# Advancement in the understanding of the field and frequency dependent microwave surface resistance of niobium

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18th International Conference on RF Superconductivity
18 July 2017

# Outline

- Experimental method and parameters extrapolation
- $R_{BCS}$ field dependence
- Trapped flux sensitivity
- N-infusion at 1.3 GHz
- Conclusions

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# Analyzed Cavities

N-doping

N-infusion

120C baking

EP/BCP

1.3 GHz, 2 K

| | 650 MHz | 1.3 GHz | 2.6 GHz | 3.9 GHz |
|---|---|---|---|---|
| **EP** | | ✓ | | |
| **BCP** | | ✓ | | ✓ |
| **120C baking** | ✓ | ✓ | ✓ | ✓ |
| **120C infusion** | | ✓ | | |
| **160C infusion** | | ✓ | | |
| **2/6 N-doping** | ✓ | ✓ | ✓ | ✓ |

# Data Analysis

For each cavity:

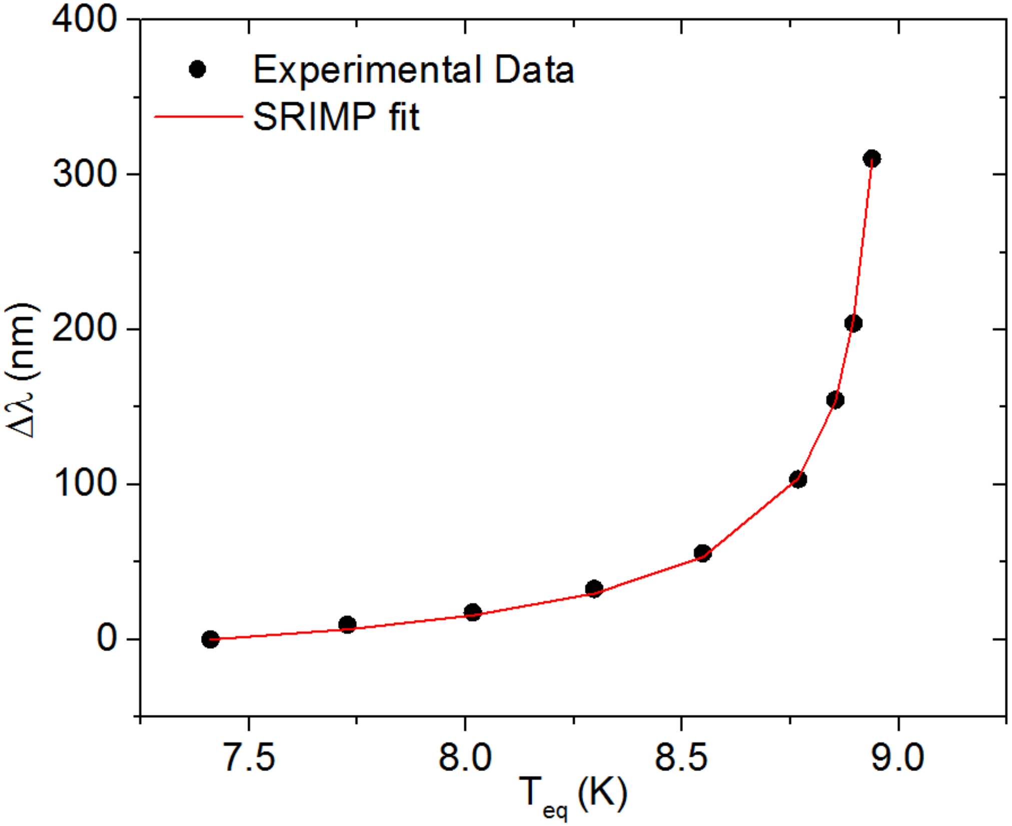
- Mean free path extrapolation: the mfp $\ell$ specifies the impurity content after each treatment
- Surface resistance decomposition:

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

1. $R_{BCS}\,(2\,K)$: BCS surface resistance at $2\,K$
2. $R_{Fl}$: Trapped flux surface resistance
3. $R_0$: Intrinsic residual resistance

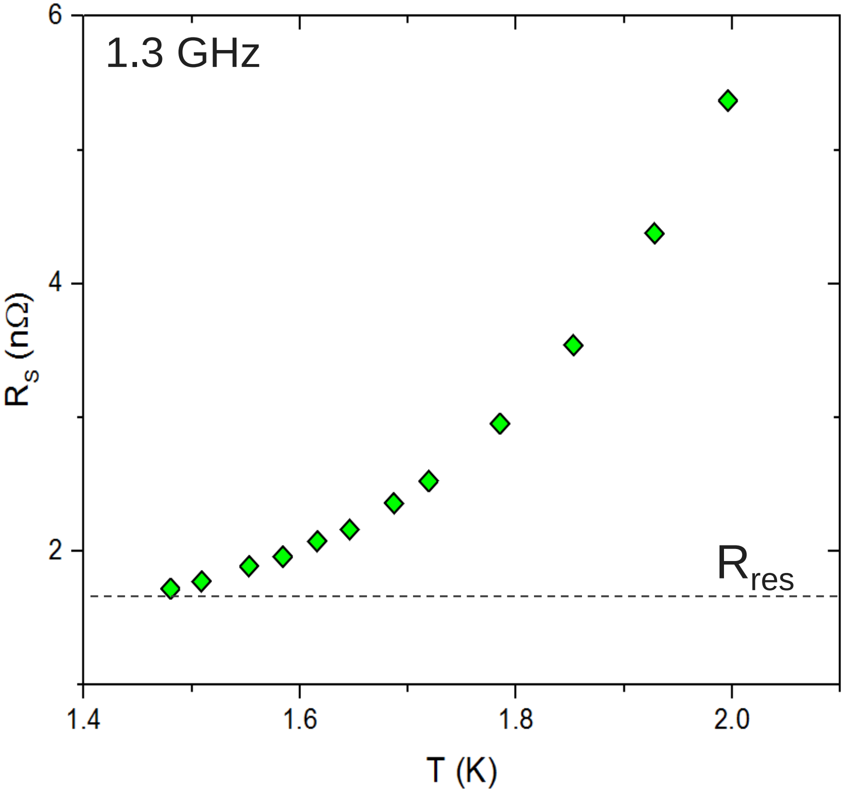
# Mean Free Path Calculation

- Measurements of Frequency vs T warming up through Tc: $\Delta f \propto -1/\Delta\lambda$
- $\Delta\lambda$ is interpolated using Halbritter SRIMP code
- The parameters are:
    - Critical temperature:
      $T_c \sim 9.2\ K$
    - London penetration depth:
      $\lambda_L = 39\ nm$
    - Intrinsic coherent length:
      $\xi_0 = 38\ nm$
    - Starting temperature: $T_0$
    - Mean free path (mfp): $\ell$
    - Energy gap: $\Delta/k_B T_c$



# 1a. BCS Surface Resistance (650 MHz and 1.3 GHz)

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



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

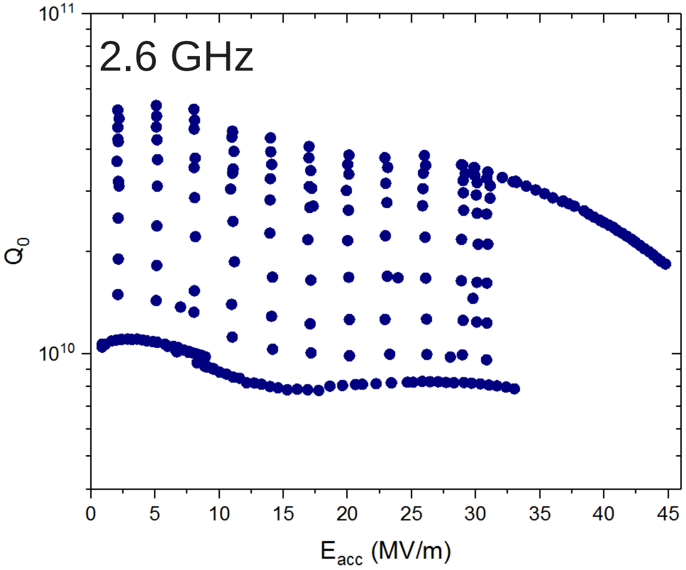
Because of the exponential decreasing with T, $R_{BCS}$ at 1.5 K is negligible at low frequencies :

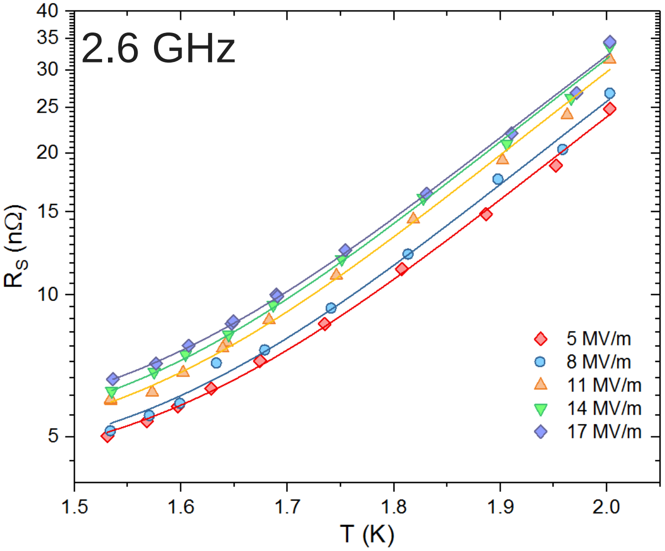
$$R_S\,(\,1.5\,K\,) \sim R_{res}$$

$R_{BCS}$ (2 K) can be calculated as:

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

# 1b. BCS Surface Resistance (2.6 and 3.9 GHz)





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

Fit with SRIMP of Rs (T) acquired at different $E_{acc}$ values:

$$R_S = A\,e^{-\frac{\Delta}{k_B T}} + R_{res}$$

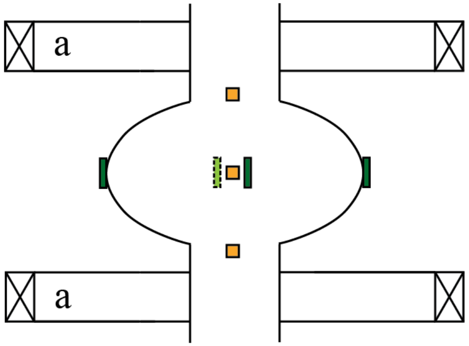
Accurate determination of $R_{res}$ ($E_{acc}$)

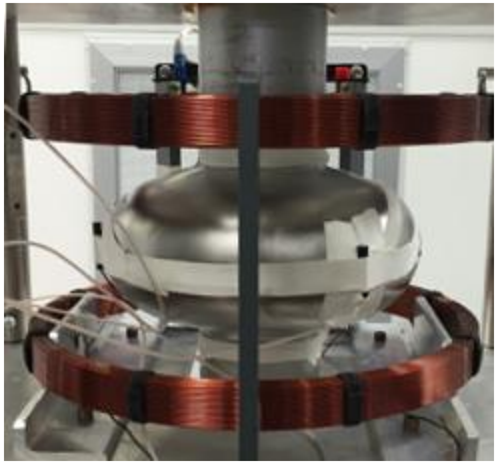
At this point $R_{BCS}$(2K) can be easily calculated:

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

# 2. Trapped Flux Surface Resistance

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





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

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

$$\boxed{R_{Fl} = R_S\left(1.5\,K, B_{Trap}\right) - R_S\left(1.5\,K, B_{Trap} = 0\right)}$$

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

# 3. Intrinsic Residual Resistance

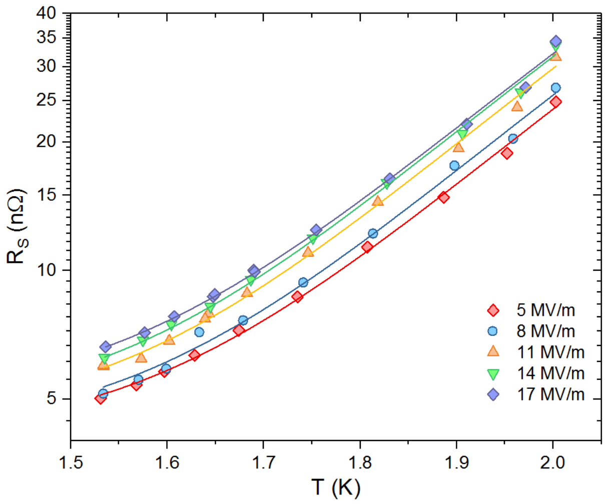
$$R_S\,(\,2\,K\,) = R_{BCS}\,(\,2\,K\,) + \boxed{R_0} + R_{Fl}$$

- For *low frequency cavities* the intrinsic residual resistance can be obtained with the low T measurement in absence of $B_{trap}$:

$$R_0 = R_S\left(1.5\,K, B_{Trap} = 0\right)$$

- For *high frequency cavities* the intrinsic residual resistance has to be calculated by fitting with SRIMP Rs (T) acquired at different $E_{acc}$ values in absence of $B_{trap}$ :

$$R_S = A\,e^{-\frac{\Delta}{k_B T}} + R_0$$



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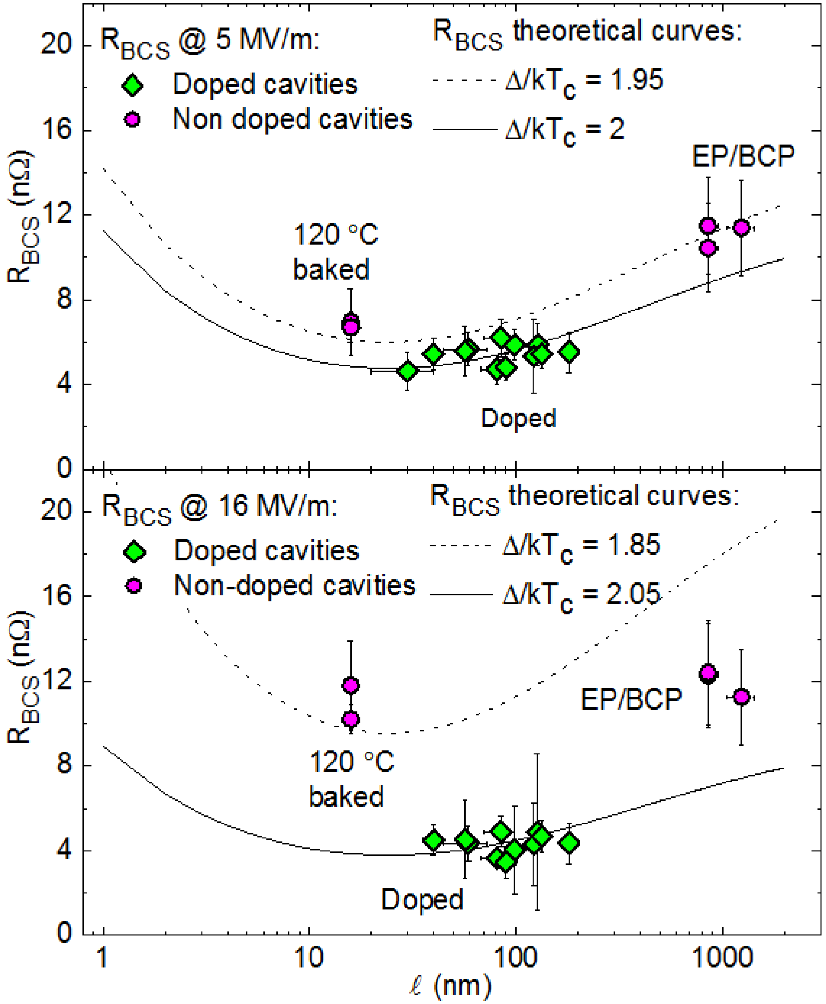
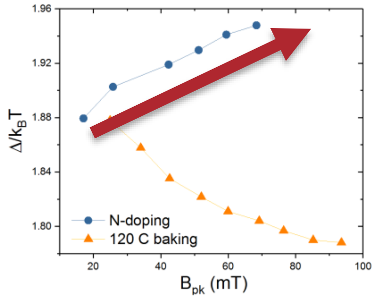
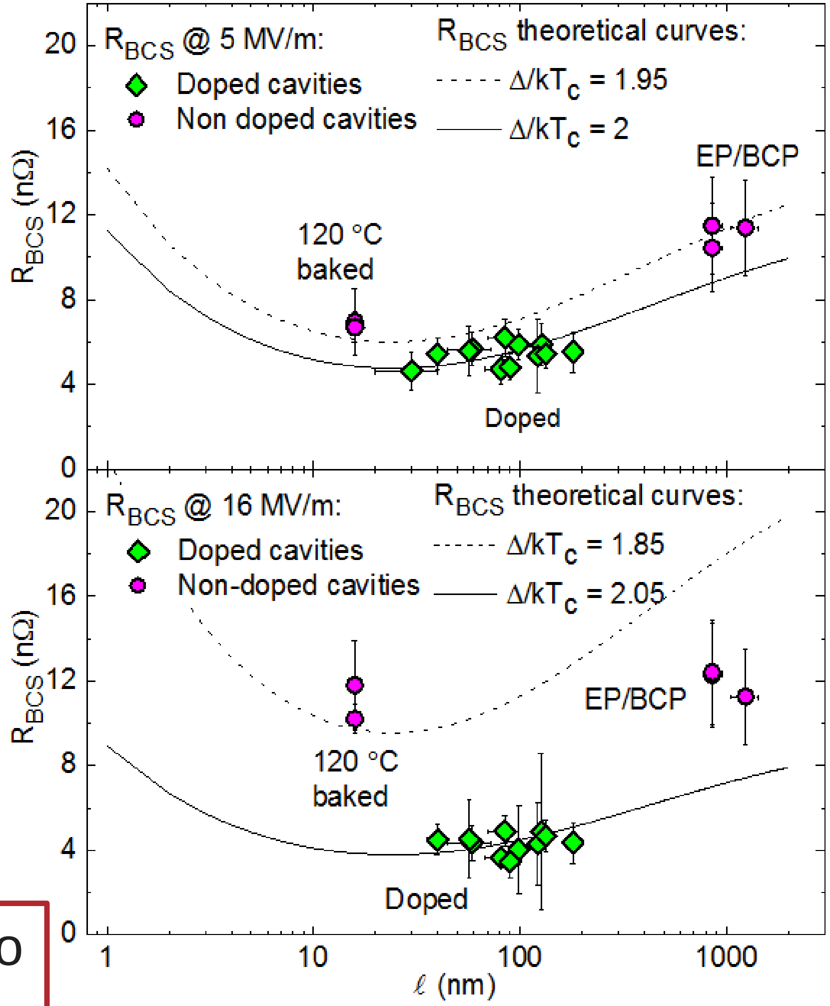
# BCS surface resistance (1.3 GHz)



A. Romanenko and A. Grassellino, App. Phys. Lett. **102**, 252603 (2013)
M. Martinello et al., App. Phys. Lett. **109**, 062601 (2016)

# BCS surface resistance (1.3 GHz)





The reduced energy gap Δ/kTc seems to increase with $E_{acc}$ for N-doped cavities causing the decreasing of $R_{BCS}$

# Field Dependence at Different Frequencies

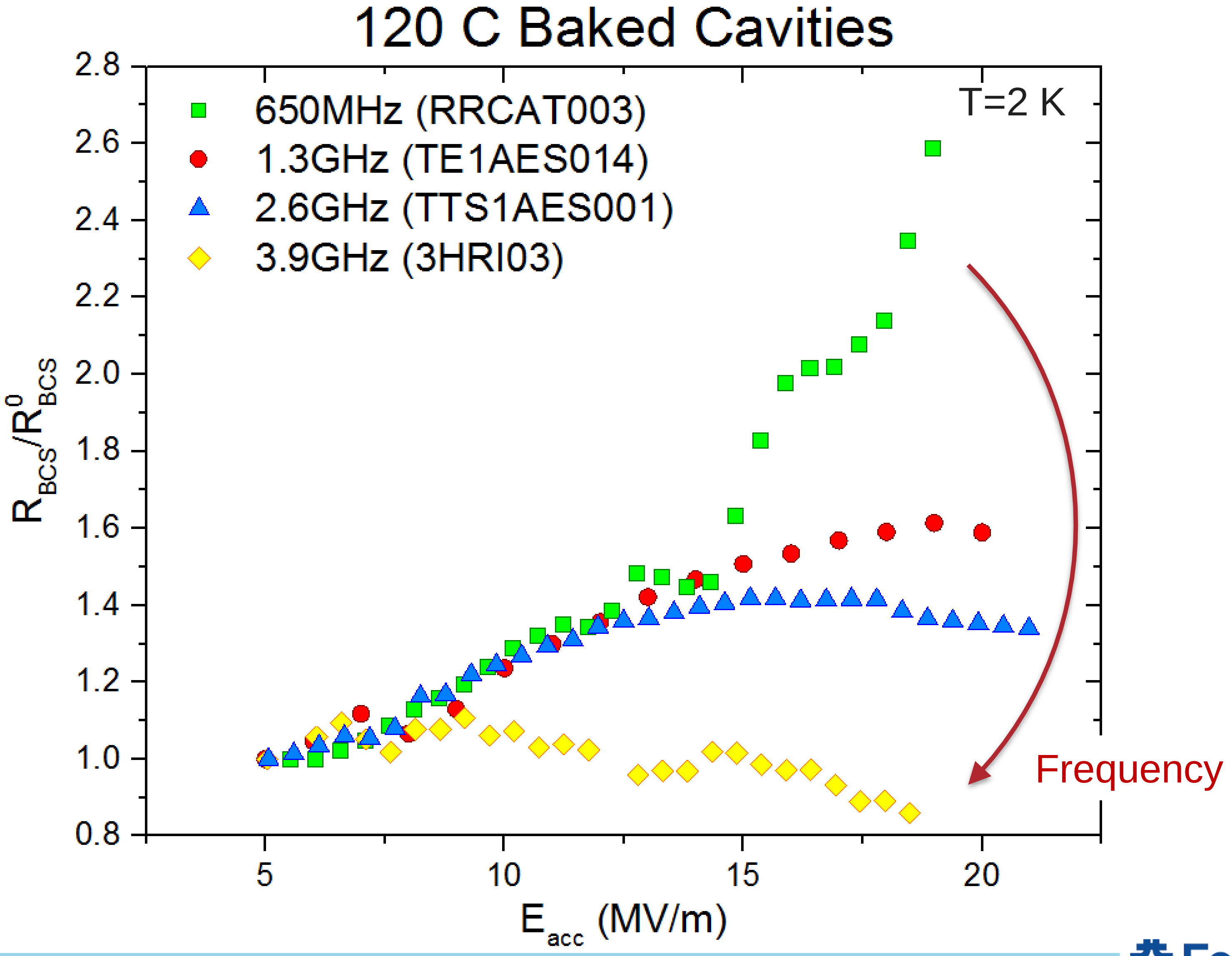
Different thermal treatments were studied at different frequencies:

1. 120 C baking
2. Buffer Chemical Polishing (BCP)
3. Nitrogen doping (2/6 recipe)

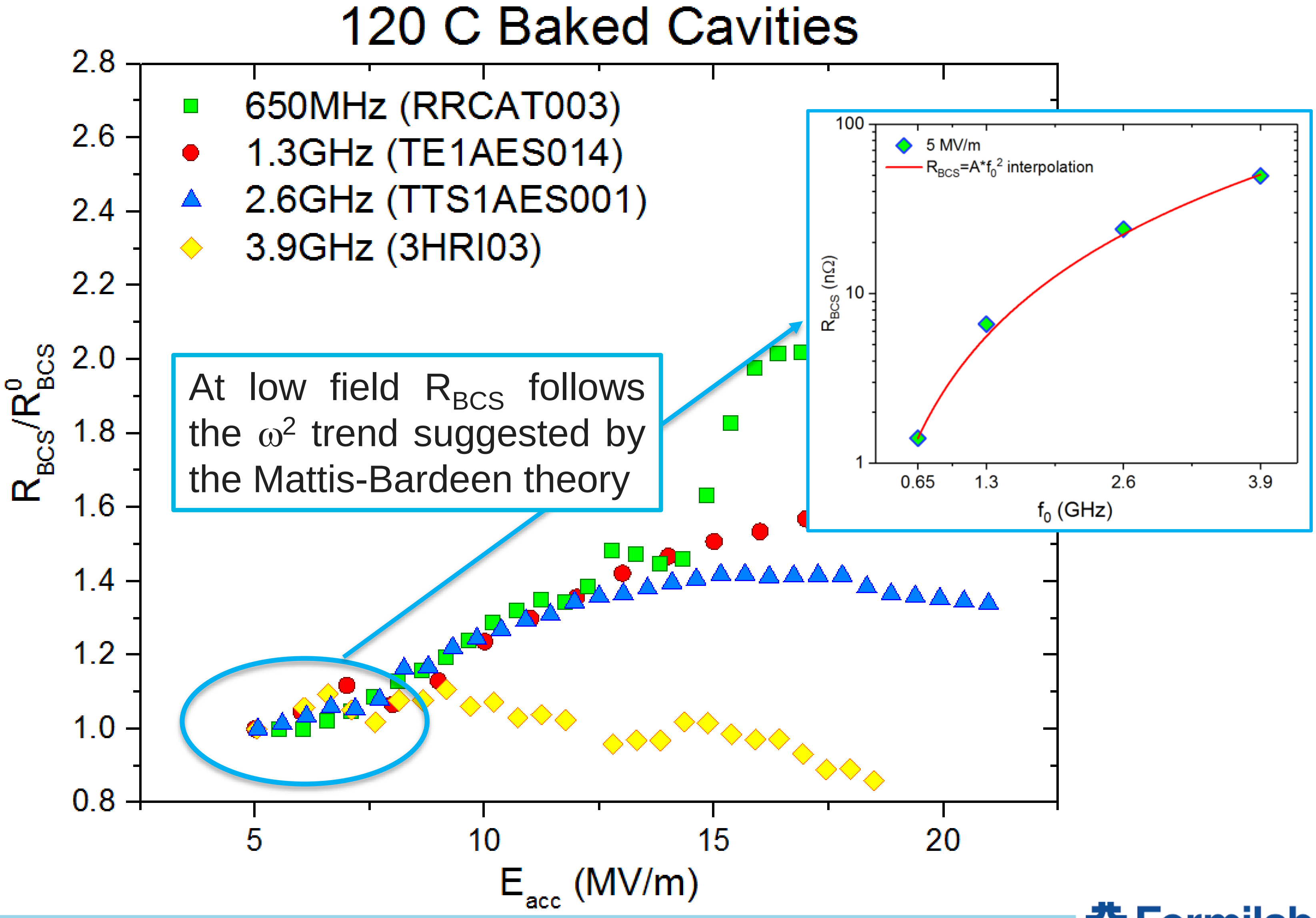
# 1.

## 120 C baking

# 1. Normalized $R_{BCS}(2\ K)$ for 120 C Baking

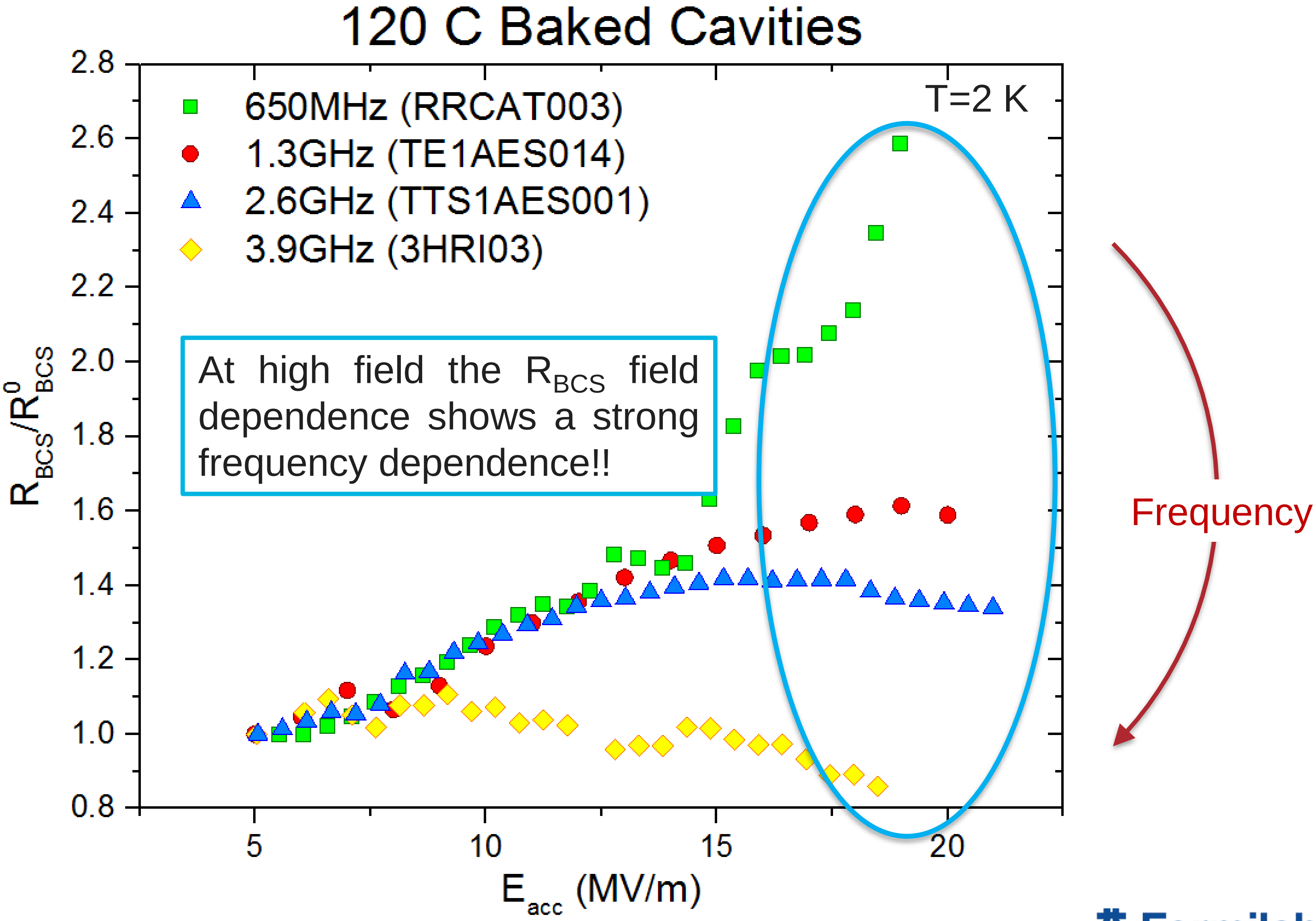


# 1. Normalized $R_{BCS}(2\ K)$ for 120 C Baking



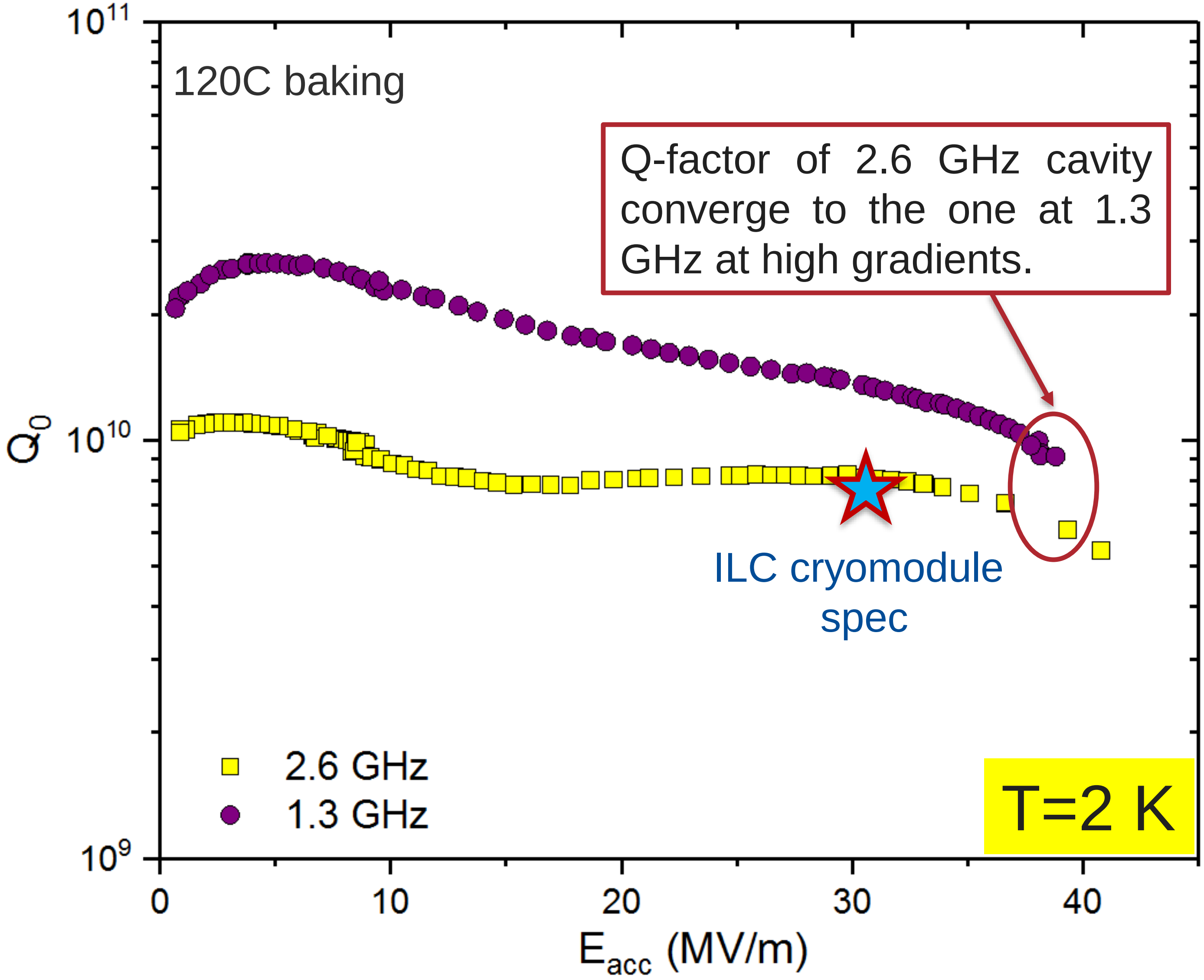
At low field $R_{BCS}$ follows the $\omega^2$ trend suggested by the Mattis-Bardeen theory

# 1. Normalized $R_{BCS}(2\ K)$ for 120 C Baking



At high field the $R_{BCS}$ field dependence shows a strong frequency dependence!!

# ILC Cryomodule Specifications at 2.6 GHz



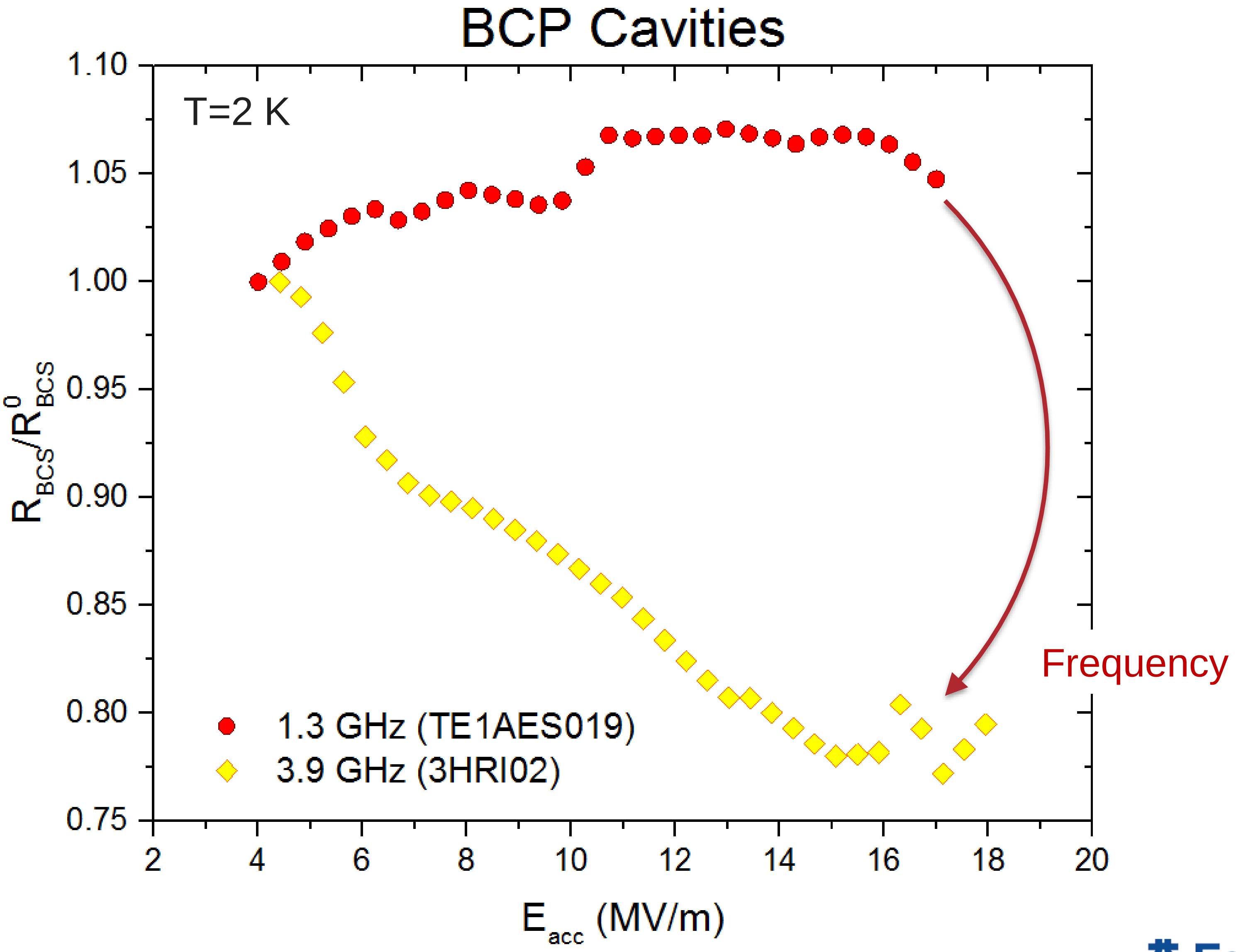
Q-factor of 2.6 GHz cavity converge to the one at 1.3 GHz at high gradients.

ILC cryomodule spec

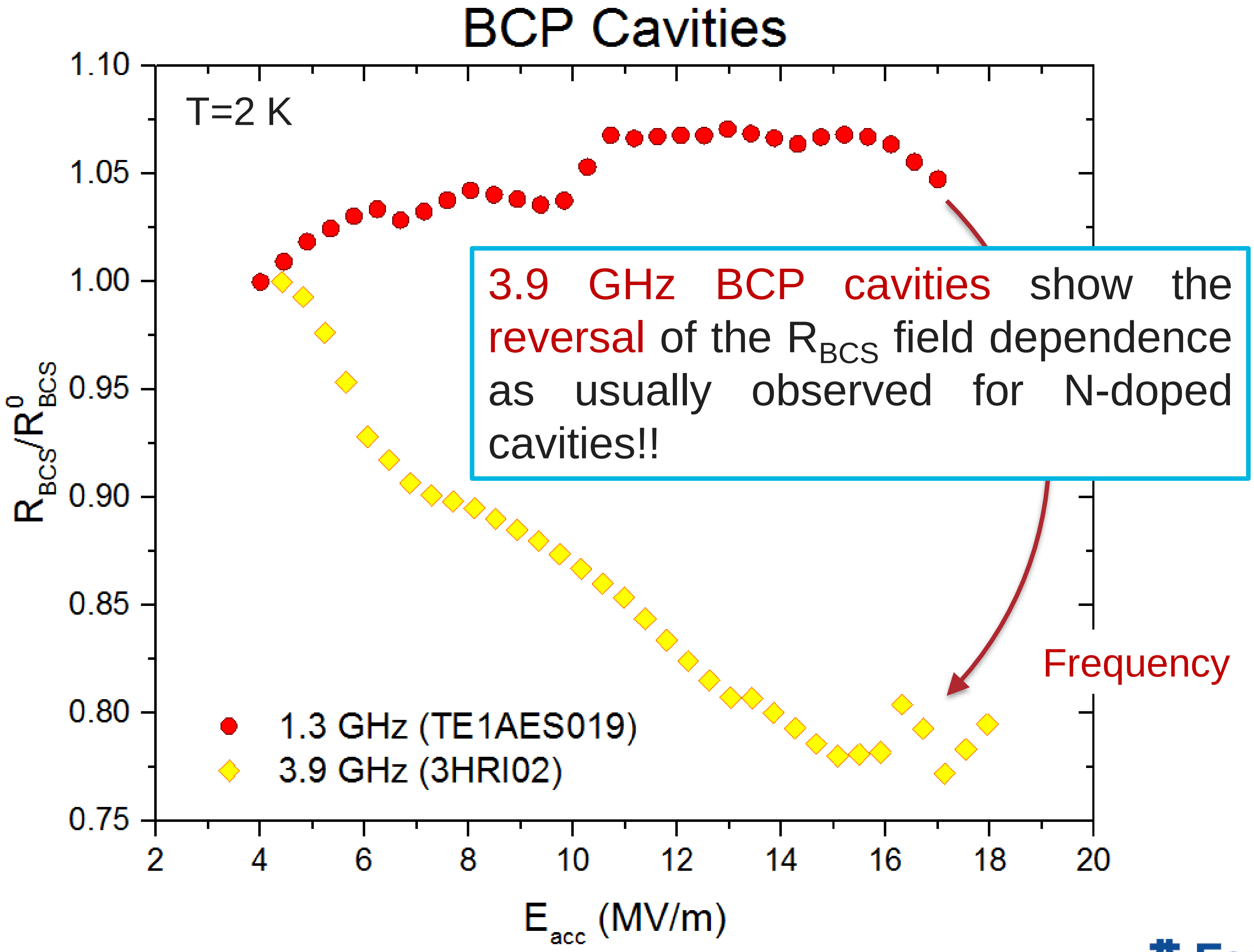
# 2.

# Buffer Chemical Polishing

# 2. Normalized $R_{BCS}(2\ K)$ for BCP

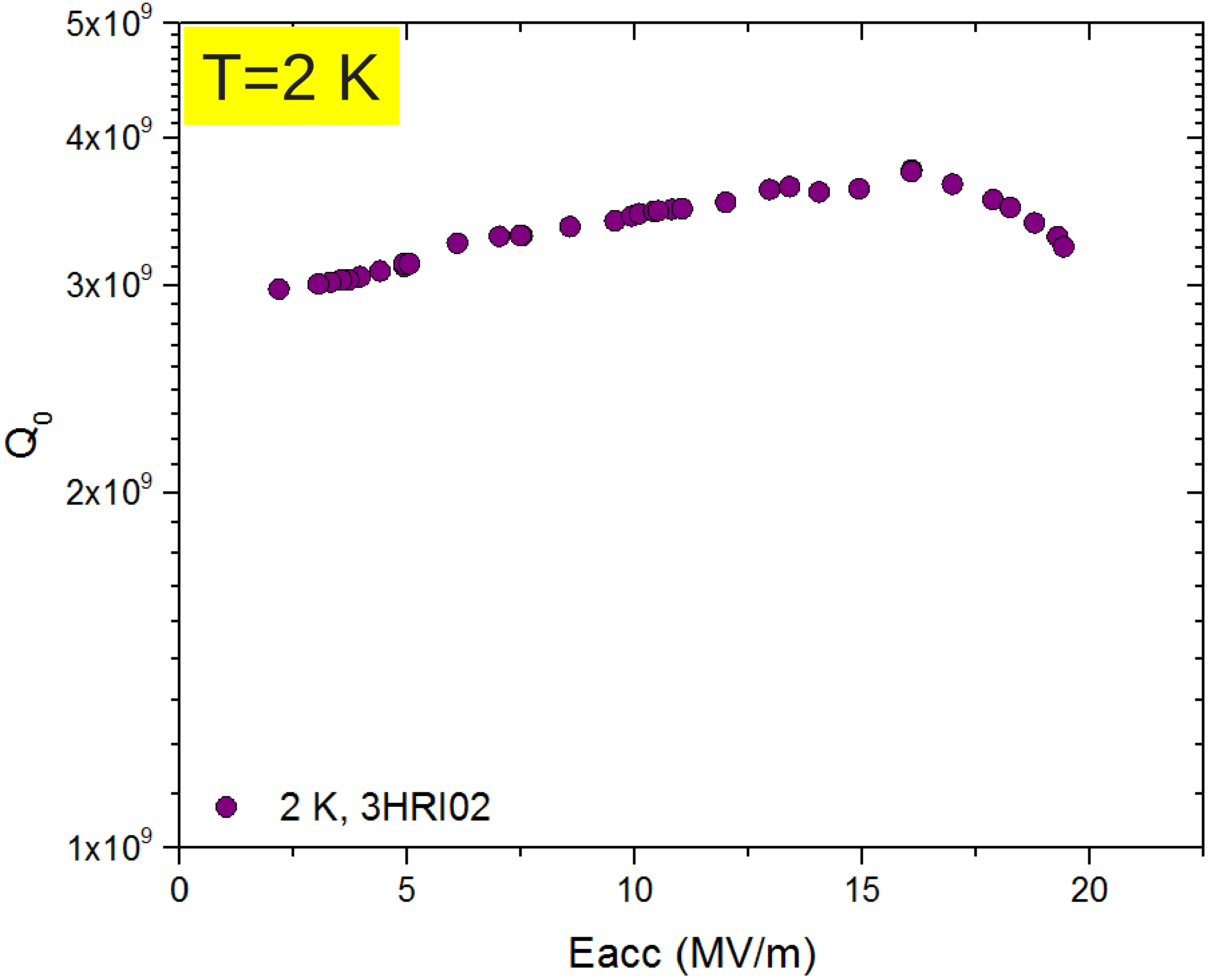


# 2. Normalized $R_{BCS}(2\ K)$ for BCP



3.9 GHz BCP cavities show the reversal of the $R_{BCS}$ field dependence as usually observed for N-doped cavities!!

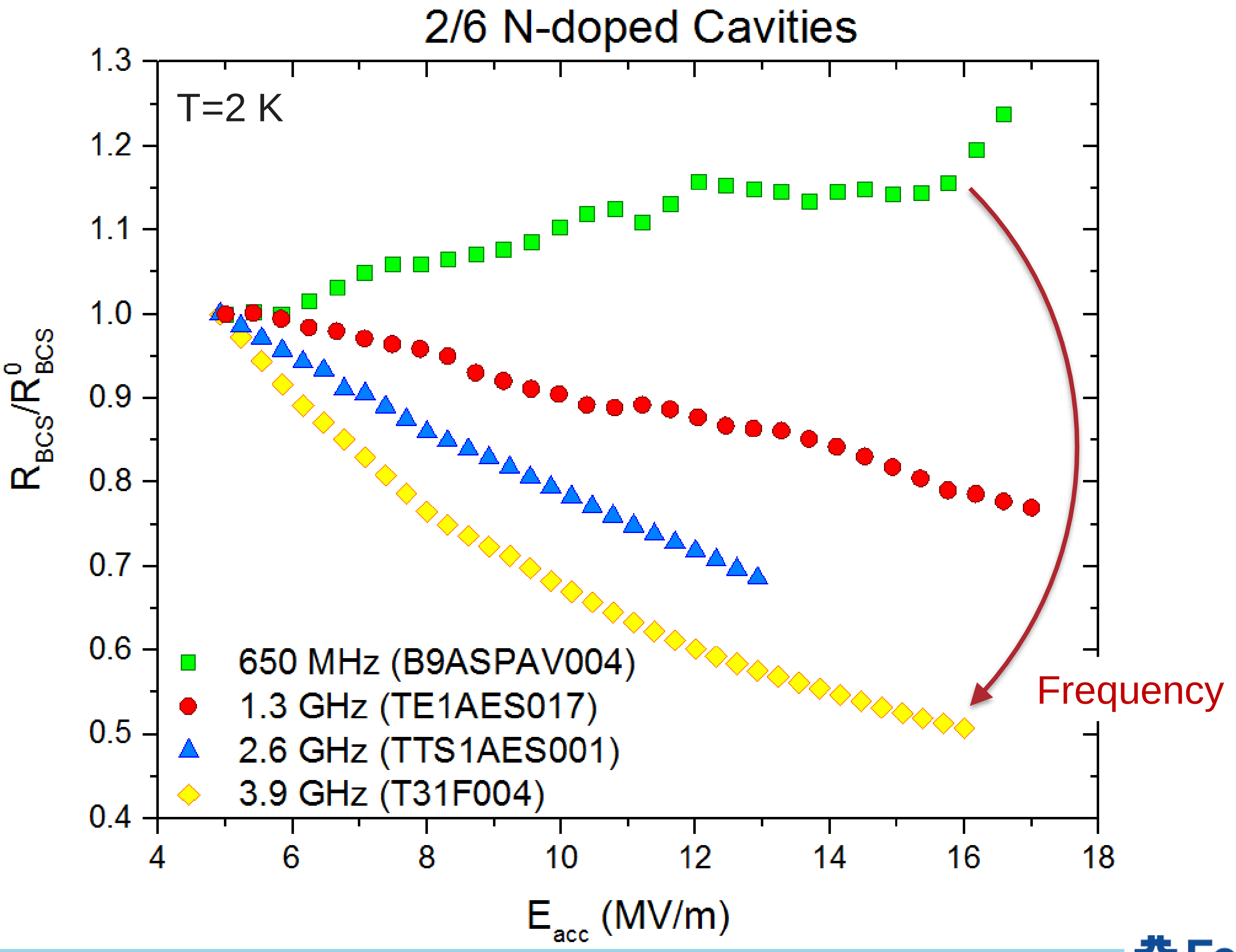
# Anti Q-slope in **BCP'd** 3.9 GHz Cavities



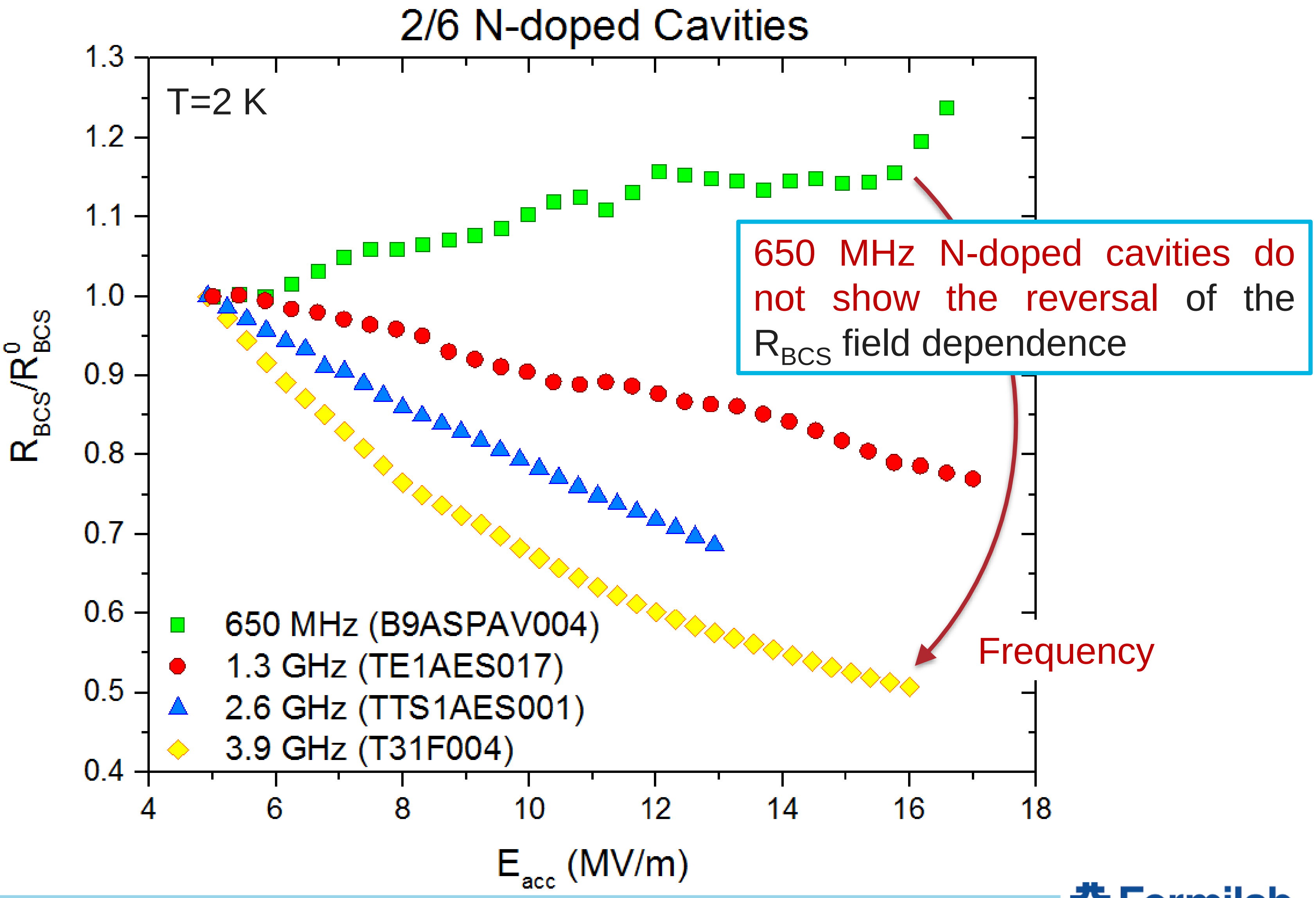
# 3.

# Nitrogen doping

# 3. Normalized $R_{BCS}(2\ K)$ for N-doping

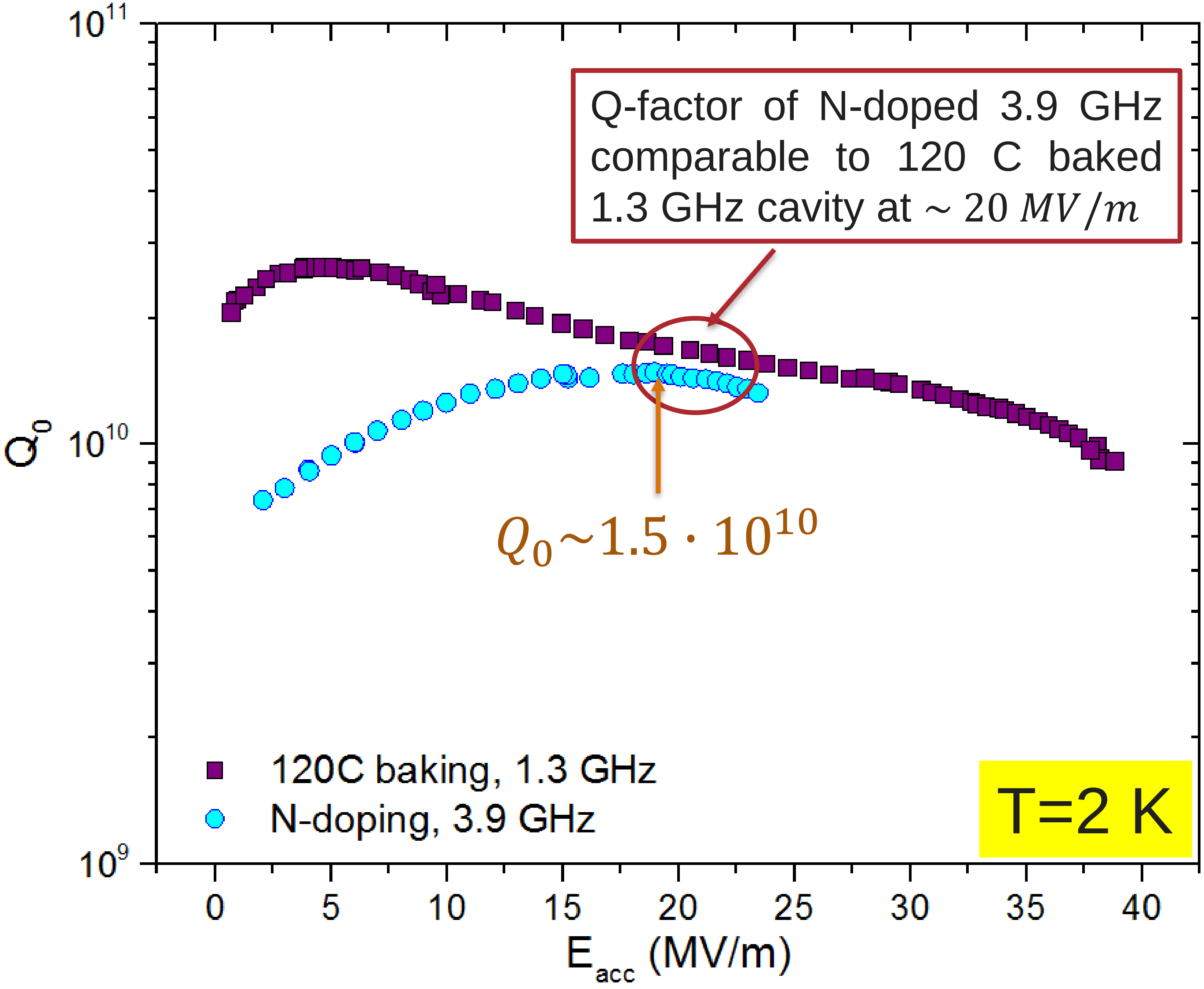


# 3. Normalized $R_{BCS}(2\ K)$ for N-doping



650 MHz N-doped cavities do not show the reversal of the $R_{BCS}$ field dependence

# Unprecedented Medium Field $Q_0$ at 3.9 GHz

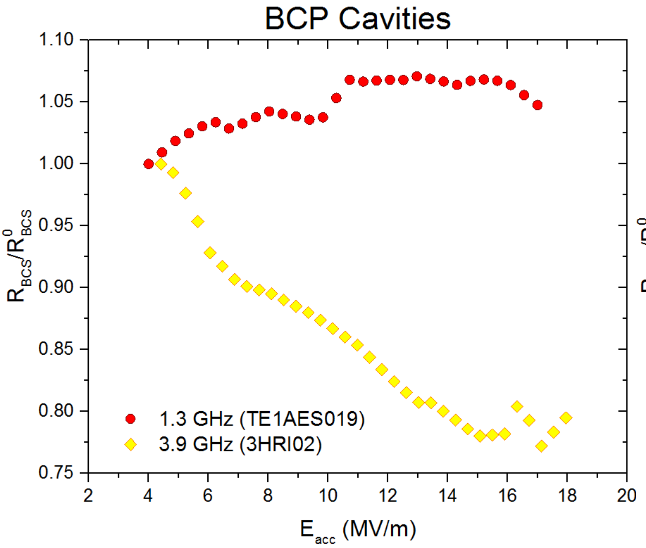


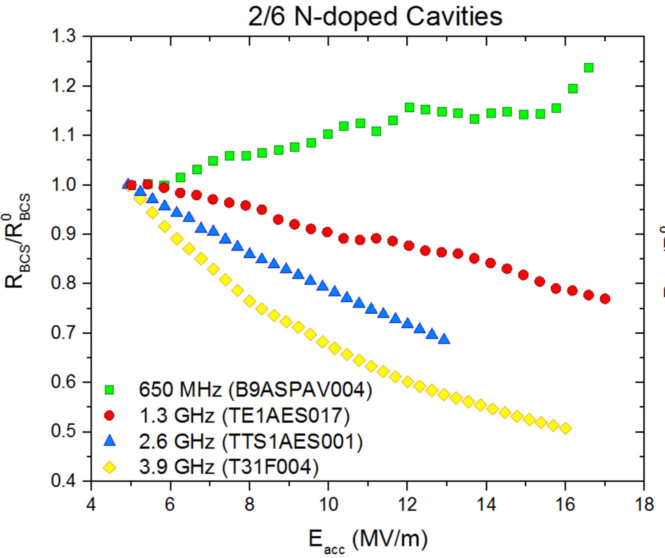
Q-factor of N-doped 3.9 GHz comparable to 120 C baked 1.3 GHz cavity at $\sim 20\ MV/m$

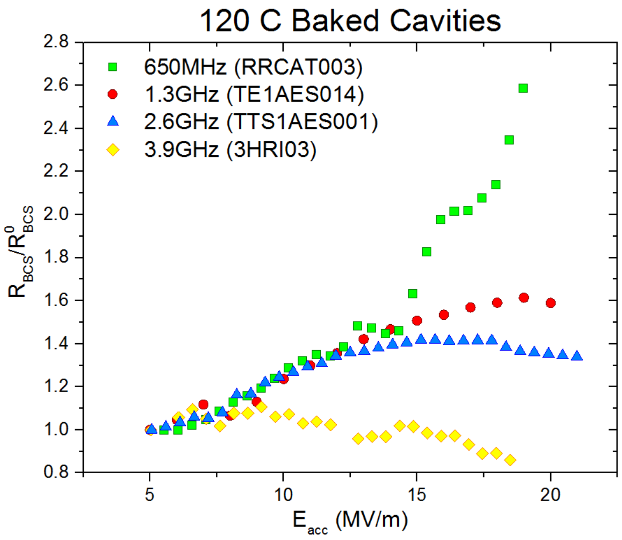
$Q_0 \sim 1.5 \cdot 10^{10}$

T=2 K

# Effect of the frequency on the $R_{BCS}(E_{acc})$ slope


BCP Cavities

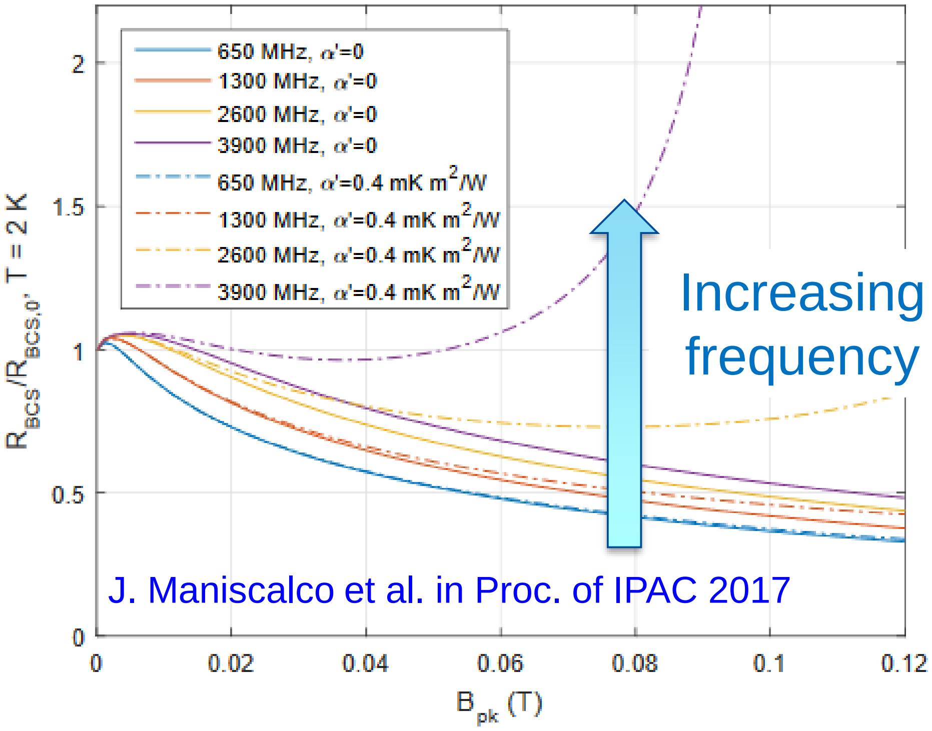

2/6 N-doped Cavities


120 C Baked Cavities

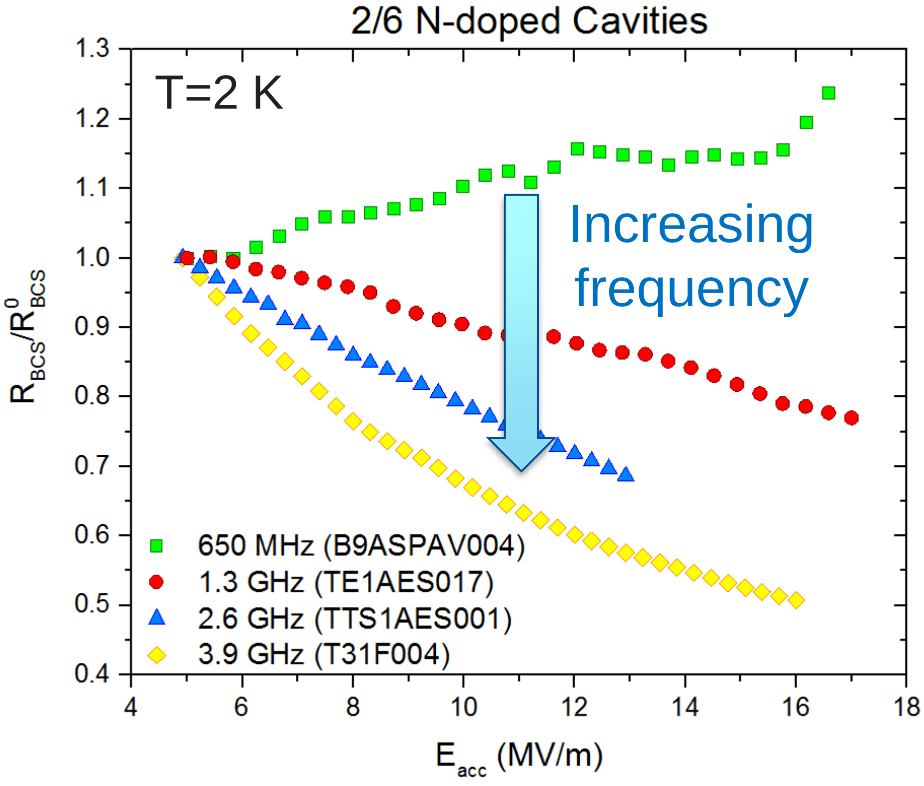
- The physical mechanism underneath the $R_{BCS}$ reversal has a stronger effect at high frequencies

- The $R_{BCS}$ reversal, that has been considered the signature of the N-doped treatment, is actually visible also in clean Nb but at high frequency
- On the other hand, N-doped cavities at low frequencies do not show the $R_{BCS}$ reversal observed at 1.3 GHz

# Frequency Dependence NOT Related to QP Overheating



J. Maniscalco et al. in Proc. of IPAC 2017



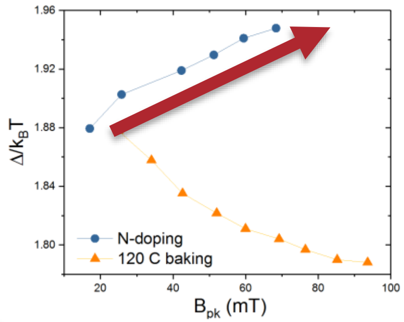
These new experimental findings disprove the prediction of the frequency dependence of $R_{BCS}(E_{acc})$ based on the quasiparticles overheating mechanism

# Understanding the reversal of $R_{BCS}$ with the RF field

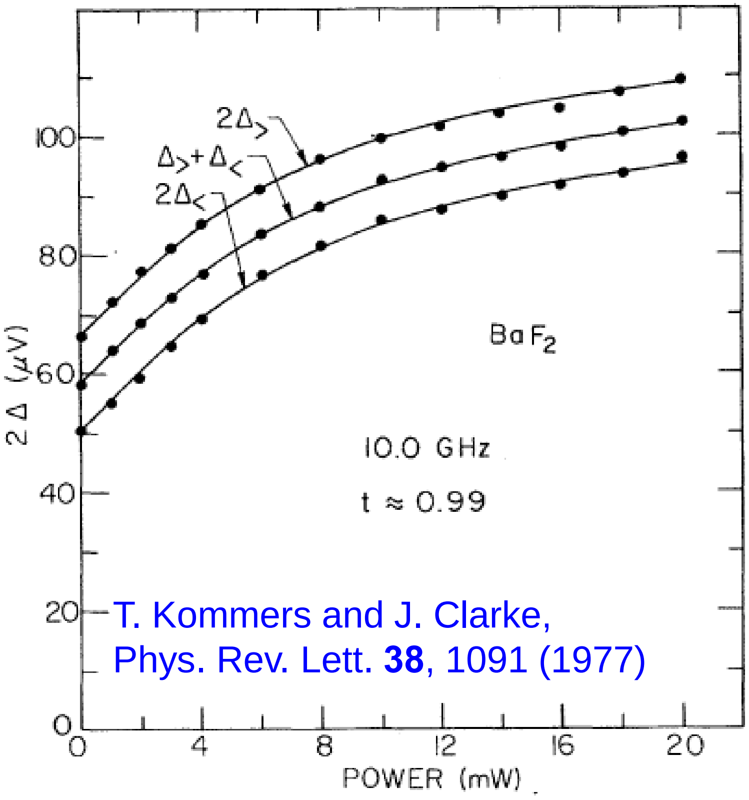
The non-equilibrium quasiparticle distribution driven by microwave fields is shown to stimulate the superconductivity[1,2,3]:

→ Δ increases with the RF field amplitude (absorbed power)

→ $R_{BCS}$ decreases with the RF field amplitude (absorbed power)



Δ increases driven by $E_{acc}$?



T. Kommers and J. Clarke, Phys. Rev. Lett. **38**, 1091 (1977)

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[1] G.M. Eliashberg, ZhETF Pis. Red. **11**, 186 (1970)

[2] J.-J. Chang and D. J. Scalapino, Phys. Rev. B **15**, 2051 (1977)

[3] D. J. Goldie and S. Withington, Supercond. Sci. Technol. **26,** 015004 (2013)

# Considerations for a Complete $R_{BCS}$ Description

Ideas for a new model to explain the $R_{BCS}$ field-dependent behavior of SRF cavities:

- Take into account the smearing of the DOS due to the RF field amplitude (as done in: A. Gurevich, Phys. Rev. Lett. 113, 087001 (2014))

- Take into account non-equilibrium effects:
    - Enhanced in presence of high frequencies
    - Enhanced by large accelerating field (higher number of QP involved)
    - Potentially enhanced by the presence of impurities that may modify the relaxation and recombination times of quasi-particles
    - Different impurities may have different effects because of their different cross section

# Considerations for a Complete $R_{BCS}$ Description

Ideas for a new model to explain the $R_{BCS}$ field-dependent behavior of SRF cavities:

- Take int F field amplitud
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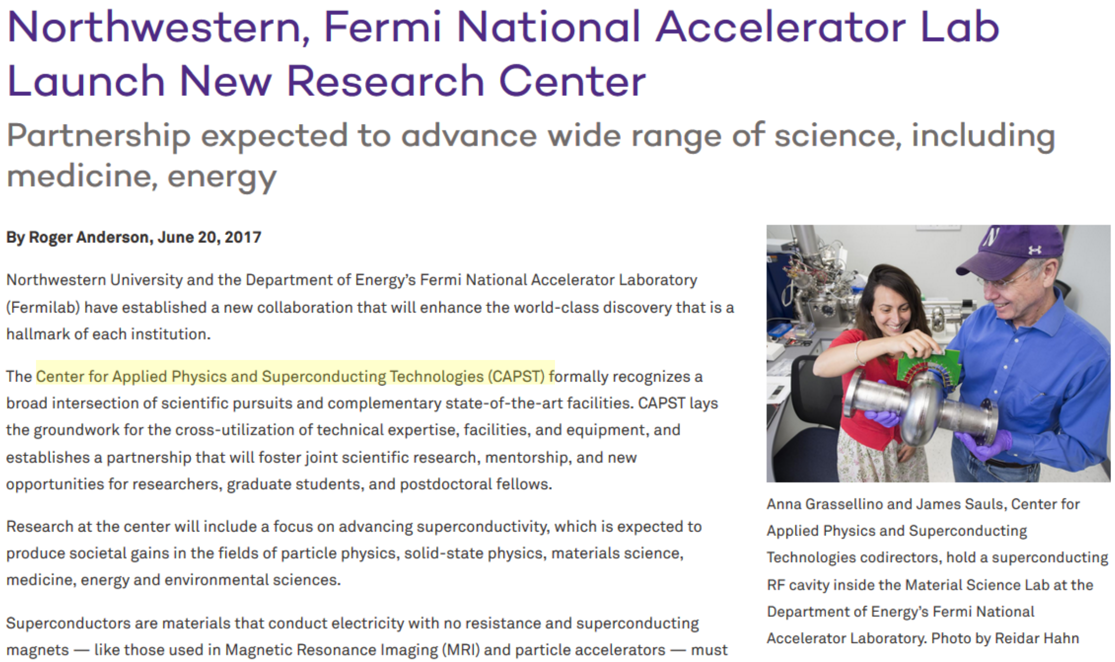
  - Different impurities may have different effects because of their different cross section

**Model under development in collaboration with Northwestern University**



## Northwestern, Fermi National Accelerator Lab Launch New Research Center

Partnership expected to advance wide range of science, including medicine, energy

**By Roger Anderson, June 20, 2017**

Northwestern University and the Department of Energy's Fermi National Accelerator Laboratory (Fermilab) have established a new collaboration that will enhance the world-class discovery that is a hallmark of each institution.

The Center for Applied Physics and Superconducting Technologies (CAPST) formally recognizes a broad intersection of scientific pursuits and complementary state-of-the-art facilities. CAPST lays the groundwork for the cross-utilization of technical expertise, facilities, and equipment, and establishes a partnership that will foster joint scientific research, mentorship, and new opportunities for researchers, graduate students, and postdoctoral fellows.

Research at the center will include a focus on advancing superconductivity, which is expected to produce societal gains in the fields of particle physics, solid-state physics, materials science, medicine, energy and environmental sciences.

Superconductors are materials that conduct electricity with no resistance and superconducting magnets — like those used in Magnetic Resonance Imaging (MRI) and particle accelerators — must

Anna Grassellino and James Sauls, Center for Applied Physics and Superconducting Technologies codirectors, hold a superconducting RF cavity inside the Material Science Lab at the Department of Energy's Fermi National Accelerator Laboratory. Photo by Reidar Hahn

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# Sensitivity vs Mean Free Path

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

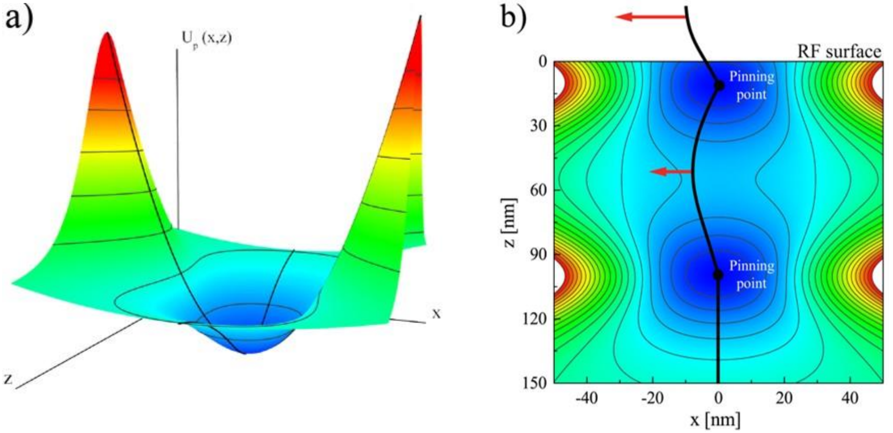
- Bell-shaped trend of $S$ as a function of mean free path

- For N-doped cavities, sensitivity minimization for either very light or very heavy doping treatments

M. Martinello et al., App. Phys. Lett. **109**, 062601 (2016)
M. Martinello et al., in Proc. of SRF 2015

# Vortex dynamic dissipation

See M. Checchin TUYAA03



- **Dissipation due to vortex oscillation under the RF field**

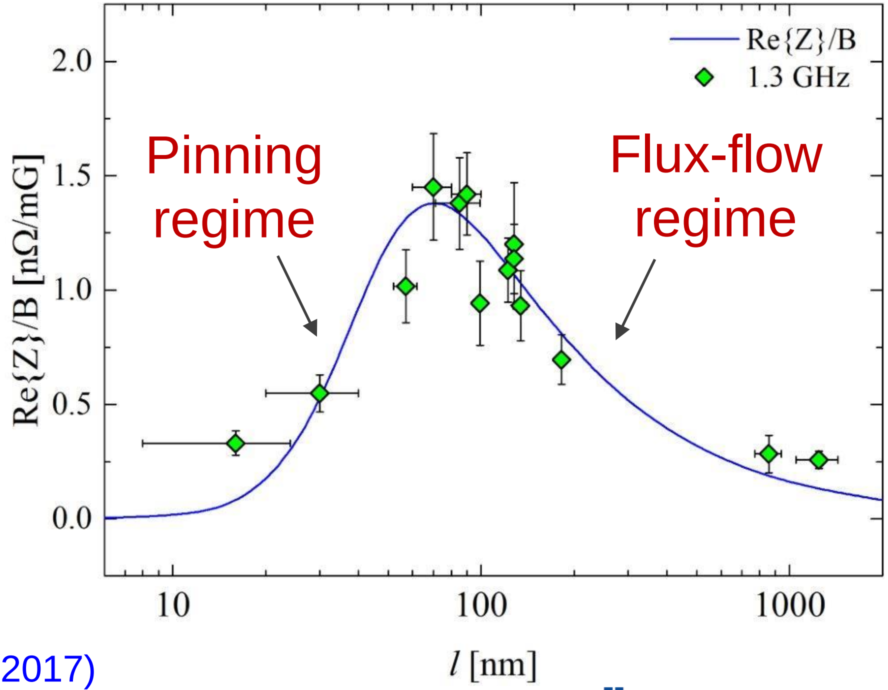
We can define two regimes:

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

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

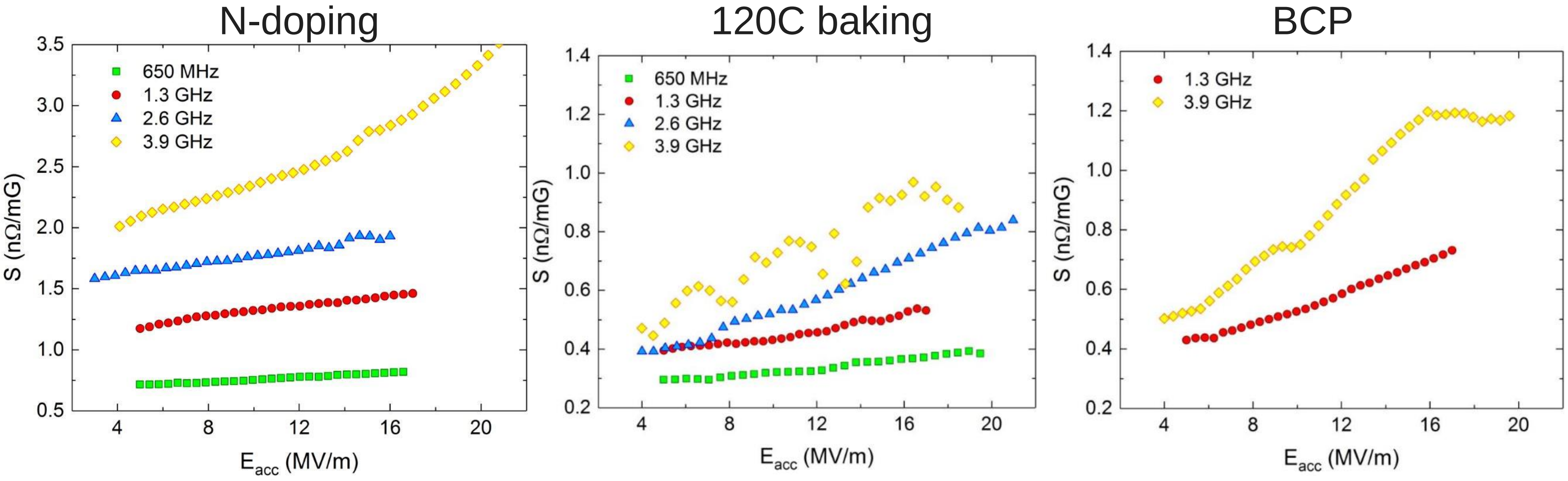
2. *<u>Small $l$ ($\eta \to 0$) – pinning regime</u>*:

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



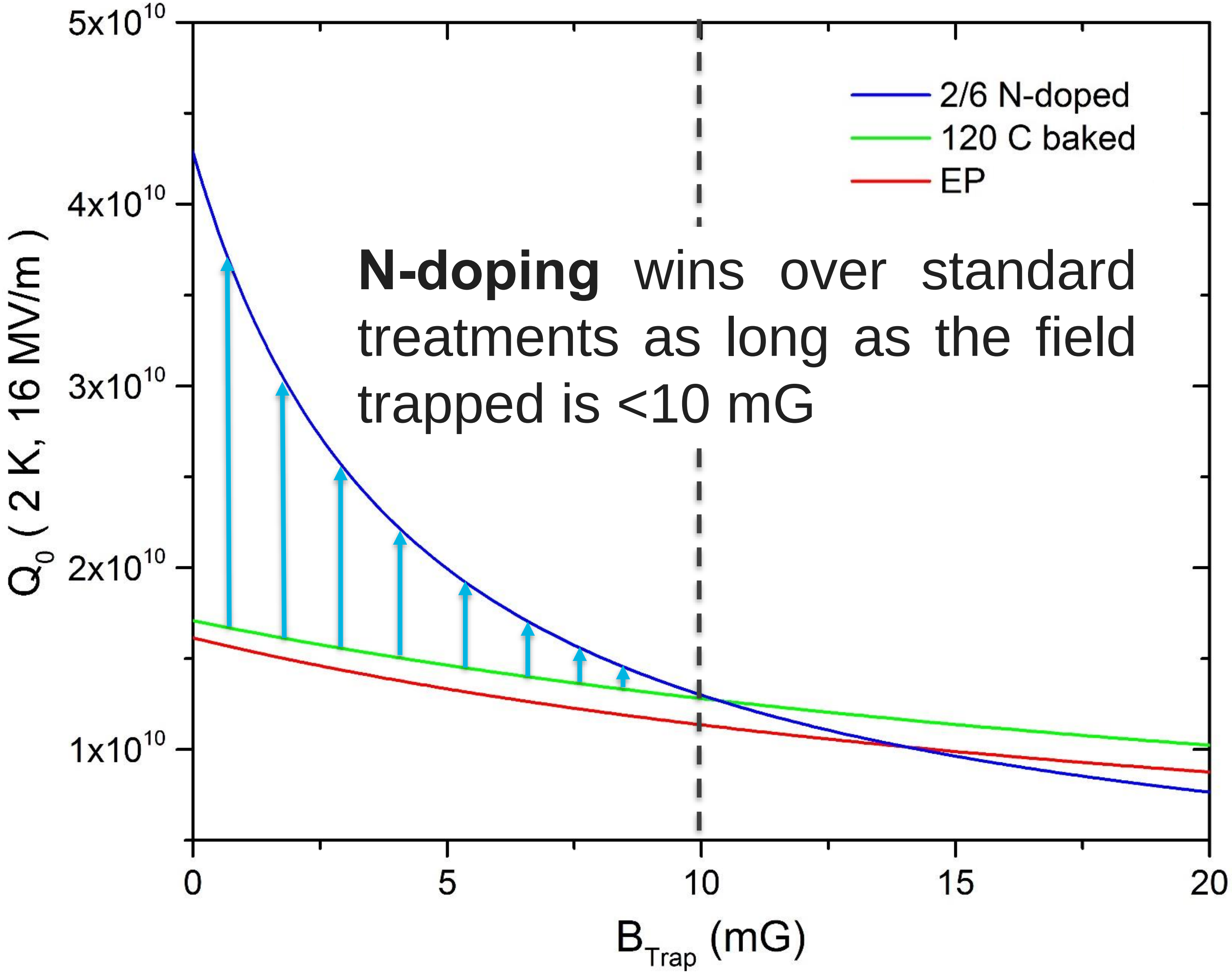
M. Checchin et al., Supercond. Sci. Technol. 30, 034004 (2017)

# Sensitivity for different frequencies



- Trapped flux sensitivity increases with frequency
- The increment strongly depends on the surface treatment, i.e. on the mean free path (see M. Checchin TUYAA03)
- Higher frequencies seem to have a larger field dependence

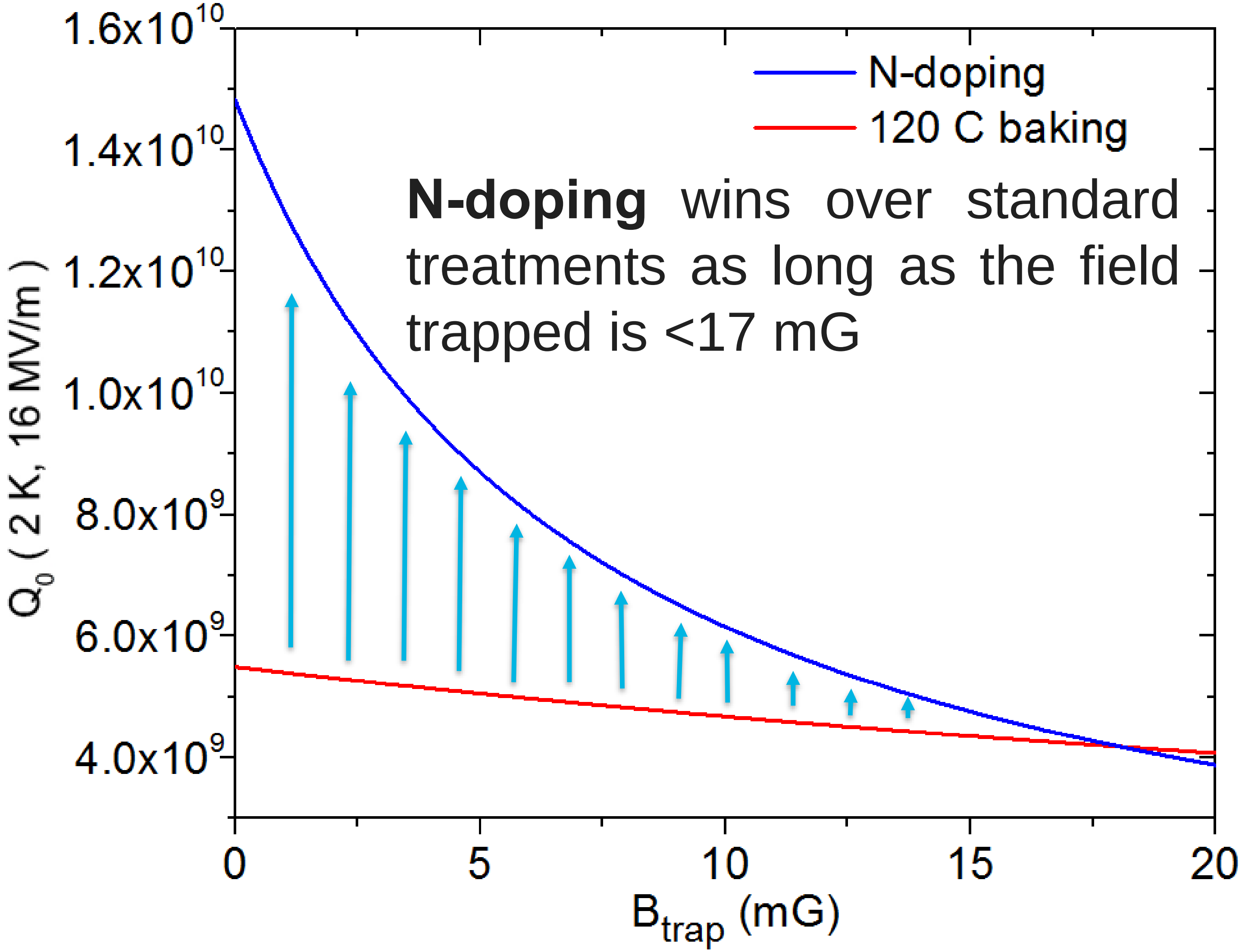
# The advantage of N-doping at 1.3 GHz



**N-doping** wins over standard treatments as long as the field trapped is <10 mG

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

# The advantage of N-doping at 3.9 GHz



**N-doping** wins over standard treatments as long as the field trapped is <17 mG

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# Motivation behind experiments

Composition and mean free path in first nanometers of cavity surface have been shown to be crucial for both Q and gradient performance

**120C baking** lowers the mean-free-path only at the very surface, **leading to high gradients**

120C bake, vacancies in first ~ 60 nanometers

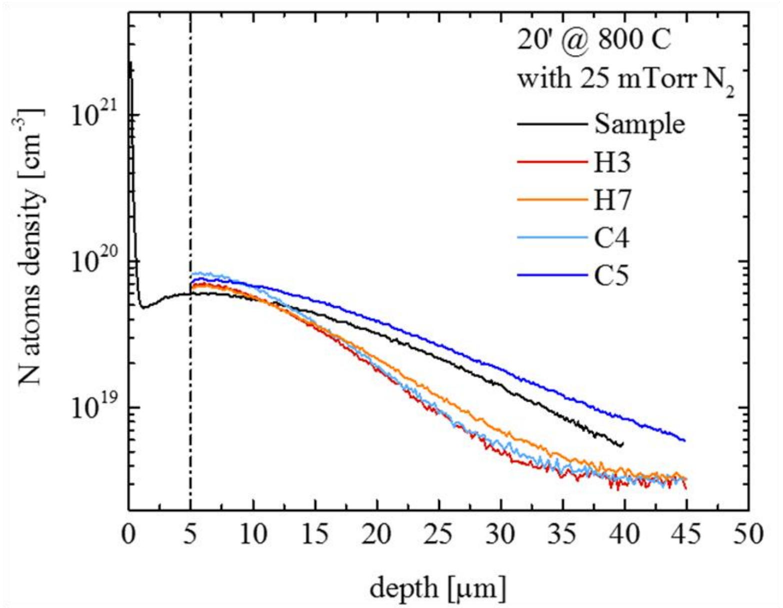
mfp ~ 2-16 nm

mfp ~ 70 nm

A. Romanenko et al, Appl. Phys. Lett. 102, 232601 (2013)

**N-Doping** lowers the mean-free-path throughout several microns, **leading to high Q-factors**

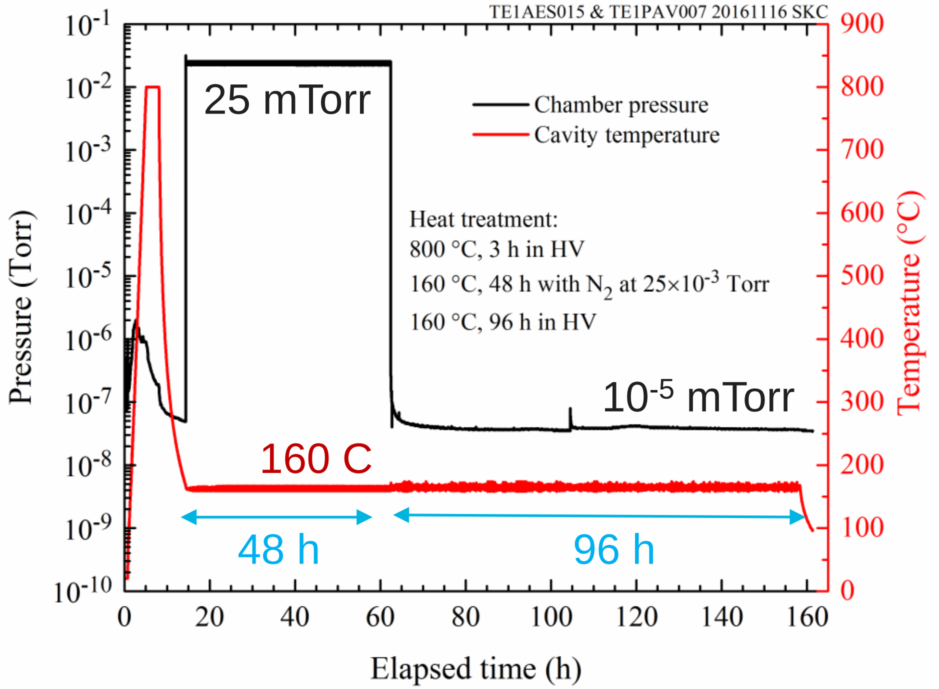
N doping: nitrogen throughout several microns

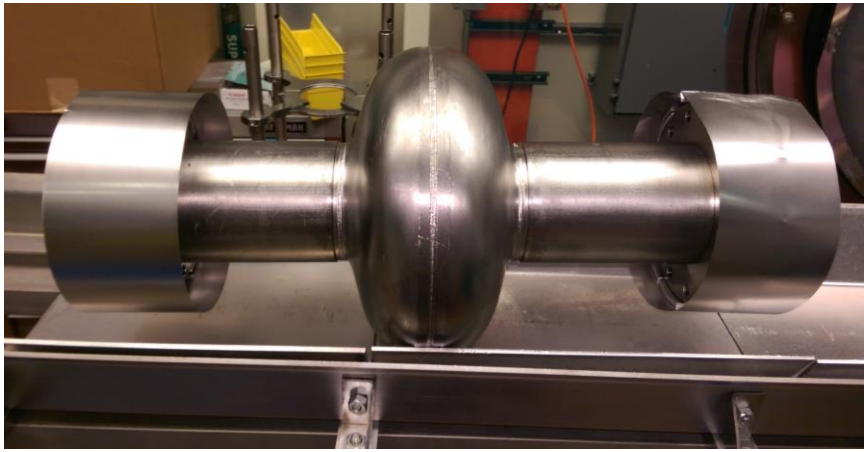


A. Grassellino et al, Proceedings of SRF 2015

# 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





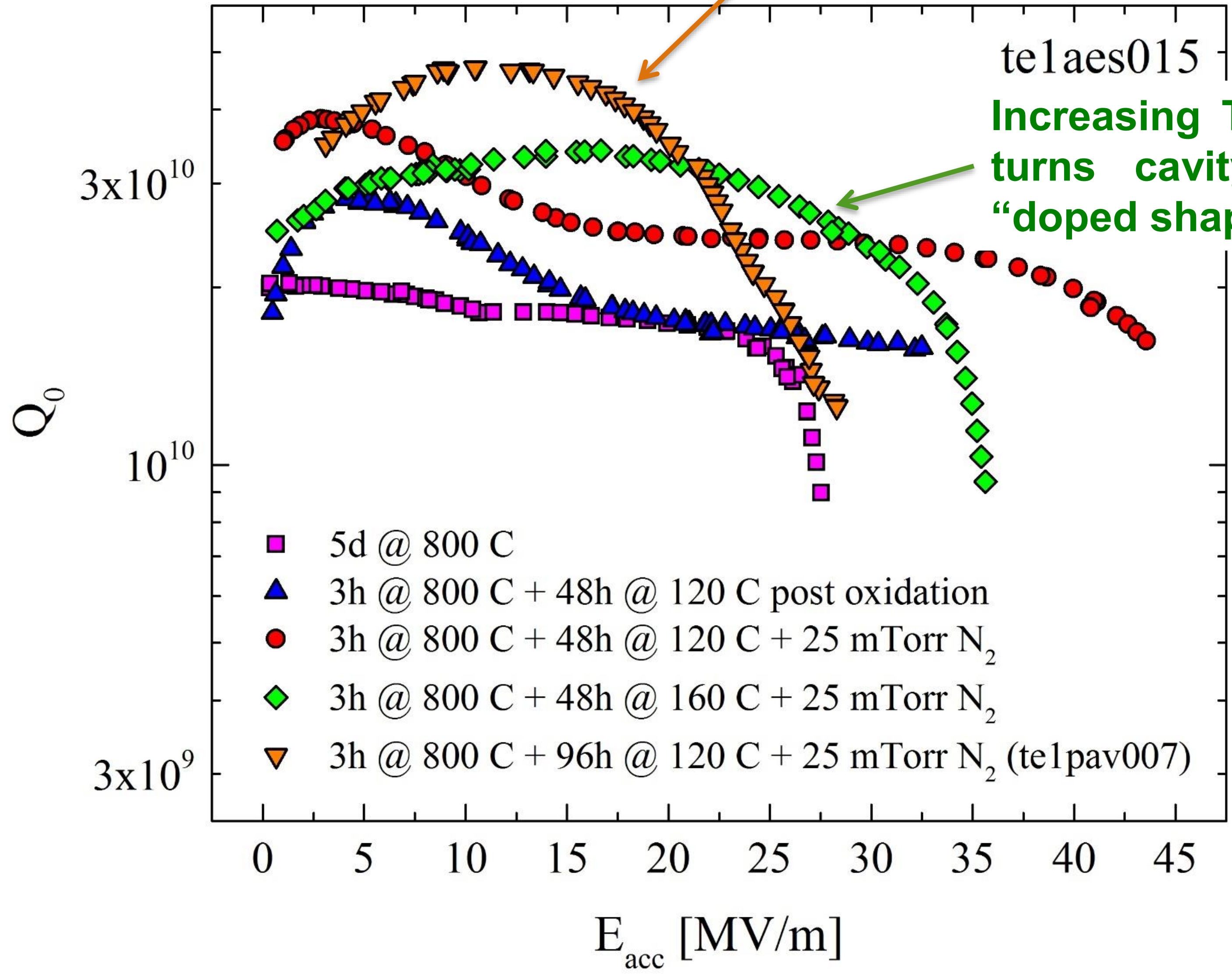
Protective caps and foils are BCP’d prior to every furnace cycle and assembled in clean room, prior to transporting cavity to furnace area

A. Grassellino *et al.*, **arXiv:1305.2182**
A. Grassellino *et al.*, **arXiv:1701.06077** in publication to SUST

# Cavity evolution

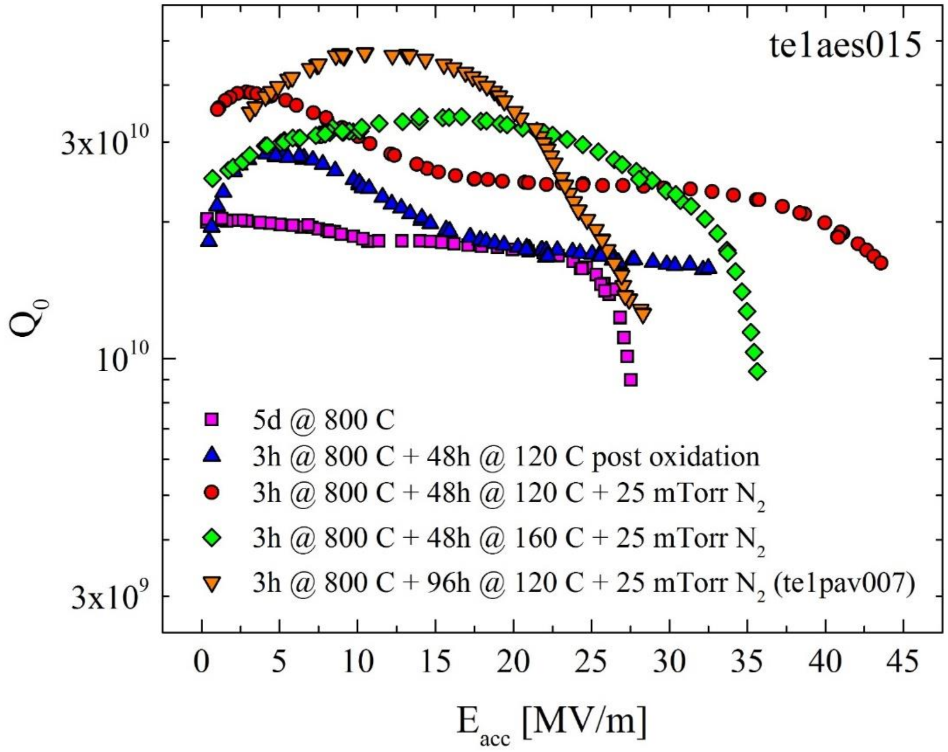
**Increasing duration x 2 turns cavity into "doped shape", even higher Q!**

**Increasing T ~40C turns cavity into "doped shape"!**

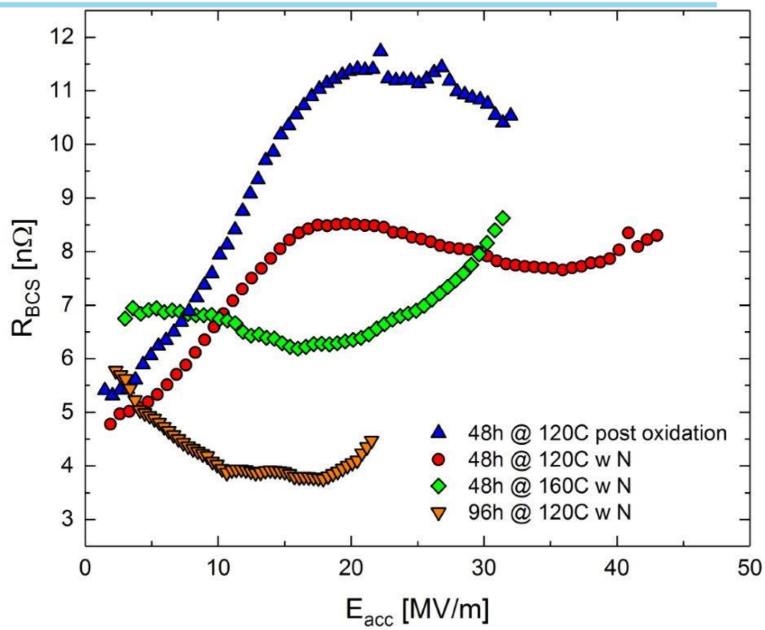


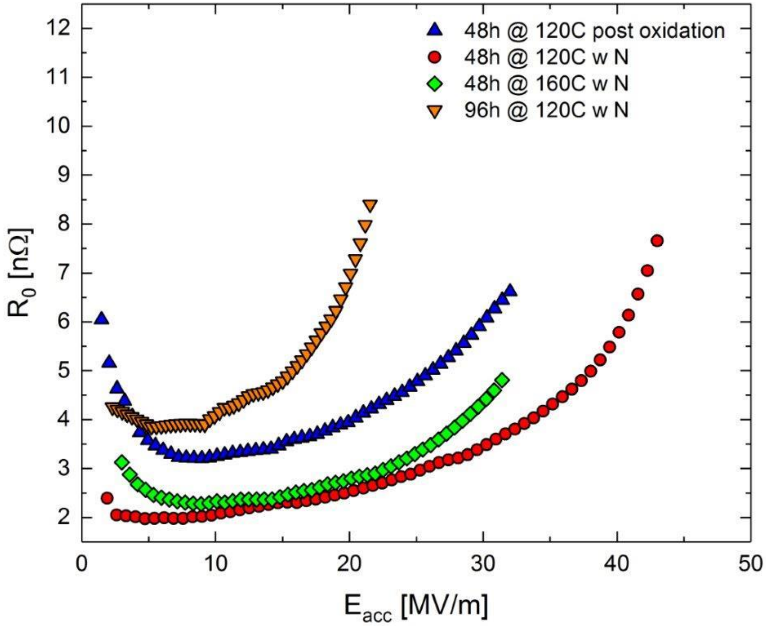
# What gives the Q improvement at high fields?

Improvement stems from both
lower residual and BCS resistance

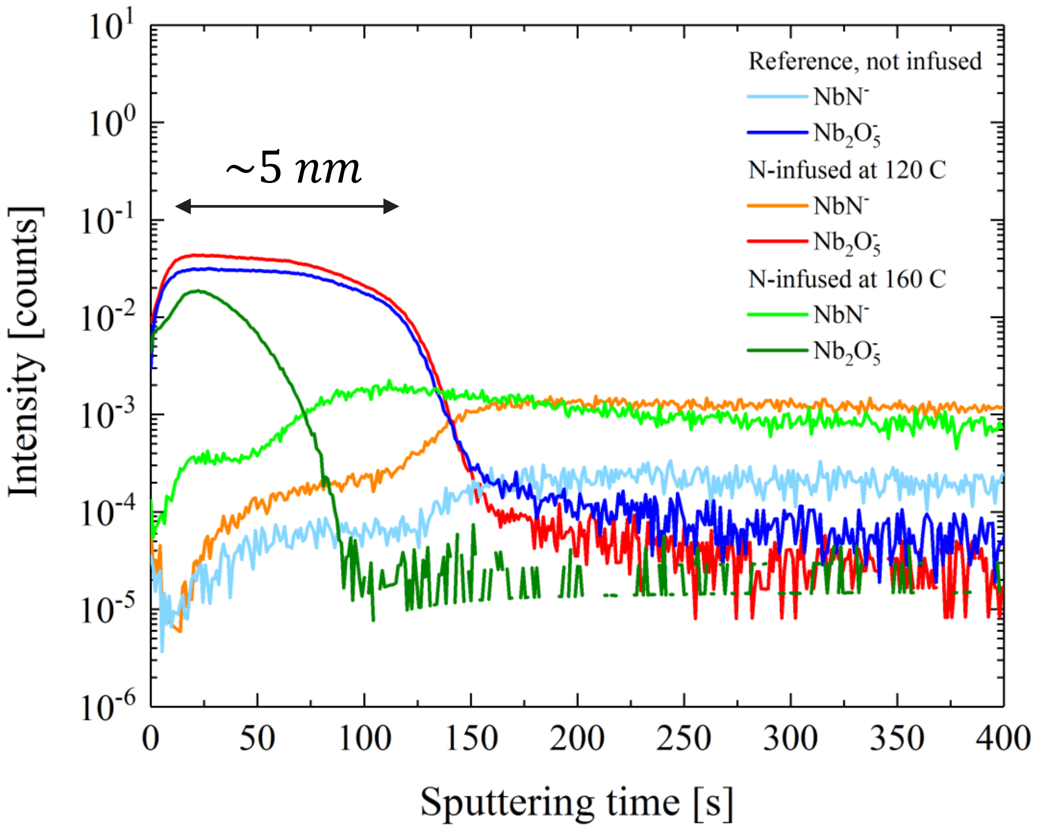


A. Grassellino *et al.*, **arXiv:1701.06077** in publication to SUST





# Role of Nitrogen in N-infusion



No nitrides formation at the RF surface

- Higher $N_2$ background than not infused samples
- Small $(\sim 1 - 2\ nm)$ $N_2$ enriched layer below native oxide
- SIMS data suggest that performances are related to the first nm from the RF surface

A. Grassellino *et al.*, **arXiv:1701.06077** (in publication to SUST)

# Superconductor-Superconductor (Dirty Layer) Potential

- High $\kappa$ film: analytical from London eqs.

  T. Kubo, *Supercond. Sci. Technol.* **30,** 023001 (2017)

RF

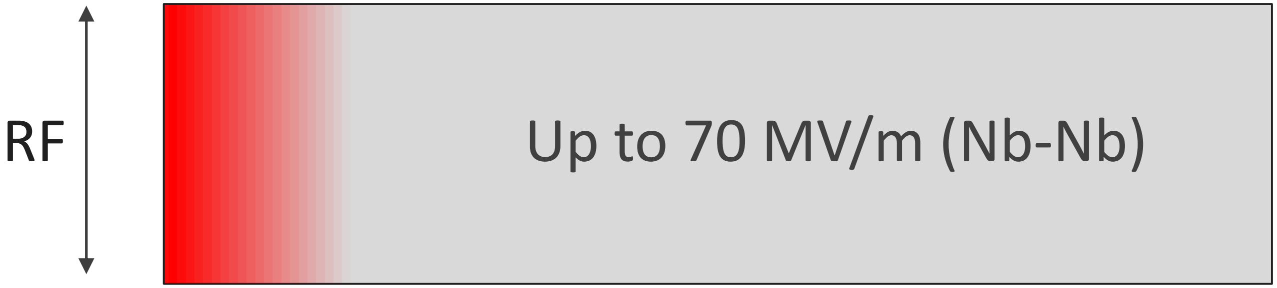
Up to 120 MV/m (thin Nb3Sn-Nb)

High $k$ film

SC bulk

- Diffused $\kappa$ profile: numerical from Ginzburg-Landau eqs.

  M. Checchin *et al.*, IPAC 2016 & LINAC 2016



RF

Up to 70 MV/m (Nb-Nb)

$k$ profile

SC bulk

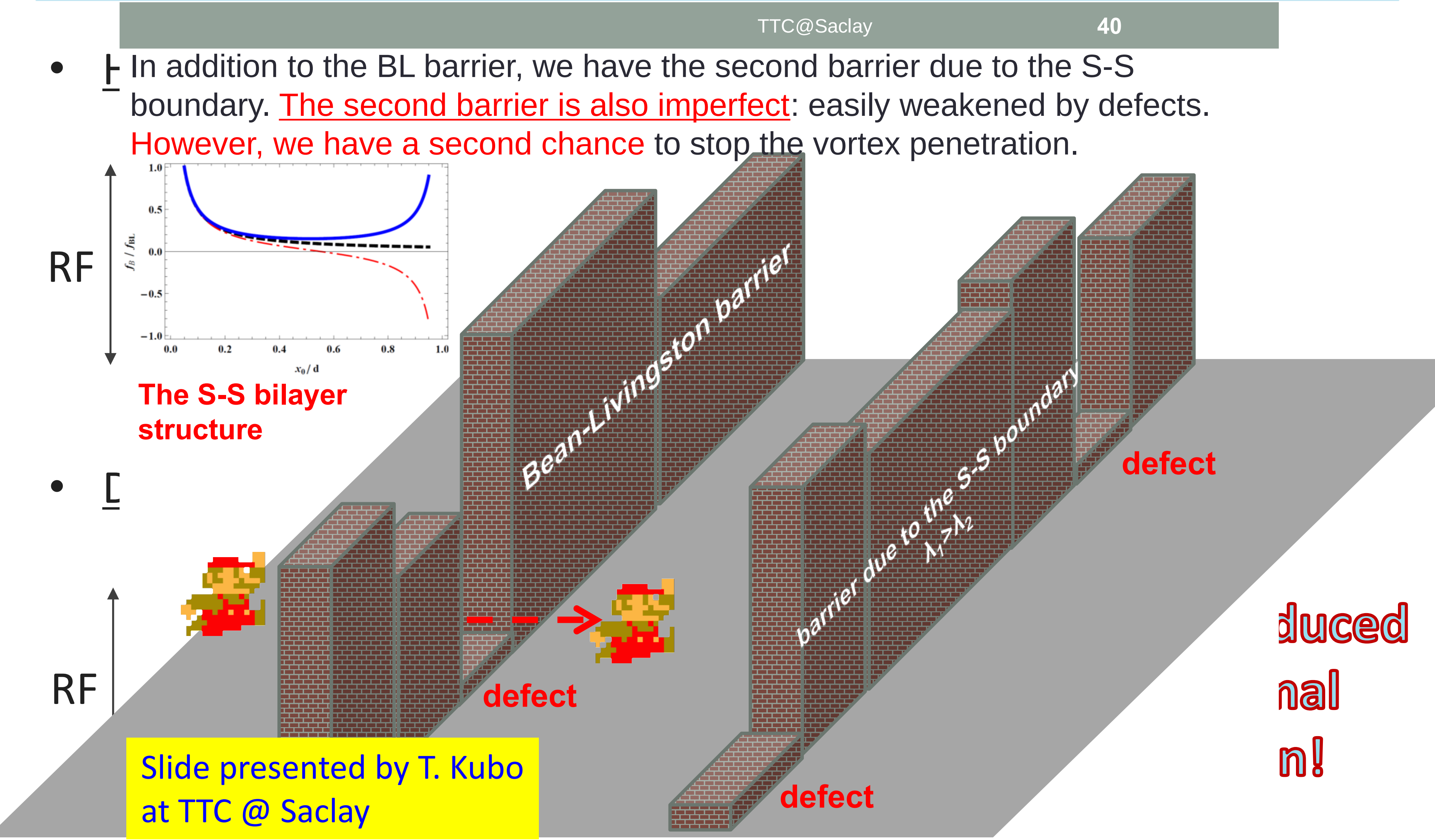
Can be produced by thermal diffusion!

# Superconductor-Superconductor (Dirty Layer) Potential

- H

RF

- D



TTC@Saclay 40

In addition to the BL barrier, we have the second barrier due to the S-S boundary. The second barrier is also imperfect: easily weakened by defects. However, we have a second chance to stop the vortex penetration.

**The S-S bilayer structure**

Slide presented by T. Kubo at TTC @ Saclay

RF

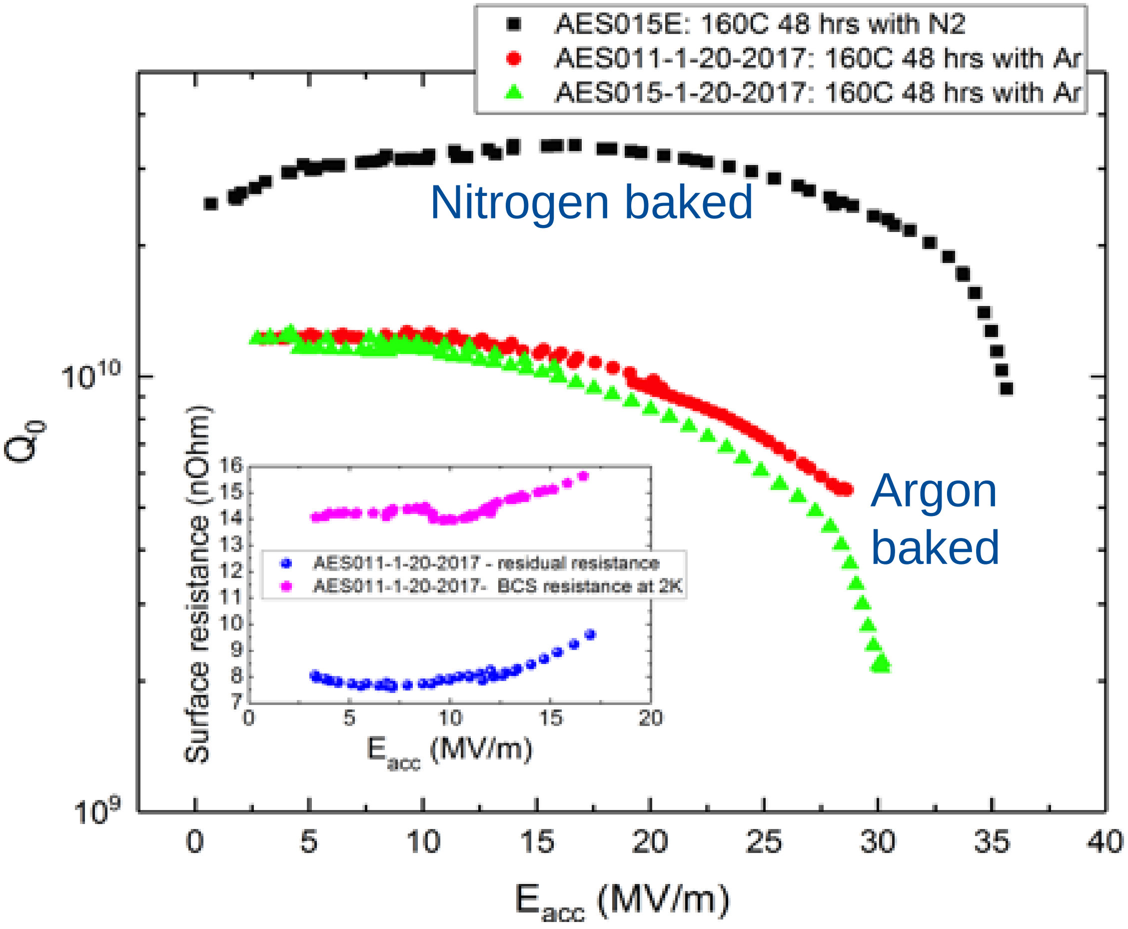
duced

nal

n!

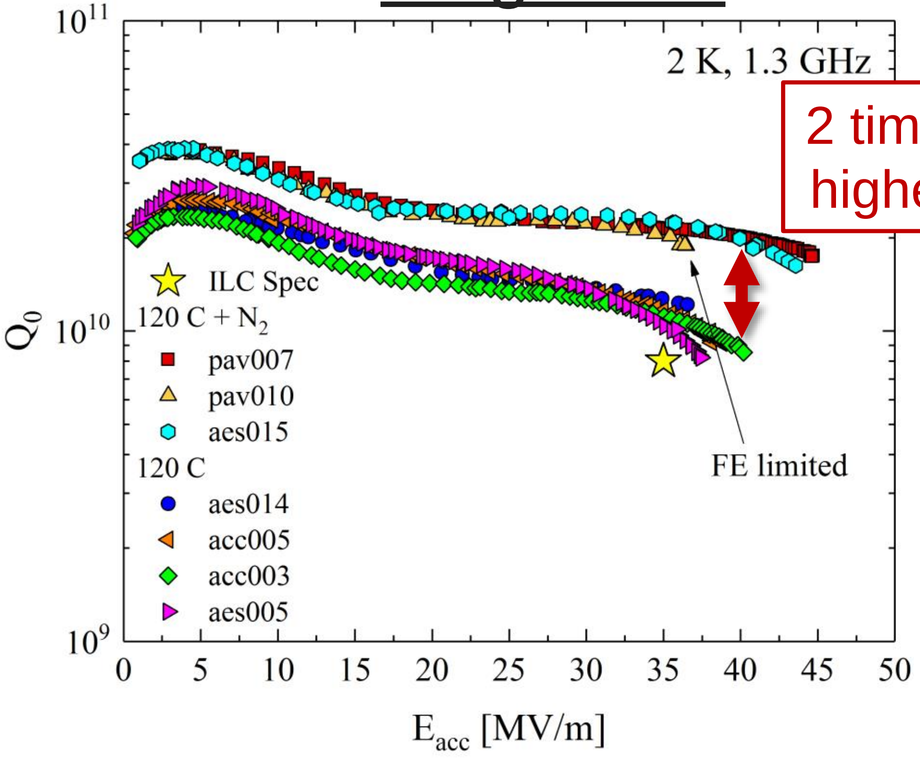
# Is nitrogen really playing a role at 160C (BCS reversal)? YES ✓

- Repeated same procedure with and without nitrogen in furnace at 160C (both of comparable ultra-purity 99.9999%)
- Check if other impurities may be the ones responsible for BCS reversal, rather than nitrogen



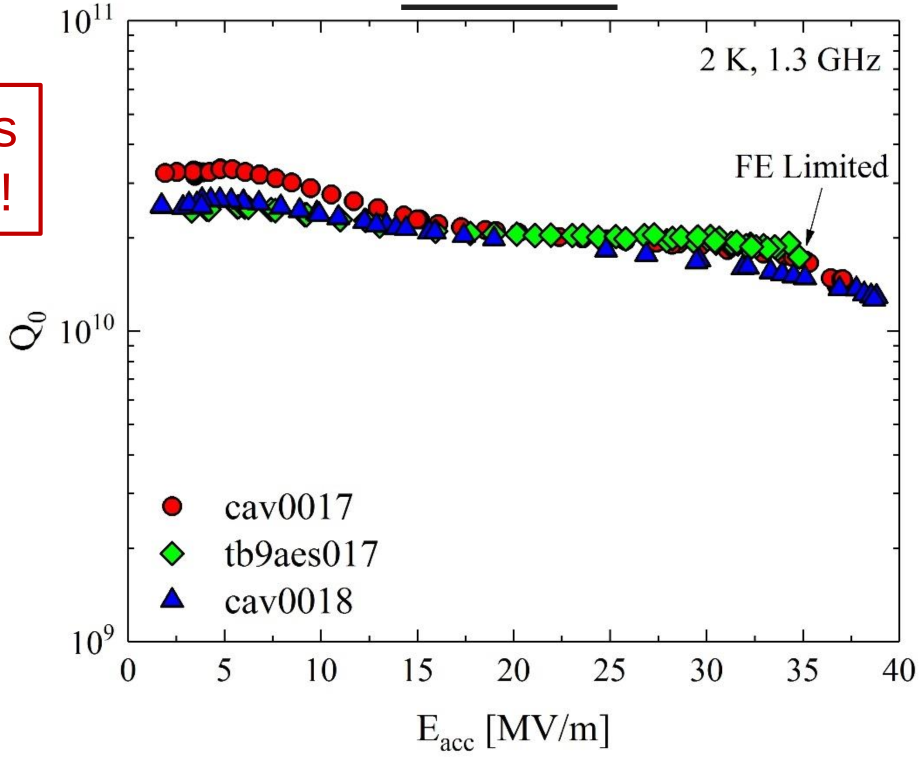
# 120 C N-infusion: high $Q_0$ at high gradients

## Single-cell



2 times higher!

## 9-cells



Higher Q-factor at higher field may allow for higher duty-cycles and therefore higher luminosity!

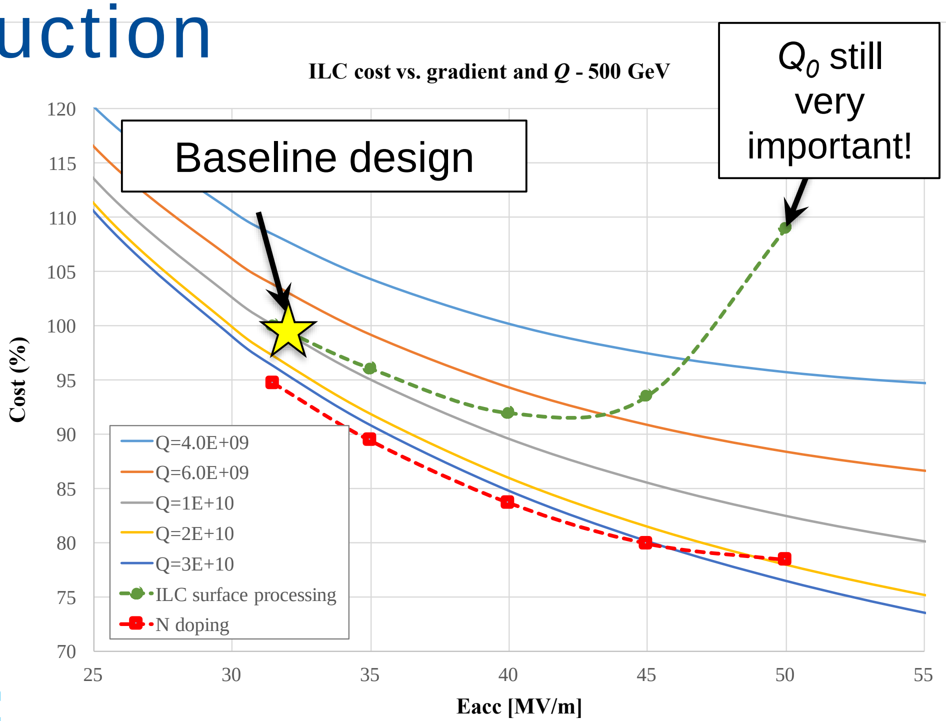
A. Grassellino *et al.*, **arXiv:1701.06077** (in publication to SUST)

# ILC possibility of cost reduction

ILC: 16,000 cavities in 31 km linac

8 cavities

~10 m



Baseline design

$Q_0$ still very important!

*Image from linearcollider.org. Tunnelflug video by European XFEL. Cost analysis by N. Solyak*

# Outline

- Experimental method and parameters extrapolation
- $R_{BCS}$ field dependence
- Trapped flux sensitivity
- N-infusion at 1.3 GHz
- Conclusions

# Conclusions

- *$R_{BCS}$ field-dependence* strongly depends on both the surface treatment and the cavity frequency
  - The reversal of the $R_{BCS}$ field dependence is favorable in presence of interstitial nitrogen and/or high frequency
  - Anti Q-slope observed also in BCP'd 3.9 GHz cavities

- The *trapped flux sensitivity* shows a bell-shaped trend as a function of the mean free path
  - At 1.3 GHz the maximum of the curve coincides with over-doped cavities
  - N-doping still favorable at 1.3 GHz compared with standard treatment if $B_{trap} < 10$ mG
  - For same mfp, sensitivity increases with the frequency

- *N-infusion* capable to modify cavity surface at the nm scale, resulting in high Q-factor at high gradient
  - Very promising for ILC cost reduction

# Thank you for your attention!