New Insights on Nitrogen Doping

Daniel Bafia

19^{th} International Conference on RF Superconductivity

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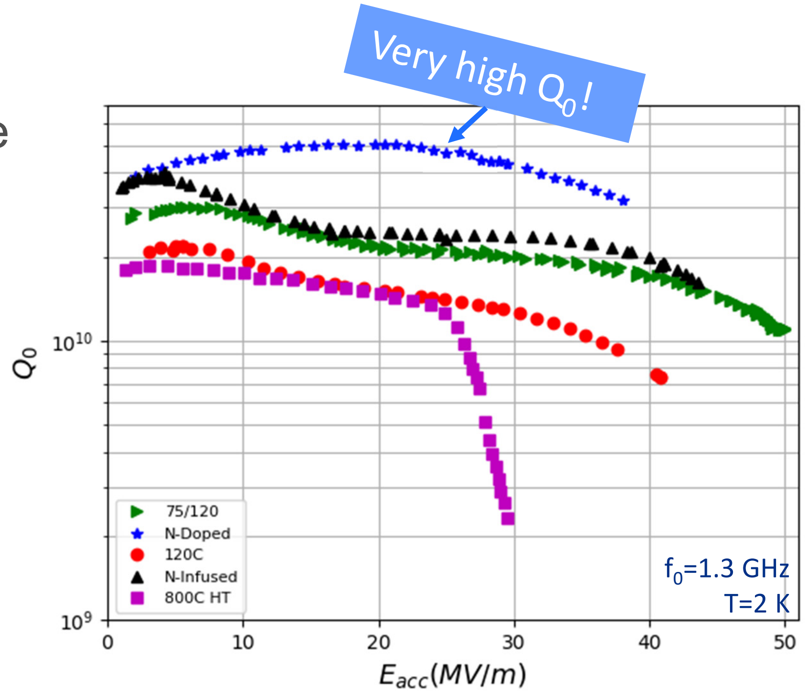
Effect of Nitrogen doping on Cavity performance

- Niobium cavity performance depends strongly on the near surface impurity structure
- Nitrogen doping gives very high Q_0, with quench limits still being pushed
- Microscopic origins of improved performance still not fully understood



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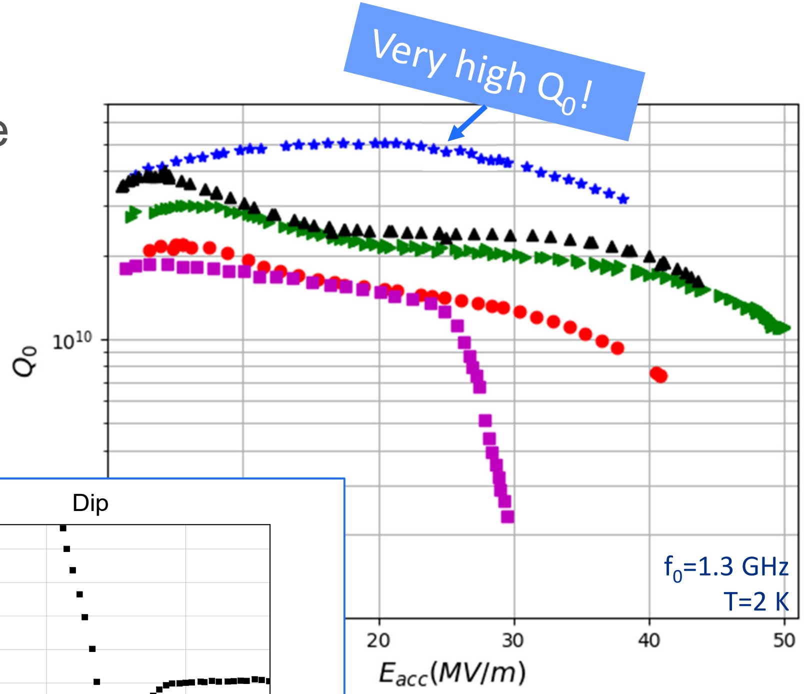
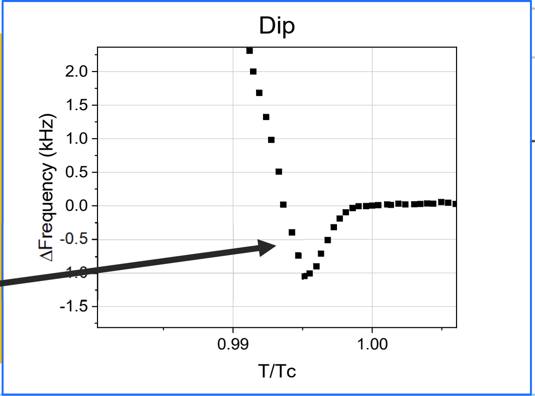
- Nitrogen doping gives very high Q_0, with quench limits still being pushed
- Microscopic origins of improved performance still not fully understood
- **New insights:**

Discovery of new feature of nitrogen doped cavities: dip in resonant frequency of the cavity just below T_c!



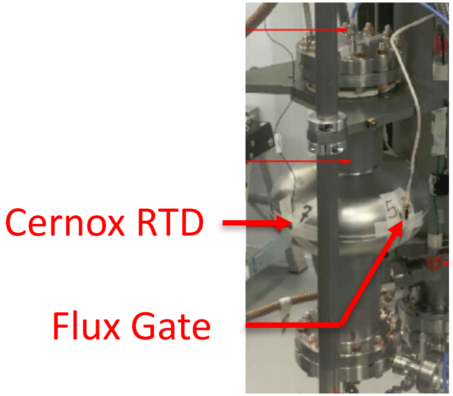


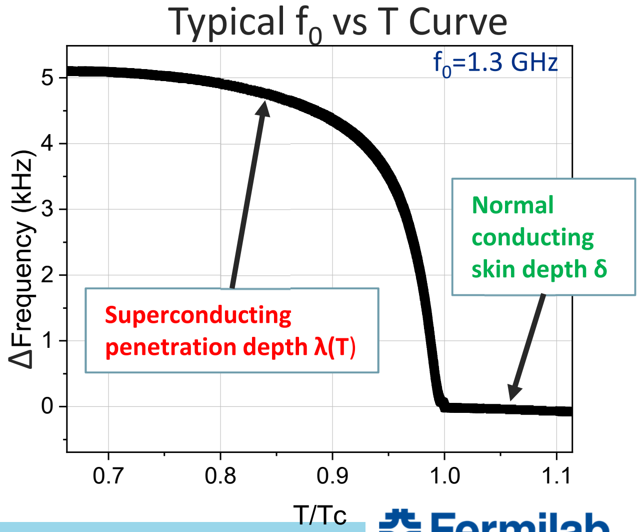
Introduction to "f_0 vs T" Measurements

- Cavity sits in a dewar filled with liquid helium at a temperature of ~4K
- Resonant frequency f_0 of a cavity is measured with a network analyzer
- Dewar temperature is increased by boiling off helium
- As temperature increases, the penetration depth increases:

$$\lambda(T) = \frac{\lambda_0}{\sqrt{1-\left(\frac{T}{T_c}\right)^4}}$$

- As λ increases, f_0 decreases
- Results in "f_0 vs T" curve





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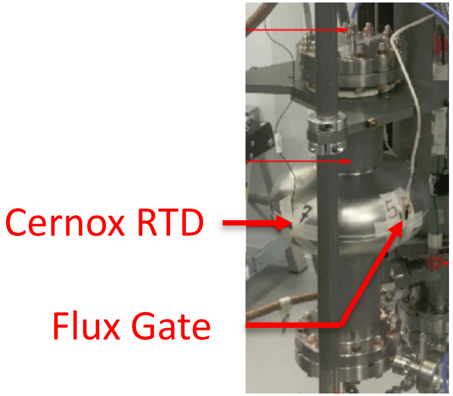

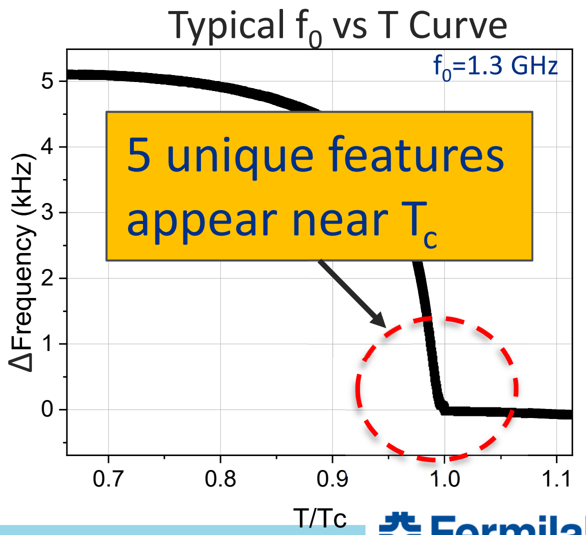

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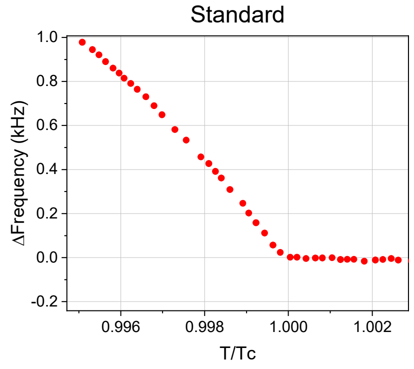
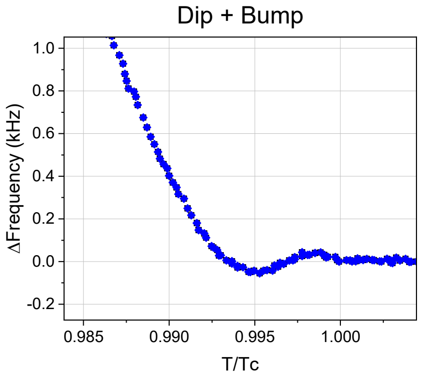
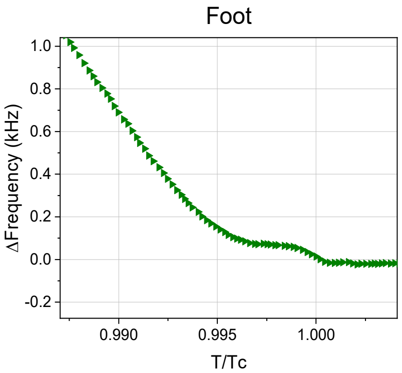
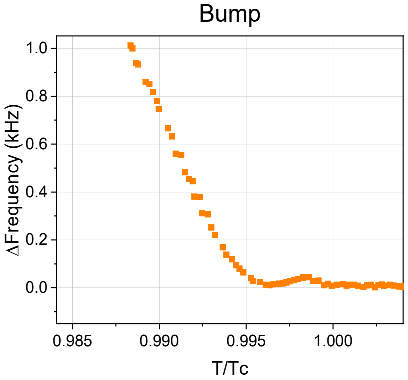
Zoology of f_0 vs T Features Near T_c

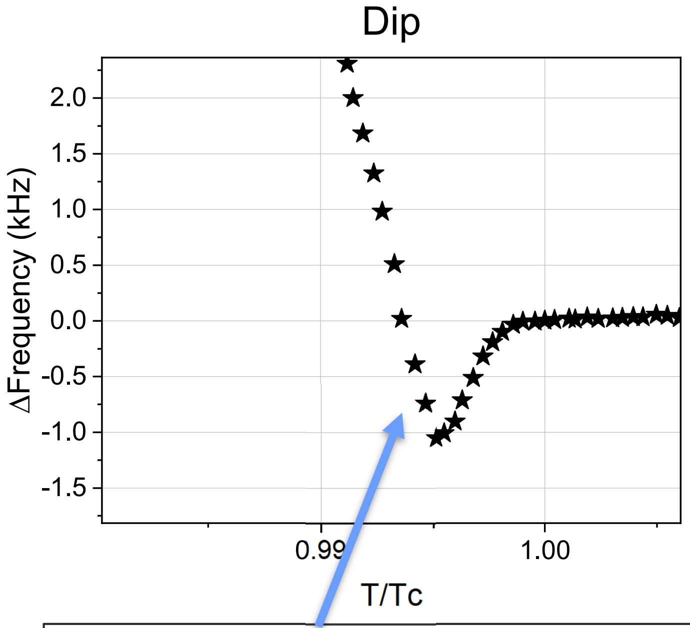
5 distinct features near T_c











Prominent dip in resonant frequency below the normal conducting value just before T_c!

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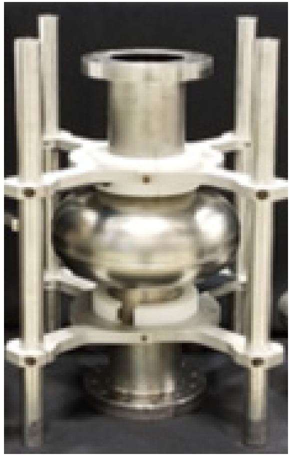
Study #1: Effect of Surface Treatments on Features Near T_c

- One cavity was subject to the following surface treatments to study the effect of surface impurity structure on the features observed in f_0 vs T data near T_c
- The surface was reset between each treatment with 40μm of electropolishing



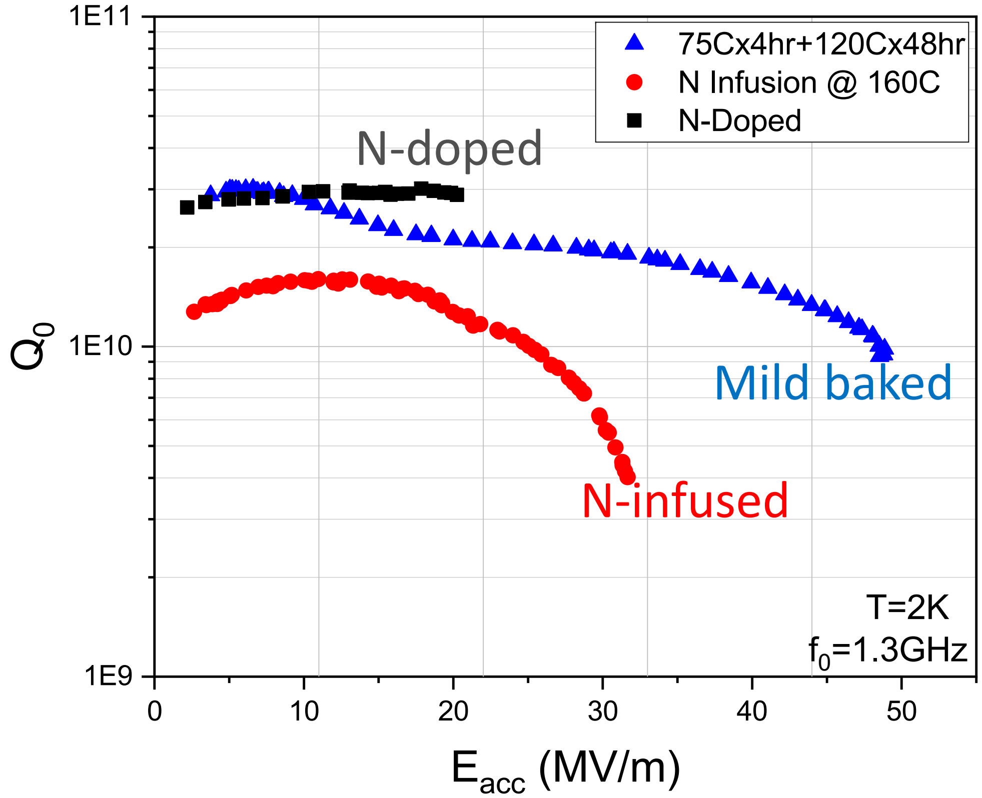
1.3GHz single cell

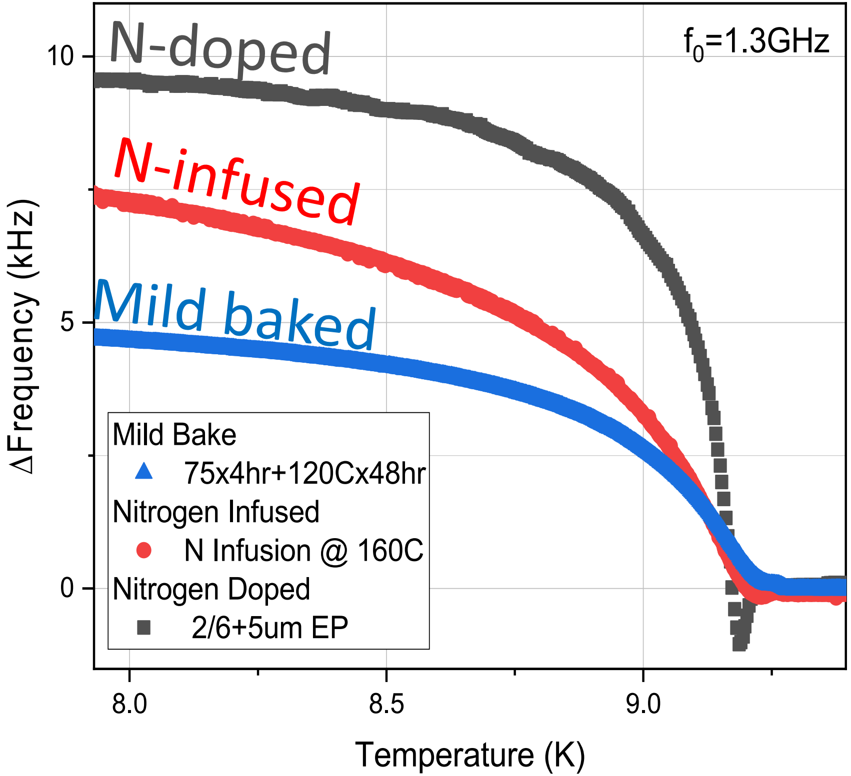
Surface Treatments Used in Sequential Study

75/120C	N Infusion	N-Doping
800Cx3hrs in UHV	800Cx3hrs in UHV	800Cx3hrs in UHV
75Cx4hrs in UHV	160Cx48hrs in 25 mTorr N	800Cx2min in 25 mTorr N
120Cx48hrs in UHV		800Cx6min in UHV
		+5um EP

See poster TUP061 for details on 75/120C bake!

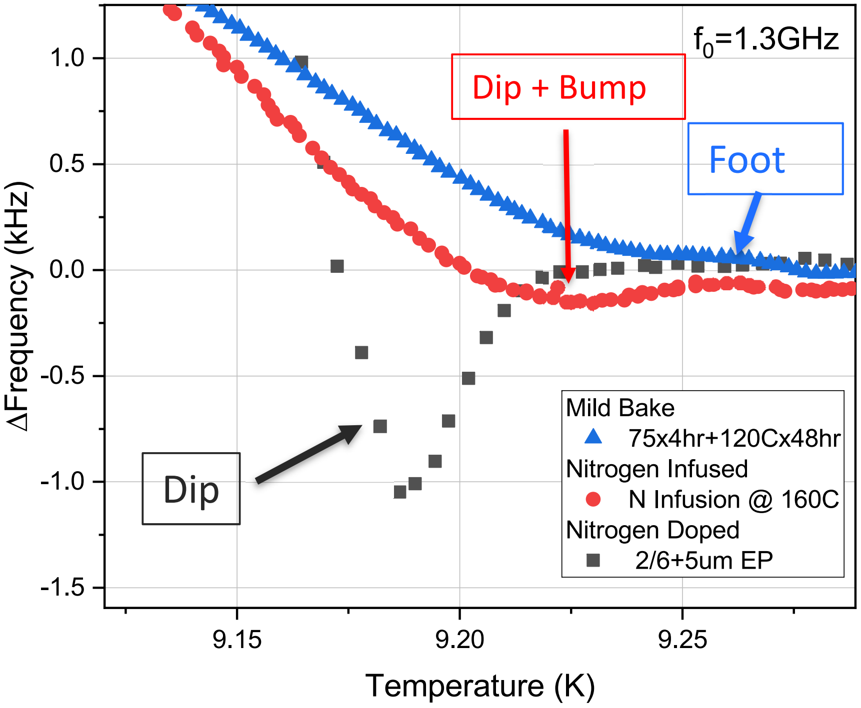
Effect of Surface Treatments on f_0 vs T Profile for a Single Cavity





*Normal conducting frequency set to 0 Hz

Effect of Surface Treatments on f_0 vs T Profile for a Single Cavity – Zoom in Near T_c



- Three different surface treatments give three different features near T_c
  - 75/120C baked – Foot
  - N infused – Dip + Bump
  - N doped - Dip
- Surface preparation controls the features observed near T_c for f_0 vs T data!
- **Only N-doping gives a dip in f_0!**

*Normal conducting frequency set to 0 Hz

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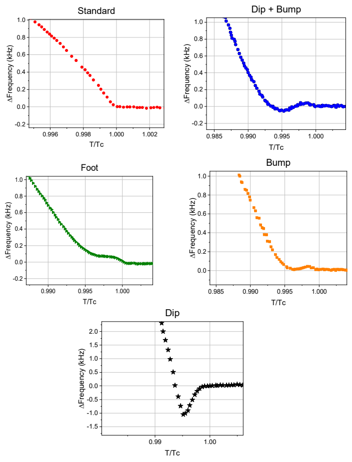
Statistics on Occurrence of Different f_0 vs T Features Near T_c

- Extended this study to 48 sets of data to cavities subject to various treatments
- N infused and 75/120C baked cavities displayed 4 out of 5 features near T_c
- EP and 120C baked cavities exhibited 2 out of 5 features near T_c
- **All 27 studied nitrogen doped cavities** had a prominent dip!

Occurrence of Features Near T_c in 48 Data Sets

Feature \ Treatment	N-Doped	N Infused	75/120C	120C	EP
Dip	27	1 (small)	1 (small)		
Foot		1	4		
Bump			1		1
Dip + Bump		2		1	
Standard		1	4	1	3



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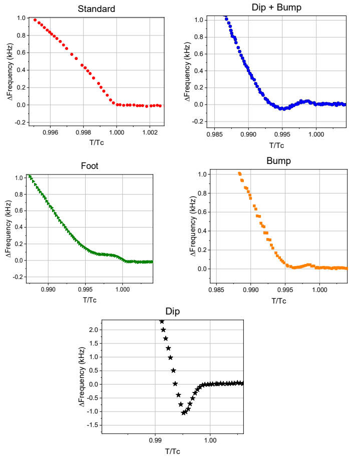
Bump			1		1
				1	
			4	1	3

100% of N-doped cavities exhibited a dip



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Statistics on Occurrence of Different f_0 vs T Features Near T_c

- Extended this study to 48 sets of data to cavities subject to various treatments
- N infused and 75/120C baked cavities displayed 4 out of 5 features near T_c
- EP a[…]
- **All 2[…]**

Conclusions of study #1:

- **Surface treatments are responsible for different features that occur near T_c in f_0 vs T data**
- **Nitrogen doping causes a prominent dip in the resonant frequency of the cavity below the normal conducting value just below T_c**

Fe[…]					
				1	
			4	1	3

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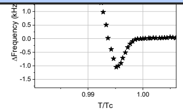
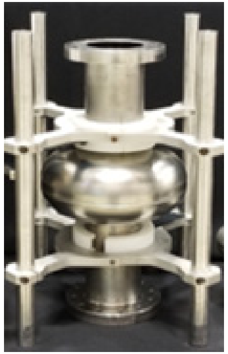


Study #2: Effect of Nitrogen Concentration on the Dip

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



1.3GHz single cell

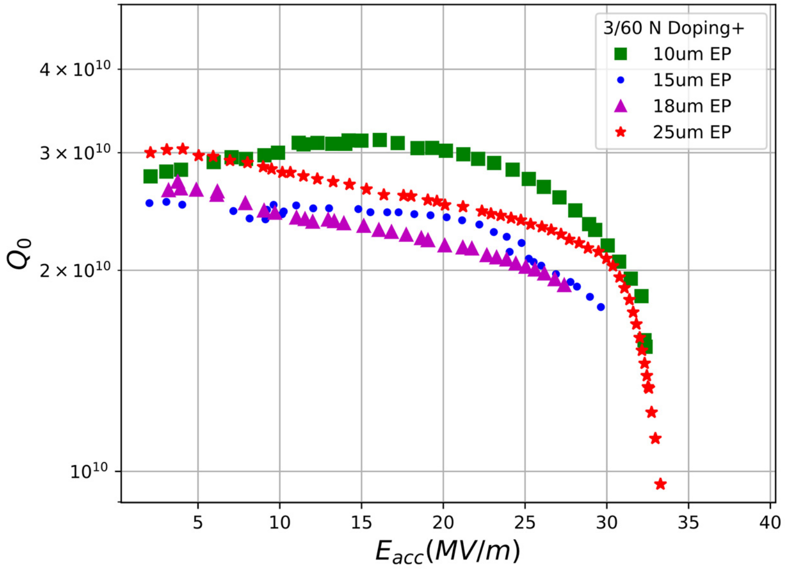
3/60 N-Doping - JLab
800Cx3hrs in UHV
800Cx3min in 25 mTorr N
800Cx60min in UHV

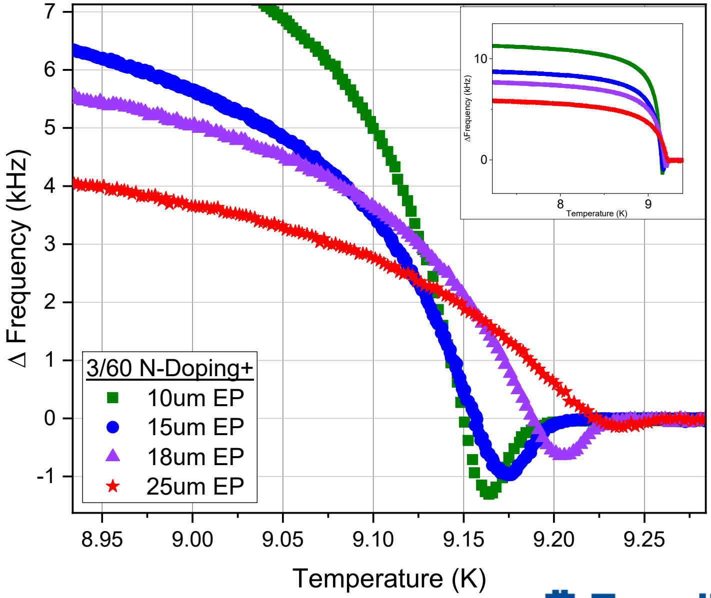
+

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

Effect of Nitrogen Concentration on Dip

- A N-doped cavity was subject to sequential removal of RF surface, decreasing the concentration of nitrogen in the RF layer
- As the concentration of nitrogen decreases, so does its effect on both Q_0 vs E_{acc} and f_0 vs T curves





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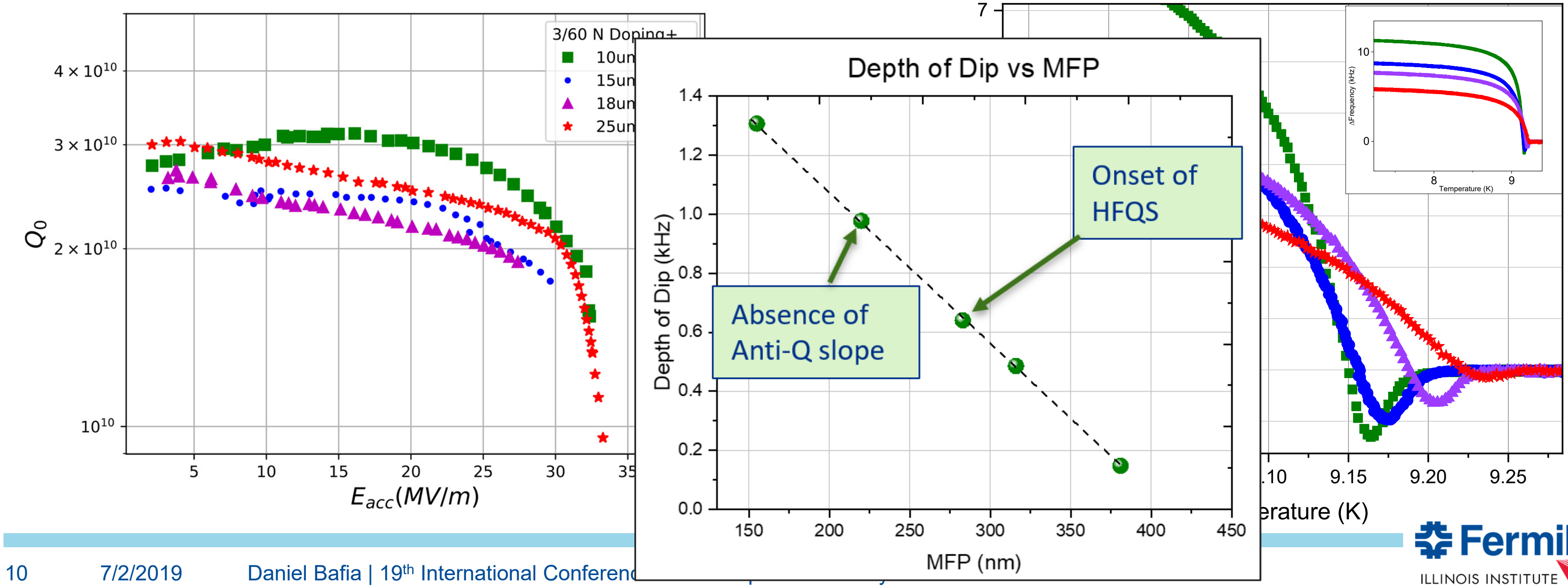

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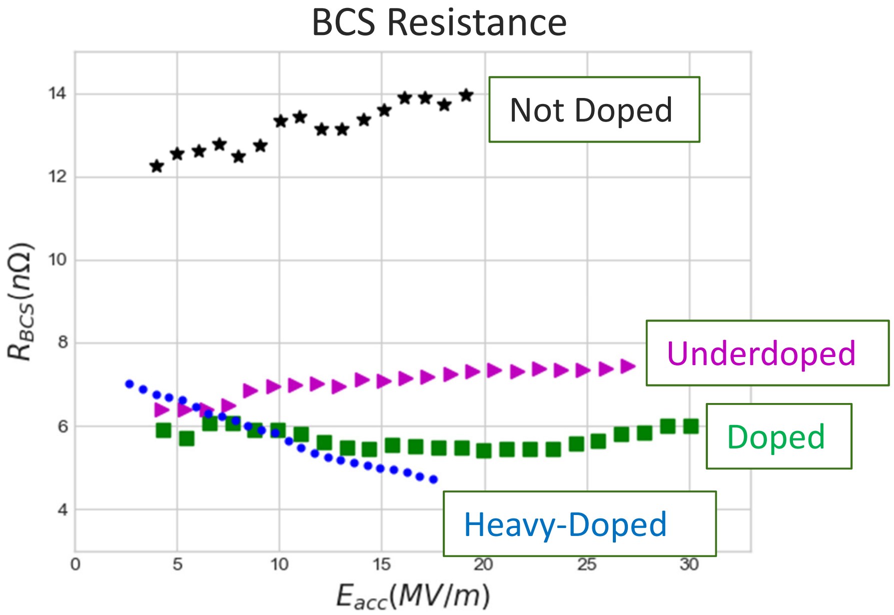
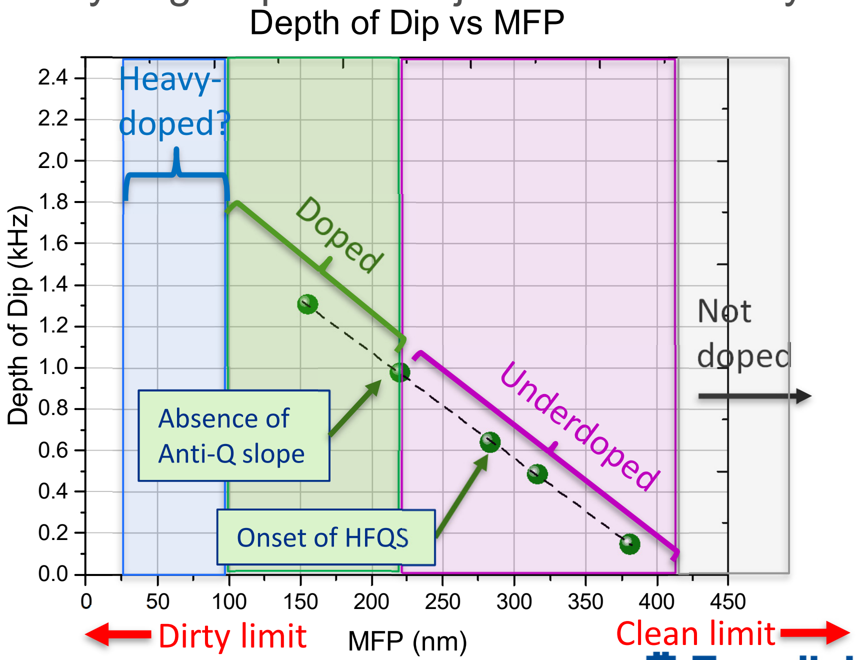
Assessing Levels of Doping with the f_0 vs T Dip

- Not doped – high quench field, high BCS, no observed dip in f_0 vs T
- Doped: More often higher quench fields and low BCS – larger dip
- Underdoped: More often higher quench, flat or increasing BCS – smaller dip
- Heavy-doped: Earlier quench, steep BCS slope – very large dip?? – Subject of future study





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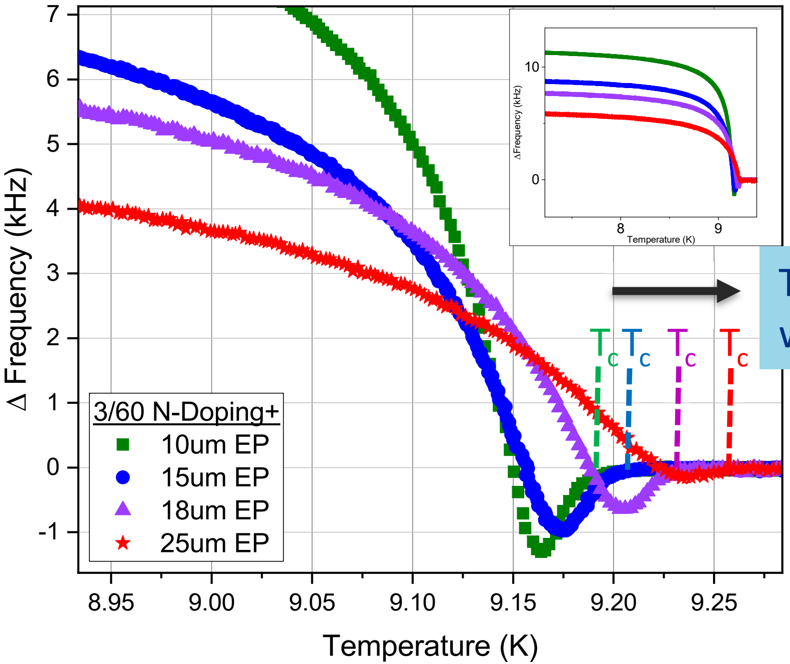
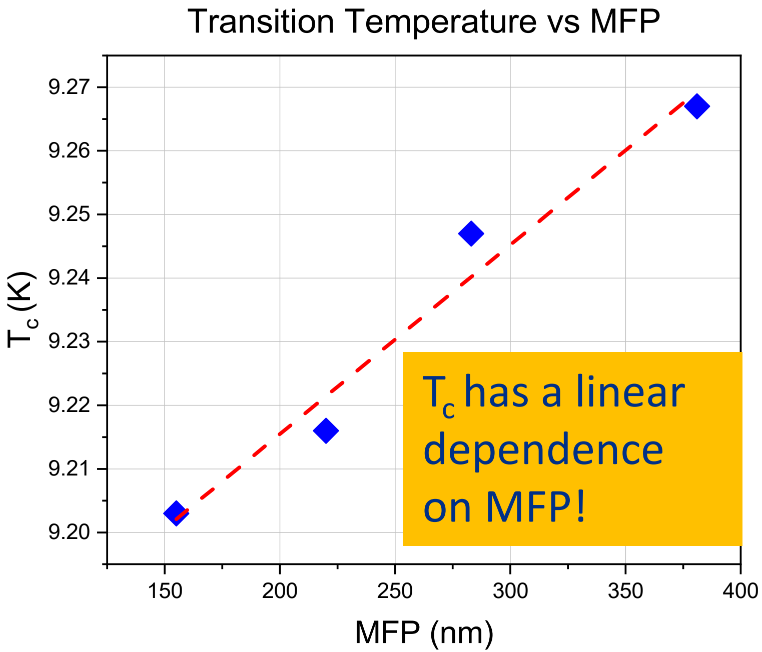
Effect of Doping Concentration on Tc

- Decreasing nitrogen concentration raises the transition temperature
  - Agrees with experimental observations shown in: W. Desorbo, *Phys. Rev.* **132**, 107 (1963)



T_c increases with removal



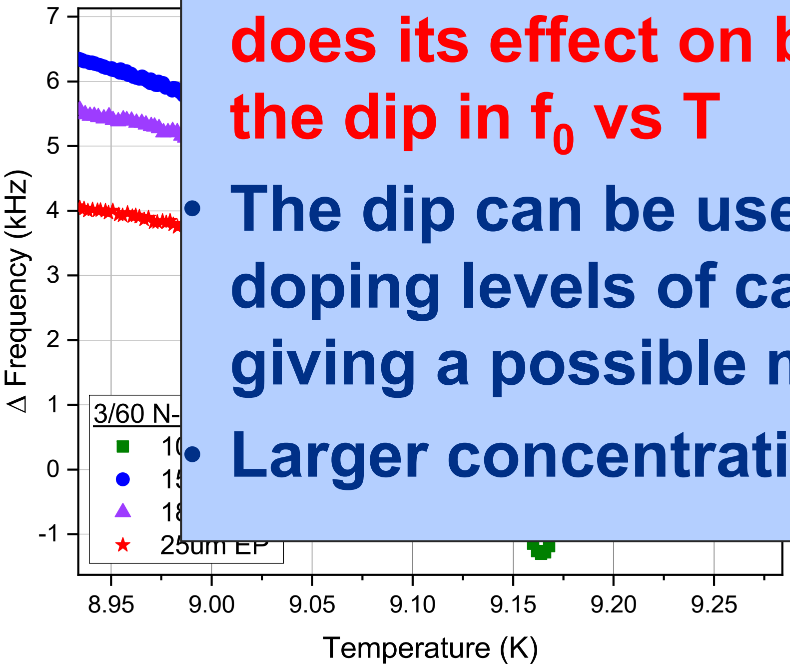
T_c has a linear dependence on MFP!

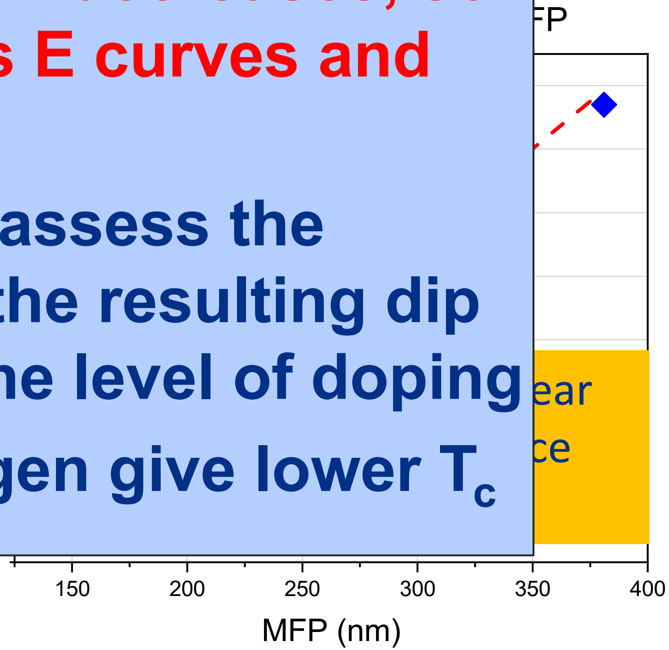
Effect of Doping Concentration on Tc

- Decre
  - Agre 1963)

Conclusions of study #2:

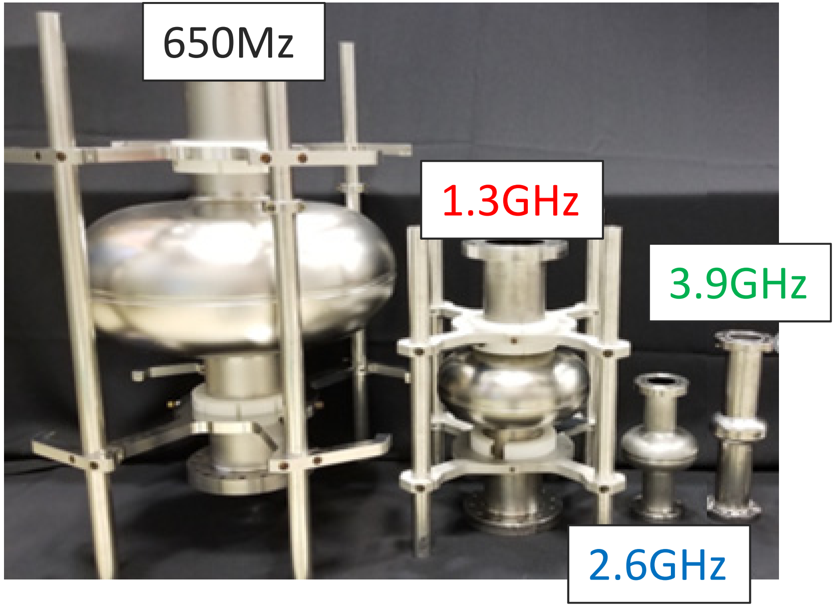
- As the concentration of nitrogen decreases, so does its effect on both the Q vs E curves and the dip in f_0 vs T
- The dip can be used to further assess the doping levels of cavities, with the resulting dip giving a possible measure of the level of doping
- Larger concentrations of nitrogen give lower T_c





Study #3: Effect of Fundamental Mode Frequency on Dip

- Four cavities of different fundamental mode frequencies (650MHz, 1.3GHz, 2.6GHz, 3.9GHz) were subject to the same 2/6 N-doping surface treatment

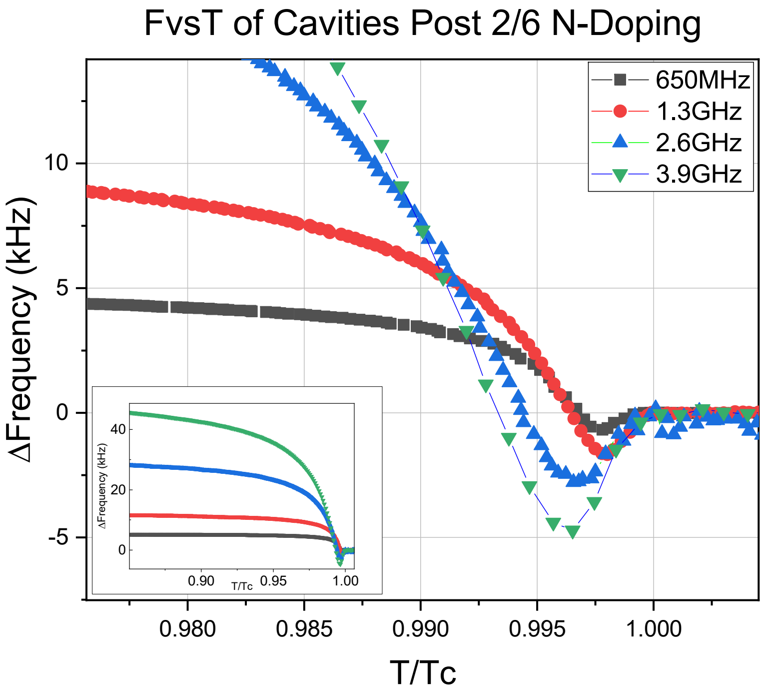


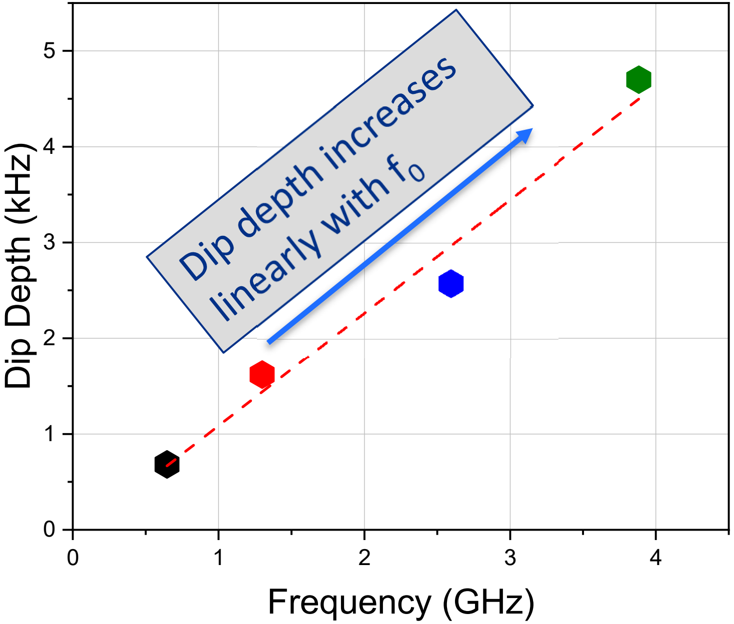
Treatment Used

2/6 N-Doping
800Cx3hrs in UHV
800Cx2min in 25 mTorr N
800Cx6min in UHV
+5um EP

Effect of Fundamental Mode Frequency on f_0 vs T Dip

- Four cavities of various frequencies (650MHz, 1.3GHz, 2.6 GHz, 3.9 GHz) post 2/6 nitrogen doping are shown below.

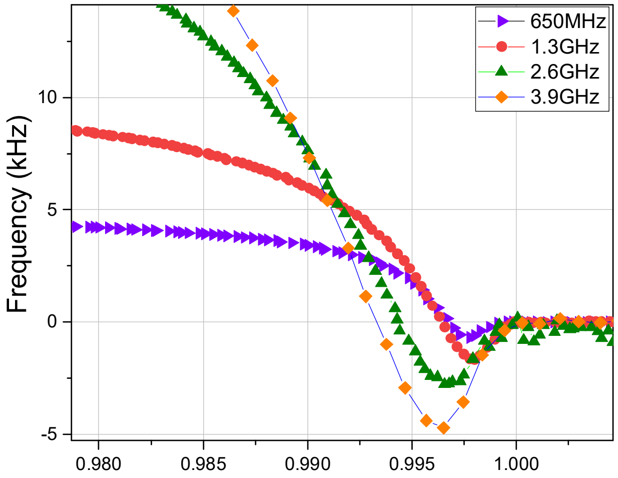




Relation to Frequency Dependence of Anti-Q Slope

- Higher resonant frequency N-doped cavities yield a larger dip depth.
- Martinello *et al*. show that higher resonant frequency N-doped cavities exhibit steeper decrease in BCS surface resistance

FvsT of Cavities Post 2/6 N-Doping



BCS Resistance of N-Doped Cavities of Various Frequencies

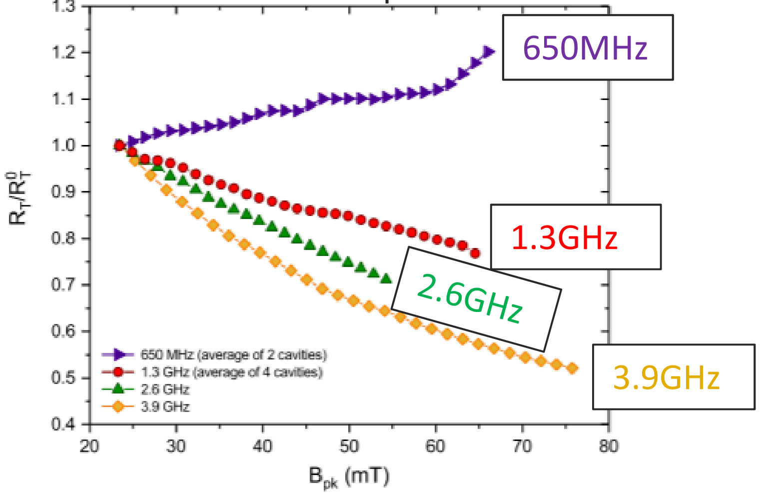


FIG. 4. Normalized data R_T/R_T^0 as a function of the peak magnetic field for N-doped cavities at 2.0 K.

Martinello *et al.* Phys. Rev. Let., **121**, 224801 (2018)

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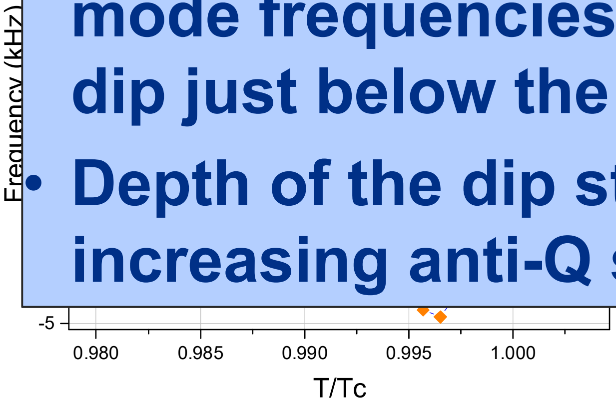
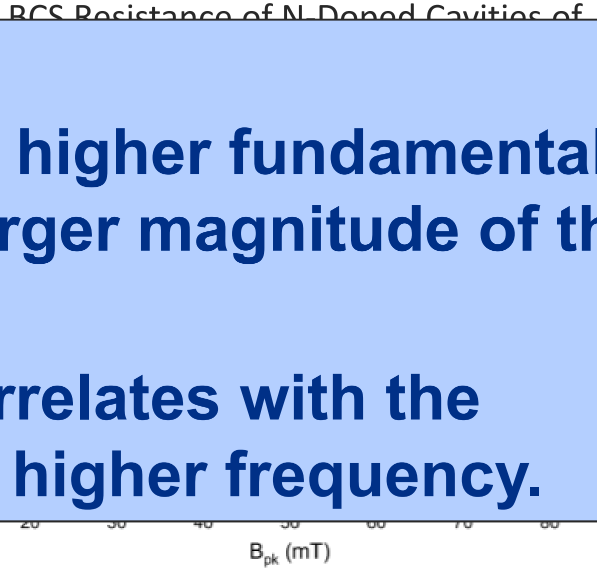


Conclusions of study #3:

- **For nitrogen doped cavities, higher fundamental mode frequencies gives a larger magnitude of the dip just below the T_c**
- **Depth of the dip strongly correlates with the increasing anti-Q slope with higher frequency.**



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Martinello *et al.* Phys. Rev. Let., **121**, 224801 (2018)

Possible Interpretations

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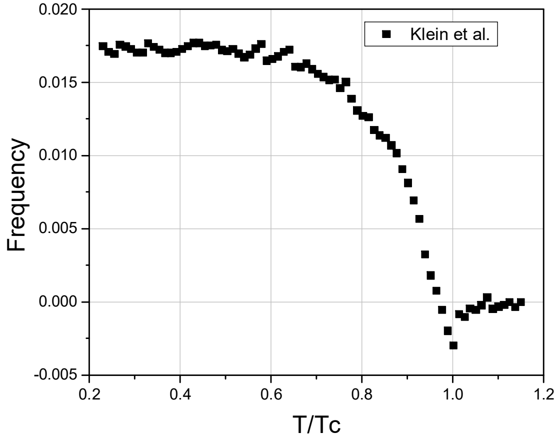
Reports of Dip in Literature

- This dip in Nb has been previously observed by previous authors (Klein, Varmazis)
- However, it was previously not understood that this occurs in the presence of N-doping
- Understanding the implications of this dip could help in understanding large increase in Q_0



PHYSICAL REVIEW B VOLUME 11, NUMBER 9 1 MAY 1975

Inductive transition of niobium and tantalum in the 10-MHz range. II. The peak in the inductive skin depth for T just less than T_c†

C. Varmazis
Columbia University, New York, New York 10027 and Brookhaven National Laboratory, Upton, New York 11973

J. R. Hook and D. J. Sandiford
Department of Physics, Manchester University, Manchester, England

M. Strongin
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

PHYSICAL REVIEW B VOLUME 50, NUMBER 9 1 SEPTEMBER 1994-I

Conductivity coherence factors in the conventional superconductors Nb and Pb

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E.J. Nicol†
Department of Physics, University of California at Santa Barbara, Santa Barbara, California 93106

K. Holczer and G. Grüner
Department of Physics, University of California at Los Angeles, Los Angeles, California 90024
(Received 29 March 1994)

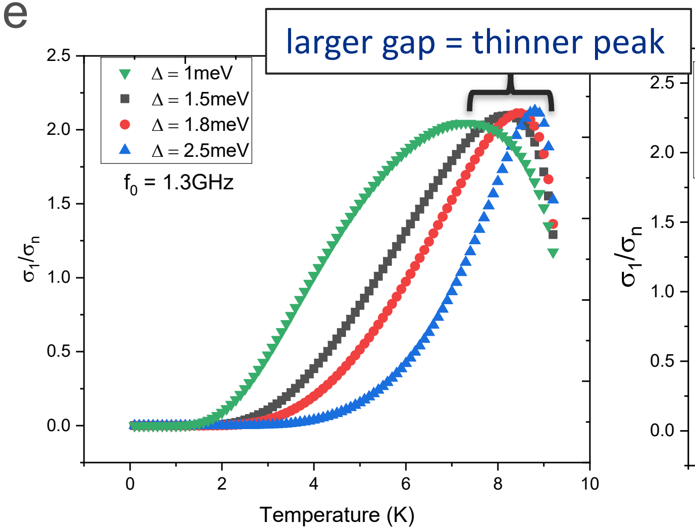
First Interpretations: Hints at Differences in e-phonon Coupling

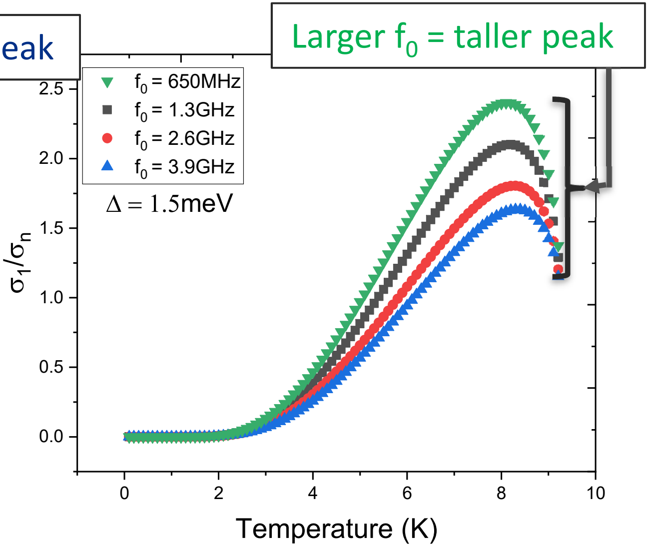
- In BCS theory, the conductivity in a superconductor is given by:

$$\sigma_s = \sigma_1 + i\sigma_2$$

Quasi-particle (σ_1) Cooper pairs ($i\sigma_2$)

- Peak exists in quasi-particle conductivity near ~0.85T_c due to the breaking of cooper pairs by phonons
  - *Coherence peak (CP)*
- Different superconducting gaps and frequencies cause differences in the width/height of the CP





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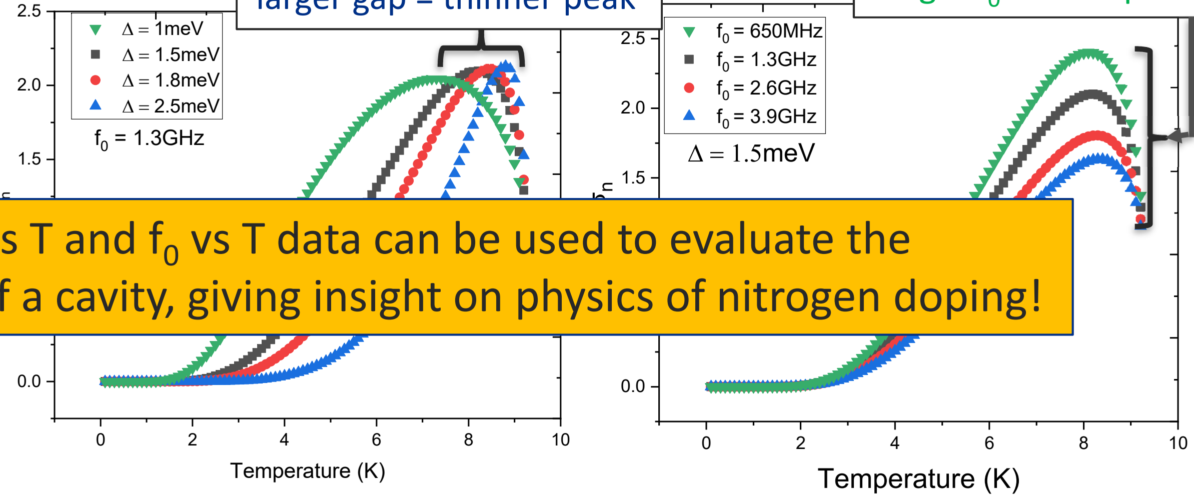
- Different superconducting gaps and frequencies cause differences in the width/height of the CP

larger gap = thinner peak

Larger f_0 = taller peak



Experimental Q_0 vs T and f_0 vs T data can be used to evaluate the coherence peak of a cavity, giving insight on physics of nitrogen doping!

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Relation of Surface Impedance to Complex Conductivity

- How to extract conductivity from experimental Q_0 vs T and f_0 vs T data
- Surface impedance: $Z_s = R_s + iX_s$

f_0 vs T dip used here

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

$$X_s(T) = \Delta X_s(T) + X_n = -2G\frac{\Delta F(T)}{F_0} + R_n$$

- Conductivity given by:

$$\frac{\sigma_1}{\sigma_n} = \frac{4R_n^2 R_s X_s}{(R_s^2 + X_s^2)^2}$$

$$\frac{\sigma_2}{\sigma_n} = \frac{2R_n^2 (X_s^2 - R_s^2)}{(R_s^2 + X_s^2)^2}$$

$$\sigma_s = \sigma_1 + i\sigma_2$$

Hints That the Dip in f_0 vs T Signifies Stronger Coupling

- Klein *et al*. showed a dip in the resonant frequency of a Nb sample taken with a 60GHz resonator.
- The resulting quasi-particle conductivity is better fit with a strong coupling model

PHYSICAL REVIEW B VOLUME 50, NUMBER 9 1 SEPTEMBER 1994-I

Conductivity coherence factors in the conventional superconductors Nb and Pb

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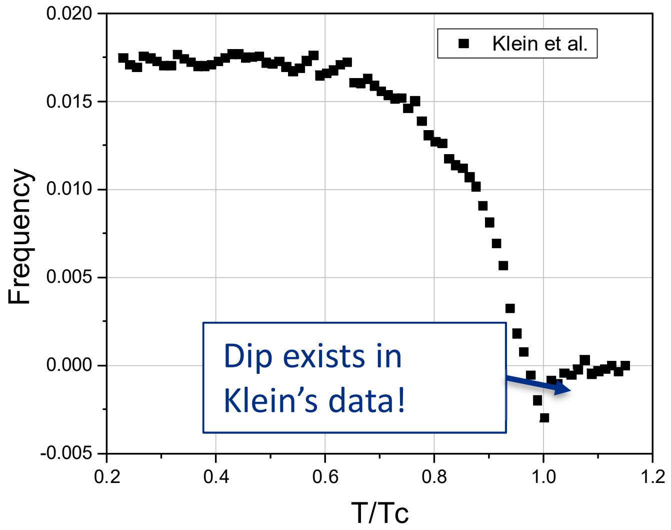

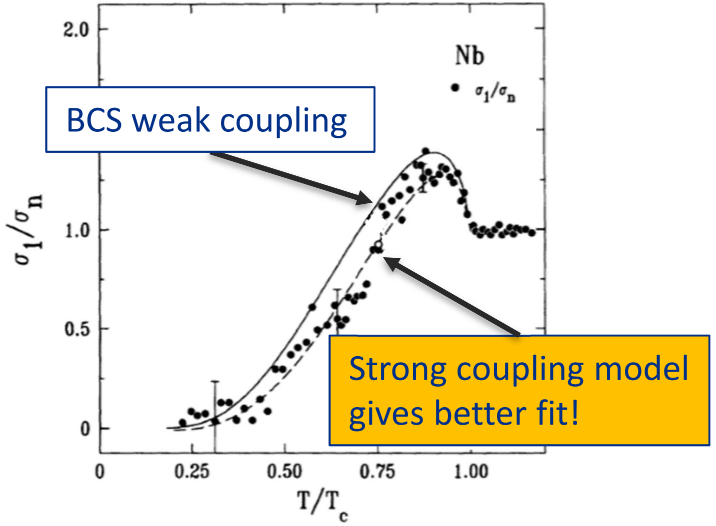

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- Klein *et al*. showed a dip in the resonant frequency of a Nb sample taken with a 60GHz resonator.
- The resulting quasi-particle conductivity is better fit with a strong coupling model

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Conductivity coherence factors in the conventional superconductors Nb and Pb

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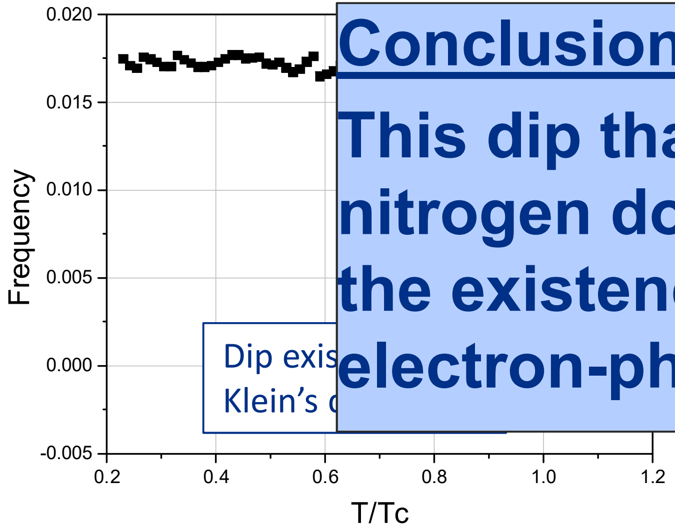
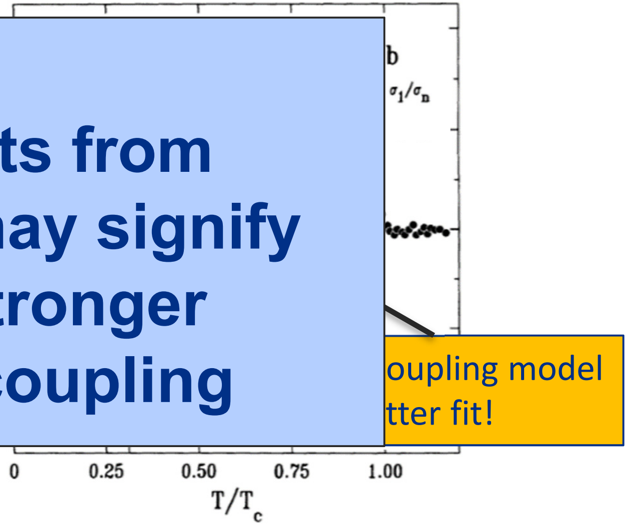




Conclusion:

This dip that results from nitrogen doping may signify the existence of stronger electron-phonon coupling

Potential Explanation of Stronger Electron Phonon Coupling Due to N-Doping

Nitrogen captures hydrogen

↓

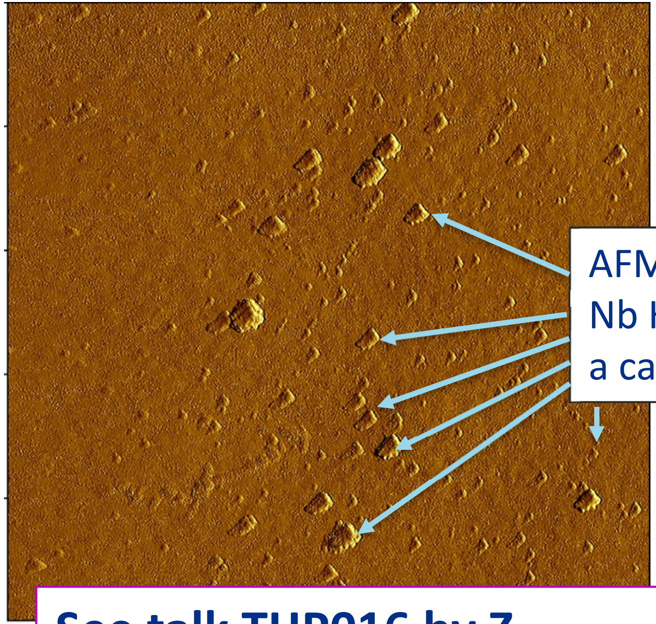
Prevents formation of hydrides

↓

Fewer inclusions that could disrupt Nb lattice

↓

Stronger e-phonon interaction



AFM image of Nb Hydrides on a cavity cutout

See talk THP016 by Z. Sung for more on niobium hydrides in SRF cavities

Conclusions and Future Work

- Newly discovered signature of nitrogen doped cavities gives potentially new insights on the origin of the improvement in Q_0, which could be a result of stronger e-phonon coupling in the superconductor
- From f_0 vs T studies, we learned that:
  - The presence of nitrogen impurities lowers the T_c of Nb SRF cavities
  - Higher fundamental mode frequencies give larger magnitudes of the dip depth and correlate strongly with increasing anti-Q slope with frequency
- The presence, absence, or magnitude of this dip can be used as a way to assess levels of doping

Future studies:

- Gain more statistics on cavities subject to different doping recipes
- Perform more sequential surface treatment studies to compare resulting quasi-particle conductivities and draw conclusions on differences in coupling

Thank you!