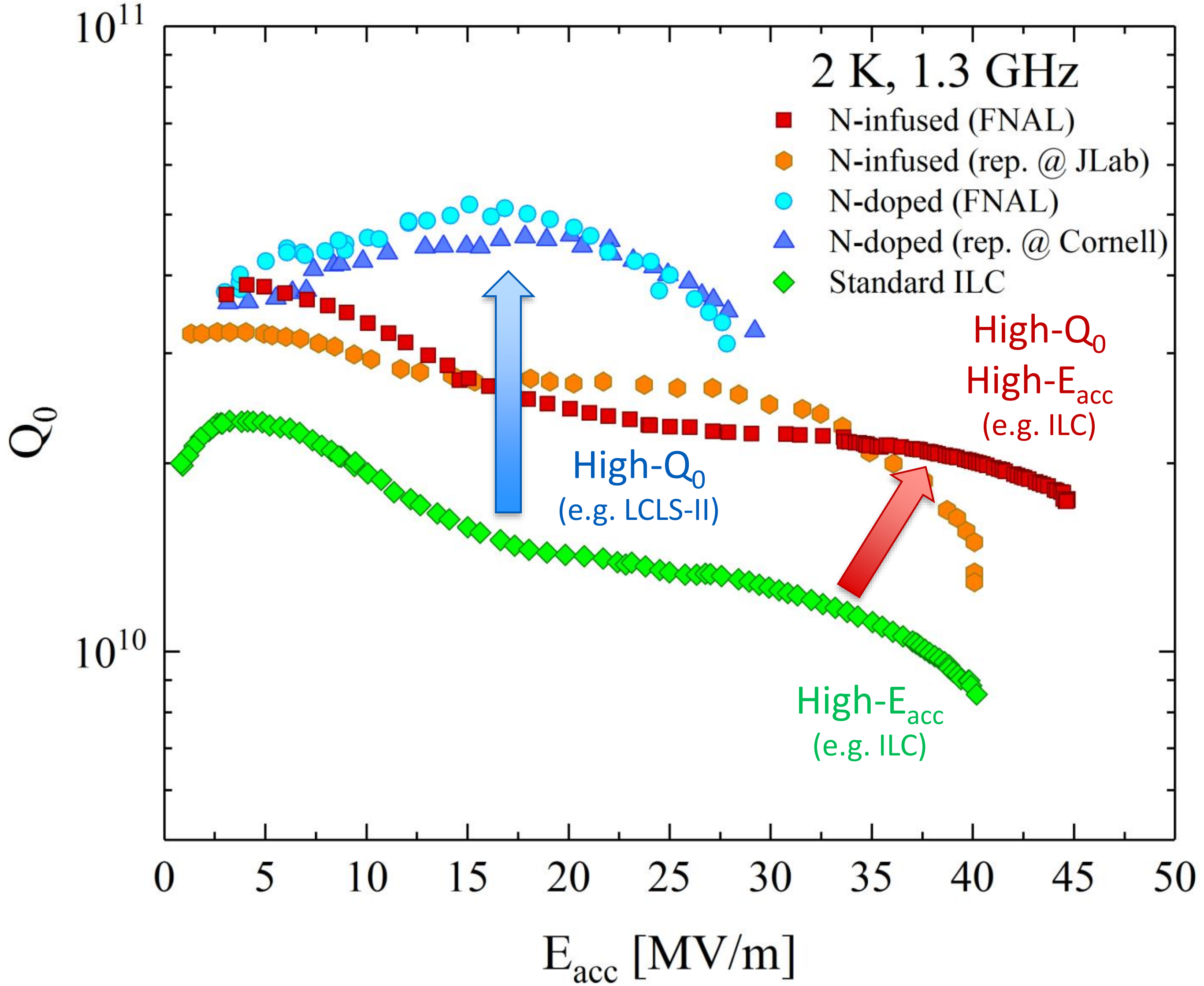
Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

High-Q Performance

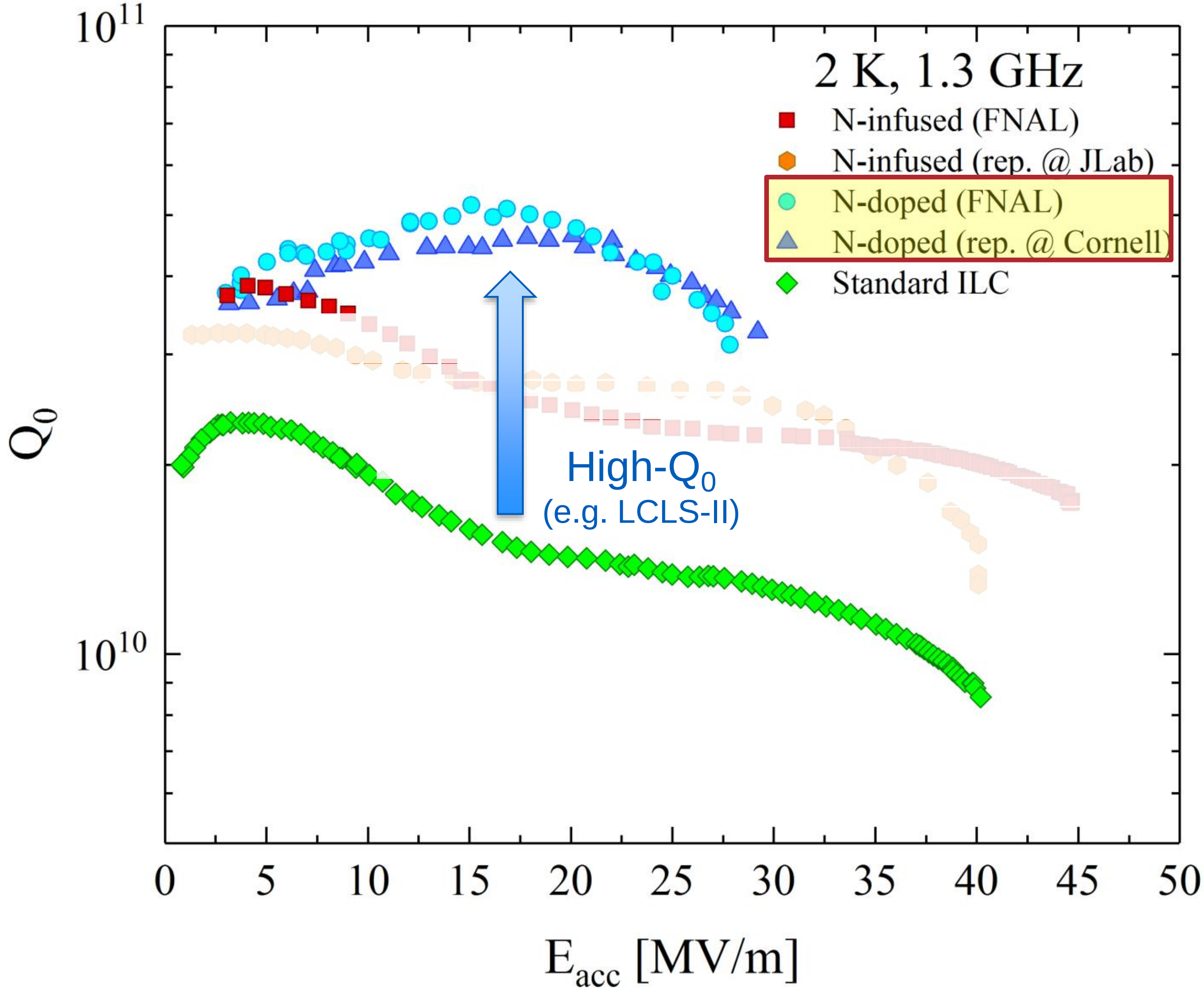
Martina Martinello
International Workshop on Cryomodule Design and Standardization
7^{th} September 2018

Overview of state-of-the-art surface treatments for SRF cavities

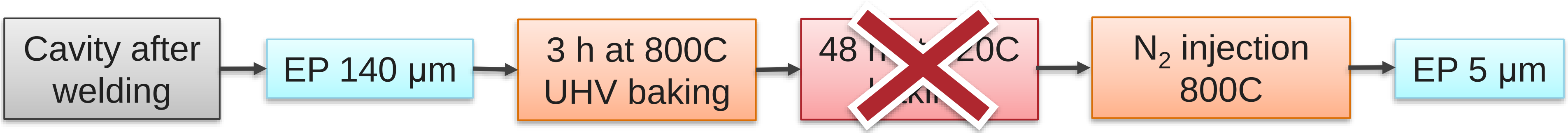
State-of-the-art treatments



High-Q_0 treatments

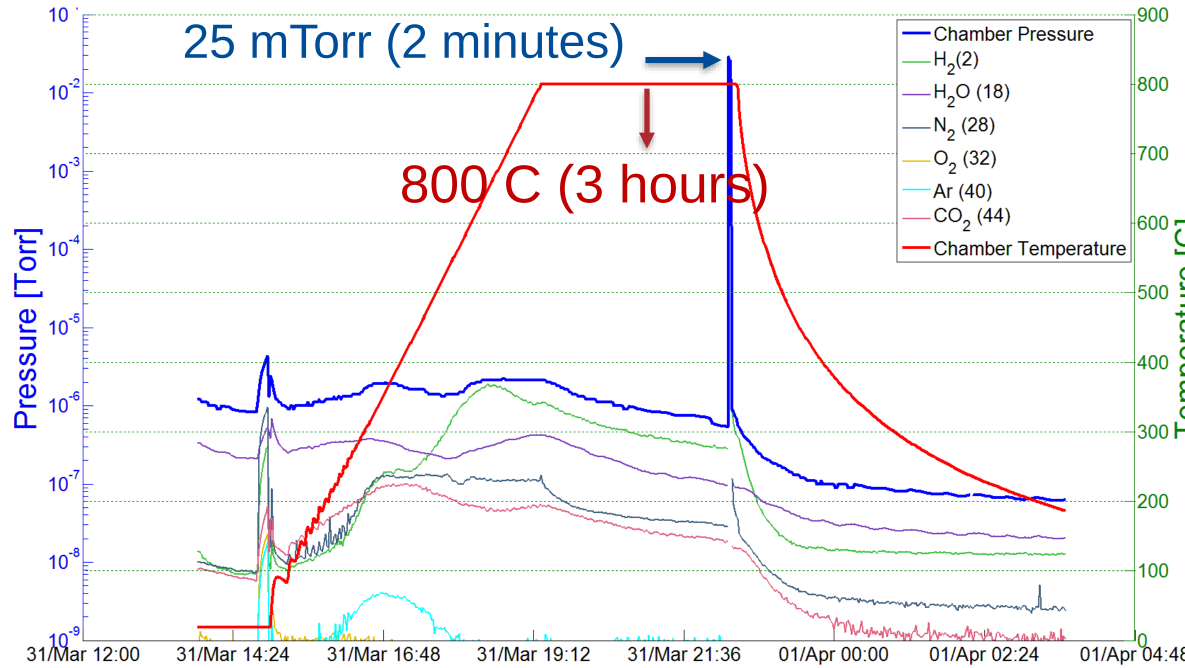


N-doping treatment

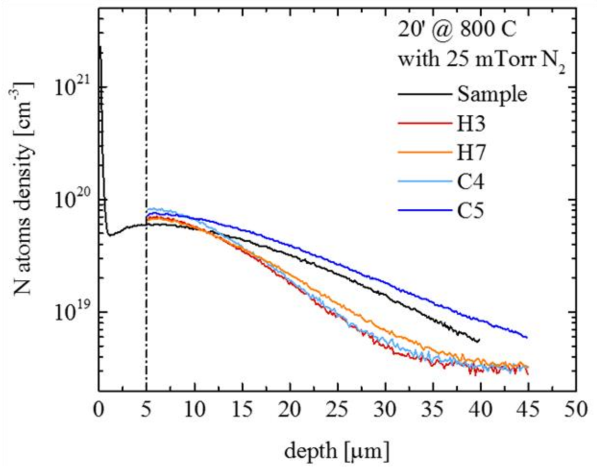


Example of a N-doping process (2/6 recipe):

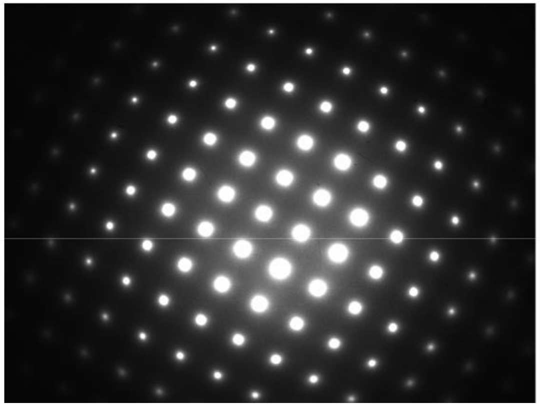
- Nb bulk EP cavity annealed for 3 hours in vacuum (UHV furnace) at 800C
- Nitrogen injected (25 mTorr) at 800C for 2 minutes
- Cavity stays for another 6 minutes at 800C in vacuum
- Cooling in vacuum
- 5 um electro-polishing (EP)



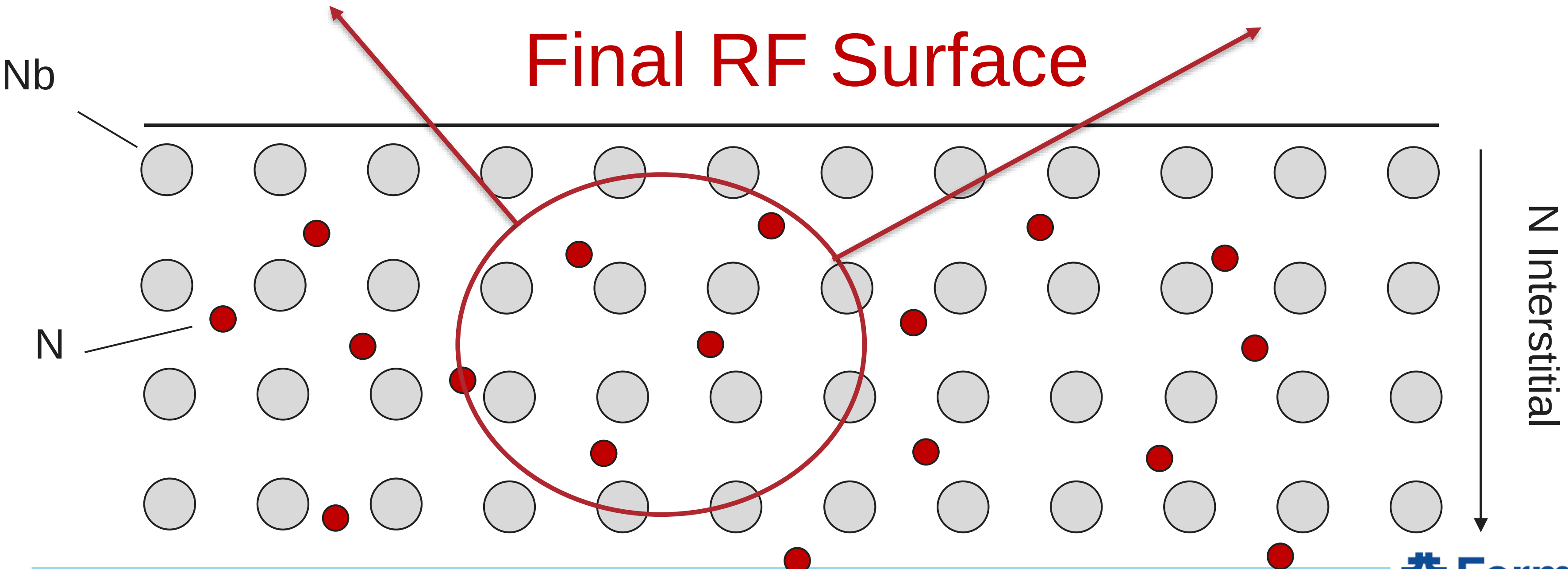
N-doping treatment (2/6 recipe)



Only Nb from TEM/NED spectra:
N must be interstitial

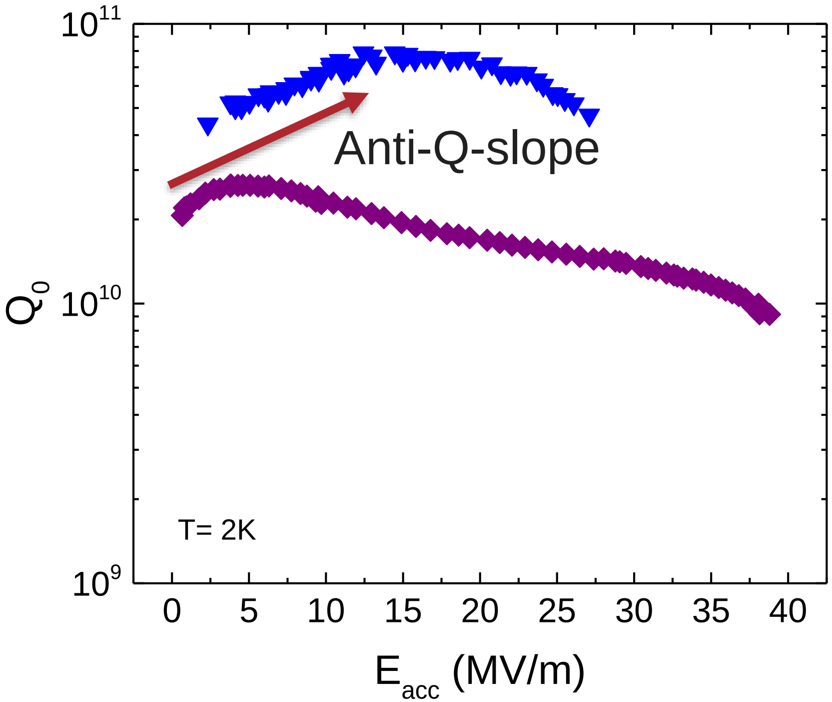


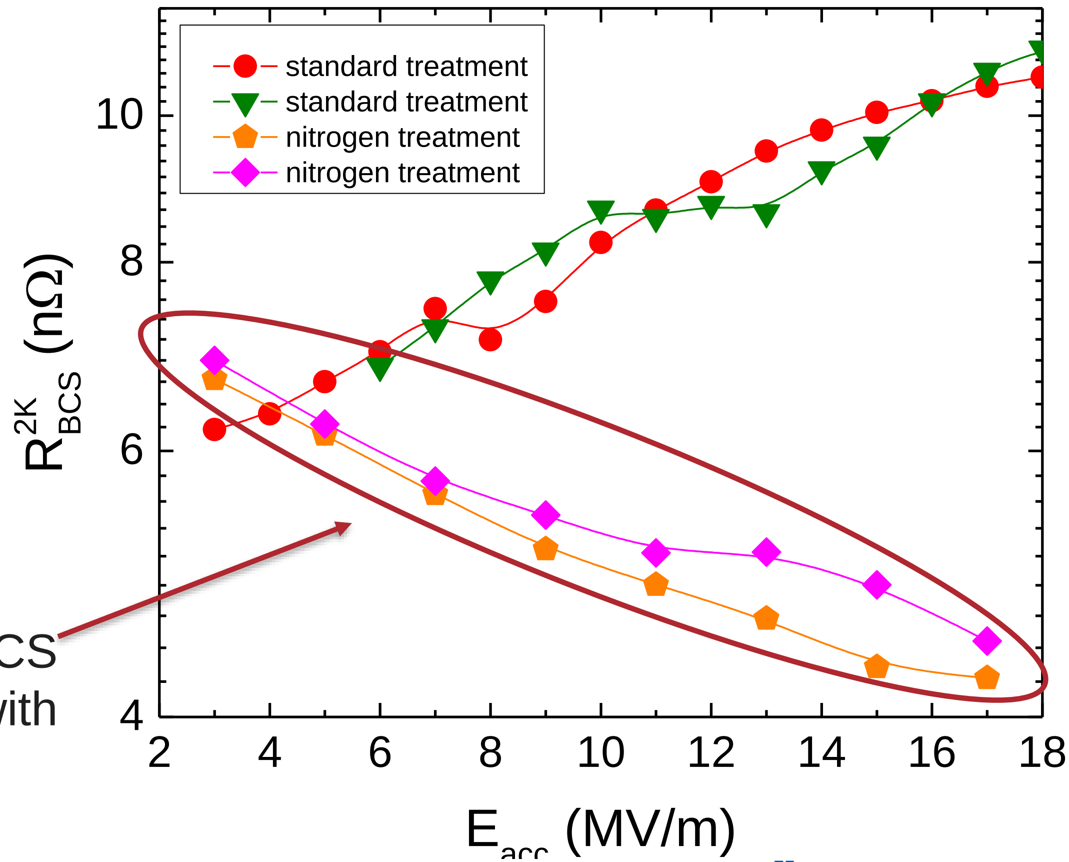
Y. Trenikhina et Al, Proc. of SRF 2015



Origin of the anti-Q-slope

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

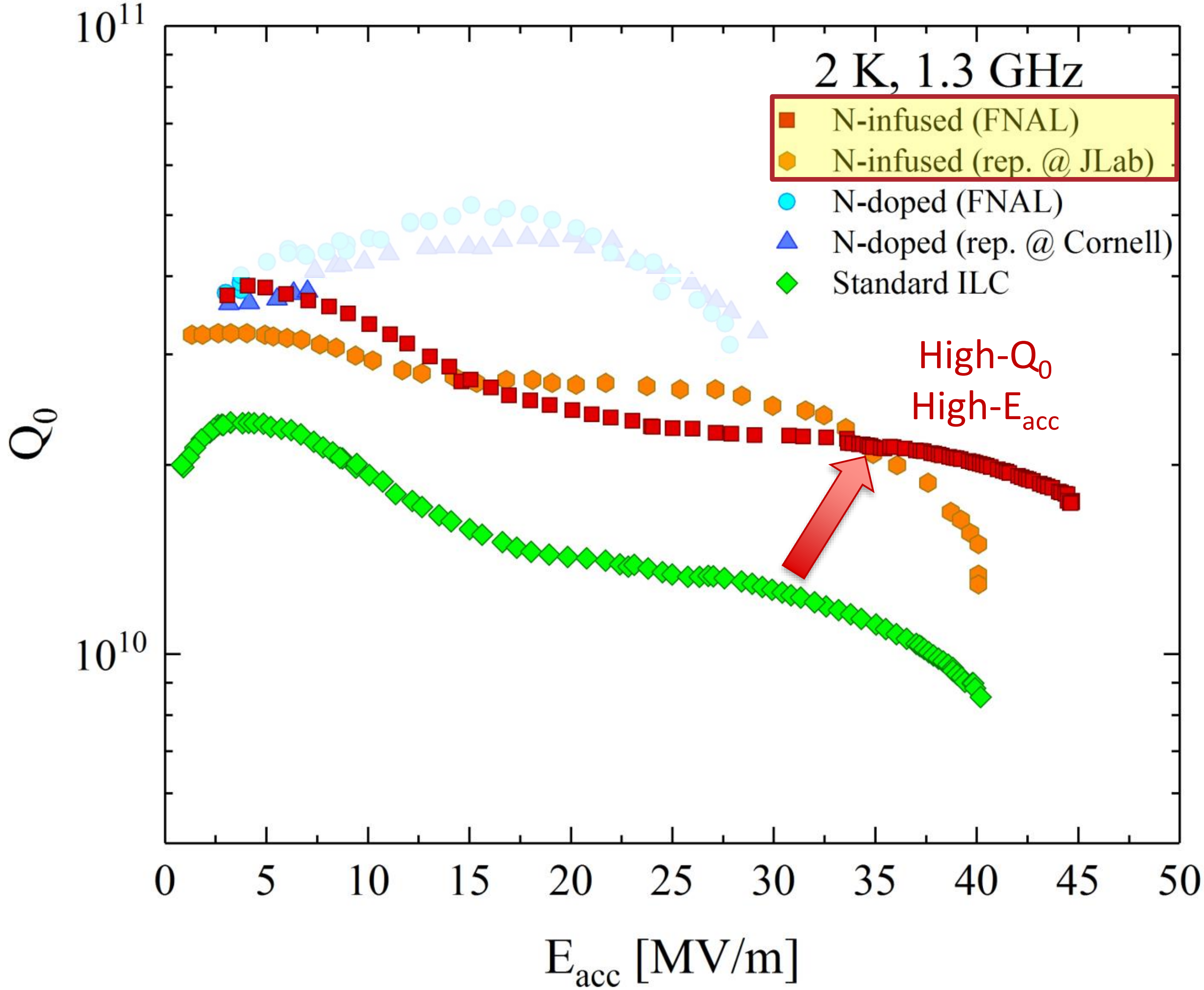




Anti-Q-slope emerges from the BCS surface resistance <u>decreasing</u> with field

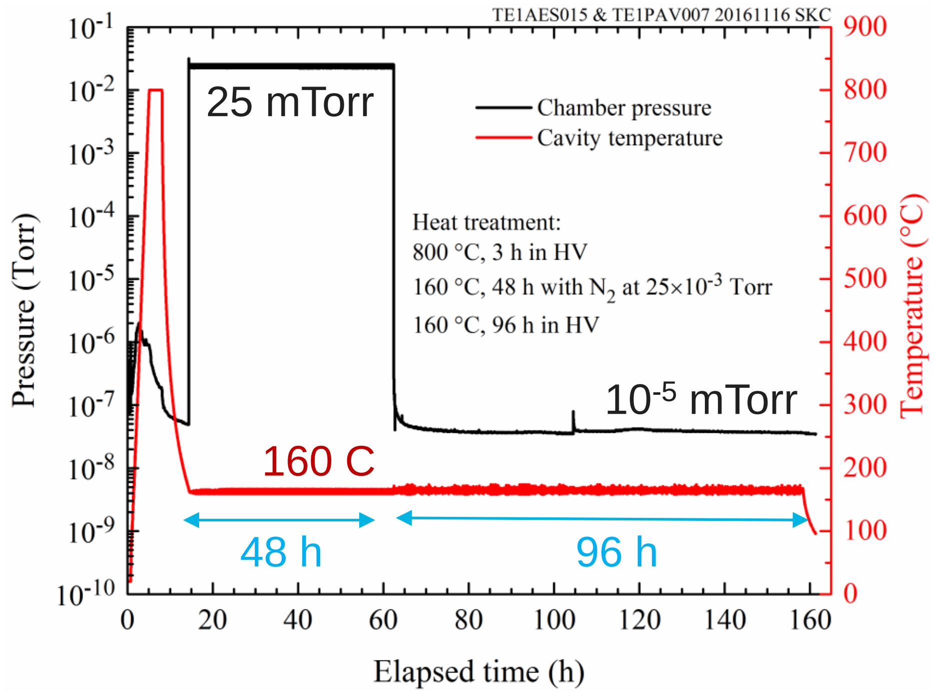
A. Grassellino et al, Supercond. Sci. Technol. **26** 102001 (2013) - Rapid Communications
A. Romanenko and A. Grassellino, Appl. Phys. Lett. **102**, 252603 (2013)

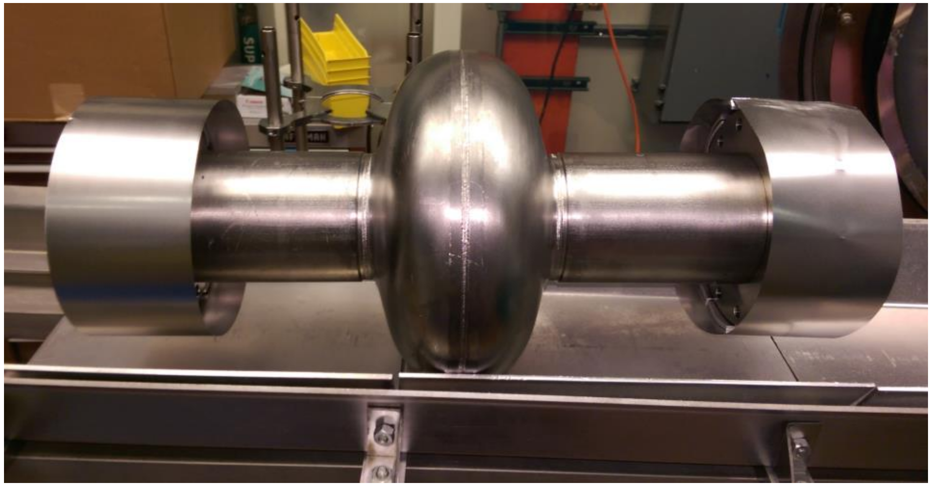
High-Q_0/High-G treatments



Example of N-infusion processing sequence

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





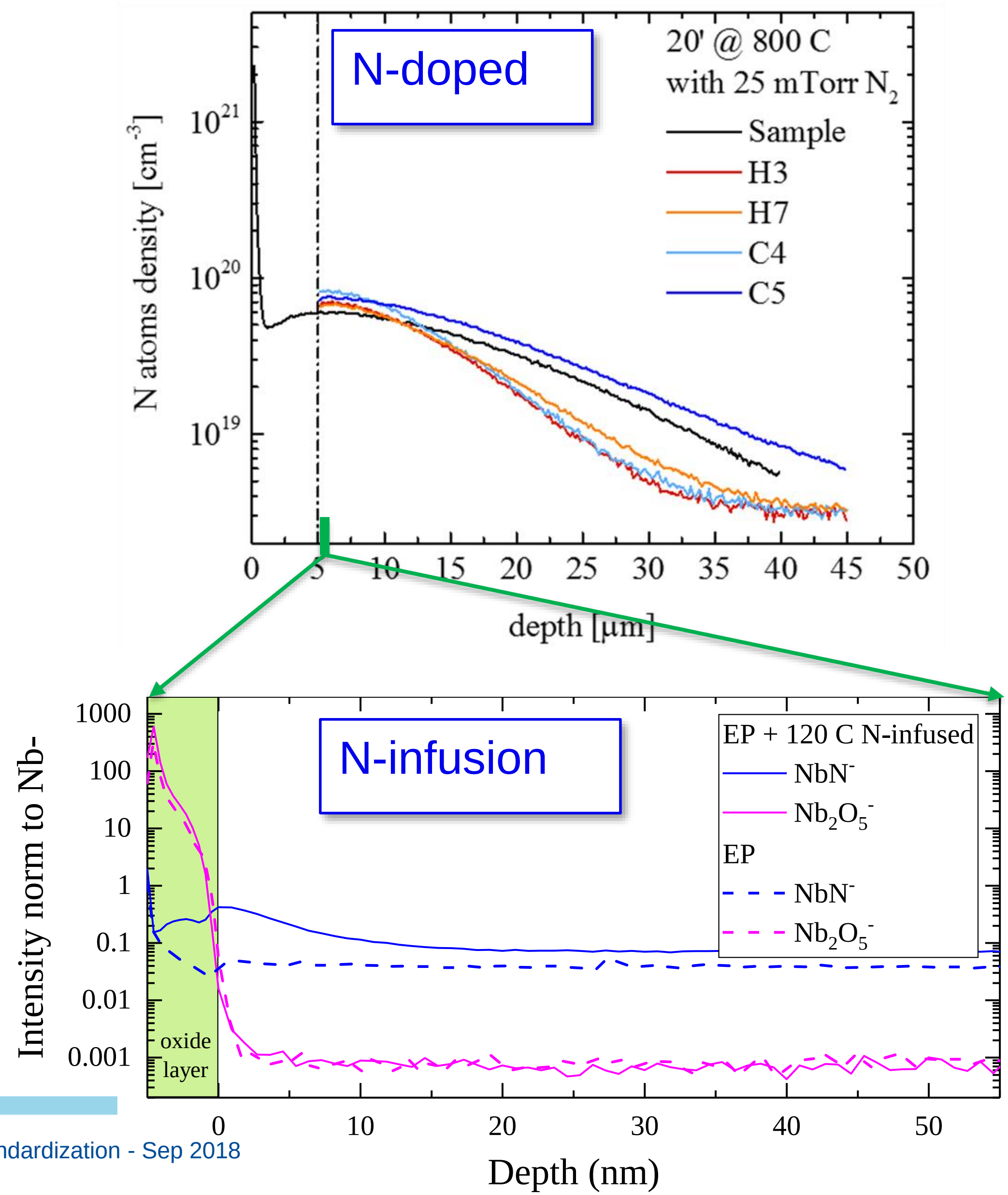
Protective caps and foils are BCP'd prior to every furnace cycle and assembled in clean room, prior to transporting cavity to furnace area

A. Grassellino *et al.*, **arXiv:1305.2182**
A. Grassellino et al 2017 Supercond. Sci. Technol. **30** 094004

Comparison N-doped vs N-infusion

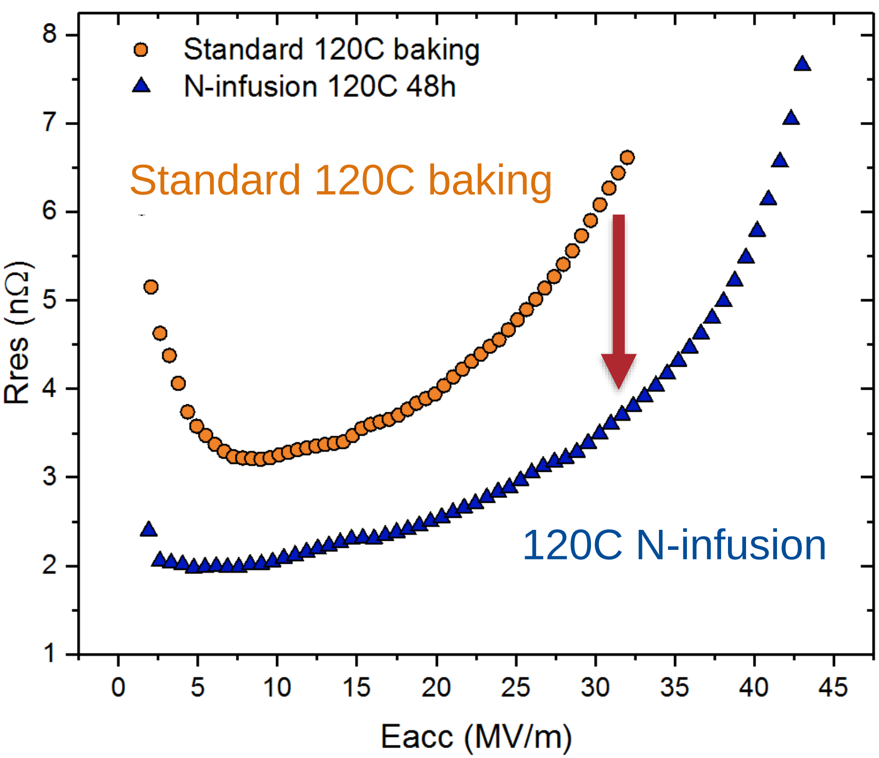
- N-doped N profiles are up to $\sim 50\ \mu m$ deep

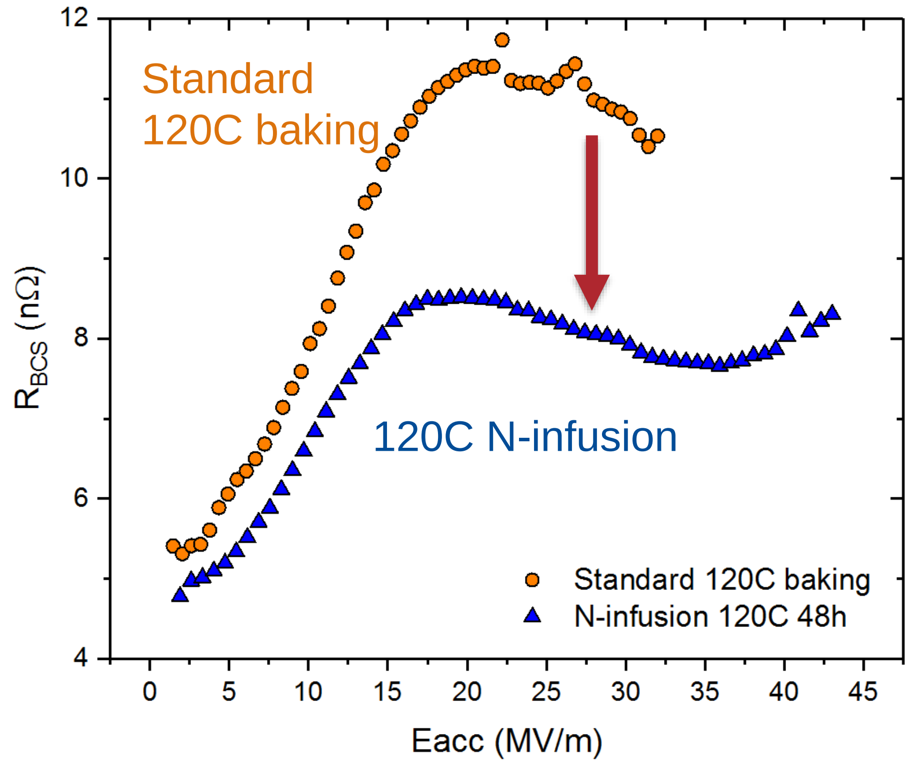
- N-infused N profiles are $\sim 20\ nm$ deep



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

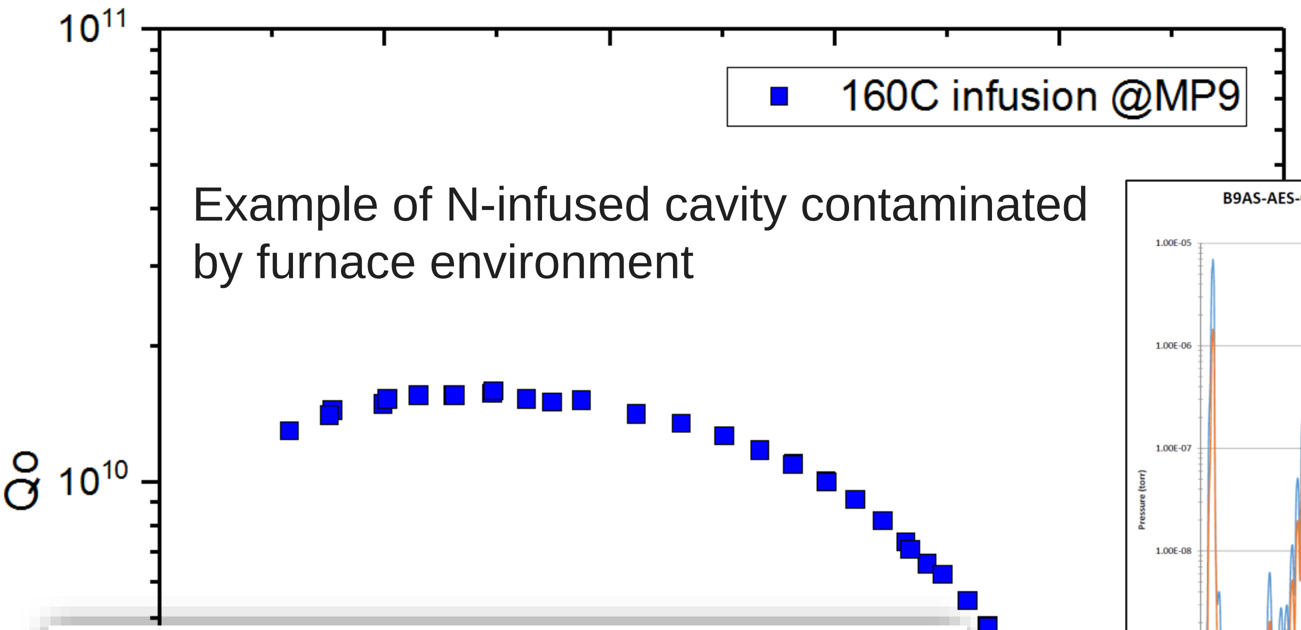
Improvement stems from both *lower residual* and *lower BCS surface resistance*





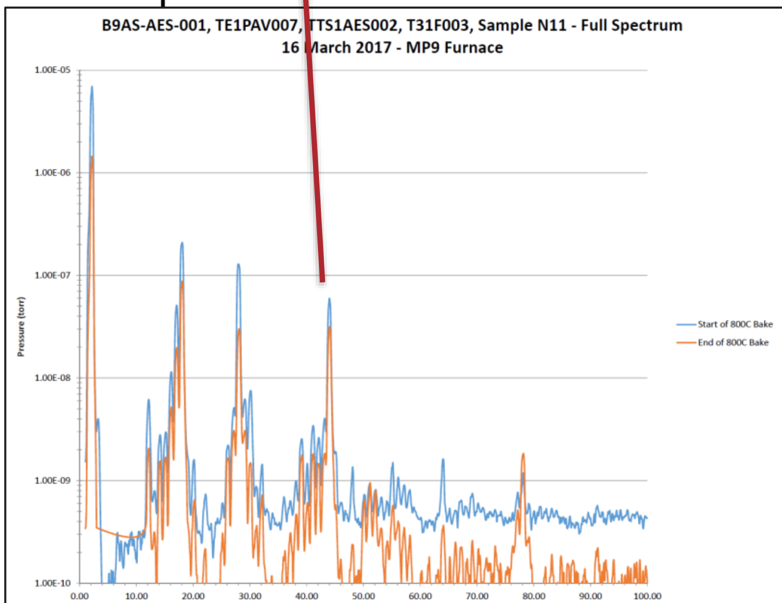
A. Grassellino et al 2017 Supercond. Sci. Technol. **30** 094004

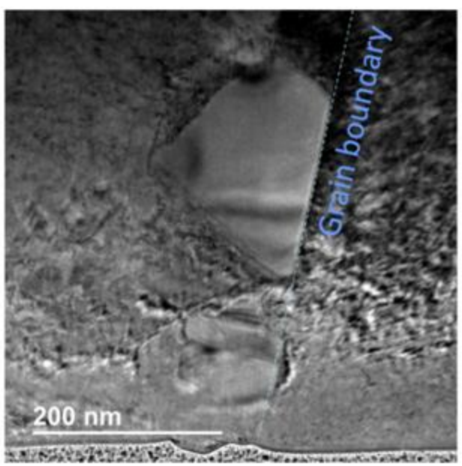
N-infusion easily affected by furnace contamination



Example of N-infused cavity contaminated by furnace environment

Quite high level of hydrocarbons may be absorbed by the cavity





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

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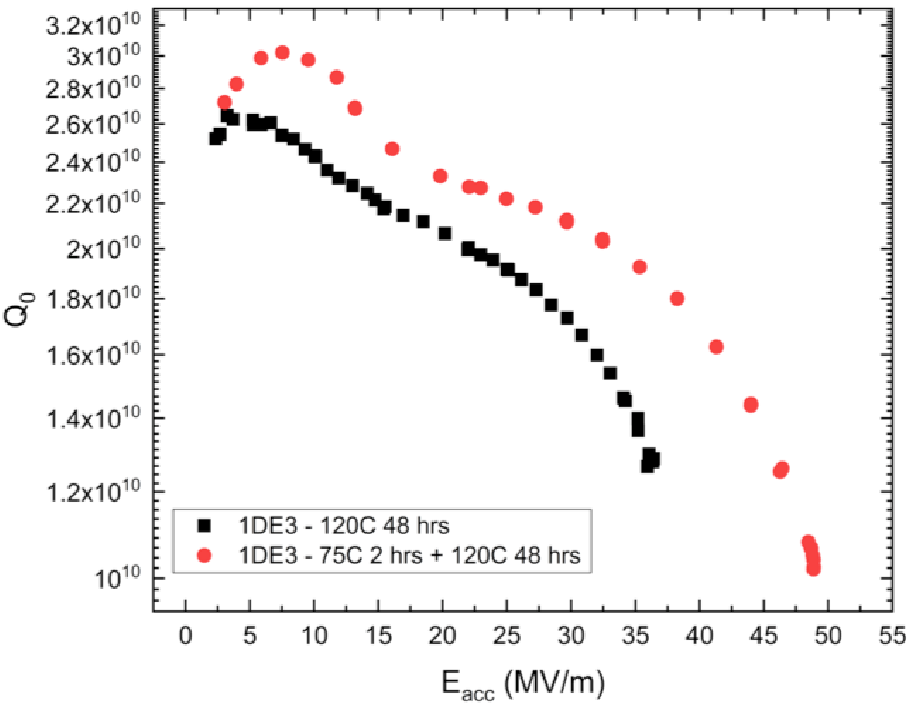
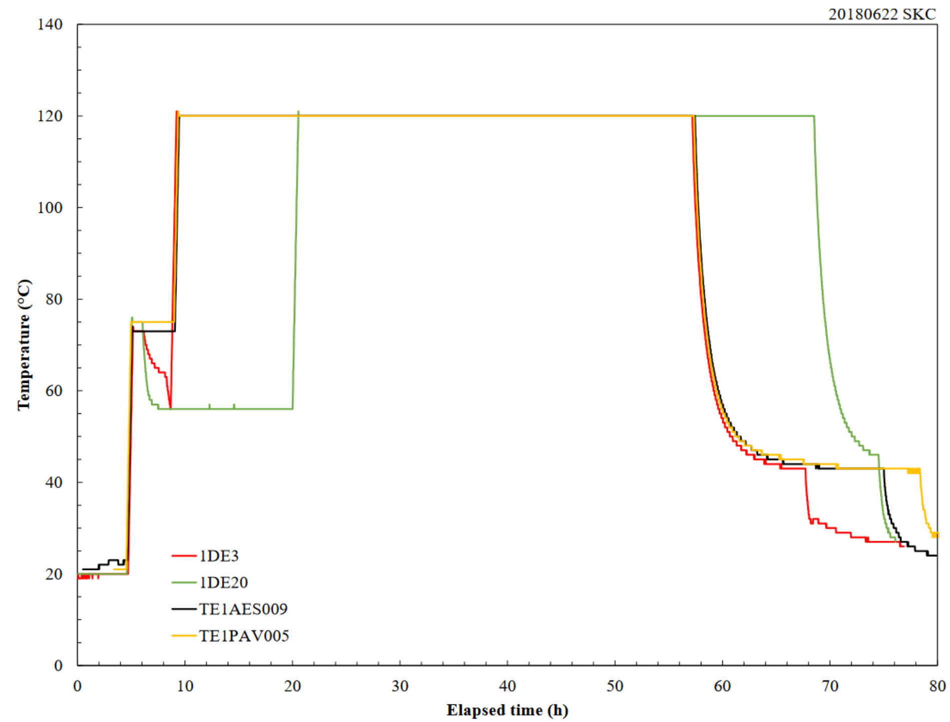
Modified 120C baking: 4h at 75C + 48h at 120C





- A thermocouple went faulty and oven went to standby. Cavity lingered around 75C for about 2 hours, then resumed the 120C 48 hours -> increase in both Q and gradient observed
- Several cavities made after that, adding the 75C step for 4 h, confirming the results -> work in progress to better understand treatment repeatability and physics

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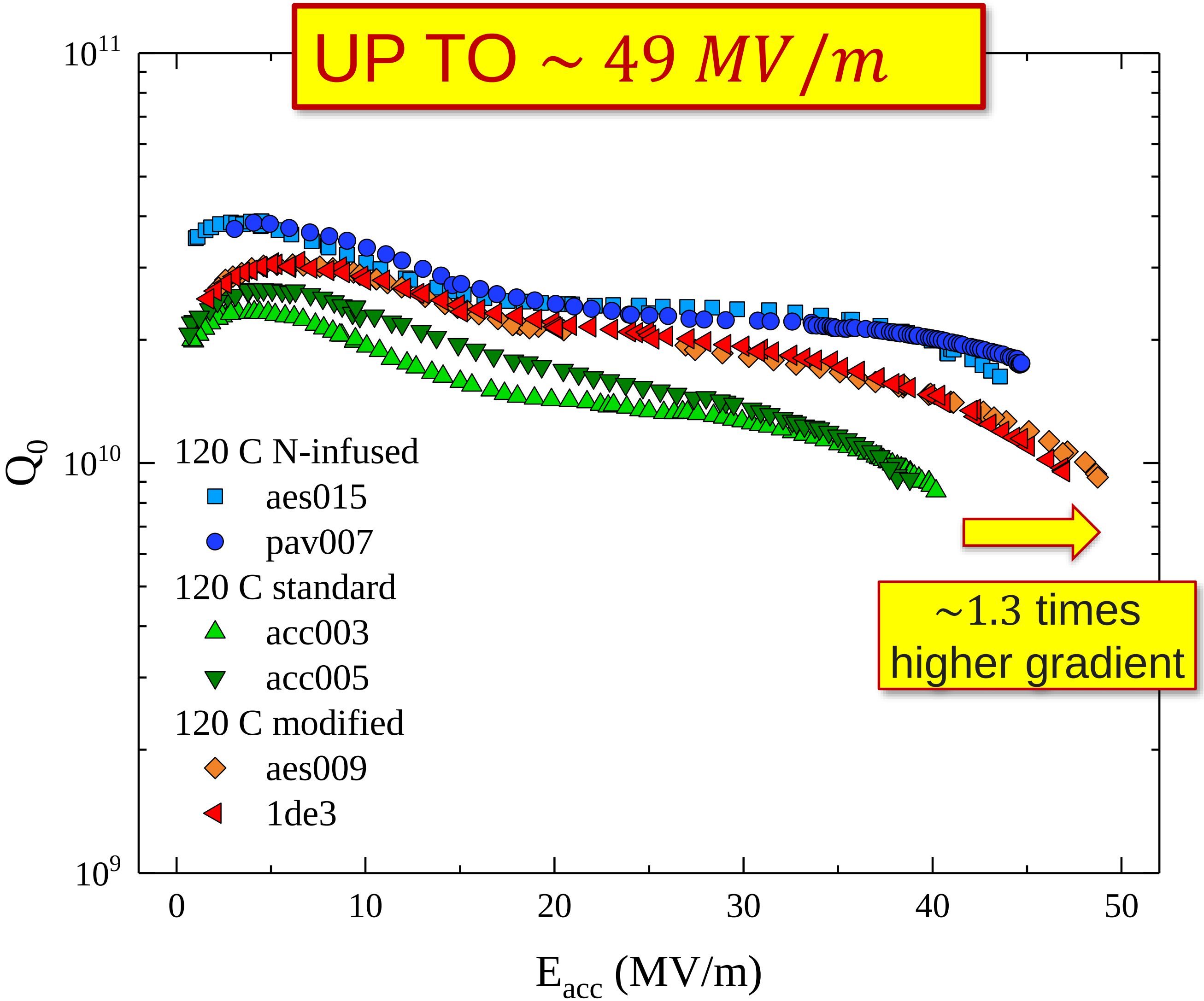
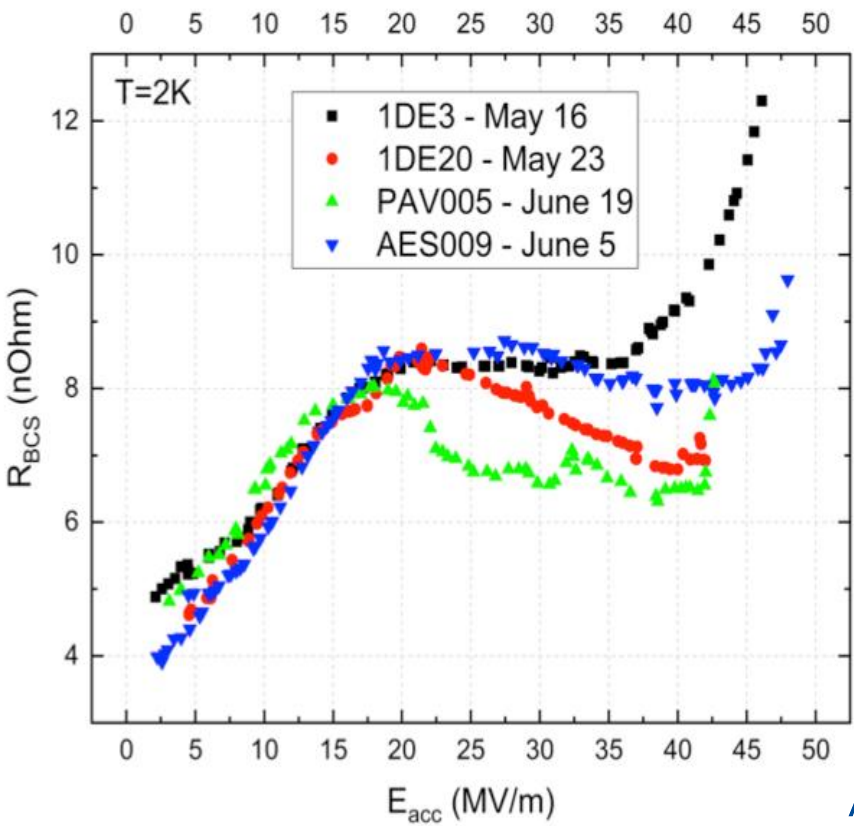
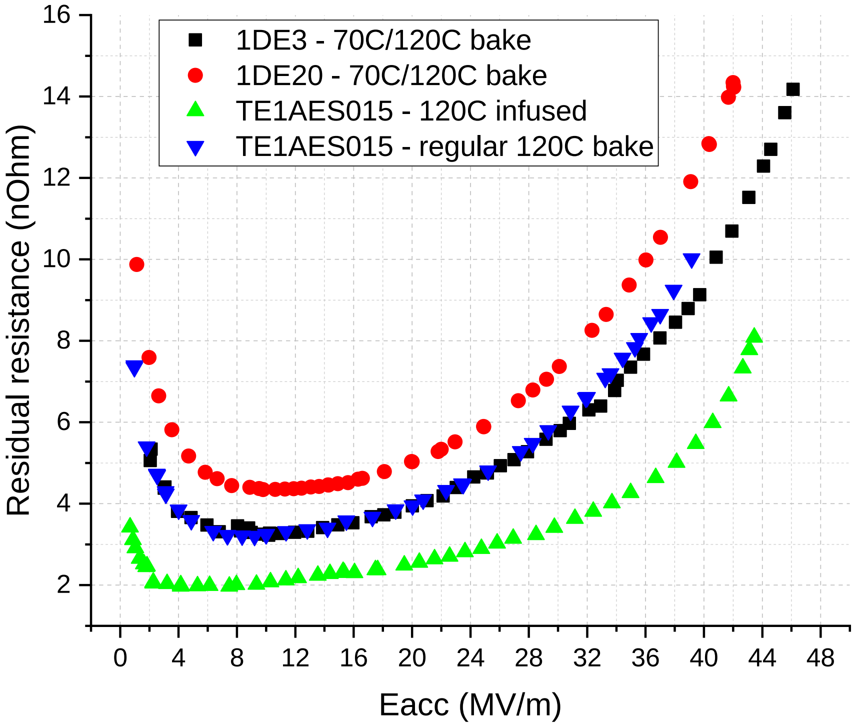
120 C modified baking: new discovery



A. Grassellino *et al.*, to be published (2018)

Next surprise: the BCS resistance is ~ as 120C N infused





A. Grassellino et al, https://arxiv.org/abs/1806.09824

- BCS surface resistance is lowered compare to standard 120C baking
- Residual resistance comparable with standard 120C baking

High-Q preservation:
from vertical test to cryomodule

Surface resistance contributions

$$R_s(T,B) = R_{BCS}(T) + R_0 + R_{fl}(B)$$

Surface resistance contributions

$$R_s(T,B) = \boxed{R_{BCS}(T) + R_0} + R_{fl}(B)$$

R_{BCS} ⇒ BCS (temperature-dependent part) surface resistance

R_0 ⇒ intrinsic residual resistance

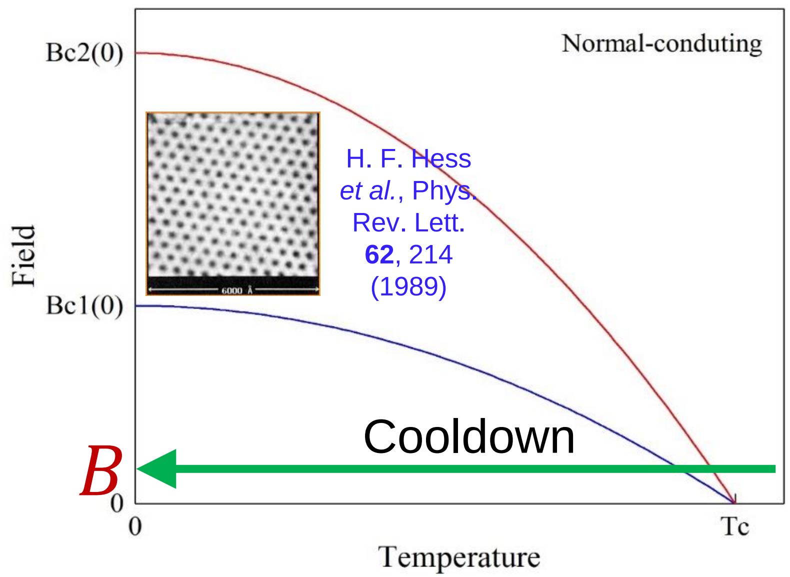
These contributions don’t change from vertical test to cryomodule, they only depends on *material properties*, *surface treatment* and *temperature*

Surface resistance contributions

$$R_s(T,B) = R_{BCS}(T) + R_0 + R_{fl}(B)$$

$R_{fl} = \eta_t S B \Rightarrow$ trapped magnetic flux surface resistance

- η_t—flux trapping efficiency
- S —trapped flux sensitivity
- B —external magnetic field



Flux trapping efficiency and the amount of external magnetic field can significant change from vertical test to cryomodule, affecting the surface resistance depending on the *trapped flux sensitivity*

Trapped flux surface resistance

$$R_s(2\,K, B) = R_{BCS}(2\,K) + R_0 + R_{fl}(B)$$

$$\boldsymbol{R_{fl} = B\,\eta_t\,S}$$

These losses can be reduced by minimizing these contributions:

B
- Magnetic shielding/hygiene improvement

η_t
- Fast Cooling
- Material Optimization

S
- Optimizing surface treatment (mean free path)

Trapped flux surface resistance

$$R_s(2\,K, B) = R_{BCS}(2\,K) + R_0 + R_{fl}(B)$$

$$\boldsymbol{R_{fl} = \boxed{B}\,\eta_t\,S}$$

These losses can be reduced by minimizing these contributions:

External magnetic field

B
- Magnetic shielding/hygiene improvement

η_t
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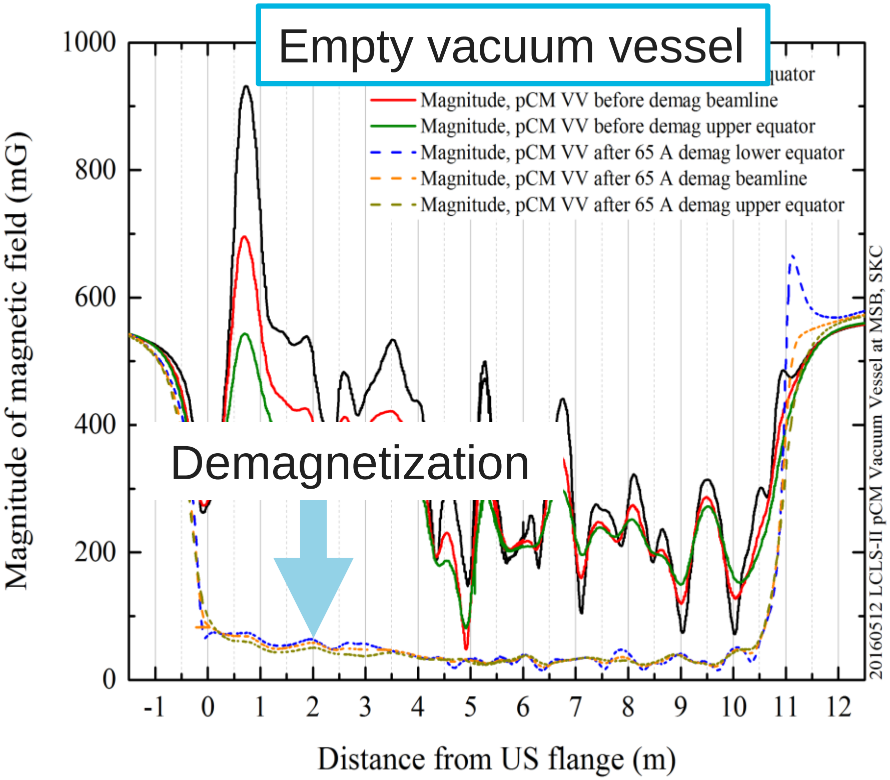
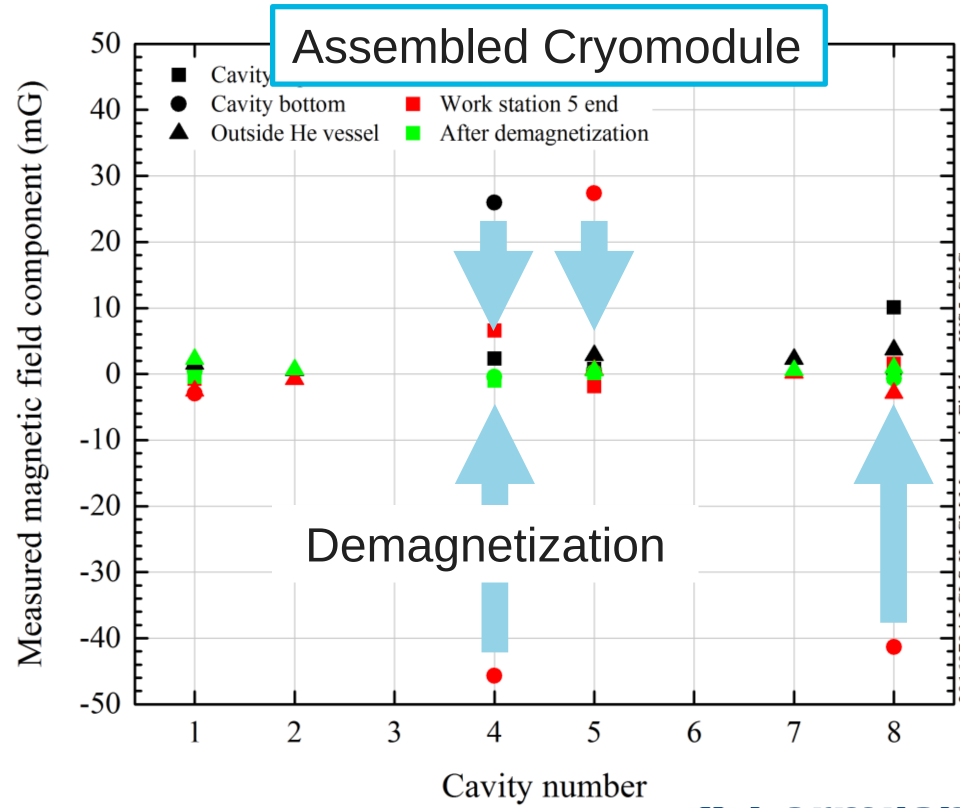
- Optimizing surface treatment (mean free path)

Minimization of remnant field in LCLS-II pCM





Trapped flux surface resistance

$$R_s(2\,K, B) = R_{BCS}(2\,K) + R_0 + R_{fl}(B)$$

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These losses can be reduced by minimizing these contributions:

B
- Magnetic shielding/hygiene improvement

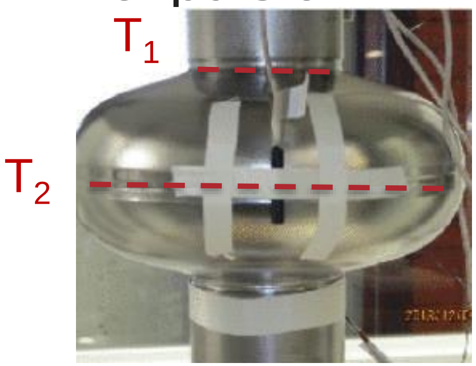
Flux Trapping Efficiency

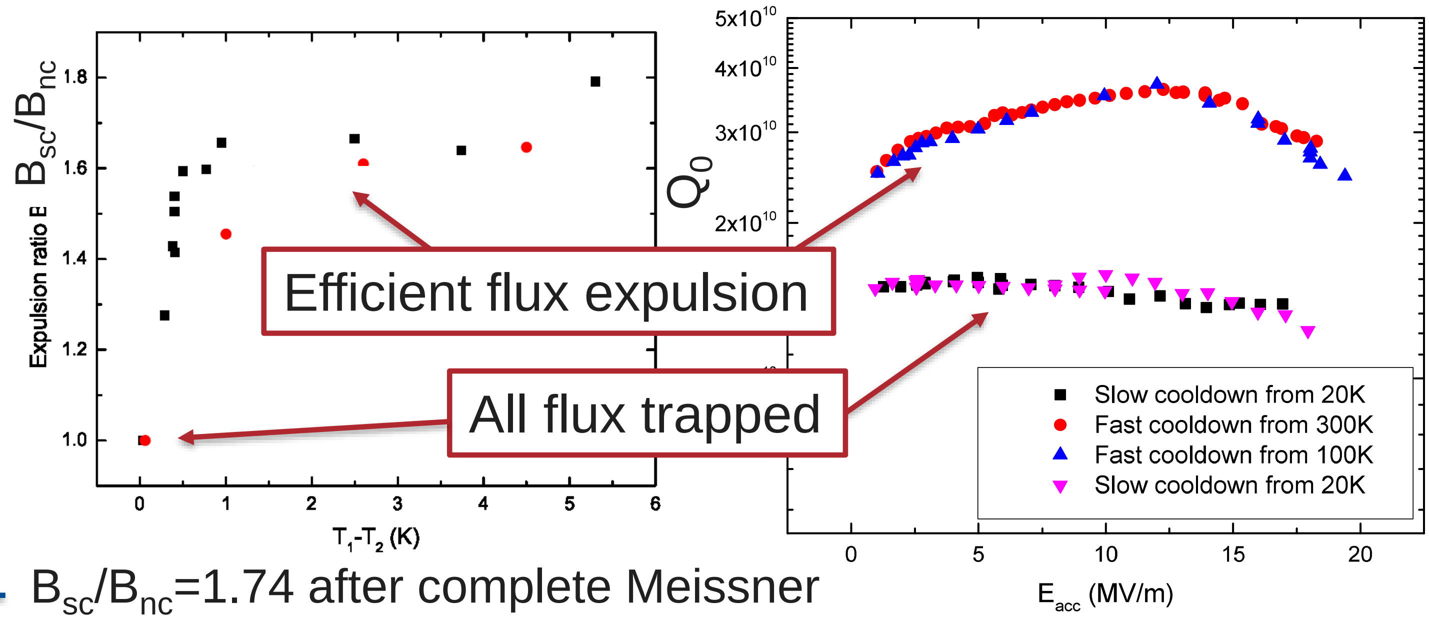
η_t
- Fast Cooling
- Material Optimization

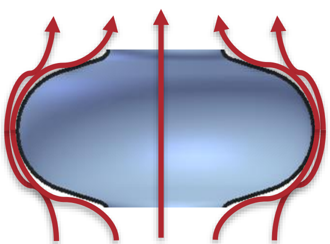
S
- Optimizing surface treatment (mean free path)

Fast cooldown helps flux expulsion

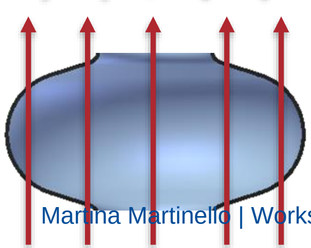
- Fast cool-down lead to large thermal gradients → efficient flux expulsion
- Slow cool-down lead to small thermal gradients → poor flux expulsion







B_{sc}/B_{nc}=1.74 after complete Meissner effect

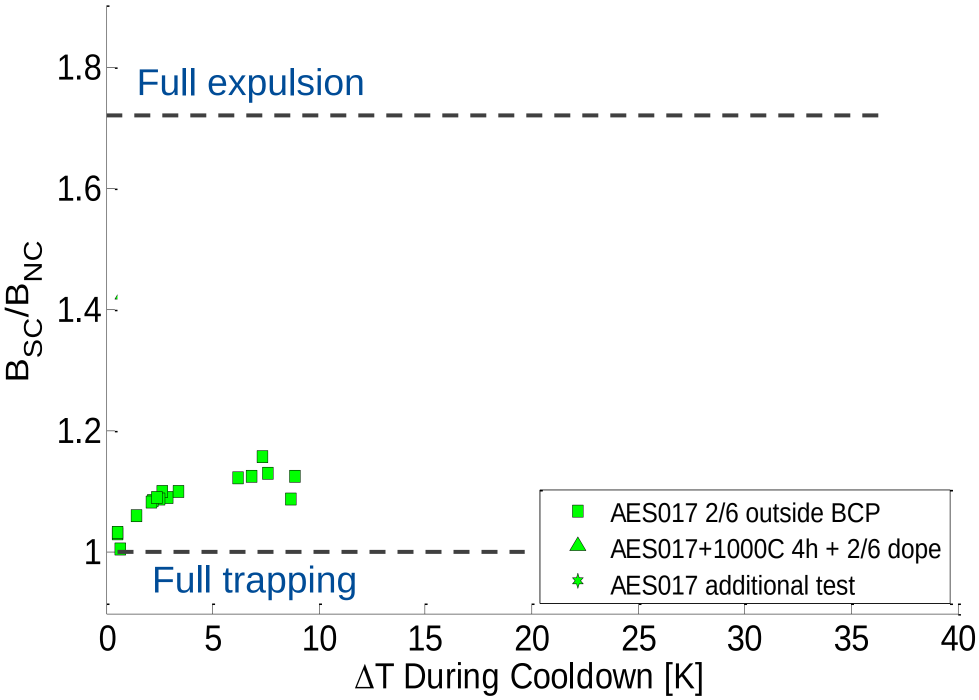


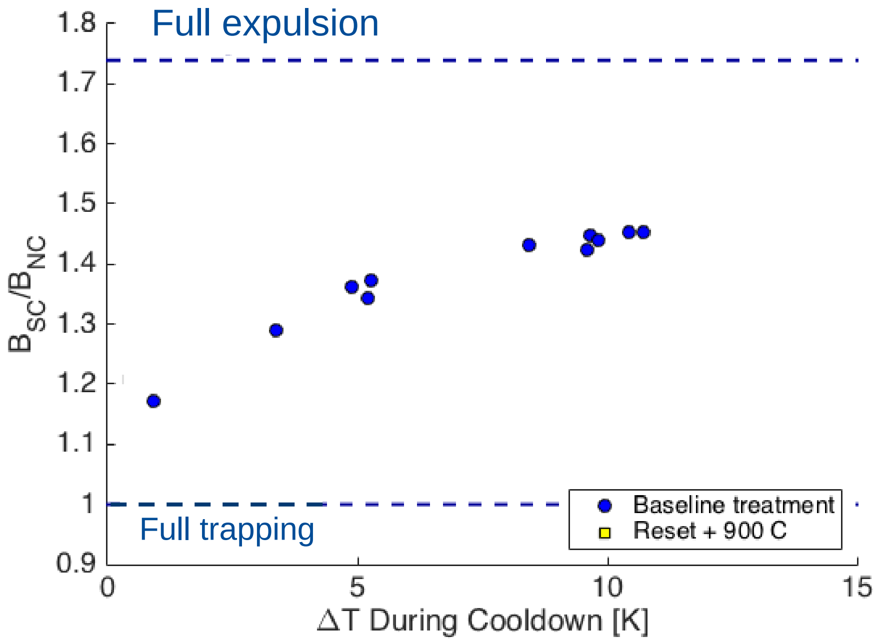
B_{sc}/B_{nc}=1 after full flux trapping

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

- Not all materials show good flux expulsion even with large thermal gradient
- High T treatments are capable to improve materials flux expulsion properties

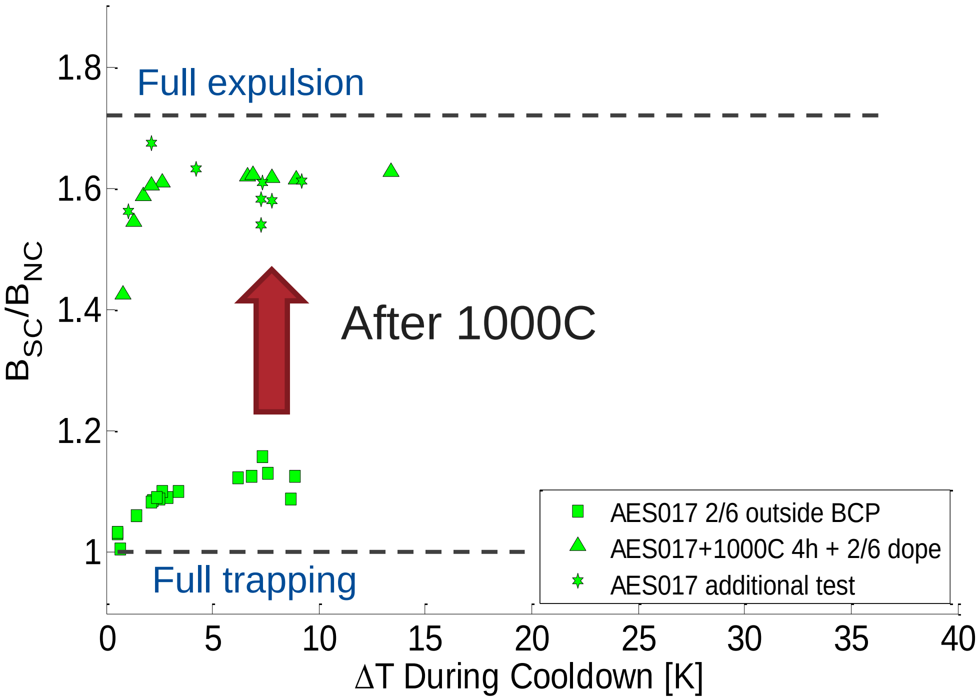


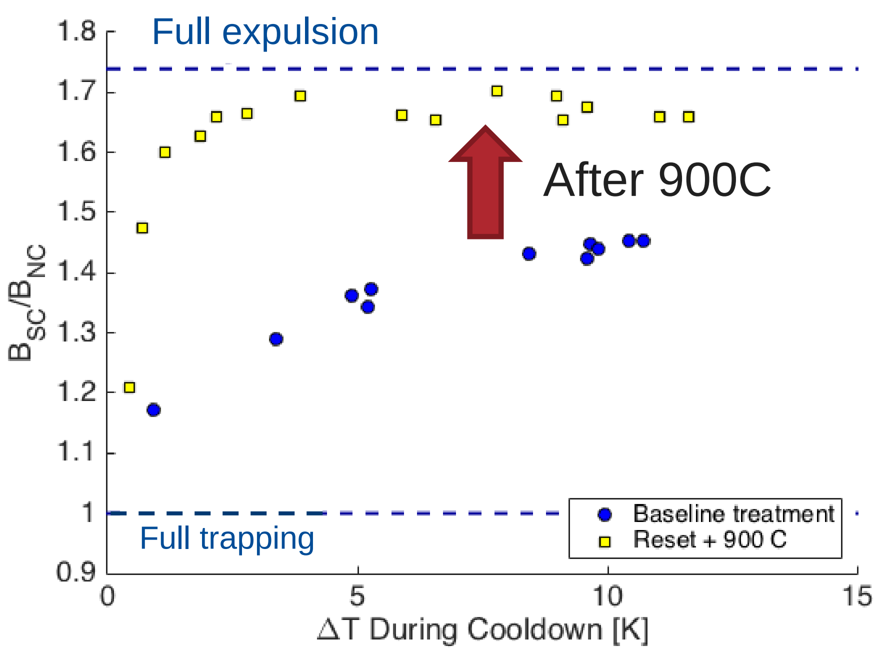


S. Posen et al., J. Appl. Phys. **119**, 213903 (2016)

High T baking for flux expulsion improvement

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





S. Posen et al., J. Appl. Phys. **119**, 213903 (2016)

Trapped flux surface resistance

$$R_s(2\,K, B) = R_{BCS}(2\,K) + R_0 + R_{fl}(B)$$

$$\boldsymbol{R_{fl} = B\,\eta_t\,\boxed{S}}$$

These losses can be reduced by minimizing these contributions:

B
- Magnetic shielding/hygiene improvement

η_t
- Fast Cooling
- Material Optimization

Trapped Flux Sensitivity

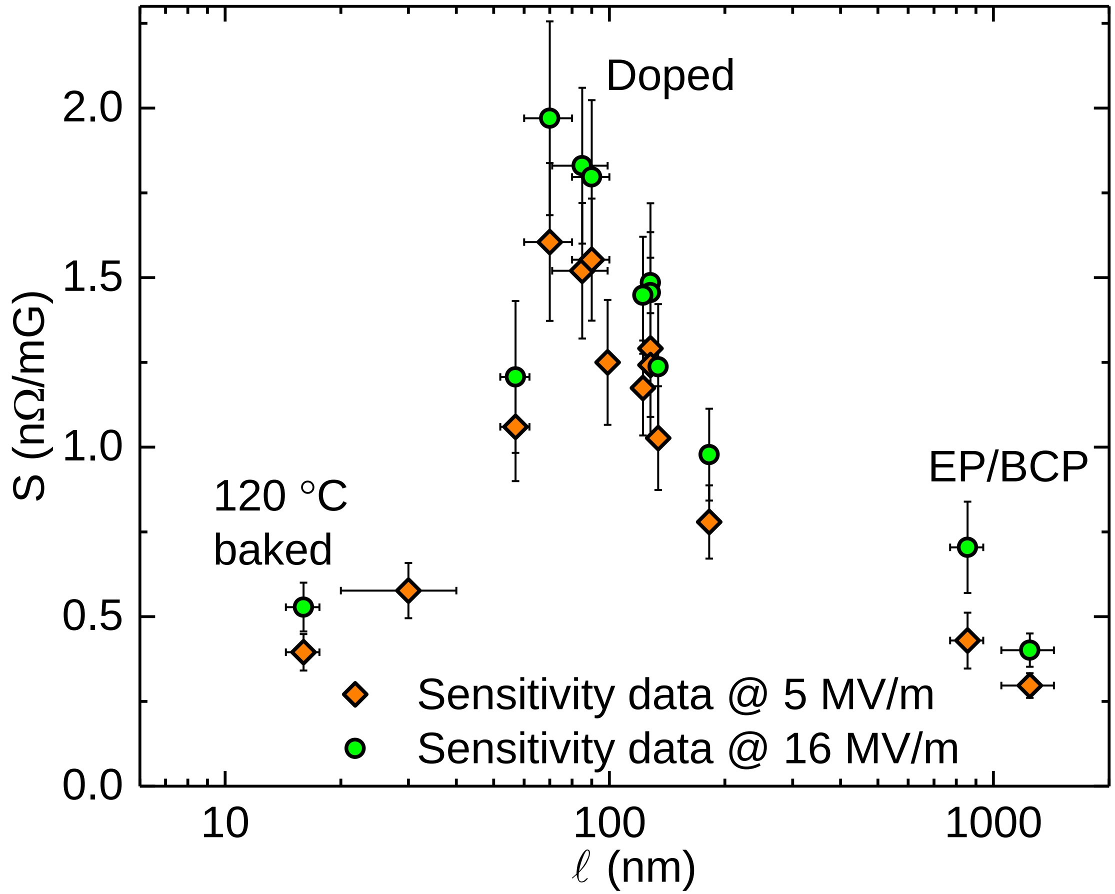
S
- Optimizing surface treatment (mean free path)

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)

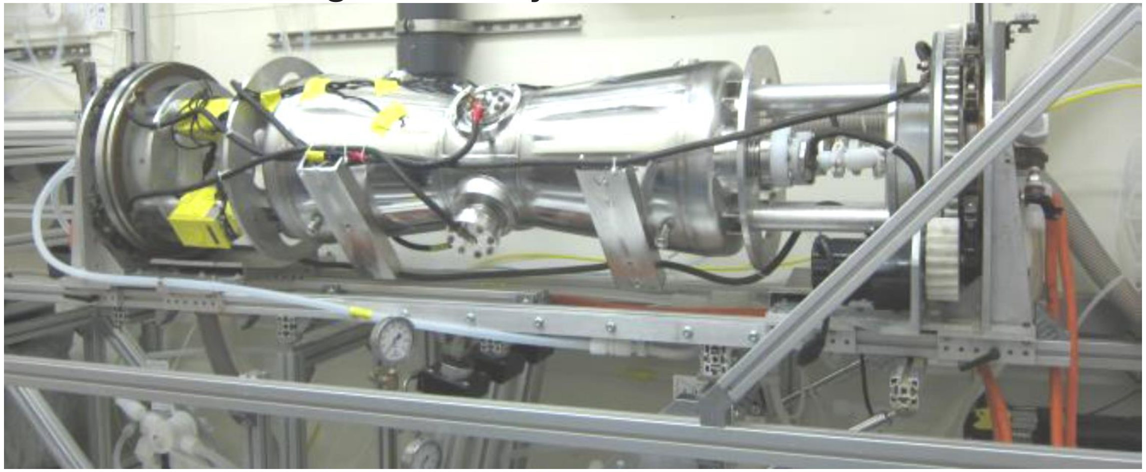
Status of SRF Technology for PIP-II

162.5 MHz Half-Wave Resonators

Surface treatments:

- Light BCP $\sim 20\ \mu m$
- Deep EP $\sim 120\ \mu m$
- Baking at $625\ °C$ for 10 hours in UHV furnace
- Light EP $\sim 20\ \mu m$

Bulk and light EP of jacketed HWR @ ANL

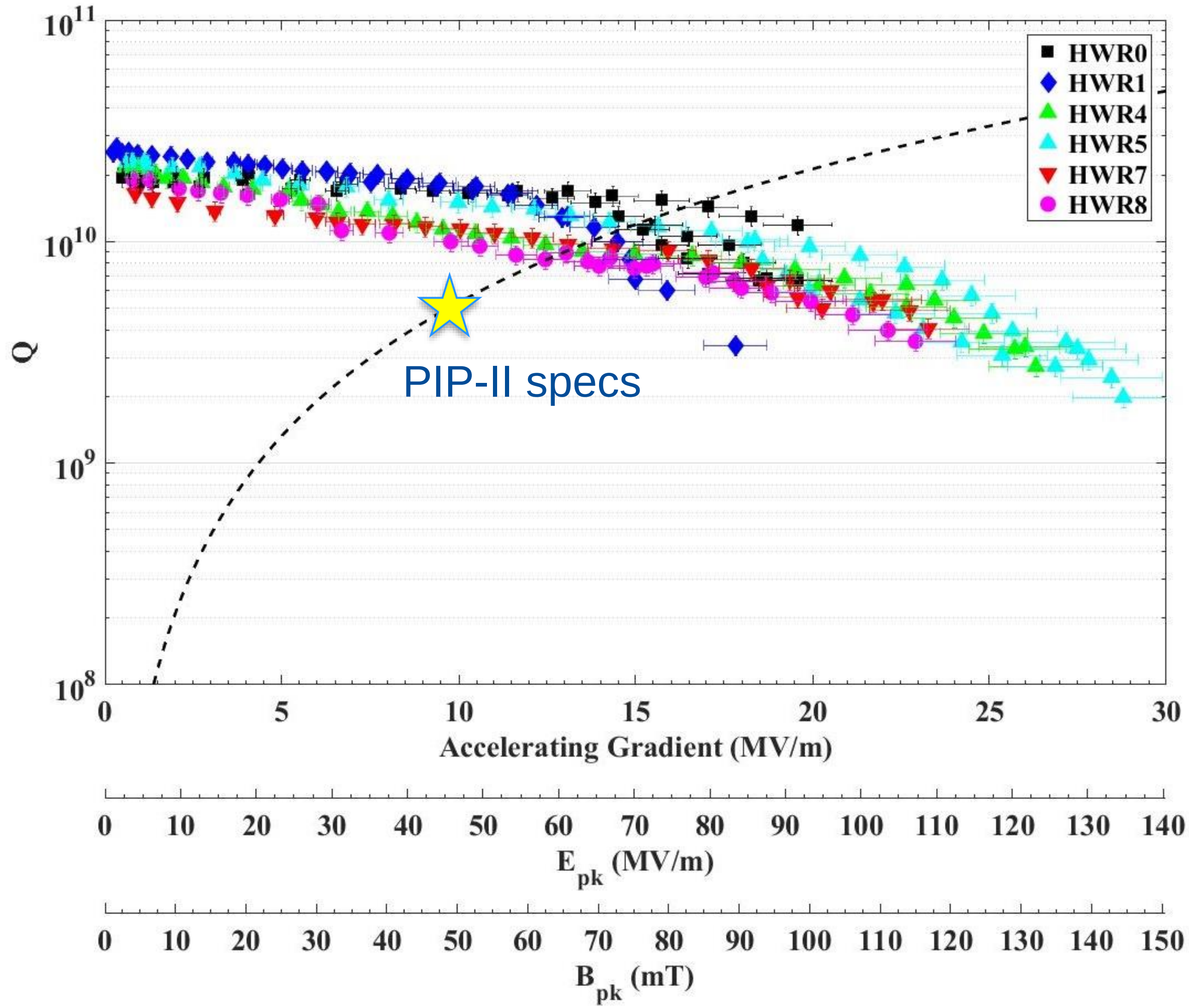


Bare HWR before jacketing

*HWR technology developed at ANL via ANL/FNAL PIP-II Collaboration.
Z. Conway, A. Barcikowski, S. Gerbik, C. Hopper, M.P. Kelly, M. Kedzie, S. Kim, P. Ostroumov, T. Reid.

HWR 2 K Test Results

Curtesy of A. Lunin and Z. Conway



SSR1: 325 MHz Single Spoke Resonators

Surface treatments:

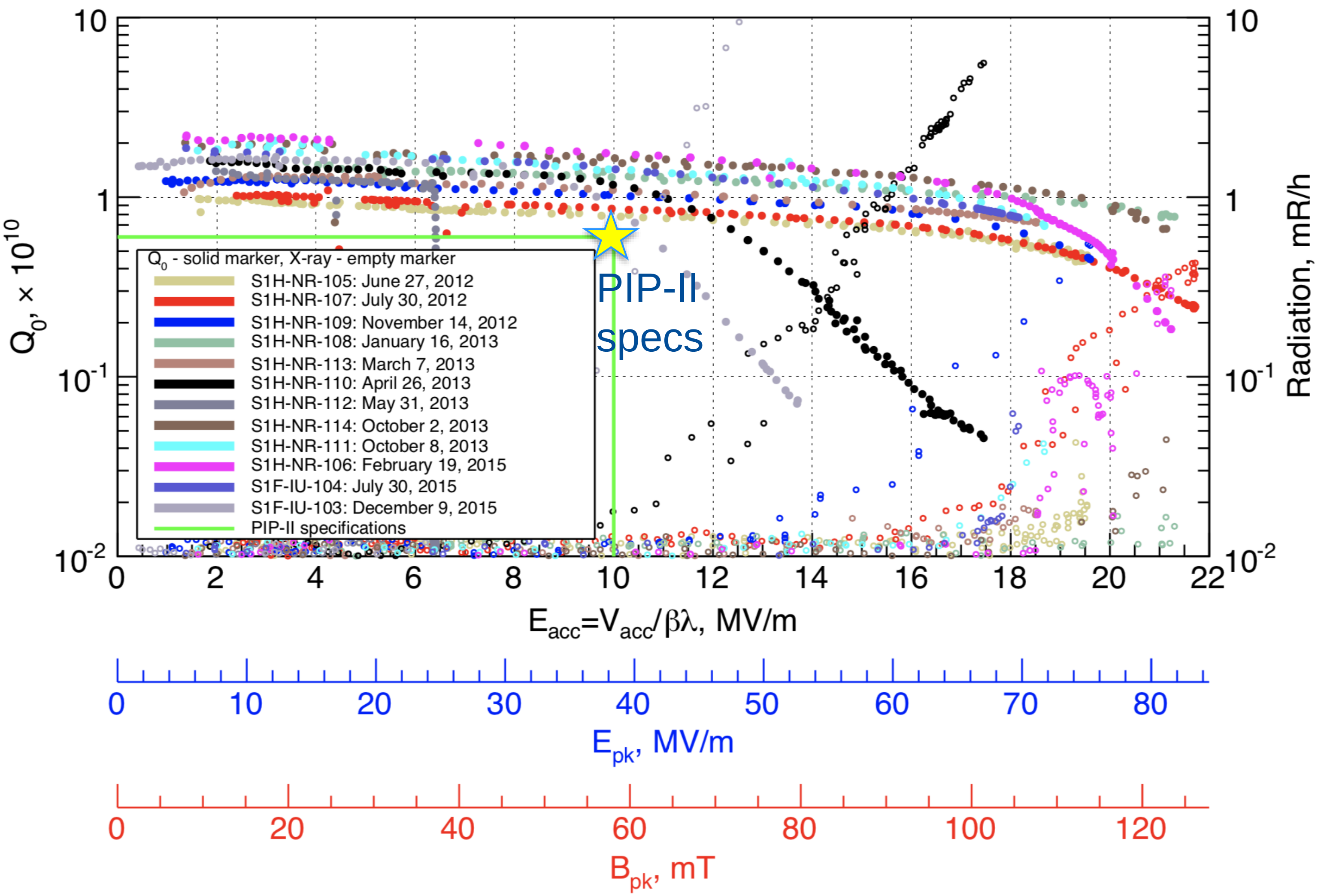
- Bulk BCP $\sim 120\ \mu m$
- Baking at $600\ °C$ for 10 hours in UHV furnace
- Light BCP $\sim 20\ \mu m$
- Low T baking at $120\ °C$ for 48 hours

  → particularly favorable to process MP

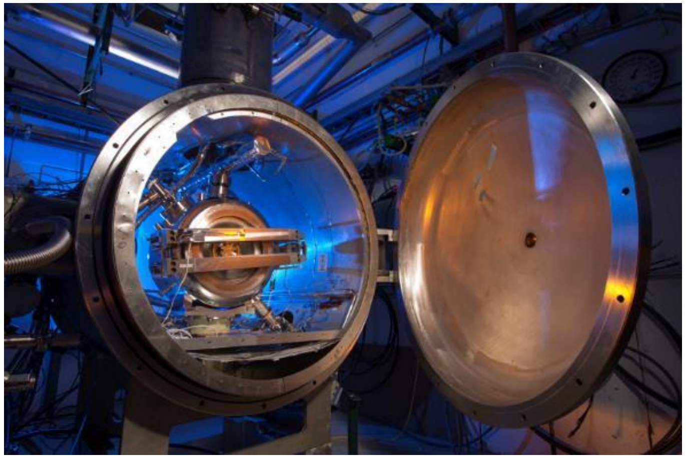
L. Ristori, M.H. Awida ,P. Berrutti, T.N. Khabiboulline, M. Merio, D. Passarelli, A. Rowe, D.A. Sergatskov, A.I. Sukhanov, Proc. of IPAC 2013, Shangai, China

SSR1 VTS Test Result

Curtesy of A. Sukanov

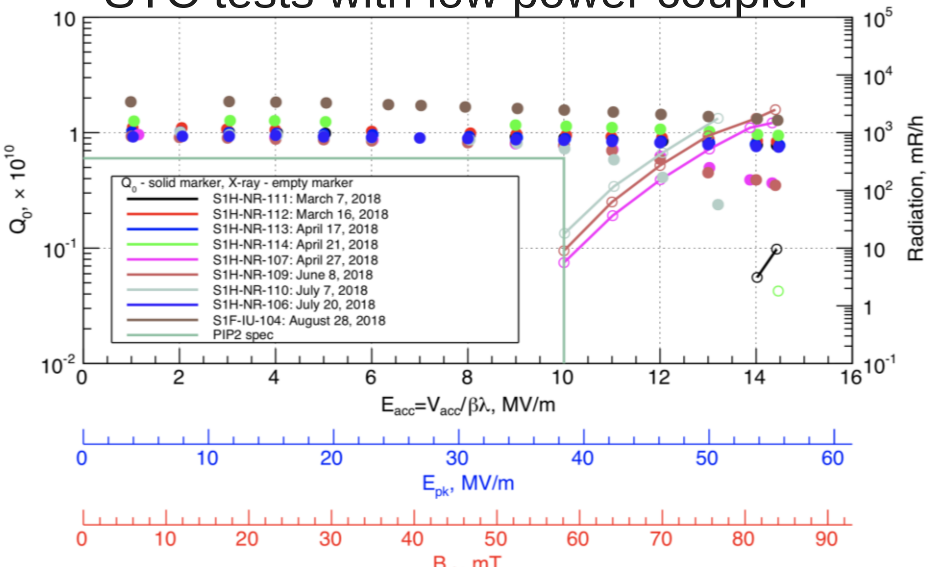


Fully-Integrated Tests in STC

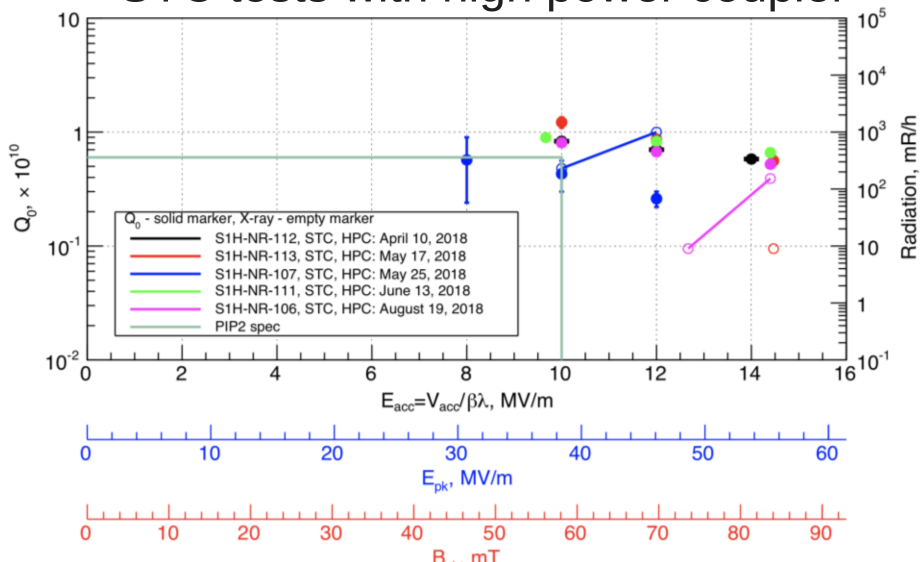


- 9 cavities pre-qualified after test at STC with low power coupler
- Some degradation observed between VTS test and STC test that may be due to *flux trapping* -> some studies are being carried out to better understand trapped flux sensitivity in SSR cavities
- 5 cavities tested with **high power coupler** → cavities meet spec and are now <u>waiting for string assembly</u>

STC tests with low power coupler



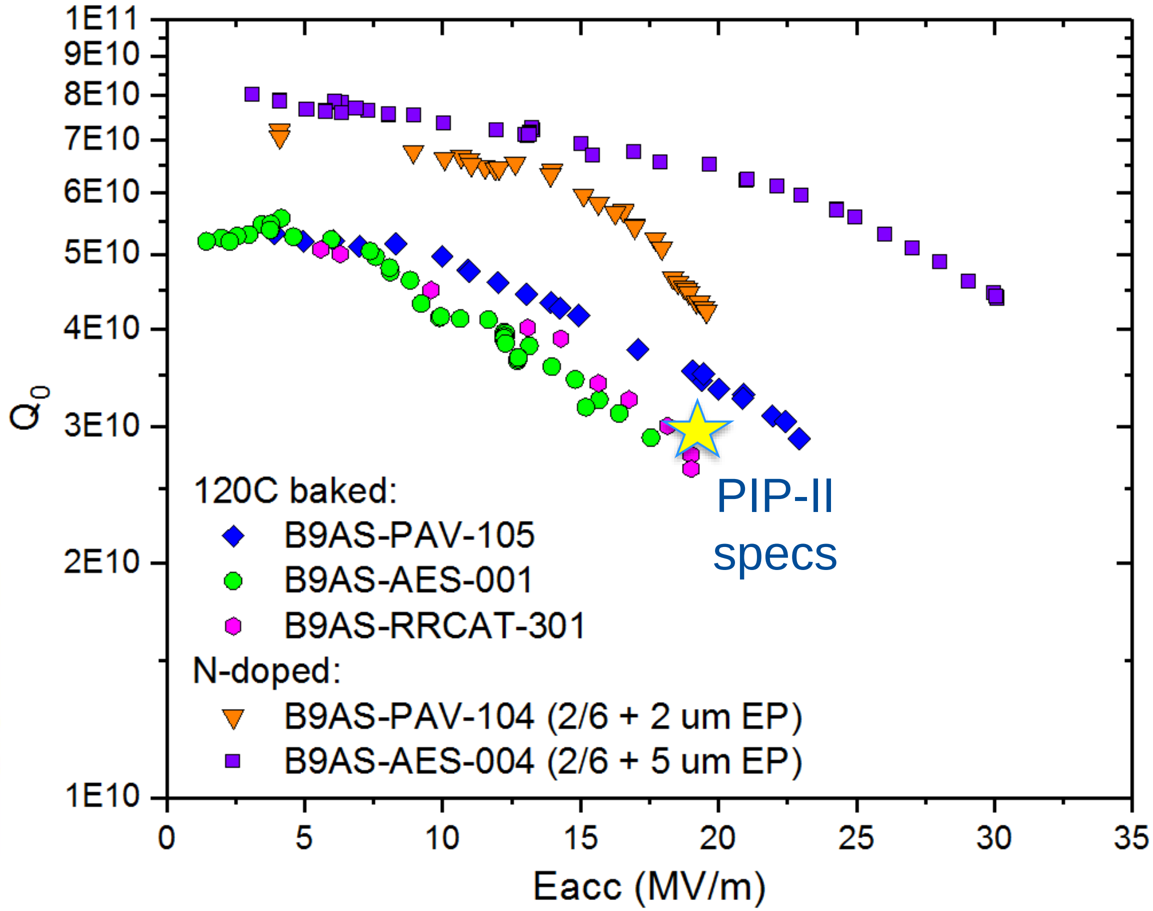
STC tests with high power coupler



Courtesy of A. Sukhanov

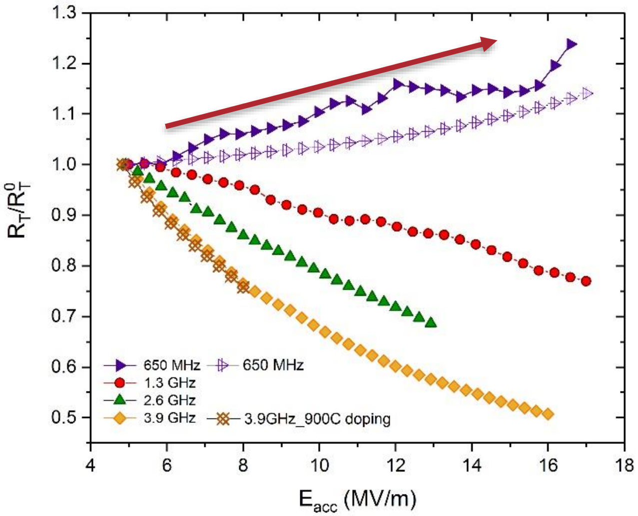
HB650 Single-cell Test Results

- 120C baked cavities not always meet specs
- N-doping capable to double the Q-factor at medium field, sometimes affected by early quench
- **World record Q-factor** of 7e10 at 2K,17 MV/m and 650 MHz with N-doping

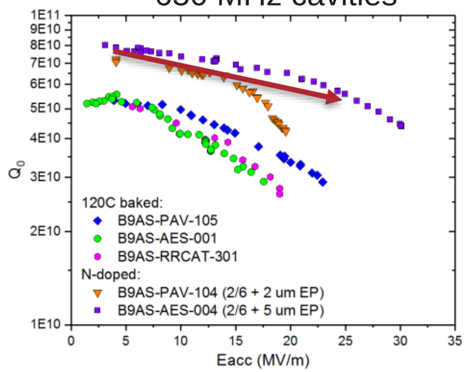


Frequency dependence of R_{BCS}(Eacc)

N-doping

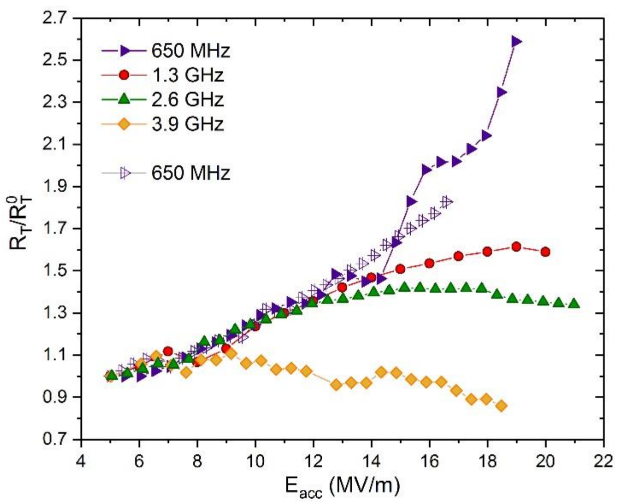


650 MHz cavities



- N-doped cavities at 650 MHz do not show the R_T reversal (anti-Q-slope) typically observed at 1.3 GHz

120C baking



- The physical mechanism underneath the reversal of R_{BCS} (here called R_T) has a stronger effect at high frequencies

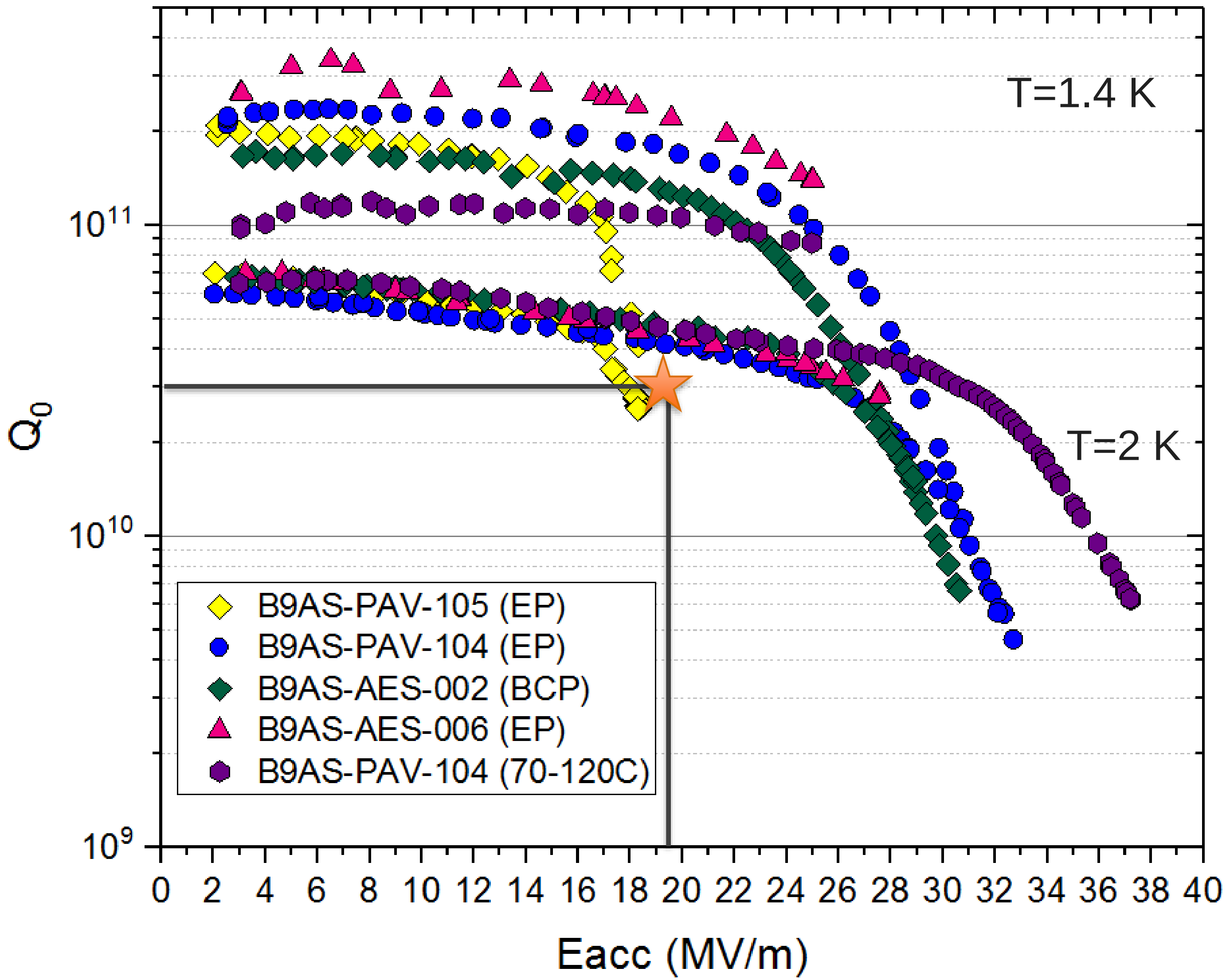
- Also for 120C baked cavities, ***the field dependence of R_T is unfavorable at low frequencies***

M. Martinello et al. SRF 2017 (**TUYAA02**), IPAC 2018 (**WEPML013**)

HB650 Single-cell R&D program

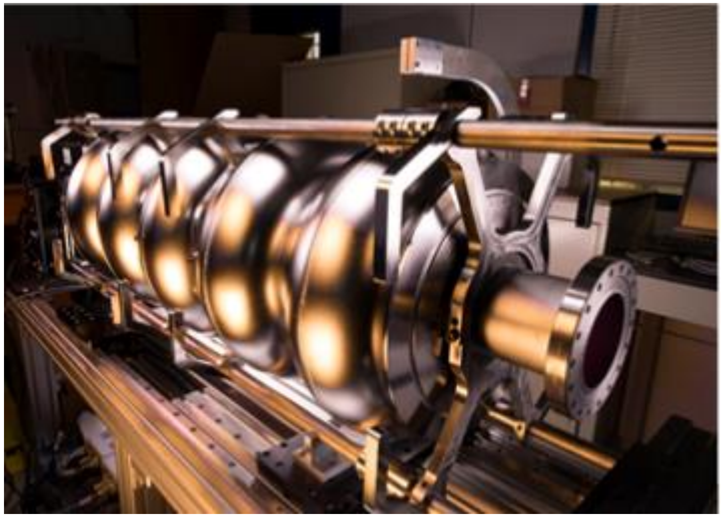
- *Because of the recent significant improvement in the SRF technology, now we started an intensive R&D program for 650 MHz cavities*
  - GOAL: reach the highest possible Q at medium/high field for 650 MHz cavities
  - Flux expulsion and trapped flux sensitivity will be also taken into account for Q preservation in cryomodule
- Surface treatments under studies: EP, BCP for baseline and modified 120C (75-120C baking), N-doping, N-infusion for Q improvement
- Trapped flux sensitivity will be acquired for each treatment to understand magnetic flux shielding requisition in cryomodule

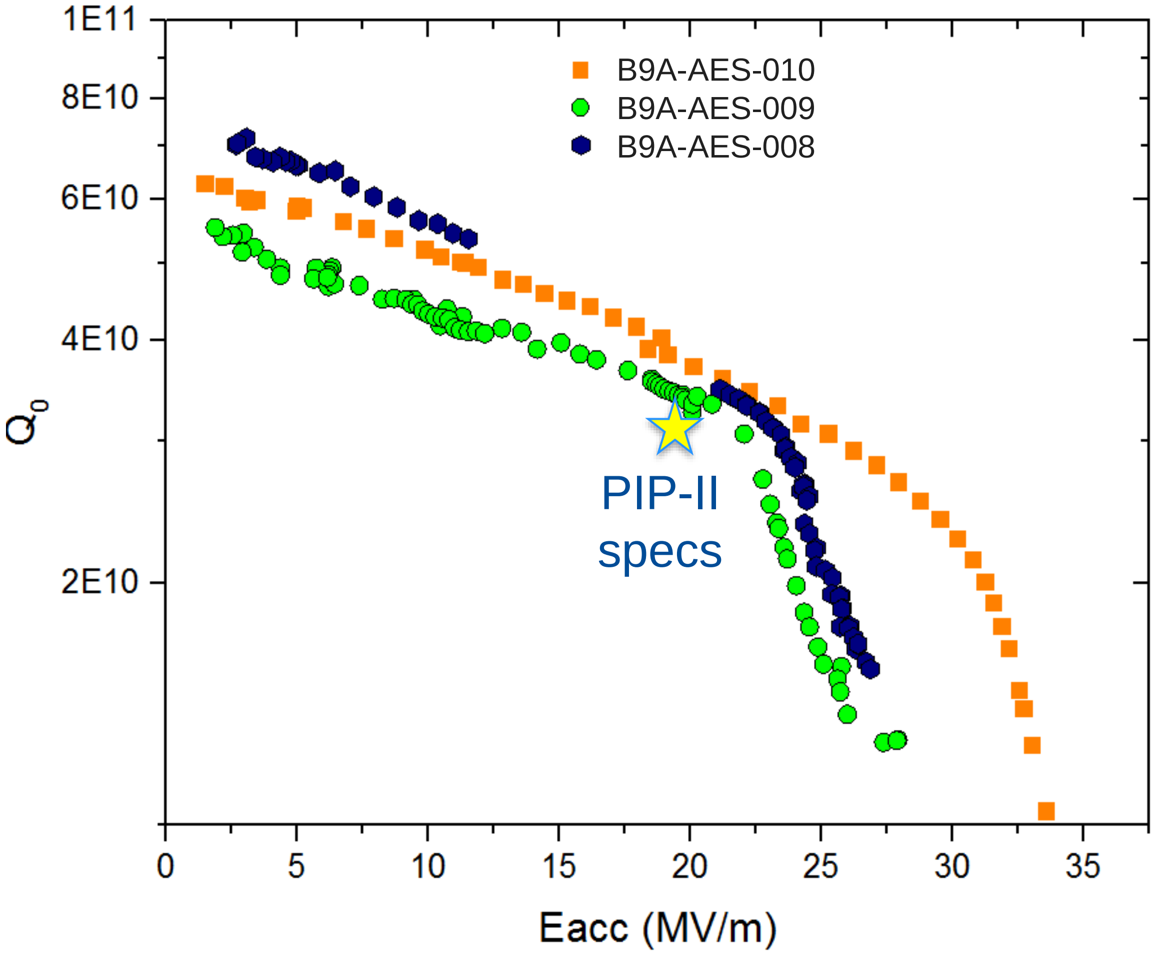
Summary RF results of 650 MHz cavities new R&D program



HB650 5-cells Tests Results (all N-doped + “heavy” EP)

- Light N-doping applied to 650 MHz cavities
- 3 N-doped 5-cells 650 MHz cavities meet PIP-II specification
- **B9A-AES-010 is now being dressed with He vessel**





Conclusion and Future plan

- Thanks to recent advance in the SRF technology, several treatments are suitable for high-Q at medium/high gradient
- Since the field dependence of Rbcs strictly varies with frequencies, N-doping in 650 MHz cavities is not as effective as in 1.3 GHz cavities
- The optimal surface treatment for 650 MHz cavities is therefore under investigation, taking into account the needed for low trapped flux sensitivity at medium field
- Trapped flux sensitivity and flux expulsion to be studied to set specification of magnetic field shielding
- HWR and SSR cavities meet PIP-II spec with standard BCP/baking treatment -> R&D is planned to further improve Q in SSR2 cavities

Thank you for your attention!