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U.S. DEPARTMENT OF ENERGY | Office of Science

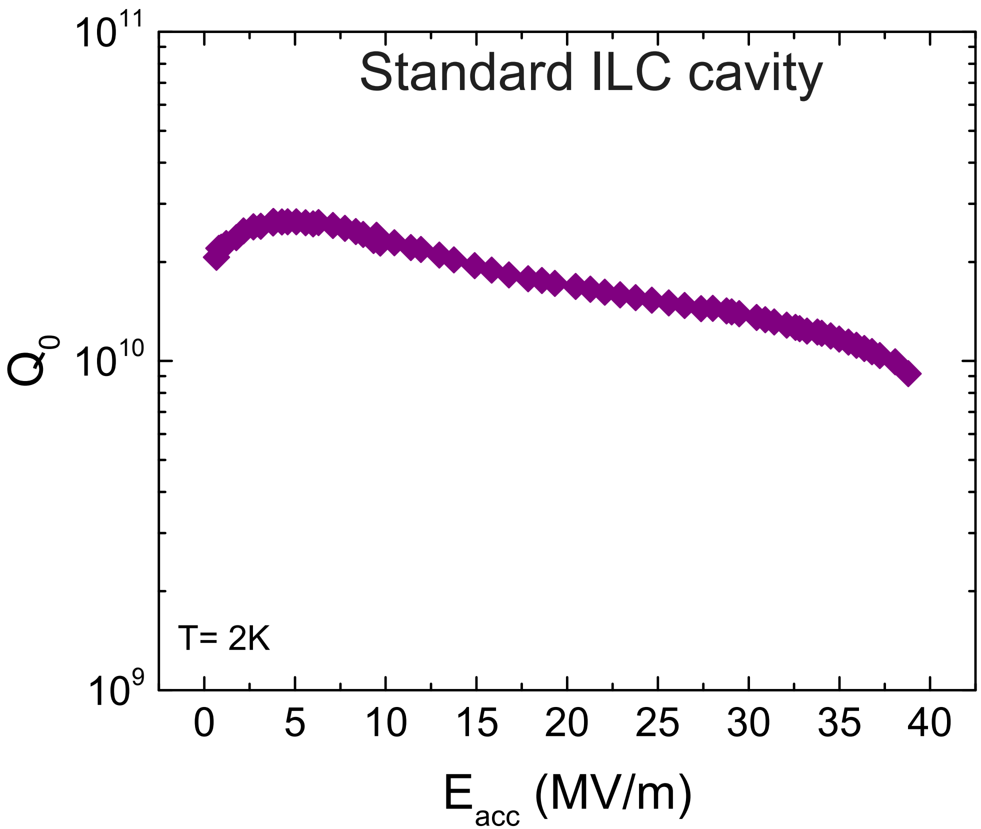
Surface Impurity Content Optimization to Maximize Q-factors of Superconducting Resonators

Martina Martinello

NAPAC 2016, Chicago IL

12th October 2016

SRF Cavities Figure of Merits



Q-factor (Q_0):

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

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

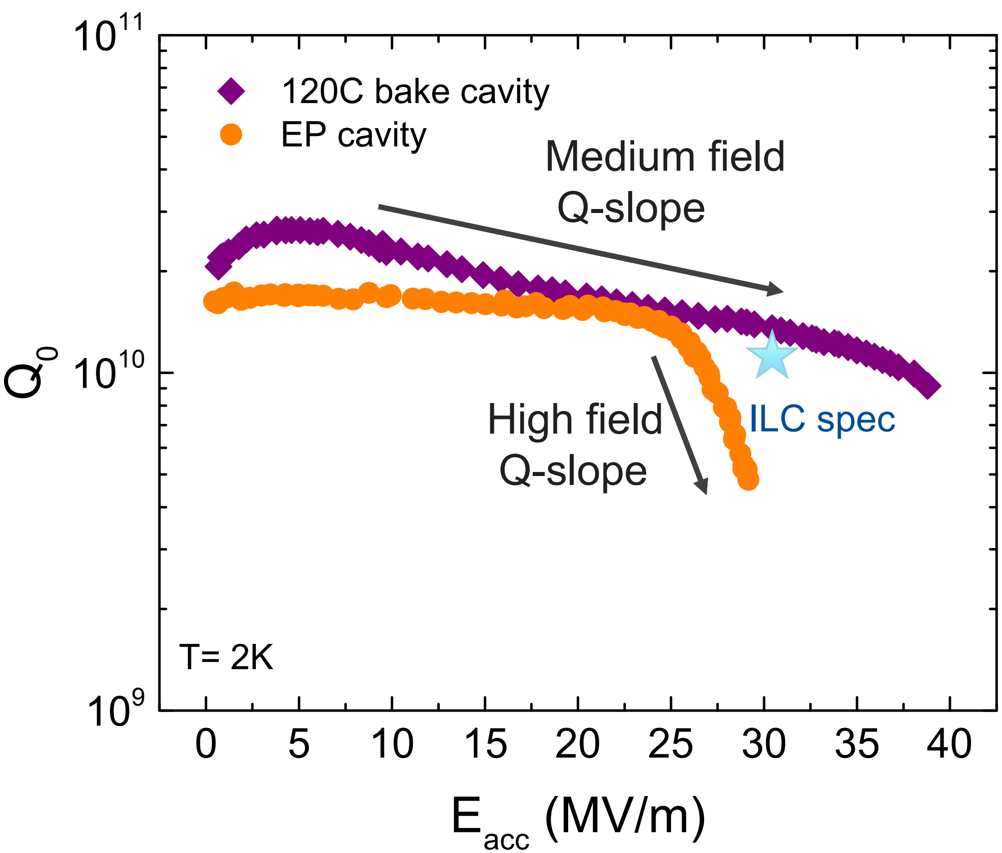
Standard Nb Surface Treatment

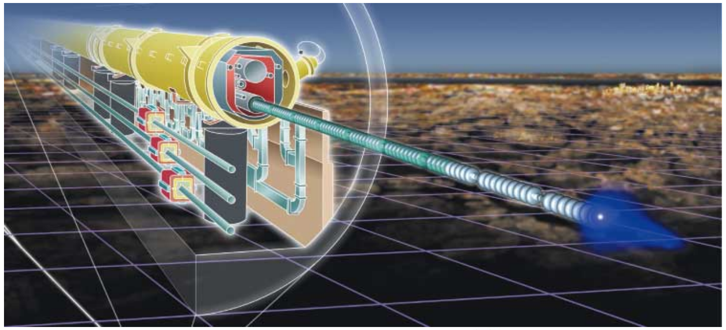
Conventional Nb Cavities Surface Treatment (main steps):

Cavity after Equator Welding → EP 140 um → 800C UHV Bake → 120C bake

800C UHV Bake ↓ EP cavities

120C bake ↓ 120C bake cavities ↓ Standard treatment for the International Linear Collider (ILC)





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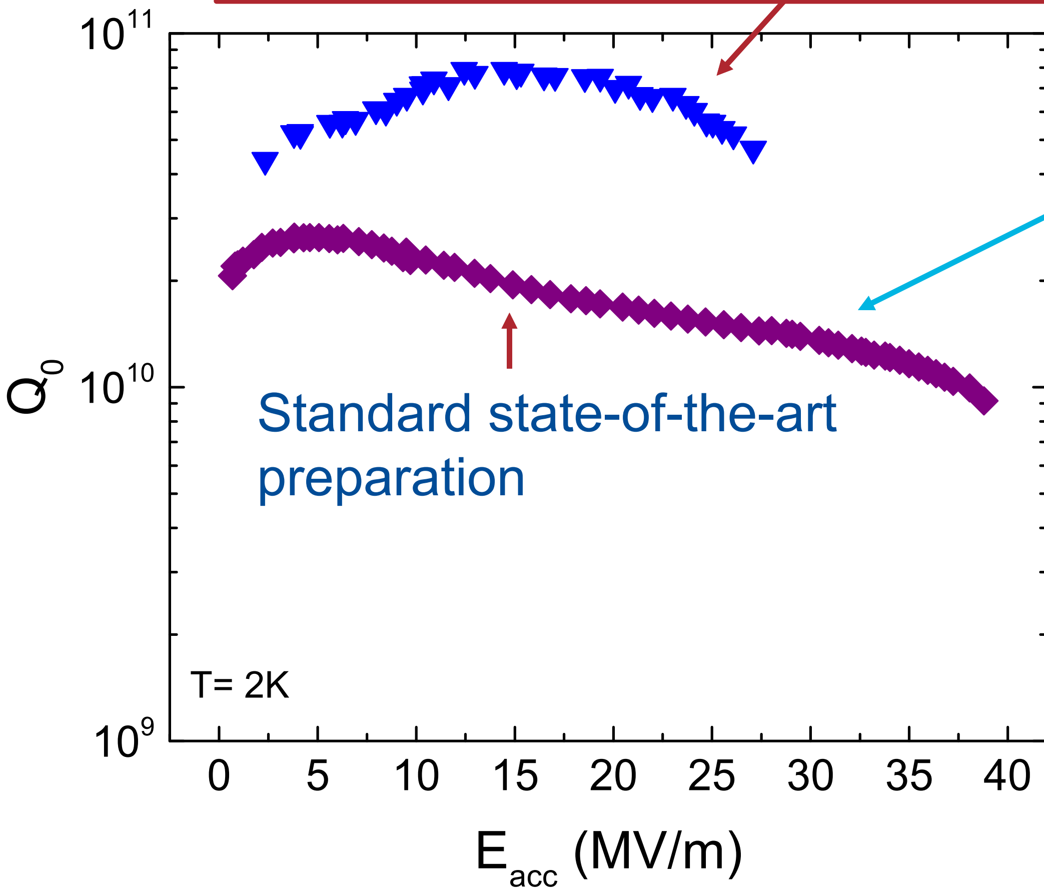
The N-doping treatment

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:

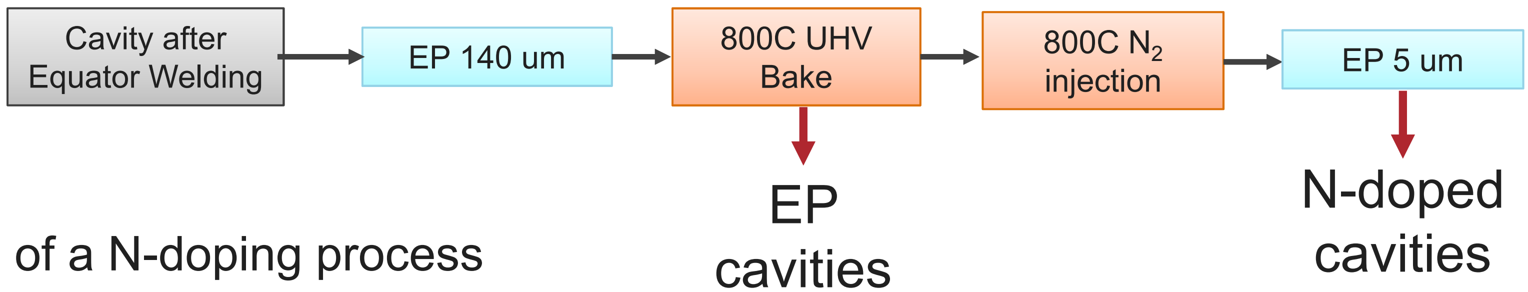
$$\langle Q \rangle \sim 1.7 \cdot 10^{10}$$

- N-doping:

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

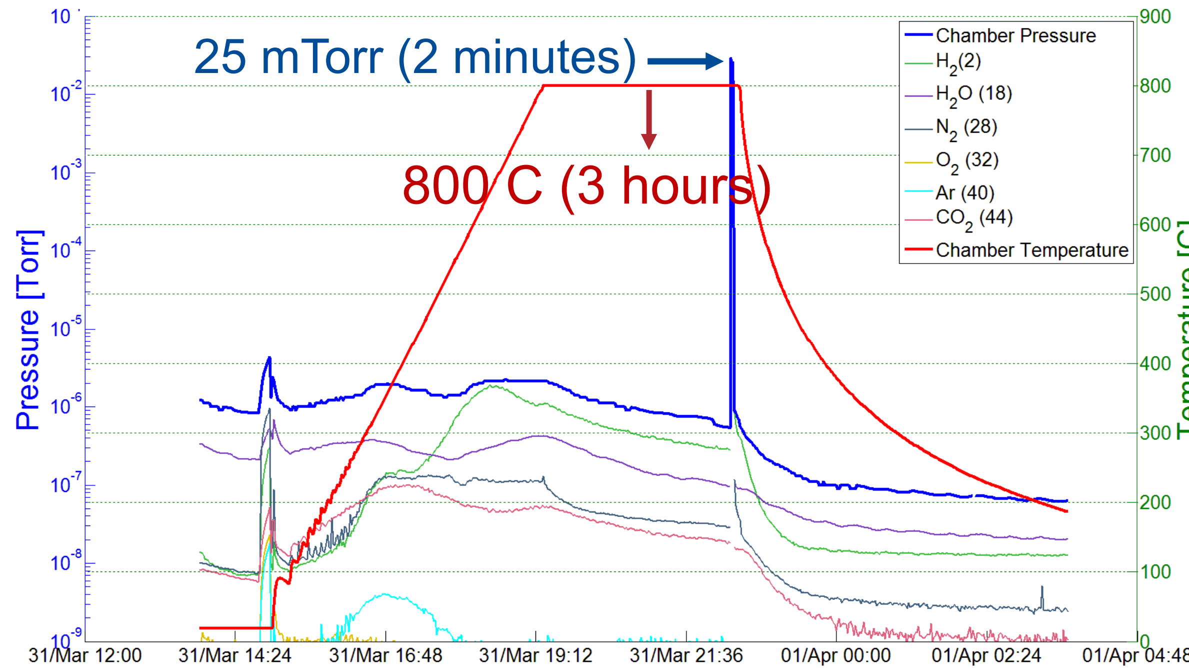
A. Grassellino et al, 2013 Supercond. Sci. Technol. **26** 102001 (Rapid Communication)

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 microns electro-polishing (EP)



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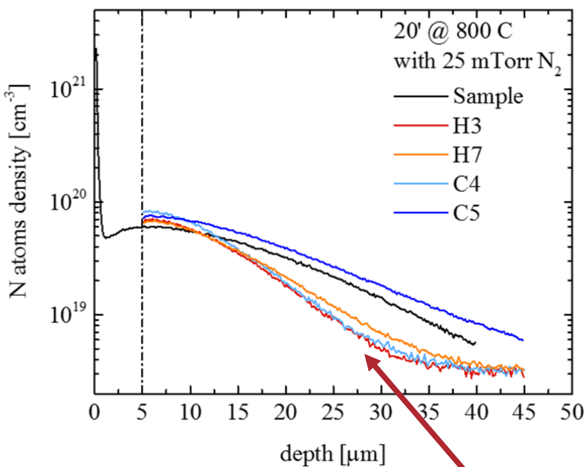
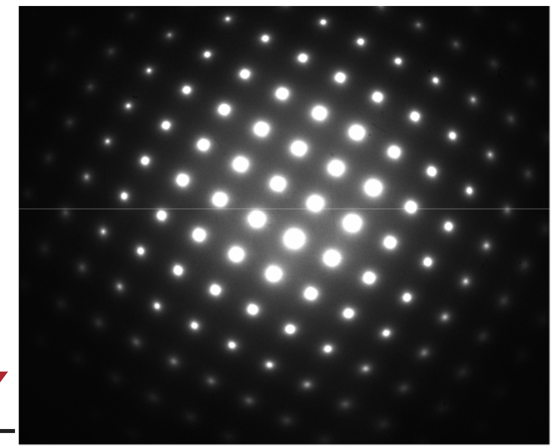
N-doping treatment

Cavity after Equator Welding → EP 140 um → 800C UHV Bake → 800C N_2 injection → EP 5 um

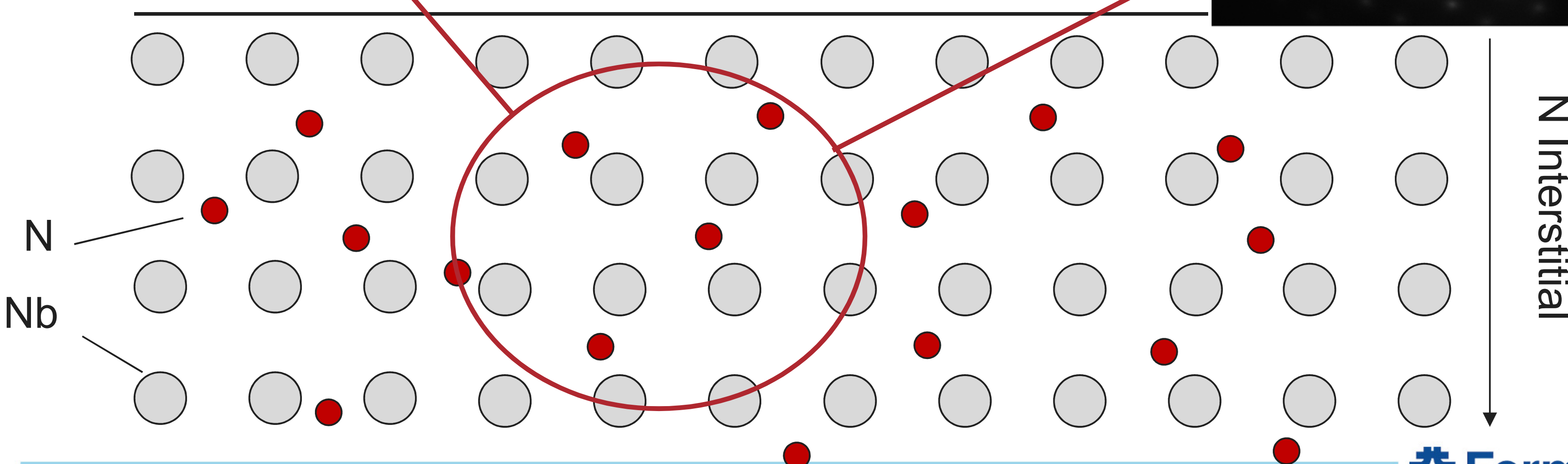


Only Nb from TEM/NED spectra:
N must be interstitial

Y. Trenikhina et Al, Proc. of SRF 20



Final RF Surface



Cavities Analysis

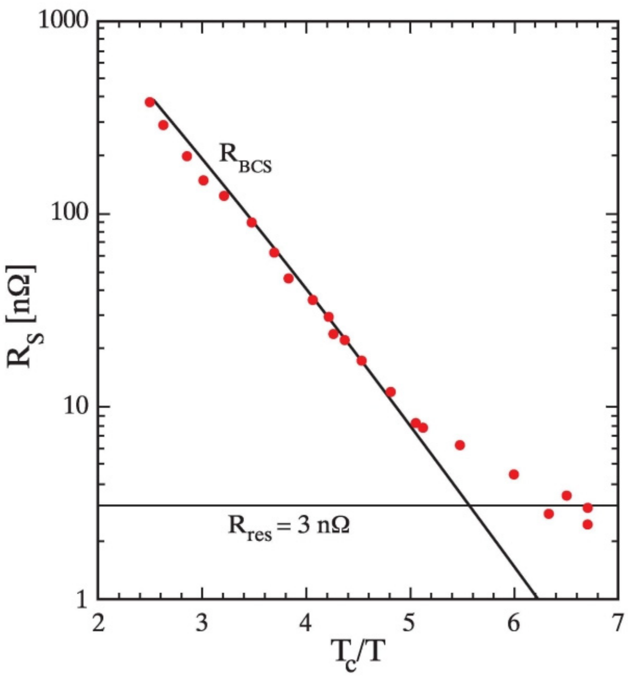
- Cavities made with different N-doping recipe (temperature, time, pressure) and standard Nb cavities
- For each cavity:
  - **Mean free path *l*** extrapolation: the mfp specifies the impurity content after each treatment
  - **Surface resistance analysis** needed to understand how maximize Q=G/Rs

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

BCS Surface Resistance

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

R_{BCS} defines by Mattis and Bardeen and based on the Bardeen-Cooper-Schrieffer theory of superconductivity:



$$R_{BCS} = A(\lambda_L, l, \Delta, \xi_0, f_0, T_c)e^{-\frac{\Delta}{k_B T}}$$

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

$$R_S\,(\,1.5\,K\,) \sim \cancel{R_{BCS}\,(\,1.5\,K\,)} + R_0 + R_{Fl}$$

$$\boxed{R_{BCS} = R_S(2\,K) - R_S(1.5\,K)}$$

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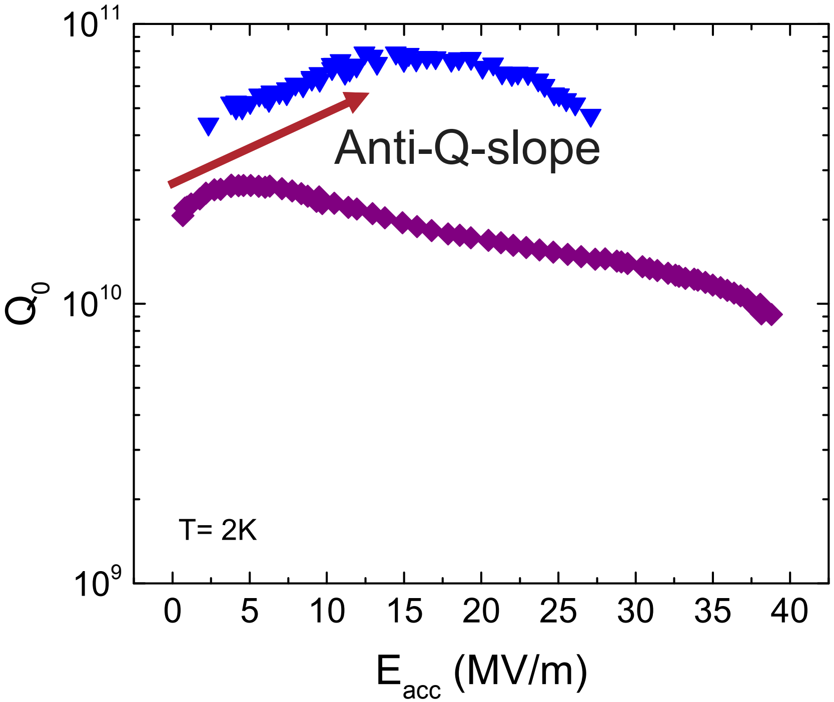
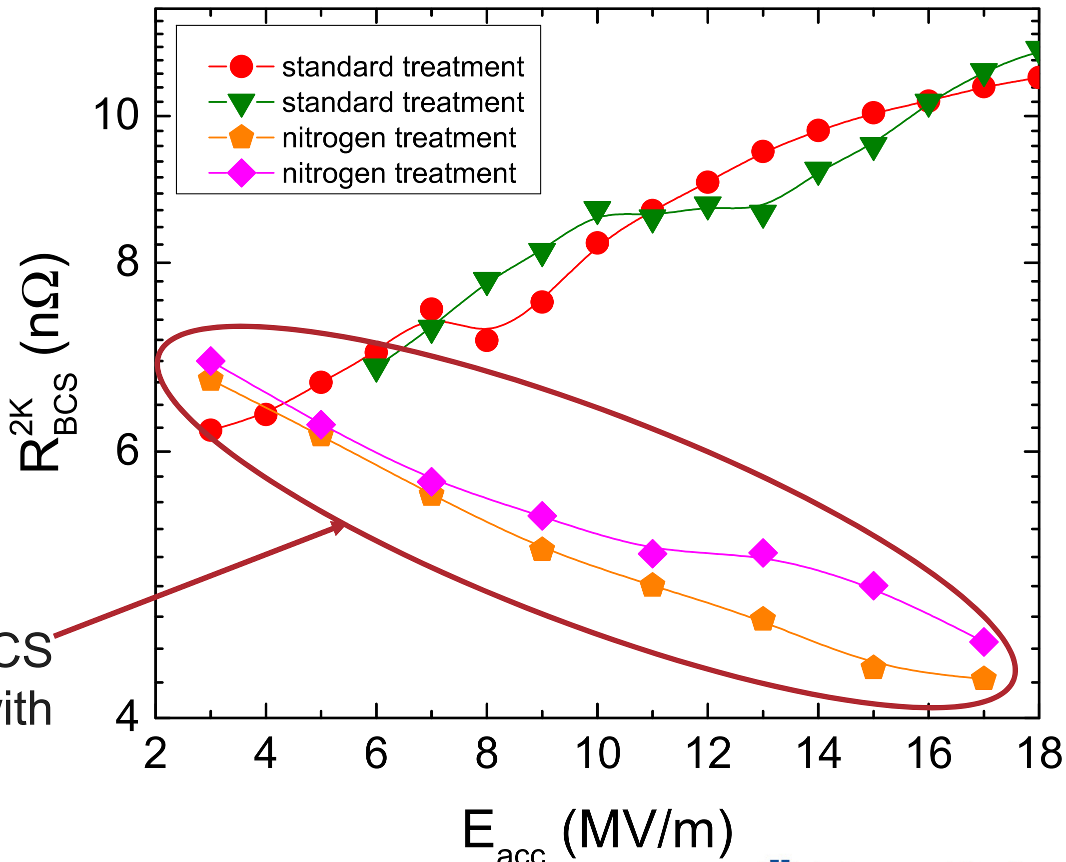
BCS Surface Resistance

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



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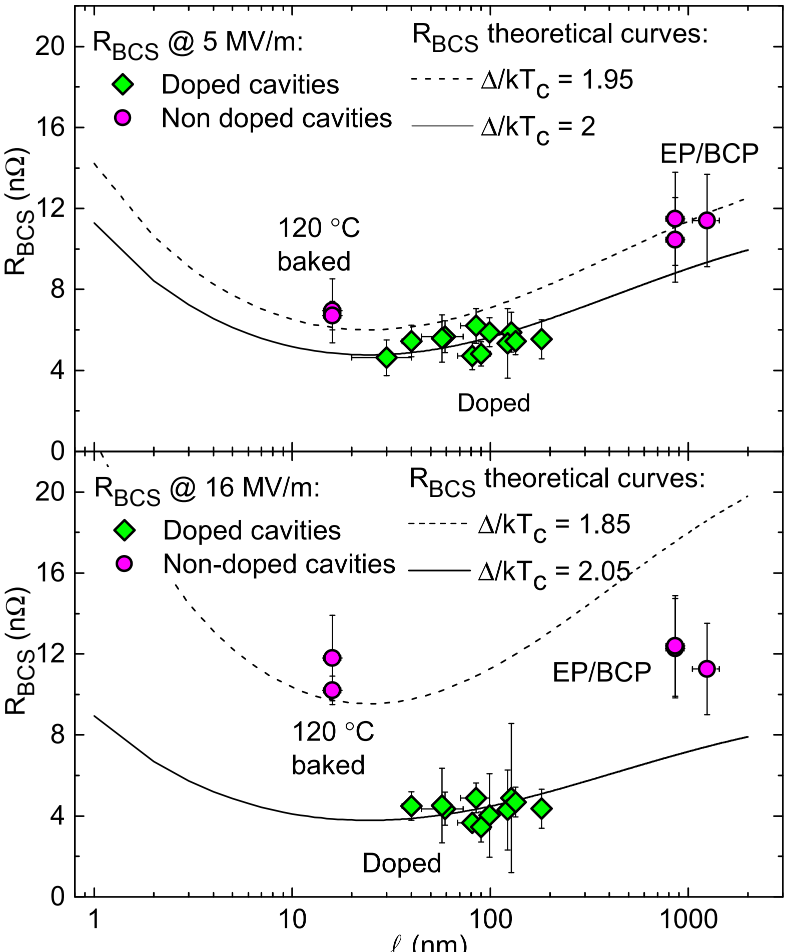
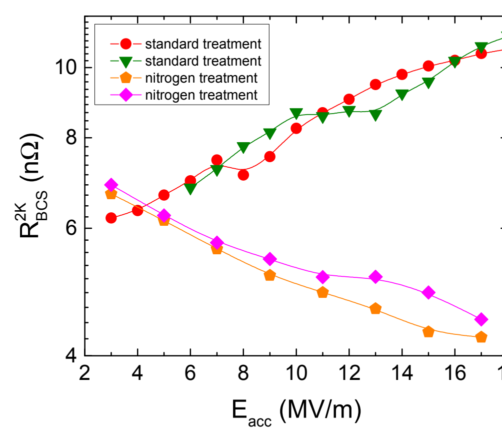


- ✓ Mean free path of N-doped cavities close to theoretical minimum of R_{BCS}
- ✓ The reduced energy gap Δ/kTc seems to increases with Eacc for N-doped cavities causing the decreasing of Rbcs



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

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Trapped Flux Surface Resistance

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

R_{Fl} defines the dissipation due to trapped flux during the SC transition:

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

External magnetic field — B_{ext}
- Magnetic shielding/hygiene improvement

Flux Trapping Efficiency — η
- Fast Cooling
- Material Optimization

Trapped Flux Sensitivity — S
- Optimizing mean free path

Trapped Flux Surface Resistance

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Trapped field

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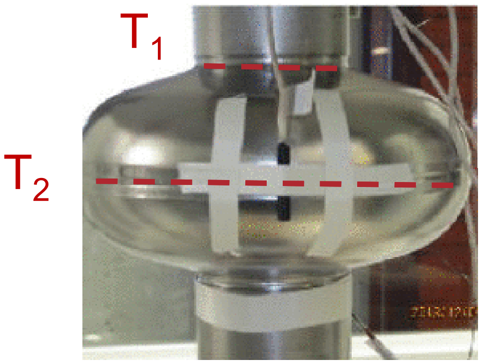
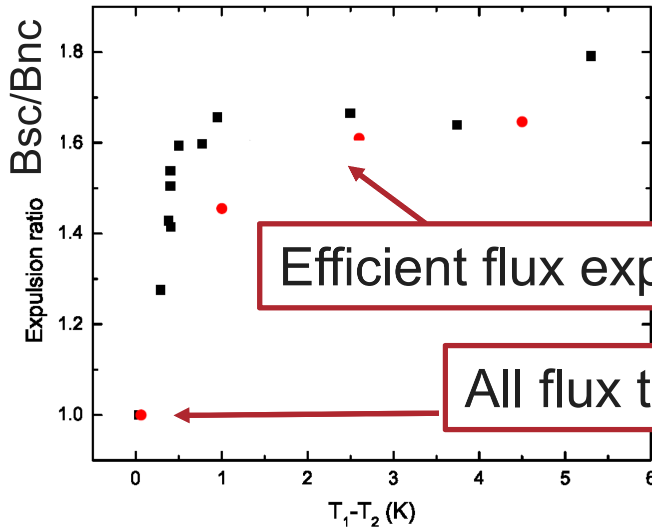
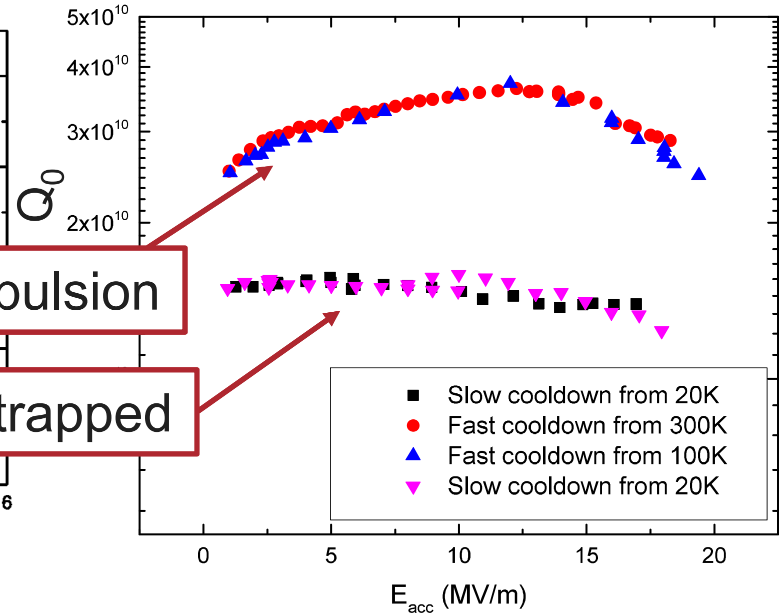
External magnetic field	B_{ext}	• Magnetic shielding/hygiene improvement
Flux Trapping Efficiency	η	• Fast Cooling • Material Optimization
Trapped Flux Sensitivity	S	• Optimizing mean free path

Fast cooldown helps flux expulsion

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

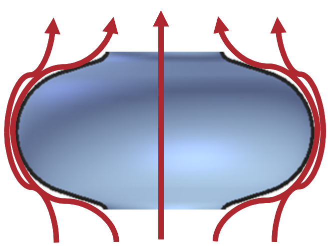




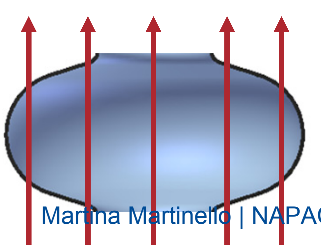


Efficient flux expulsion

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)

Trapped Flux Surface Resistance

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

R_{Fl} defines the dissipation due to trapped flux during the SC transition:

$$\boldsymbol{R_{Fl} = B_{trap} \cdot S}$$

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Trapped Flux Surface Resistance

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R_{Fl} defines the dissipation due to trapped flux during the SC transition:

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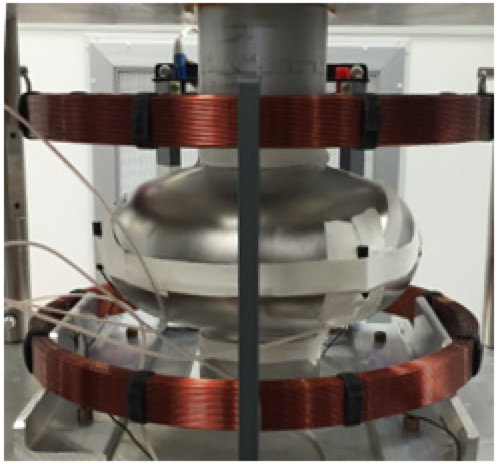
$$R_S\left(1.5\,K, B_{Trap}\right) \sim R_0 + R_{Fl}\,(B_{Trap}, l)$$



$$\boxed{R_{Fl} = R_S\left(1.5\,K, B_{Trap}\right) - R_0}$$

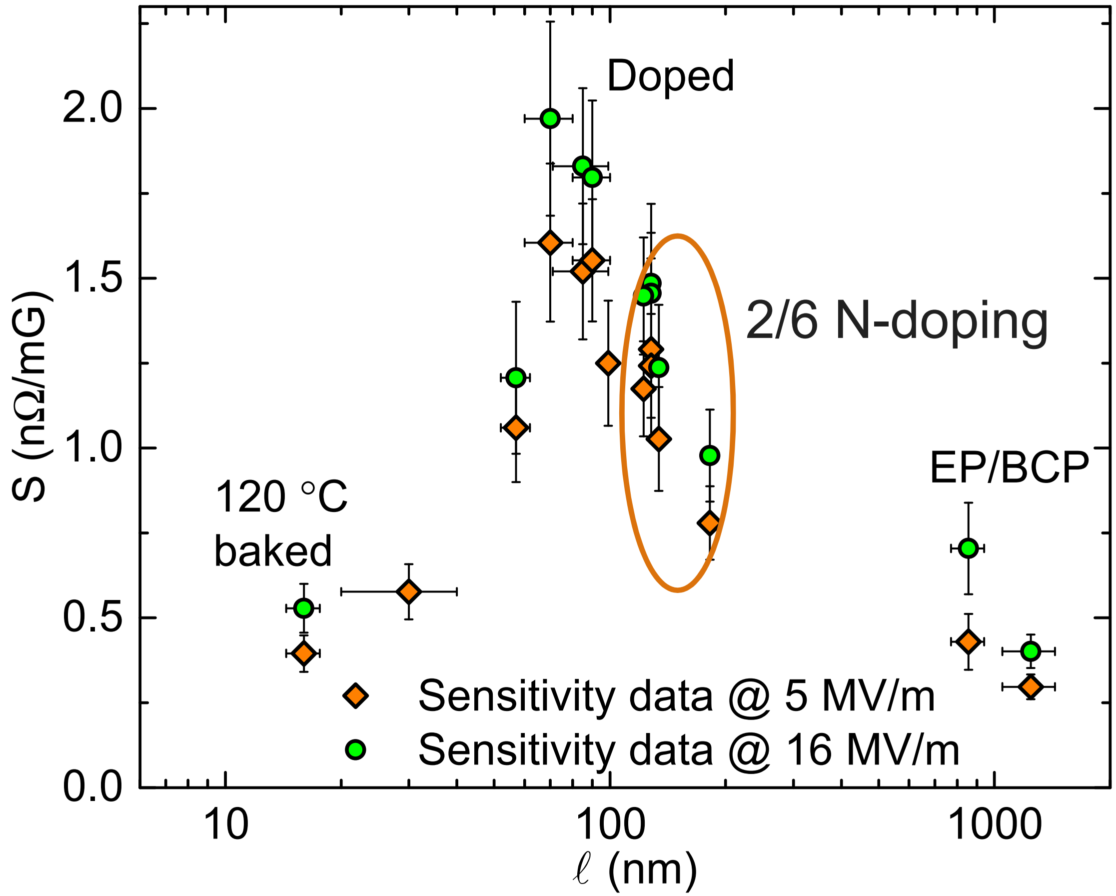
- $R_S(1.5\,K, B_{Trap})$ measured after **slow cooldown** in a known amount of external magnetic field: $B_{ext} = B_{Trap}$
- R_0 measured after **fast cooldown in compensated magnetic field**: $B_{ext} = 0,\ R_{fl} = 0$

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)

Understanding the Sensitivity vs Mean-free-path

- Dissipation due to vortex oscillation under the RF field

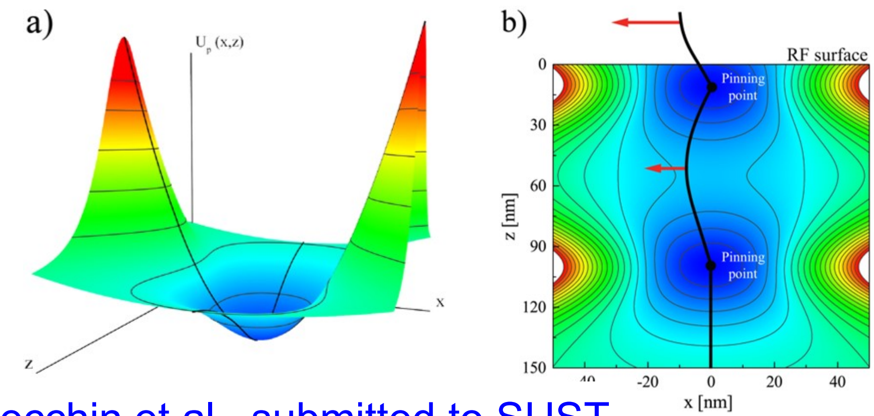
We can define two regimes:

1. Large l (p → 0) – flux flow regime:

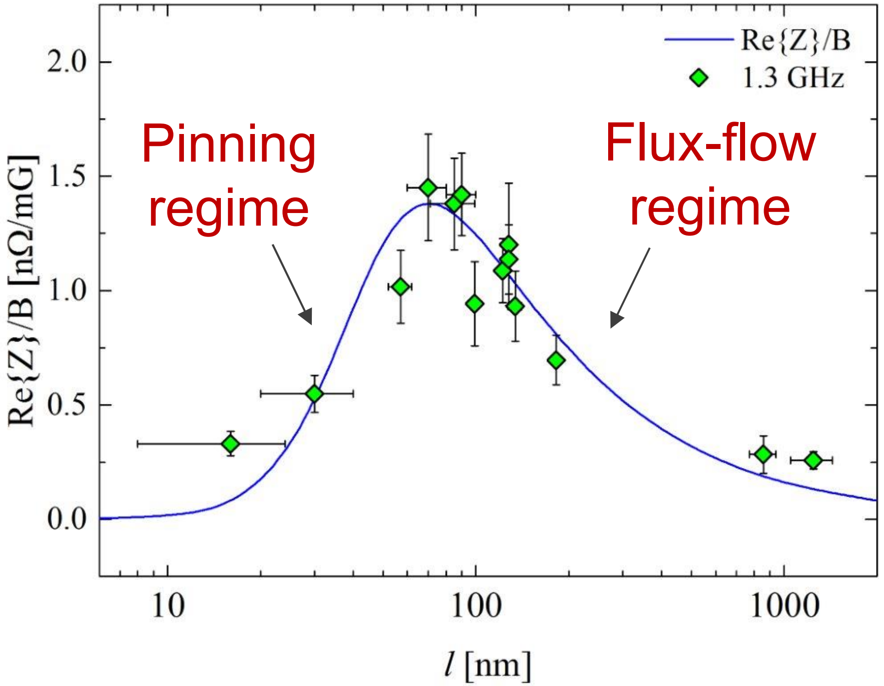
   ⇒ $\rho_1(l) \sim \frac{1}{\eta\omega}$, decreases with l

2. Small l (η → 0) – pinning regime:

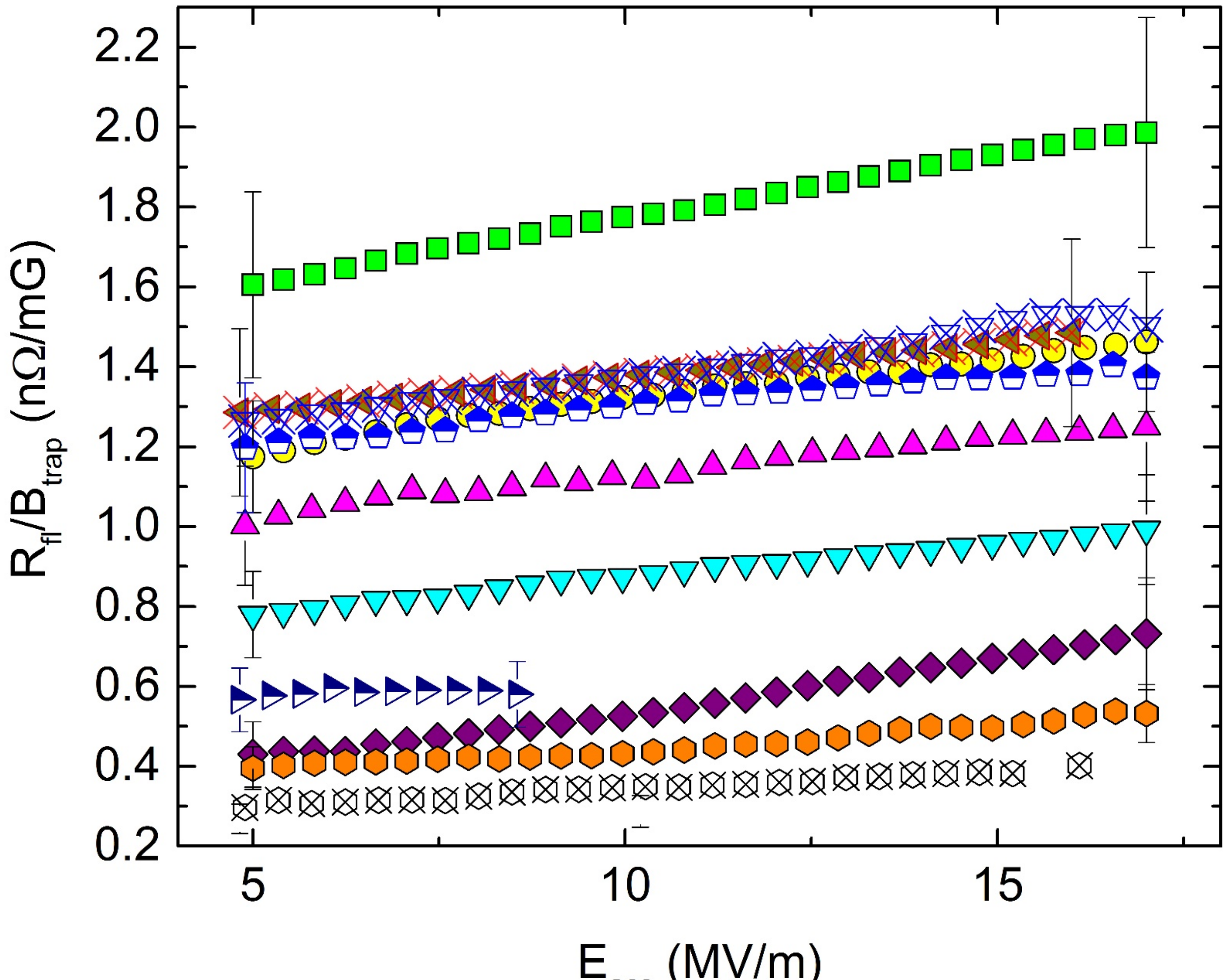
   ⇒ $\rho_1(l) \sim \frac{\eta\omega}{p^2}$, increases with l



M. Checchin et al., submitted to SUST



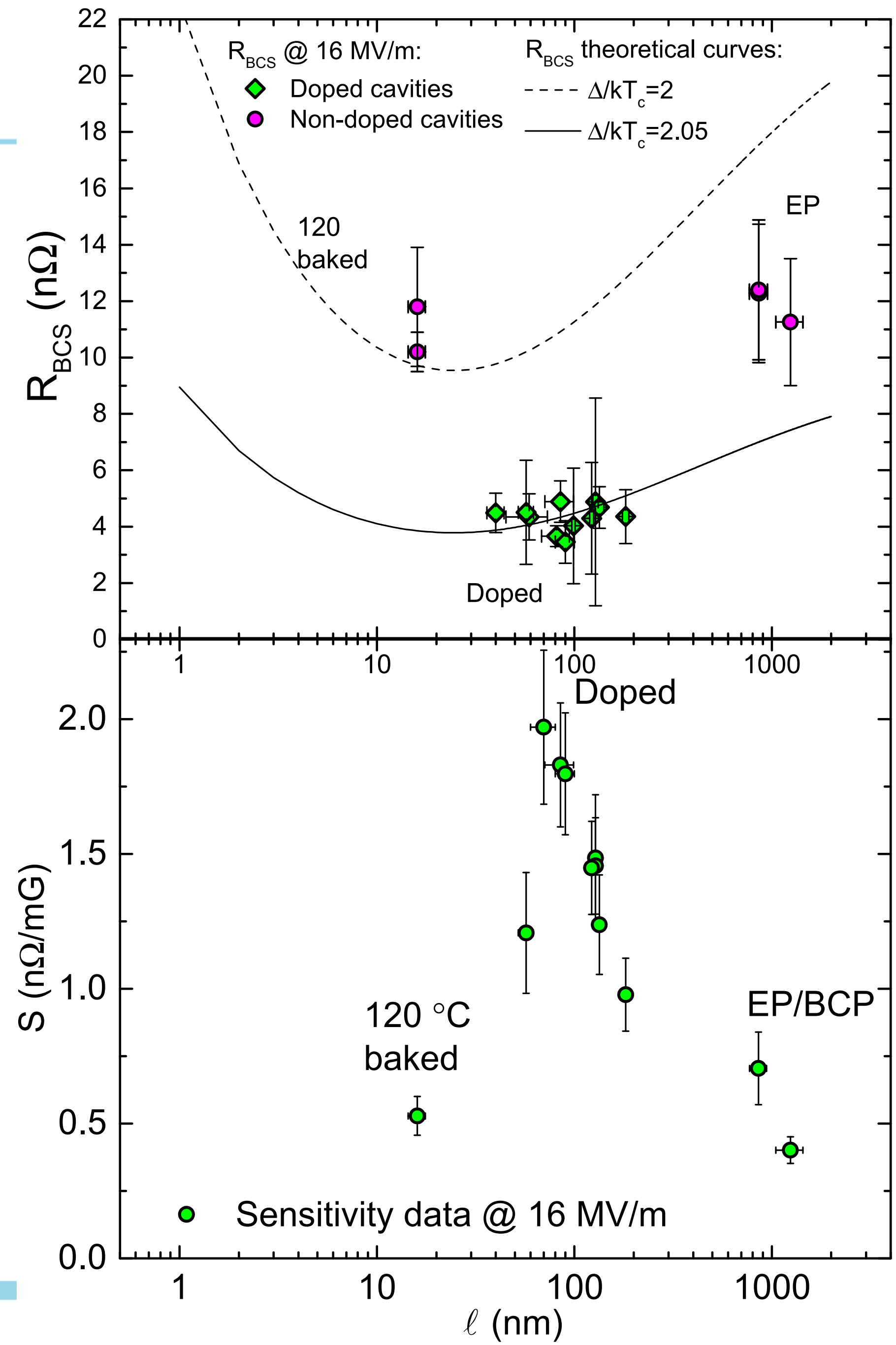
Trapped Flux Sensitivity Field Dependence



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

Minimizing Rs

The best surface treatment has to **minimize** both the **BCS surface resistance** and the **trapped flux sensitivity**



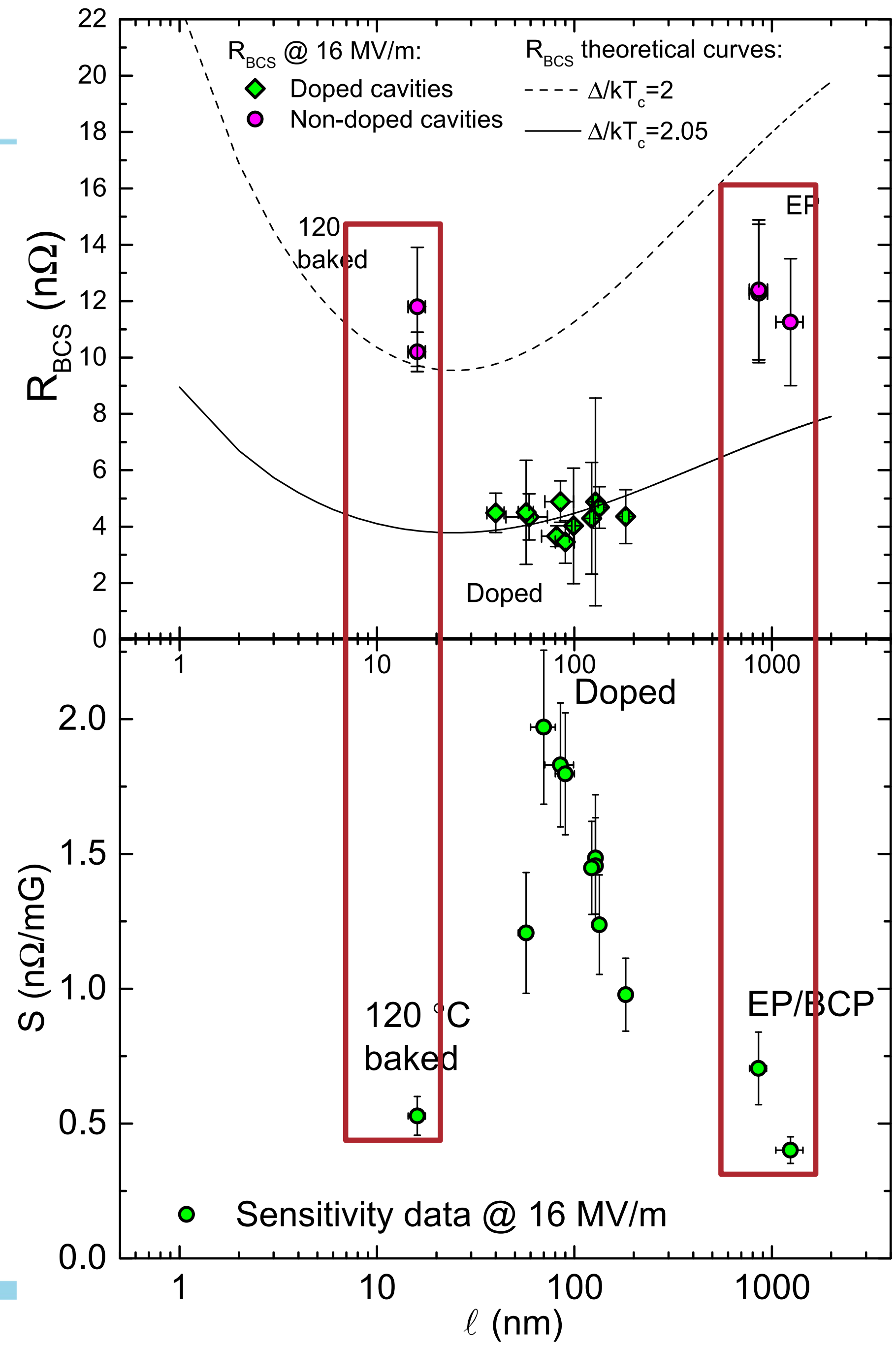
Minimizing Rs

The best surface treatment has to **minimize** both the **BCS surface resistance** and the **trapped flux sensitivity**

Standard Nb cavities:

Low values of sensitivity 🙂

Very high values of R_{BCS} 🙁



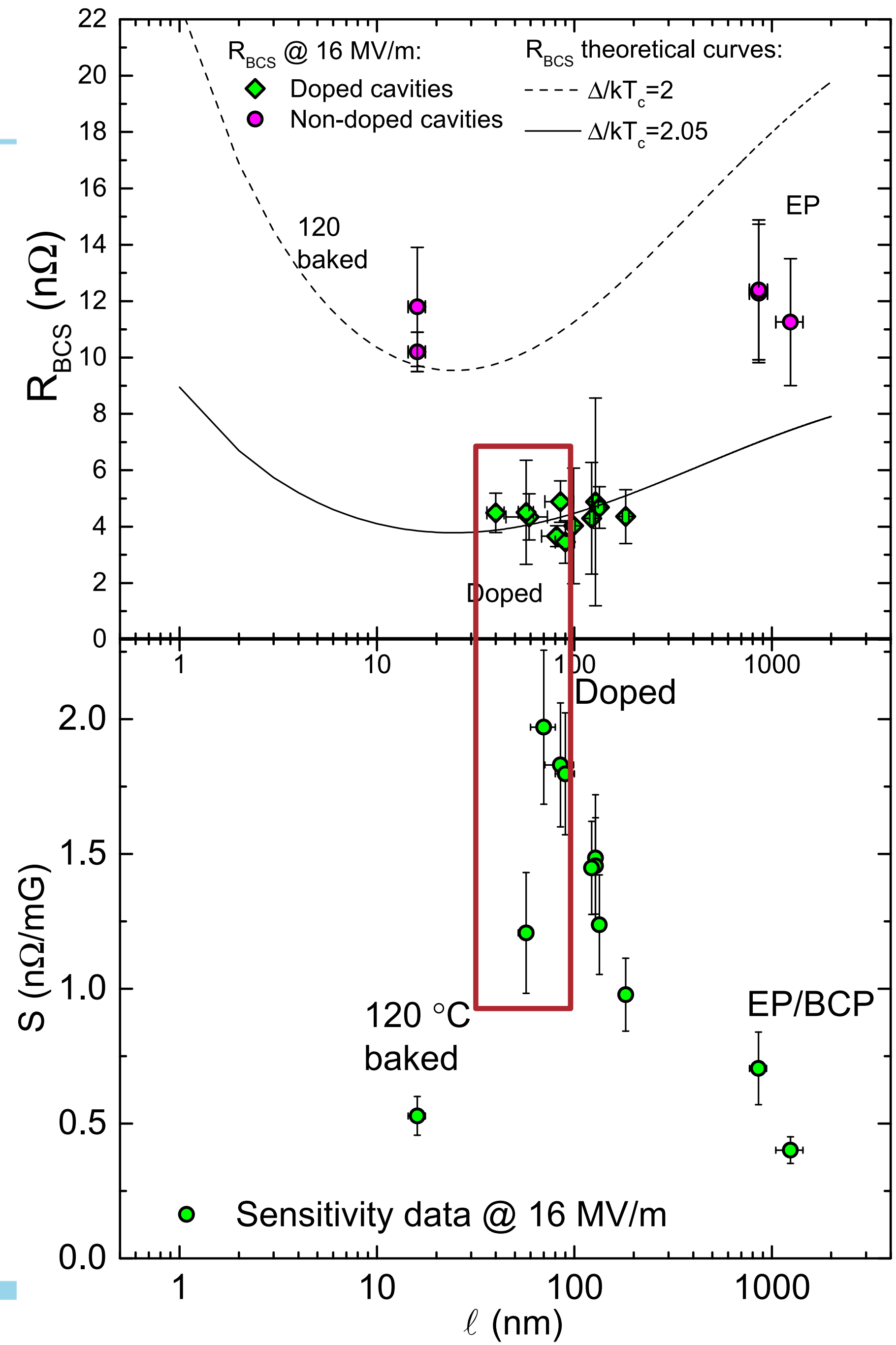
Minimizing Rs

The best surface treatment has to **minimize** both the **BCS surface resistance** and the **trapped flux sensitivity**

Heavily N-doped cavities:

Very low values of R_{BCS} 🙂

Very large sensitivity ☹



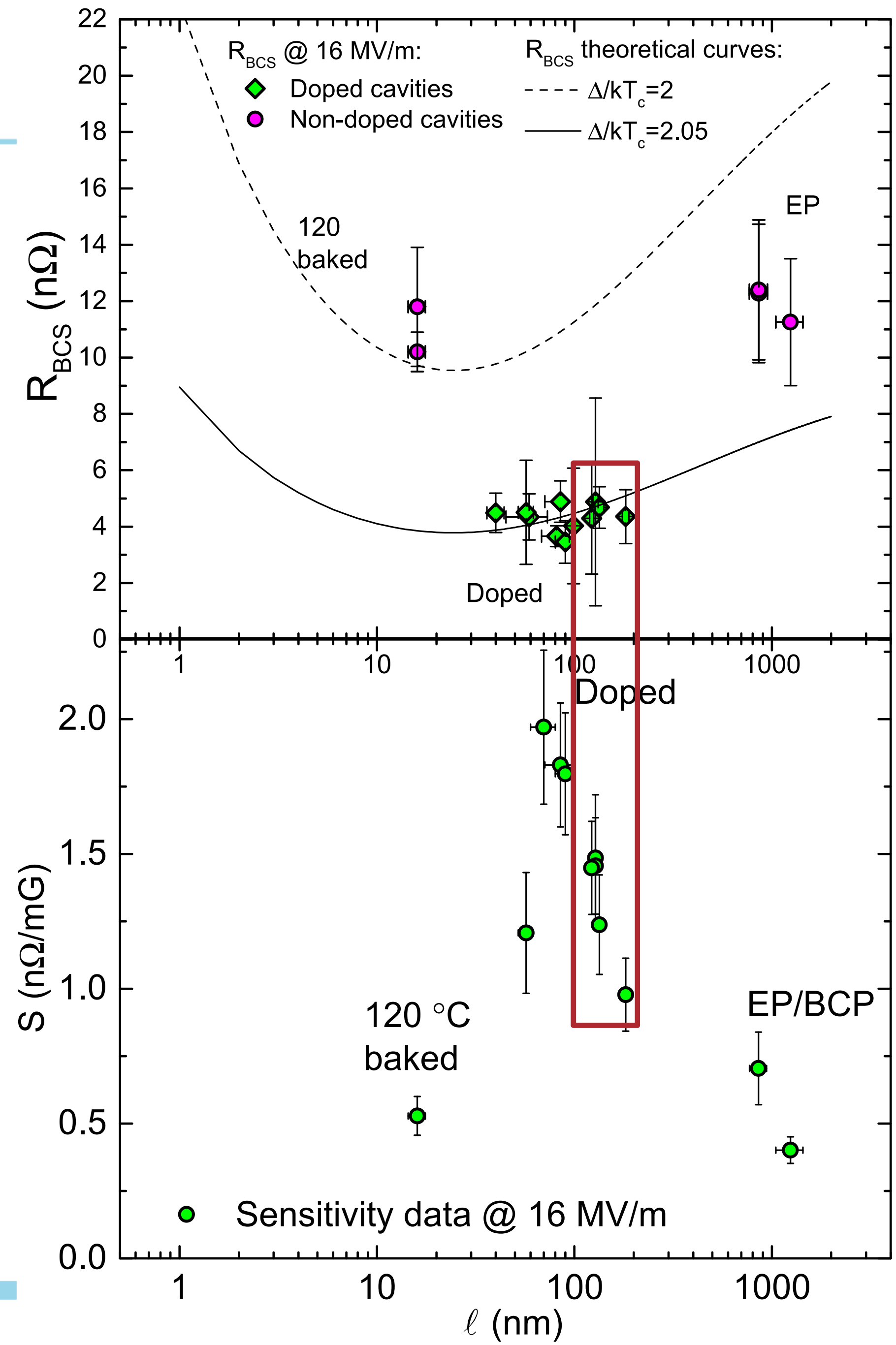
Minimizing Rs

The best surface treatment has to **minimize** both the **BCS surface resistance** and the **trapped flux sensitivity**

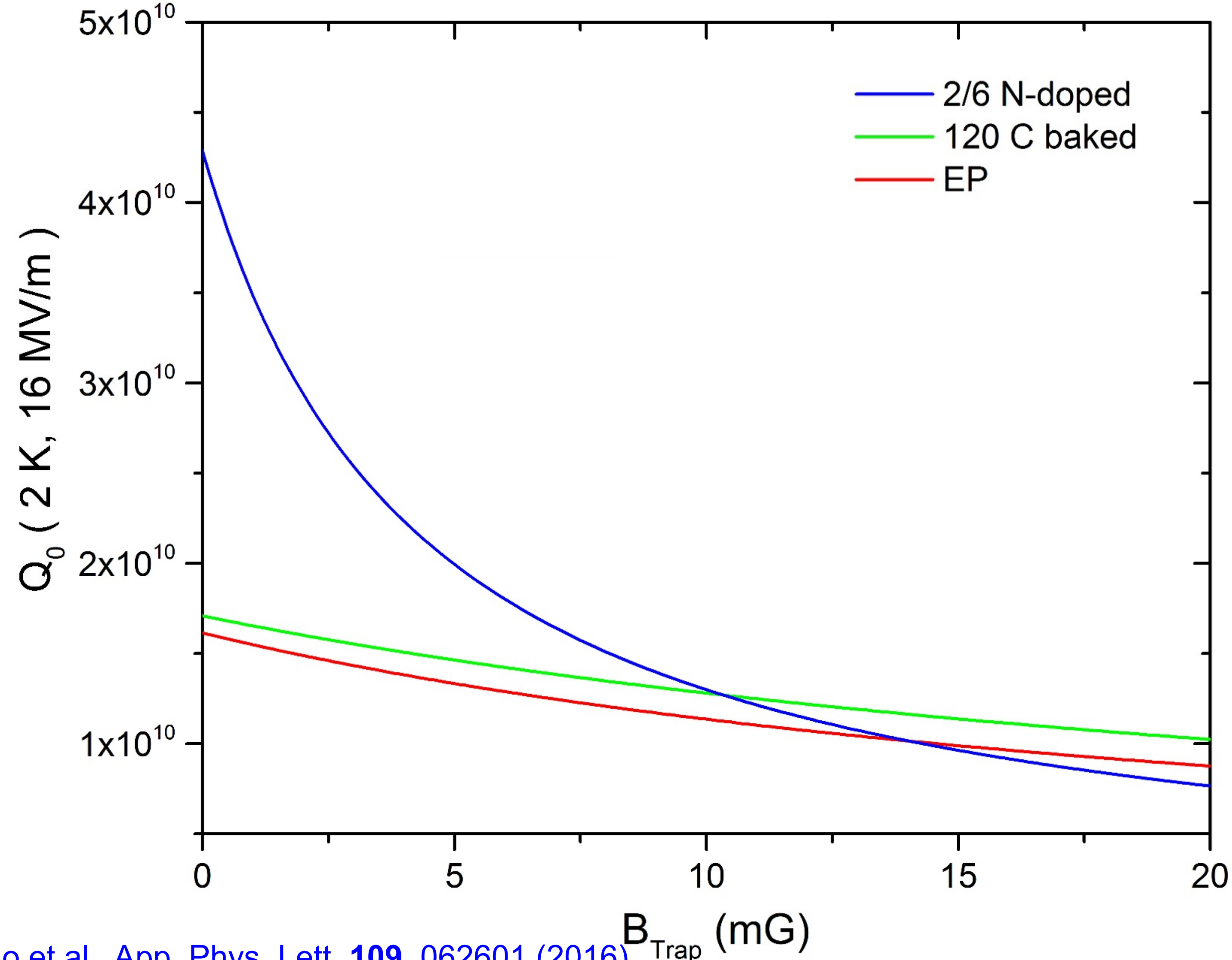
Light N-doped cavities:

Very low values of R_{BCS} 🙂

Decent values of sensitivity 🙂



Q-factor vs Trapped Flux for different surface treatments



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

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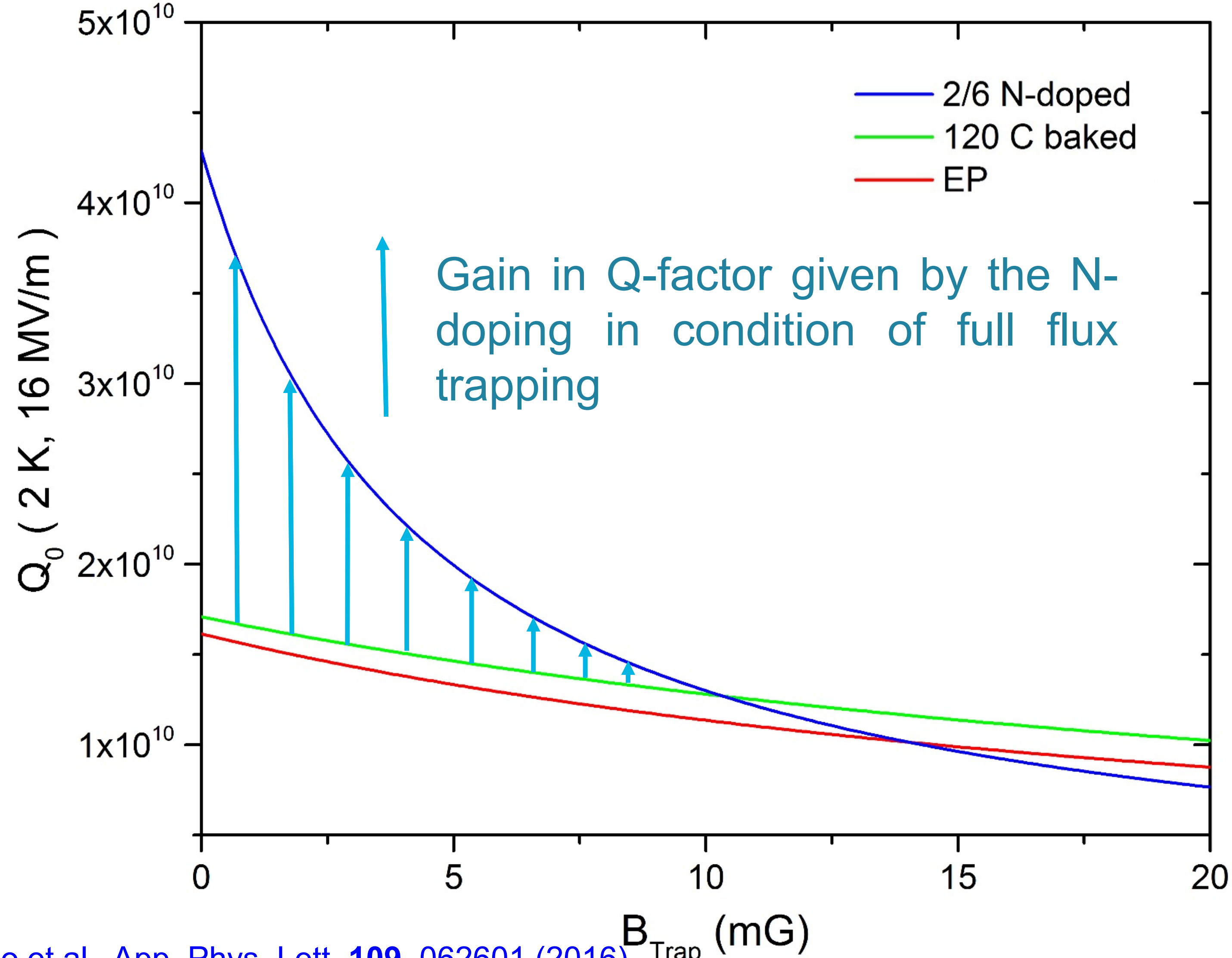

M. Martinello et al., App. Phys. Lett. **109**, 062601 (2016)

Conclusions

- N-doped cavities lowest values of R_{BCS}
- Bell-shaped trend of trapped flux sensitivity as function of mean free path
- N-doped cavities close to the maximum of sensitivity: larger losses due to trap flux
- **The 2/6 N-doping recipe gives the highest Q-factor at 2 K and 16 MV/m as long as the trapped field is less than 10 mG**

Thank you for your attention