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High Q-factor accelerating cavities as enabling technology for CW accelerators

Martina Martinello

Peoples Fellow (Associate Scientist), Fermilab

IEEE/NPSS PAST Thesis Award

IPAC 2018, Vancouver

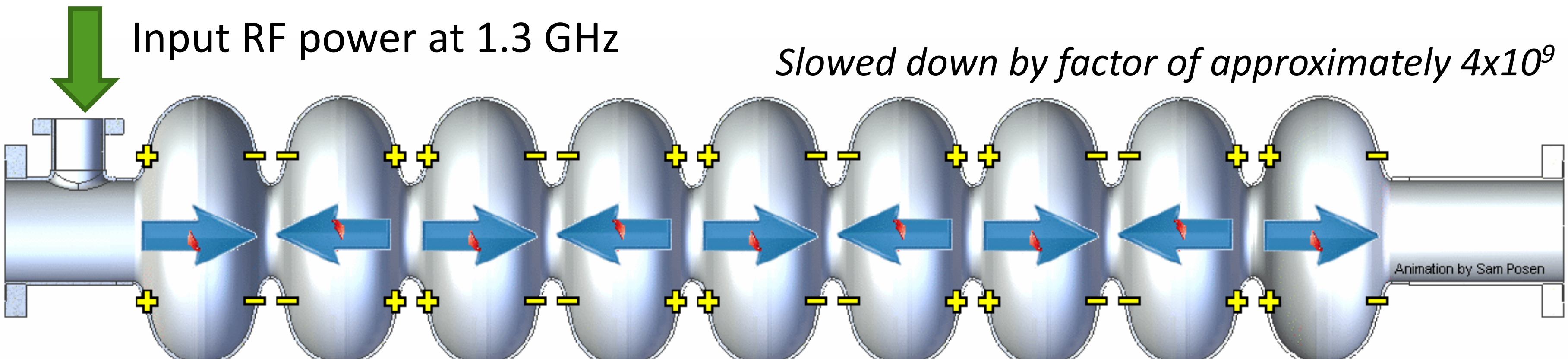
IPAC18

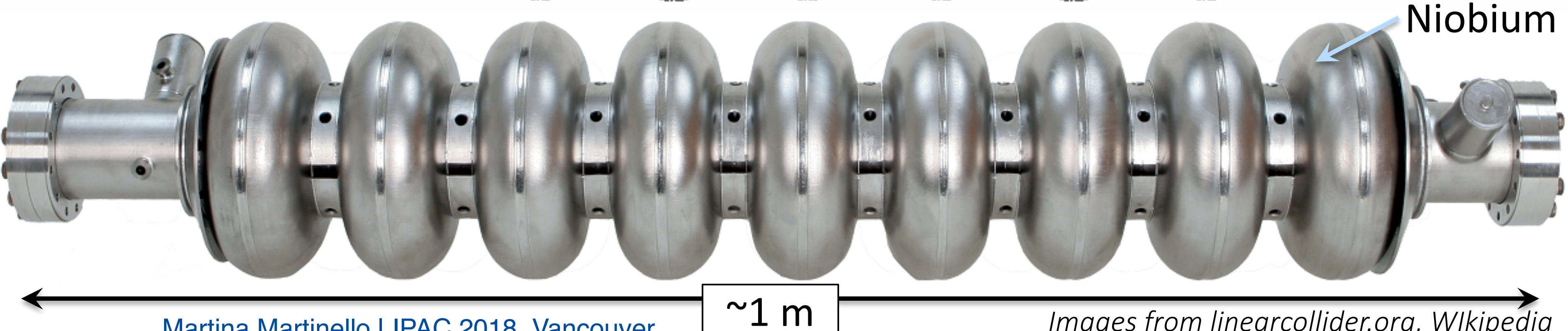
Particle Acceleration via SRF Cavities

- **Superconducting radiofrequency (SRF) cavities**
- High quality EM resonators: Typical $Q_0 > 10^{10}$
- Large electric field generated along the cavity axis
- Particle beam gains energy as it passes through

Input RF power at 1.3 GHz

Slowed down by factor of approximately 4×10^9

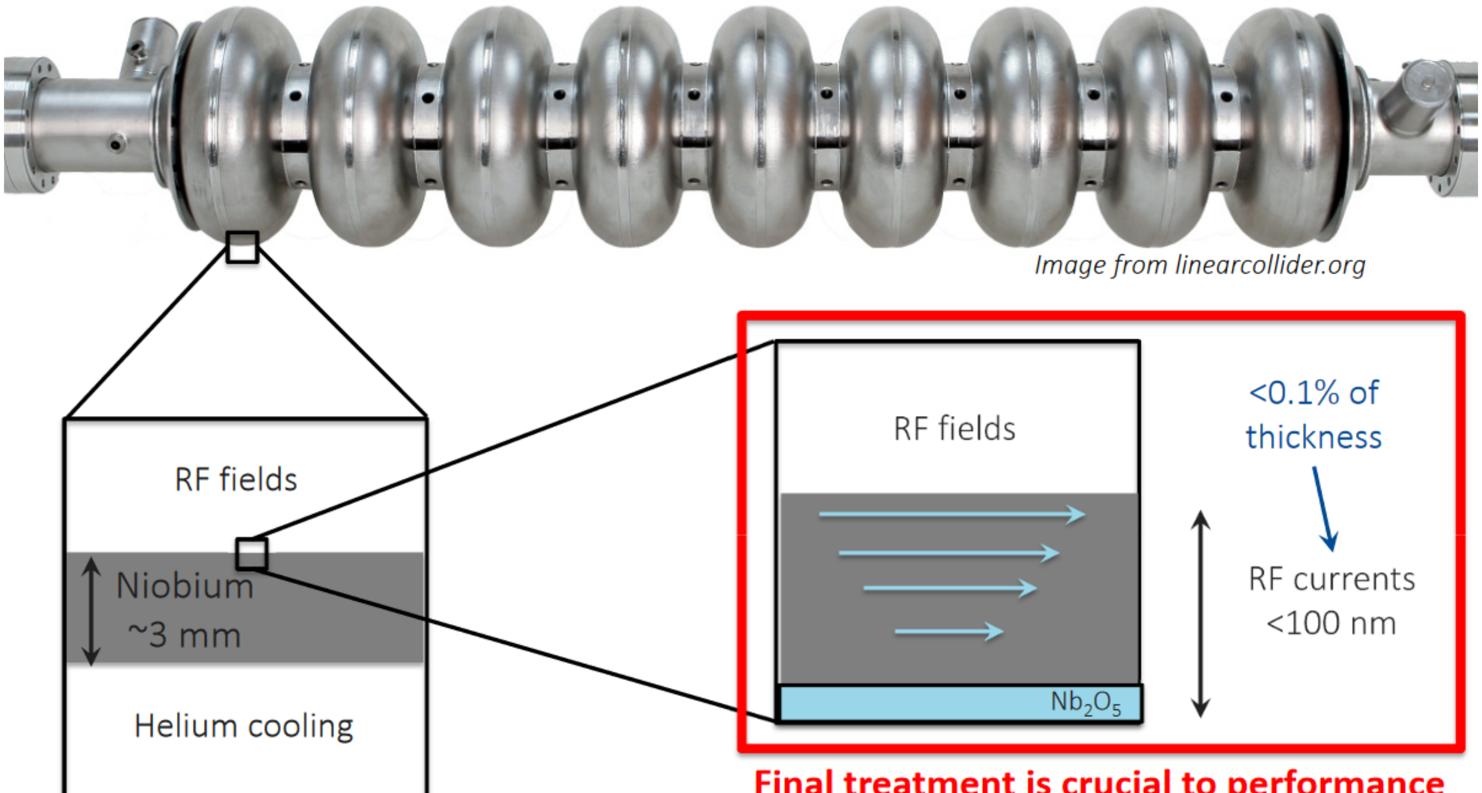




Images from linearcollider.org, WIkipedia

Superconducting RF Cavities

- Niobium (Tc=9.2 K), T operation 2-4.5 K
- RF surface resistance → <u>fighting against nΩ</u>
- Losses concentrate on the first ~100 nm of the **inner surface**



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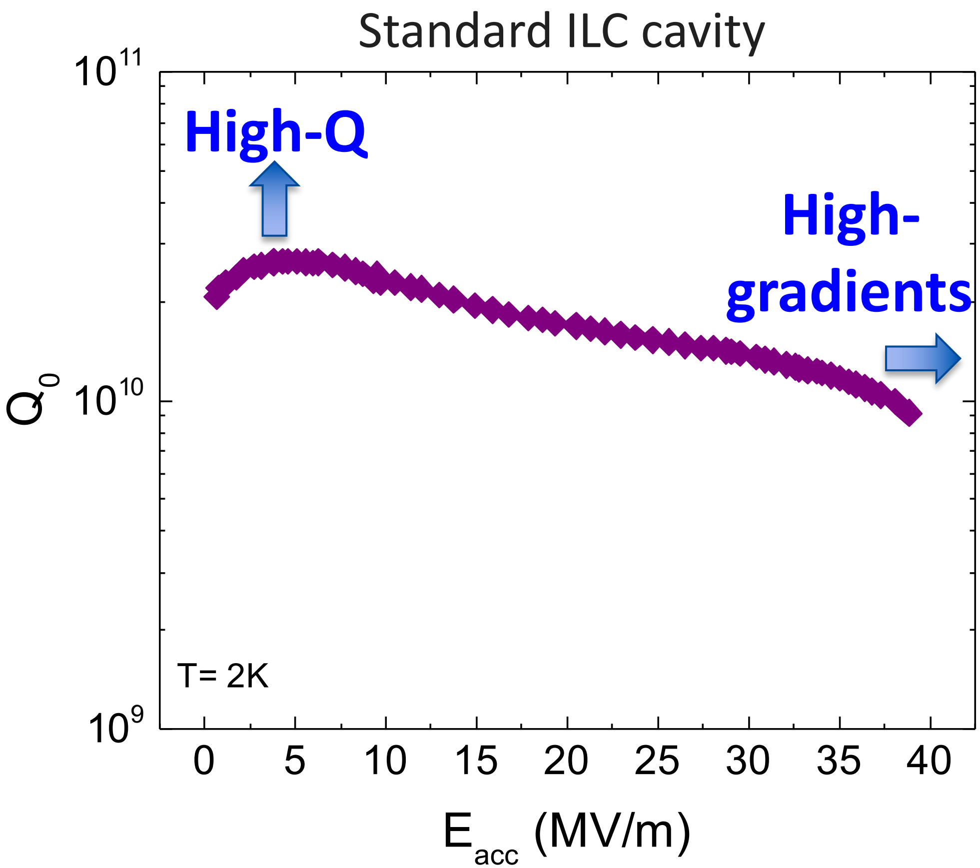
SRF Cavities Figure of Merits



Q-factor (Q_0):

$$Q_0 = \frac{G}{R_s} = \frac{\omega_0 U}{P_d}$$

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

High Q_0 → lower power consumption

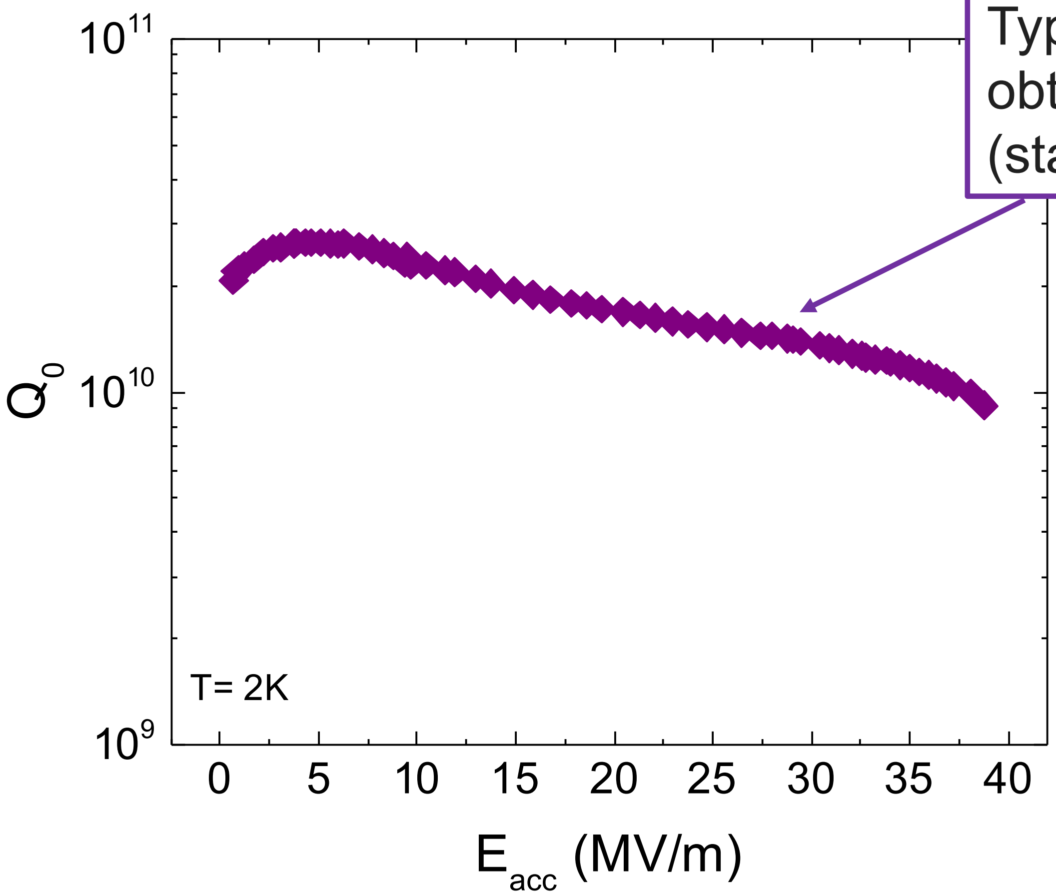
Accelerating field (E_{acc}):

Determine the energy transferred to charged particles

High E_{acc} → lower accelerator length

High Q at large gradient may reduce both capital and operational costs of accelerators

The Discovery of N-doping



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

Average Q at 16MV/m:

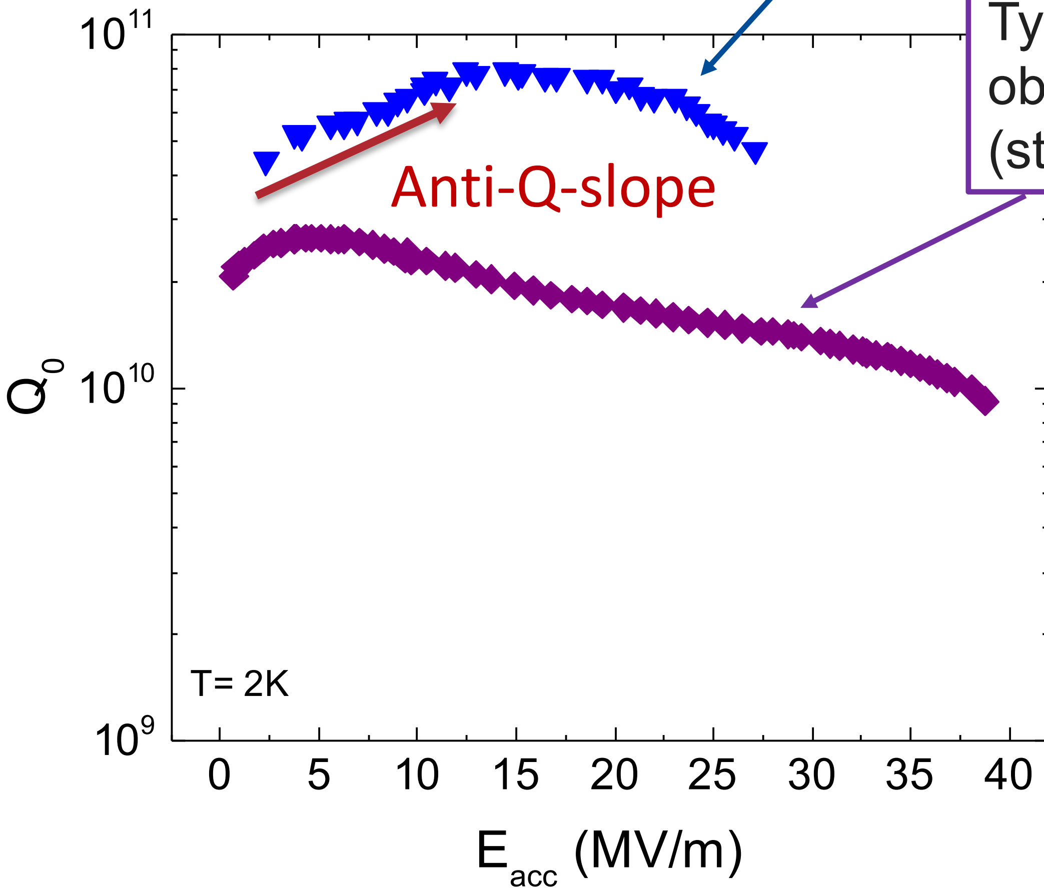
- Standard ILC treatment:

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

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

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 120 °C 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)

The Discovery of N-doping

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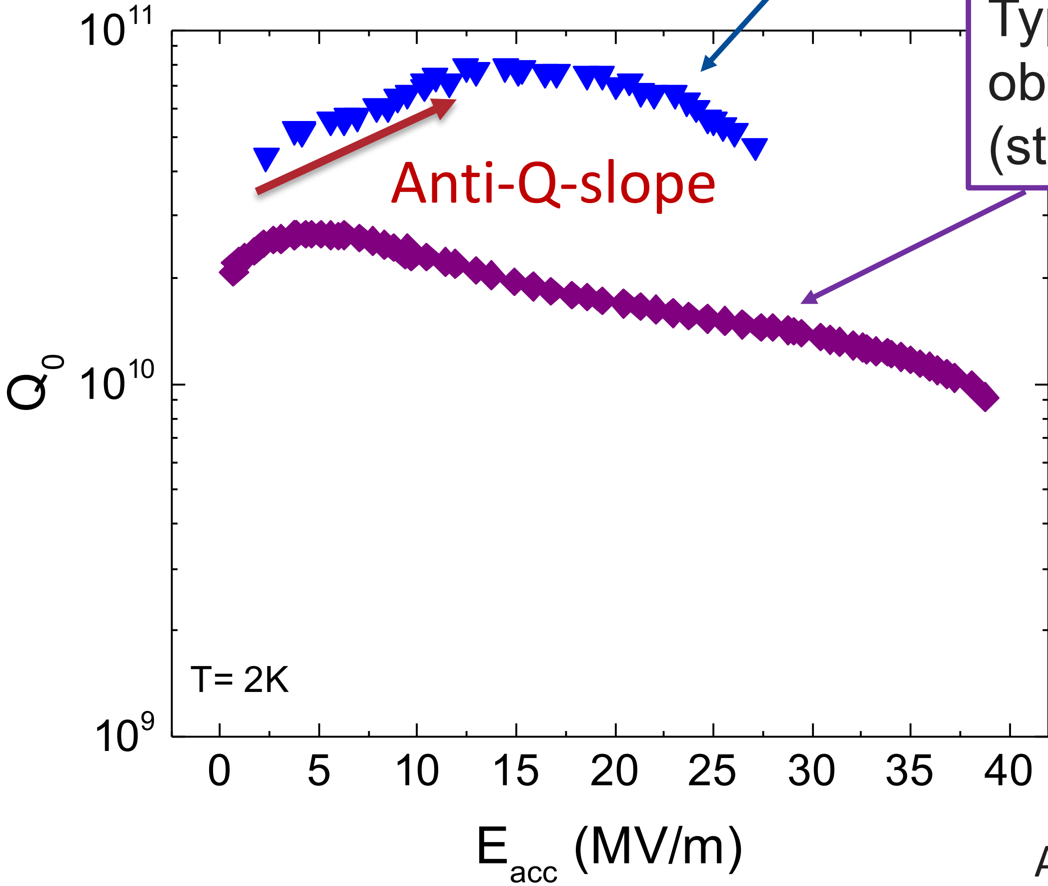
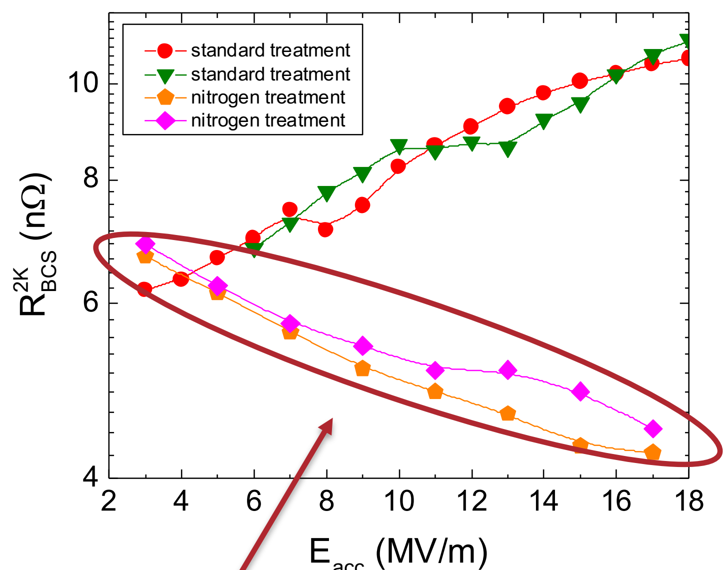
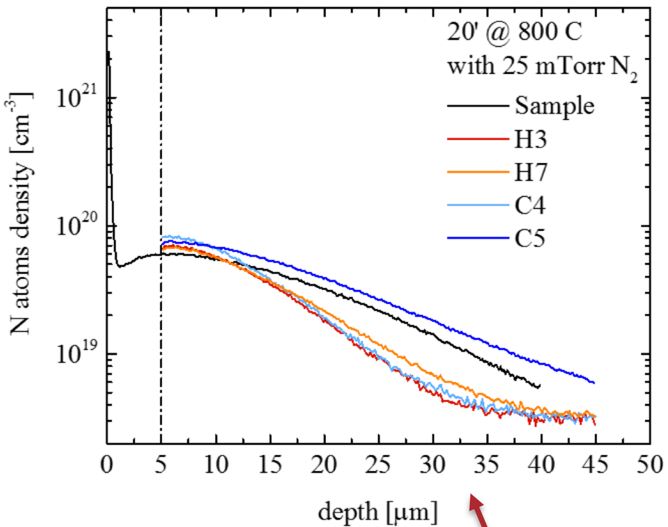




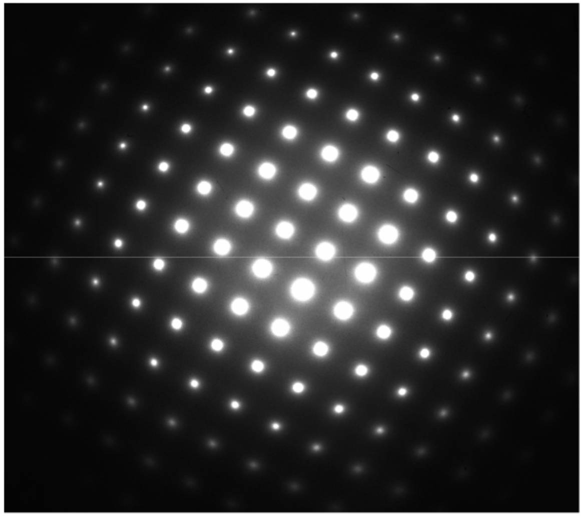
Anti-Q-slope emerges from the BCS surface resistance decreasing with field

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

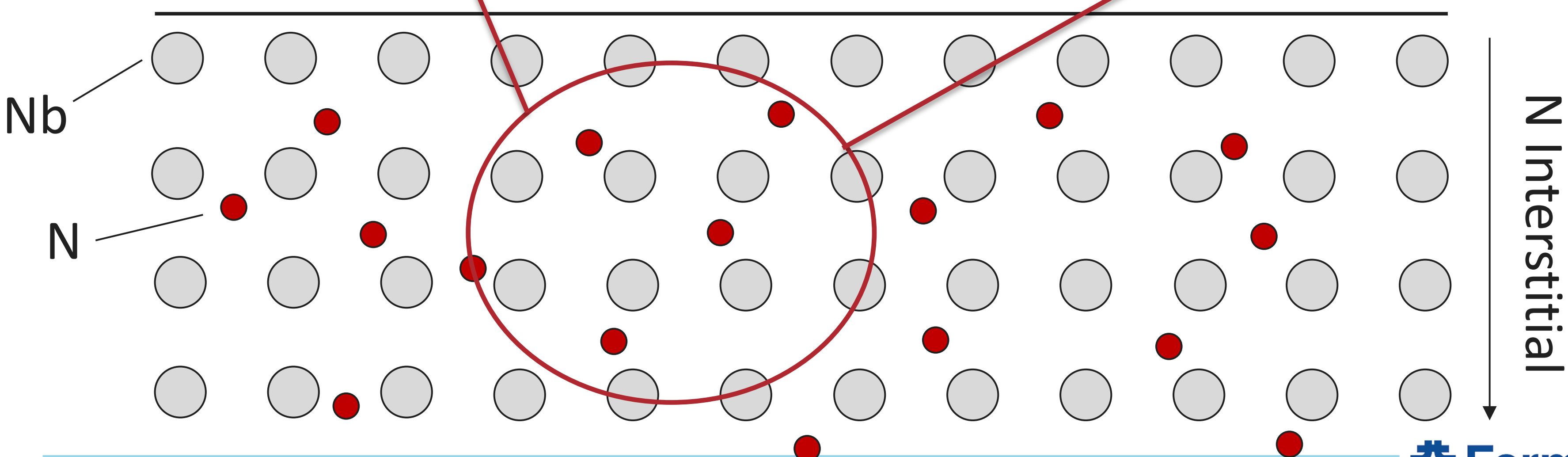
Interstitial Nitrogen After Doping Treatment



Only Nb from TEM spectra:
N must be interstitial



Final RF Surface



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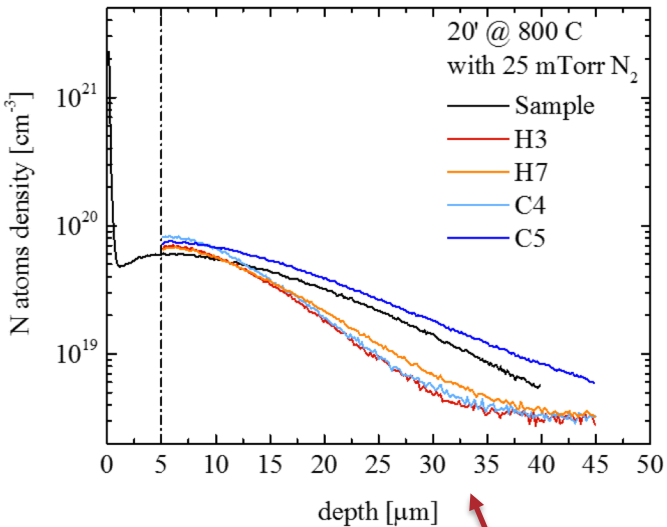
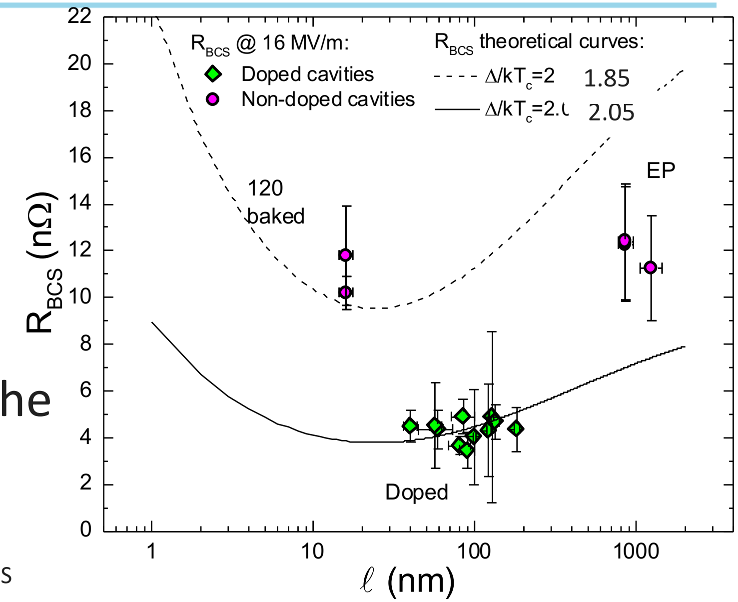
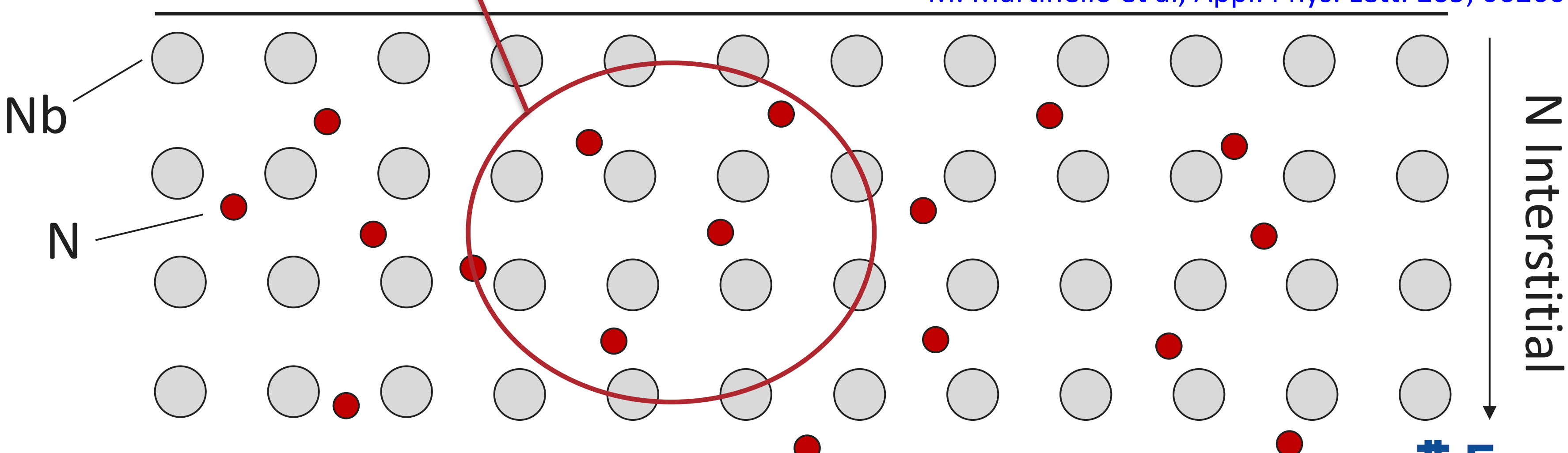


N-doping lowers the mean-free-path

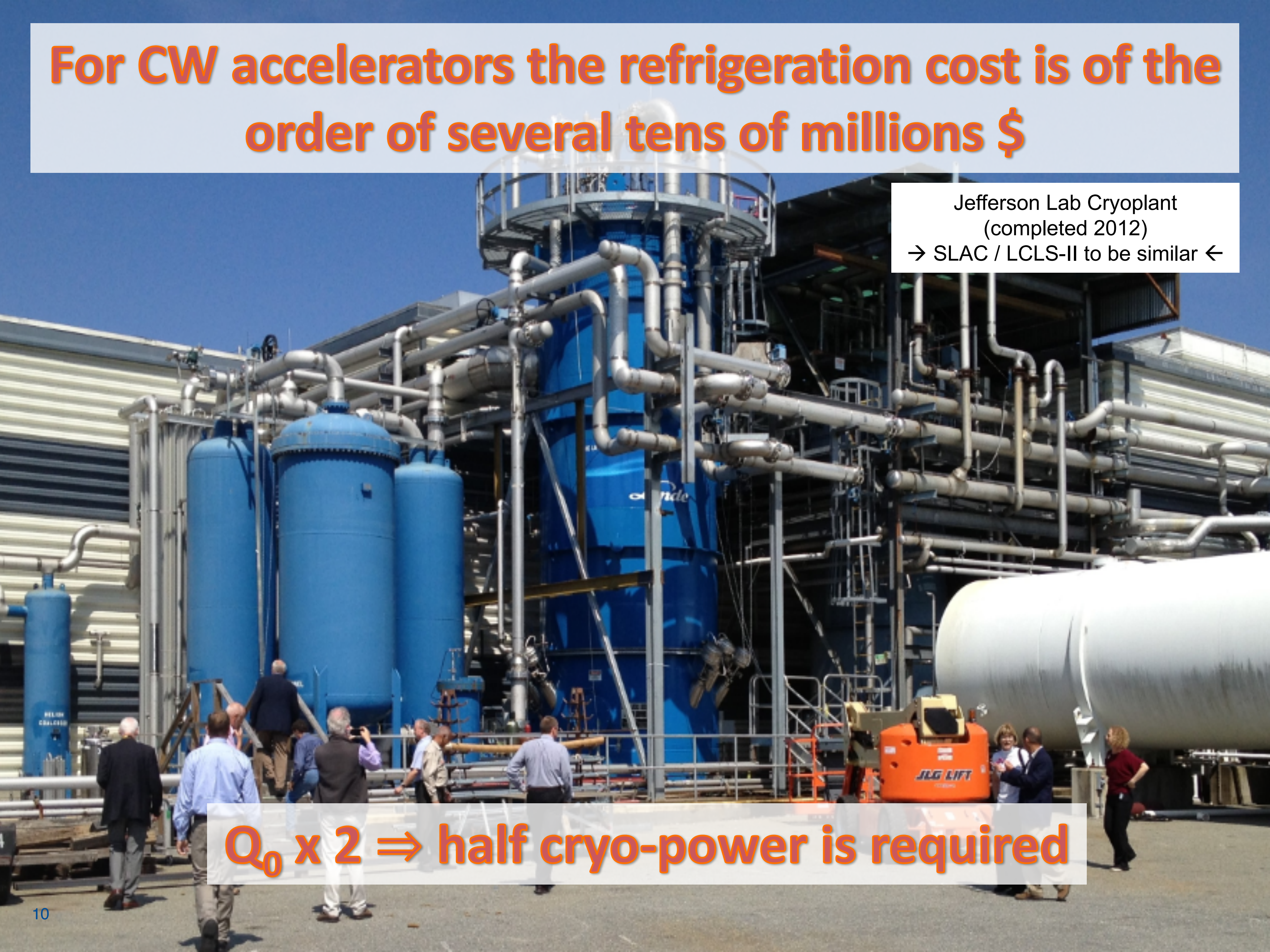
→Mean-free-path close to theoretical minimum of R_{BCS}



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



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

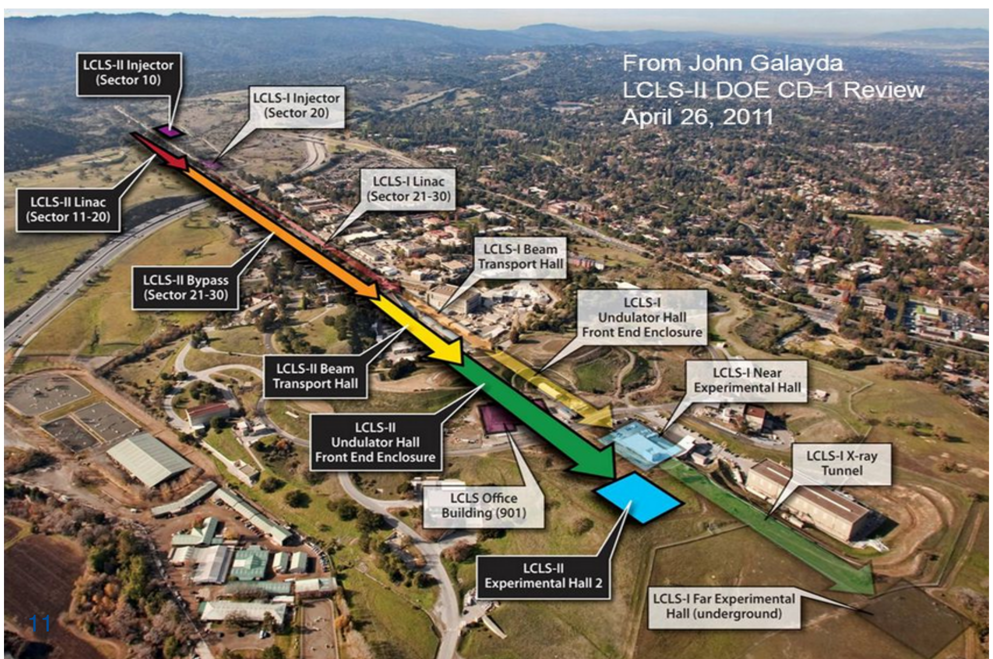


Jefferson Lab Cryoplant
(completed 2012)
→ SLAC / LCLS-II to be similar ←

Q_0 x 2 ⇒ half cryo-power is required

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 $Q_0 = 2.7\times10^{10}$



HIGH-Q PRESERVATION IN CRYOMODULES

SC Transition in Presence of External Magnetic Field

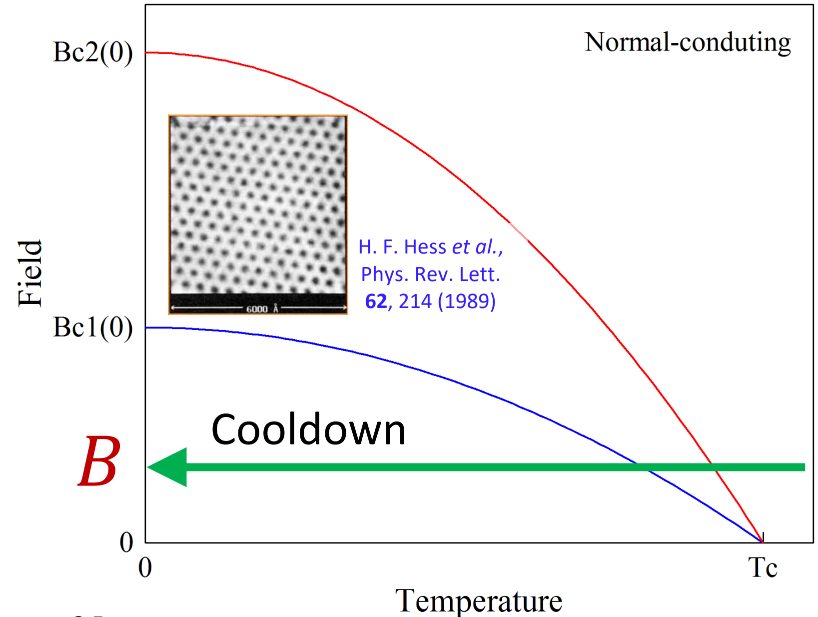
$$R_s(T,B) = R_{BCS}(T) + \boxed{R_{fl}(B)} + R_0$$

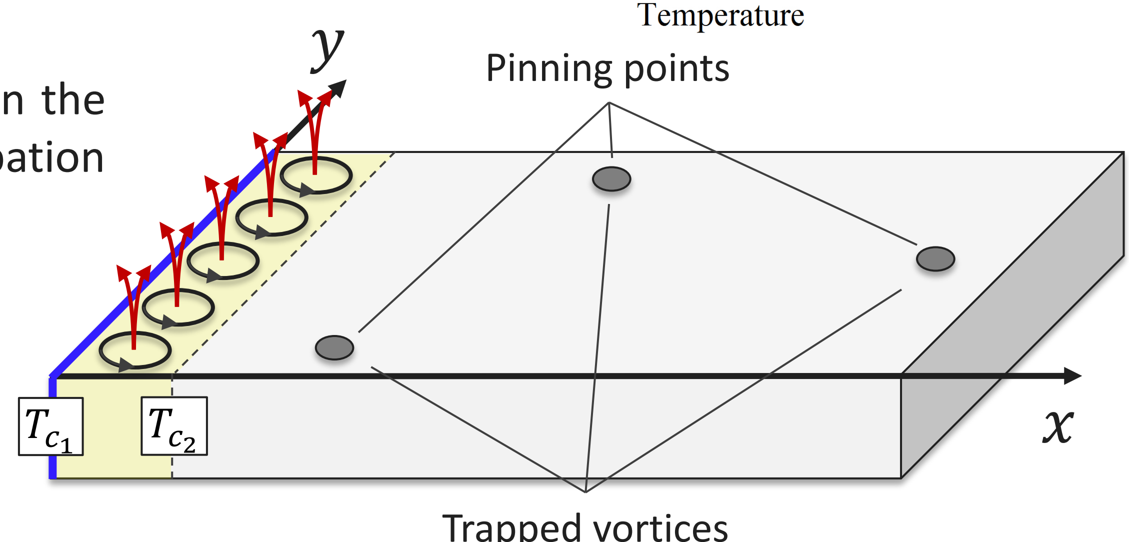
R_{BCS} ⇒ temperature-dependent part of the surface resistance

R_0 ⇒ intrinsic residual resistance

$R_{fl} = \eta_t S B$ ⇒ trapped flux surface resistance:

- If pinned, vortices may survive in the Meissner state introducing dissipation
- η_t—flux trapping efficiency
- S—trapped flux sensitivity
- B—external magnetic field





Slide adapted from M. Checchin

Trapped Flux Surface Resistance

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

- S — Trapped flux sensitivity
- η — Flux trapping efficiency
- B_{ext} — External magnetic field

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Trapped Flux Surface Resistance

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

- S — Trapped flux sensitivity
- η — Flux trapping efficiency
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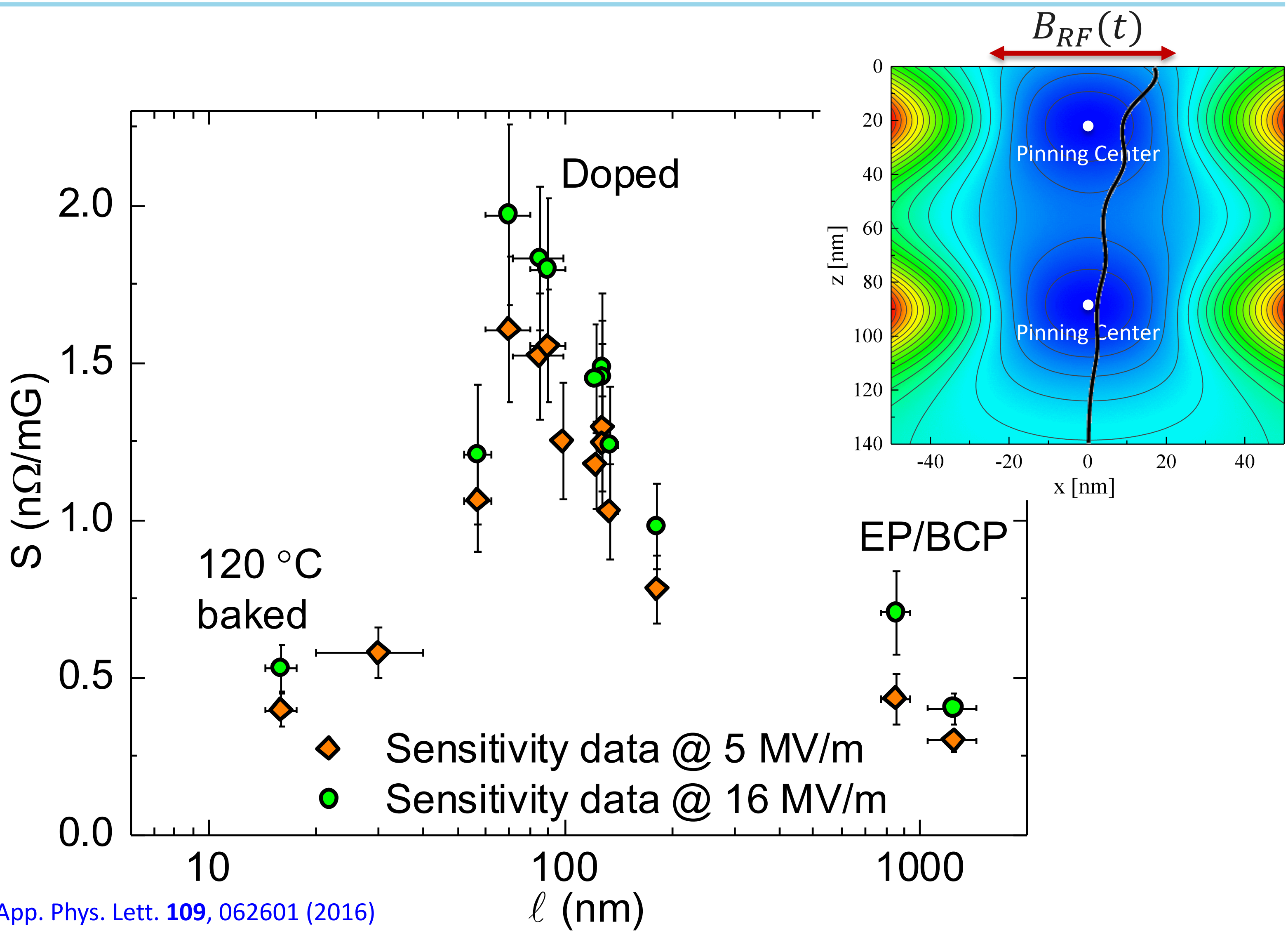
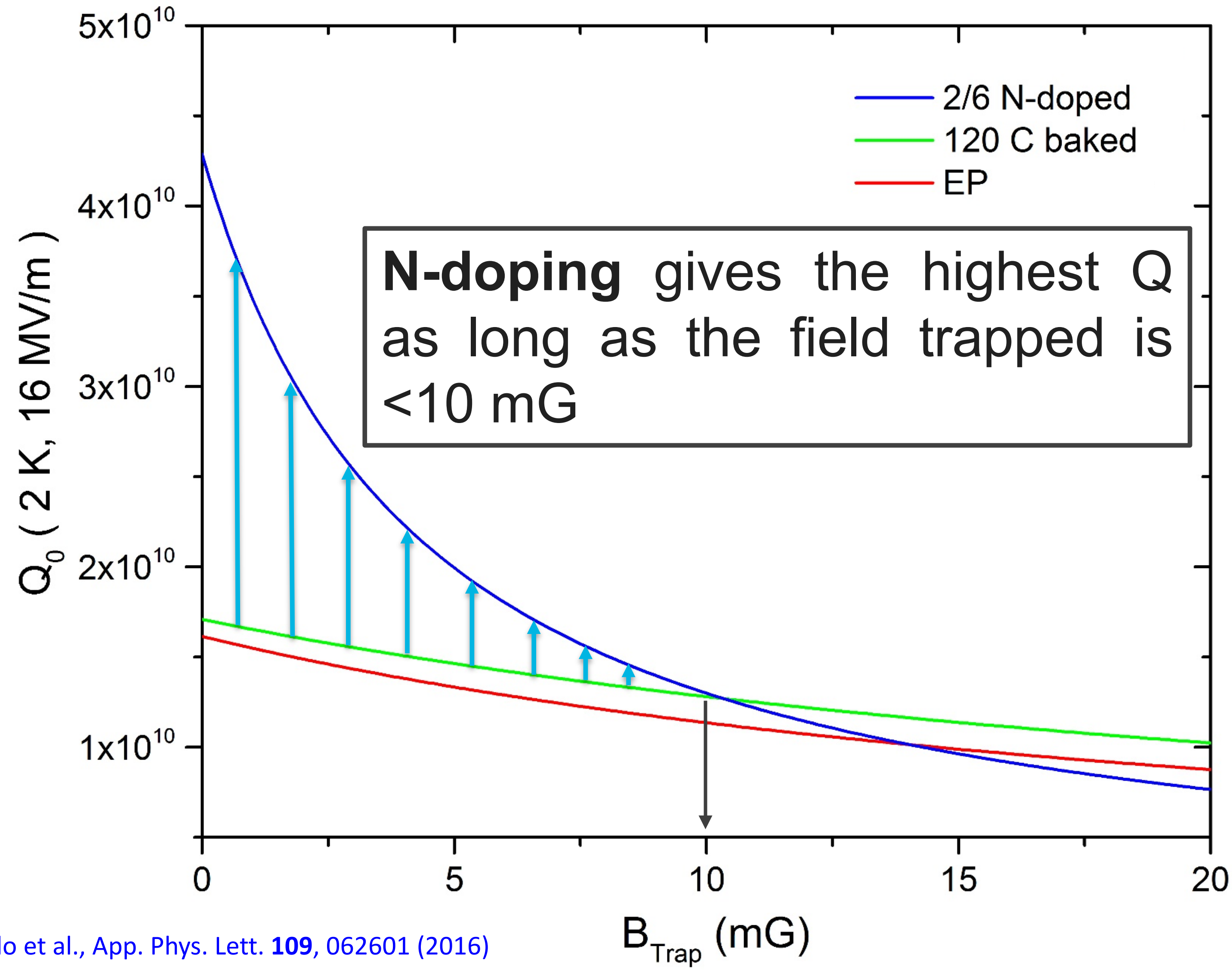
Sensitivity Higher in N-doped Cavities



M. Martinello et al., App. Phys. Lett. **109**, 062601 (2016)
M. Checchin et al., Supercond. Sci. Technol. 30, 034003 (2017)

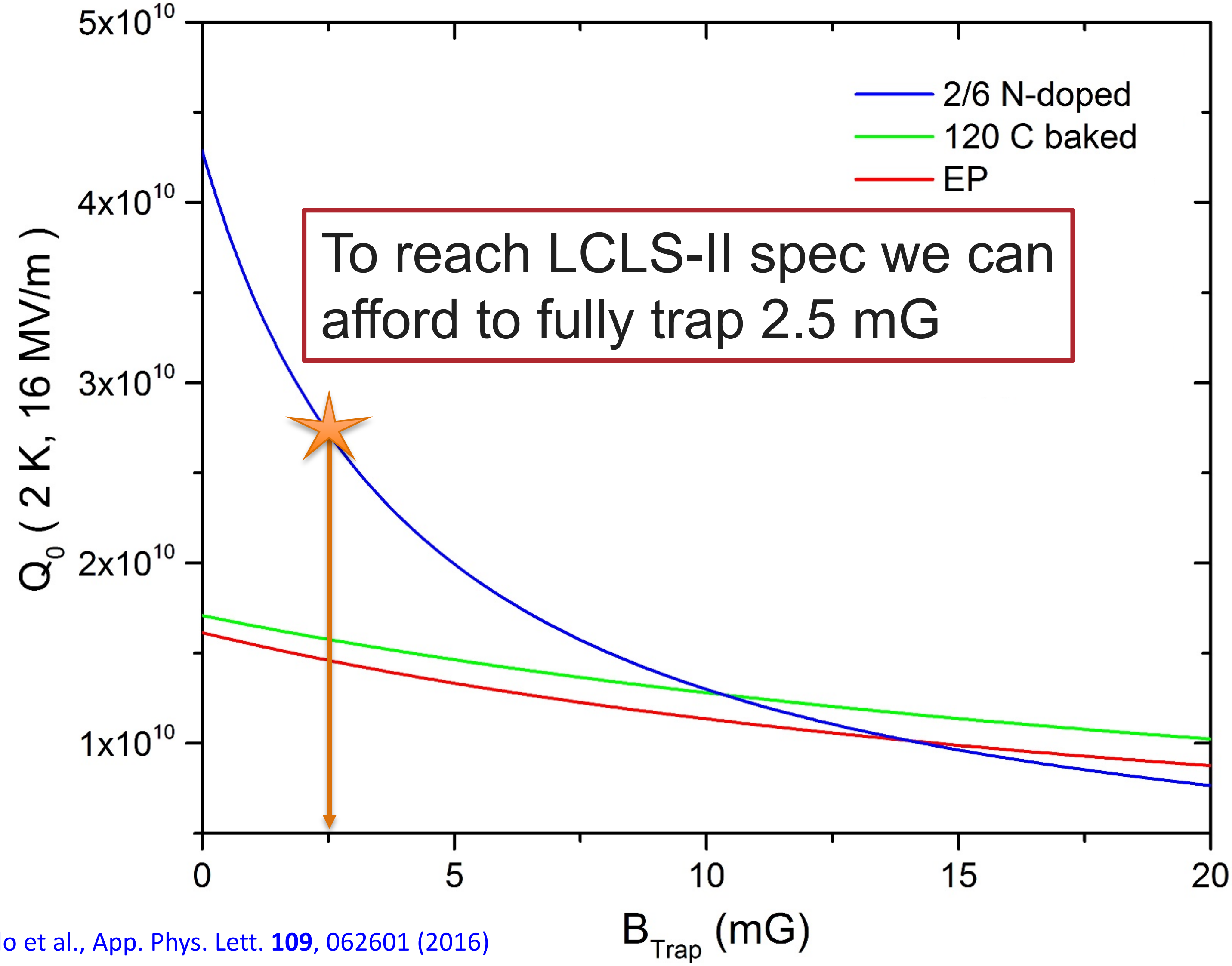
Q-factor Degradation Due to Trapped Flux



N-doping gives the highest Q as long as the field trapped is <10 mG

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

Q-factor Degradation Due to Trapped Flux



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

Trapped Flux Surface Resistance

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

S
- Trapped flux sensitivity

η
- Flux trapping efficiency

B_{ext}
- External magnetic field

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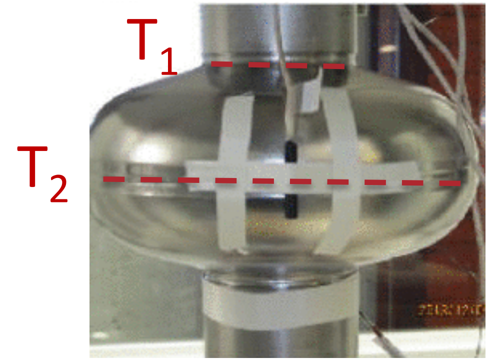
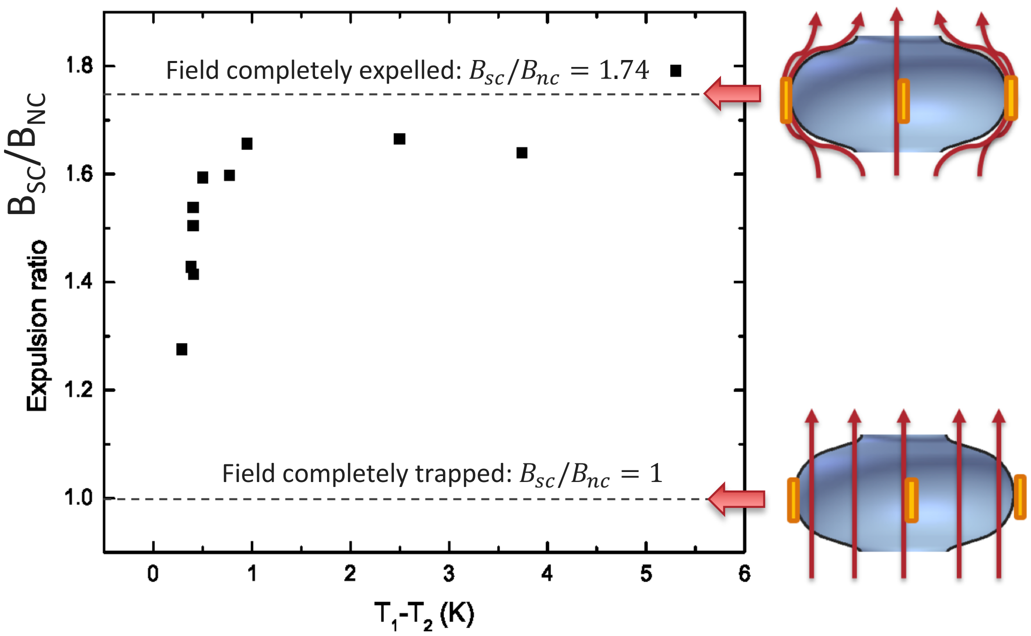
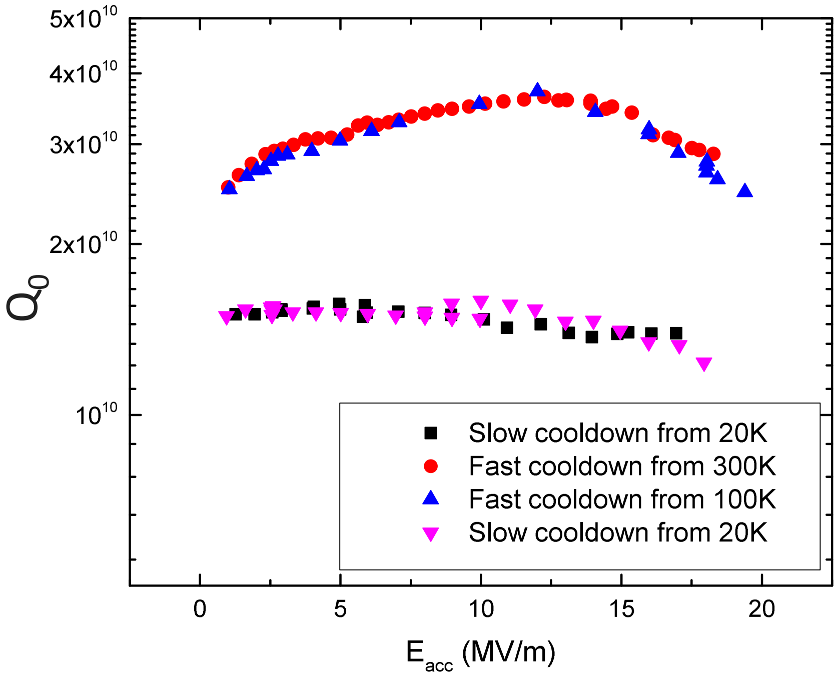
Fast Cooldown Promotes Flux Expulsion

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



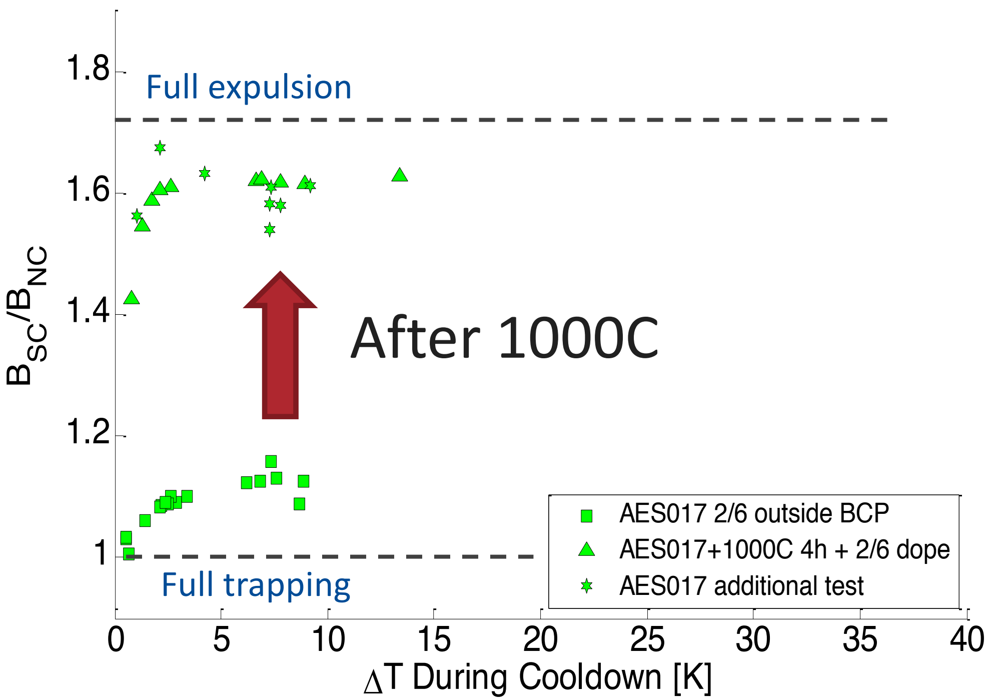


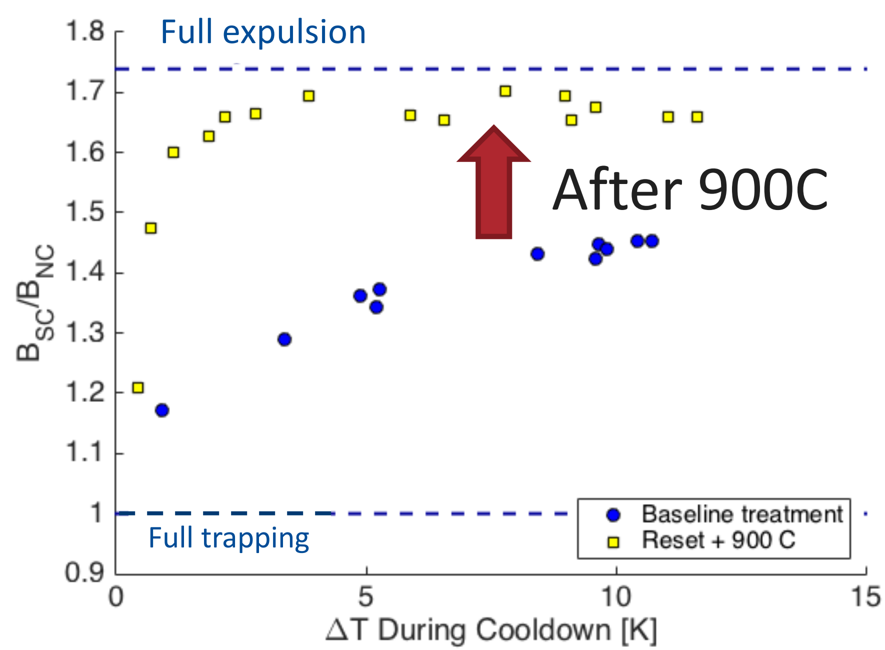


A. Romanenko et al., Appl. Phys. Lett. **105**, 234103 (2014)
A. Romanenko et al., J. Appl. Phys. **115**, 184903 (2014)
M. Martinello et al., J. Appl. Phys. **118**, 044505 (2015)
S. Posen et al., J. Appl. Phys. **119**, 213903 (2016)

High-T Baking for Flux Expulsion Improvement

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





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

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**	

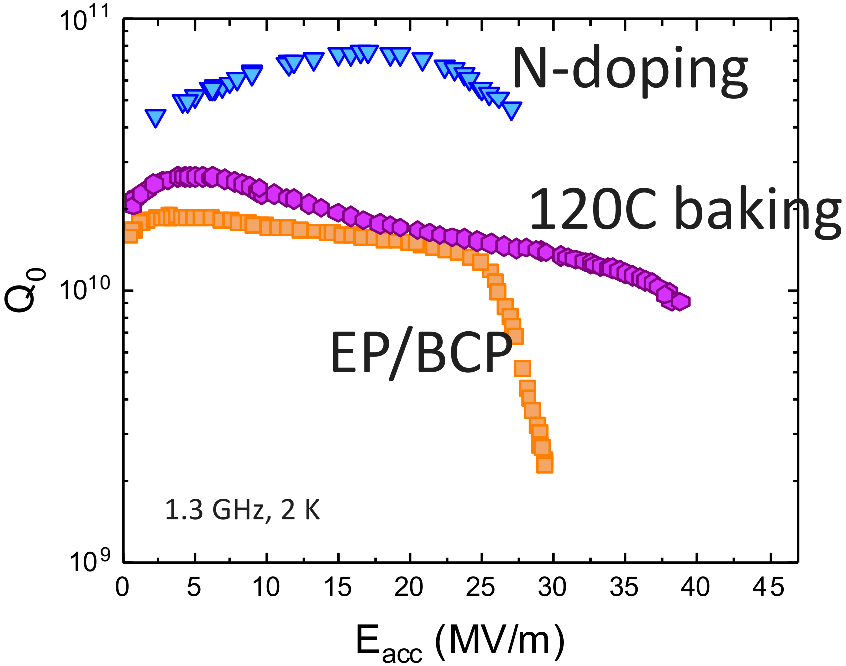
Spec: 133 MV

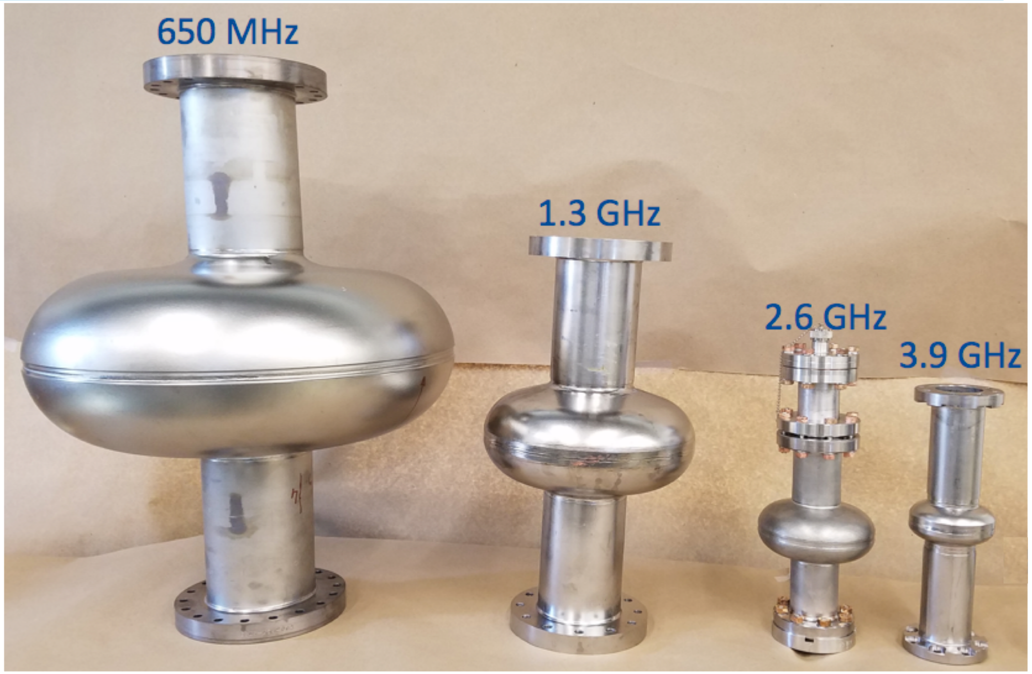
Spec: 2.7×10^{10}

World record cryomodule with twice efficiency

FIELD AND FREQUENCY DEPENDENCE OF THE SURFACE RESISTANCE

Study of Cavities at Different Fequency

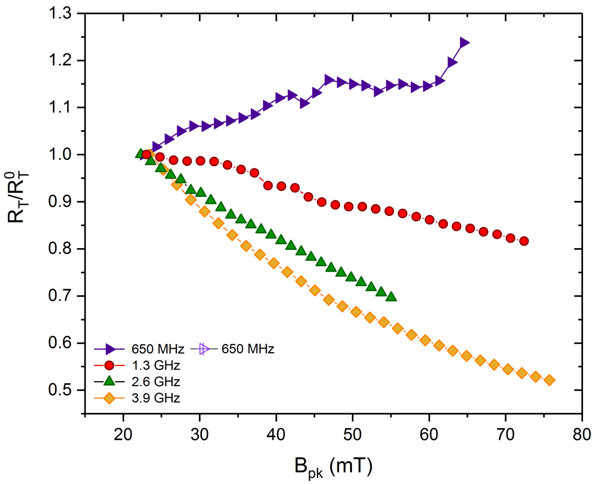




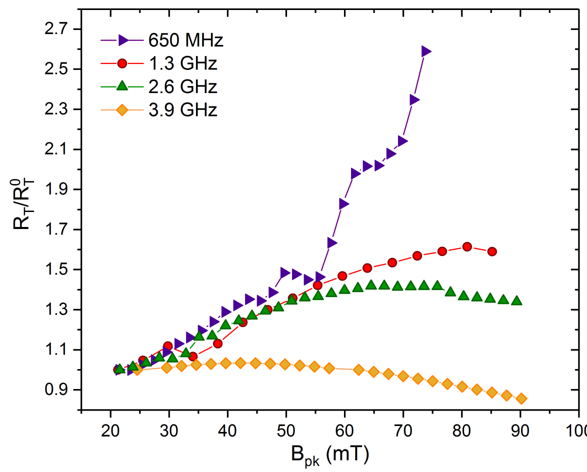
	650 MHz	1.3 GHz	2.6 GHz	3.9 GHz
EP		✓	✓	
BCP		✓		✓
120 C baking	✓	✓	✓	✓
2/6 N-doping	✓	✓	✓	✓

Summary of the Frequency Dependence of R_{BCS}(Eacc)

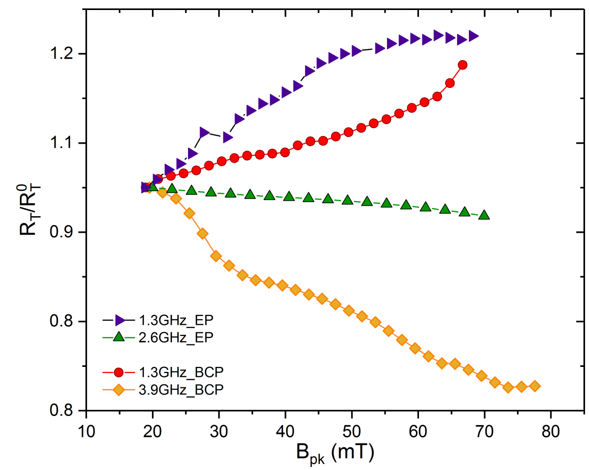
N-doping



120C baking



EP/BCP



R_T or R_{BCS}: temperature-dependent component of the surface resistance, also called BCS surface resistance

- The physical mechanism underneath the R_T reversal has a stronger effect at high frequencies
- On the other hand, N-doped cavities at low frequencies do not show the R_{BCS} reversal observed at 1.3 GHz
- The R_{BCS} reversal, that has been considered the signature of the N-doped treatment, is actually visible also in clean Nb (EP BCP) but at high frequency

M. Martinello et al. SRF 2017 (**TUYAA02**), TTC Meeting FNAL 2017, TTC Meeting Milan 2018, IPAC 2018 (**WEPML013**)

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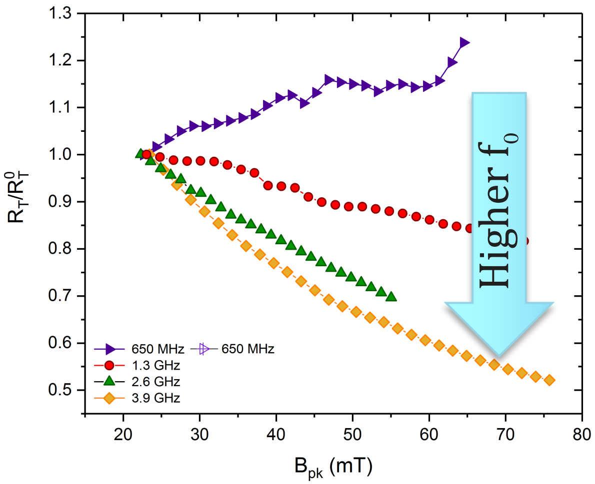
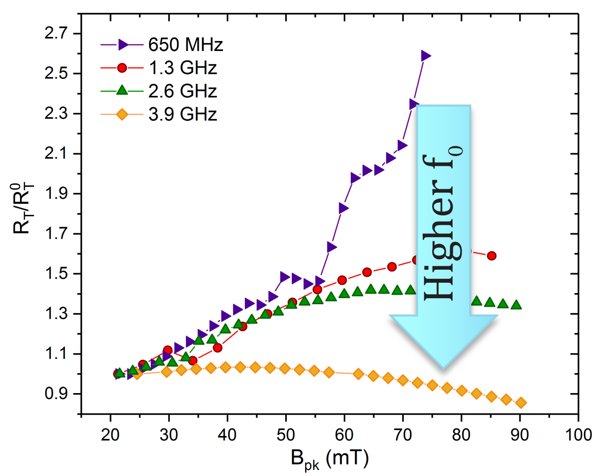
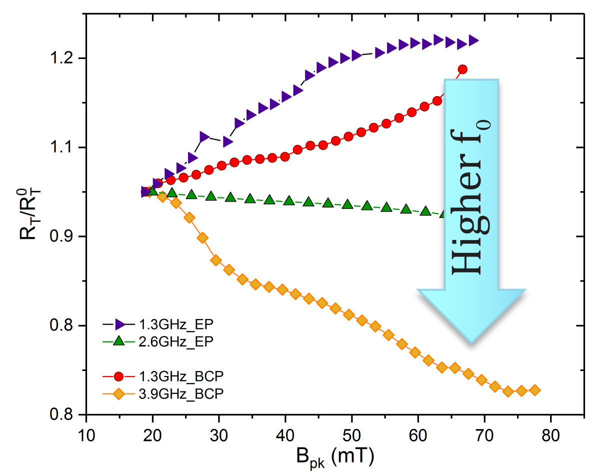


120C baking



EP/BCP



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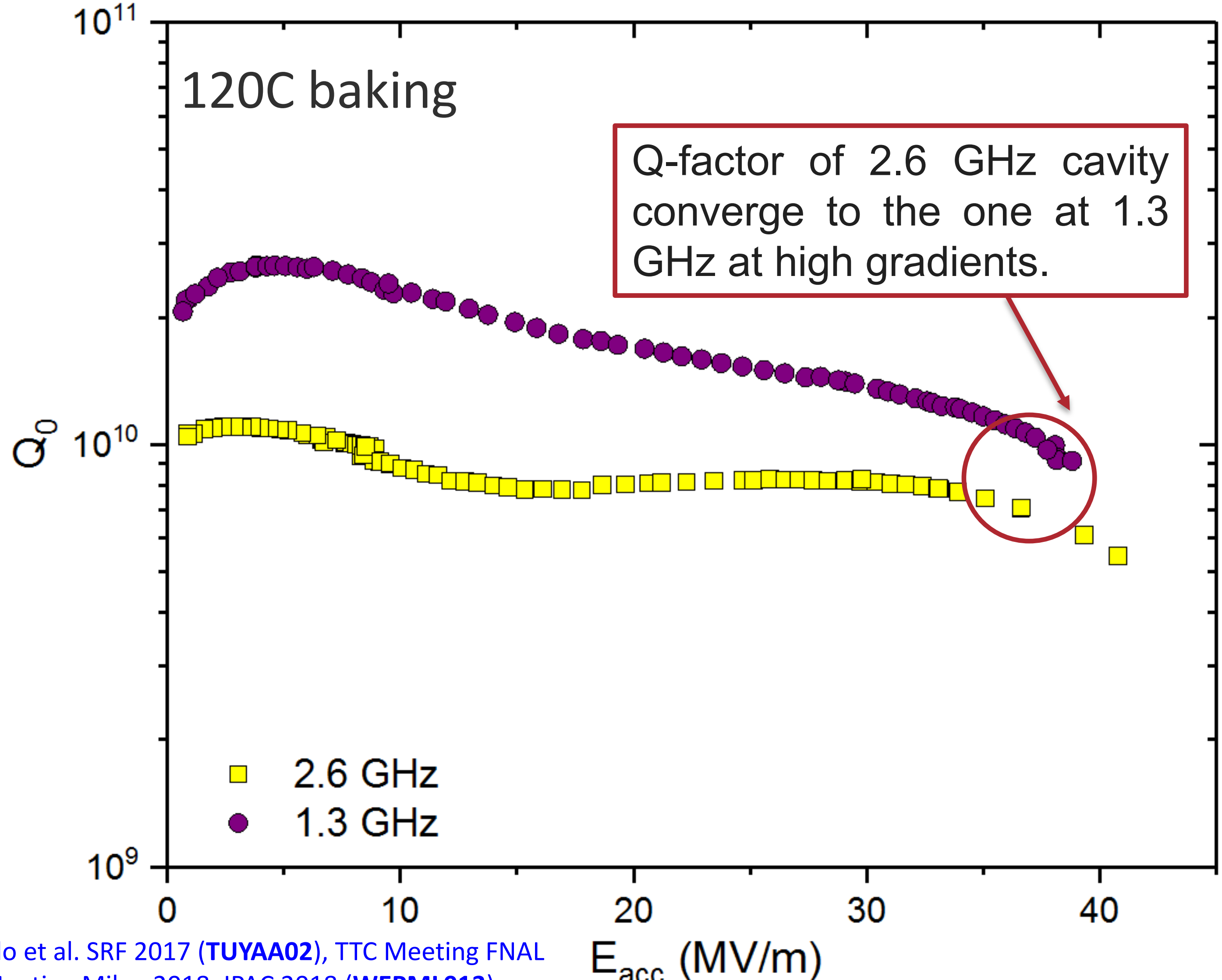
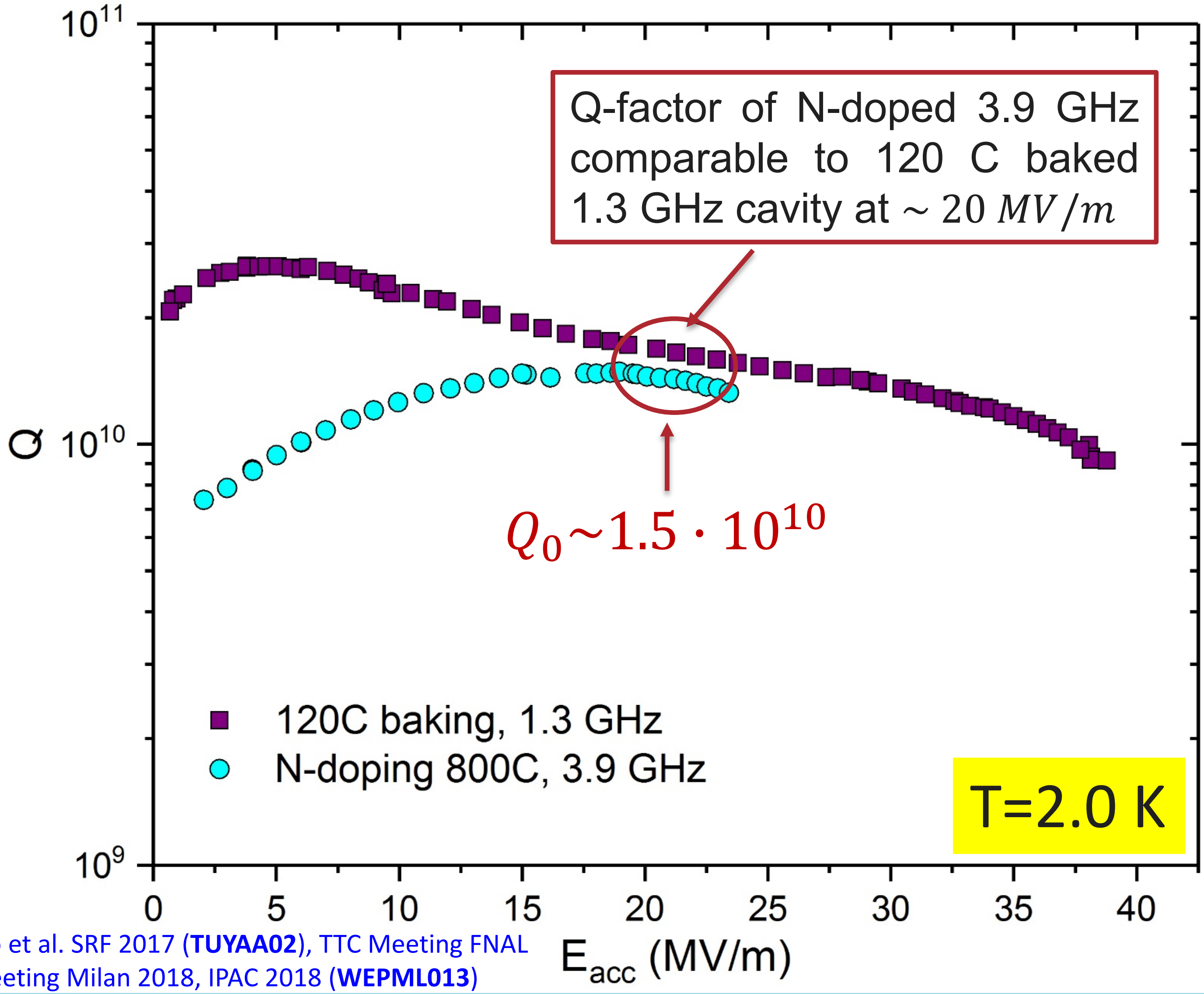
High Frequency Cavities Favorable at High Field



M. Martinello et al. SRF 2017 (**TUYAA02**), TTC Meeting FNAL 2017, TTC Meeting Milan 2018, IPAC 2018 (**WEPML013**)

Unprecedented Medium Field Q_0 at 3.9 GHz



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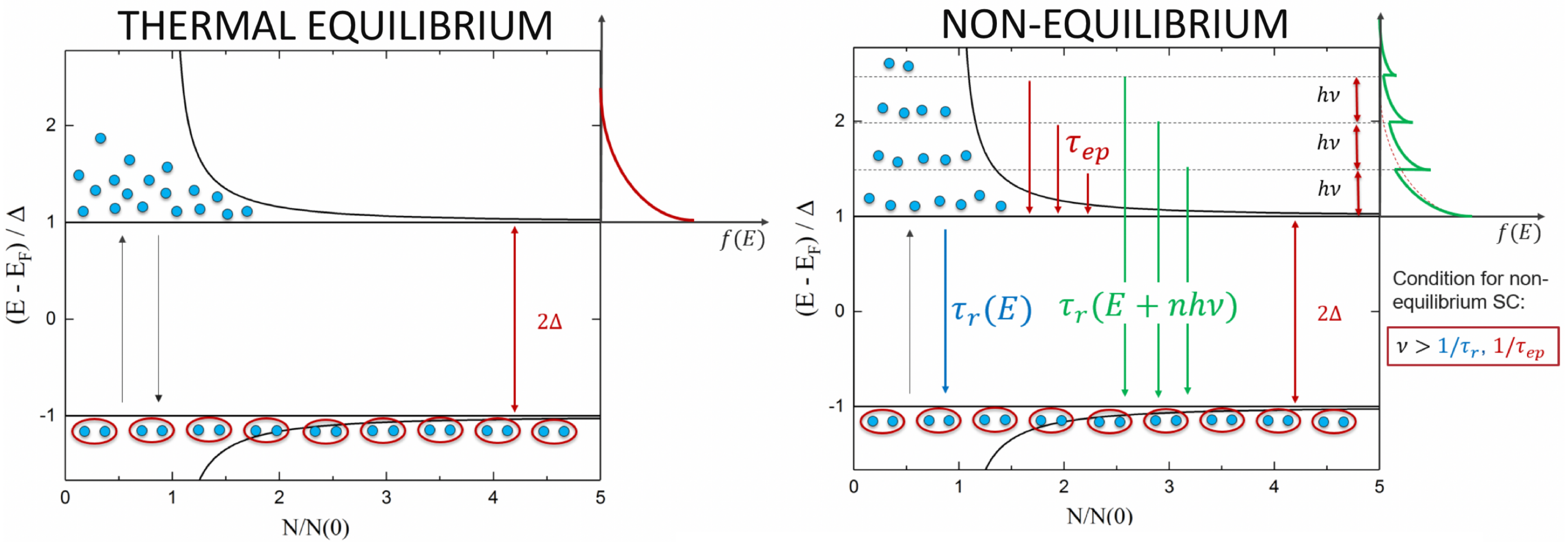
Doping and Frequency Effect on the QPs Distribution

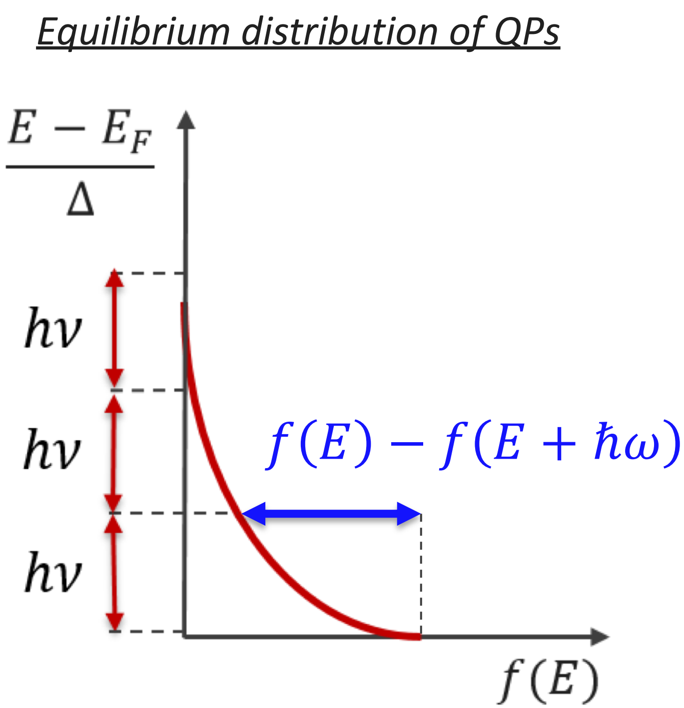


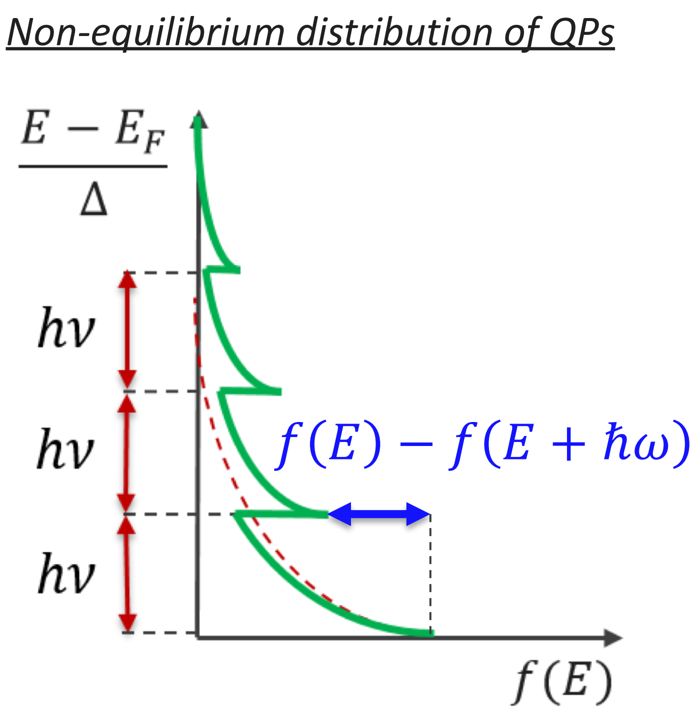
- Higher the frequency, higher the probability to match the condition for non-equilibrium
- N-doping (surface treatments in general) may modifies τ_{ep} and τ_r enhancing non-equilibrium effects

A. Romanenko, LINAC 2014

Non-equilibrium Lowers Surface Resistance

When the SC is out-of-equilibrium the surface resistance is minimized





$$\frac{\sigma_1}{\sigma_N} = \frac{2}{\hbar\omega}\int_{\Delta}^{\infty} [f(E)-f(E+\hbar\omega)]g_1(E)dE$$

Smaller with **non-equilibrium** QPs distribution

Conclusions

- N-doping promote very high Q-factors at medium field, but larger sensitivity to trapped flux so important minimize trapped field
- Trapped flux minimization can be achieved by maximizing flux expulsion via fast cooling
- BCS surface resistance field dependence more favorable at high frequencies. High-Q at medium and high field achievable with high frequency cavities
- Understanding of the surface resistance critical to improve further performance of SRF cavities and enable realization of future machines

Thank you for your attention!