Progress in High Q SRF cavities development: from Single Cell to Cryomodule

Anna Grassellino

NAPAC 2016, Chicago

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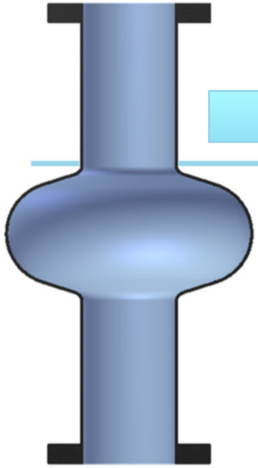
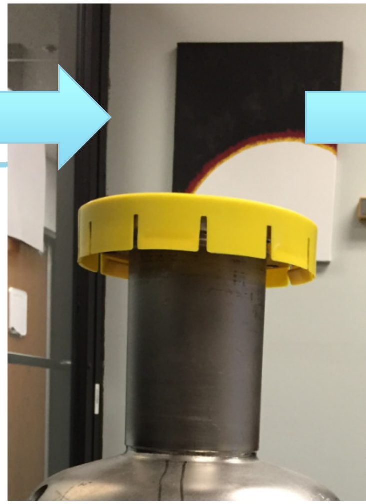
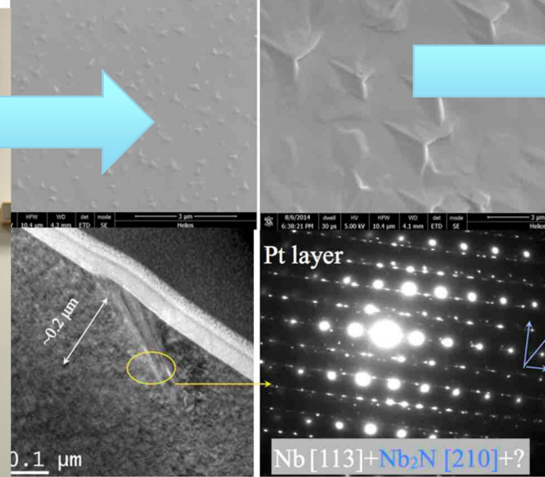
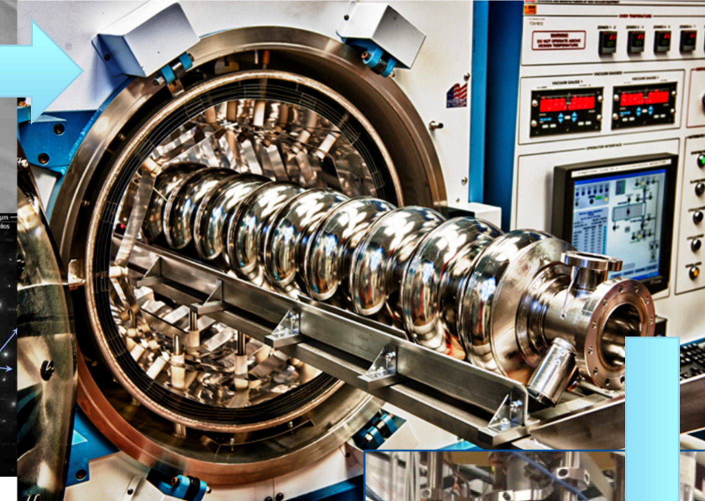
Outline

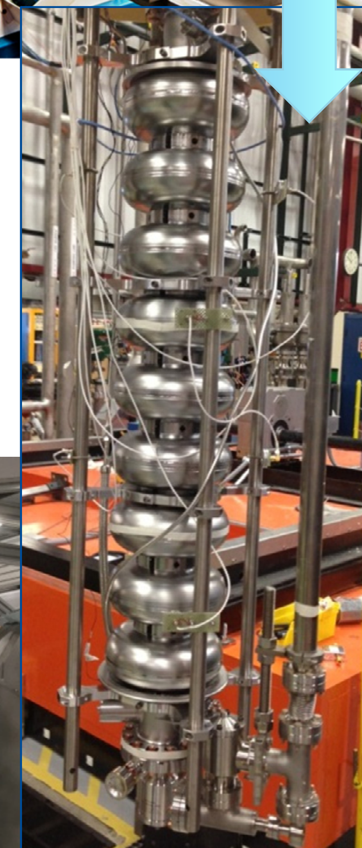
- SRF Cavity Surface Treatments producing the Highest Q: N-doping
- High Q Preservation - Magnetic Flux trapping/expulsion and sensitivity
- State of the art High Q Cavity and Cryomodule Performance, LCLS-II and future applications

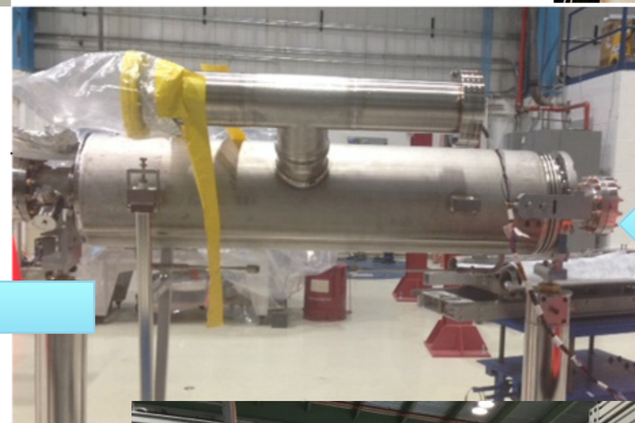


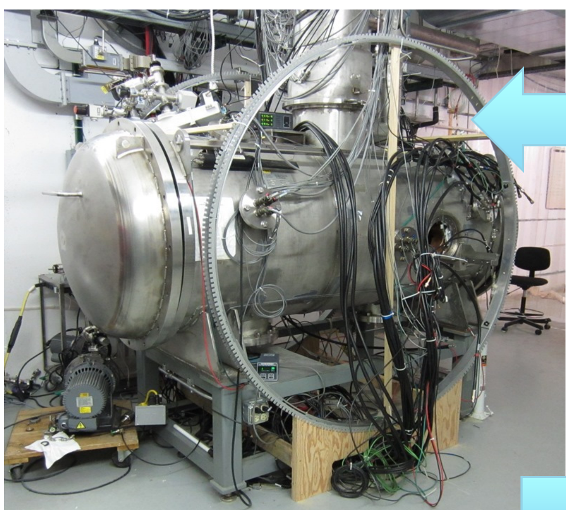



~0.2 µm
0.1 µm
Pt layer
Nb [113]+Nb₂N [210]+?





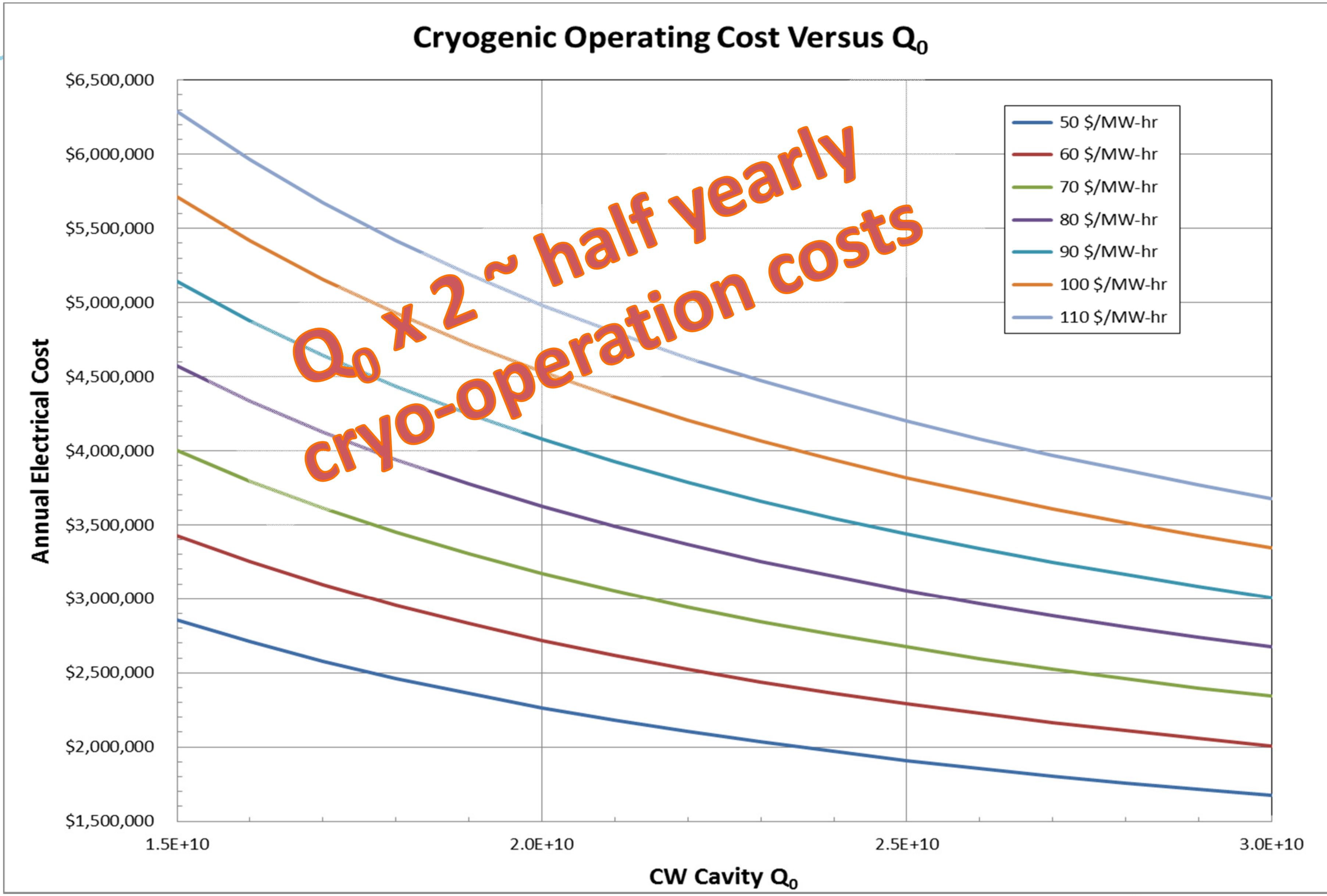




Why High Q SRF cavities?
For CW accelerators the refrigeration cost is of the order of several tens of millions $

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


Q_0 x 2 = half
refrigeration costs



Cryogenic Operating Cost Versus Q_0
$6,500,000
$6,000,000
$5,500,000
$5,000,000
$4,500,000
$4,000,000
$3,500,000
$3,000,000
$2,500,000
$2,000,000
$1,500,000
Annual Electrical Cost
1.5E+10
2.0E+10
2.5E+10
3.0E+10
CW Cavity Q_0
50 $/MW-hr
60 $/MW-hr
70 $/MW-hr
80 $/MW-hr
90 $/MW-hr
100 $/MW-hr
110 $/MW-hr
Q_0 x 2 ~ half yearly cryo-operation costs

The High-Q Milestones Timeline @ FNAL

2012

Discovery of N-doping

2013

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

2014

Discovery of efficient/inefficient Meissner expulsion– slow vs fast cooling through Tc

2014

LCLS-II choice of N-doping,

High Q collaboration FNAL, JLAB and Cornell University

2015

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

2015

N doping technology successfully transferred to industry

2015 and 2016

R&D continues deepening the understanding and improvement of doping, flux expulsion
Low-T N-infusion → higher Q with quench fields up to 45 MV/m
First Cryomodule with doped cavities demonstrates avg Q ~ 2.7e10 at 2K, 16 MV/m

Outline

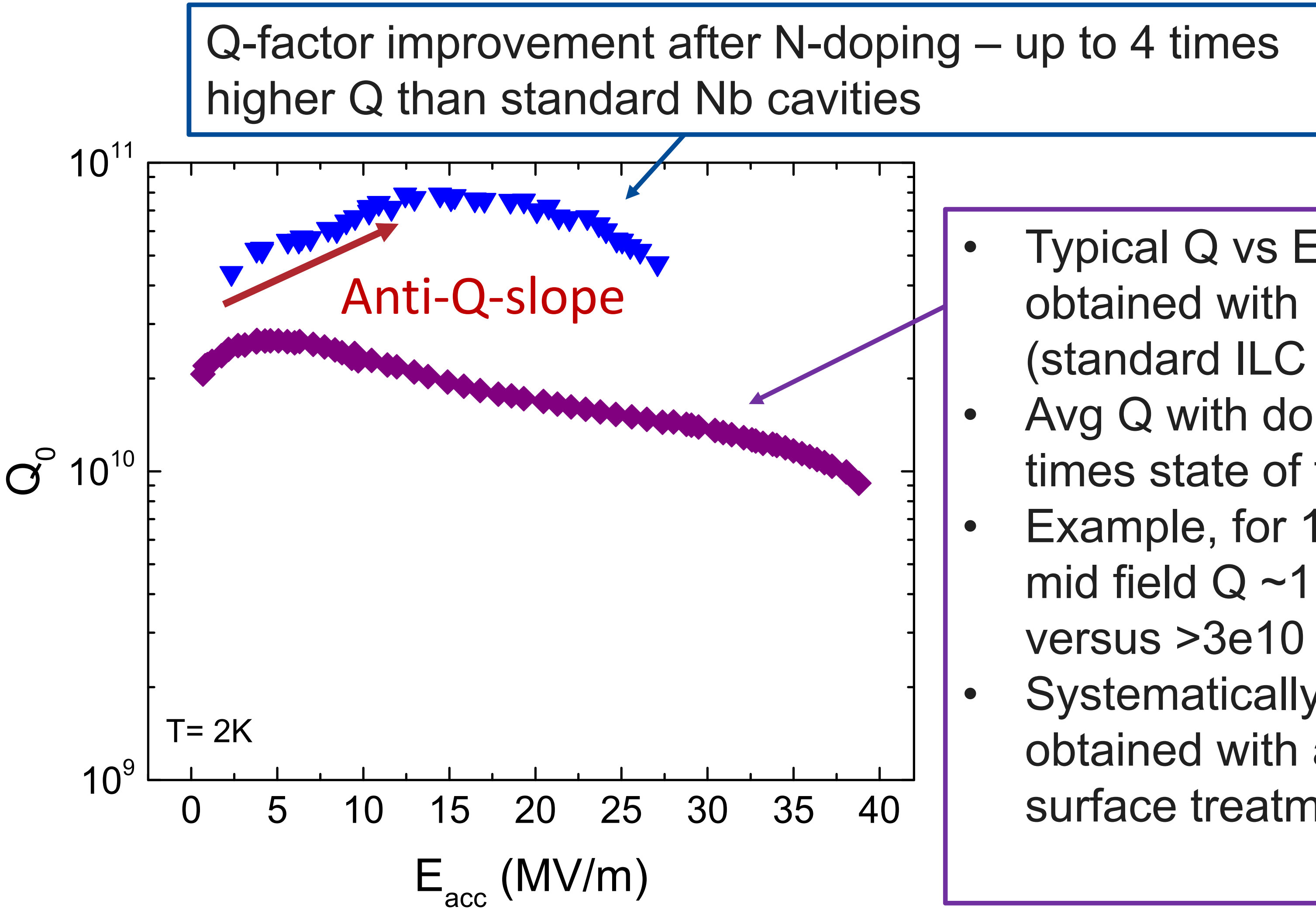
N-DOPING – PHYSICS AND TECHNIQUE

HIGH-Q PRESERVATION

STATE OF THE ART PERFORMANCE AND APPLICATIONS

CONCLUSIONS

The discovery of N-doping

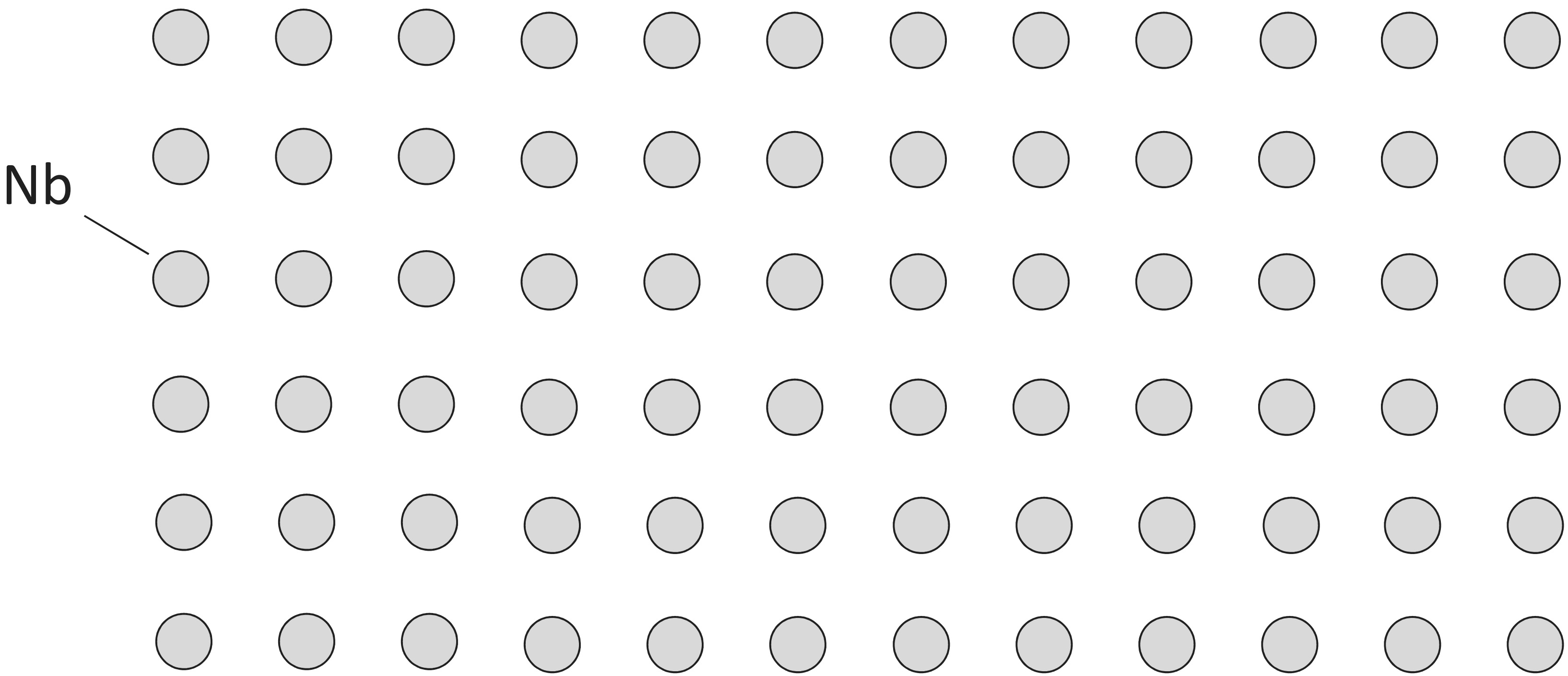


- Typical Q vs Eacc curve obtained with 120C bake (standard ILC treatment)
- Avg Q with doping is 2-4 times state of the art
- Example, for 1.3GHz, 2K, mid field Q ~1.5e10 versus >3e10
- Systematically above Q obtained with any other surface treatment

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

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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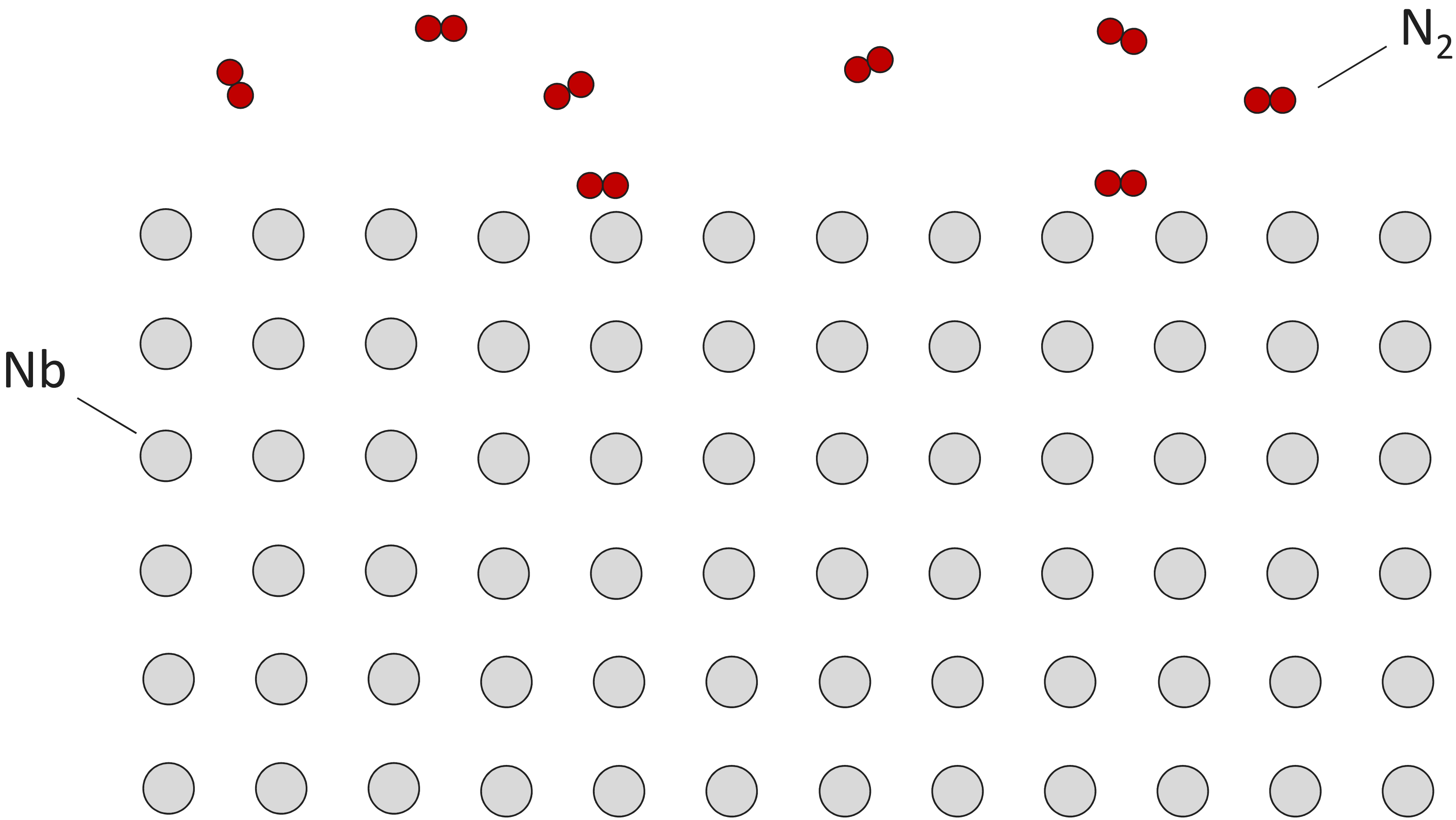
UHV cooling

5 um EP



Fermilab

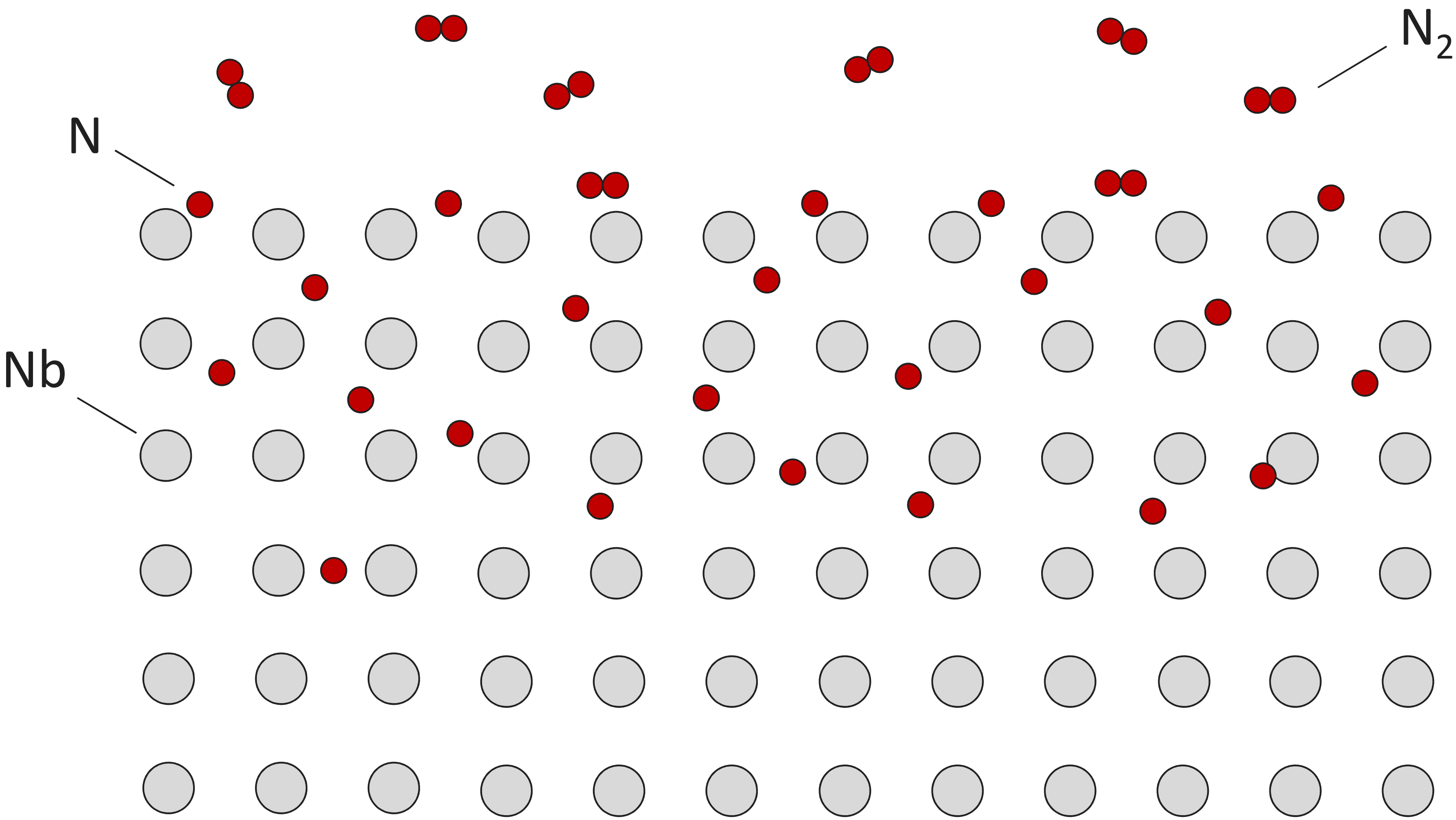
N-doping treatment (example: the "2/6 recipe")

800C UHV, 3 hours → 800C N_2 injection p=25mTorr → 800C N_2 2 minutes

800C UHV, 6 minutes

UHV cooling

5 um EP



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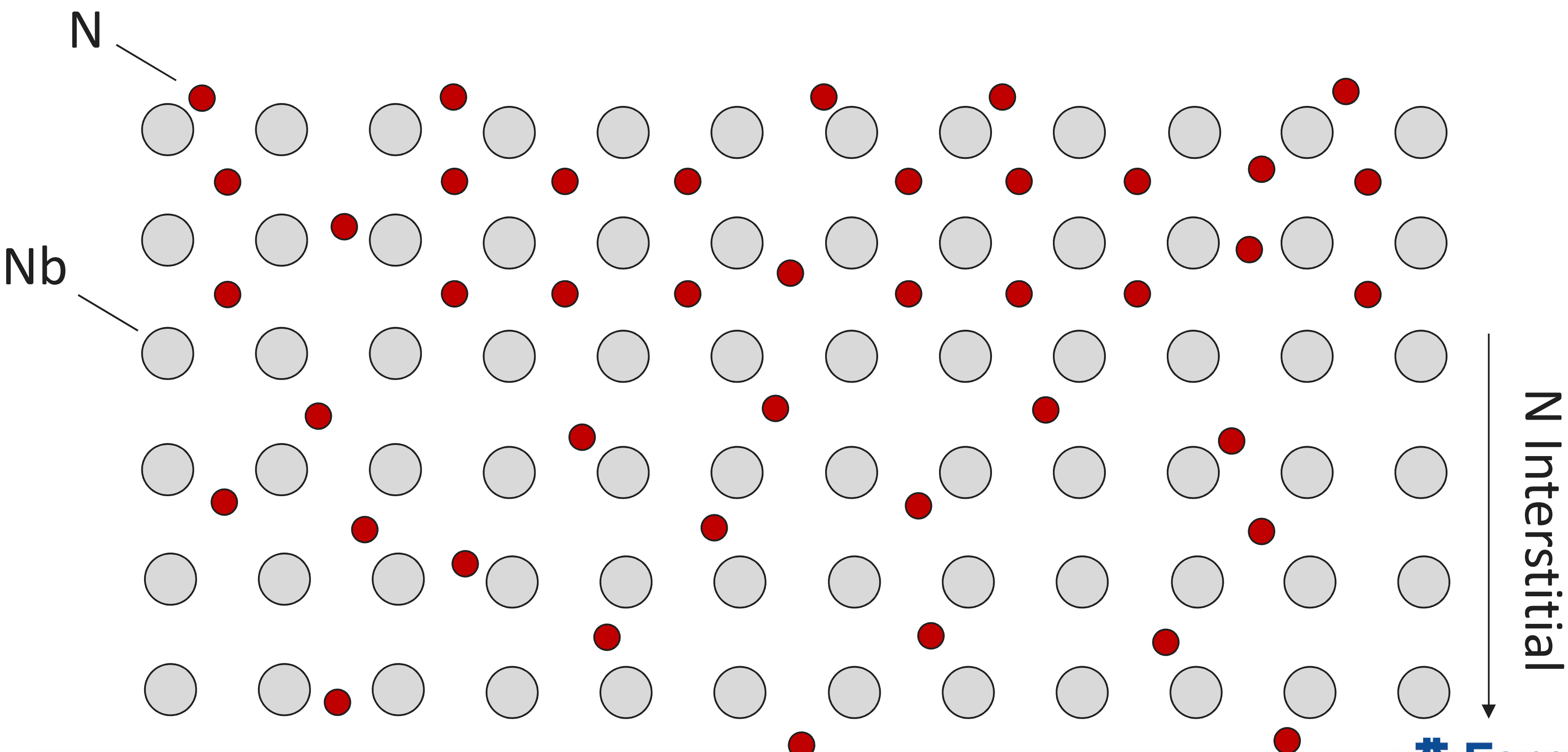

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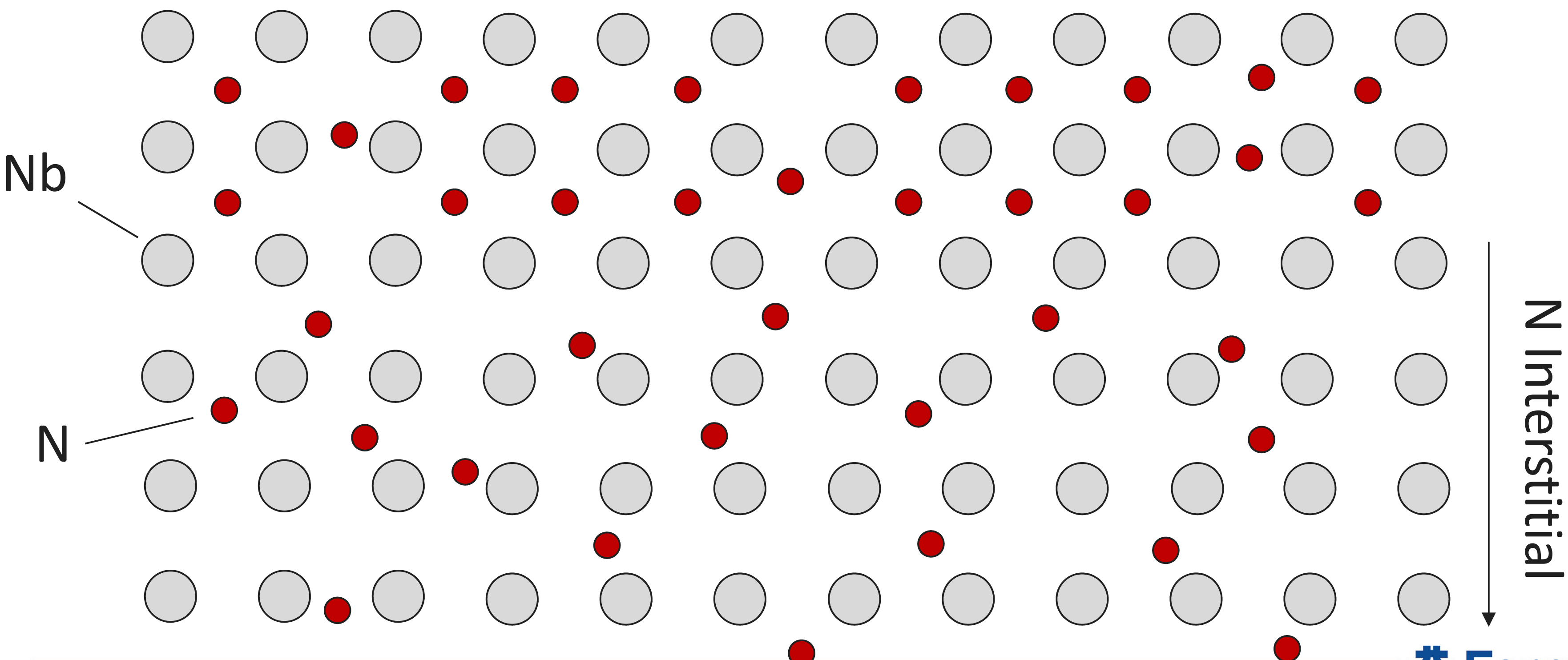

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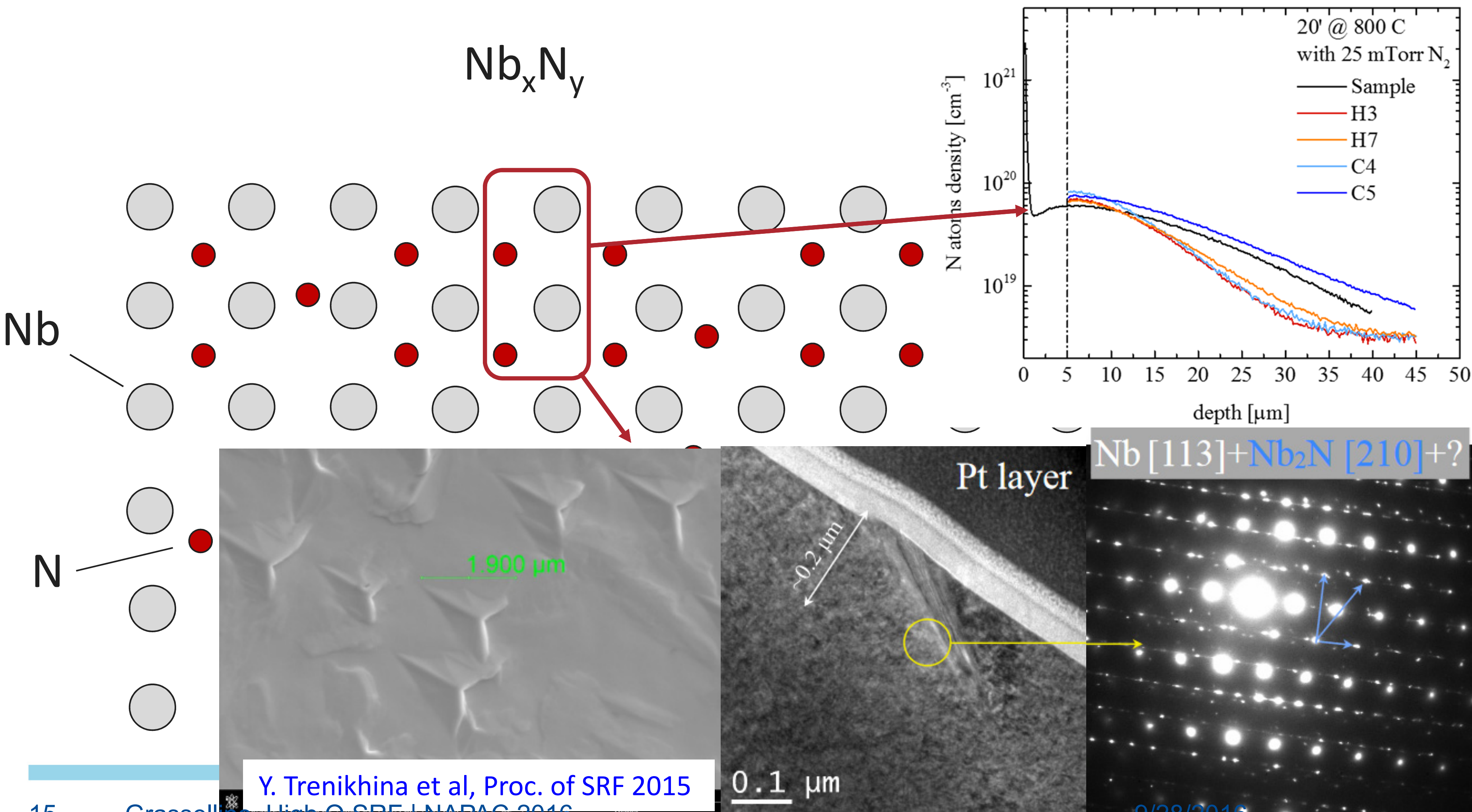

Y. Trenikhina et al, Proc. of SRF 2015

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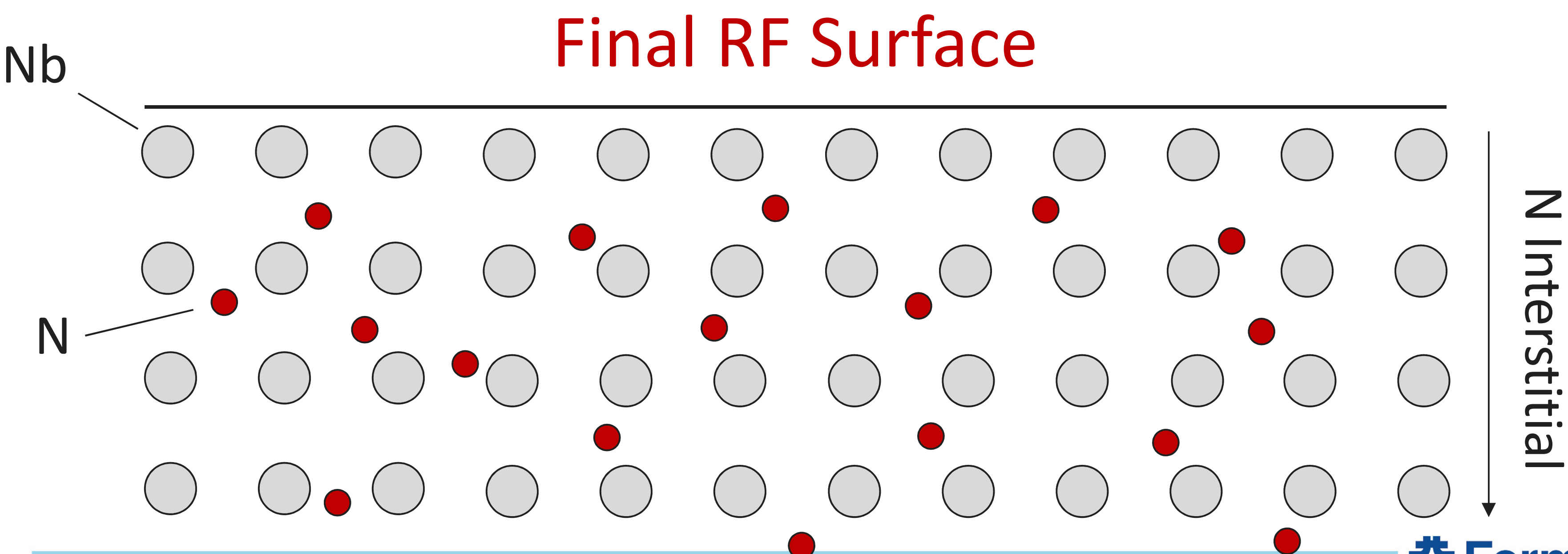

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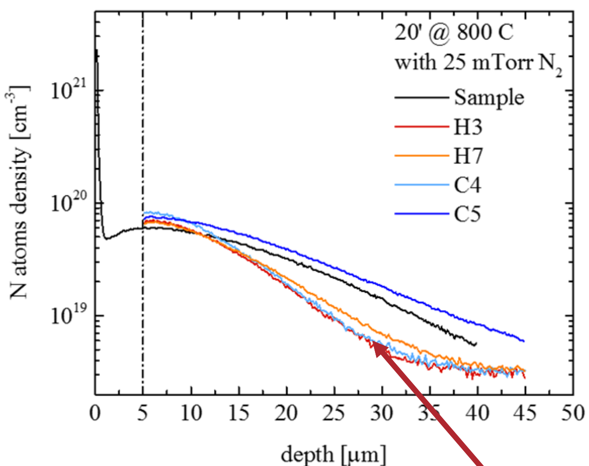
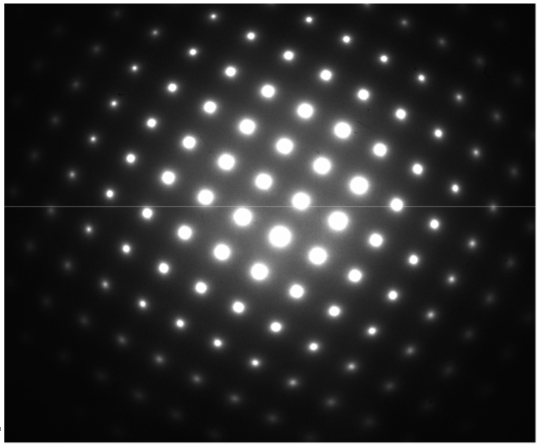
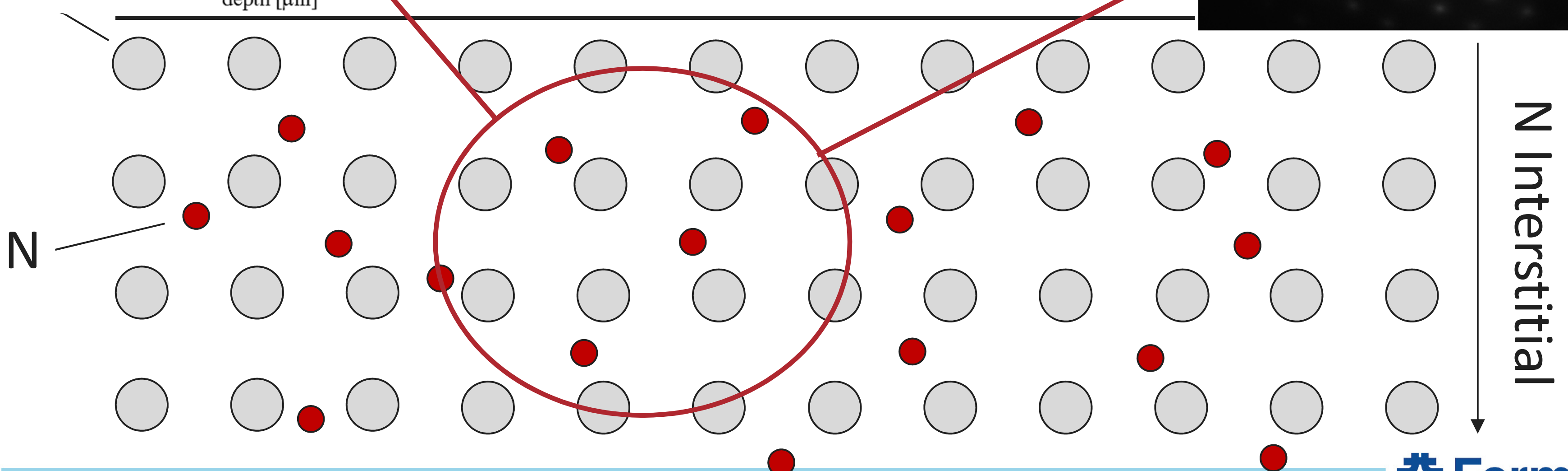


Y. Trenikhina et Al, Proc. of SRF 2015



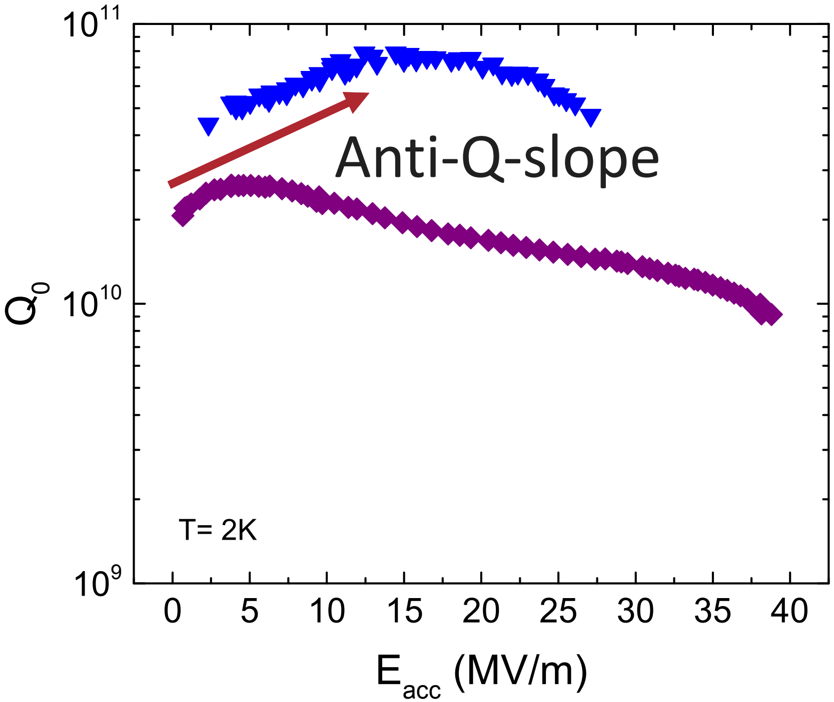
Only Nb from TEM/NED spectra:
N must be interstitial

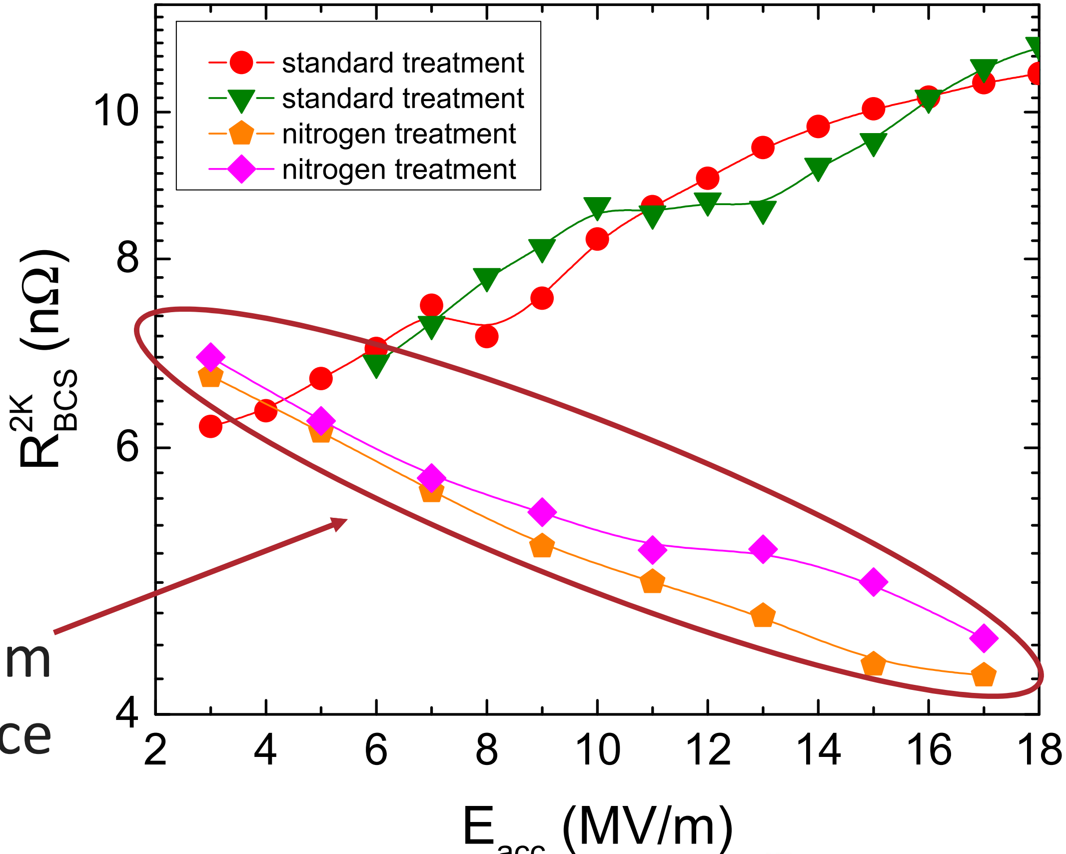
Final RF Surface



Origin of the anti-Q-slope

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



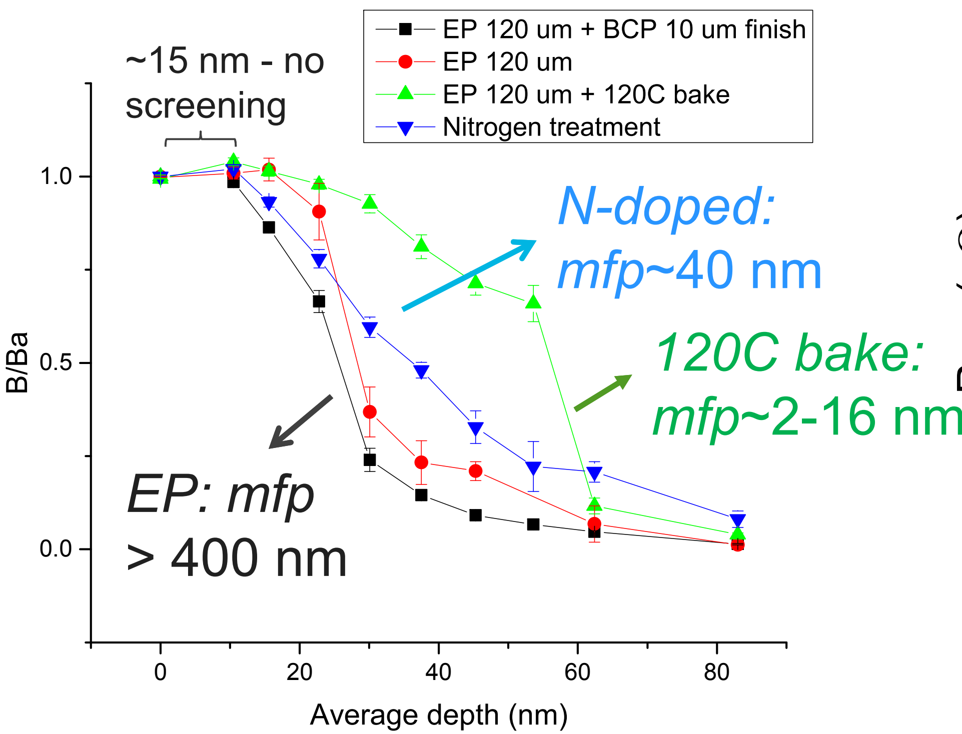


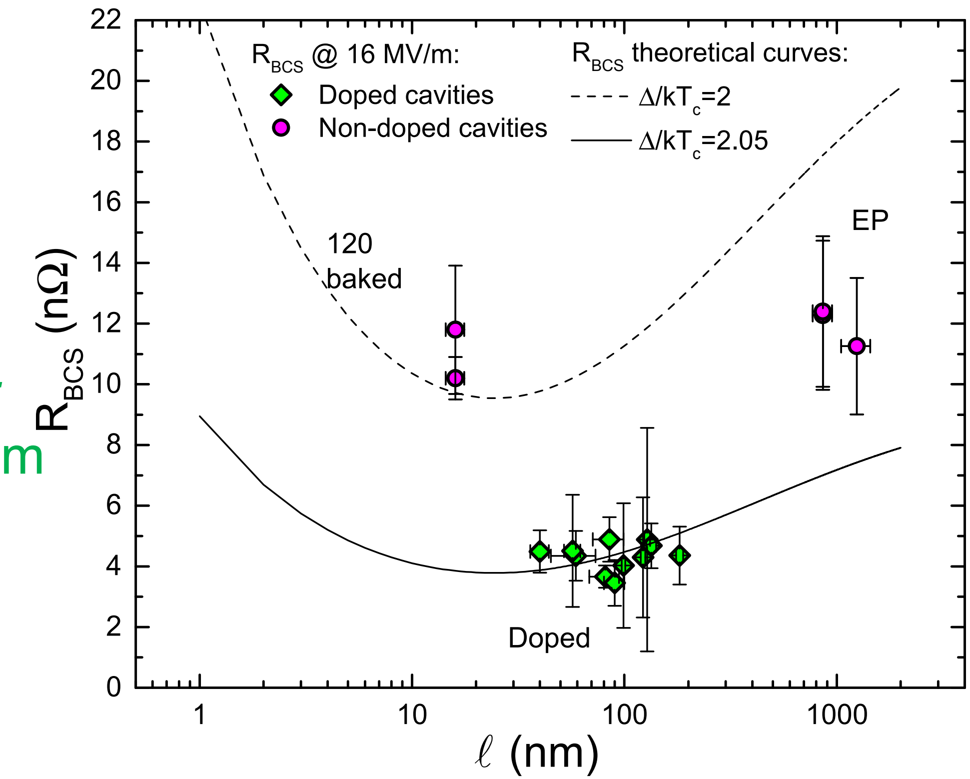
Anti-Q-slope emerges from the BCS surface resistance <u>decreasing</u> with field

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

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)

- ✓ 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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CONCLUSIONS

Trapped Flux Surface Resistance

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

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

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

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

These losses can be reduced by minimizing these contributions:

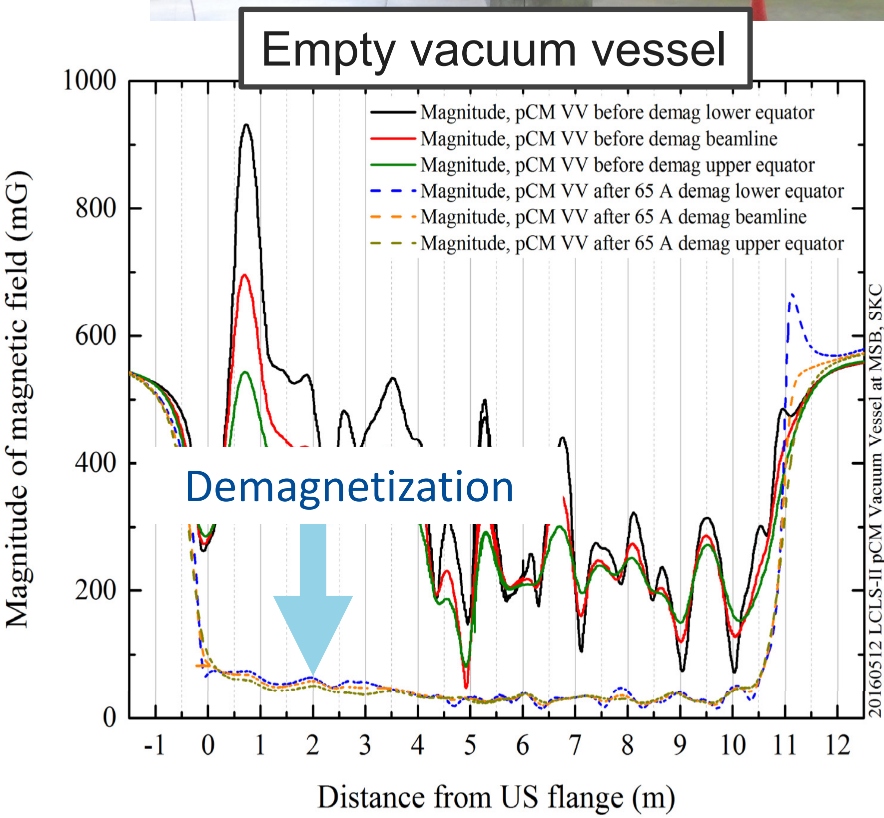
External magnetic field

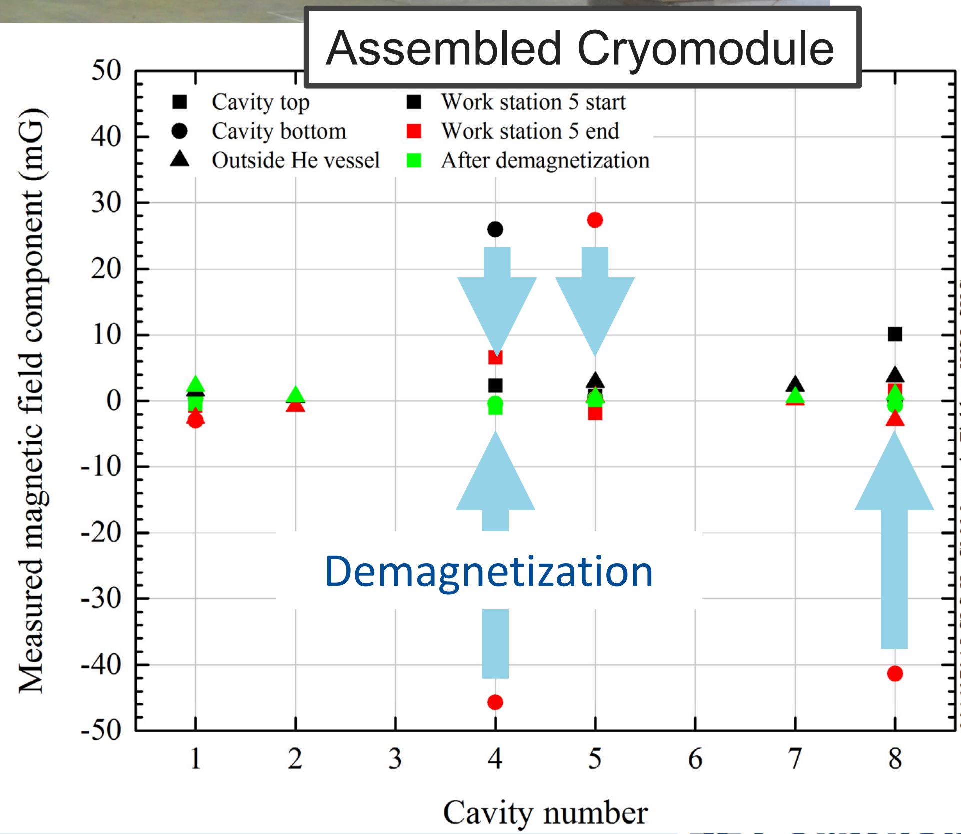
B_{ext}
- Magnetic shielding/hygiene improvement

η
- Fast Cooling
- Material Optimization

S
- Optimizing mean free path

Minimization of remnant field in the cryomodule





A. C. Crawford, https://arxiv.org/pdf/1507.06582.pdf
S. K. Chandrasekaran et al, TUPLR027, LINAC16

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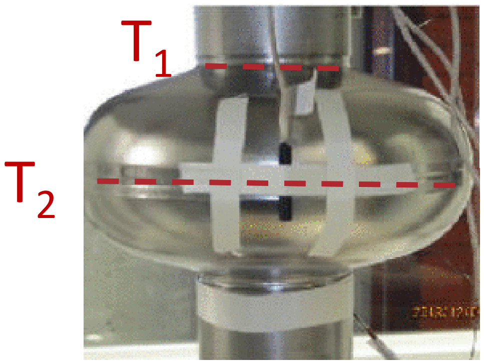
Flux Expulsion Efficiency

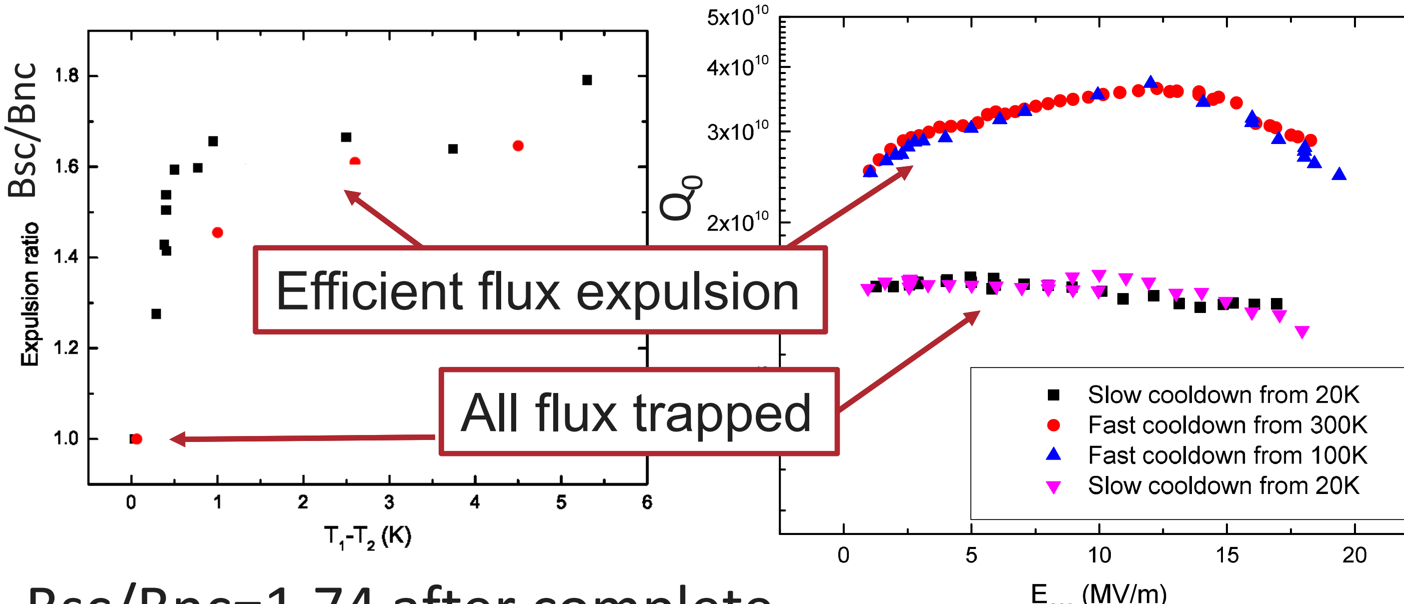
η
- Fast Cooling
- Material Optimization

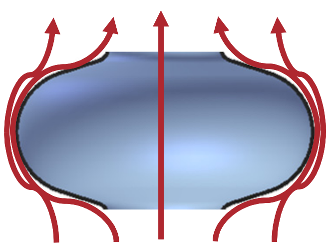
S
- Optimizing mean free path

Fast cooldown helps flux expulsion

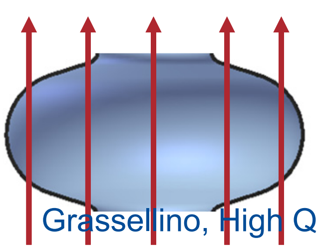
- **Fast cool-down** lead to **large thermal gradients** which promote efficient flux expulsion
- Slow cool-down → poor flux expulsion







← Bsc/Bnc=1.74 after complete Meissner effect

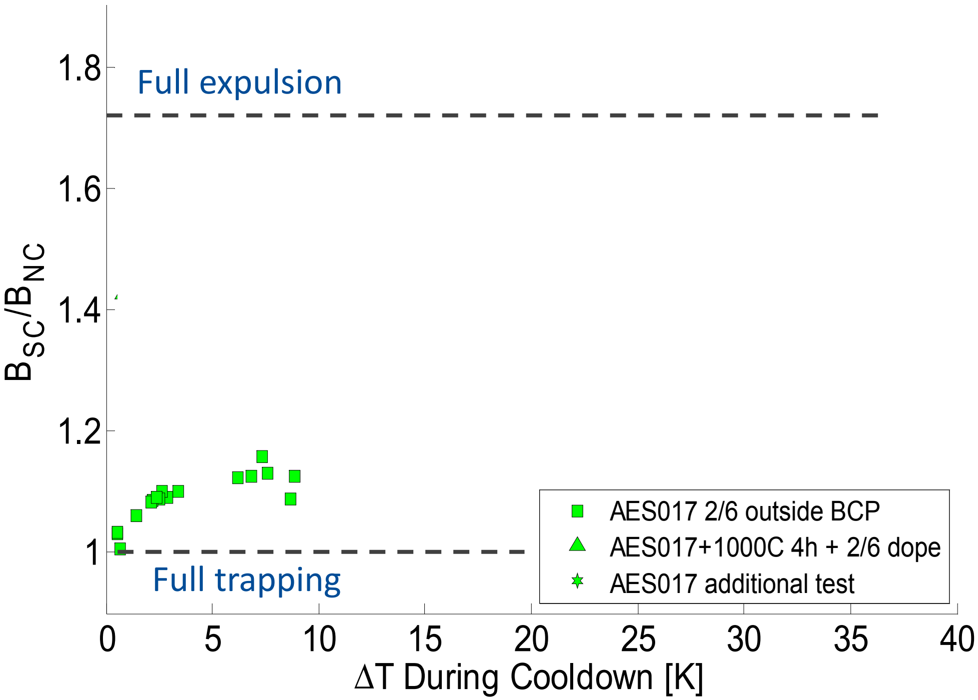


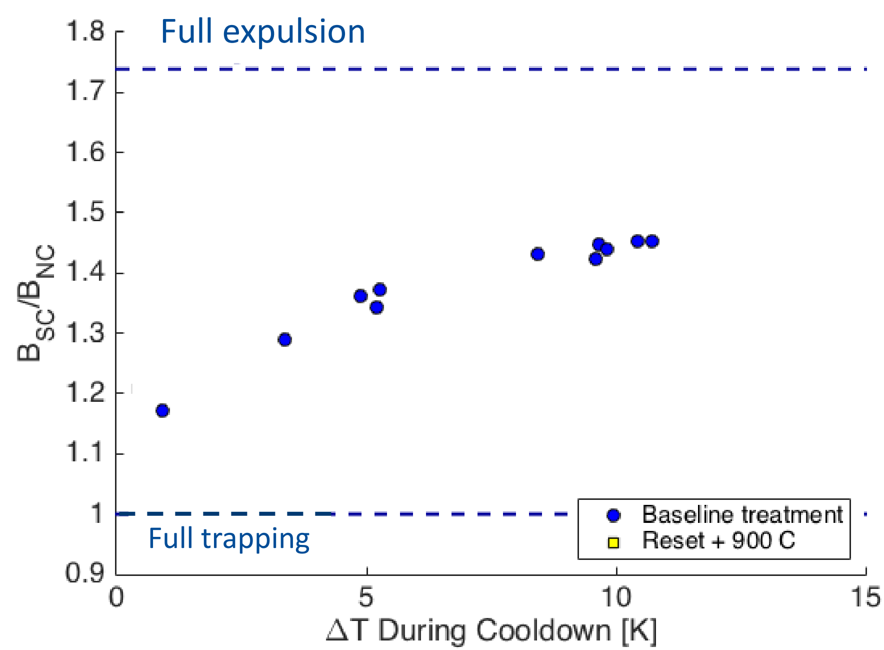
← Bsc/Bnc=1 after full flux trapping

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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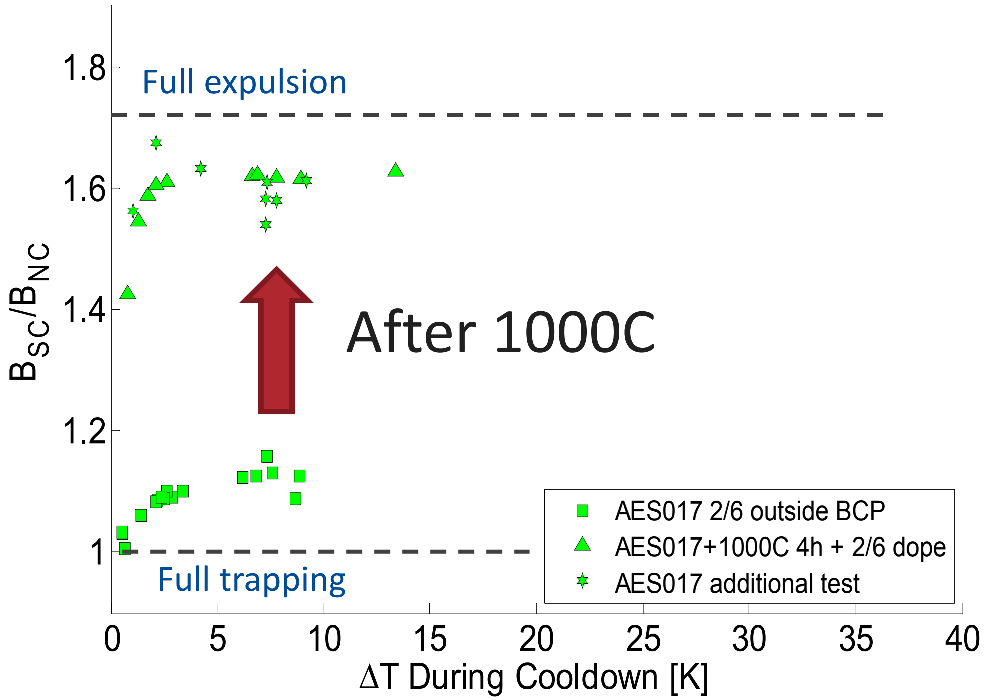

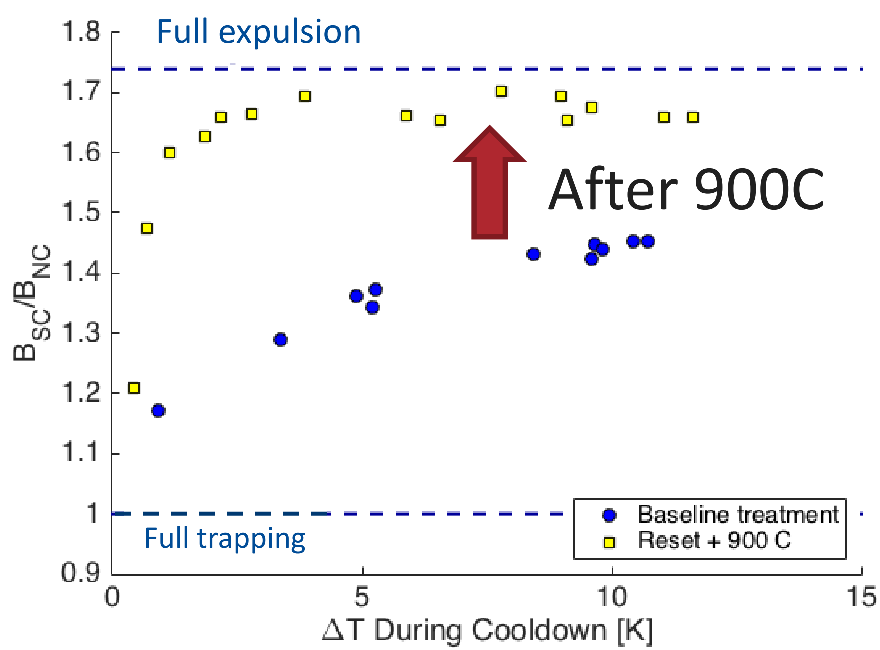

S. Posen et al., J. Appl. Phys. **119**, 213903 (2016)

Trapped Flux Surface Resistance

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

These losses can be reduced by minimizing these contributions:

B_{ext}
- Magnetic shielding/hygene improvement

η
- Fast Cooling
- Material Optimization

S
- Optimizing mean free path

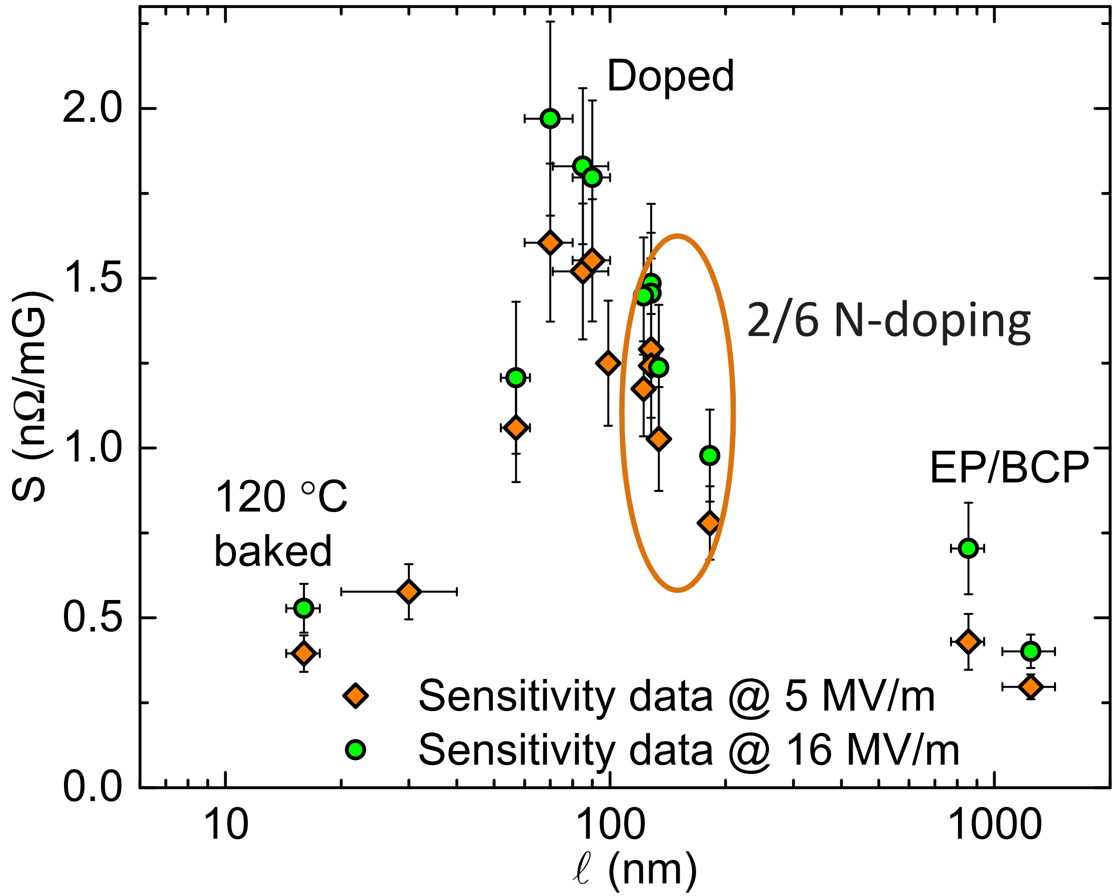
Trapped Flux Sensitivity

Light doping to minimize trapped flux sensitivity

Trapped flux sensitivity:

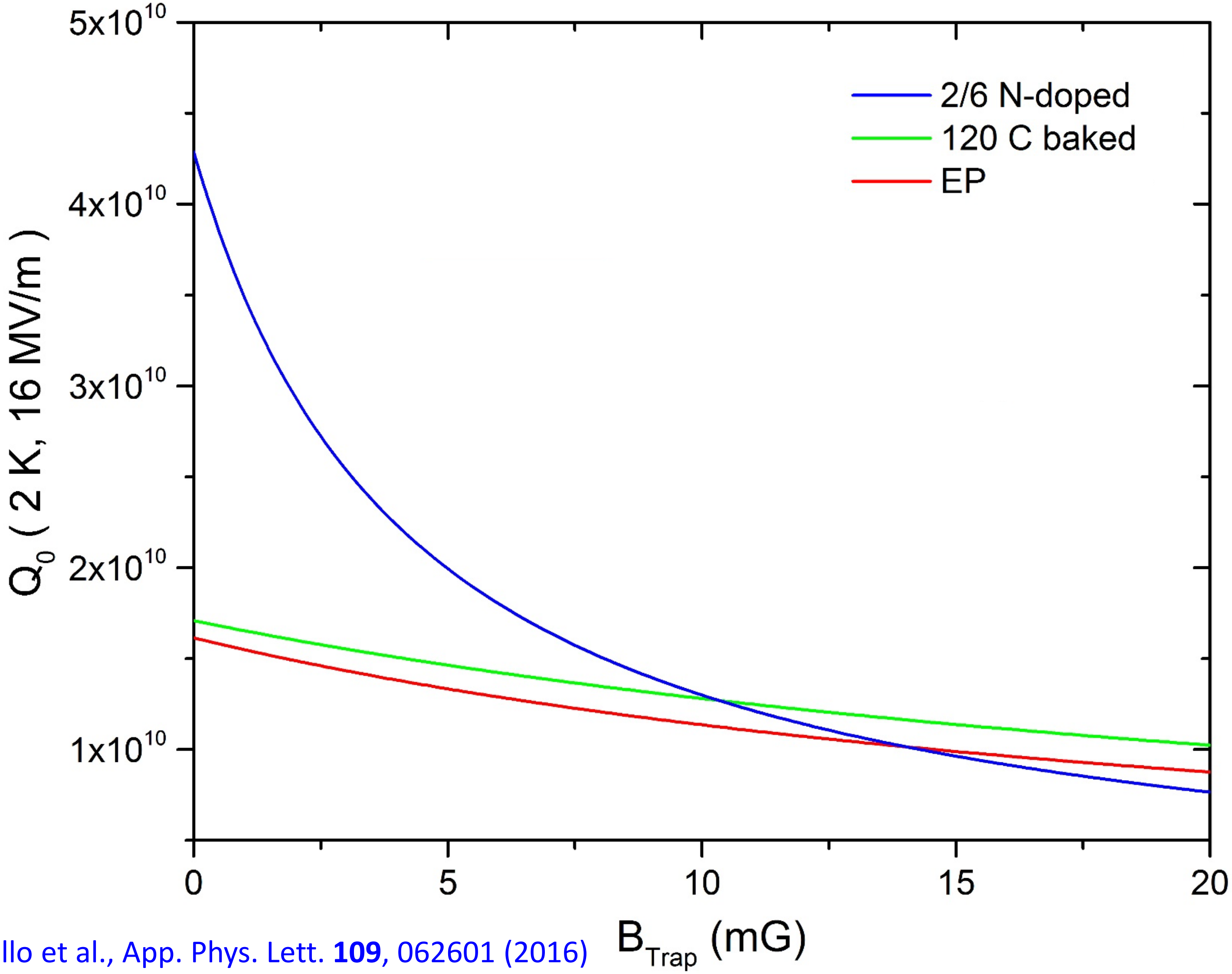
$$S = \frac{R_{Fl}}{B_{Trap}}$$

- 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)

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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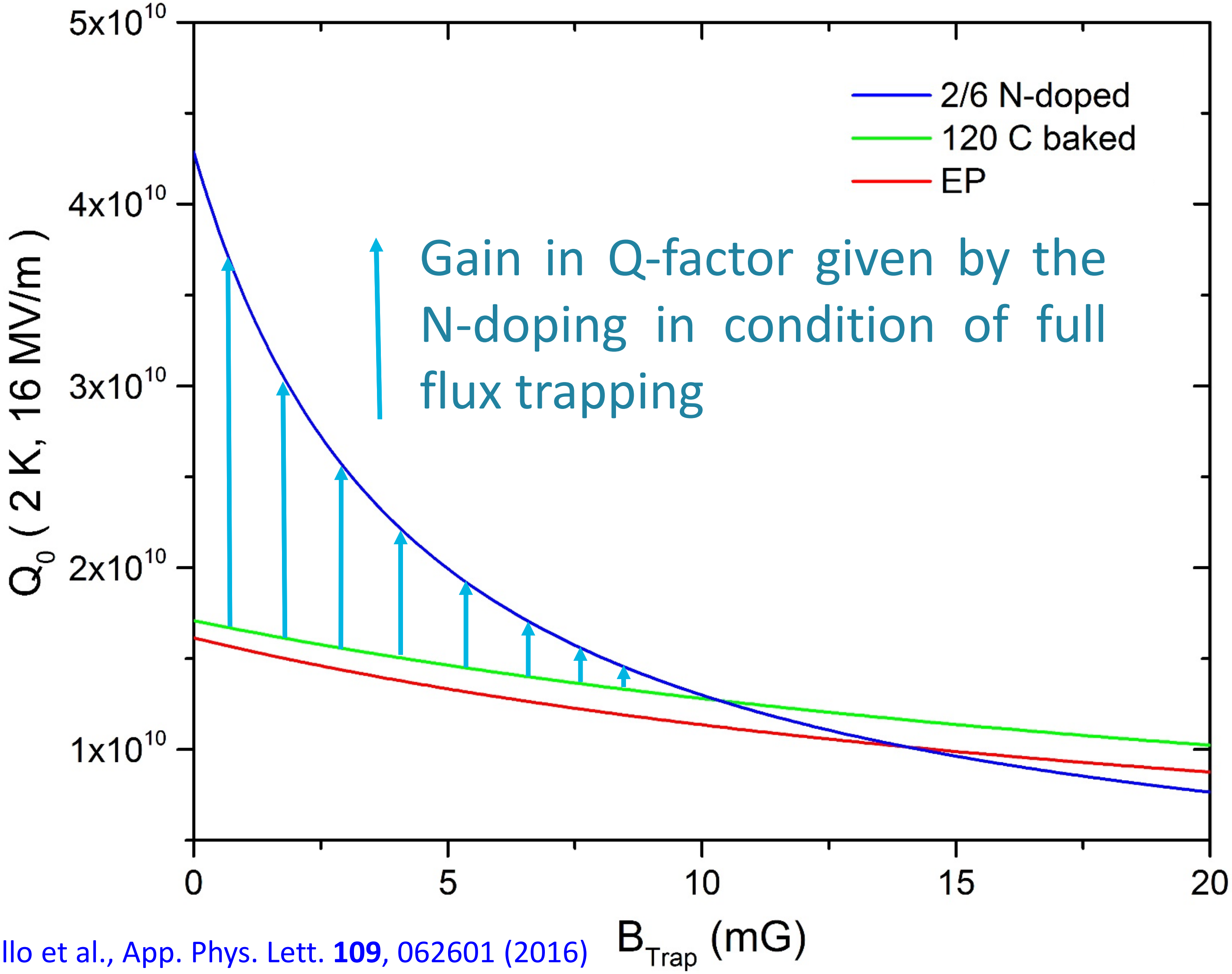
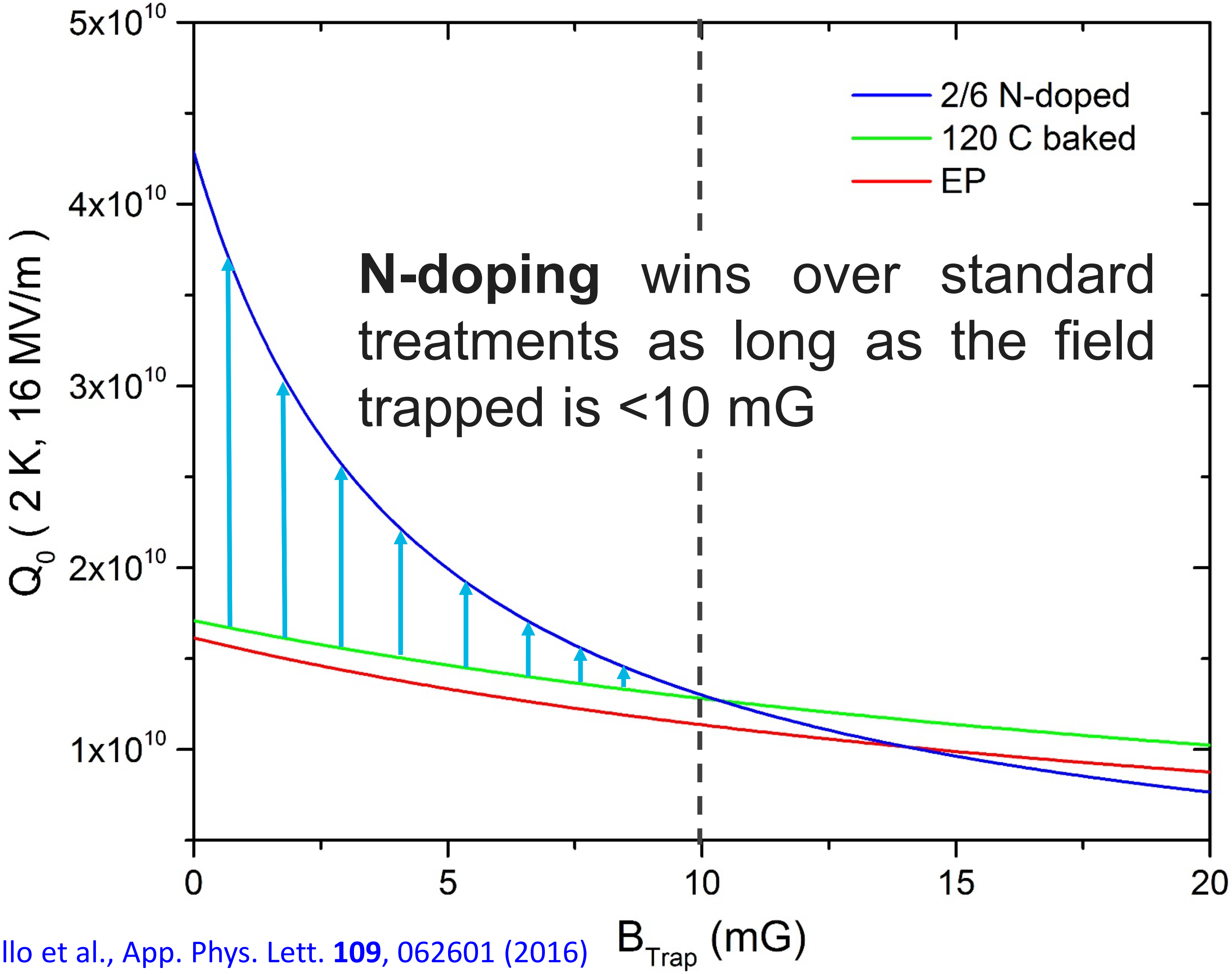


M. Martinello et al., App. Phys. Lett. **109**, 062601 (2016)

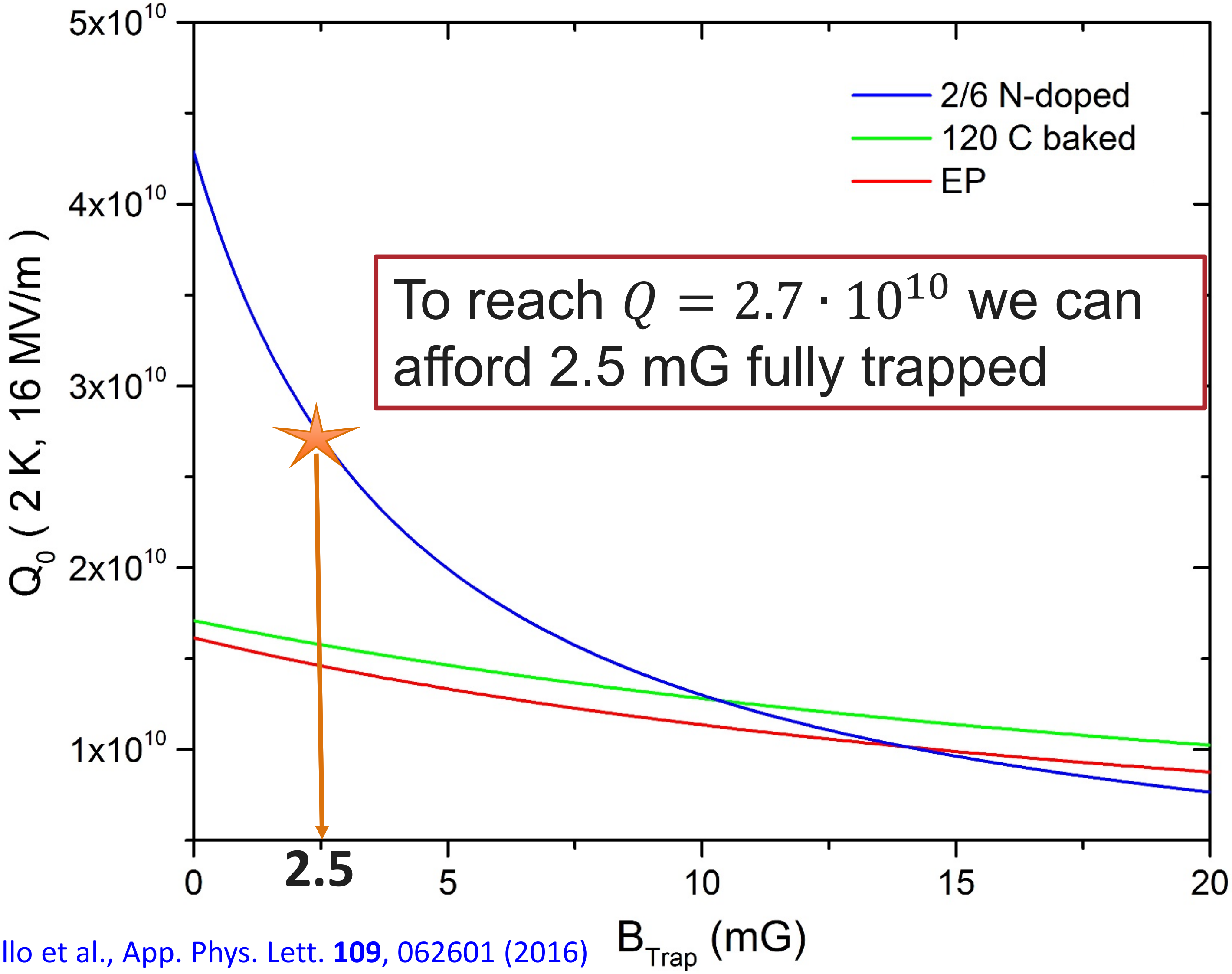
Fermilab

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



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

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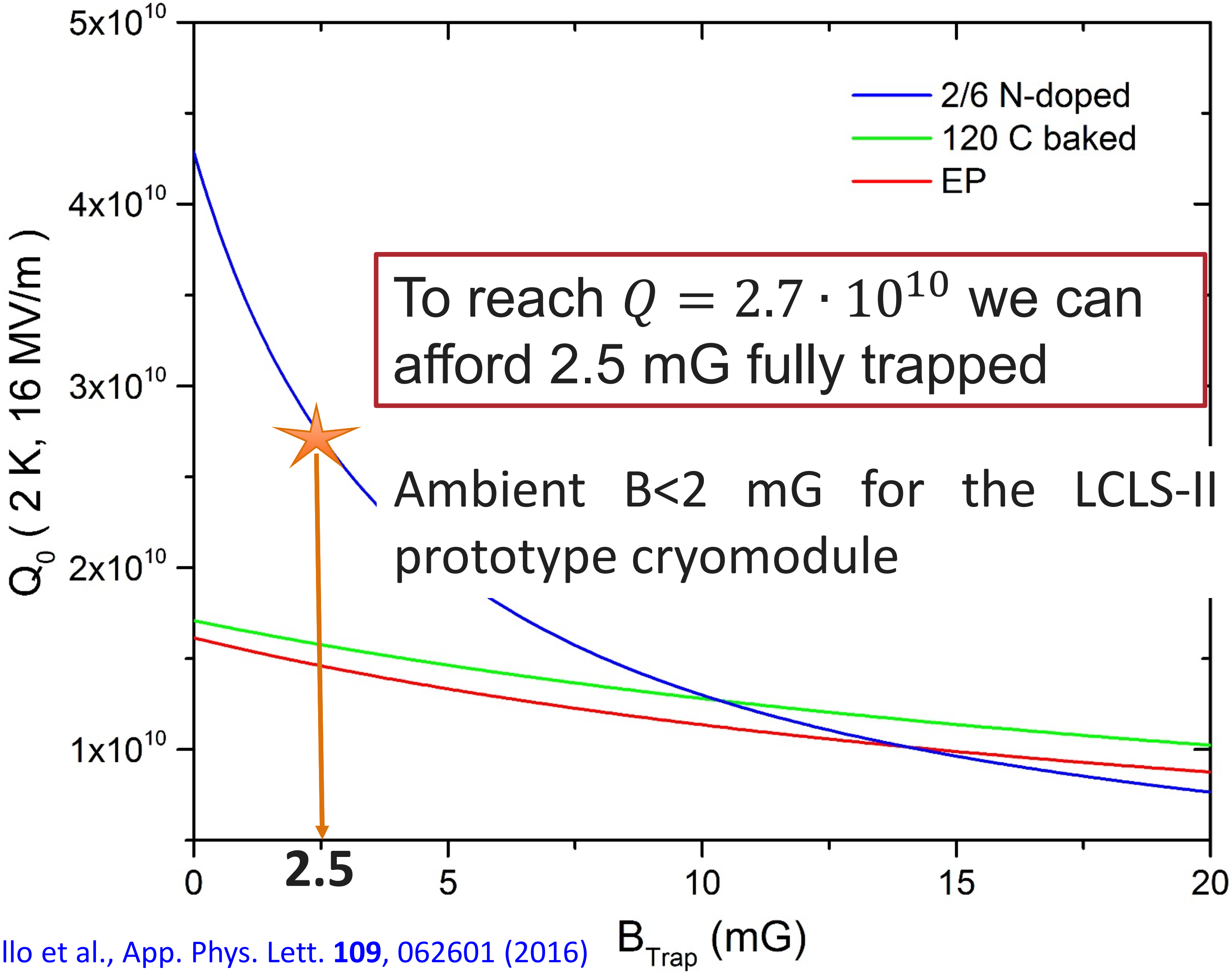

To reach $Q = 2.7 \cdot 10^{10}$ we can afford 2.5 mG fully trapped

Ambient B<2 mG for the LCLS-II Fermilab prototype cryomodule

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

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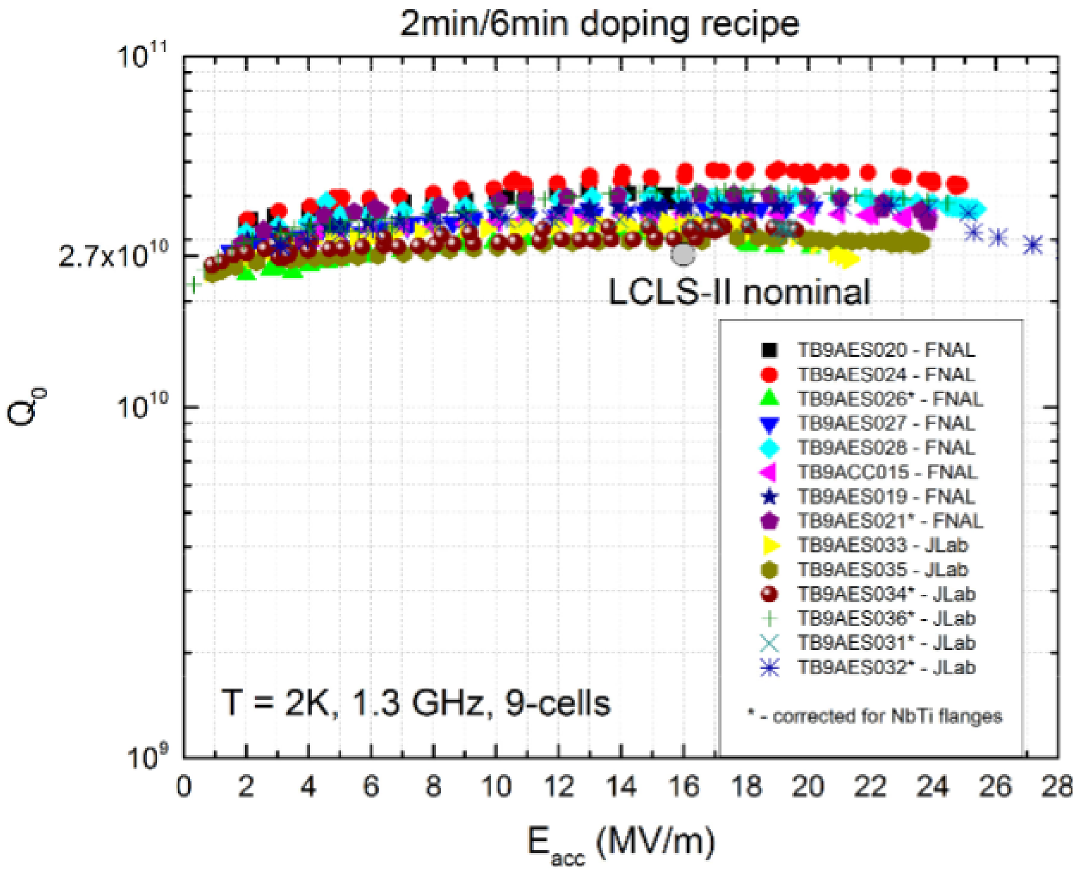
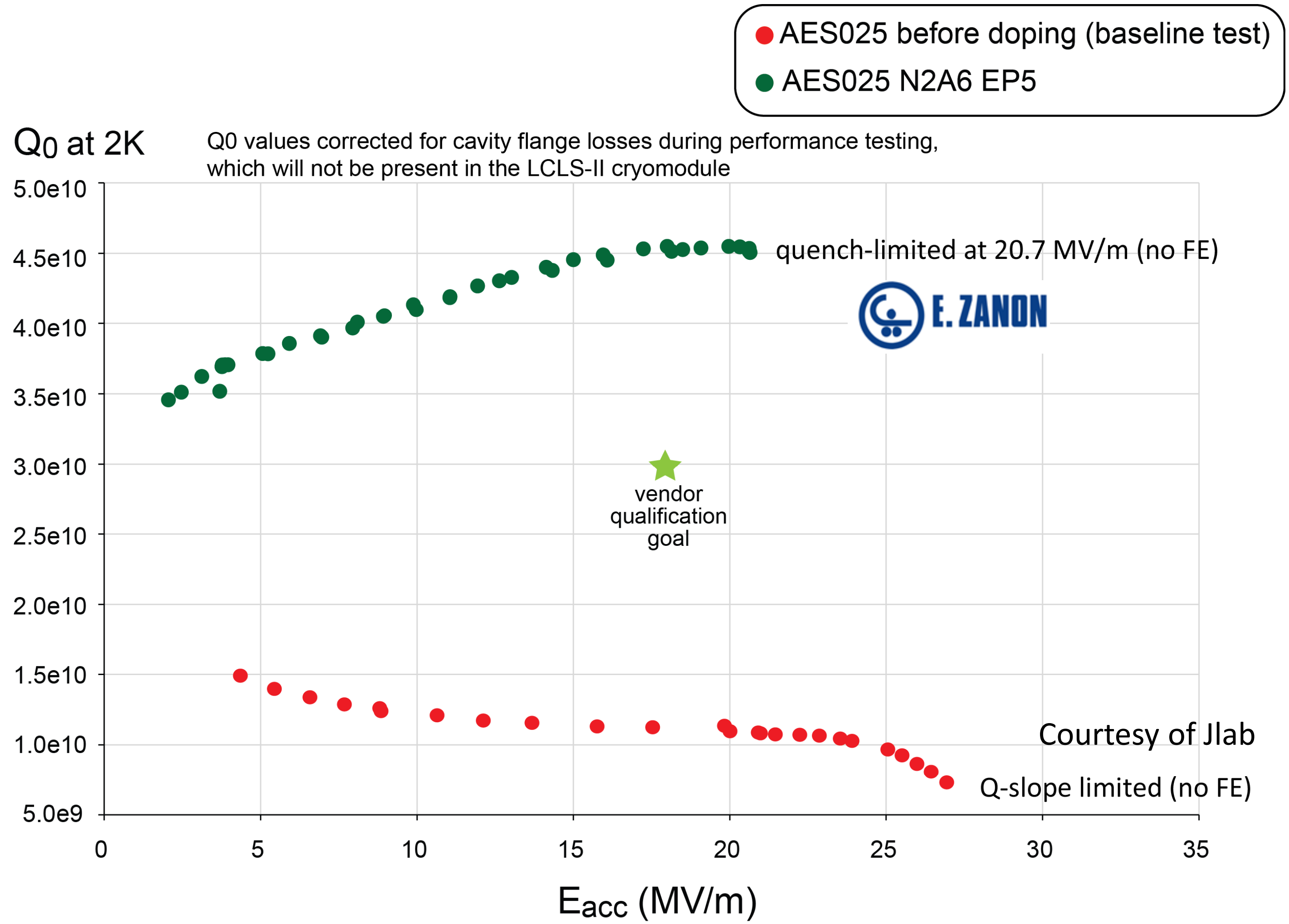
LCLS-II: from single cell to cryomodule



- **LCLS-II specification: Q = 2.7e10, 2K, 16 MV/m**

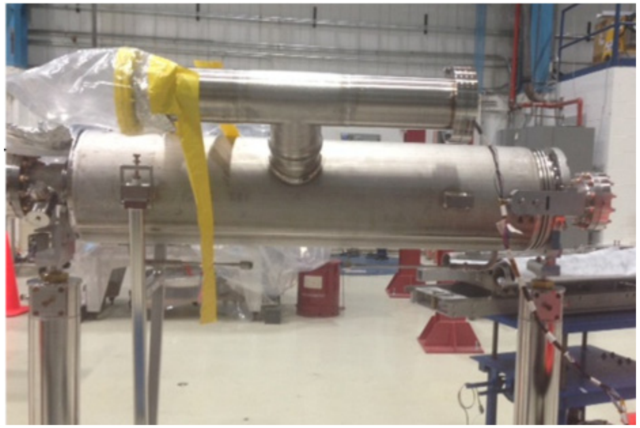
- Prototype cavities for LCLS-II:
  <Q> ~ 3e10 @ 2K 16 MV/m, <Eacc> ~ 22 MV/m

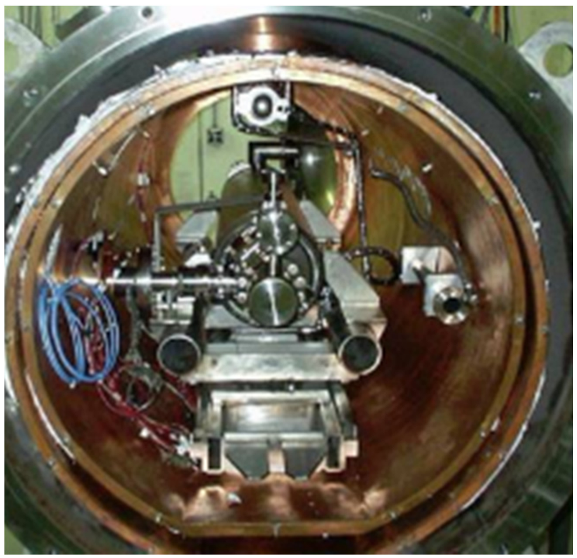
LCLS-II: successful transfer to industry of N doping



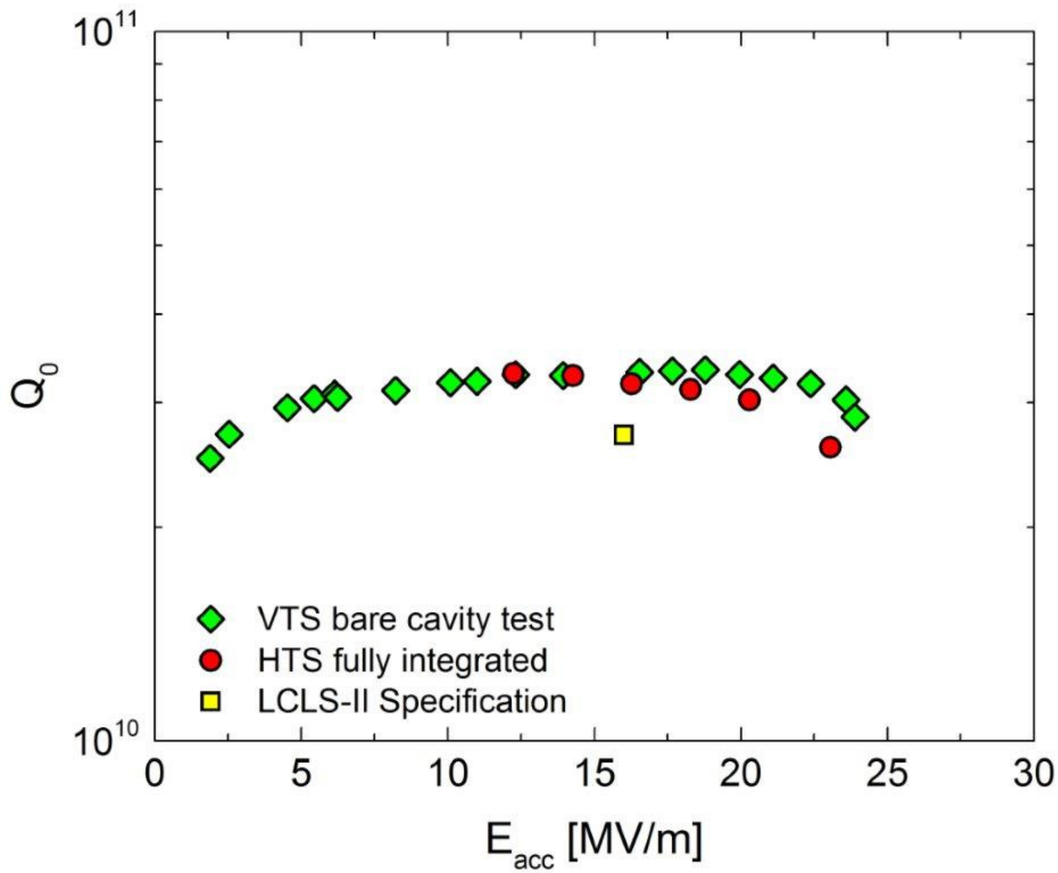
– Four times higher Q (cavity efficiency) at LCLS-II operating gradient

Demonstration in a cryomodule-like environment



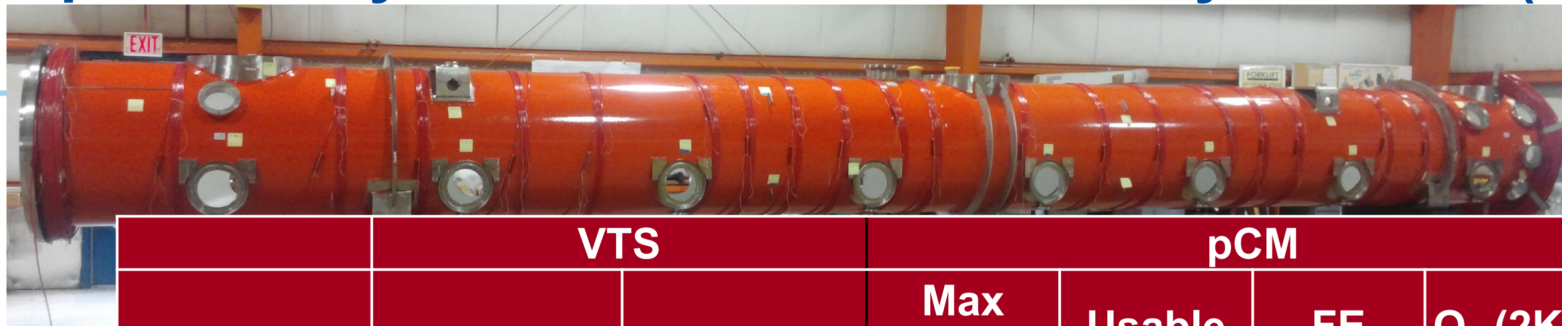


Q can be fully preserved from bare cavity test to fully jacketed state with RF ancillaries, in cryomodule environment



Fermilab

New: preliminary results for first LCLS-2 cryomodule (FNAL)



	VTS		pCM			
Cavity	Eacc [MV/m]	Q_0 (2K) @16MV/m	Max Gradient Reached * [MV/m]	Usable Gradient ** [MV/m]	FE onset [MV/m]	Q_0 (2K) @ 16MV/m***
TB9AES021	23	3.1E+10	19.6	18.2	14.6	2.6E+10
TB9AES019	19.5	2.8E+10	17	16.8	15.6	2.6E+10
TB9AES026	21.4	2.6E+10	17.3	17.2	No FE	2.7E+10
TB9AES024	22.4	3.0E+10	16.5	16.0	No FE	2.5E+10
TB9AES028	28.4	2.8E+10	14.9	13.8	11.5	2.4E+10
TB9AES016	18	2.8E+10	16.7	16.7	14.5	2.9E+10
TB9AES022	21.2	2.8E+10	17.4	17.1	12.7	3.2E+10
TB9AES027	22.5	2.8E+10	16.8	16.6	13.8	2.5E+10
Average	**22.1**	**2.8E+10**	**17.0**	**16.6**	**14.7**	**2.7E+10**
Total Voltage	**176.4**		**136.2**	**132.5**		

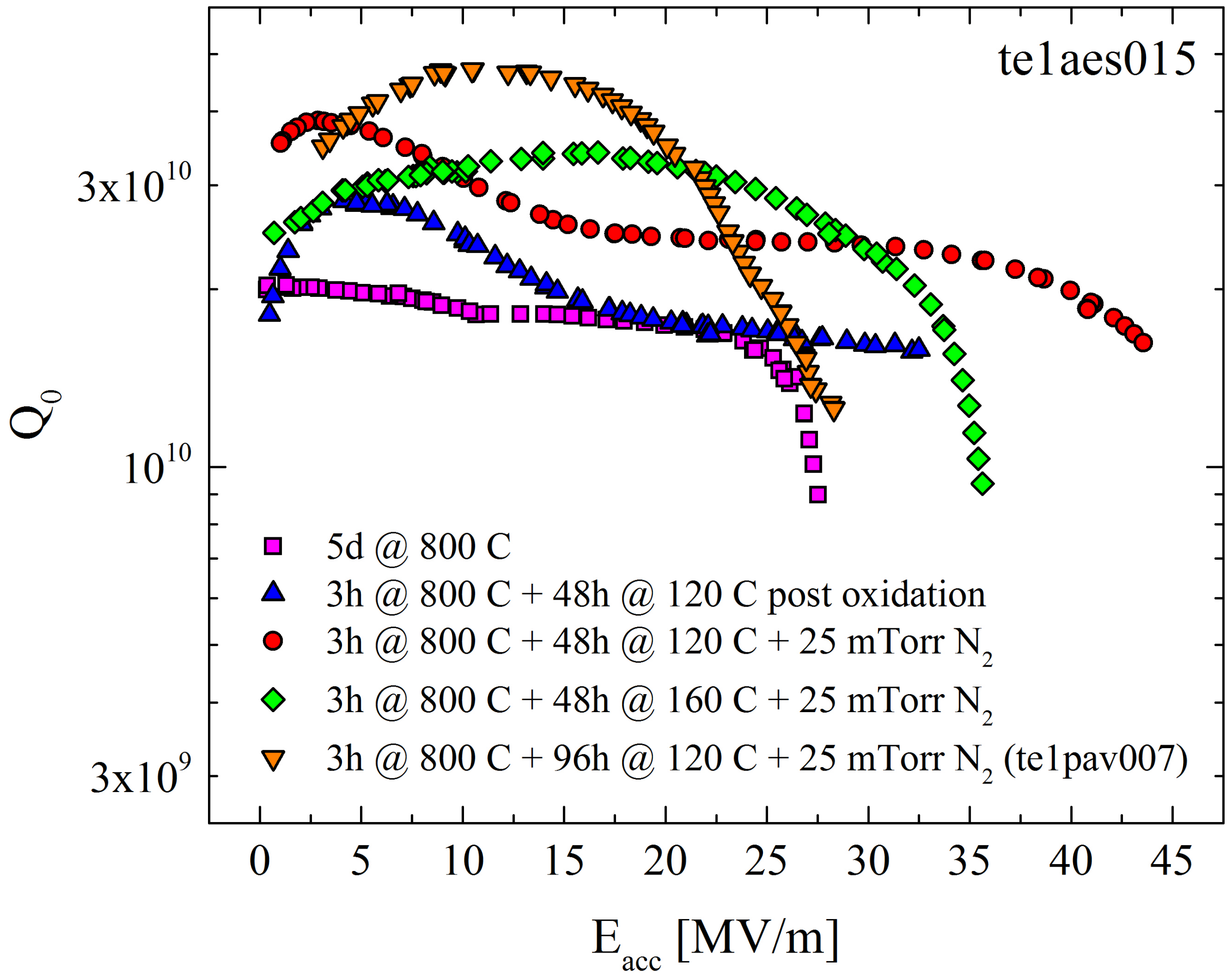
*Max gradient currently reached, limited by RF limits, multipacting or field emission

**Usable Gradient: demonstrated to stably run CW, FE < 50 mR/h, no dark current

***Fast cooldown from 45K, 40 g/sec, extrapolated from 2.11K

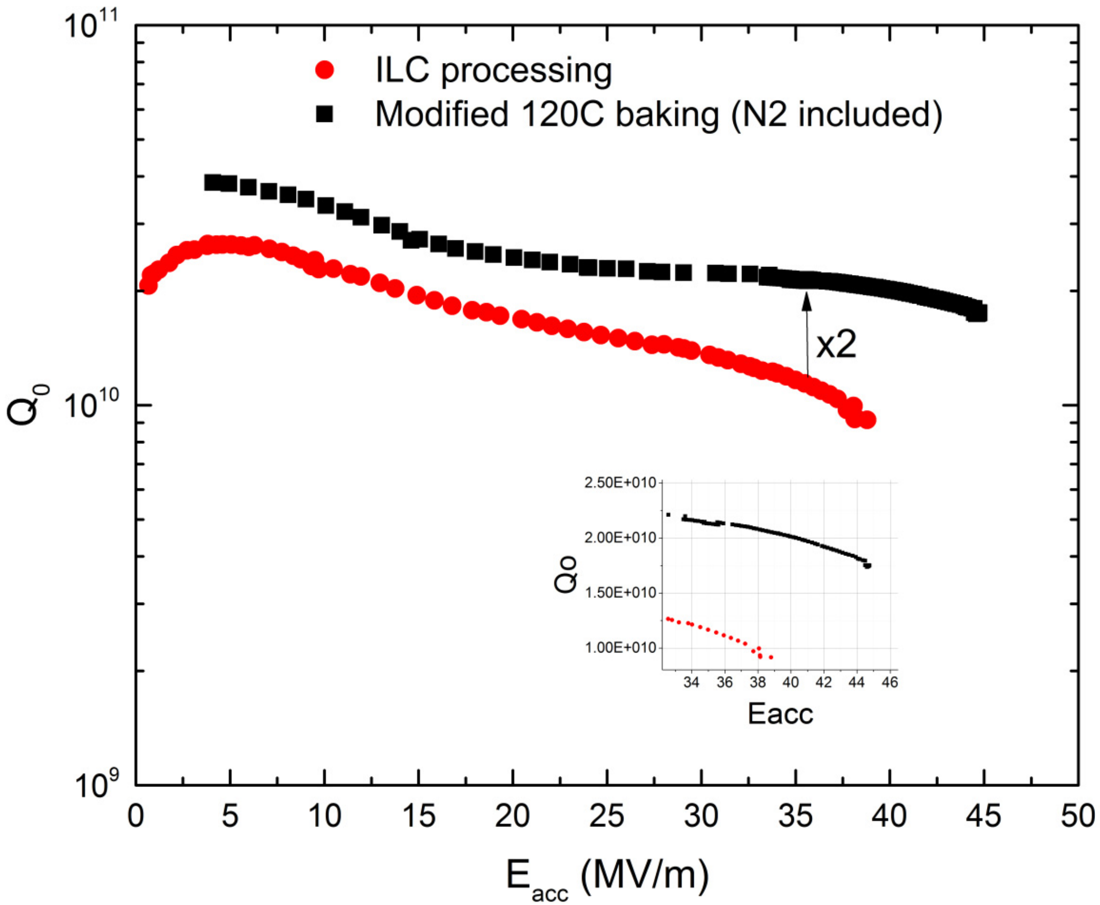
World Record Q cryomodule!

New recent findings: low T (120-160C) N-doping



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

Zoom in on “standard” vs “N infused” cavity surface treatment



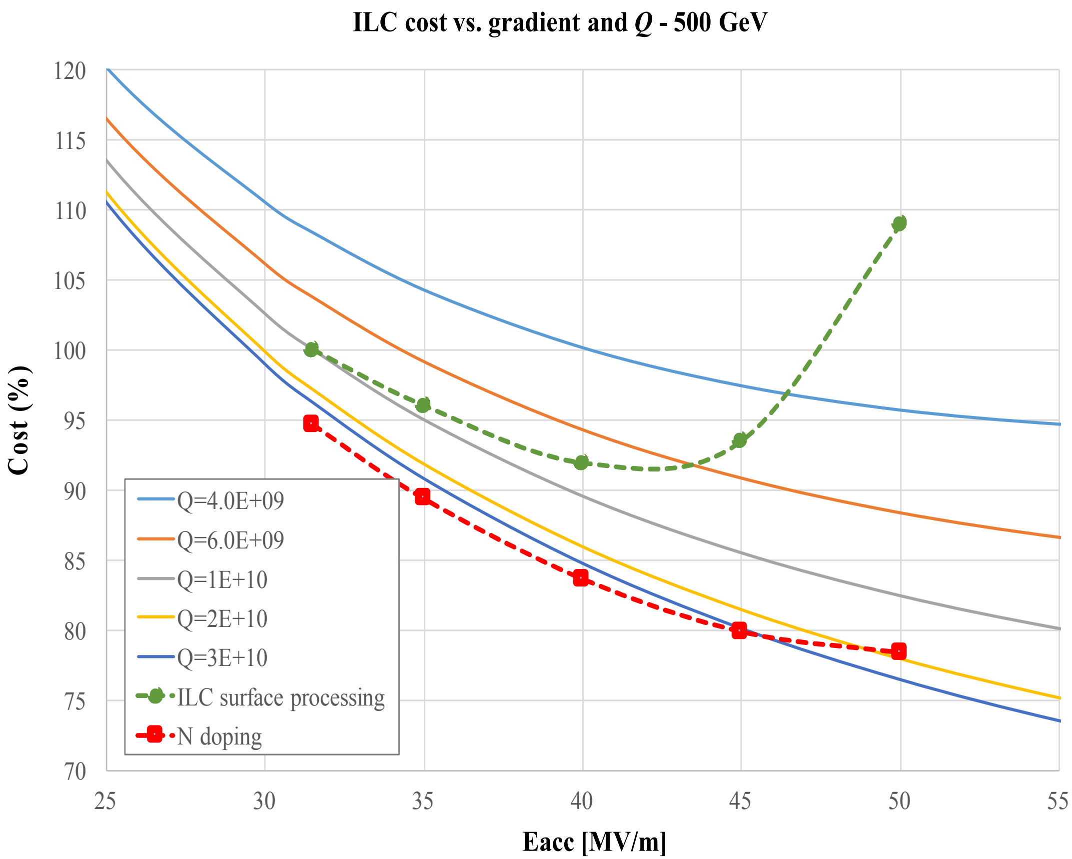
Increase in Q by a factor of two
Increase in gradient ~15%

- FNAL recently demonstrated (on single-cell cavities) a new treatment, which utilizes “nitrogen infusion”.
- Achieved so far:

  45.6 MV/m → 194 mT
  with Q > $2 \cdot 10^{10}$!
- Systematic effect observed on several cavities.
- R&D to focus on :
  a) Optimize the recipe;
  b) Implement and demonstrate improvement with statistics on nine cells cavities;
  c) Demonstrate preservation of performance in cryomodule;
  d) Transfer technology to industry.

The importance of High at High Gradients

- Raising Q at high gradients is necessary for cost reduction of high gradient machines like ILC
- For a machine like ILC, these findings can turn into >10% cut in machine costs



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 and proven all the way down to cryomodule

- Efficient magnetic flux expulsion discovered, can be achieved with fast cooldown and material optimization

- Unprecedentedly low magnetic field levels <2mGauss achieved in cryomodule

- 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 – more to come!

Thank you for your attention!

Fermilab