Investigating the Anomalous Frequency Variation Near T_c of Nb SRF Cavities

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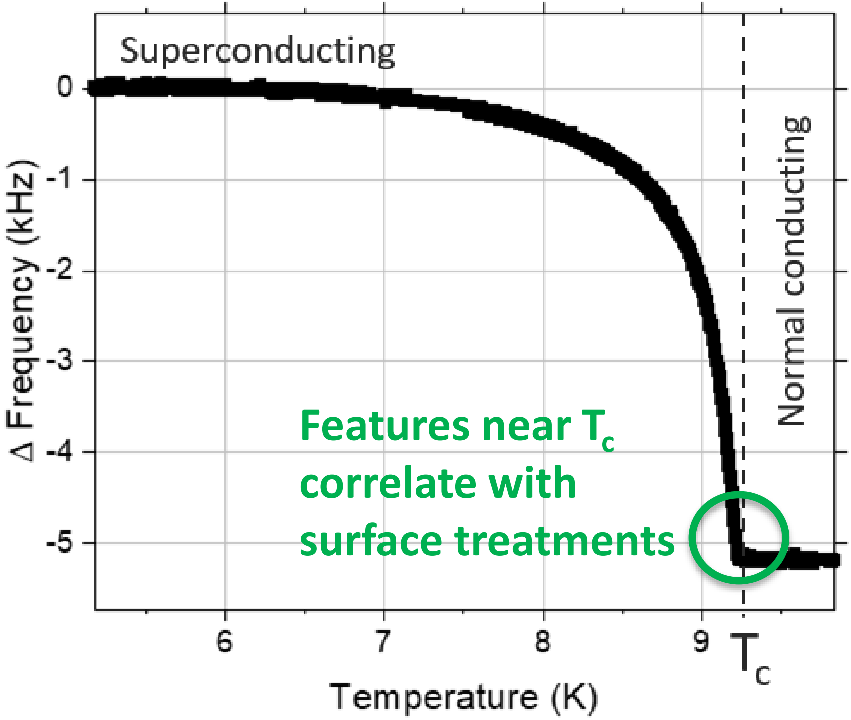
SRF'21

Using Frequency Response of Cavities to Explore Performance

- Usual lens: Q_0 (or R_s) vs E_{acc}
- f_0 vs temperature gives information on the SCing carriers
  - Use VNA at low power while warming slowly
- Use $\Delta f_0(T)$ to gain insight on fundamental properties that enable exceptional performance
  - N-Doping
  - Mid-T baking
  - Low Temperature baking

Common Frequency vs T Curve of a 1.3 GHz Nb Cavity



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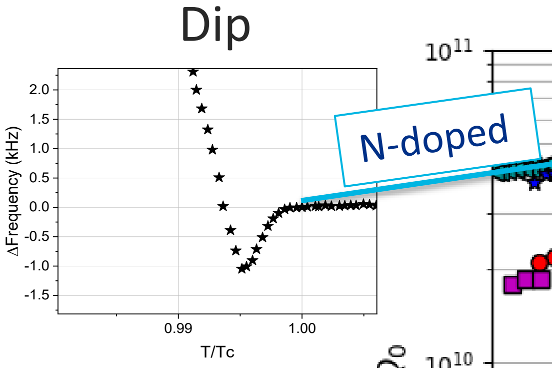
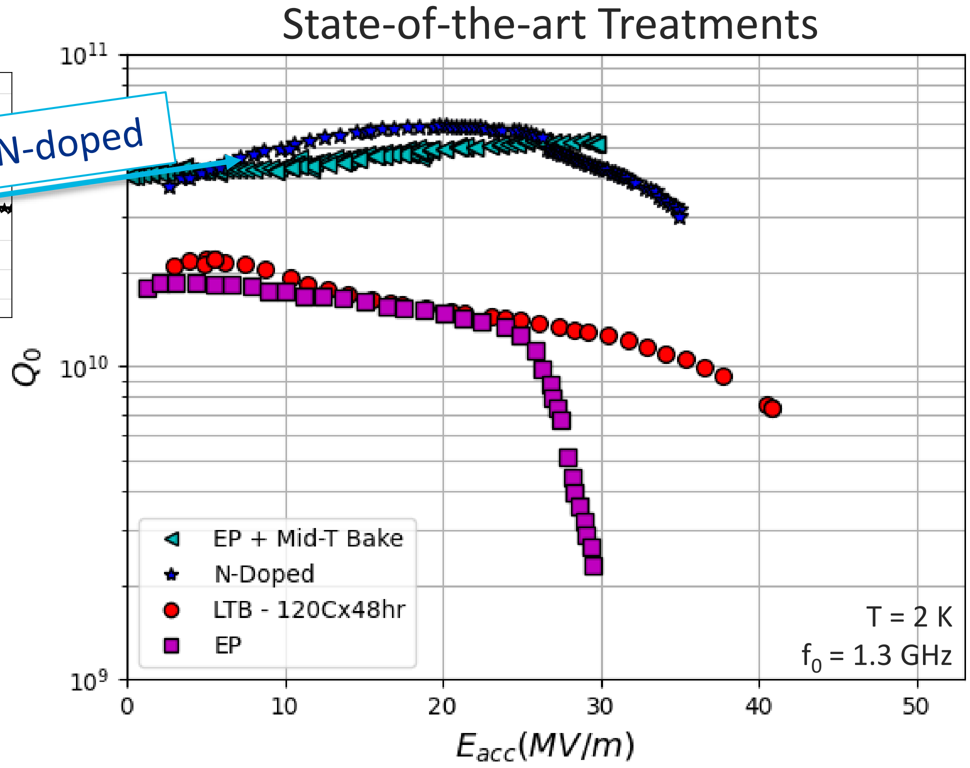
SRF'19: Correlating Frequency Features with Surface Treatment





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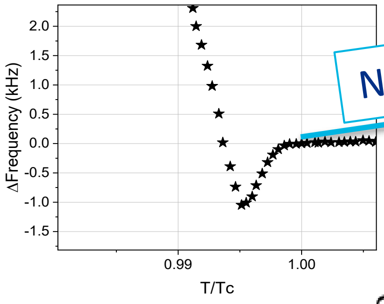
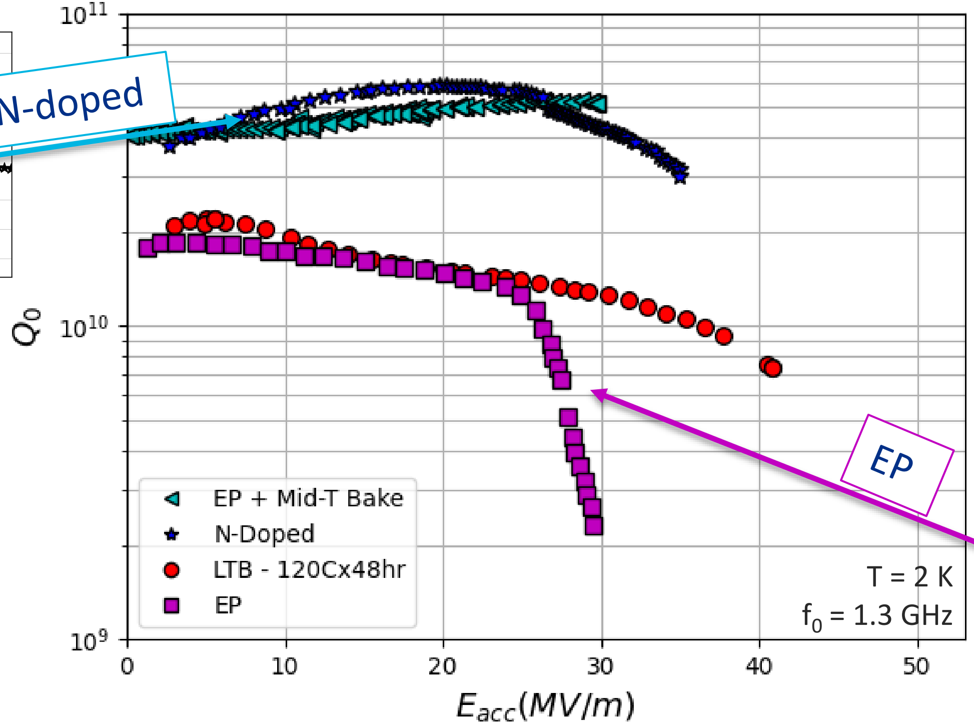
SRF'19: Correlating Frequency Features with Surface Treatment

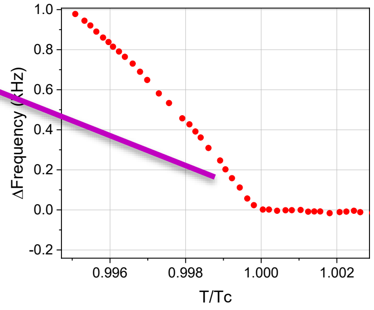
Dip



State-of-the-art Treatments



Standard



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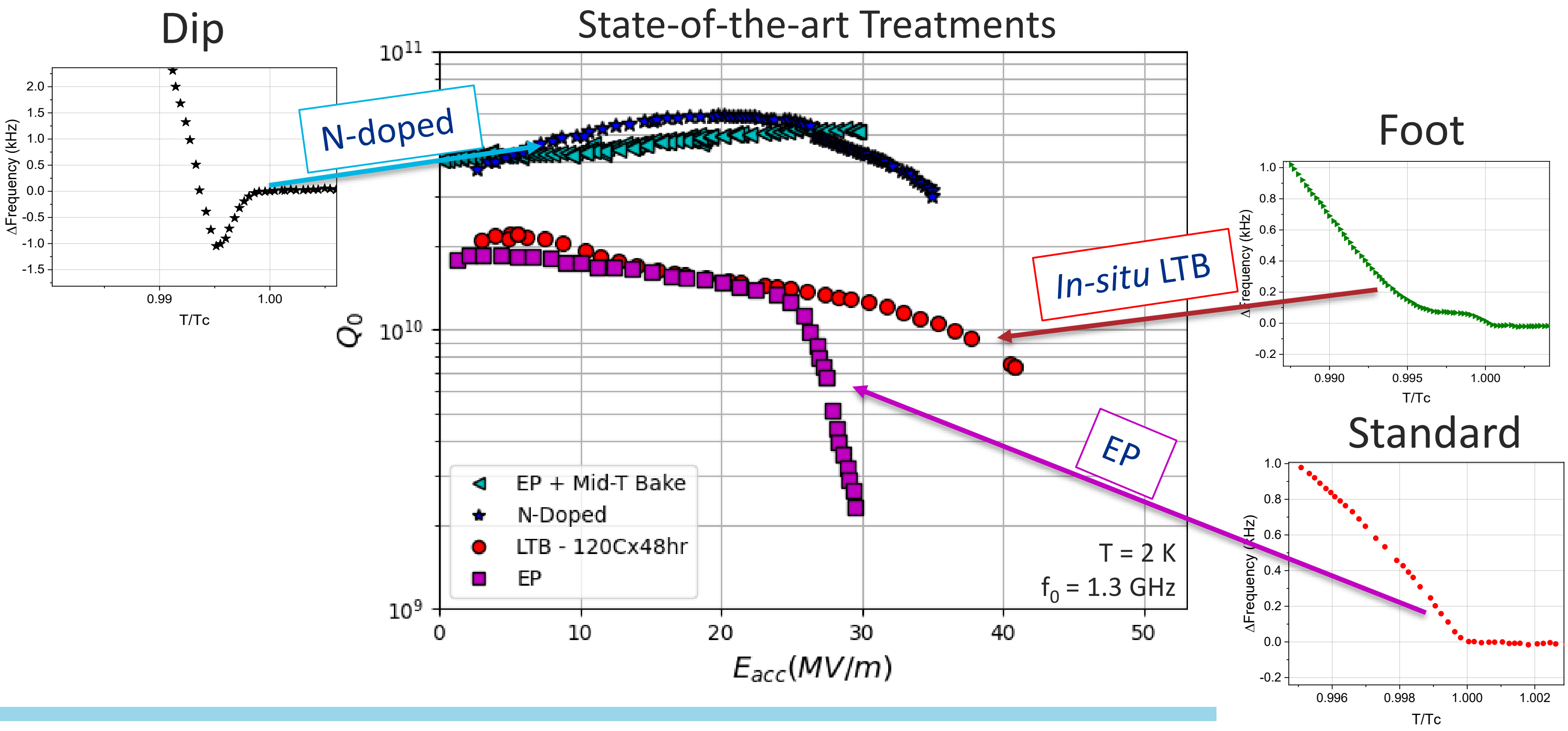

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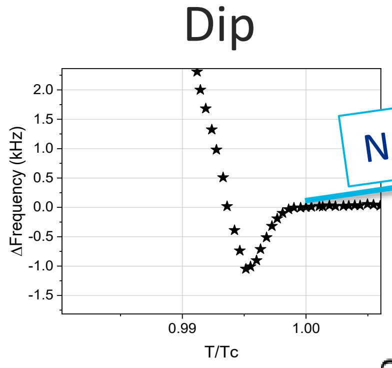
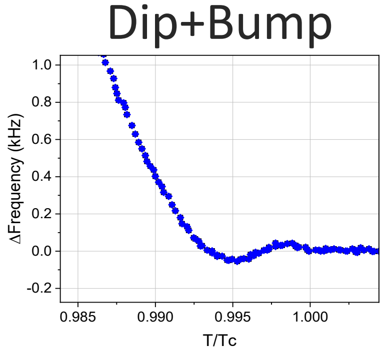
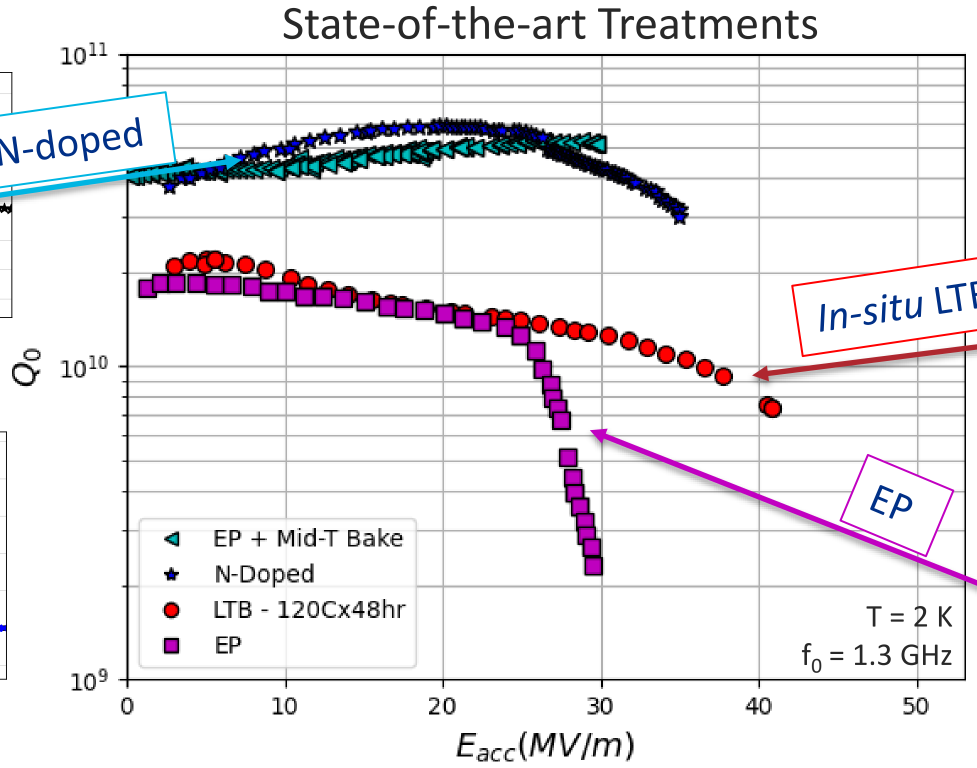
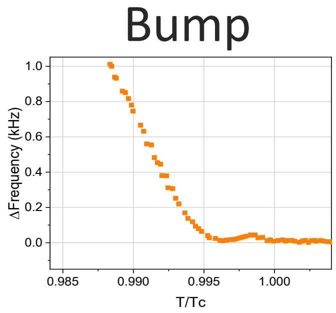
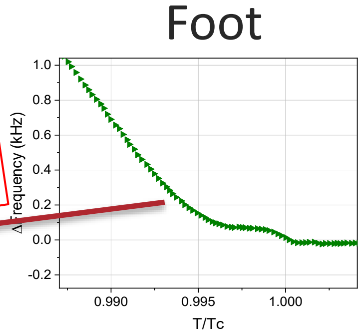
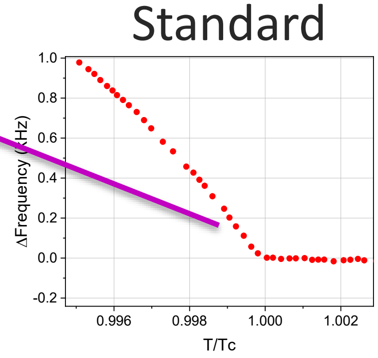












Study #1: Effect of Nitrogen Concentration on the Dip

- One 1.3 GHz SRF single-cell cavity subjected to a single N-doping treatment
- Cavity was tested after **sequential removal of the surface via EP**
- **More removal = lower concentration of nitrogen in RF layer**

1.3 GHz single cell

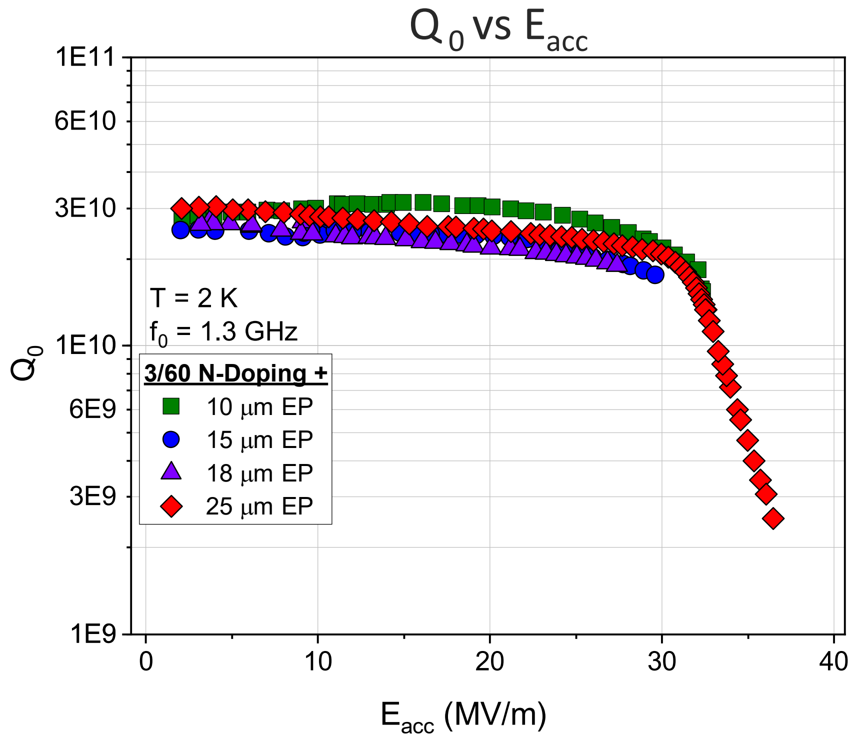
+

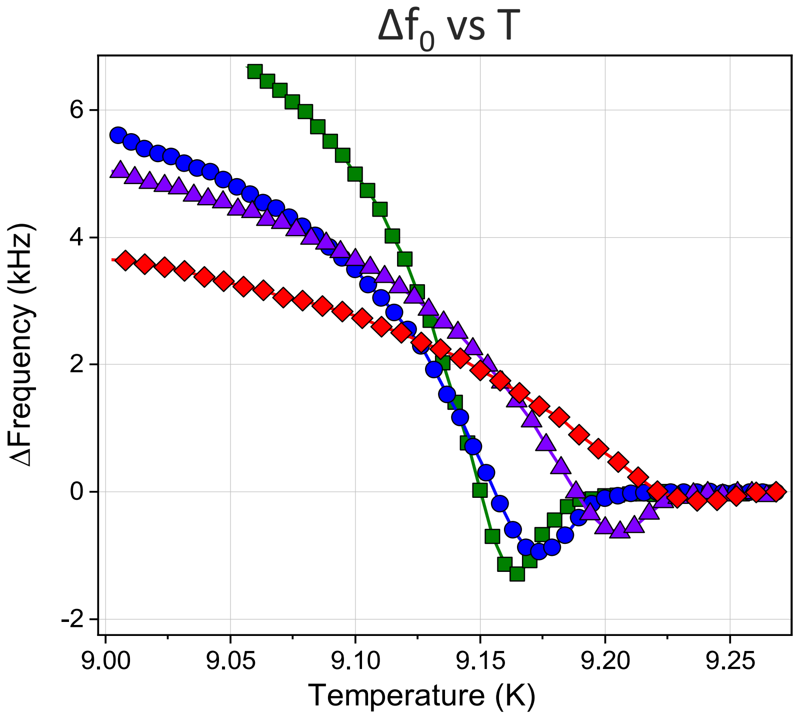
3/60 N-Doping
800Cx3hrs in UHV
800Cx3min in 25 mTorr N
800Cx60min in UHV

+

Total Removal via EP
+10 μm
+15 μm
+18 μm
+25 μm
+30 μm

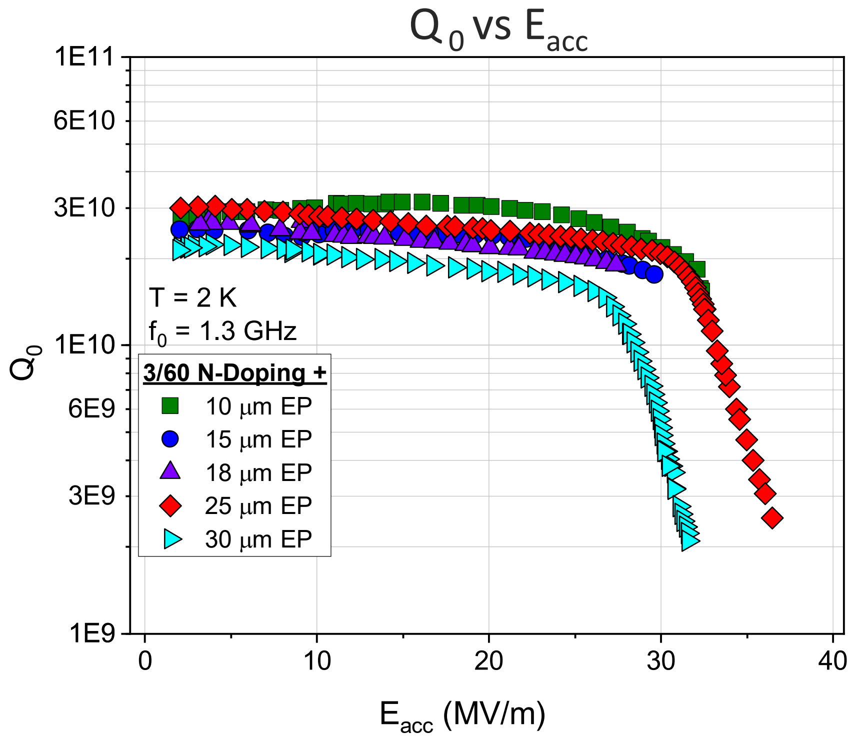
Effect of Nitrogen Concentration on Dip

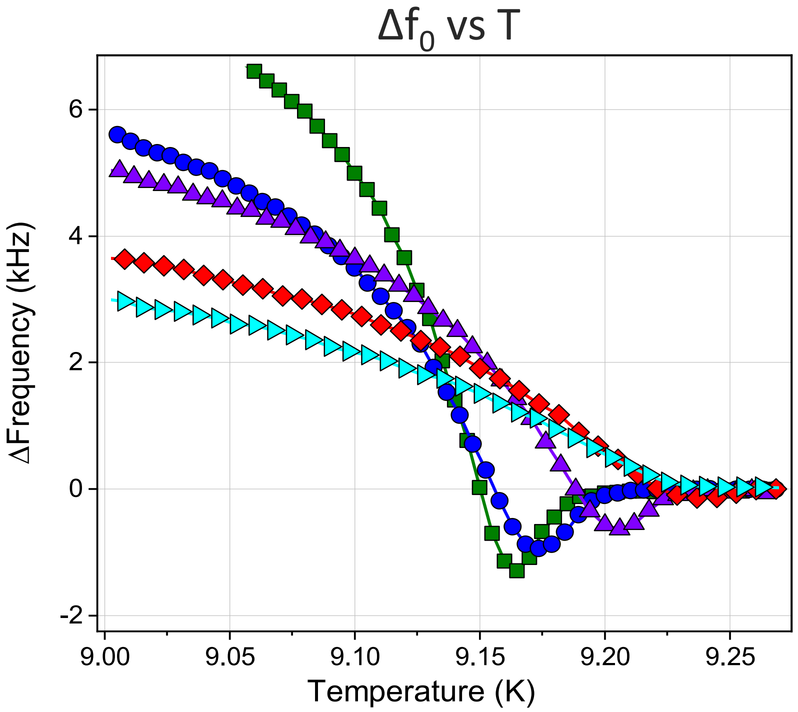




Effect of Nitrogen Concentration on Dip

- After a total removal of **+30um EP**: standard HFQS occurs, dip disappears

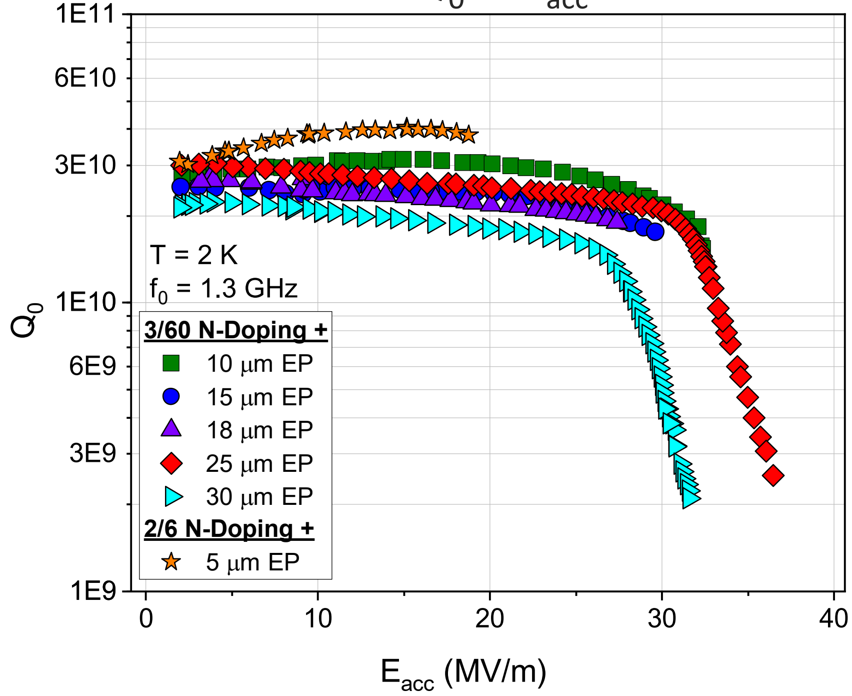




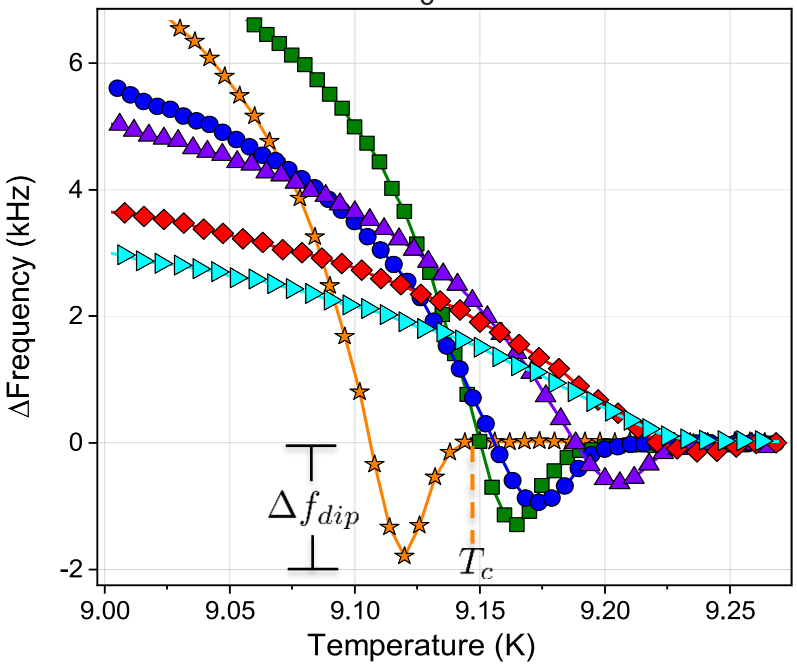
Effect of Nitrogen Concentration on Dip

- After a total removal of **+30um EP**: standard HFQS occurs, dip disappears
- After reprocessing with **2/6 N-doping**: highest Q_0 achieved, largest dip

Q_0 vs E_{acc}



Δf_0 vs T



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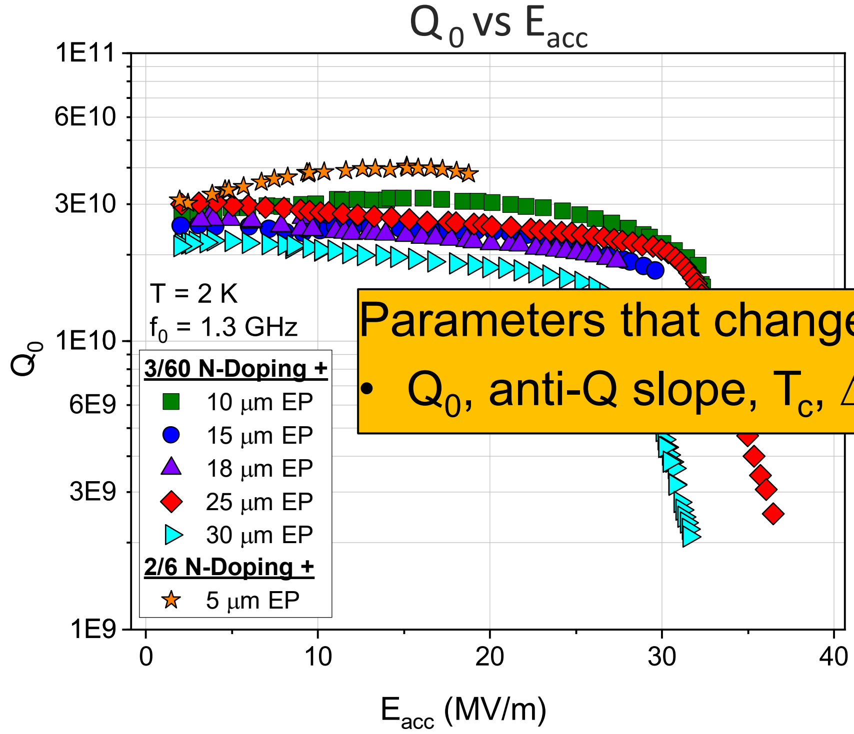

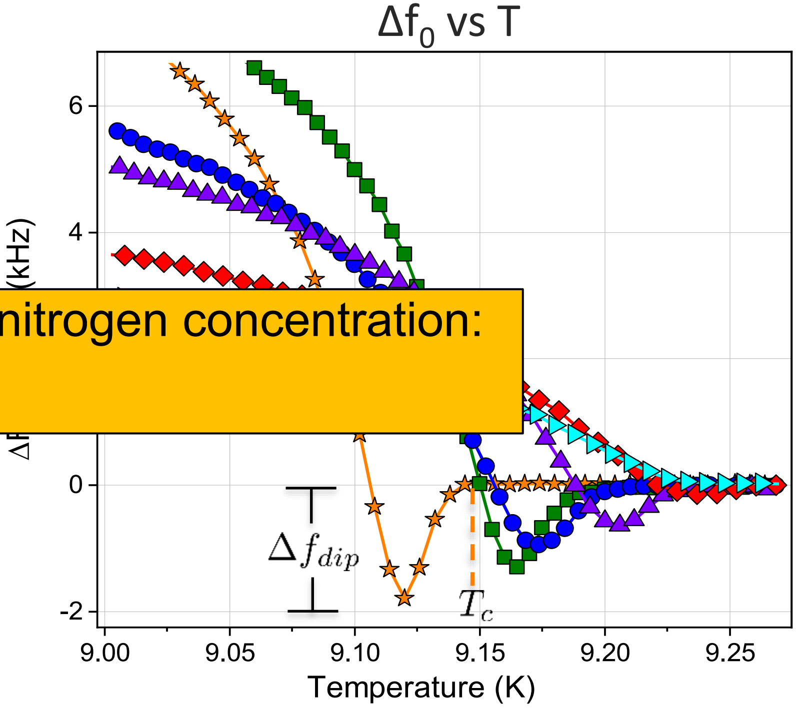

Parameters that change with nitrogen concentration:

- Q_0, anti-Q slope, T_c, Δf_{dip}

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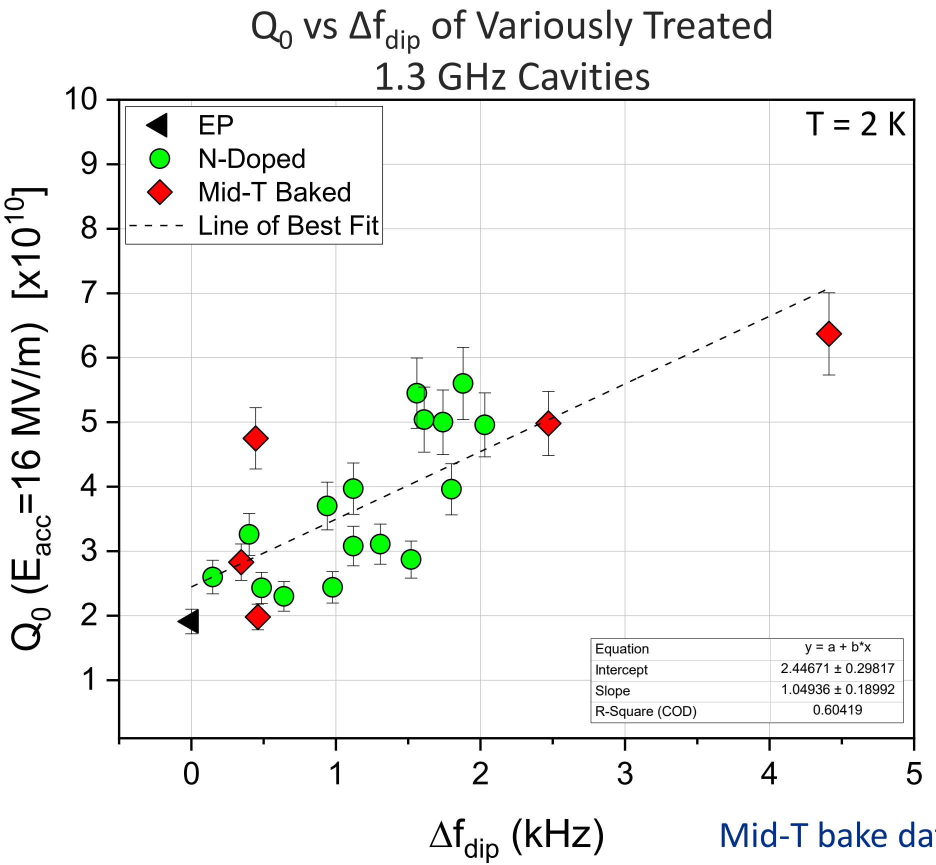
Correlating Quality Factor at 16 MV/m with Dip Magnitude



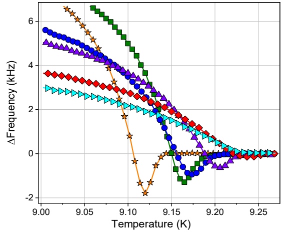
Linear relationship between quality factor and dip magnitude

Both Q_0 and dip tied to same interface properties

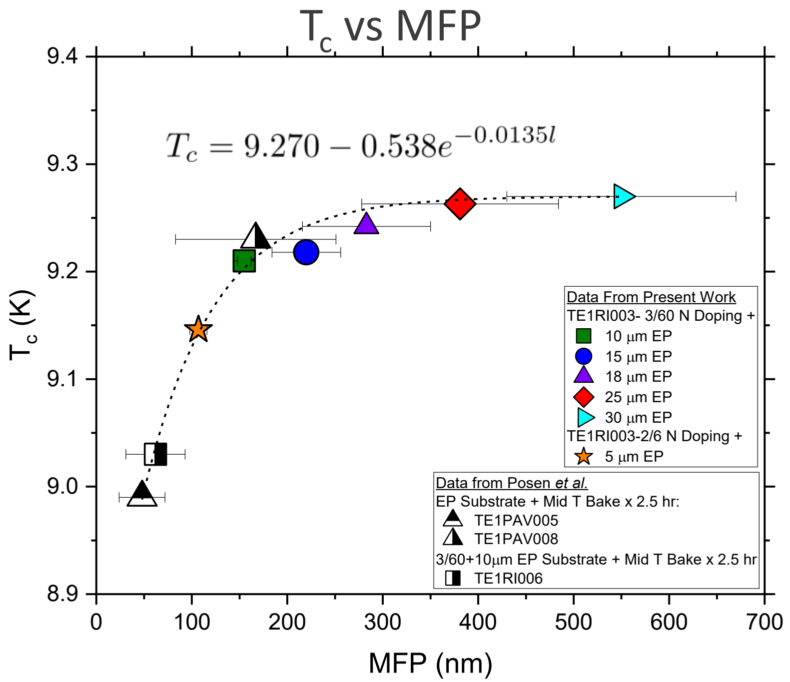
May estimate Q_0 (E_{acc}=16 MV/m) from low power (~10mW) measurements

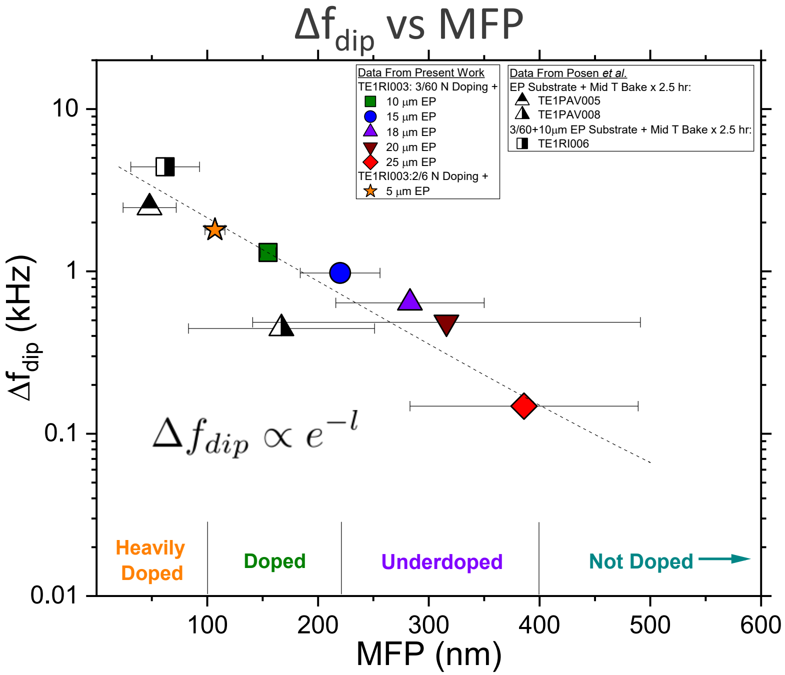
Mid-T bake data comes S. Posen *et al.* Phys. Rev. Appl. **13**, 014024 (2020)

Tracking Δf_{dip} and T_c Evolution with Average MFP



- Fitted Δf_0 vs T curves to extract the avg e^- MFP (distance between N impurities)
- T_c and Δf_{dip} depend on MFP ➔ may serve as a measure of N-doping level





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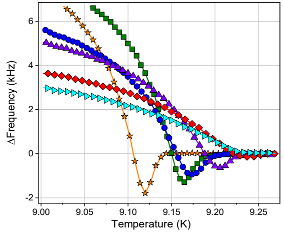
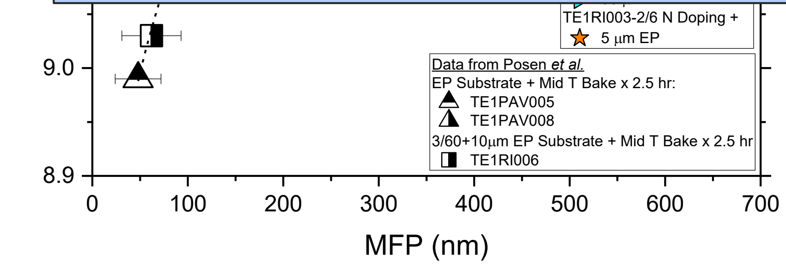
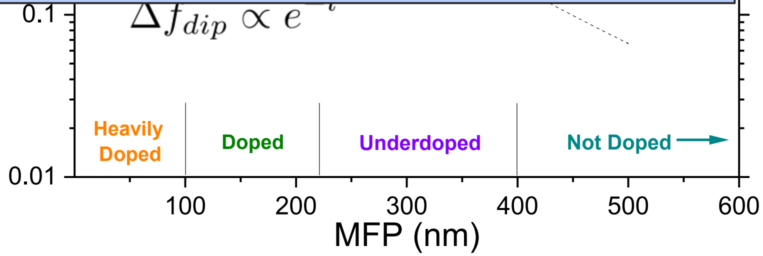


Conclusions of study #1:

- **N concentration plays a crucial role in both RF performance and the dip in Δf_0 vs T**
  - **Both tied to same interface properties**
- **Dip magnitude and anti-Q slope appear to be related**





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Study #2: Effect of Low T Baking on Frequency Features Near T_c

- One 1.3 GHz SRF single-cell cavity was subjected to sequential rounds of *in-situ* low temperature baking at 200 C and tested after each step
- Cavity maintained vacuum throughout entire study

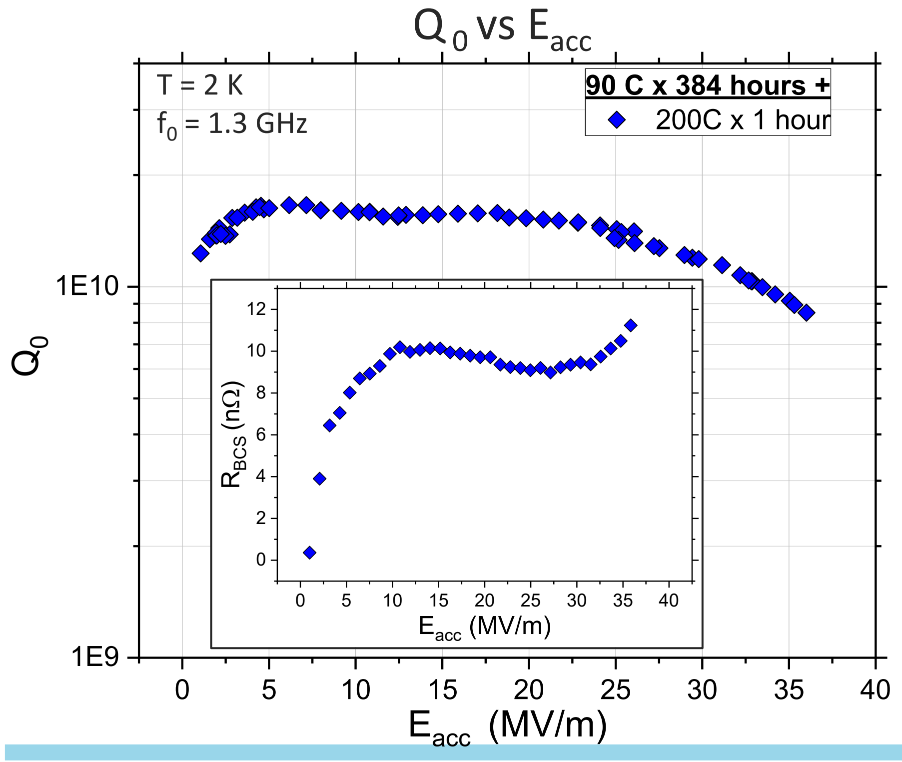
1.3 GHz single cell

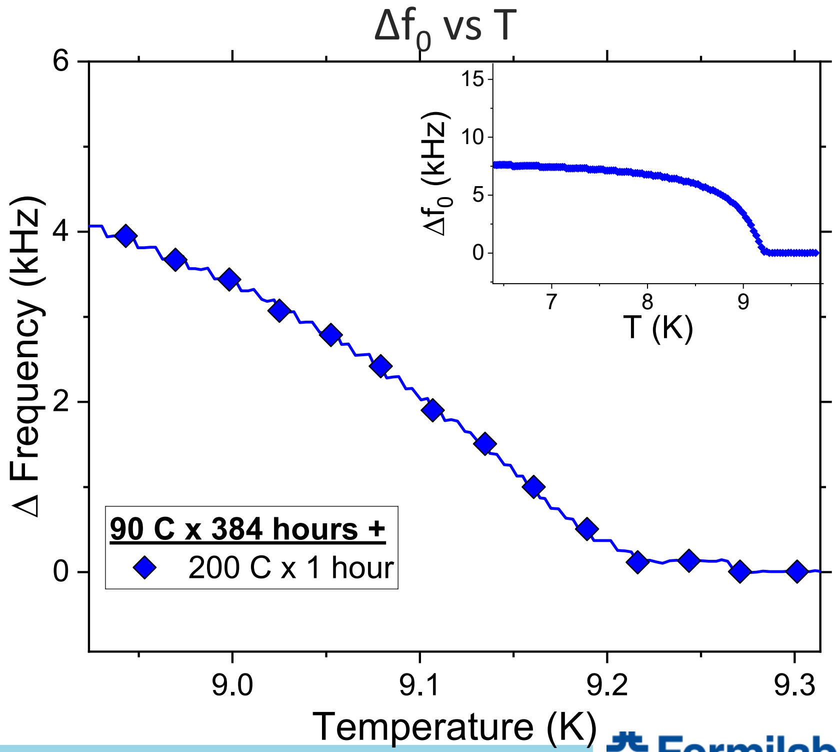
+

Low Temperature Bake
90 C x 384 hours
+200 C x 1 hours
+200 C x 11 hours

Effect of Low T Baking on Frequency Features Near T_c

- Slight "foot" feature just before T_c





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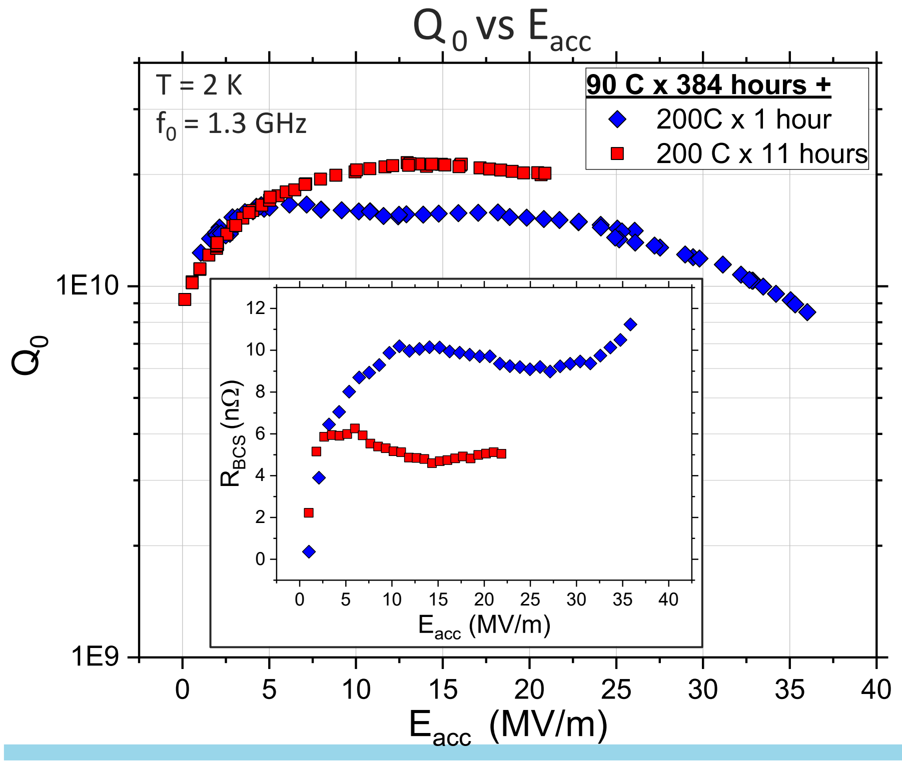
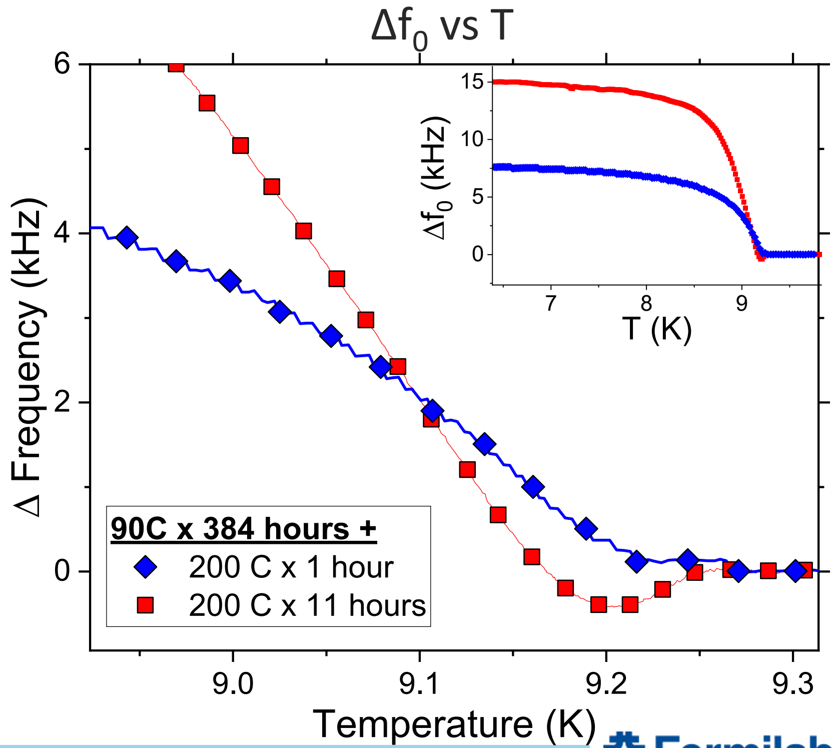
Effect of Low T Baking on Frequency Features Near T_c

- Slight "foot" feature just before T_c
- Anti-Q slope and frequency dip unexpectedly present after **200C x 11 hours!**





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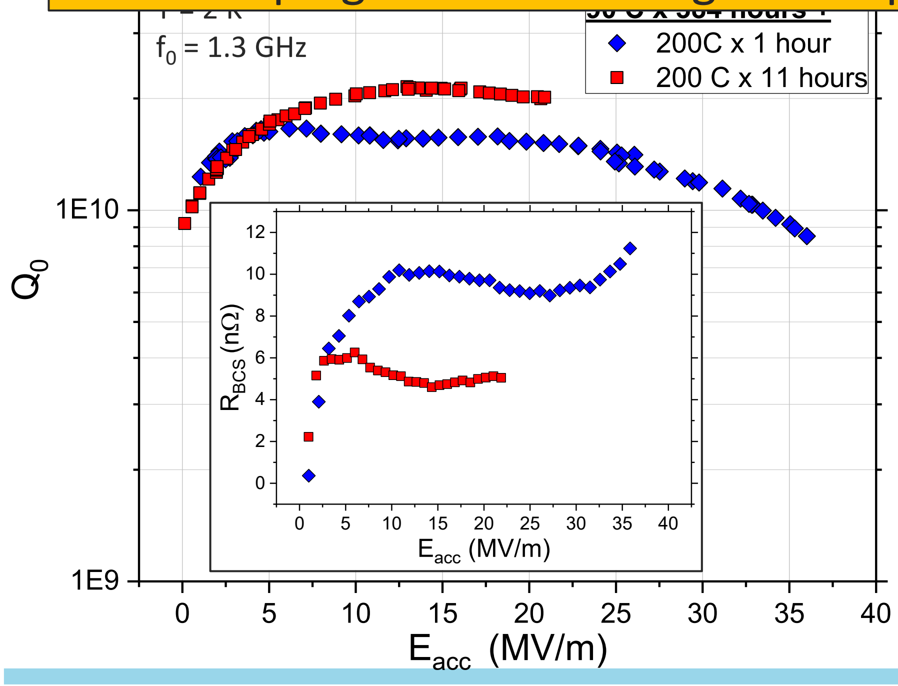
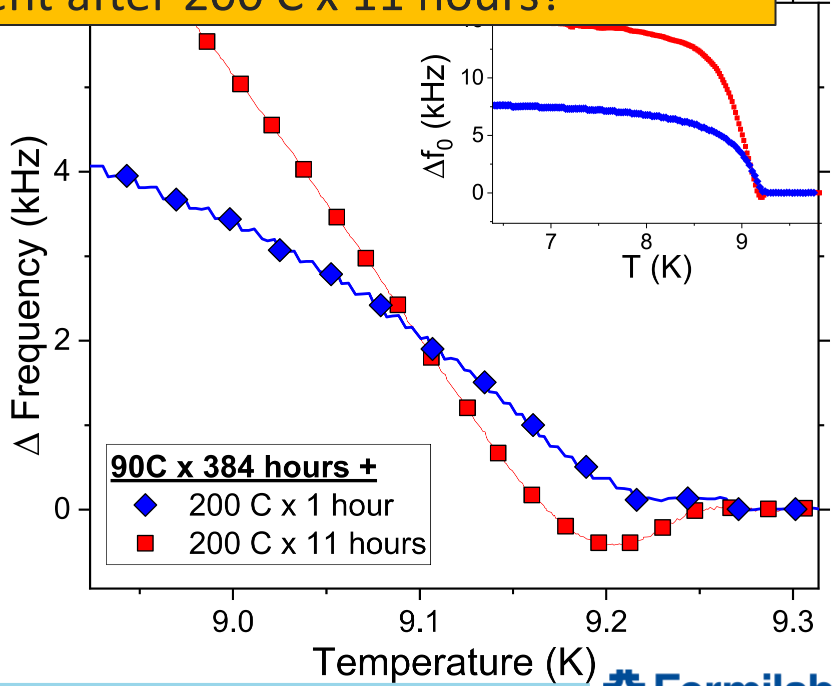
Effect of Low T Baking on Frequency Features Near T_c

- Slight "foot" feature just before T_c

Previously saw that anti-Q slope and frequency dip were driven by N impurities after N-doping or mid-T baking → Is N present after 200 C x 11 hours?



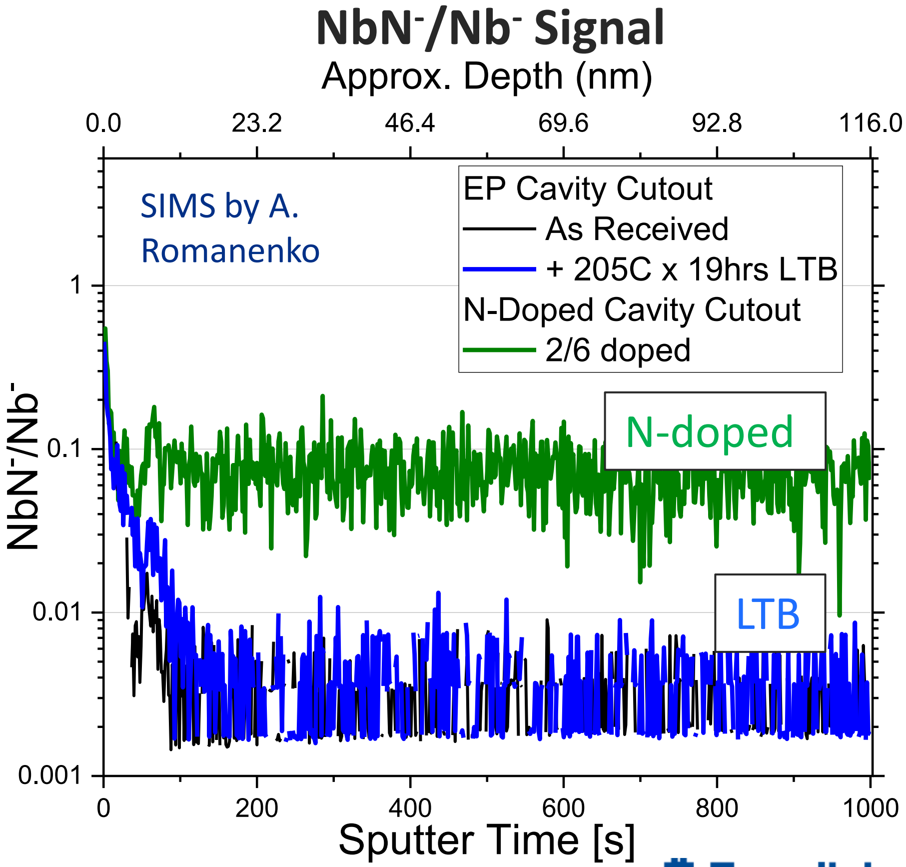


TOF-SIMS Studies on Cavity Cutouts Post Low T Baking

Depth profiles with TOF-SIMS after *in-situ* baking treatments EP cavity cutouts ➔ replicates treatment

- **205 C x 19 hours LTB**
  - Much lower NbN^- signal than what is achieved from an N-doped cutout

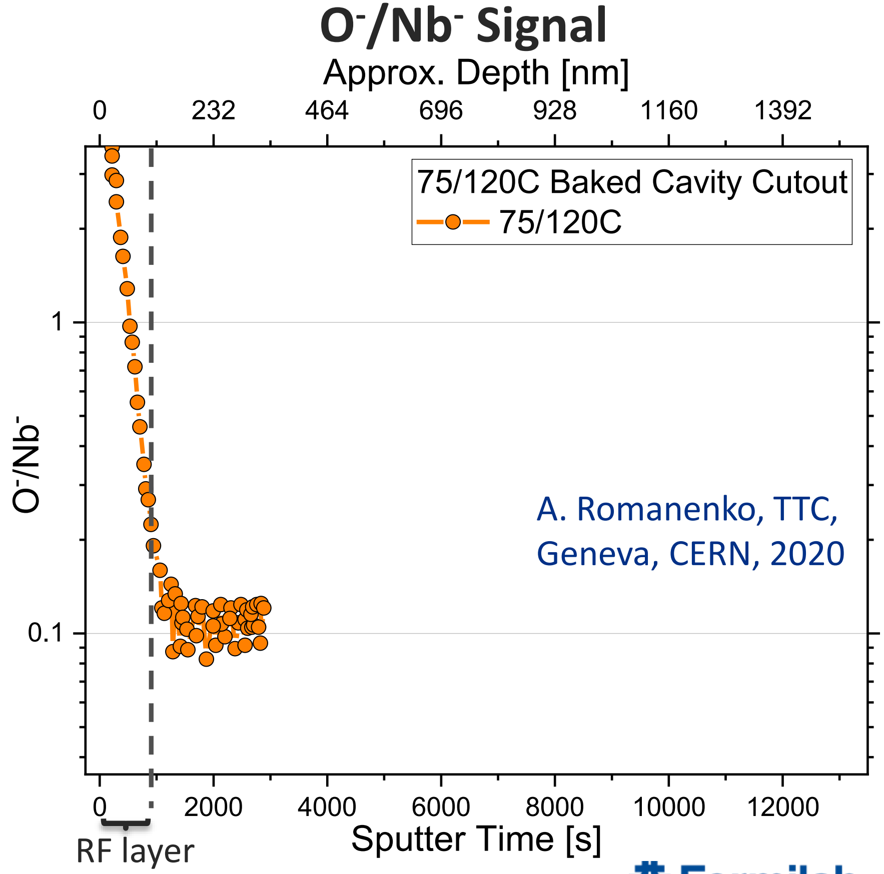
N may not be responsible for the anti-Q slope and dip behaviors present after low temperature baking



Oxygen as a Possible Driver for "Doping" Behavior Post LTB

Low T baking diffuses oxygen from oxide toward bulk on cavity cutouts

- 120 C x 48 hour LTB:
  - Diffuses oxygen ~100 nm

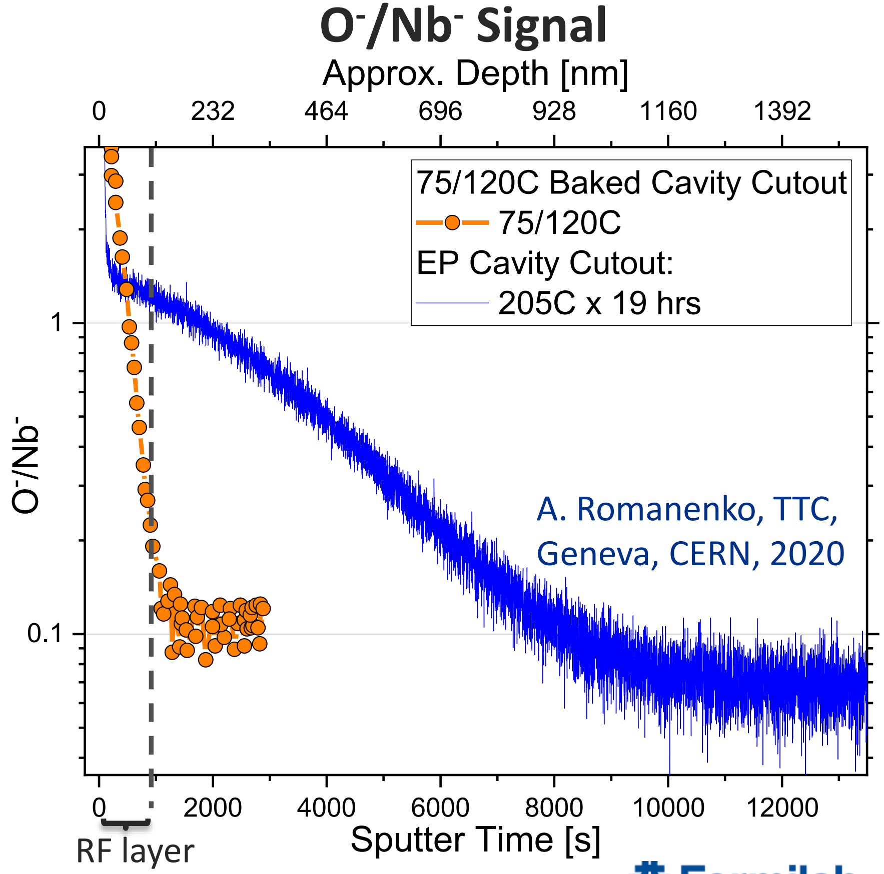


Oxygen as a Possible Driver for “Doping” Behavior Post LTB

Low T baking diffuses oxygen from oxide toward bulk on cavity cutouts

- 120 C x 48 hour LTB:
  - Diffuses oxygen ~100 nm
- 205 C x 19 hr LTB
  - Diffuses oxygen ~1000 nm

O diffused from the oxide may be driving the anti-Q slope and frequency dip behaviors → “Oxygen” doping?



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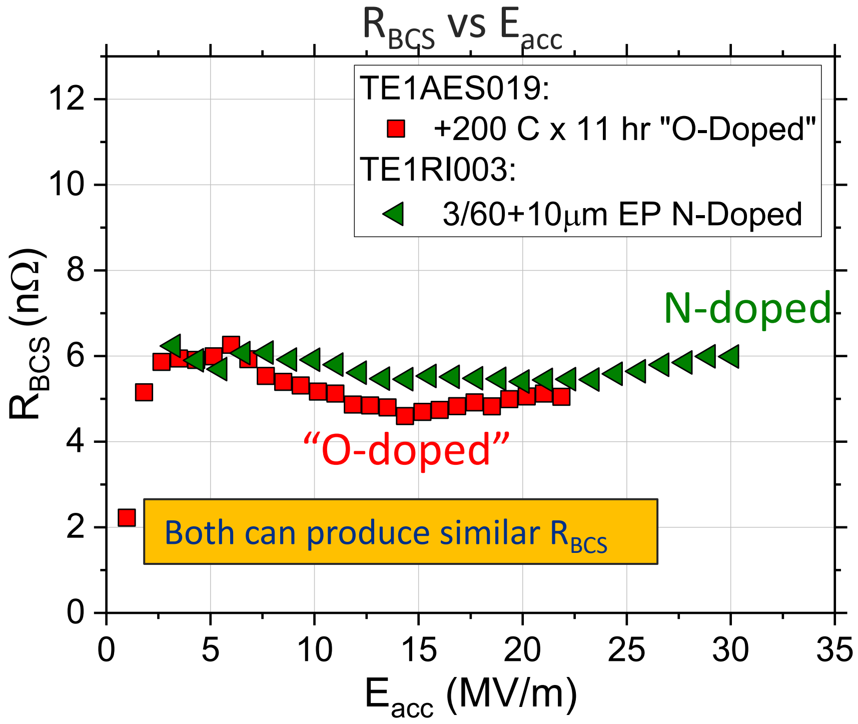
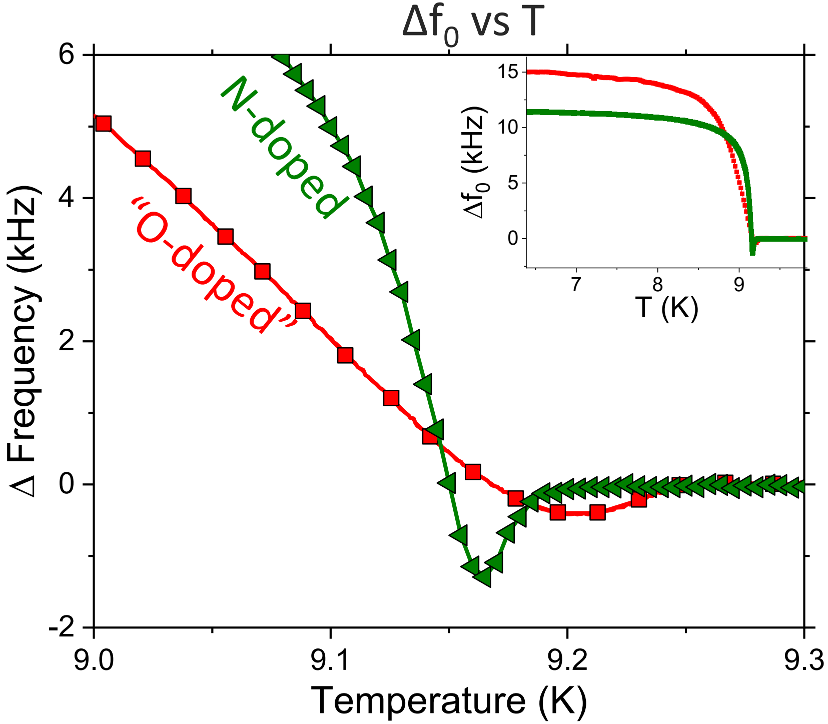
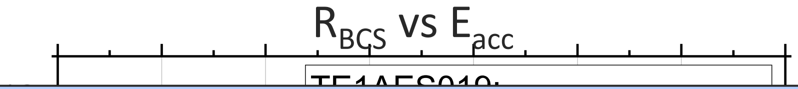
Comparing Effect of N-Doping and "O-Doping" on $\Delta f_0(T)$ Dip

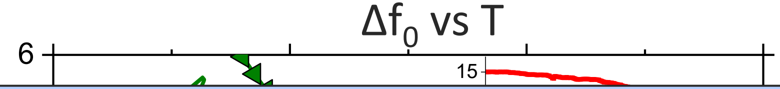




- For similar BCS behavior, N more strongly suppresses T_c, but has a sharper dip
- Wider FWHM after O-doping = larger distribution of T_c? More inhomogeneity?

Comparing Effect of N-Doping and "O-Doping" on $\Delta f_0(T)$ Dip





Conclusions of study #2:

- **Oxygen may drive the anti-Q slope and dip behaviors after LTB if baked long enough - "Oxygen" doping?**
- **Impurity dependent frequency behavior and dip**
- **f_0 behavior near T_c suggests that O-doping produces a more inhomogeneous RF surface than N-doping**

See my poster THPTEV016 for more on the effect of O in SRF cavity performance!

- Wider FWHM after O-doping = larger distribution of T_c? More inhomogeneity?

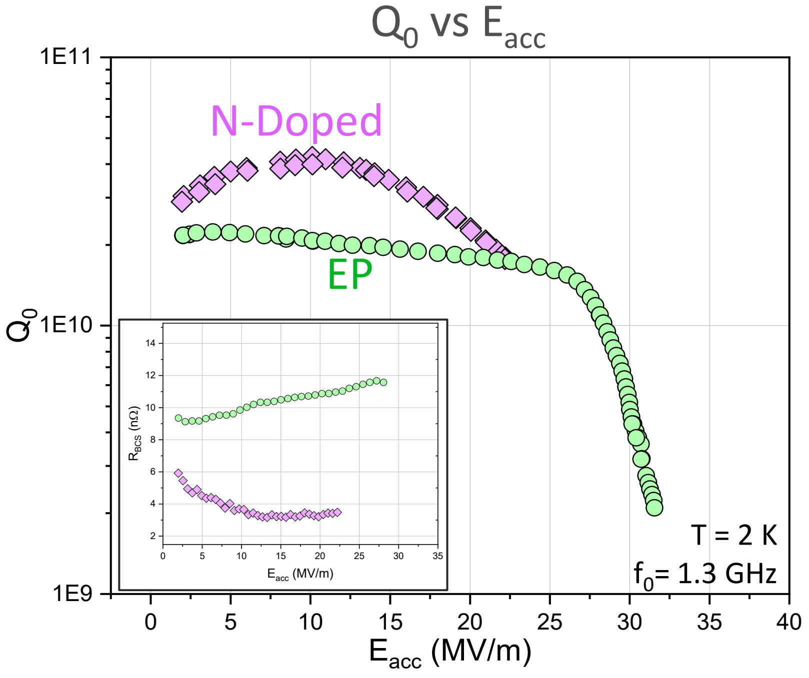
Study #3: Implications of Dip on Complex Conductivity

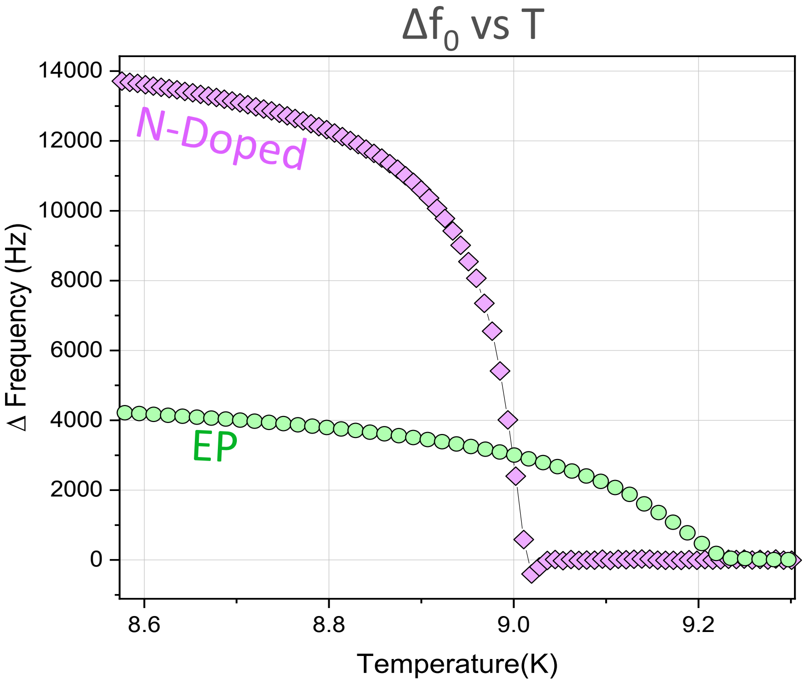
- Two 1.3 GHz single cells subjected to either EP or N-doping
- Performed: RF measurements, impedance vs temperature measurements, and calculated the experimental RF conductivity

EP
30μm EP

2/6 + 5 μm EP @ 900C N-Doping
900Cx3hrs in UHV
900Cx2min in 25 mTorr N
900Cx6min in UHV
+5μm EP

RF Performance of N-Doped and EP Cavities





EP: HFQS

N-Doped: High Q_0/anti-Q slope

EP: Standard feature near T_c

N-Doped: Prominent dip near T_c

Calculating and Fitting Experimental Conductivity

$$\sigma = \sigma_1 + i\sigma_2$$

$$\sigma_1 = \omega\mu_0 \frac{2R_s X_s}{(R_s^2 + X_s^2)^2} \qquad \sigma_2 = \omega\mu_0 \frac{X_s^2 - R_s^2}{(R_s^2 + X_s^2)^2}$$

$$R_s(T) = \frac{G}{Q_0(T)}$$

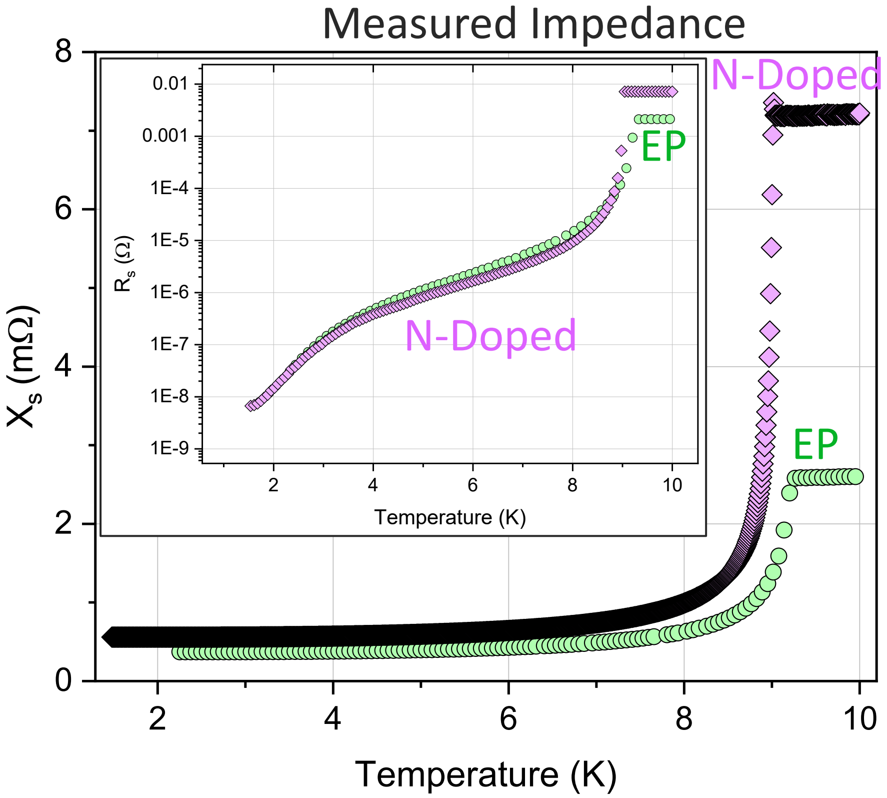
Δf_0 vs T dip used here

$$X_s(T) = \Delta X_s(T) + X_n = -2G\frac{\Delta f_0(T)}{f_0} + X_n$$

To model the conductivity:

- Included Dynes parameter (Γ) in the DOS in Mattis-Bardeen conductivity:

$$\frac{N}{N_0} = \frac{E + i\Gamma}{\sqrt{((E + i\Gamma)^2) - \Delta^2}}$$



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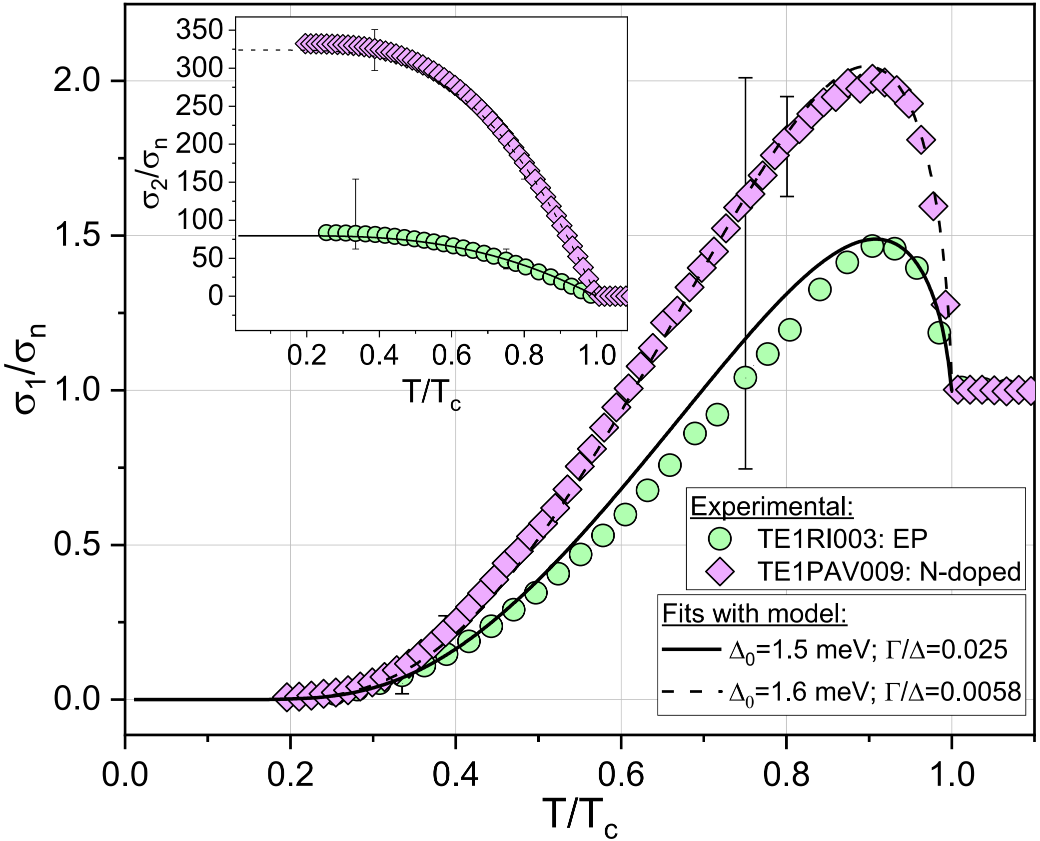
Conductivity of N-Doped and EP Cavities



Fitting Parameters

	N-Doped	EP
Γ/Δ	0.0058	0.025
Δ [meV]	1.6	1.5

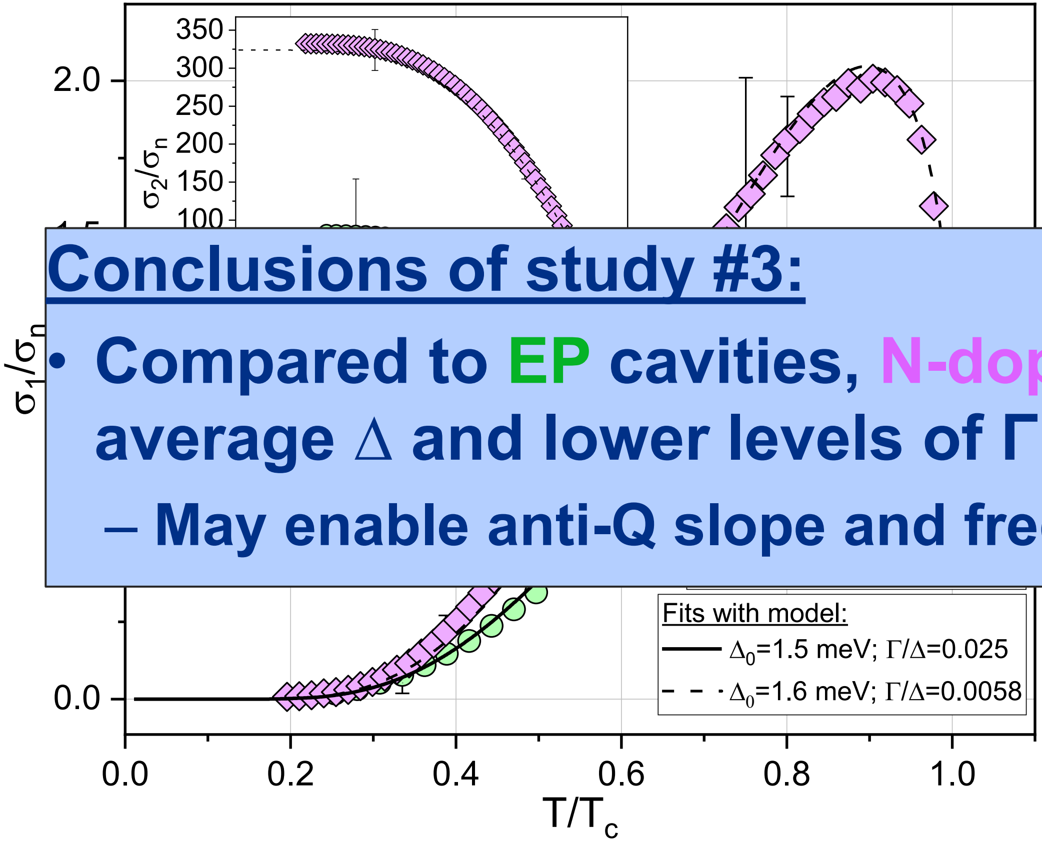
N-doped cavity better fitted w/

- Larger (avg) Δ_0
- Lower (avg) inelastic scattering Γ
  - Less proximity coupling

Agrees w/:

- PCTS by Groll *et al.* on similarly treated cavity cutouts arXiv:1805.06359
- Theory by Kubo PRR **2**, 013302 (2020)

Conductivity of N-Doped and EP Cavities



Fitting Parameters

	N-Doped	EP
Γ/Δ	0.0058	0.025
Δ [meV]	1.6	1.5

Conclusions of study #3:

- **Compared to EP cavities, N-doped cavities exhibit larger average Δ and lower levels of Γ within the interface**
  - **May enable anti-Q slope and frequency dip phenomena**

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Conclusions

The dip in f_0 near T_c and anti-Q slope may occur in the presence of uniform, dilute concentrations of impurities (nitrogen, oxygen)

For uniform concentrations of N impurities:

- Q_0 @ 16 MV/m varies linearly with Δf_{dip} for different recipes
- T_c and Δf_{dip} follow roughly exponential relationships with MFP

Fits of RF conductivity correctly reproduce observations made in previous studies

- N-doped cavities exhibit larger average Δ and lower Γ than EP cavities
- May enable anti-Q slope and frequency dip

Thank you for your attention!