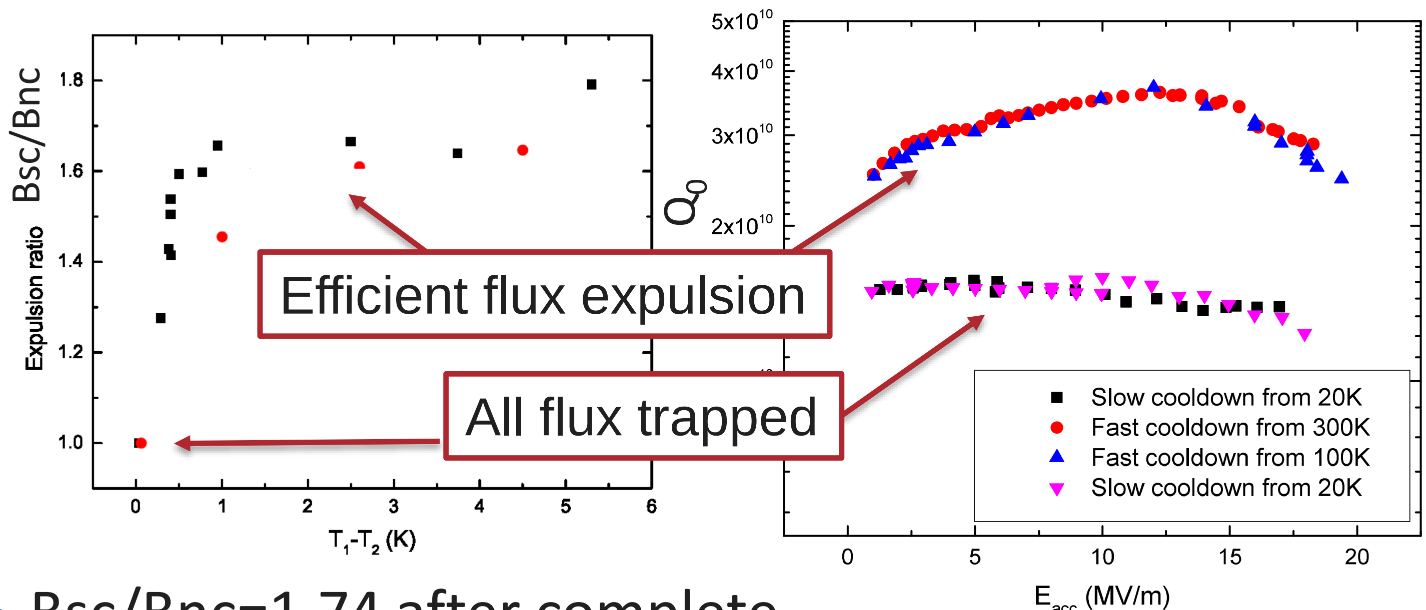
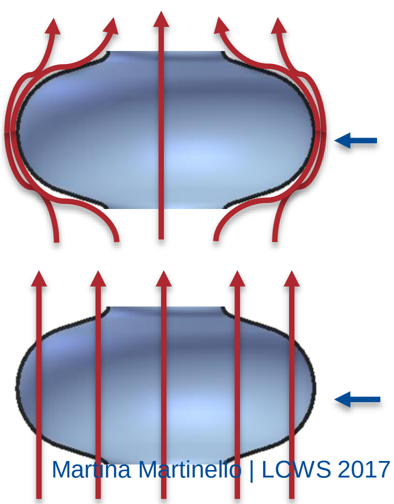
Fast cooldown helps flux expulsion

- **Fast cool-down** lead to **large thermal gradients** which promote efficient flux expulsion
- Slow cool-down → poor flux expulsion





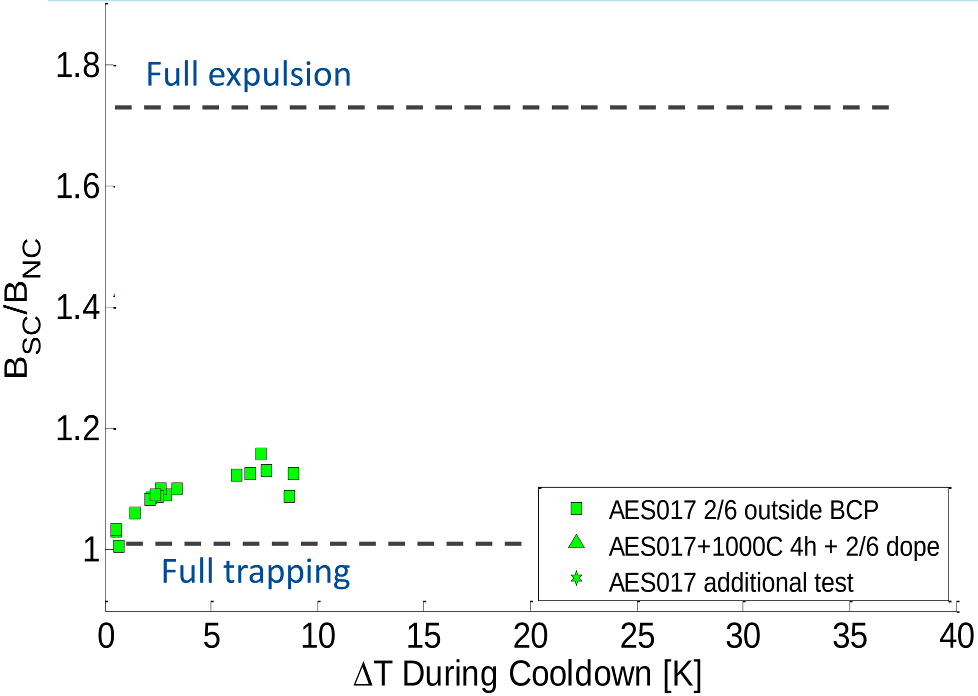


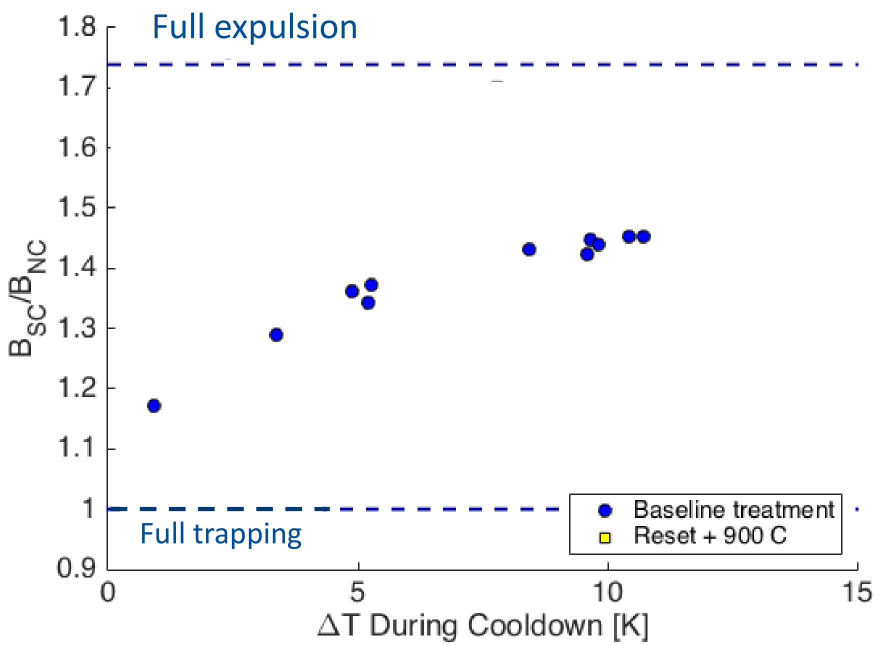
Bsc/Bnc=1.74 after complete Meissner effect

Bsc/Bnc=1 after full flux trapping

A. Romanenko et al., Appl. Phys. Lett. **105**, 234103 (2014)
A. Romanenko et al., J. Appl. Phys. **115**, 184903 (2014)
D. Gonnella et al, J. Appl. Phys. **117**, 023908 (2015)
M. Martinello et al., J. Appl. Phys. **118**, 044505 (2015)
S. Posen et al., J. Appl. Phys. **119**, 213903 (2016)
S. Huang, Phys. Rev. Accel. Beams **19**, 082001 (2016)

High T baking for flux expulsion improvement

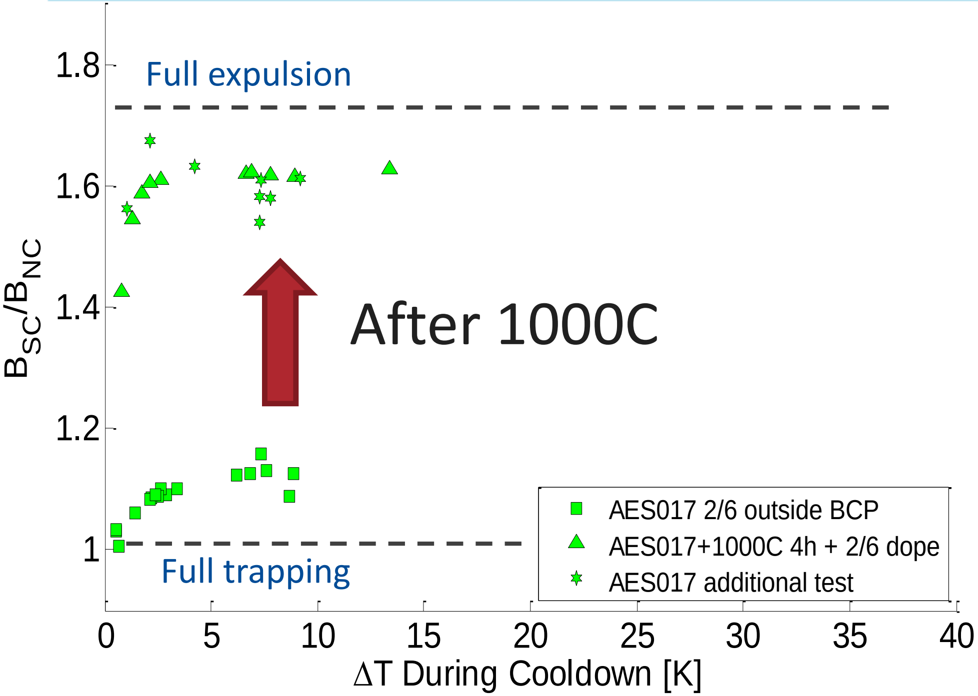


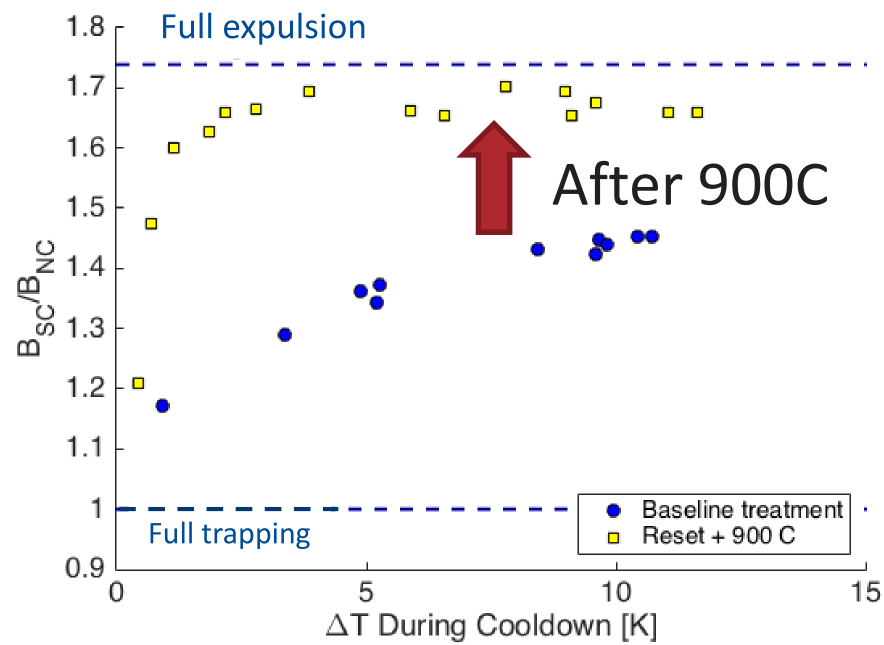


S. Posen et al., J. Appl. Phys. **119**, 213903 (2016)), A. Palchewski in Proc. of LINAC 2016

- Not all materials show good flux expulsion even with large thermal gradient

High T baking for flux expulsion improvement





S. Posen et al., J. Appl. Phys. **119**, 213903 (2016)), A. Palchewski in Proc. of LINAC 2016

- Not all materials show good flux expulsion even with large thermal gradient
- High T treatments are capable to improve (most of the times) materials flux expulsion properties

Trapped Flux Surface Resistance

$$R_S\,(2\,K, B_{Trap}) = R_{BCS}\,(2\,K) + R_0 + R_{Fl}$$

$$\boldsymbol{R_{Fl} = B_{ext} \cdot \eta \cdot \boxed{S}}$$

These losses can be reduced by minimizing these contributions:

- B_{ext}
  - Magnetic shielding / hygiene improvement
- η
  - Fast cooling / high T treatment
- S
  - Optimizing surface treatment

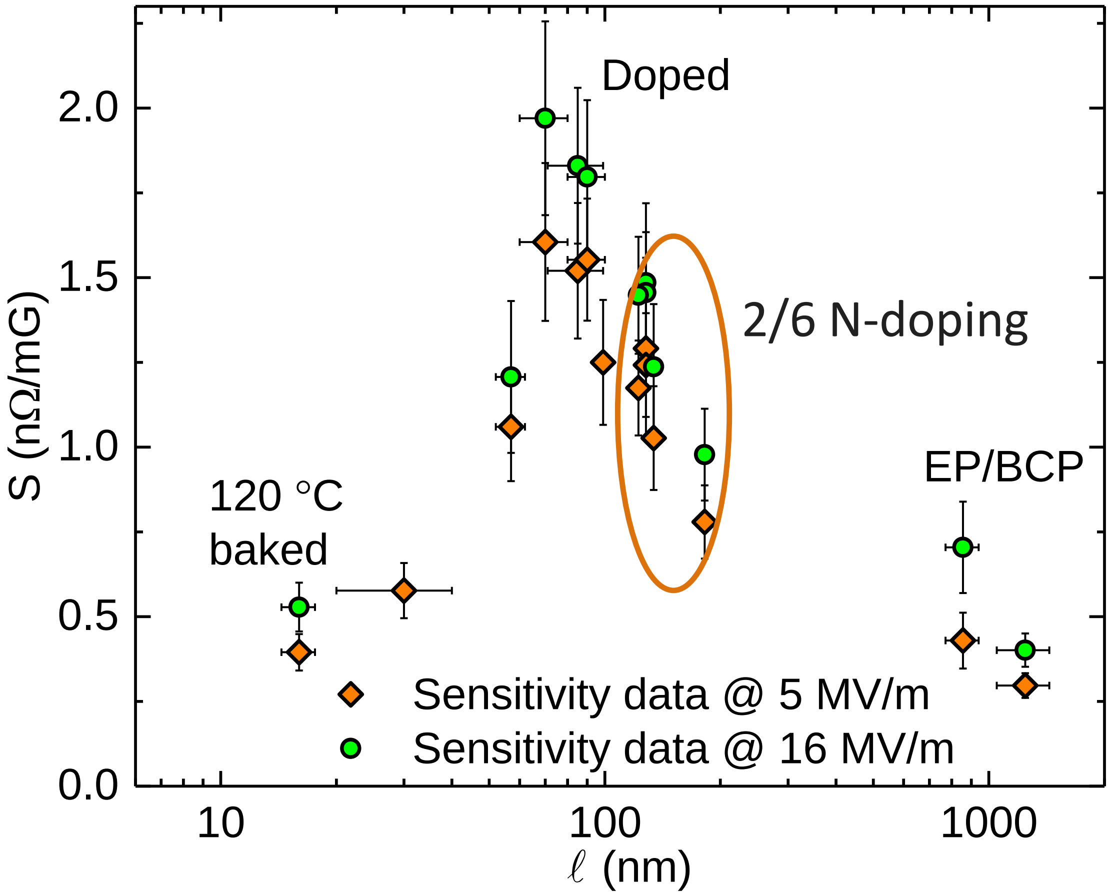
Trapped Flux Sensitivity

Light doping to minimize trapped flux sensitivity

Trapped flux sensitivity:

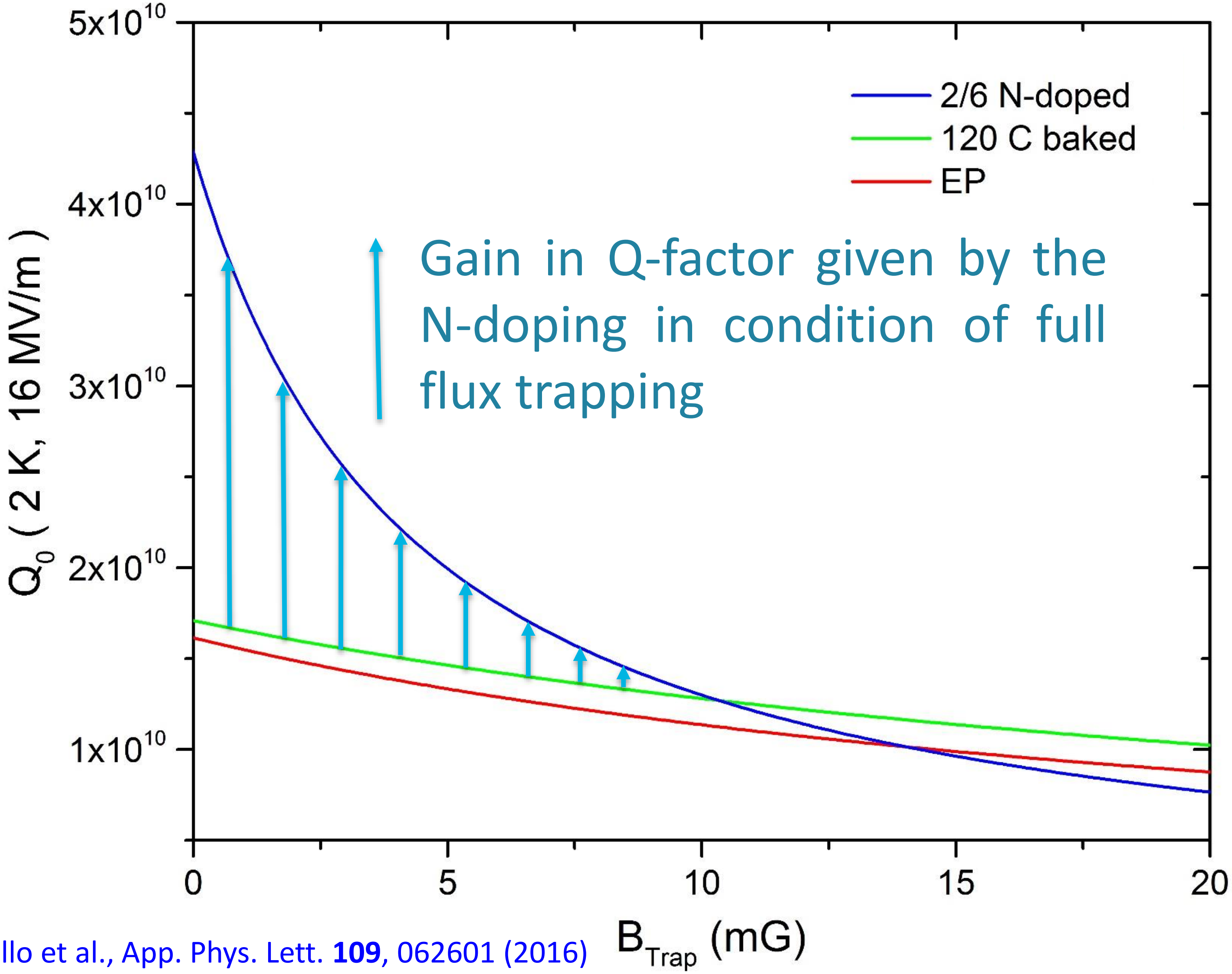
$$S = \frac{R_{Fl}}{B_{Trap}}$$

- Bell-shaped trend of S as a function of mean free path
- N-doping cavities present higher sensitivity than standard treated cavities
- **Light doping is needed to minimize trapped flux sensitivity**



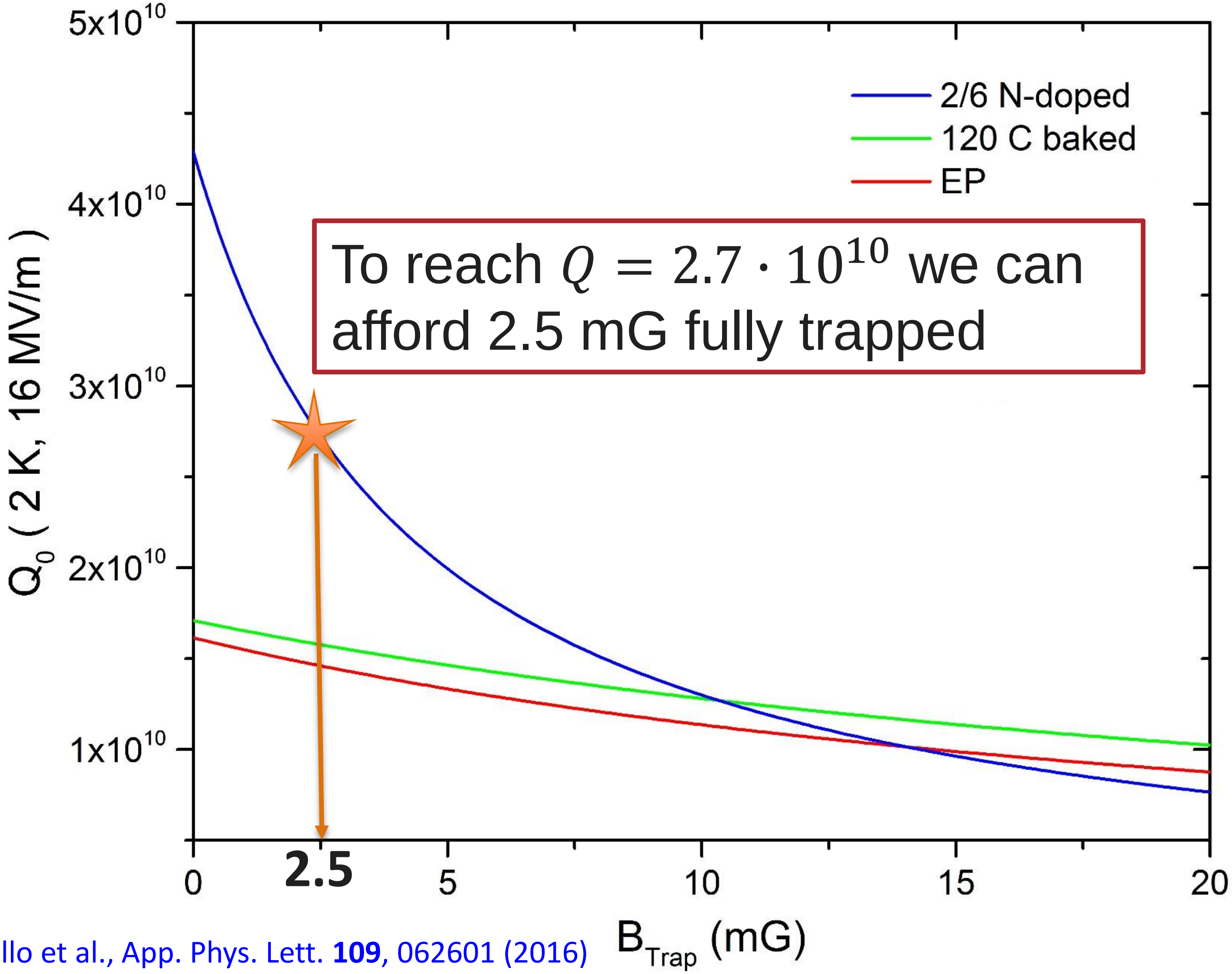
M. Martinello et al., App. Phys. Lett. **109**, 062601 (2016)
M. Checchin et al., Supercond. Sci. Technol. 30, 034004 (2017)
D. Gonnella et al., J. Appl. Phys. **119**, 073904 (2016)

The advantage of N-doping in condition of full flux-trapping



M. Martinello et al., App. Phys. Lett. **109**, 062601 (2016)

Example with LCLS-II specifications

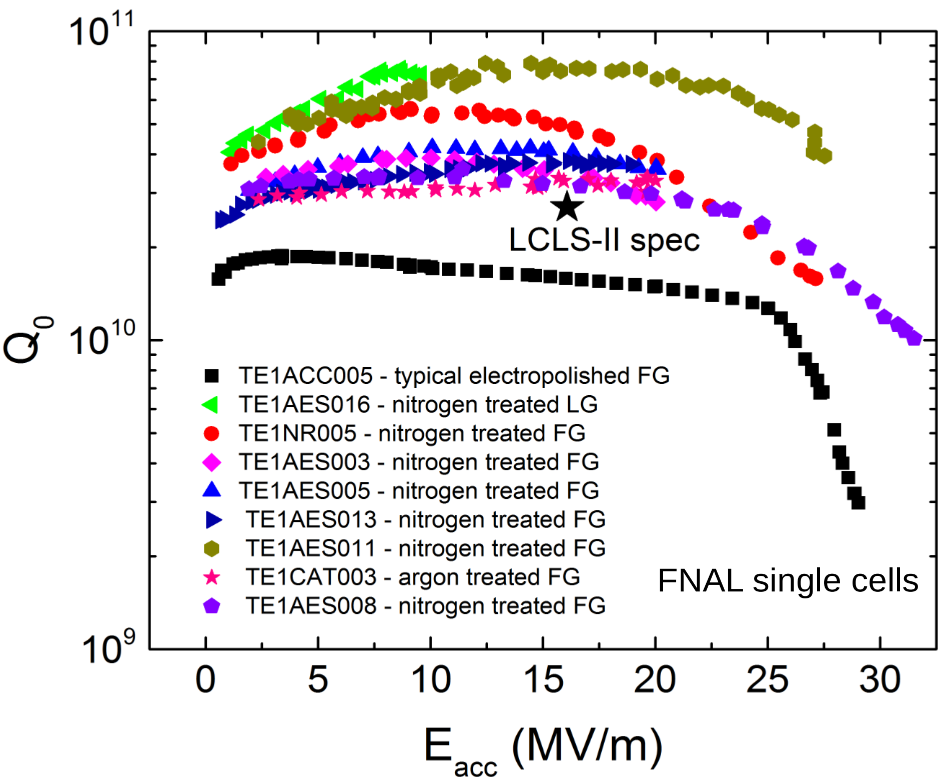


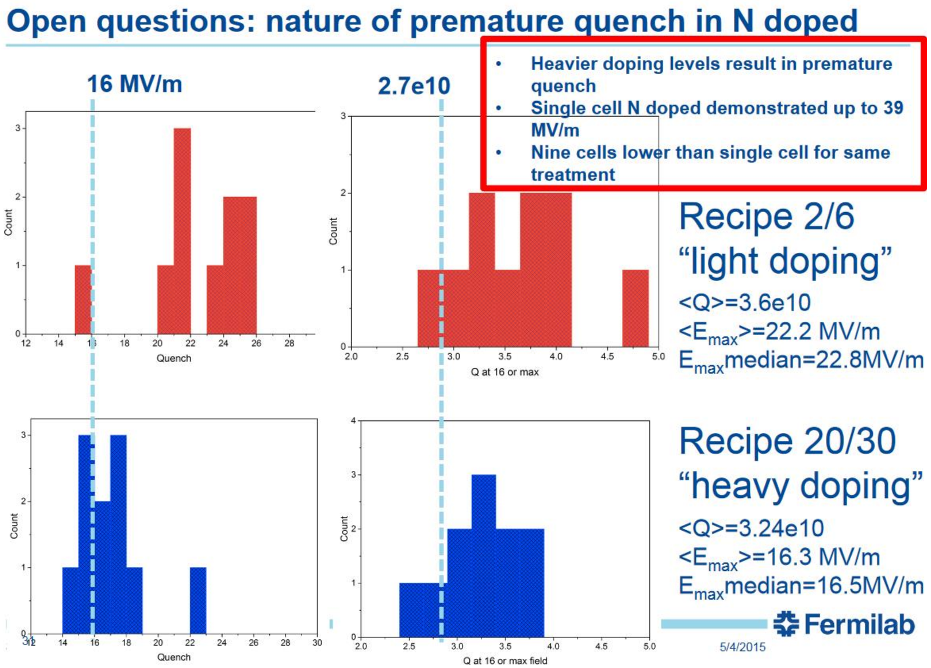
To reach $Q = 2.7 \cdot 10^{10}$ we can afford 2.5 mG fully trapped

M. Martinello et al., App. Phys. Lett. **109**, 062601 (2016)

The path to the production Stage

Optimization of N-doping recipe in single-cell cavities





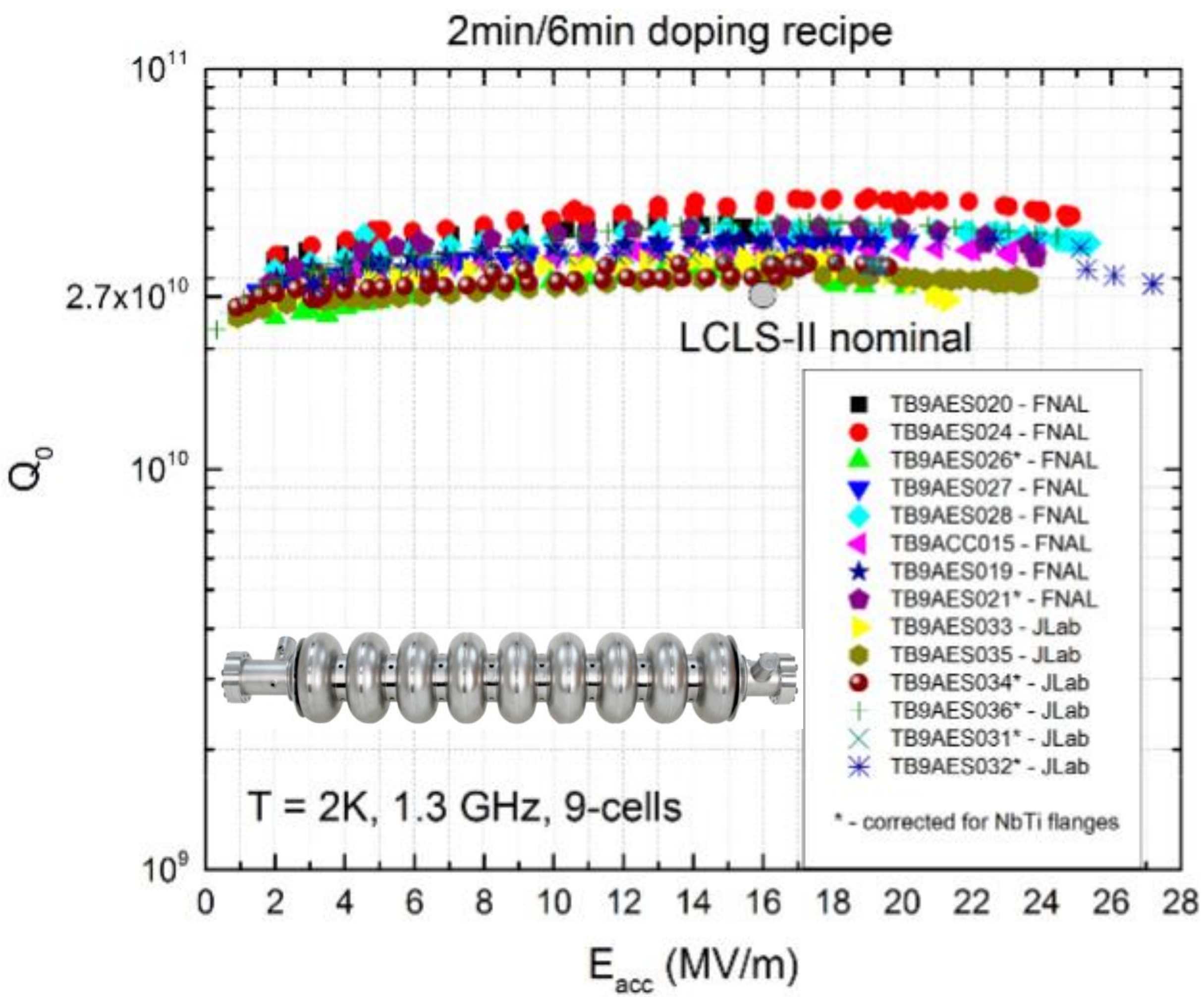
→ <u>2/6 recipe best in terms of both Q and Eacc:</u>

$\langle Q \rangle = 3.6 \cdot 10^{10}$ (the lower sensitivity helps to avoid drastic deterioration)

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

2/6 doping transferred on 9-cells

FNAL/JLAB 9-cell cavities with 2/6 doping recipe



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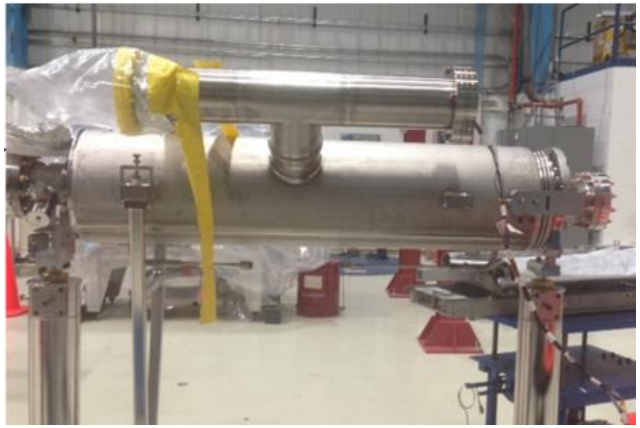
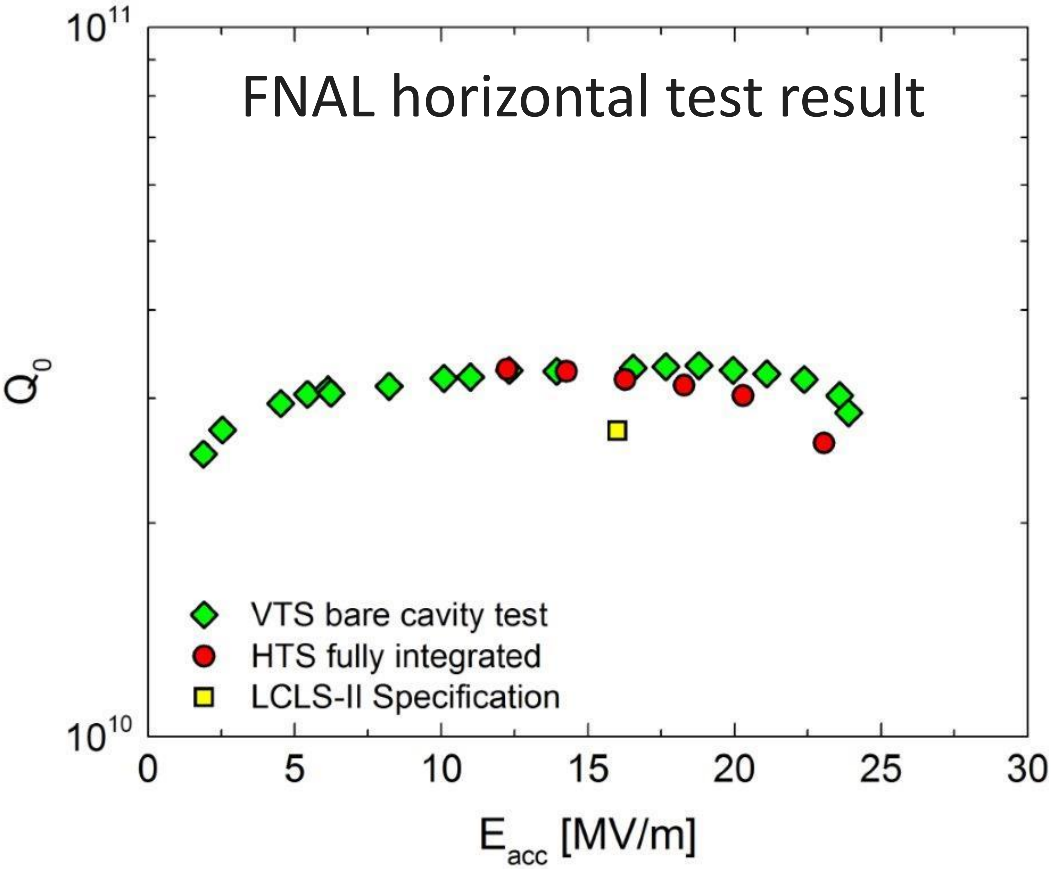
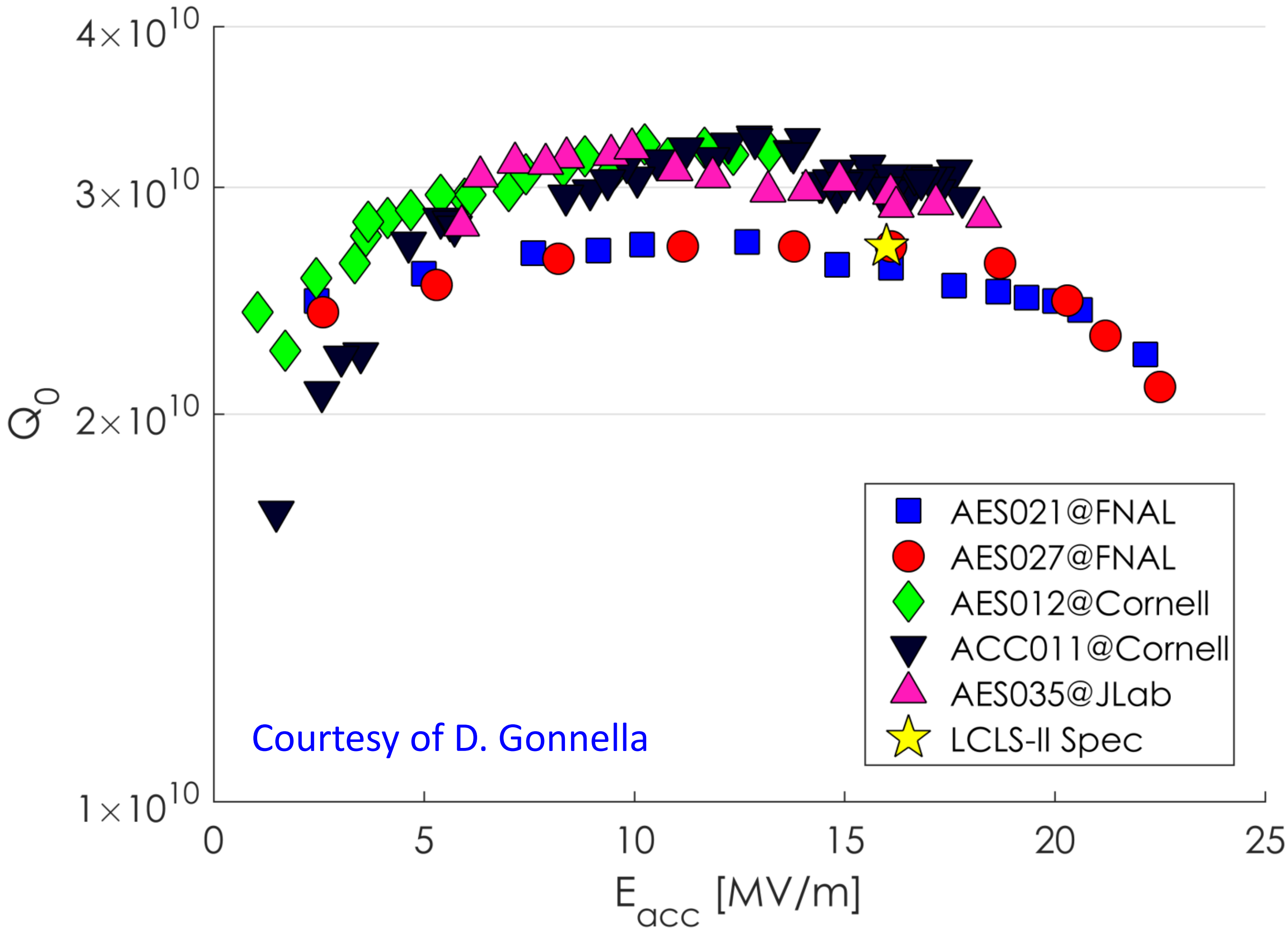
Demonstration in a cryomodule-like environment



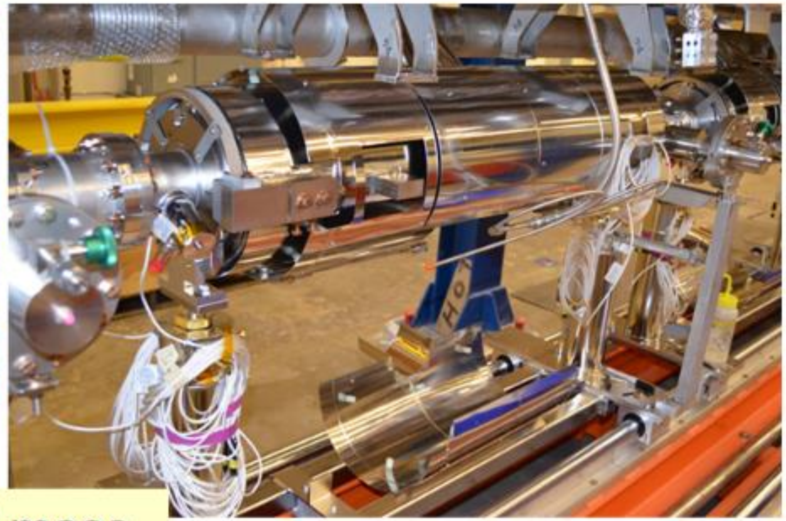
Q can be perfectly preserved from bare cavity test to fully jacketed state with RF ancillaries, in cryomodule environment



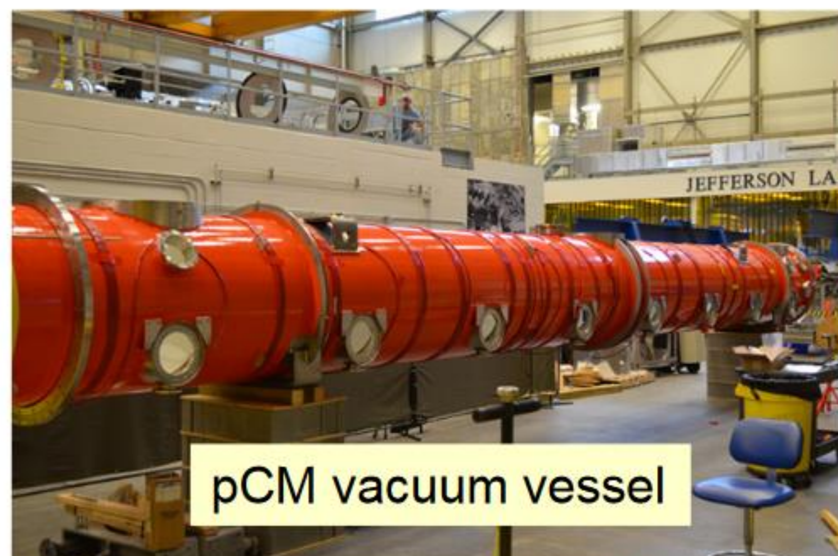
Horizontal dressed cavity tests at FNAL, Cornell, Jlab Meeting final LCLS-2 specs in cryomodule environment!



Prototype CM at JLab:



pCM cold mass

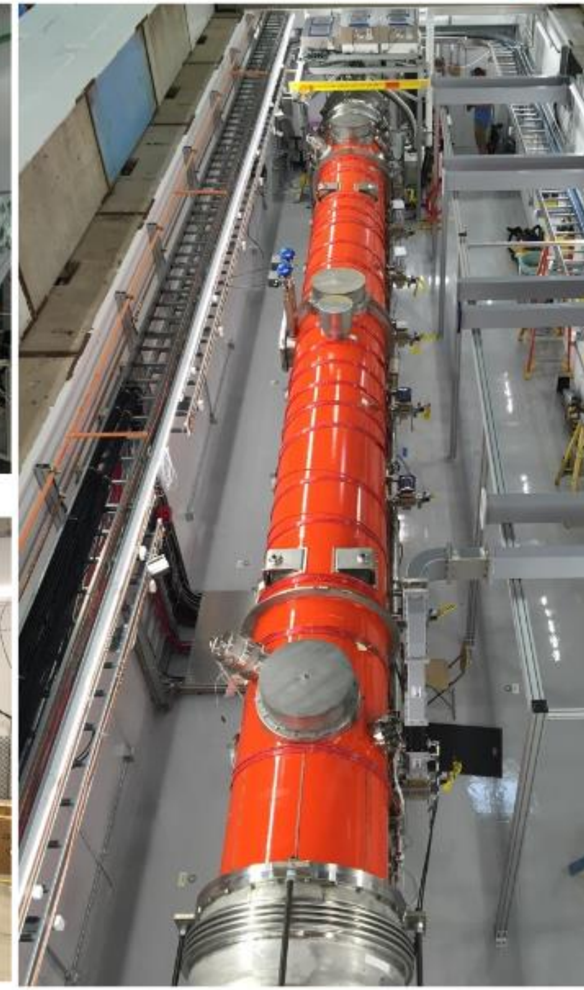


pCM vacuum vessel

Prototype CM at Fermilab:

Transport

Staging Area



pCM in Fermilab
Test Area

TUPLR007 LCLS-II Cryomodules Production at Fermilab

FNAL prototype LCLS-II cryomodule results

Fermilab Prototype LCLS-II Cryomodule

Cavity	Usable Gradient* [MV/m]	Q0 @16MV/m* 2K Fast Cool Down
TB9AES021	18.2	2.6E+10
TB9AES019	18.8	3.1E+10
TB9AES026	19.8	3.6E+10
TB9AES024	20.5	3.1E+10
TB9AES028	14.2	2.6E+10
TB9AES016	16.9	3.3E+10
TB9AES022	19.4	3.3E+10
TB9AES027	17.5	2.3E+10
Average	**18.2**	**3.0E+10**
Total Voltage	**148.1 MV**	

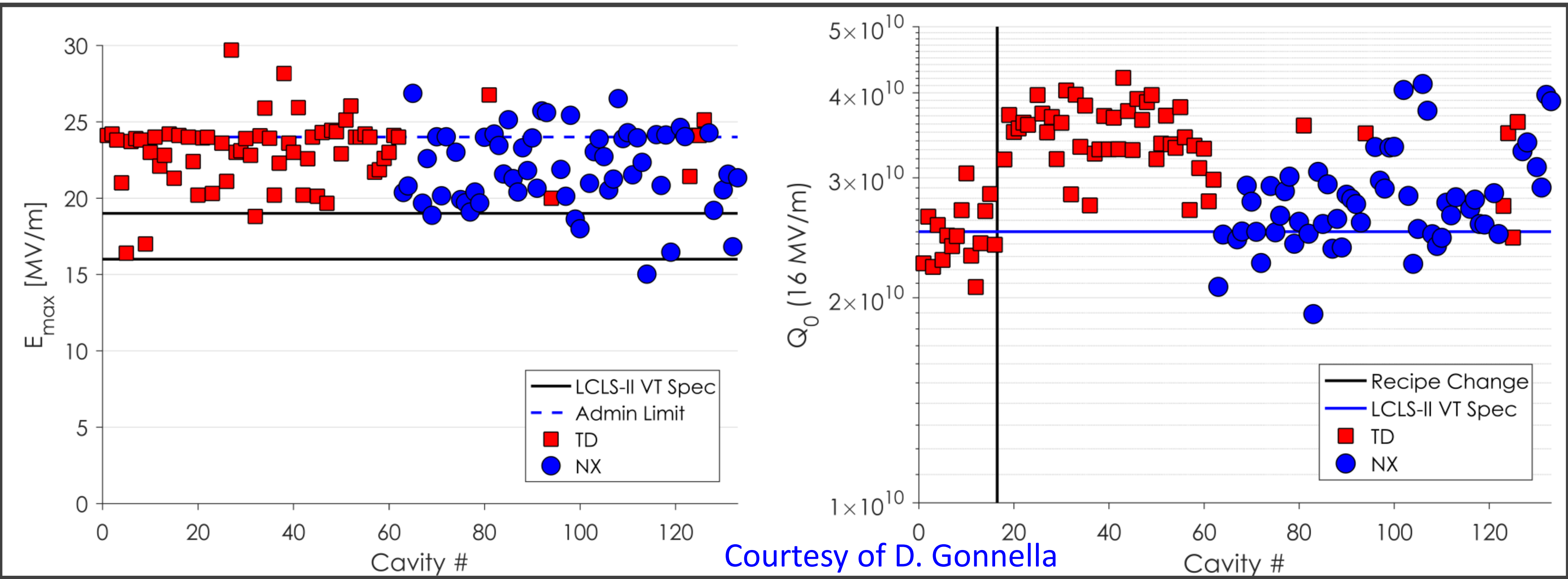
Spec: 133 MV

Spec: 2.7×10^{10}

LCLS-II Production cavities

- 2 vendors for LCLS-II cavity production: Research Instruments (RI) and Ettore Zanon (EZ)
- N-doping successfully transferred to industry (effort leads by JLAB)
- More than 100 production cavities tested between FNAL and JLAB

See also D. Gonnella talk: "LCLS-II High Q0 Cavities: Lessons Learned"



Courtesy of D. Gonnella

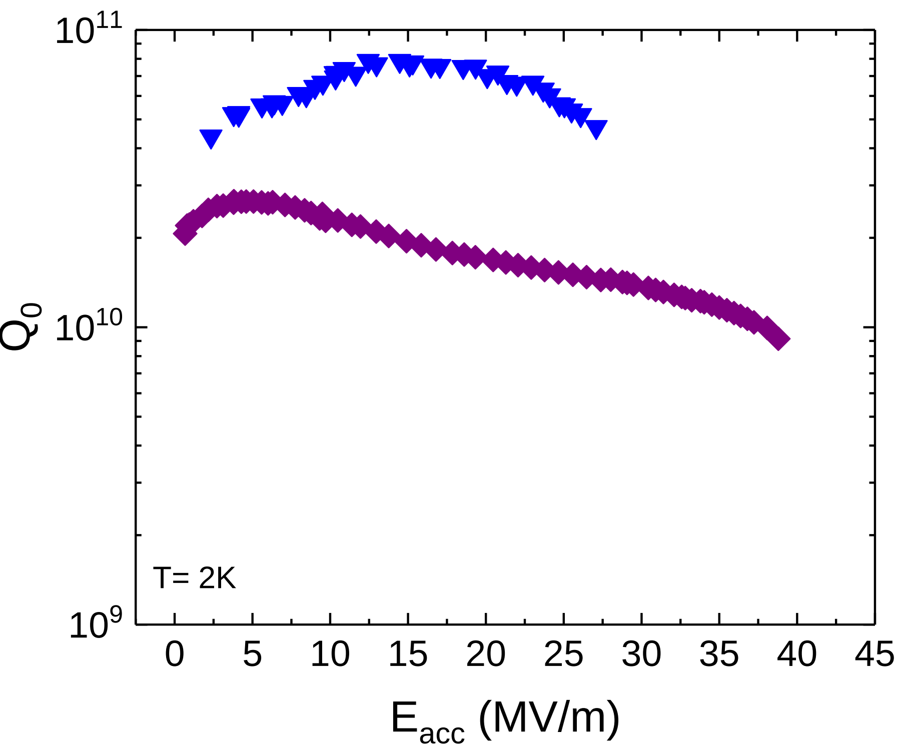
N-infusion for high-Q at high gradients

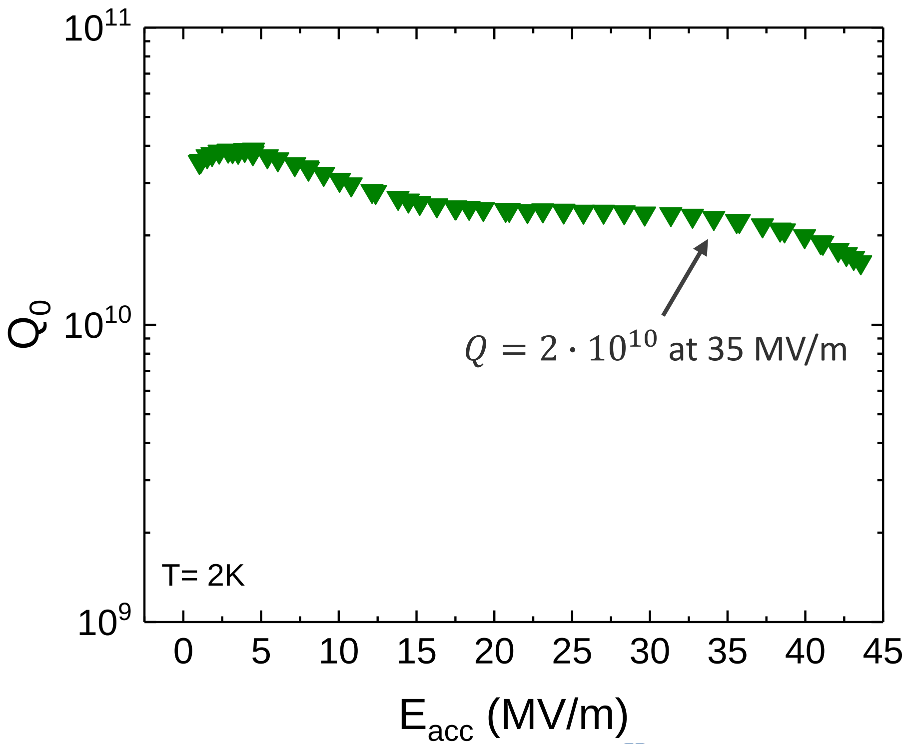
Motivation behind experiments

Composition and mean free path in first nanometers of cavity surface have been shown to be crucial for both Q and gradient performance

N Doping (high-Q)
+
120C baking (high gradients)

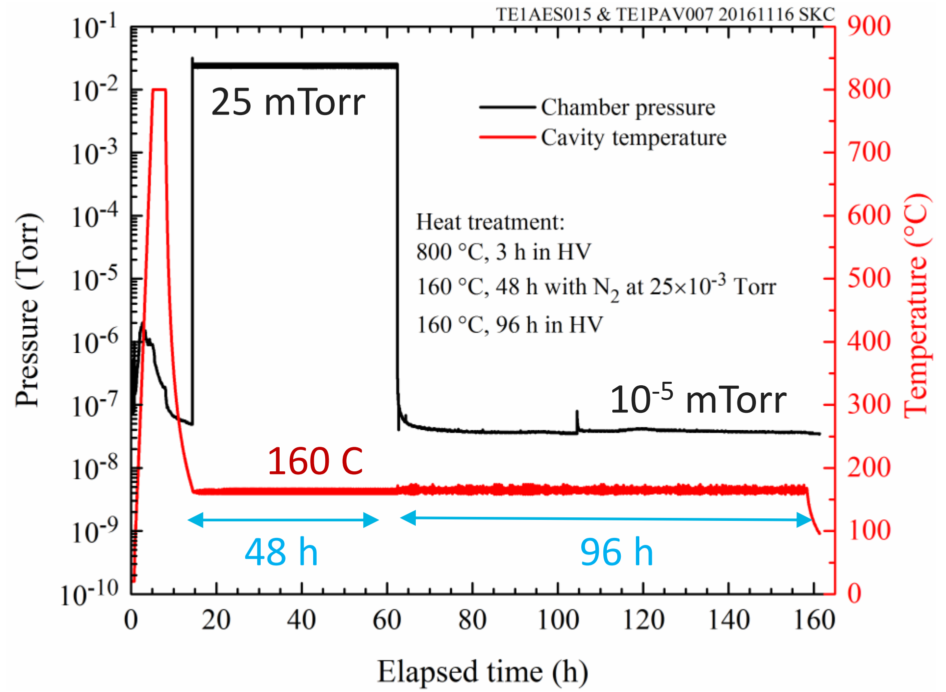
N-infusion: high-Q at high gradient

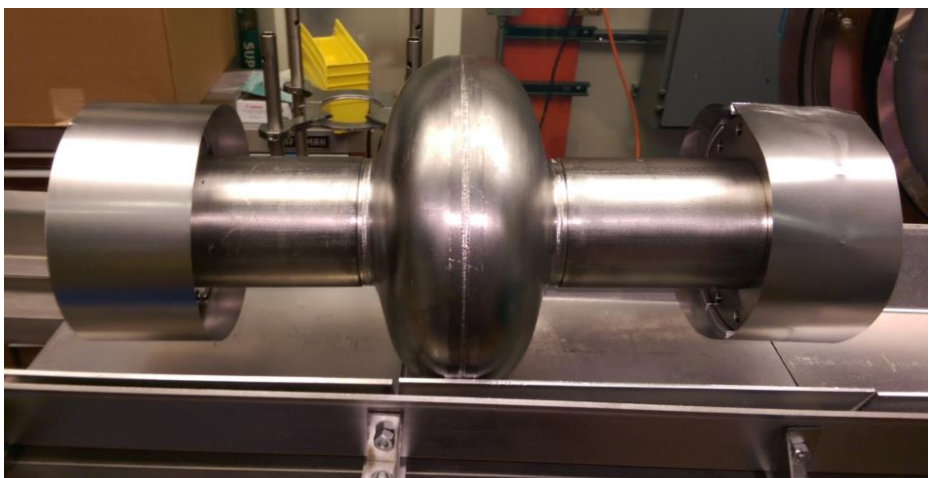




Example of N-infusion processing sequence

- Bulk electro-polishing
- High T furnace (with caps to avoid furnace contamination):
  - 800C 3 hours HV
  - 120-160C 48 hours with N_2 (25 mTorr)
- NO chemistry post furnace
- HPR, VT assembly





Protective caps and foils are BCP'd prior to every furnace cycle and assembled in clean room, prior to transporting cavity to furnace area

A. Grassellino *et al.*, **arXiv:1305.2182**

A. Grassellino et al 2017 Supercond. Sci. Technol. **30** 094004

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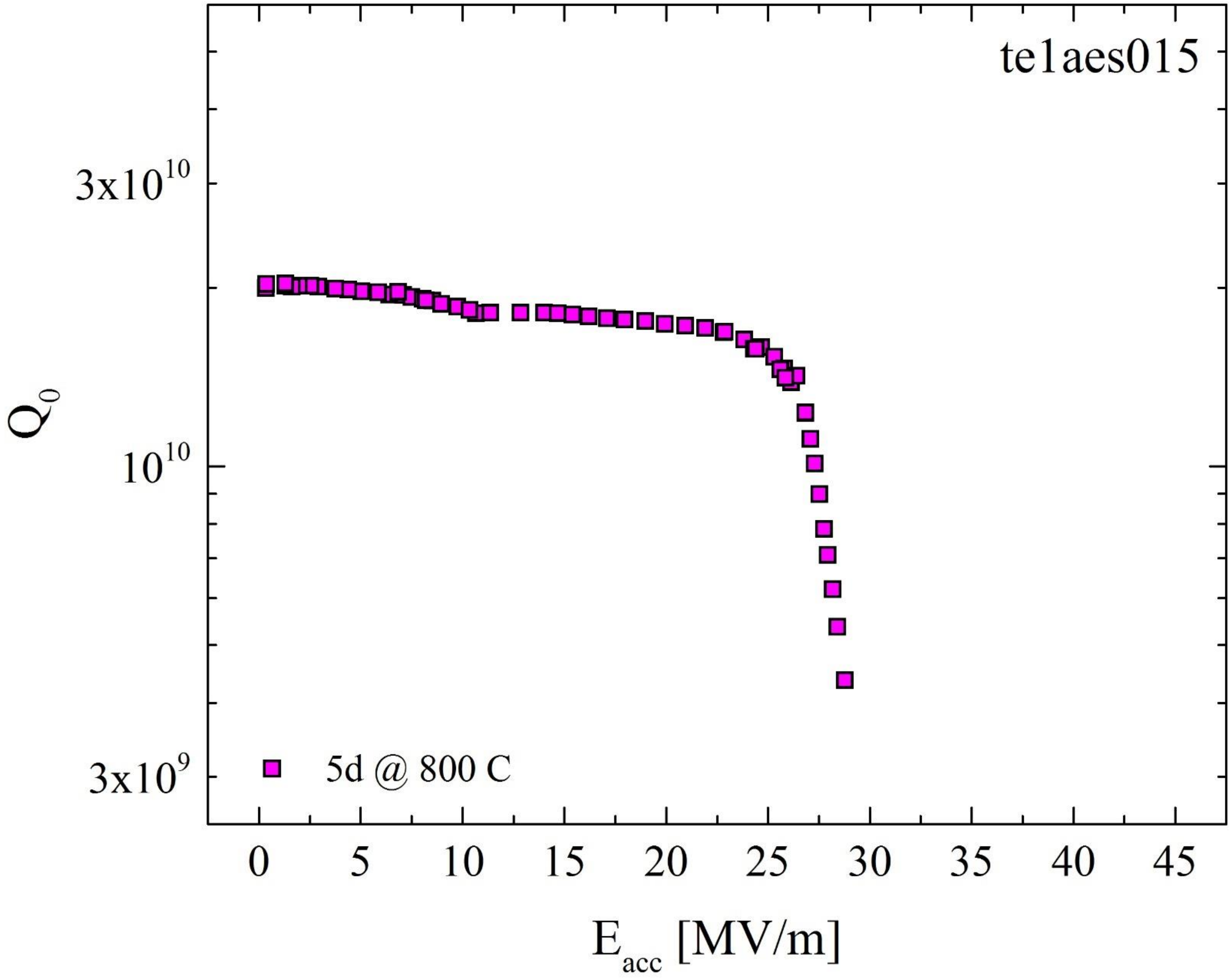
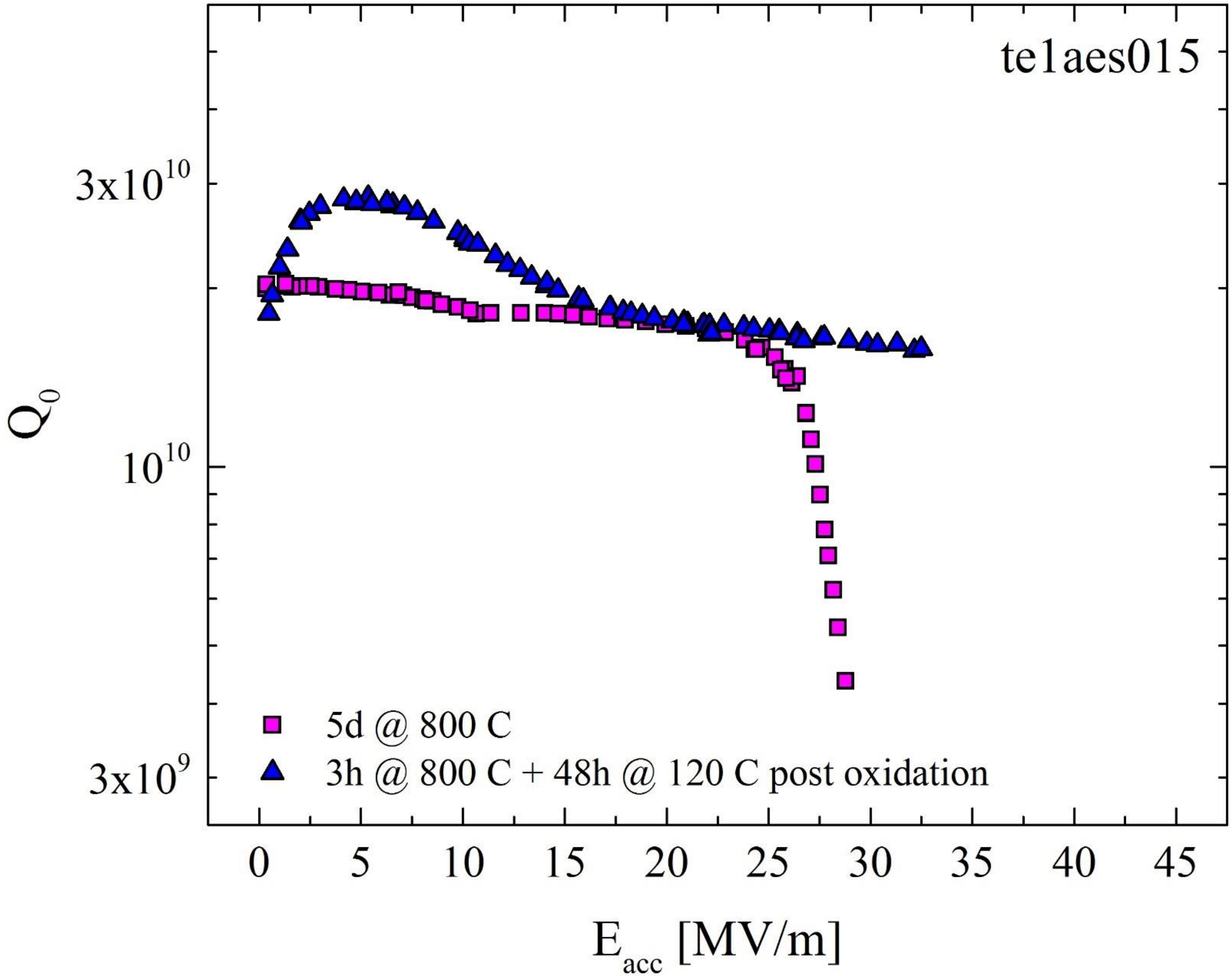
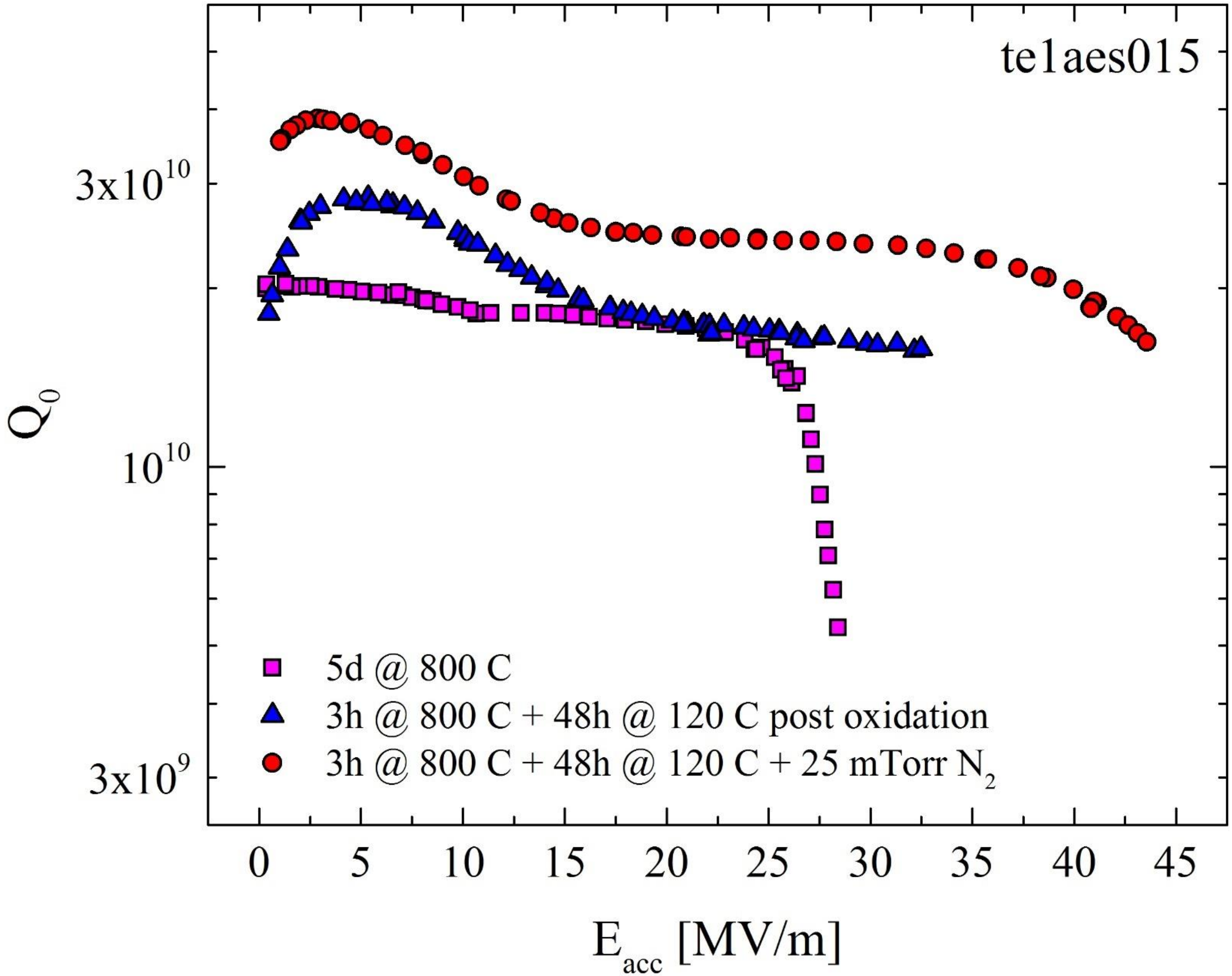
Cavity evolution- EP



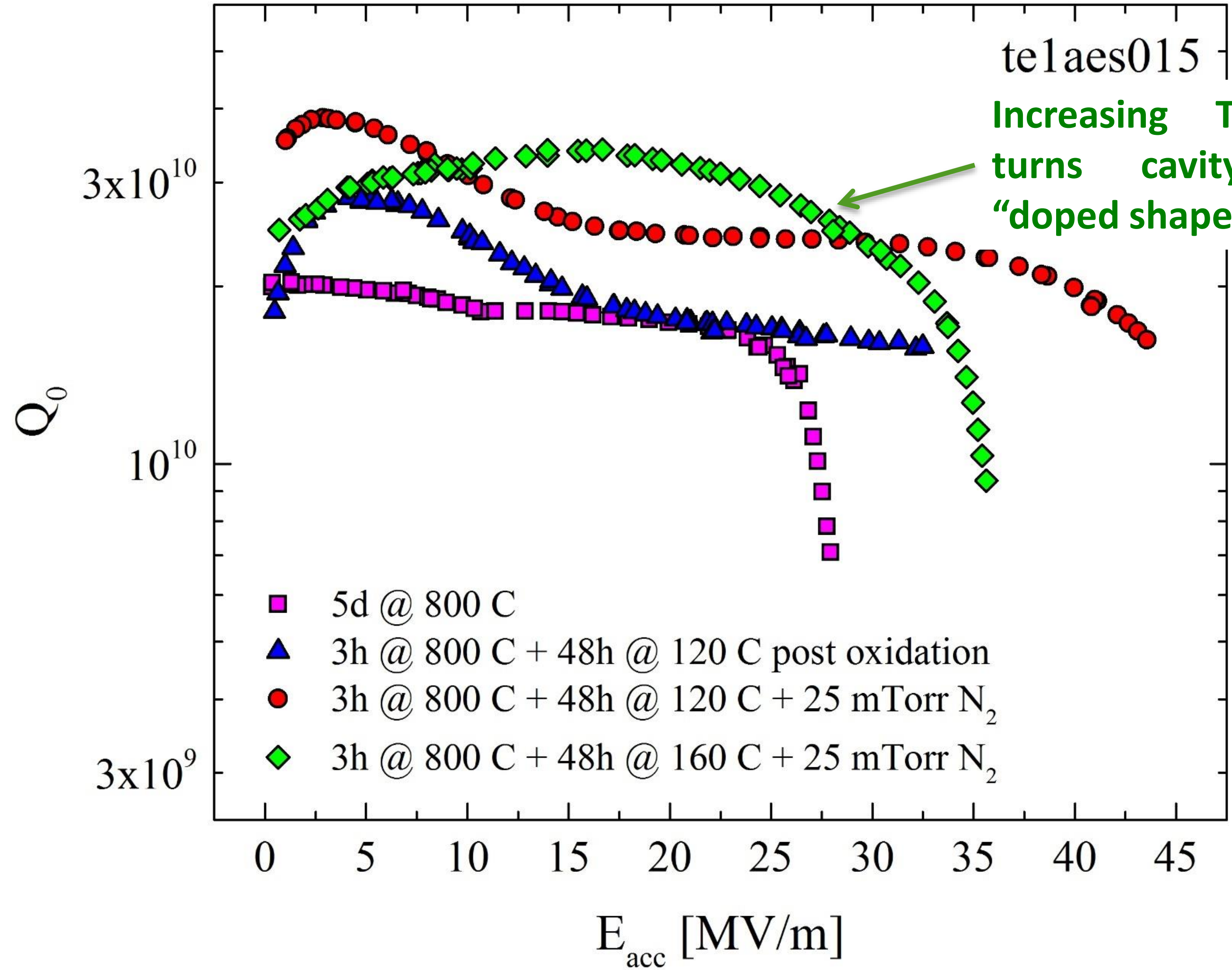
Cavity evolution – 120C baking



Cavity evolution – 120C N-infusion



Cavity evolution – probing the parameter space



Increasing T ~40C turns cavity into "doped shape"!

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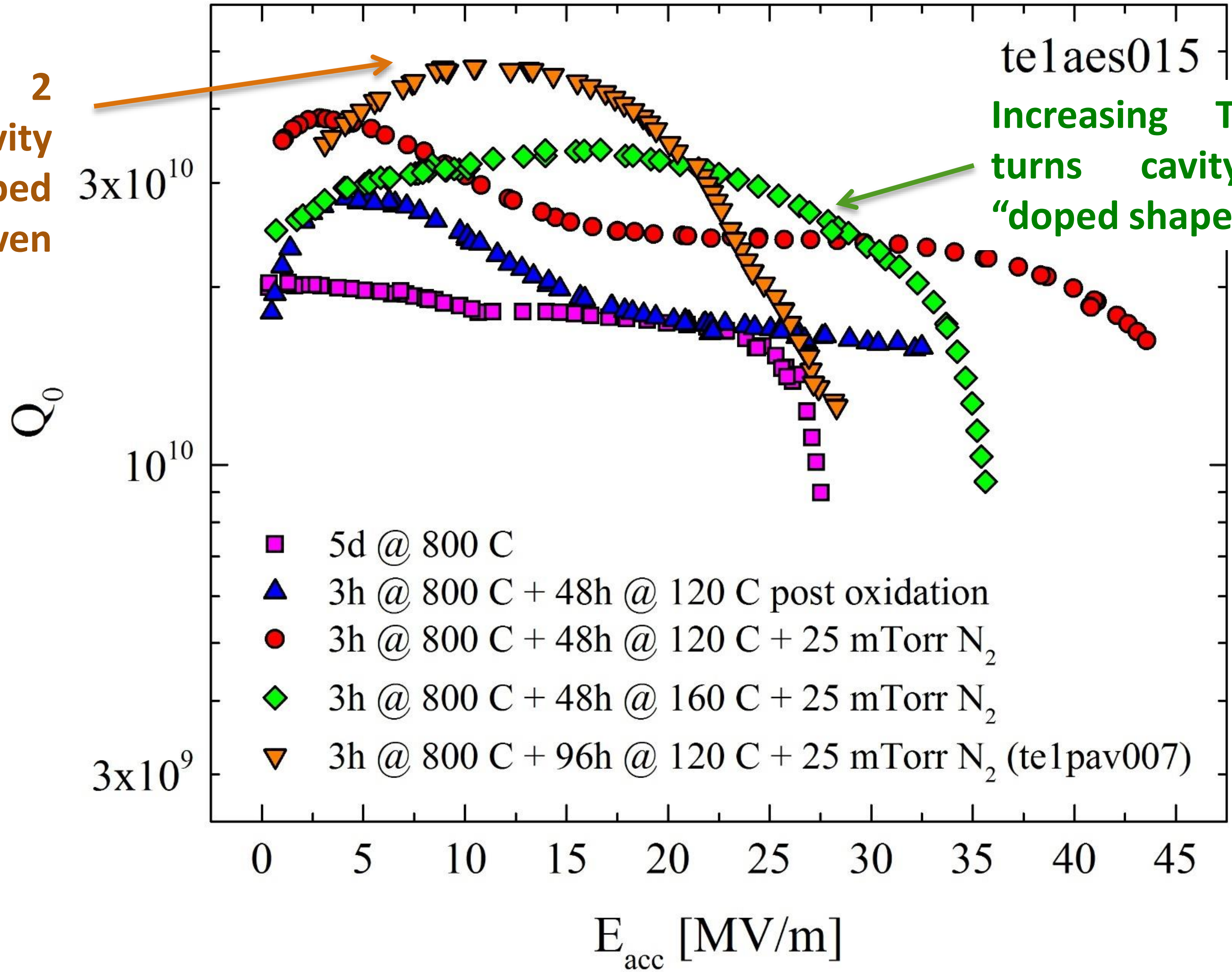
Cavity evolution – probing the parameter space

Increasing duration x 2 turns cavity into “doped shape”, even higher Q!



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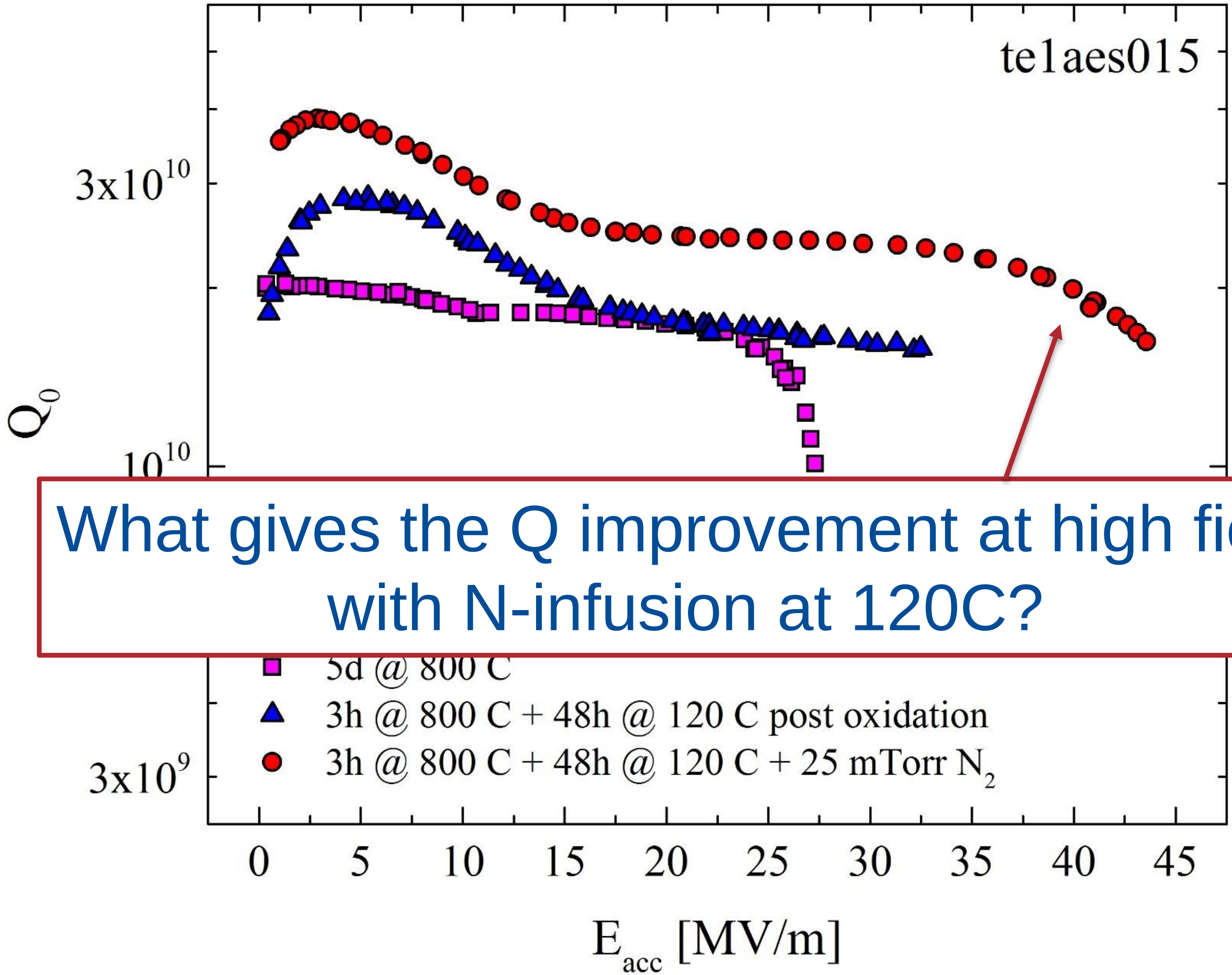
Cavity evolution – 120C N-infusion



What gives the Q improvement at high field with N-infusion at 120C?

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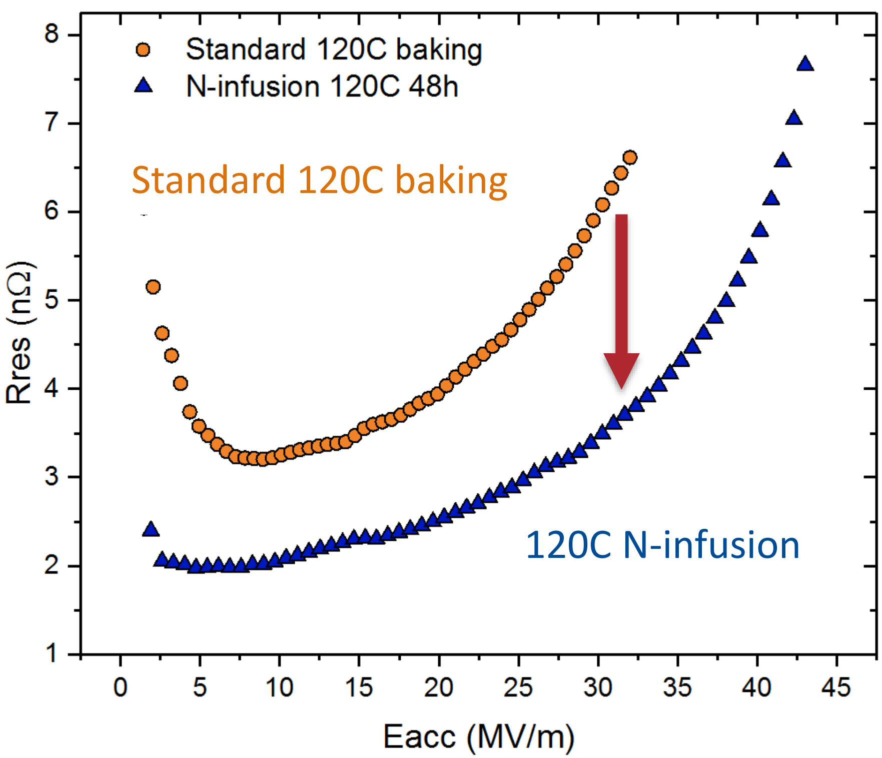
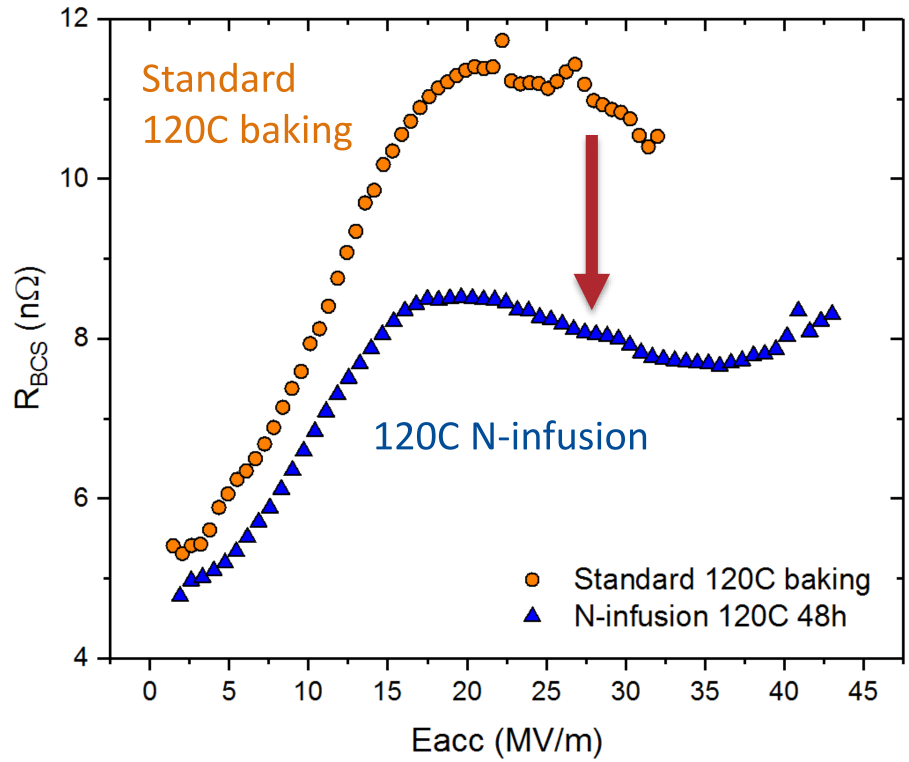
What gives the Q improvement at high field with 120C infused?

Improvement stems from both lower residual and lower BCS surface resistance





A. Grassellino et al 2017 Supercond. Sci. Technol. **30** 094004

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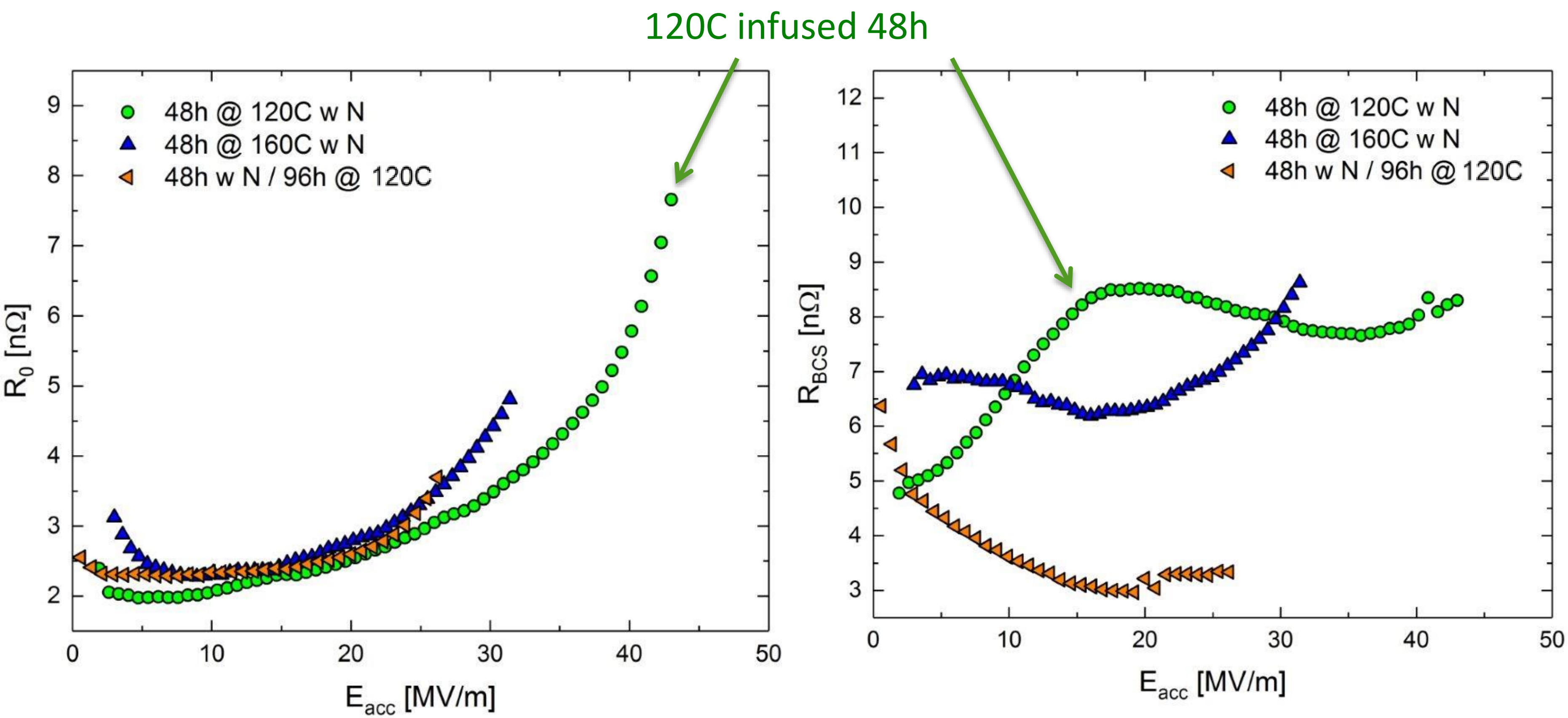
What gives the Q improvement at high field with longer duration/higher T N-infused?

Improvement stems from both lower residual and lower BCS surface resistance



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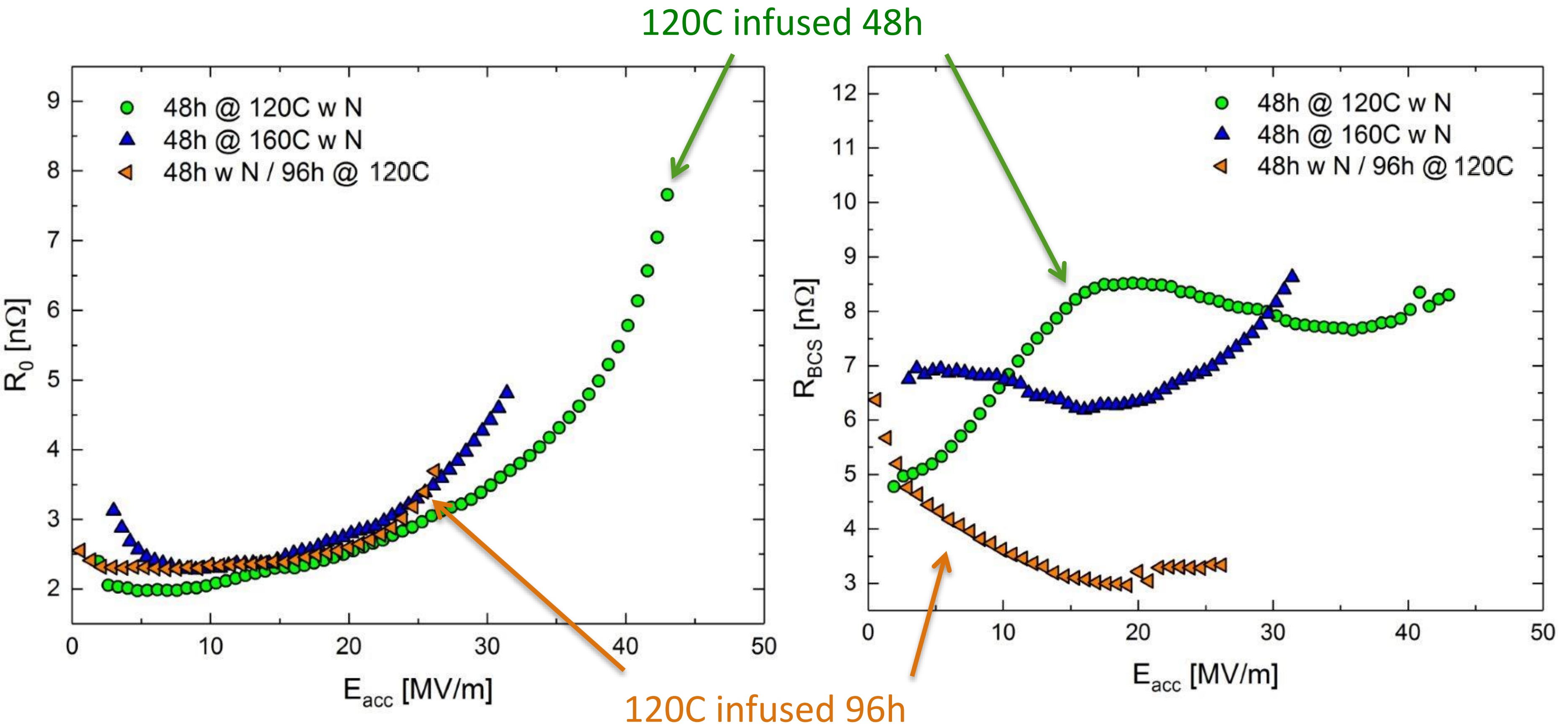

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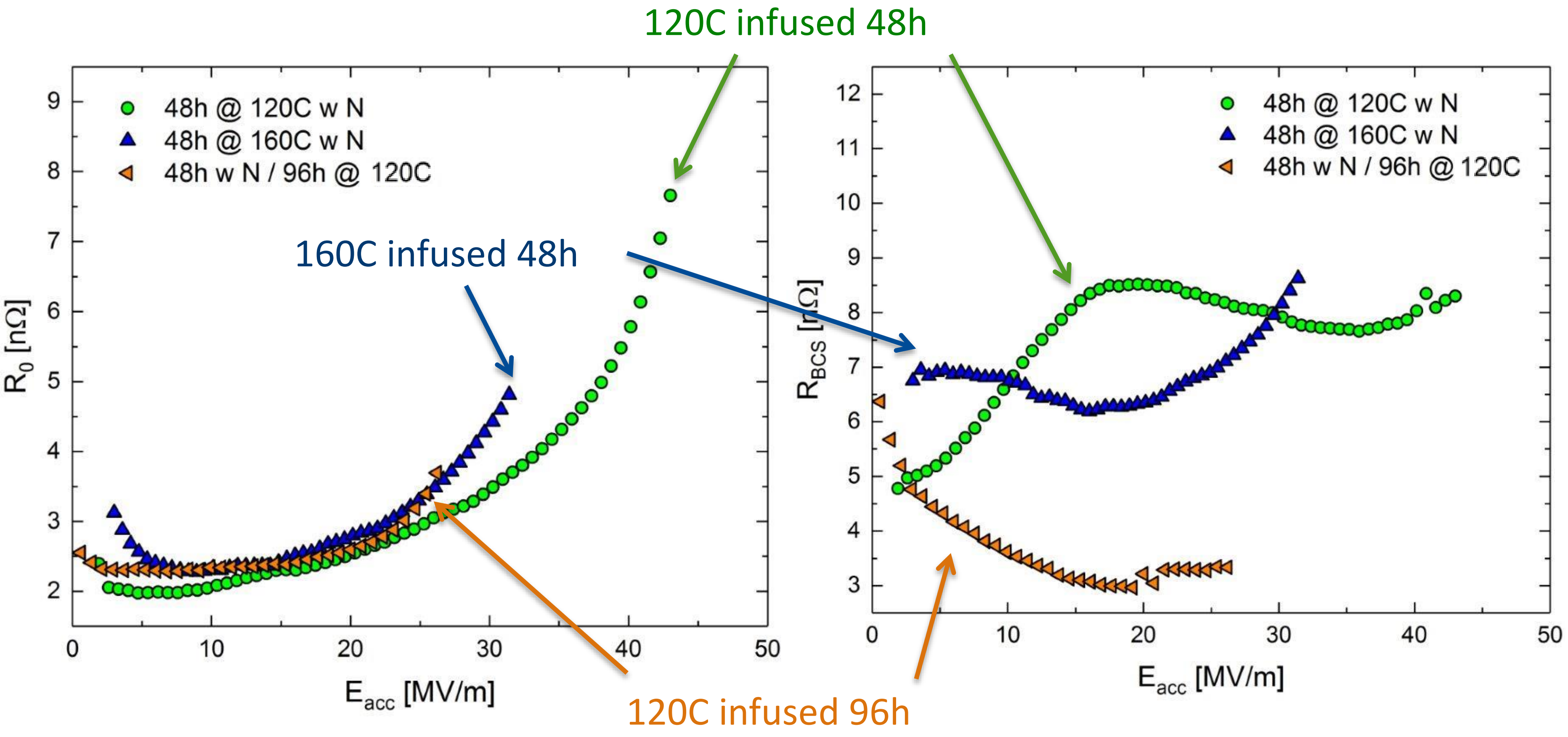

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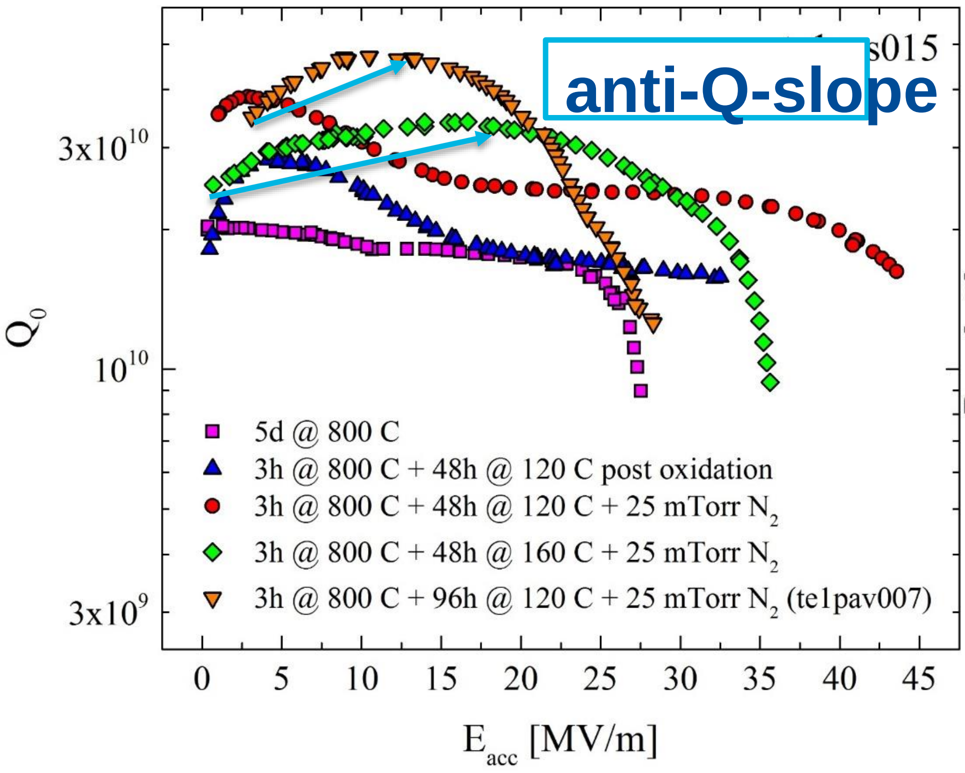
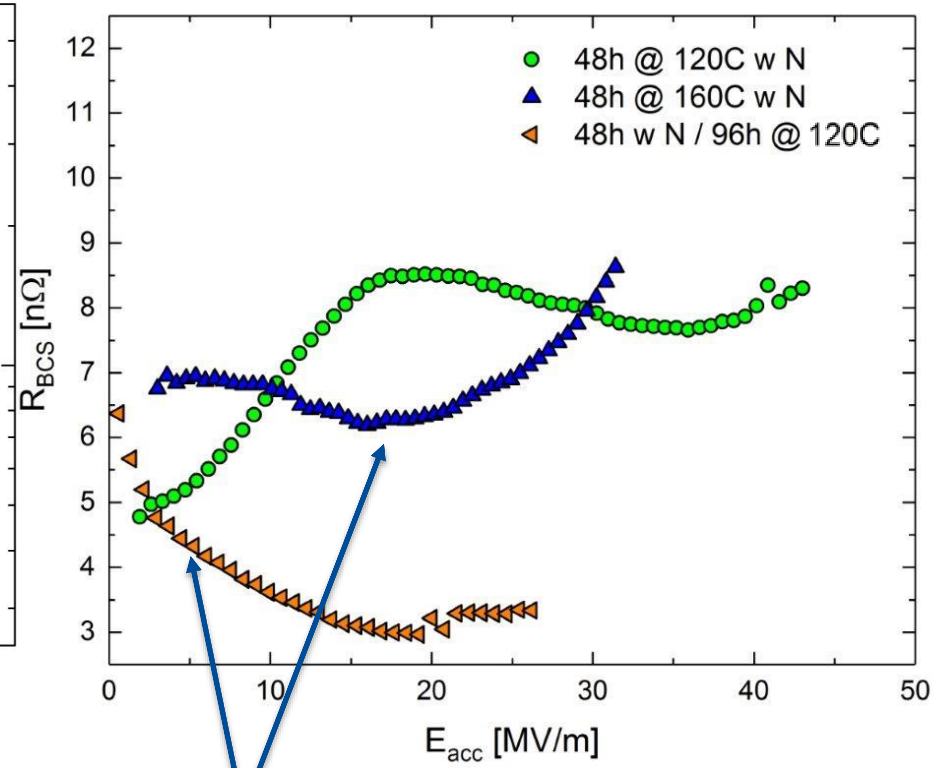


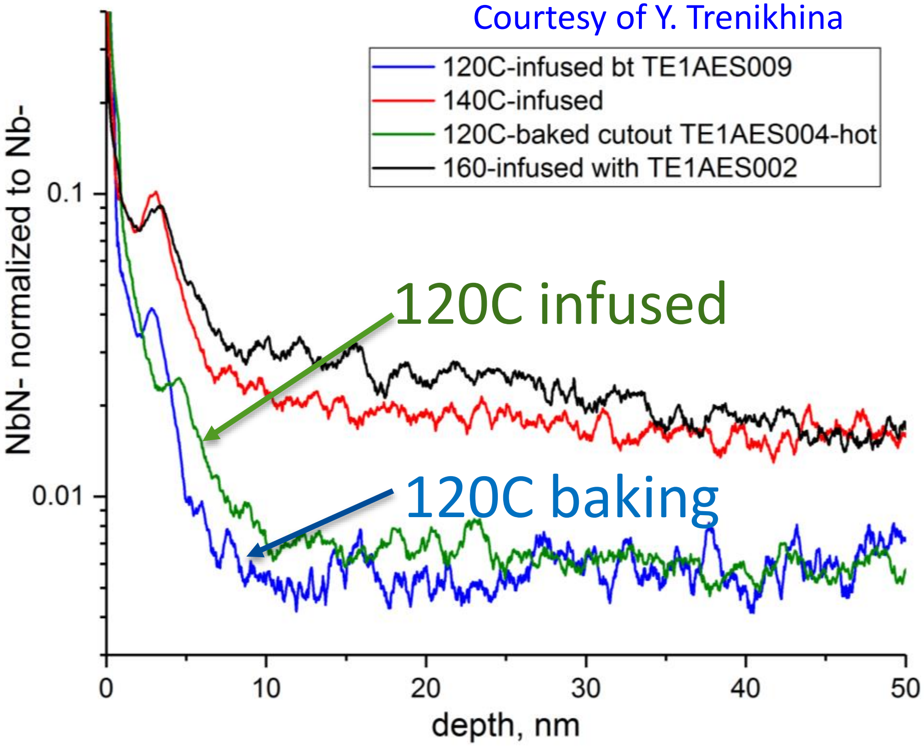


The decreasing of R_{BCS} with the field allows the manifestation of the **anti-Q-slope**

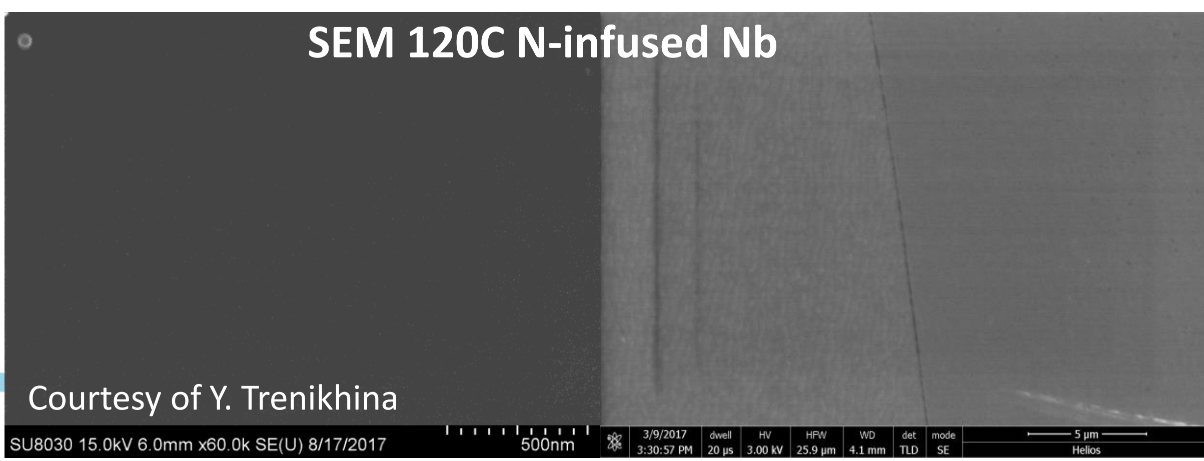
Fermilab

Nitrogen role in 120C N-infusion

Courtesy of Y. Trenikhina



- Small ($\sim 10 - 15\,nm$) N_2 enriched layer below native oxide
- SIMS data suggest that performances are related to the first nm from the RF surface
- Being investigated with subsequent HF rinsing experiment

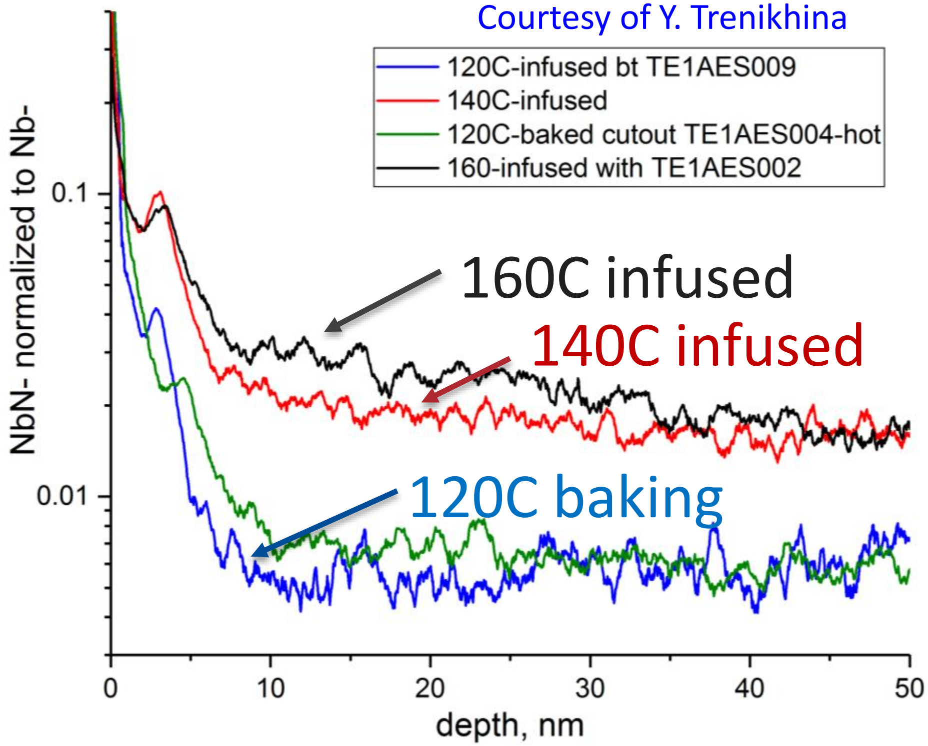


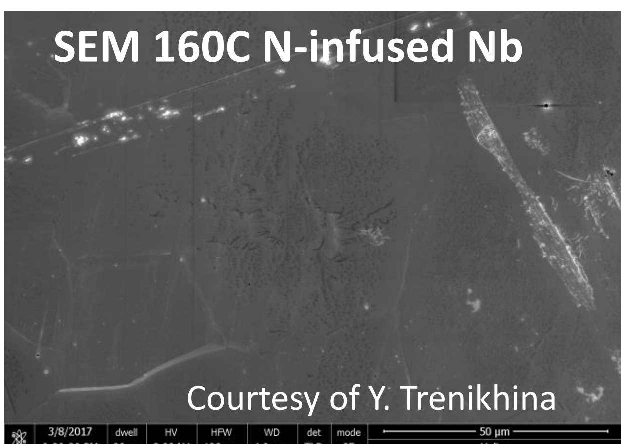
No (clear) nitrides formation at the RF surface

Fermilab

Nitrogen role in 140/160C N-infusion

Courtesy of Y. Trenikhina



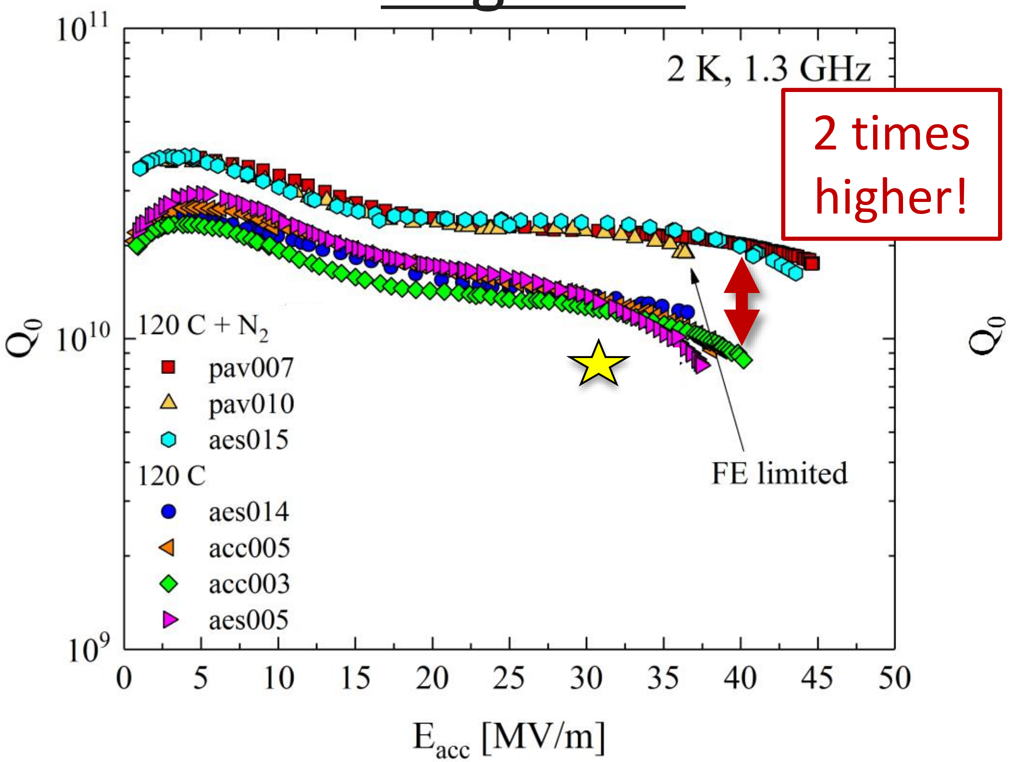


No (clear) nitrides formation at the RF surface

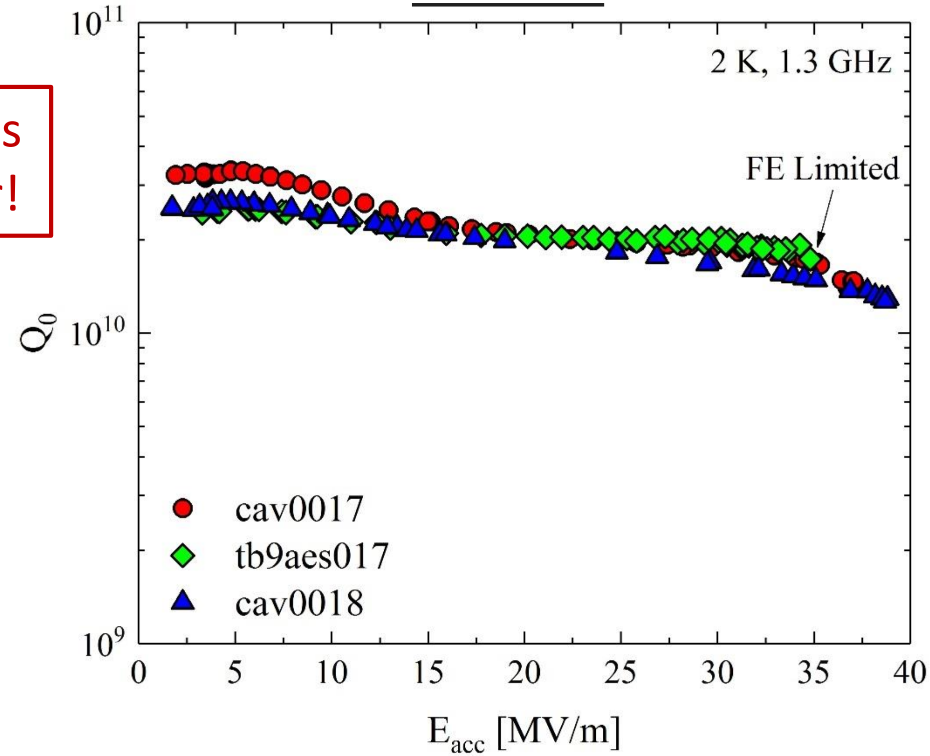
- Higher N_2 background than not infused samples, through the whole penetration depth
- Very similar to N_2 signal after EP in N-doped samples
- No (clear!) presence of nitrides at the surface
- Being investigated with subsequent HF rinsing experiment

120 C N-infusion: high Q_0 at high gradients

Single-cell



9-cells



N-Infusion successful also on 9-cell cavities!

A. Grassellino et al 2017 Supercond. Sci. Technol. **30** 094004

120 C N-infusion: high Q_0 at high gradients

RI XFEL: Maximum Gradient Yield (2D)

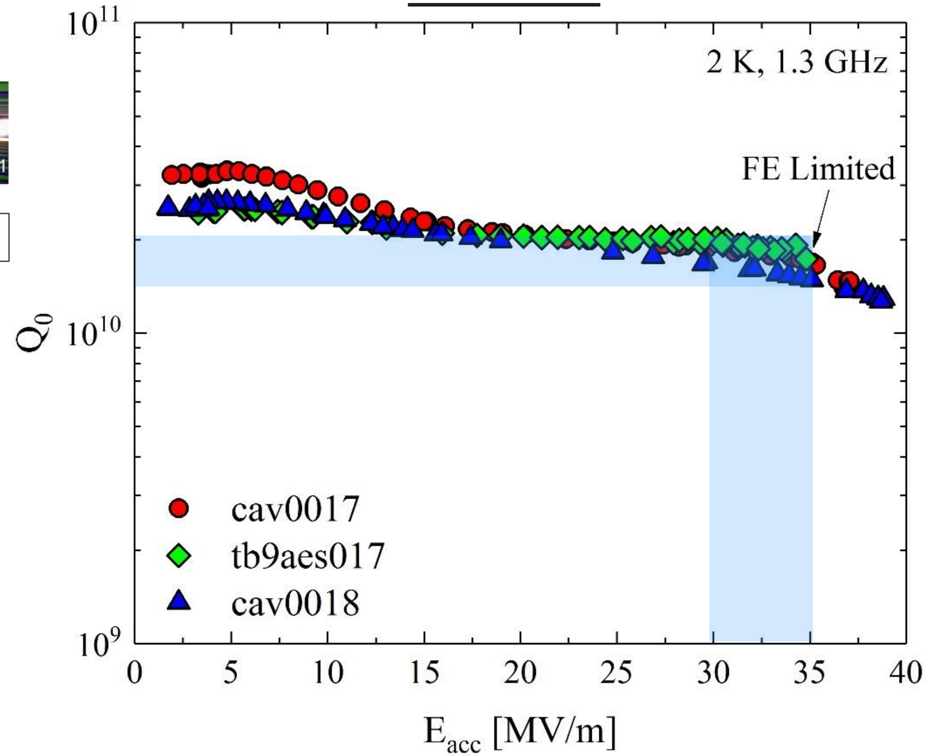
RI XFEL cavities accepted for module assembly
(includes those cavities which have been retreated)

N. Walker

$\geq G_{max}$ MV/m

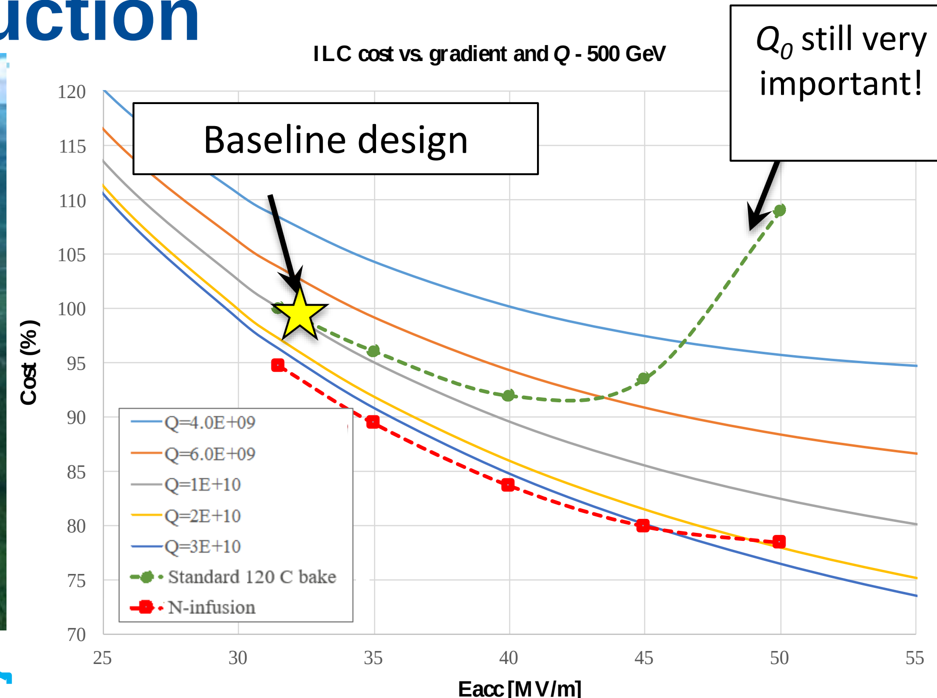
$\geq Q_0$	20	25	30	35	40	45
0.	100%	98%	84%	51%	10%	0%
$5.\times10^9$	98%	97%	84%	51%	10%	0%
$1.\times10^{10}$	31%	30%	25%	15%	6%	0%
XFEL 1.5×10^{10}	1%	1%	1%	1%	0%	0%
$2.\times10^{10}$	0%	0%	0%	0%	0%	0%

9-cells



Compared to this table values for E-XFEL, results of 9-cell N-infused cavities would lay in top 1%

ILC possibility of cost reduction

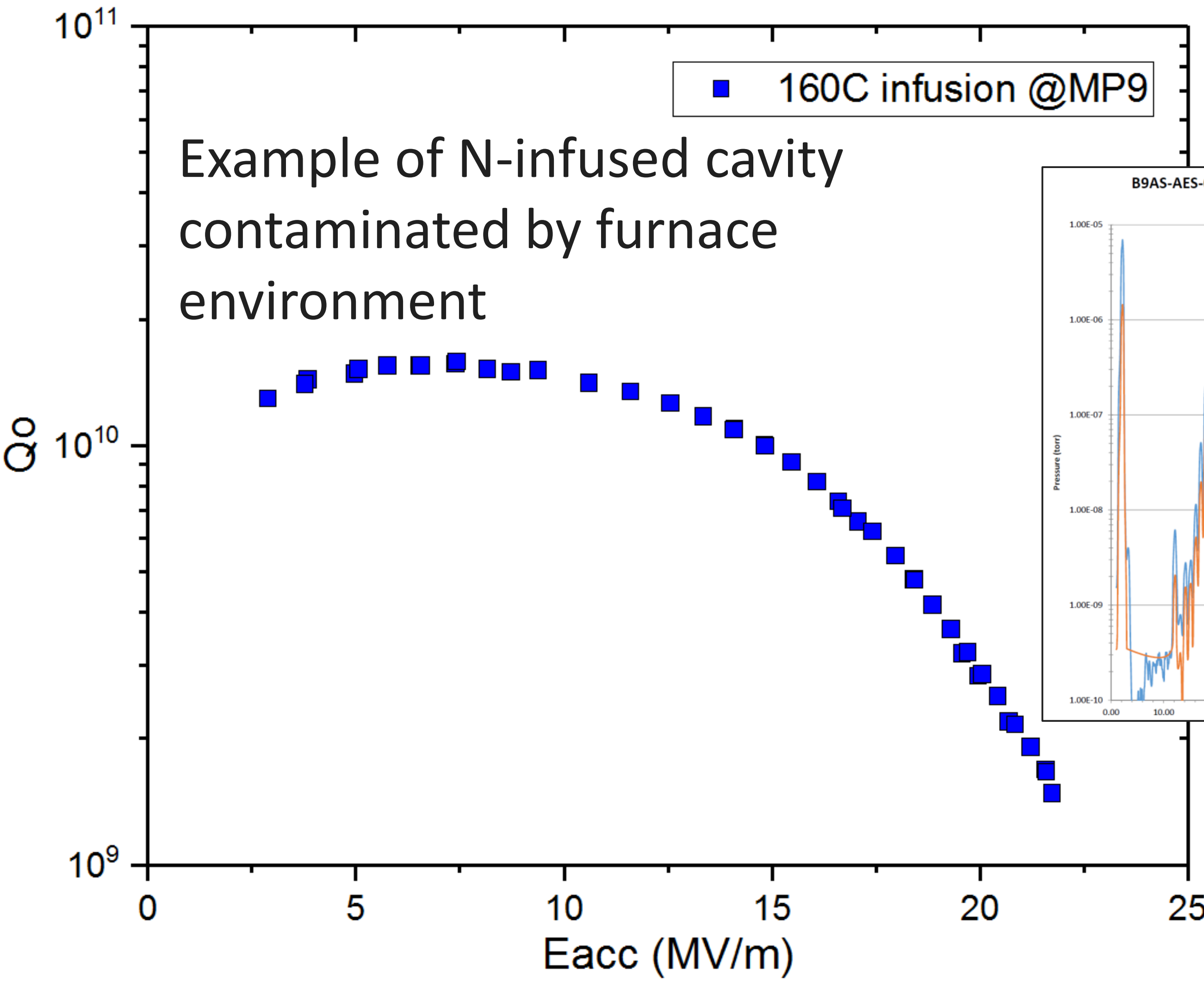


Fermilab

*N-infusion cost reduction takes into account also the difference cost of the processing chain

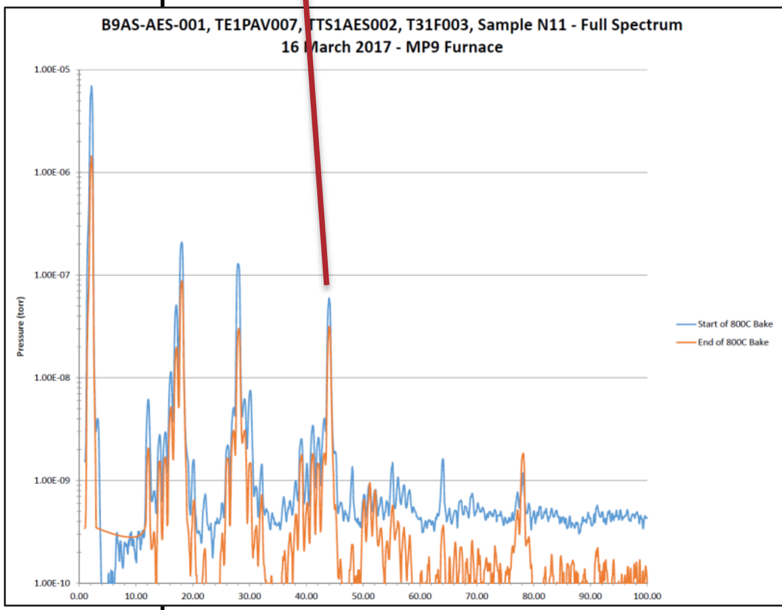
Image from linearcollider.org. Tunnelflug video by European XFEL. Cost analysis by N. Solyak

N-infusion easily affected by furnace contamination



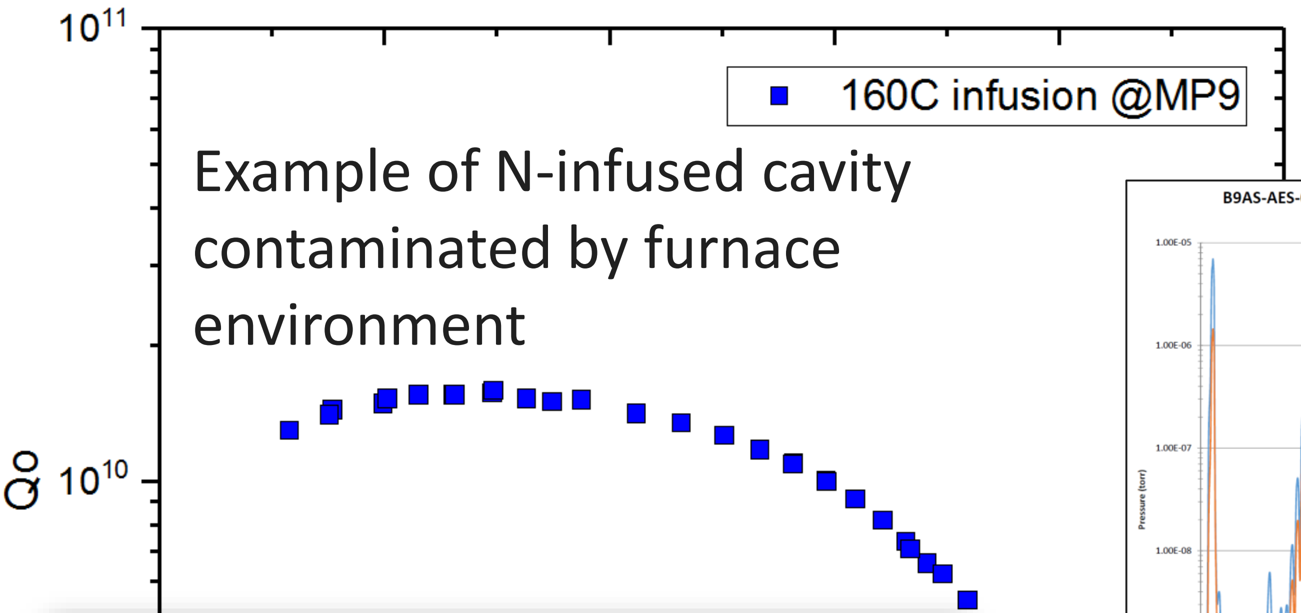
Example of N-infused cavity contaminated by furnace environment

Quite high level of hydrocarbons may be absorbed by the cavity

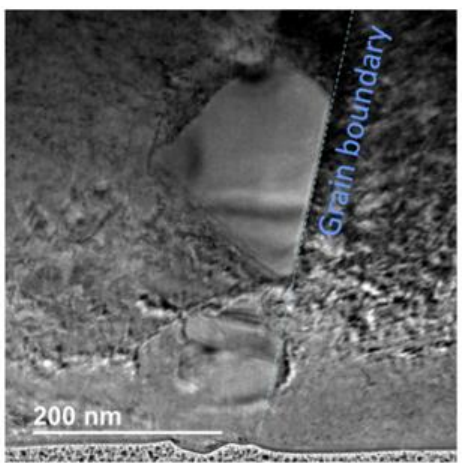


Fermilab

N-infusion easily affected by furnace contamination

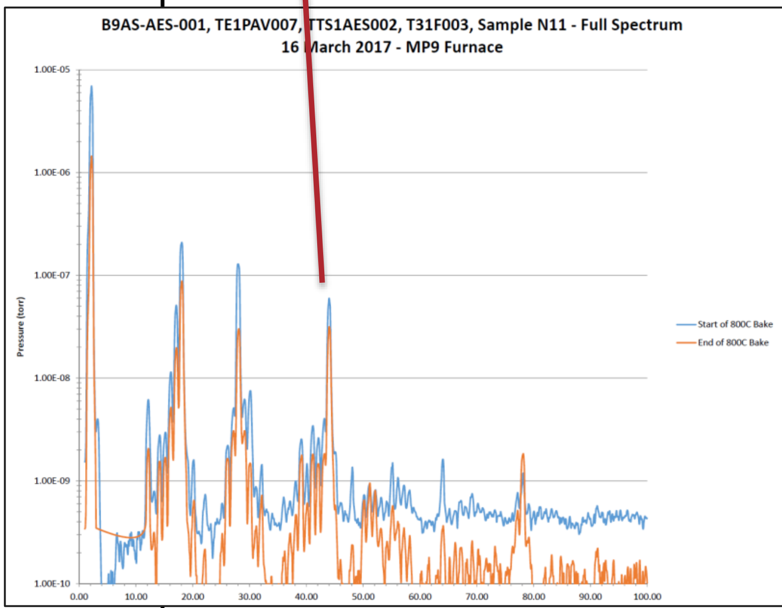


Example of N-infused cavity contaminated by furnace environment



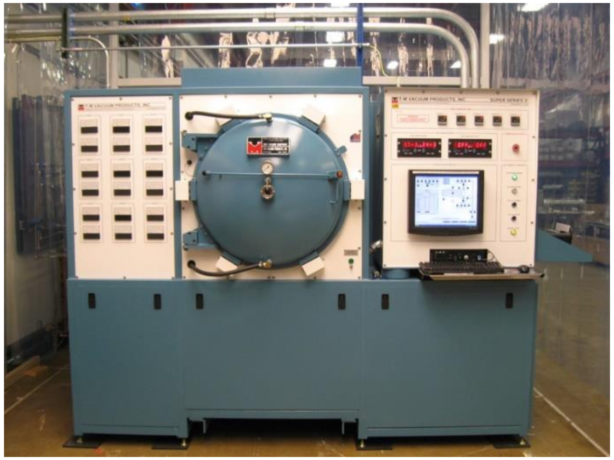
Once carbon diffuse inside Nb tends to accumulate at the grain boundaries forming Nb_xC_y non-superconducting phases

Quite high level of hydrocarbons may be absorbed by the cavity



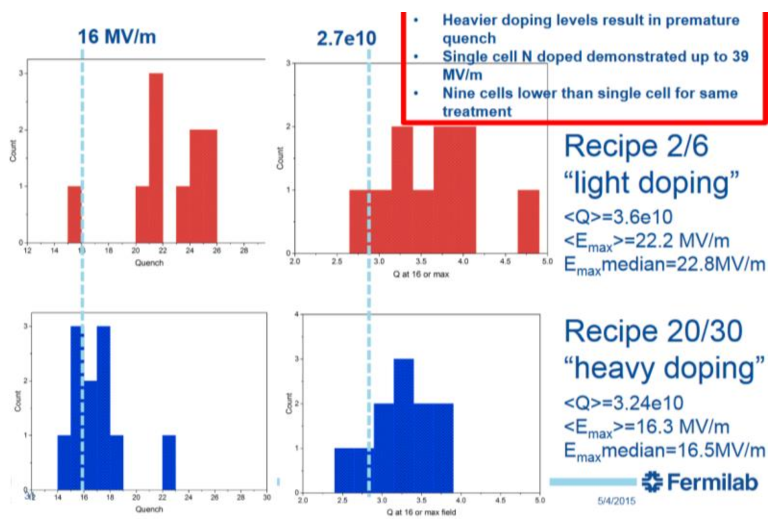
Strategies to implement the N-infusion technology

1. Very clean furnace environment



2. R&D to investigate other regime that are less affected by contamination

- High-T N treatment that allows post chemistry and capable to create a thin N-enriched layer
- Probe the parameter space to find an optimal spot for N diffusion rather than C
- Etc..



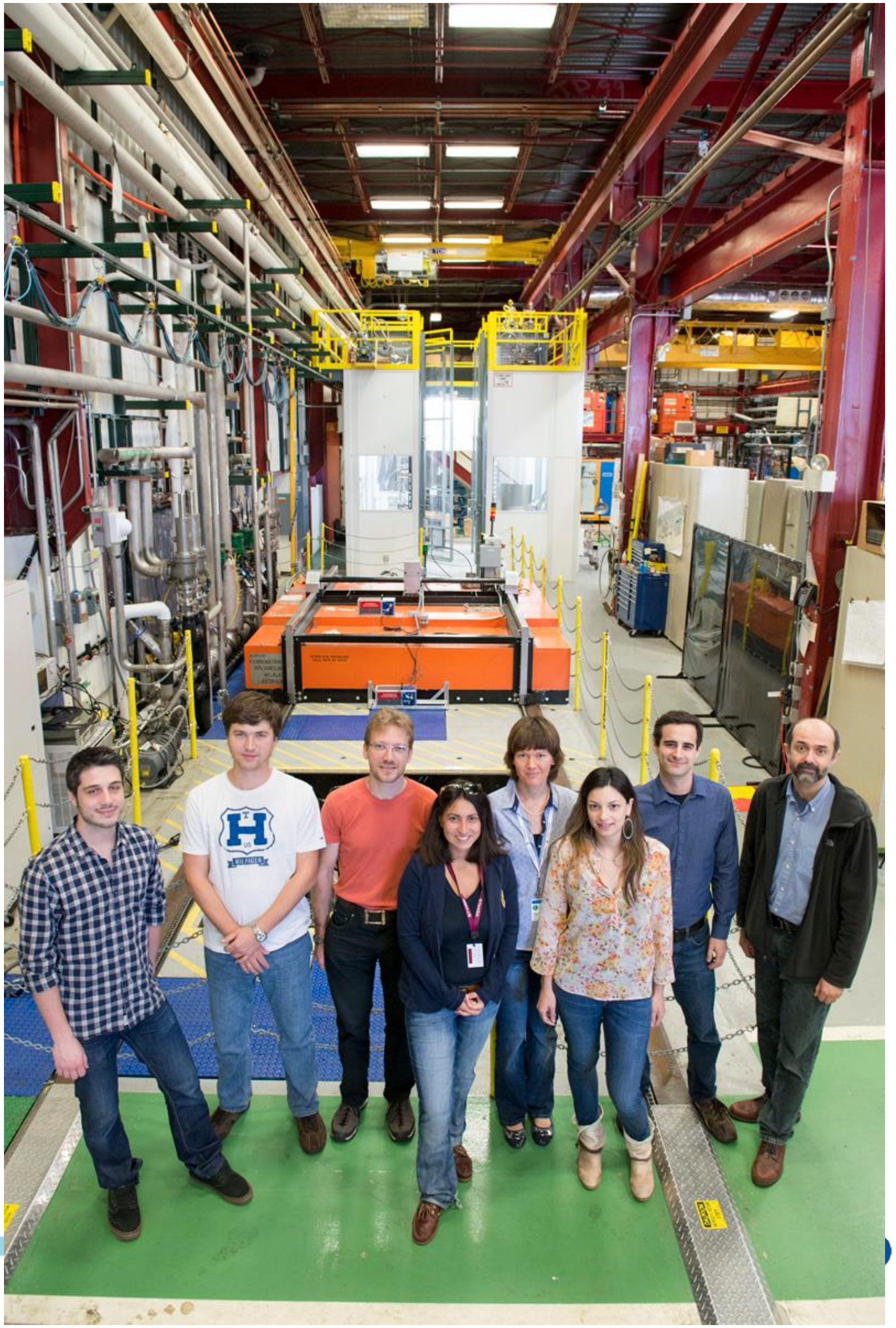
Conclusions

- N-doping suitable for high-Q at medium gradient, production ready technology for SRF accelerators
- High Q preserved also in cryomodule applying lessons learned from R&D
- N-infusion suitable treatment to obtain high-Q at high gradient
- Modification of the superficial mean-free-path at the nanometer scale
- Successful results obtained also on 9-cell cavities, potentially useful for ILC cost reduction
- More R&D needed to increase reliability of the process

Team Effort

- Results shown here are due to many hardworking people

- Thanks to SRF department for contributions with graphs, slides, etc.



Thank you for your attention!