ILLINOIS INSTITUTE OF TECHNOLOGY

Fermilab

U.S. DEPARTMENT OF ENERGY | Office of Science

N-doping: A Breakthrough Technology For SRF Cavities

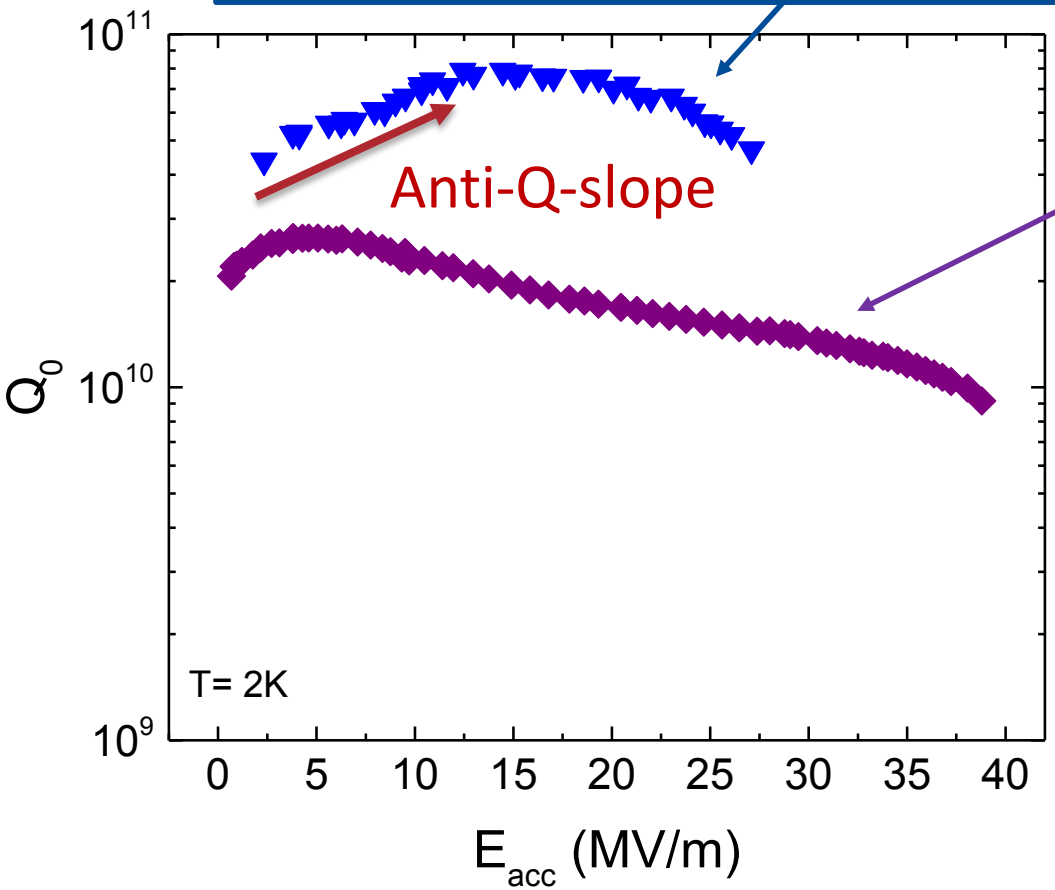
Martina Martinello

LINAC 2016

28 September 2016

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 bake (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

Jefferson Lab Cryoplant
(completed 2012)
→ SLAC / LCLS-II to be similar ←

For CW accelerators the refrigeration cost is of the order of several tens of millions $

The N-doping Timeline

2012

Discovery of N-doping

2013

R&D effort to make N-doping controllable and reproducible

2013

Discovery of 'light doping': improvement of the accelerating field maintaining high Q-factors

2014

LCLS-II invested in the technology, collaboration FNAL, JLAB and Cornell University

2014 and 2015

More than 100 N-doped cavities tested, 18 cavities qualified for the 2 prototype cryomodules

2015 and 2016

R&D continues for further understanding and improvement

Low-T N-infusion combines higher Q with quench fields up to 45 MV/m

Outline

N-DOPING – PHYSICS AND TECHNIQUE

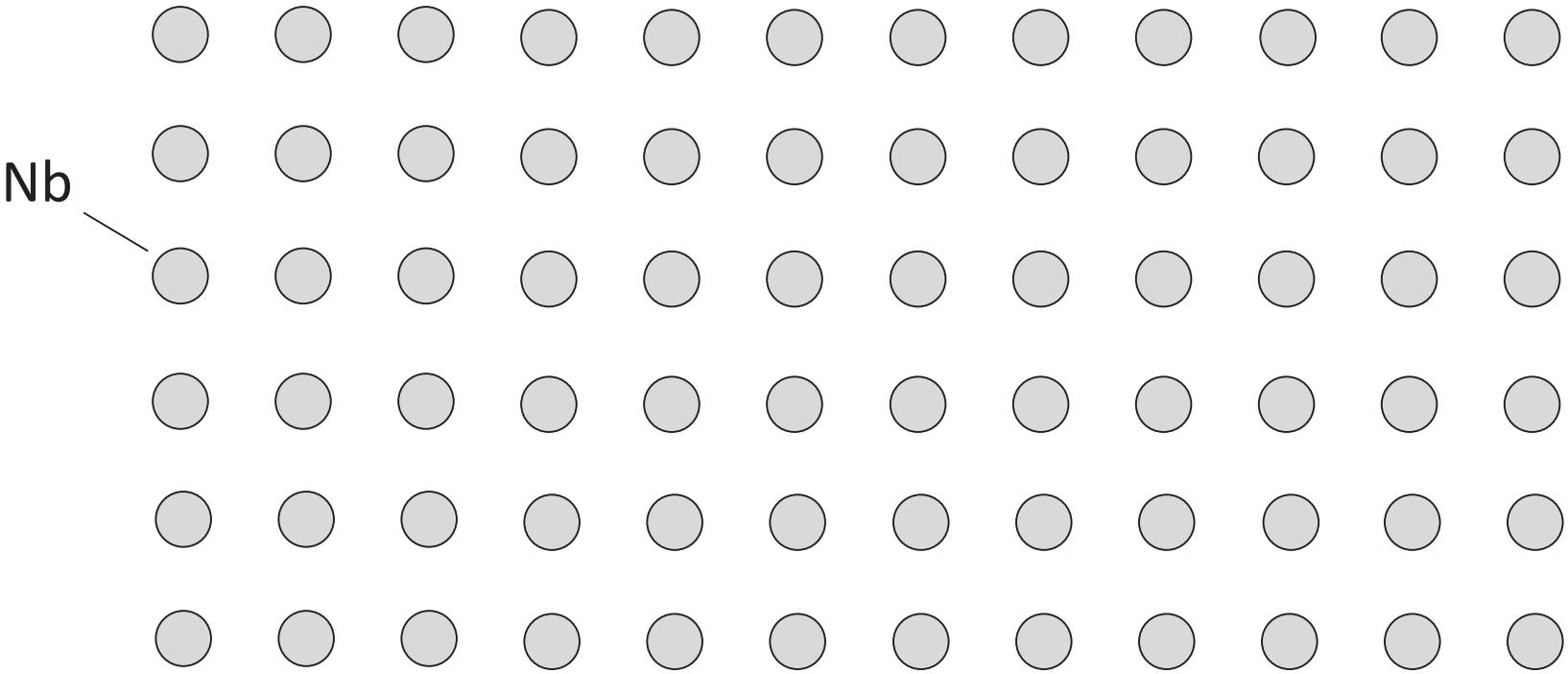
HIGH-Q PRESERVATION

STATE OF THE ART PERFORMANCE AND APPLICATIONS

CONCLUSIONS

N-doping treatment

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



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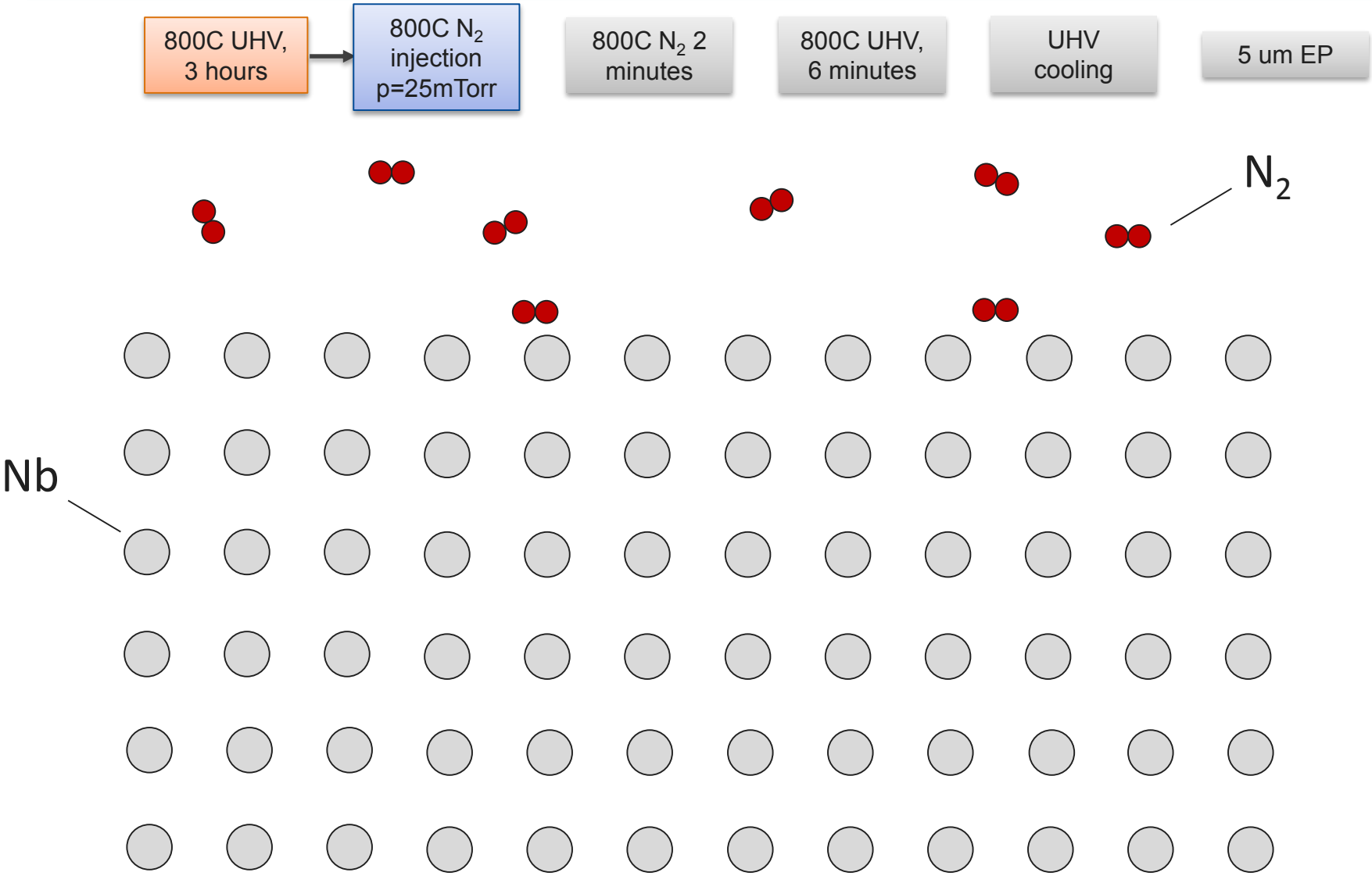
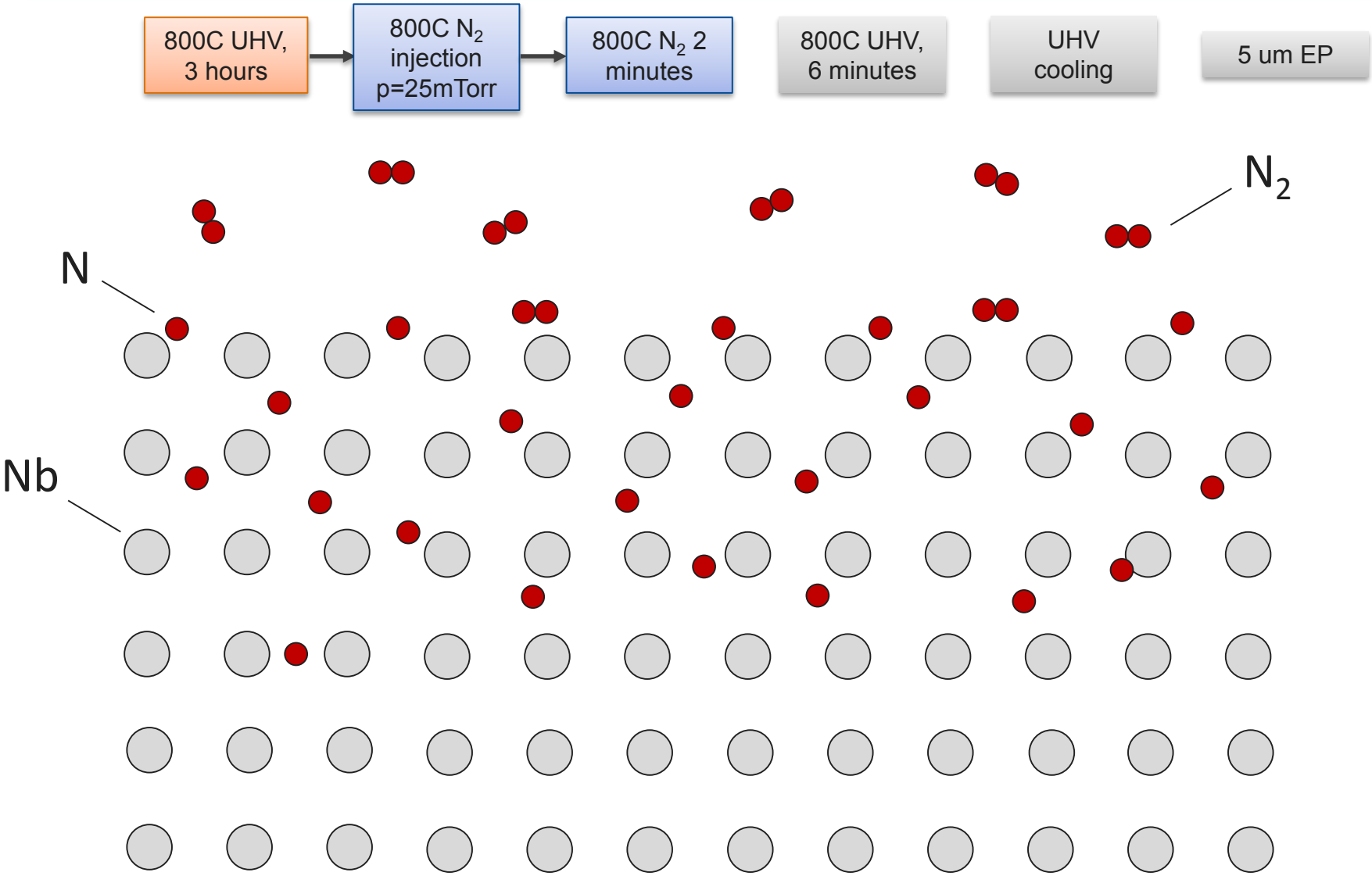


N-doping treatment (example: the “2/6 recipe”)



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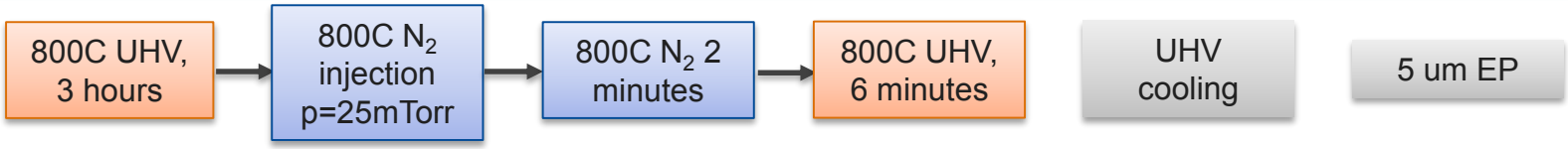

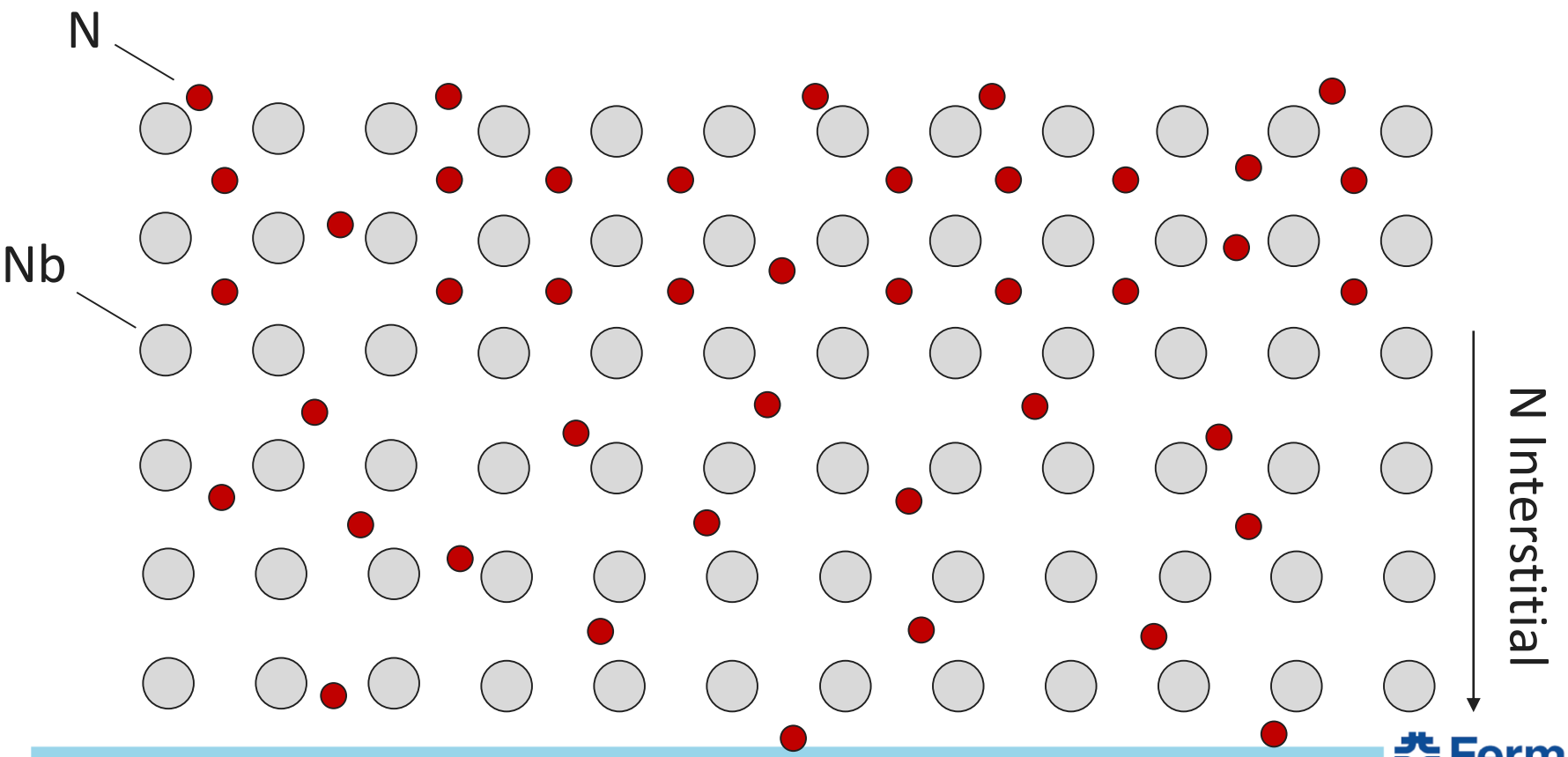

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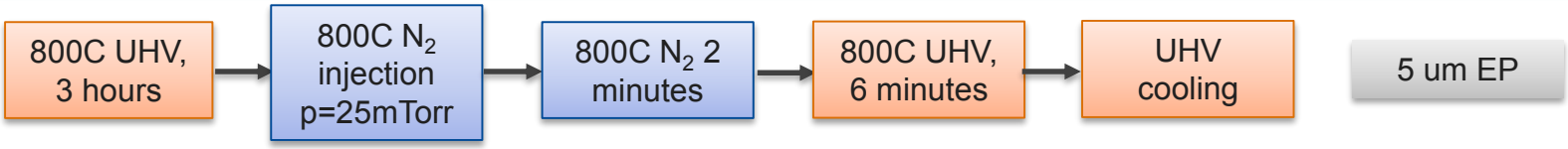

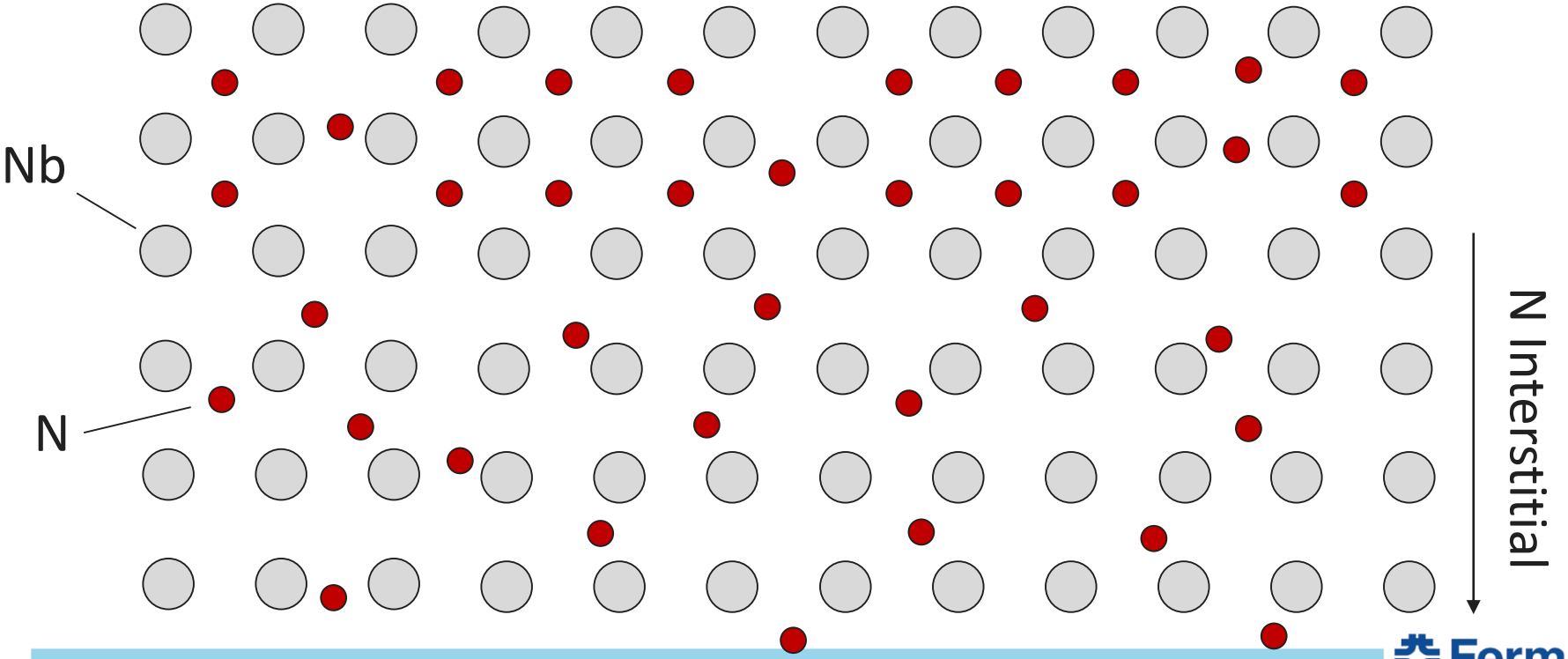

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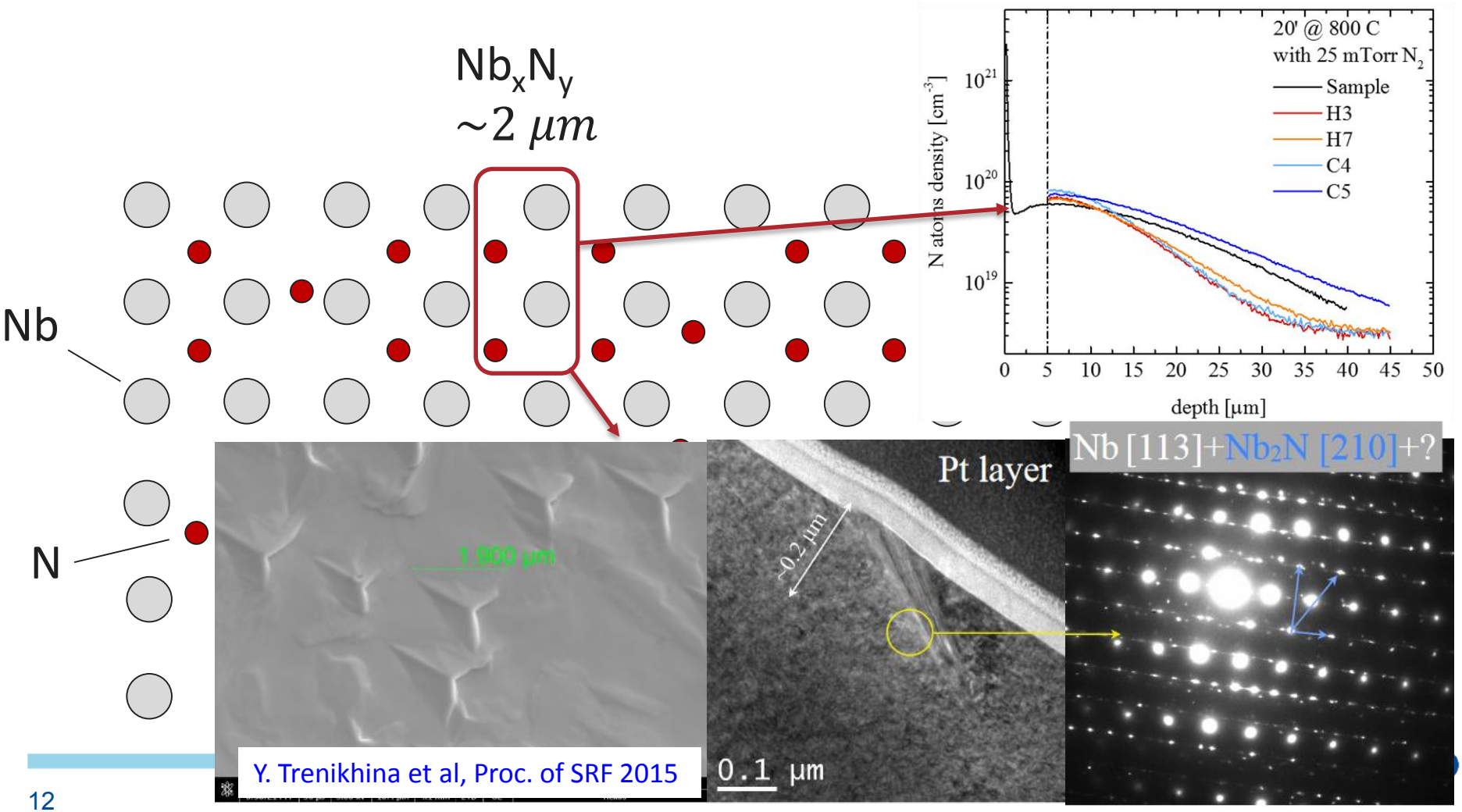
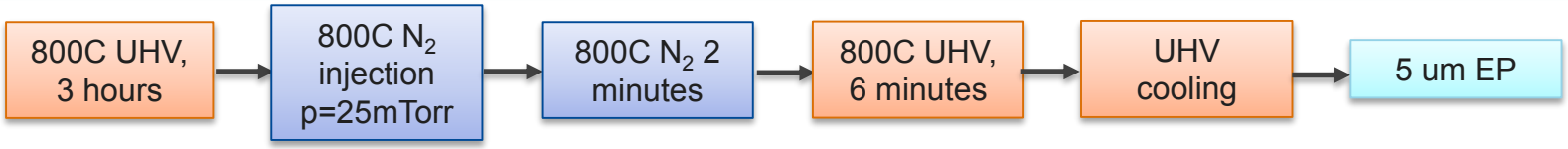
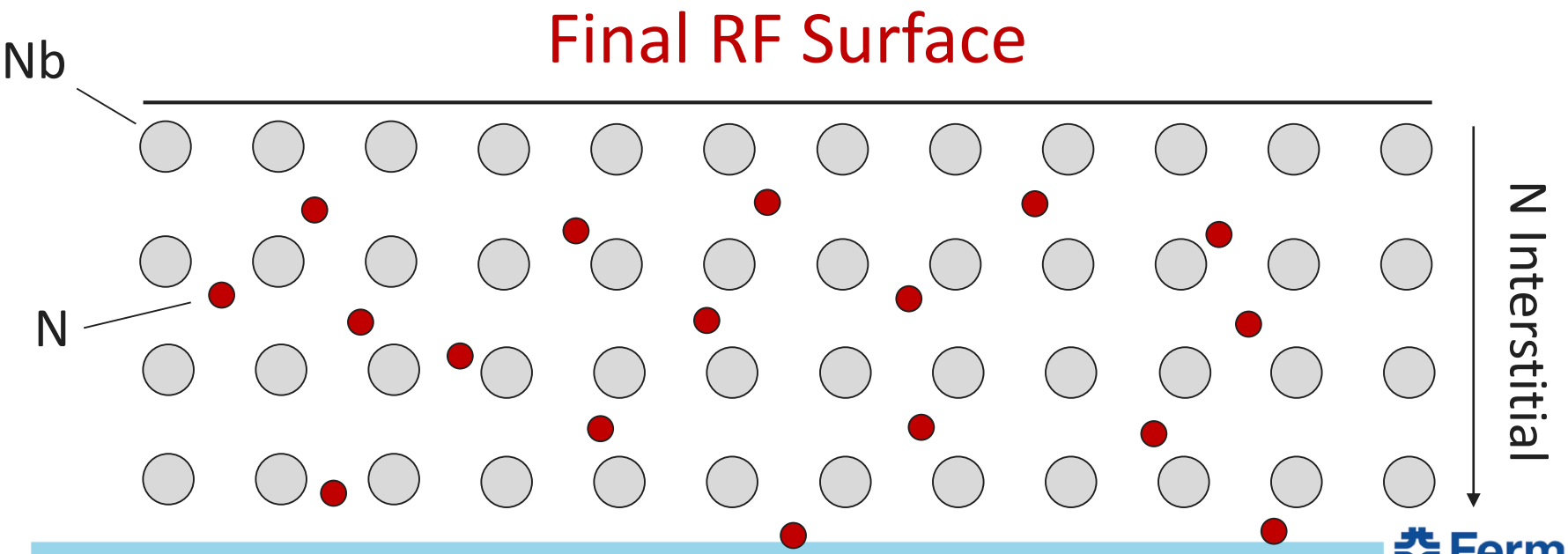


Y. Trenikhina et al, Proc. of SRF 2015

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





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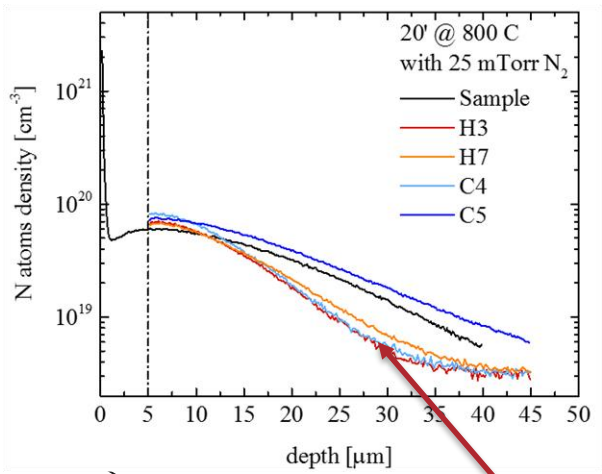
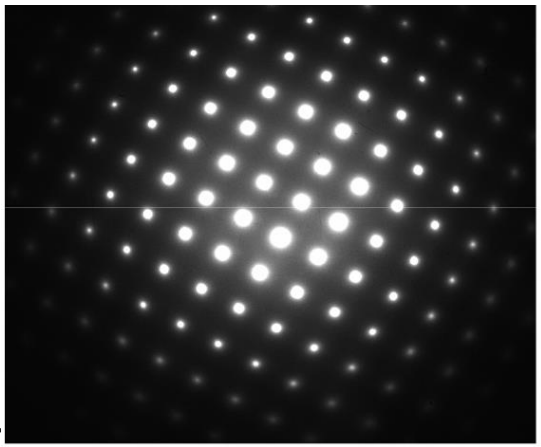
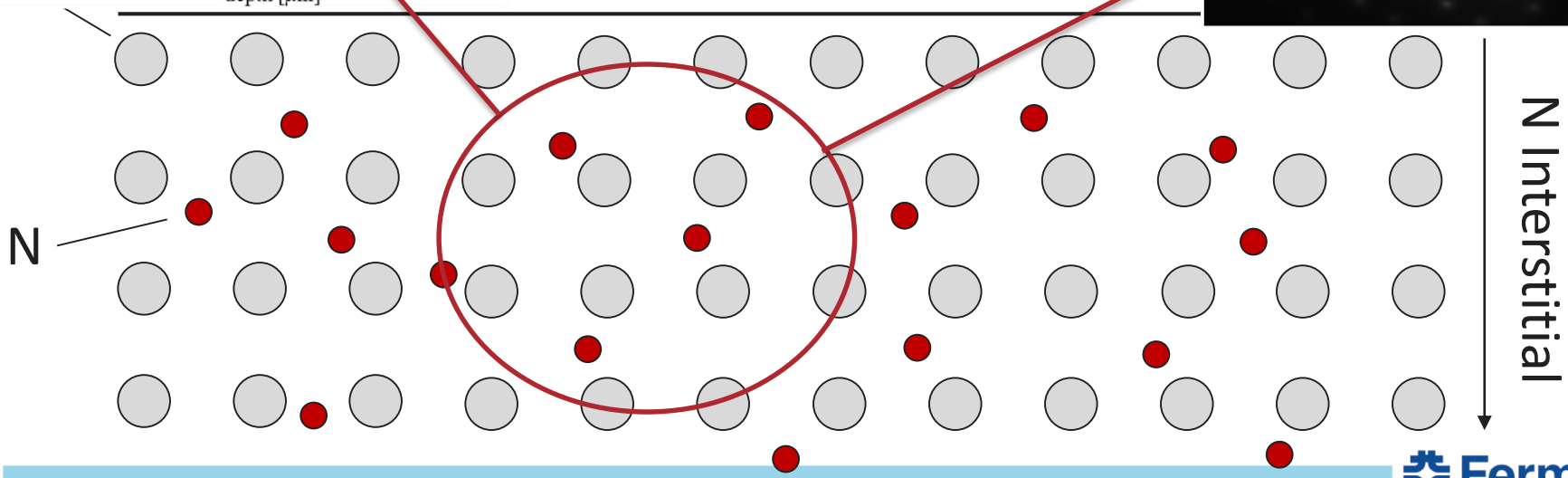


Only Nb from TEM/NED spectra:
N must be interstitial

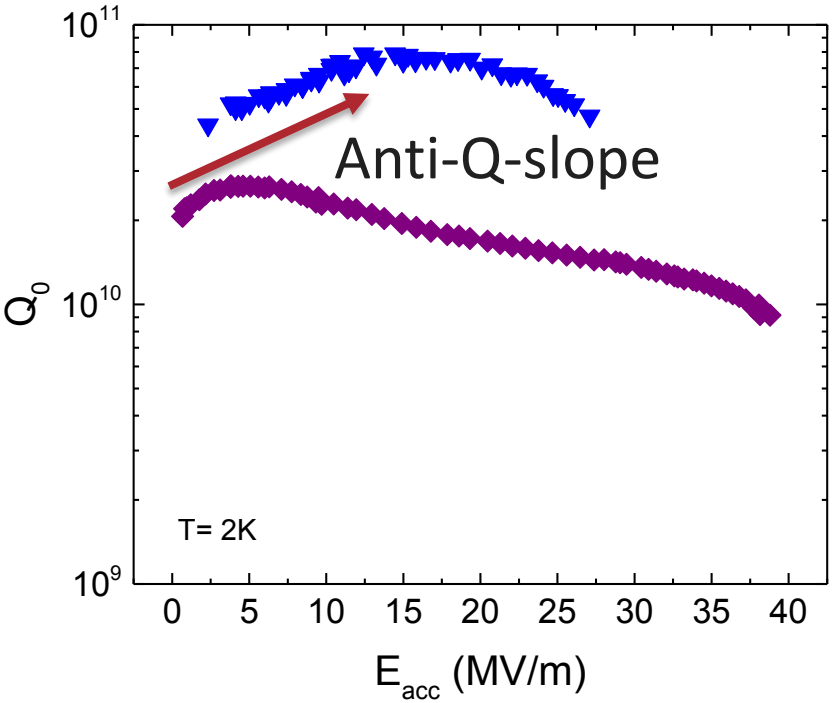


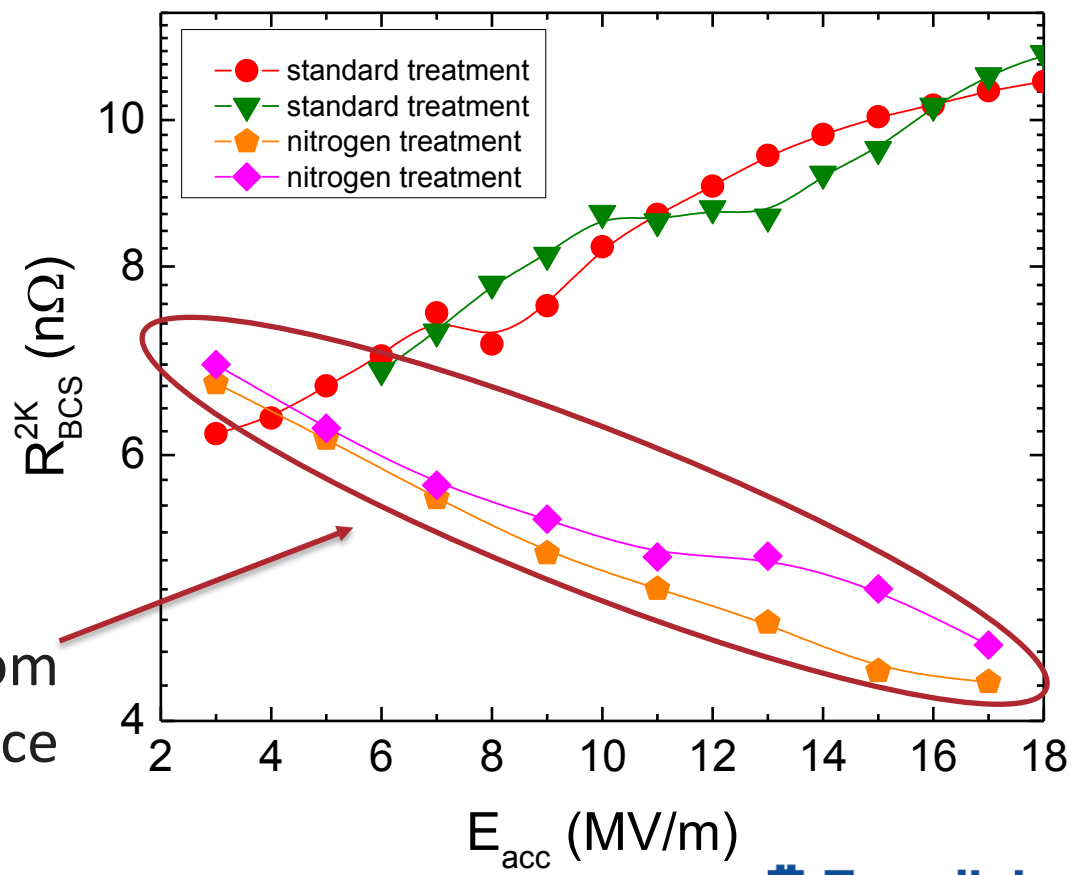
Final RF Surface



Origin of the anti-Q-slope

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



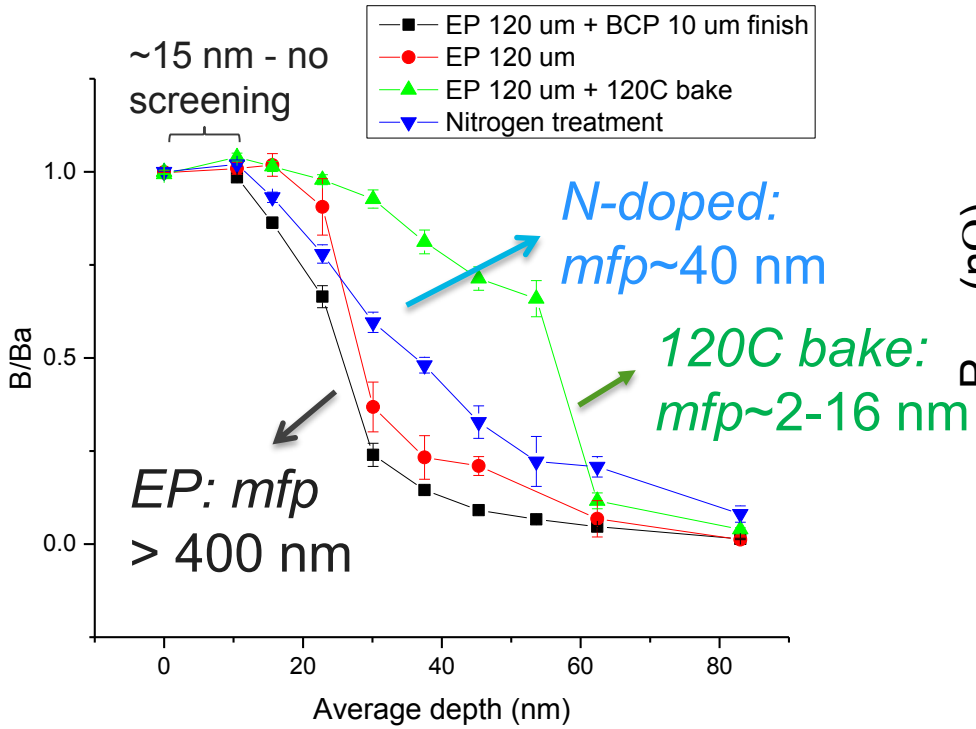


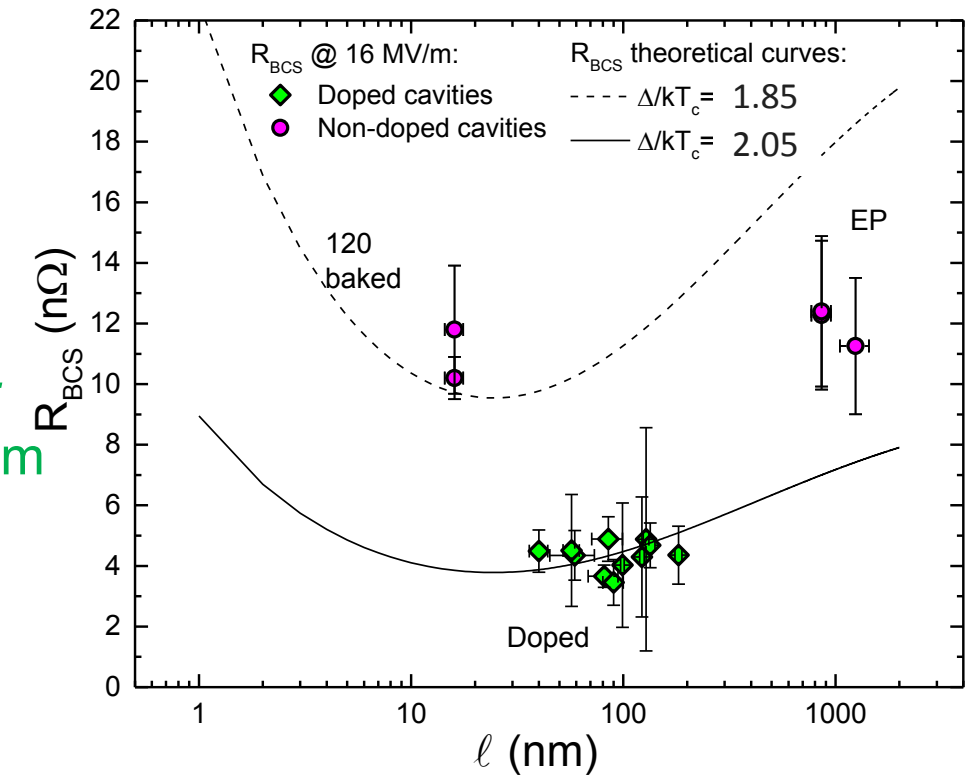
Anti-Q-slope emerges from the BCS surface resistance <u>decreasing</u> with field

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

Origin of reduction of RF surface resistance via N-doping

LE-μSR measurements (Ba=25mT)





A. Romanenko et al, Appl. Phys. Lett. **104**, 072601 (2014)
A. Grassellino et al, Proc. of SRF2015

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

M. Martinello **TUPLR023**

- ✓ N-doping modify the mean free path
  - →Mean free path close to theoretical minimum of R_{BCS}
- ✓ N-doping seems to increase the reduced energy gap Δ/kTc

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Trapped Flux Surface Resistance

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

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

These losses can be reduced by minimizing these contributions:

B_{ext}
- Magnetic shielding/hygiene improvement

η
- Fast Cooling
- Material Optimization

S
- Optimizing mean free path

Trapped Flux Surface Resistance

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

These losses can be reduced by minimizing these contributions:

External magnetic field

B_{ext}
- Magnetic shielding/hygiene improvement

η
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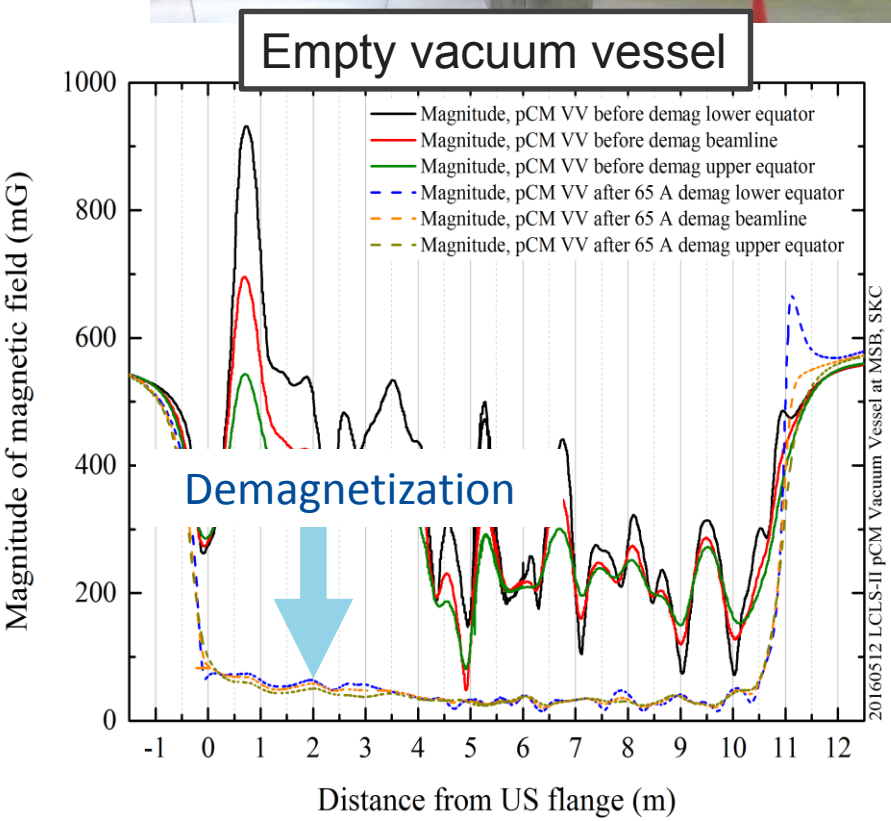
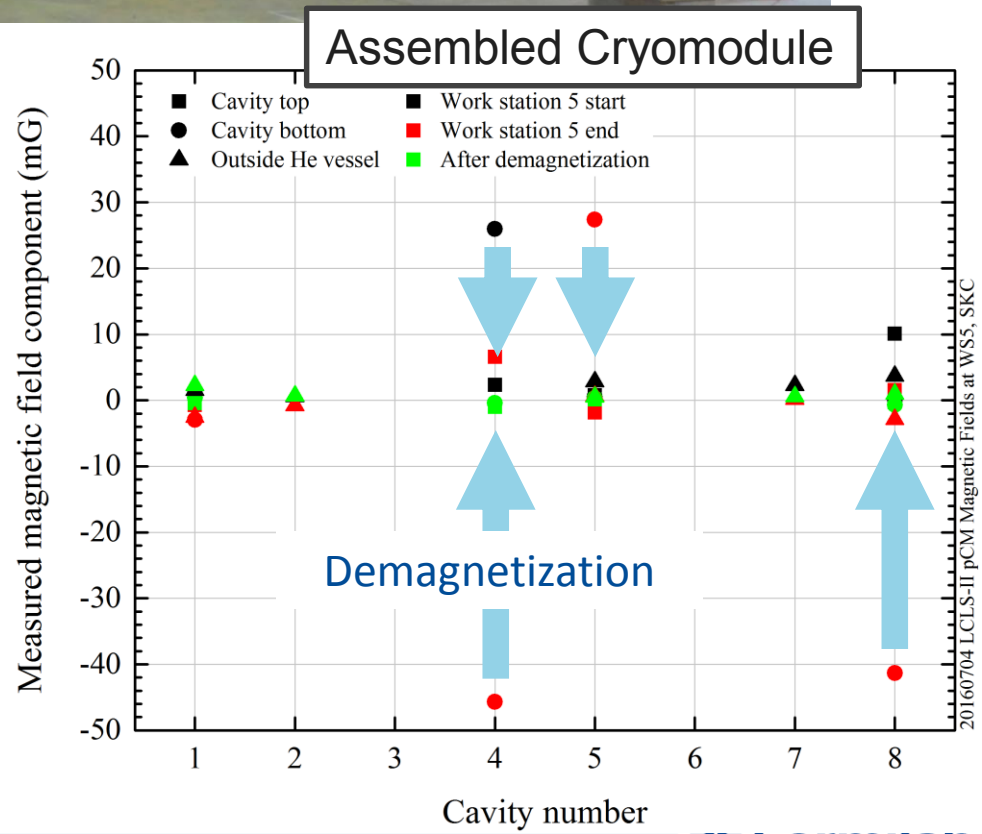
Minimization of remnant field in the cryomodule





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These losses can be reduced by minimizing these contributions:

Flux Trapping Efficiency

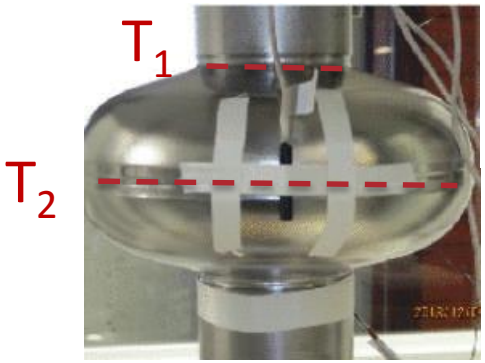
B_{ext}
- Magnetic shielding/hygene improvement

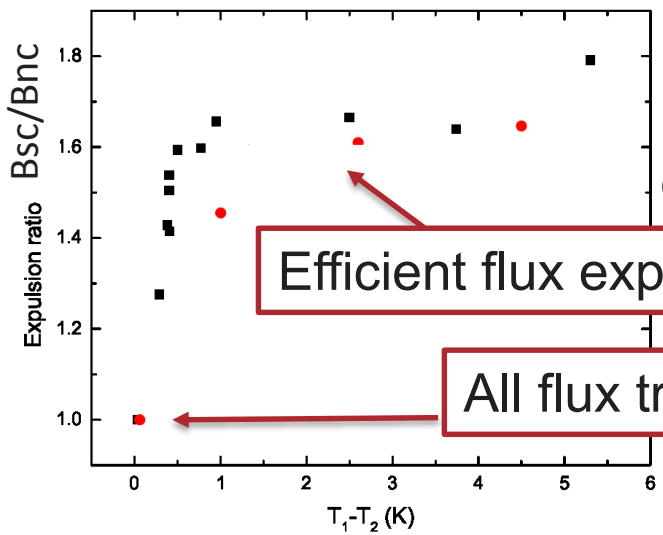
η
- Fast Cooling
- Material Optimization

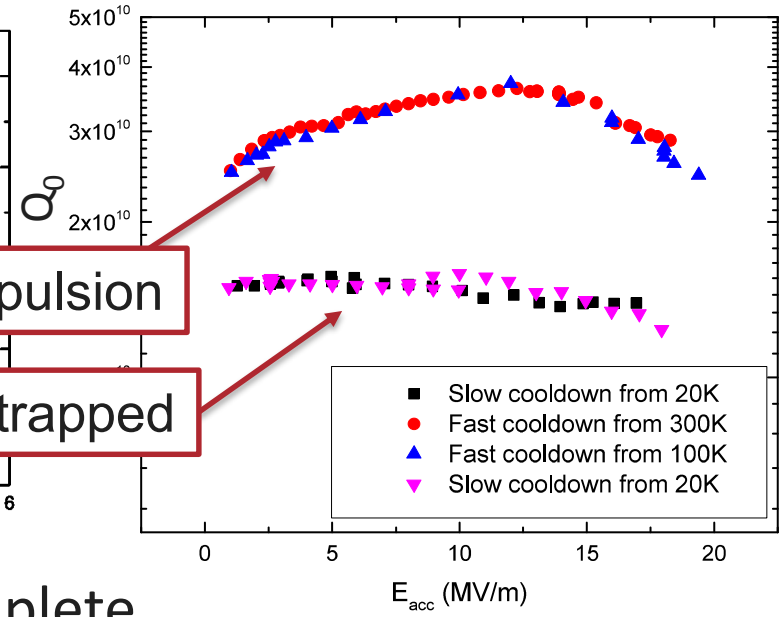
S
- Optimizing mean free path

Fast cooldown helps flux expulsion

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

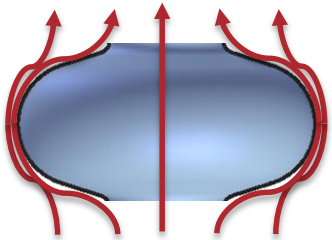




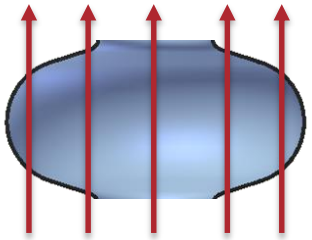


Efficient flux expulsion

All flux trapped



Bsc/Bnc=1.74 after complete Meissner effect

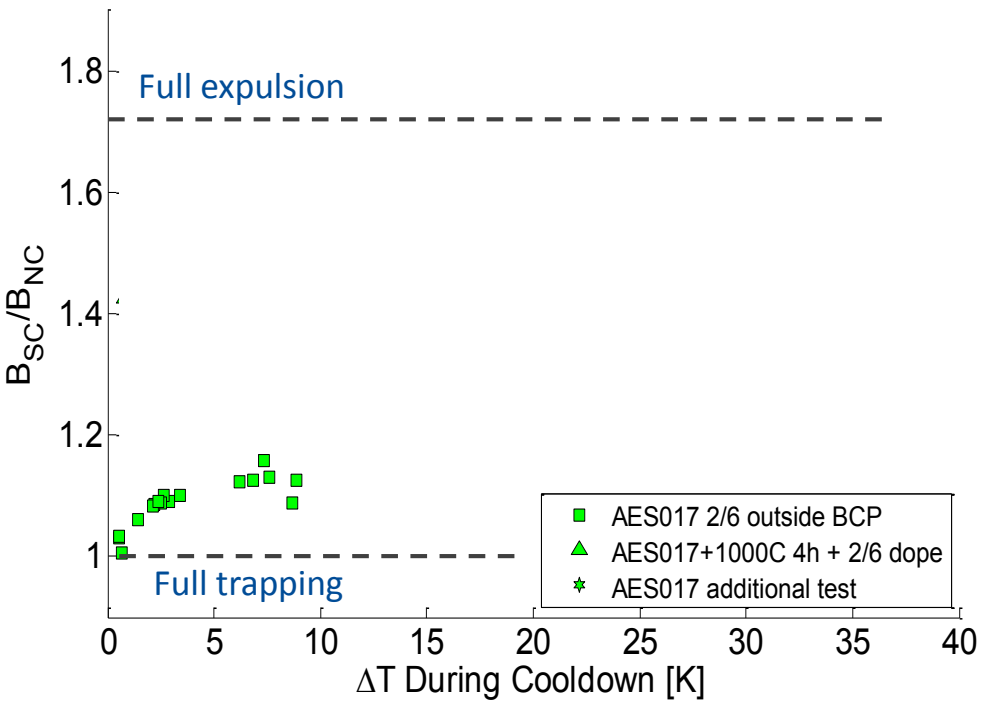


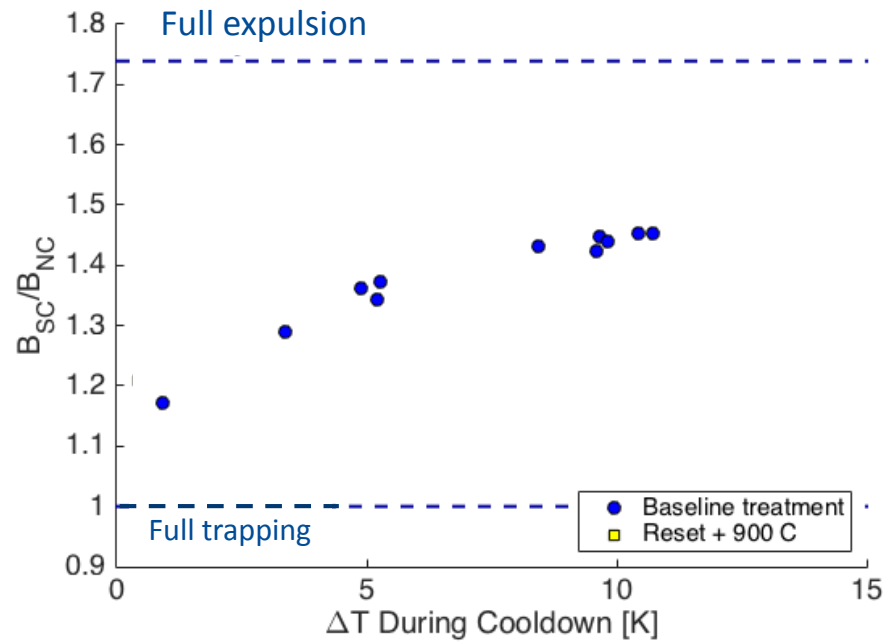
Bsc/Bnc=1 after full flux trapping

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

- 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)

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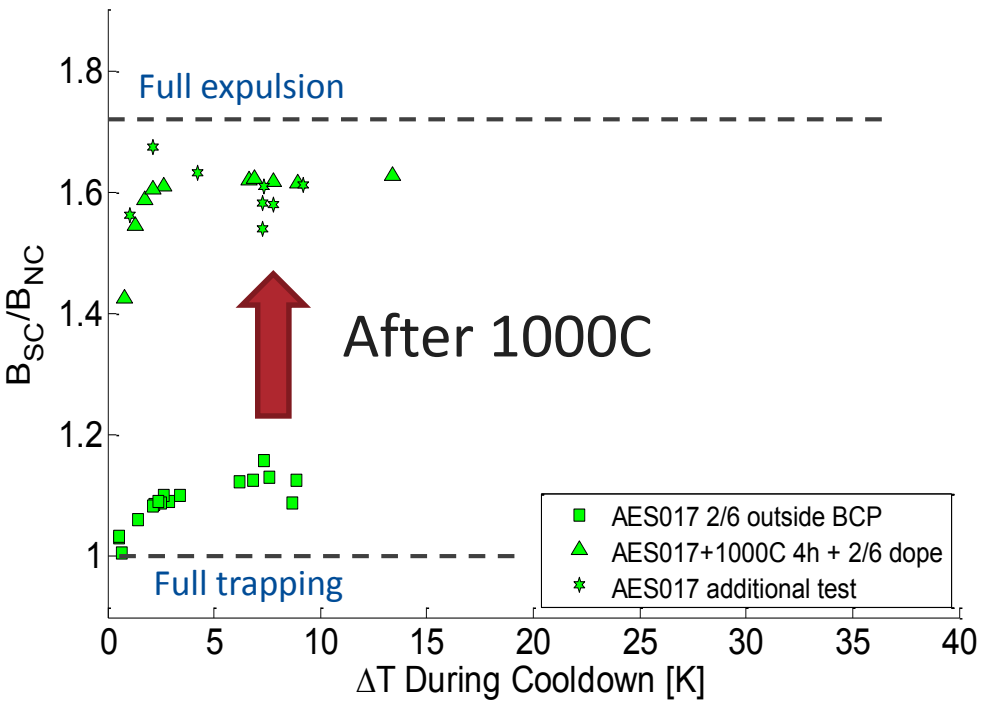

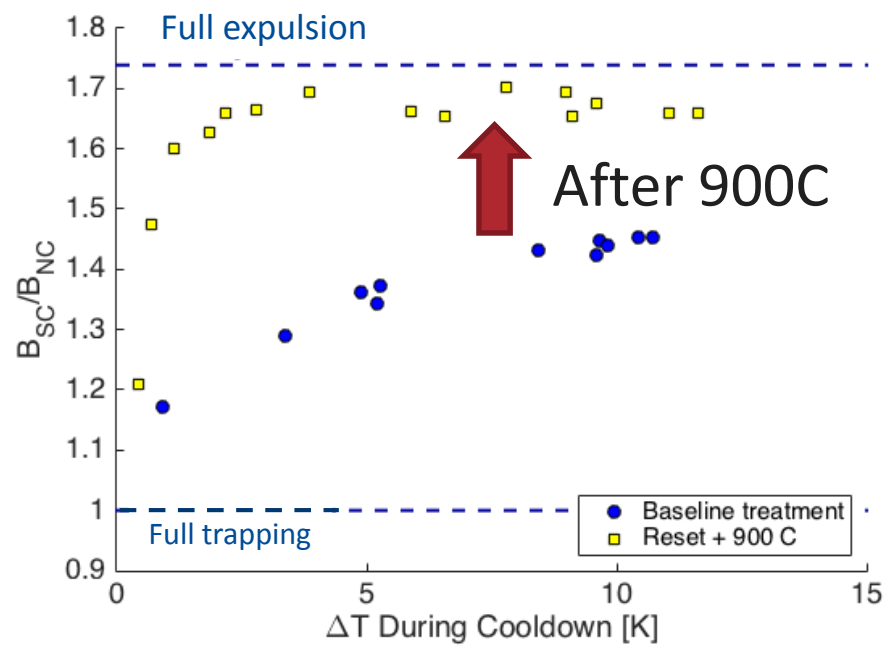

S. Posen et al., J. Appl. Phys. **119**, 213903 (2016)

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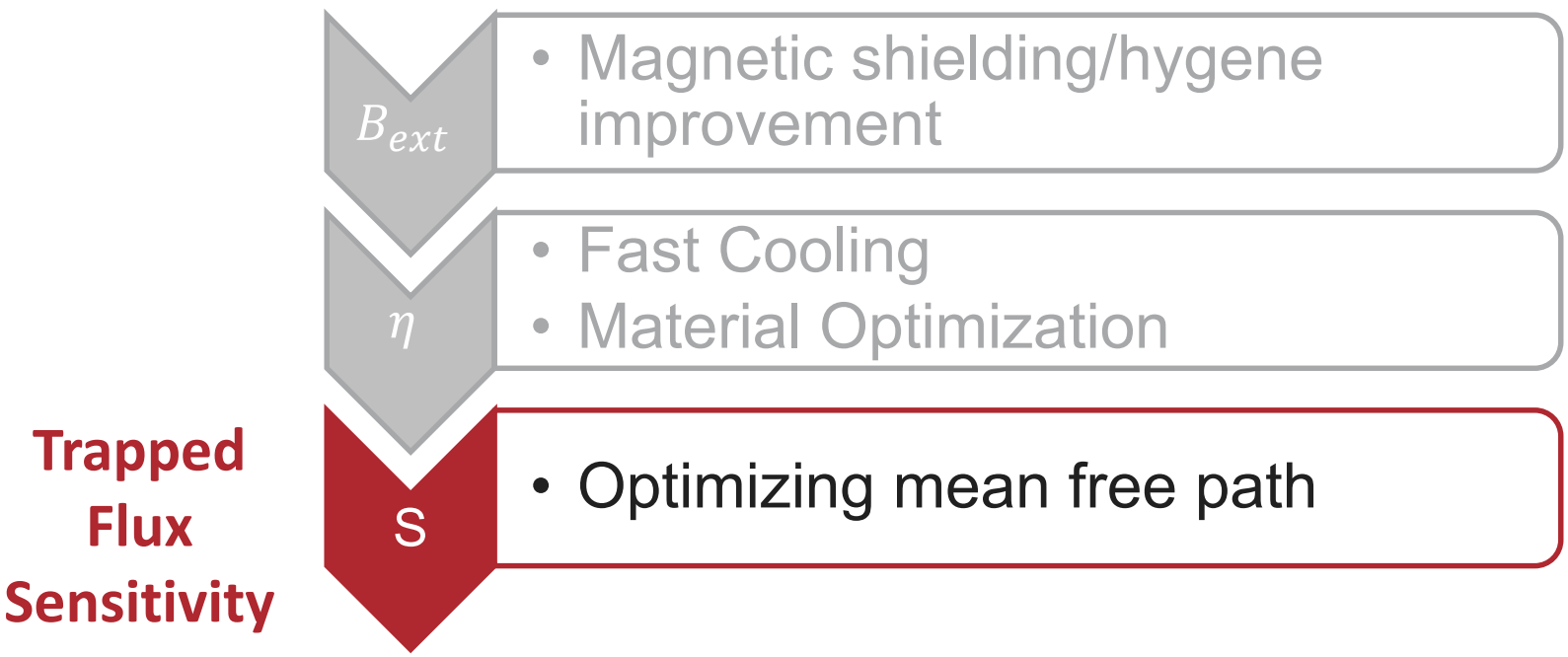
$$\boldsymbol{R_{Fl} = B_{ext} \cdot \eta \cdot \boxed{S}}$$

These losses can be reduced by minimizing these contributions:

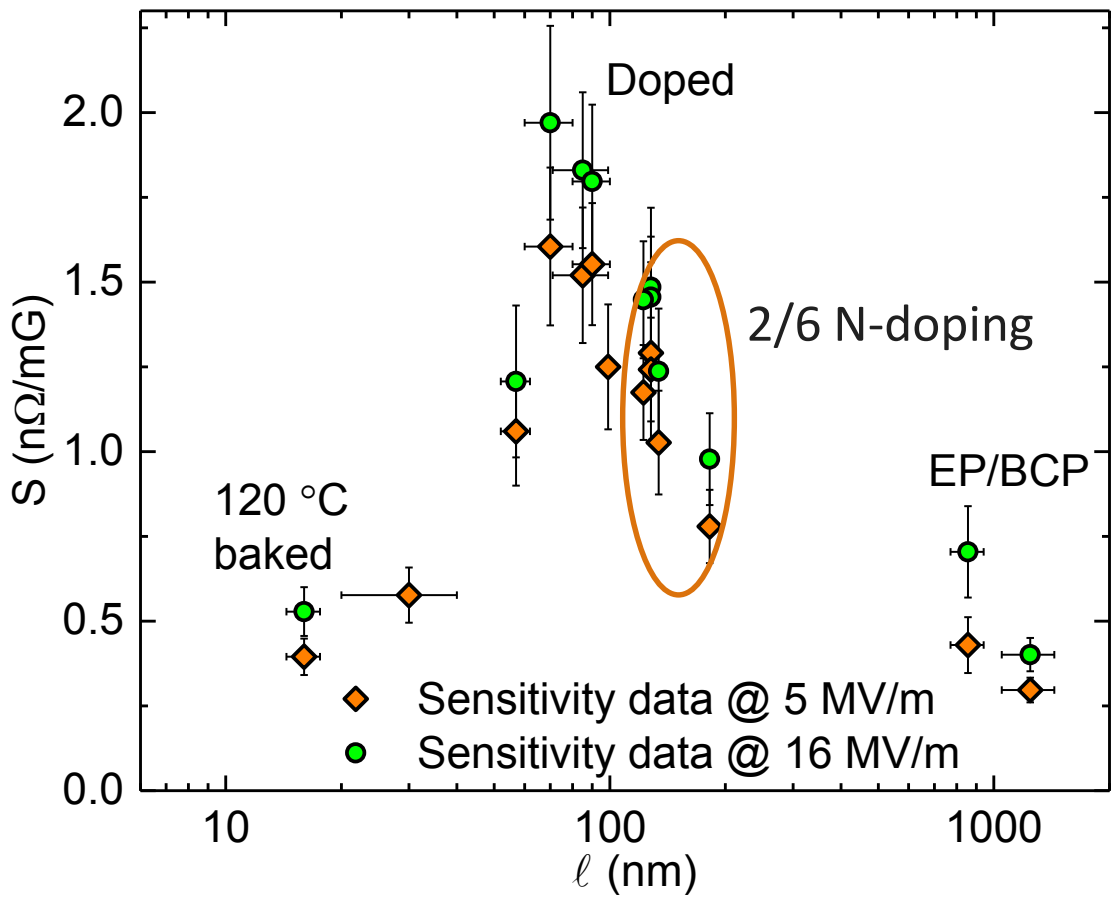


Light doping to minimize trapped flux sensitivity

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**

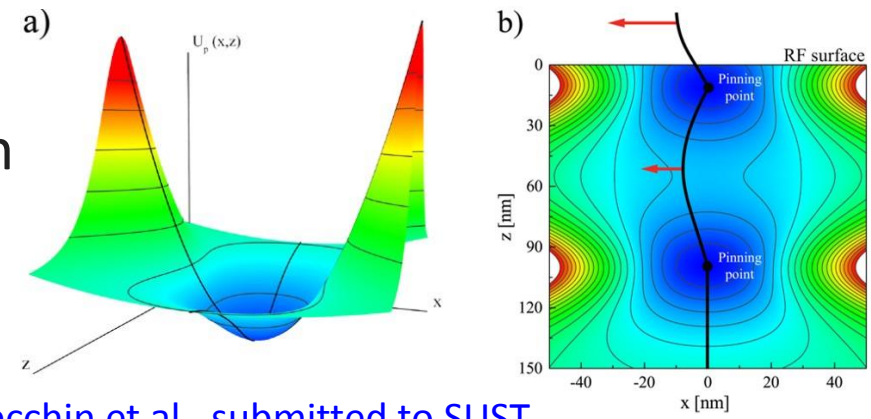


M. Martinello **TUPLR023**

M. Martinello et al., App. Phys. Lett. **109**, 062601 (2016)
D. Gonnella et al., J. Appl. Phys. **119**, 073904 (2016)

Understanding the Sensitivity vs Mean-free-path

- Dissipation due to vortex oscillation under the RF field



M. Checchin et al., submitted to SUST

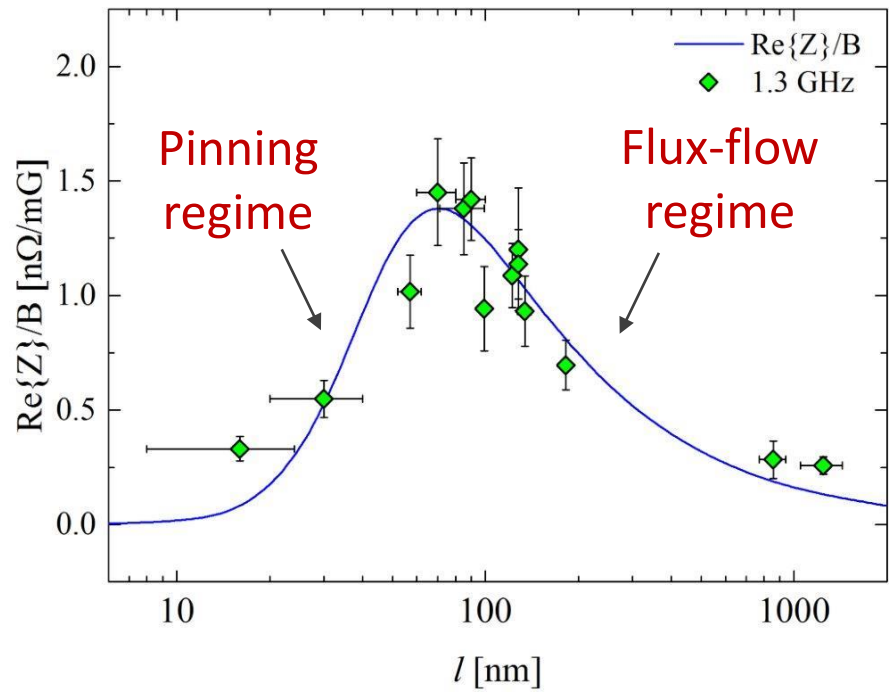
We can define two regimes:

1. *Large l ($p \to 0$) – flux flow regime*:

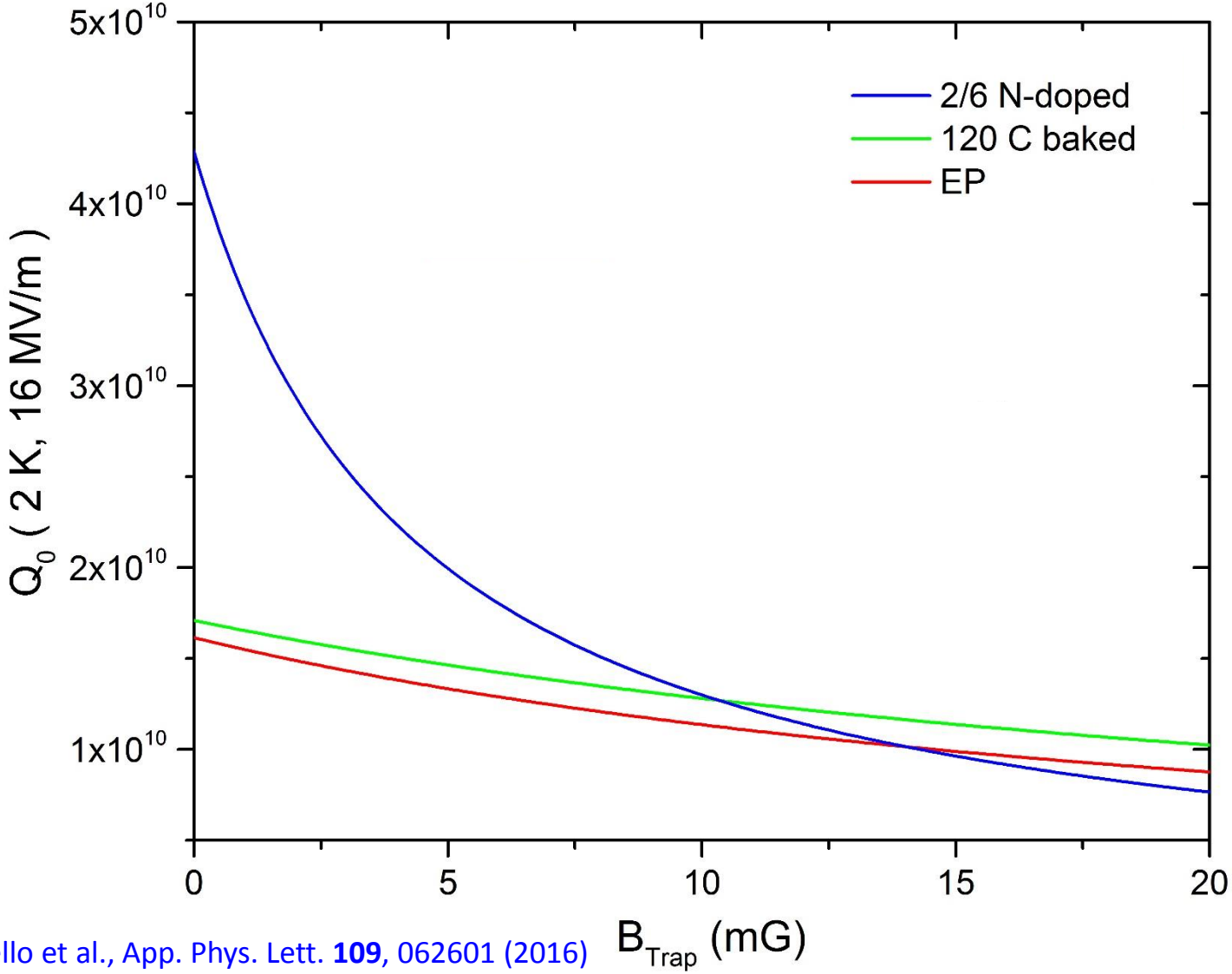
   $\Rightarrow \rho_1(l) \sim \frac{1}{\eta\omega}$, decreases with l

2. *Small l ($\eta \to 0$) – pinning regime*:

   $\Rightarrow \rho_1(l) \sim \frac{\eta\omega}{p^2}$, increases with l



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



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

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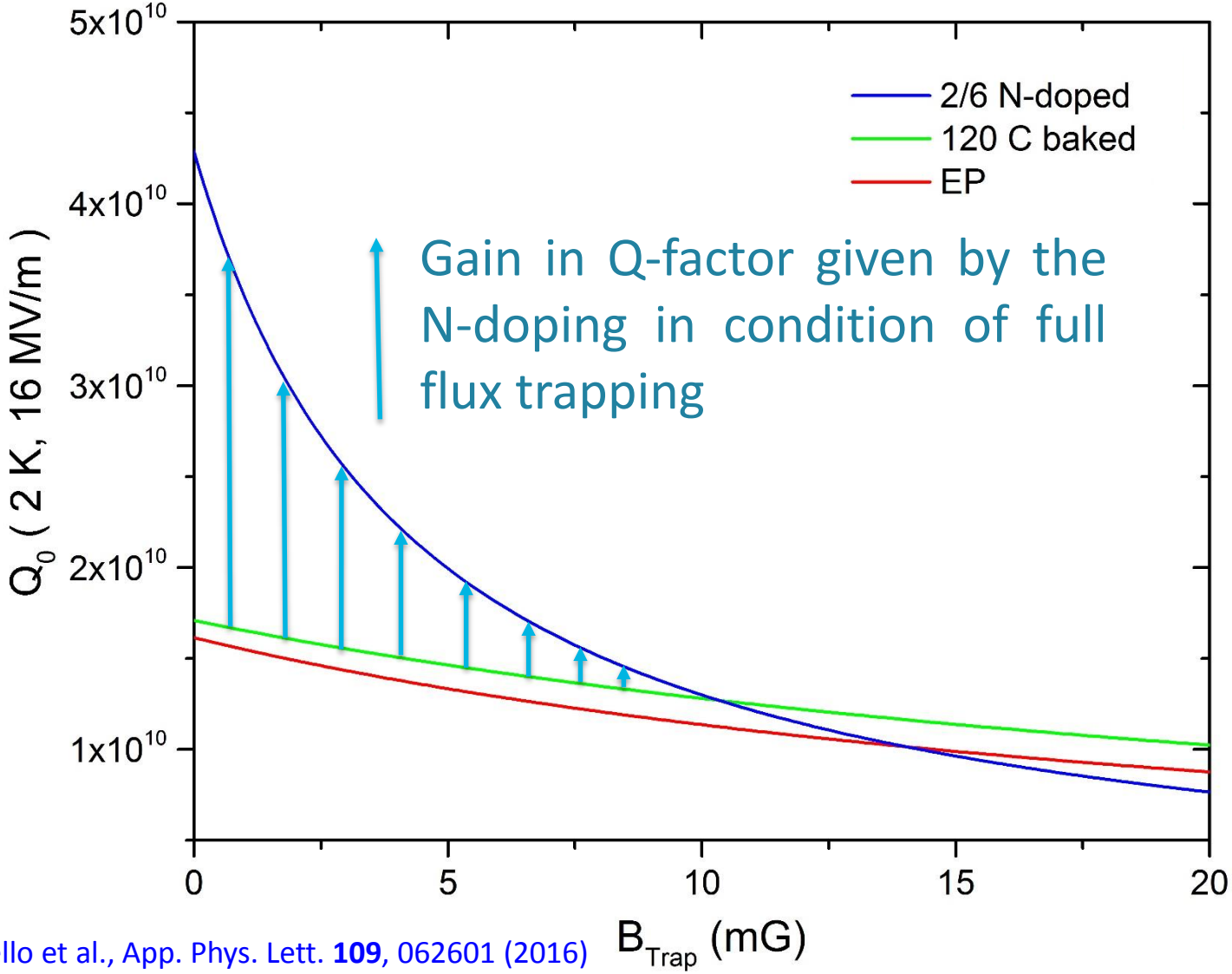

M. Martinello et al., App. Phys. Lett. **109**, 062601 (2016)

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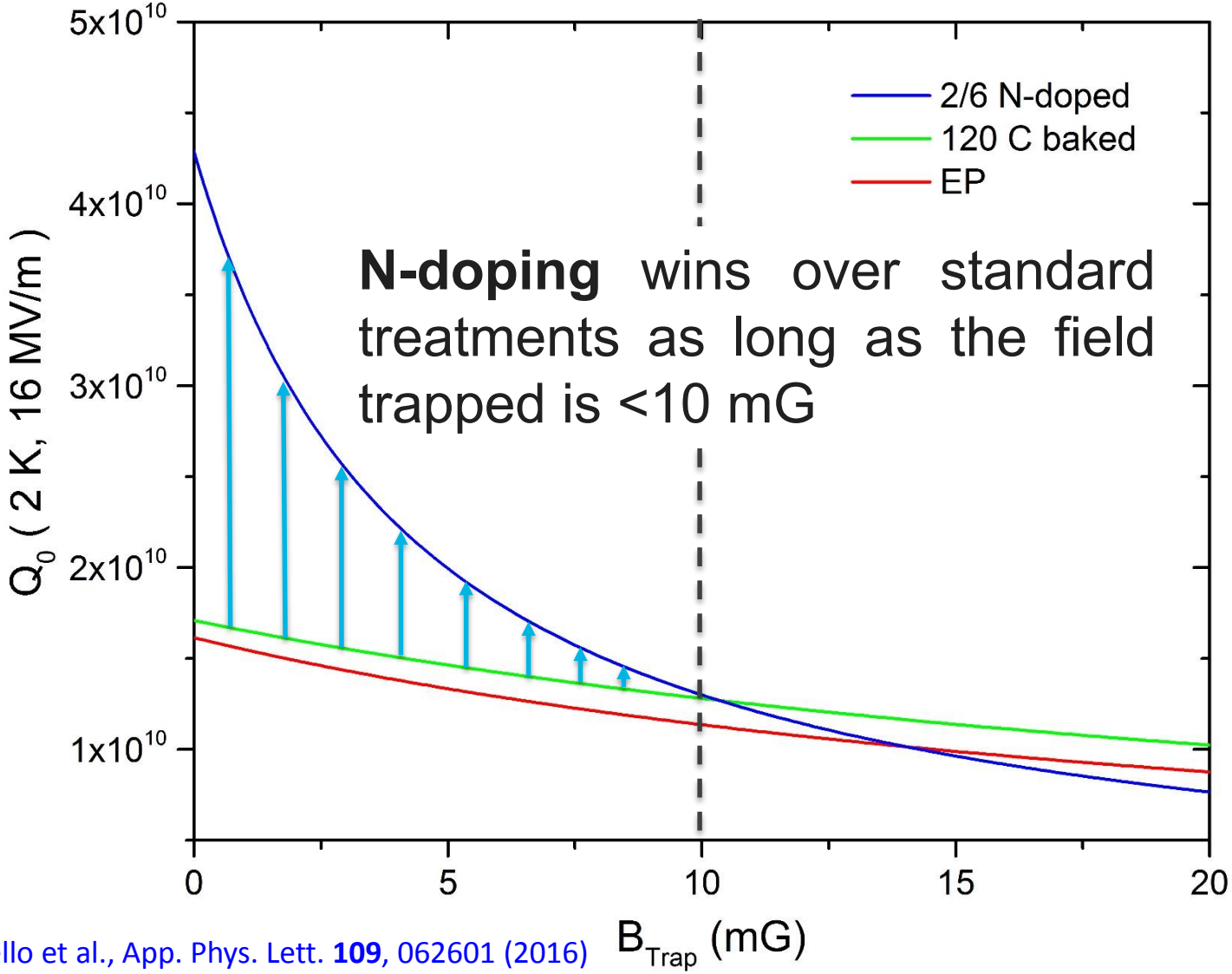
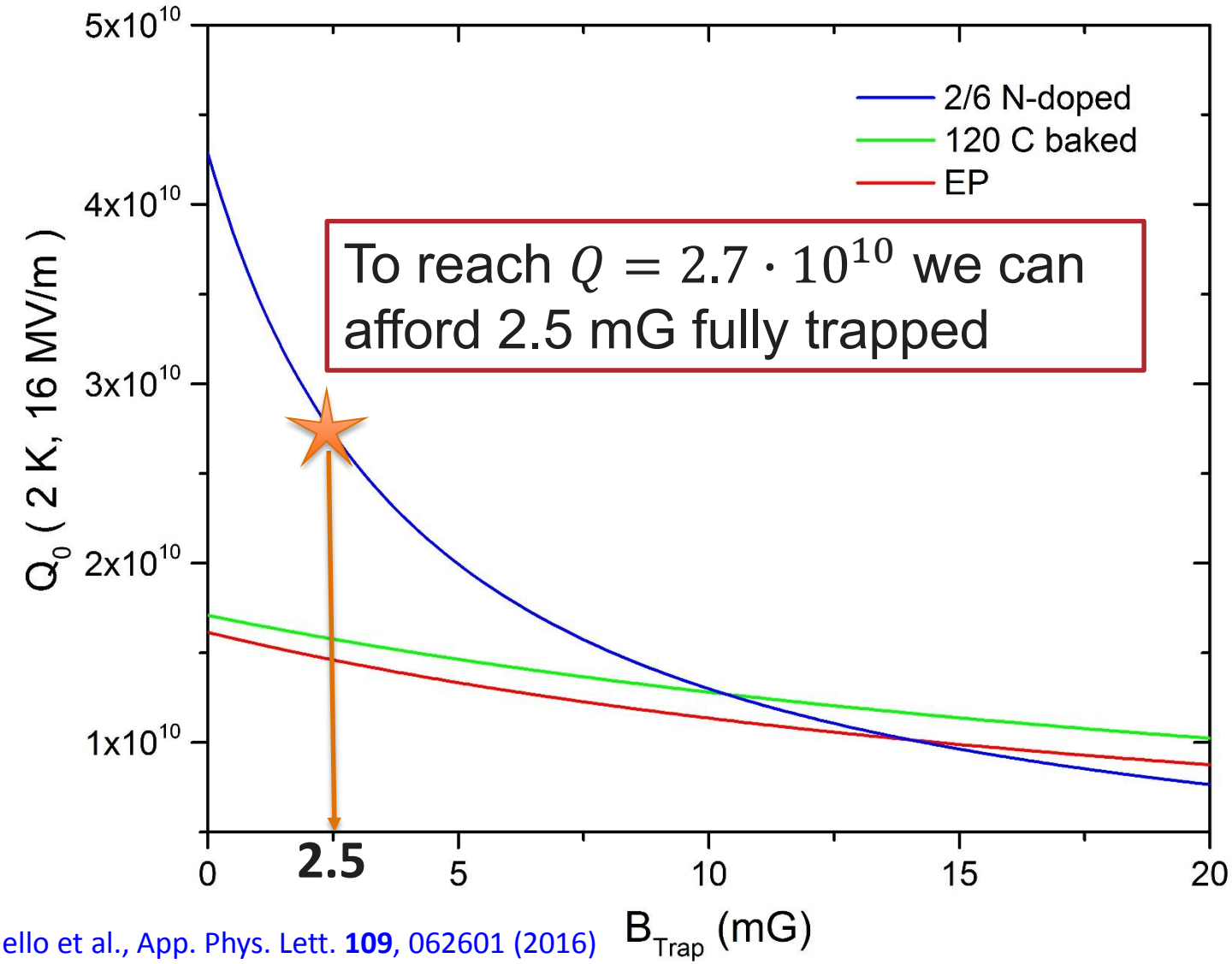


M. Martinello et al., App. Phys. Lett. **109**, 062601 (2016)

Example with LCLS-II specifications



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

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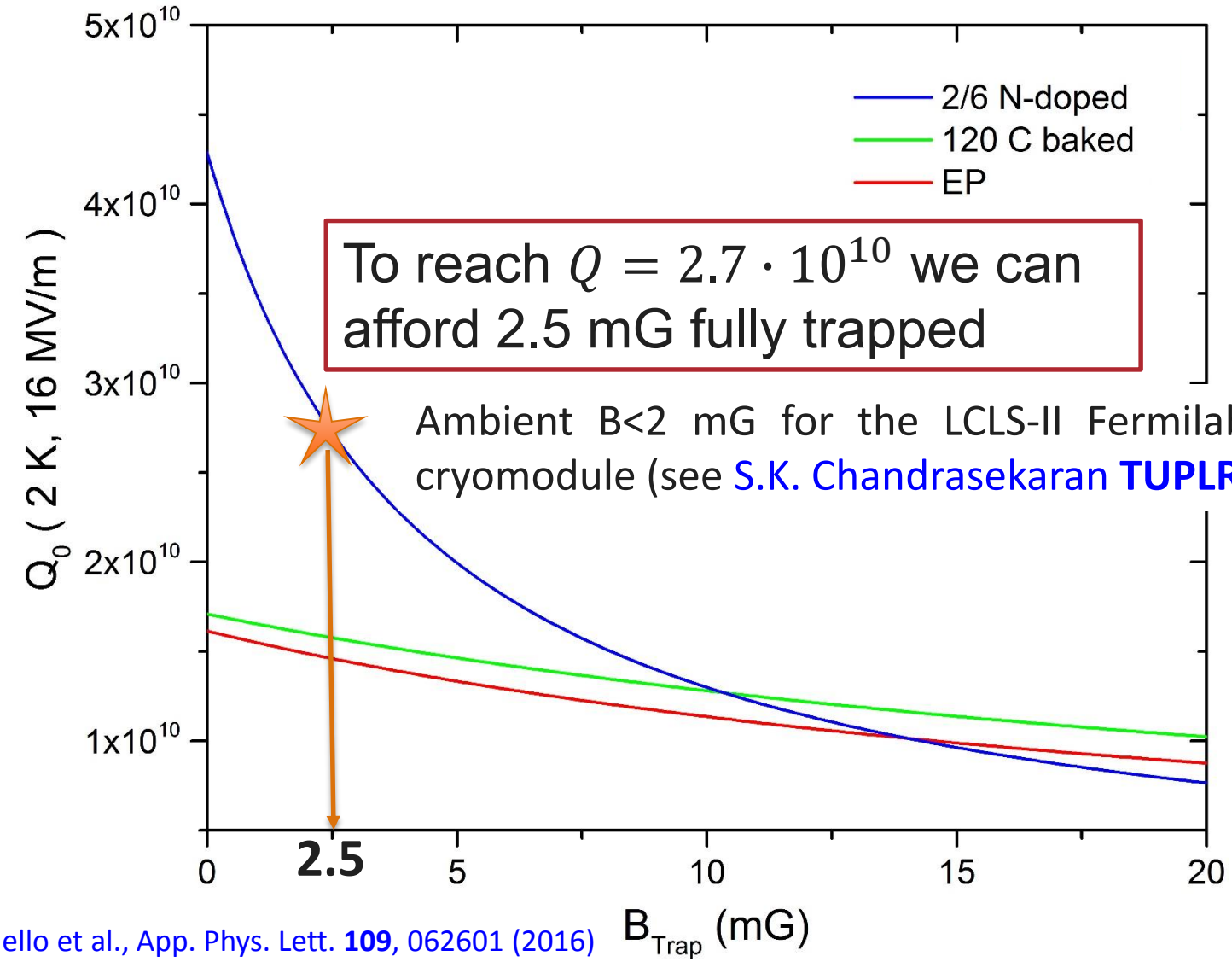

To reach $Q = 2.7 \cdot 10^{10}$ we can afford 2.5 mG fully trapped

Ambient B<2 mG for the LCLS-II Fermilab prototype cryomodule (see S.K. Chandrasekaran **TUPLR027**)

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

M. Martinello **TUPLR023**

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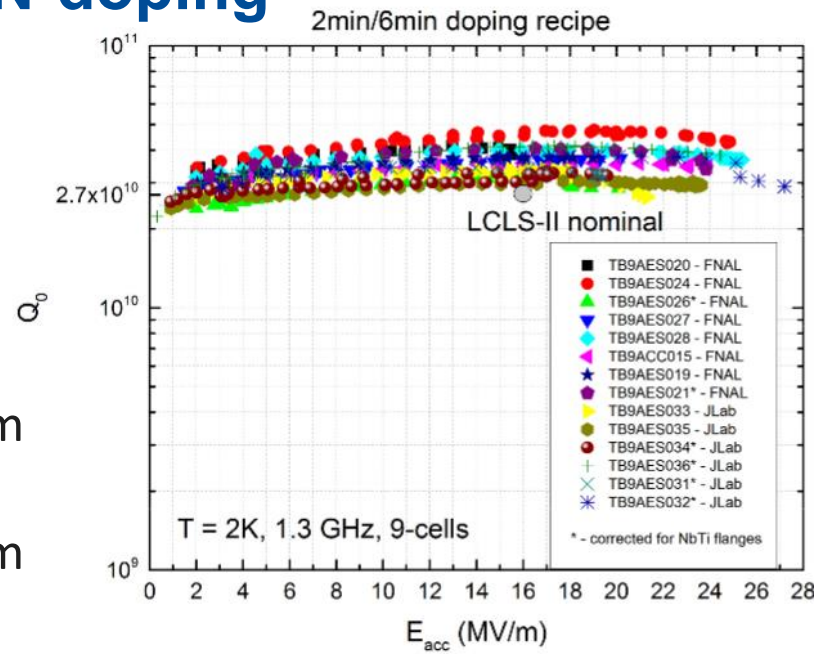
State of the art: high T and low T N-doping

High T (800C) N-doping:

- >100 processed cavities 1.3 GHz and 650 MHz single and multicells
- Typical Q factors ~ twice state of the art
- Prototype cavities for LCLS-II:
  <Q> ~ 3.5e10 @ 2K 16 MV/m, <Eacc> ~ 22 MV/m
- First production cavities for LCLS-II:
  <Q> ~ 2.5e10 @ 2K 16 MV/m, <Eacc> ~ 23 MV/m

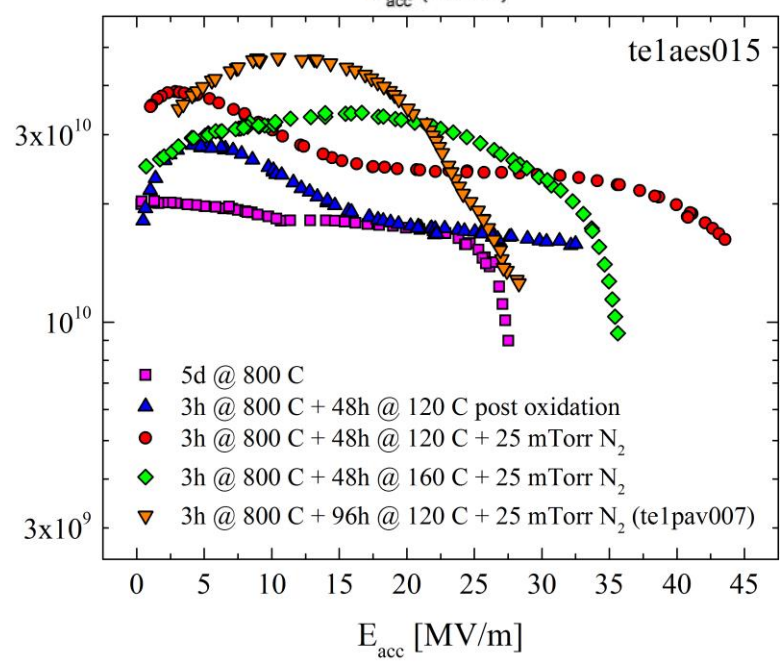
(see M.C. Ross **MOA01)**



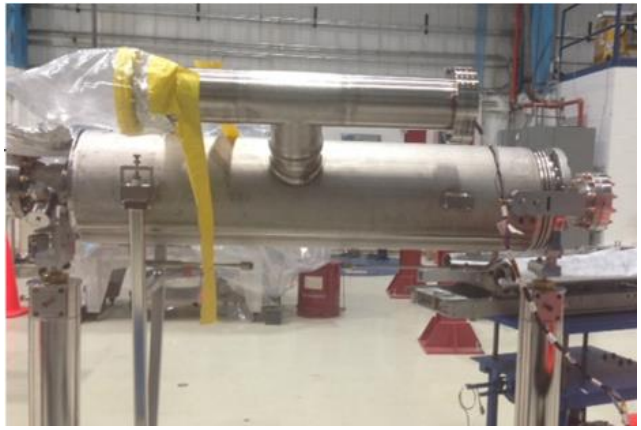
NEW- Low temperature (120-160 C) N-doping:

- Doping at very low T – few nanometers of N enriched layer
- Very High Q at both medium and high accelerating fields
- No quench field limitations (up to 45 MV/m)
- Work ongoing

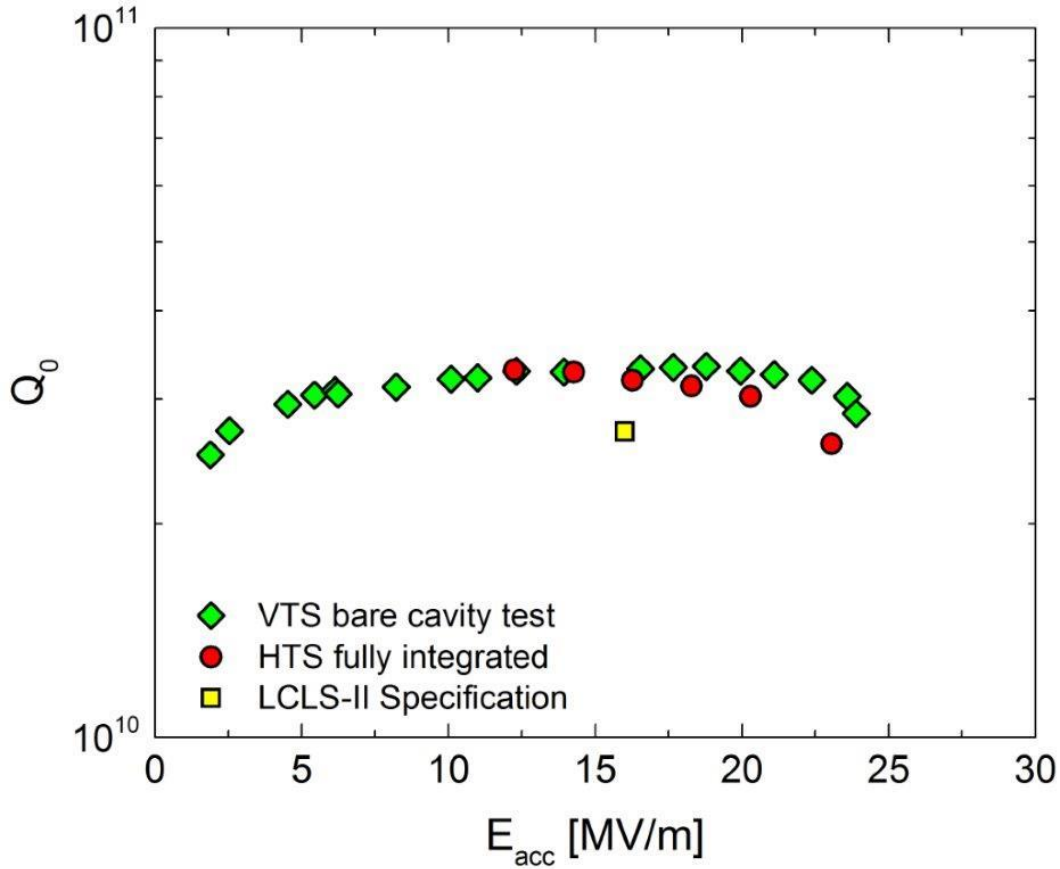
(See M. Checchin **TUPLR024** for theoretical model)



Demonstration in a cryomodule-like environment

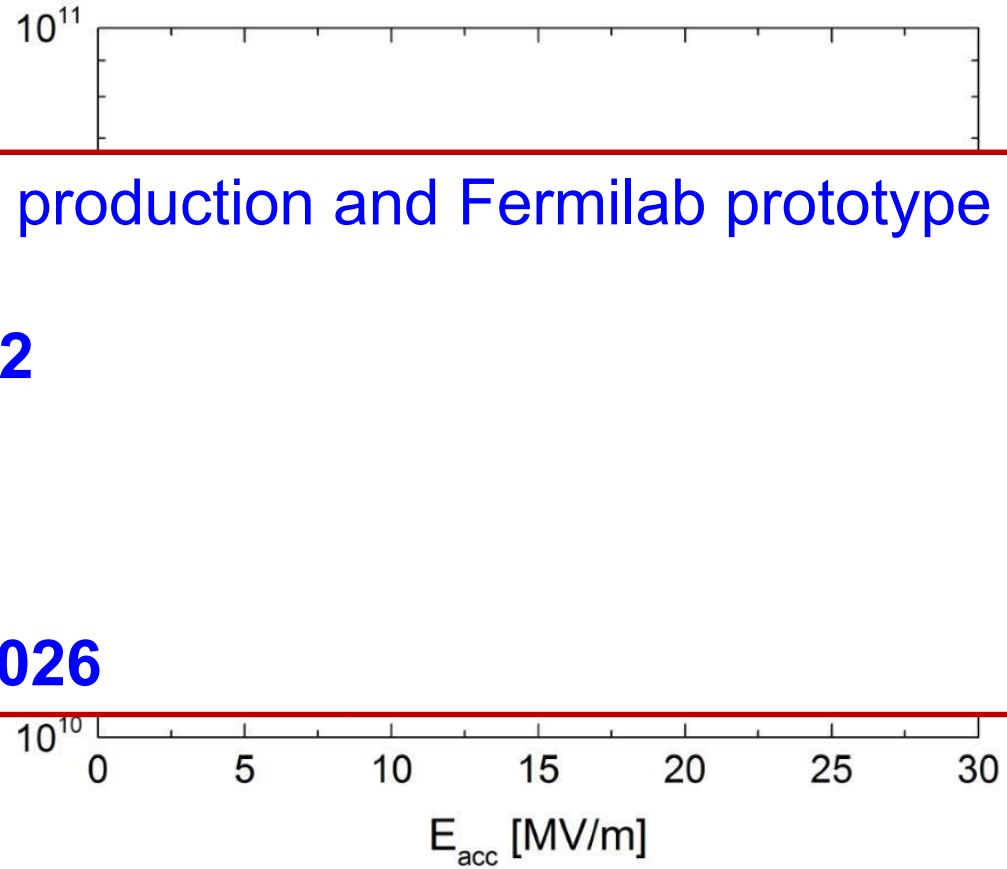


Q can be perfectly preserved from bare cavity test to fully jacketed state with RF ancillaries, in cryomodule environment



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



More on LCLS-II cavity production and Fermilab prototype cryomodule results:

E.R. Harms **MOPLR022**

M.C. Ross **MOA01**

A. Burrill **MOPLR020**

G. Wu **TUPLR008**

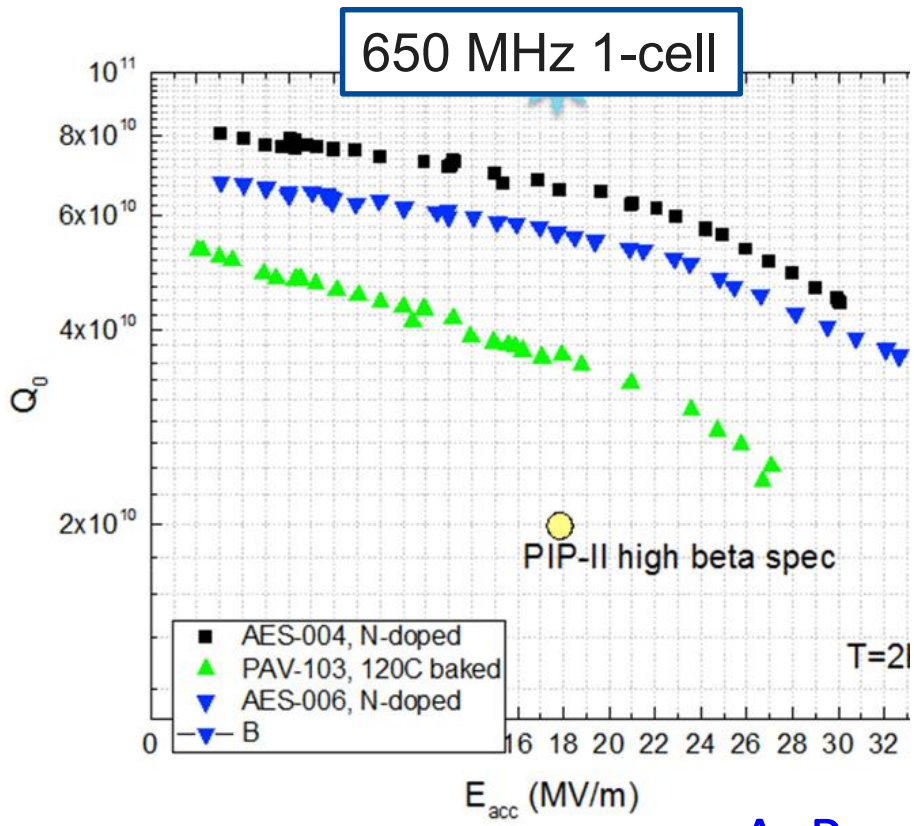
A. Palchewski **MOPLR026**

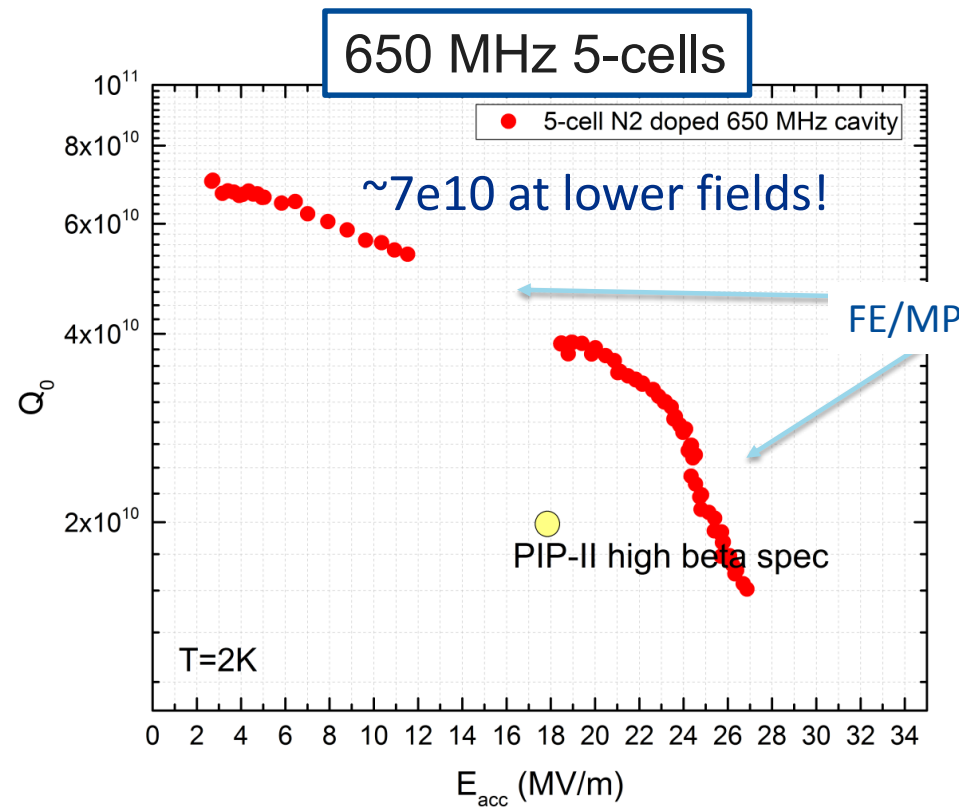
Fermilab ILLINOIS INSTITUTE OF TECHNOLOGY

N doping applied to FNAL PIP-II 650 MHz cavities

- **650 MHz**: single cell processing developed and several multi-cells successfully tested with Q at 2K, mid field > 4e10

Nitrogen doping of a 5-cell 650 MHz ca





A. Rowe **MOPLR043**

Outline

N-DOPING – PHYSICS AND TECHNIQUE

HIGH-Q PRESERVATION

STATE OF THE ART PERFORMANCE AND APPLICATIONS

CONCLUSIONS

Conclusions

- Record Q at medium and high accelerating gradients reproducibly achieved with N doping technology, from single cell cavities to multi-cells cavities in accelerator environment, at different labs, technology now transferred to industry
- LCLS-II specifications exceeded at three different institutions via N doping
  - Prototype cryomodule measurement at FNAL already started!
- Efficient magnetic flux expulsion can be achieved with fast cooldown and material optimization
- N-doping even with larger B-sensitivity leads to higher Q-factors than state of the art treatments for trapped B< 10 mG
- Very High-Q at ultra high gradients now possible with low T N-doping

Thank you for your attention!