Radio-Frequency Superconductivity R&D at Fermilab for Accelerators and Quantum Applications

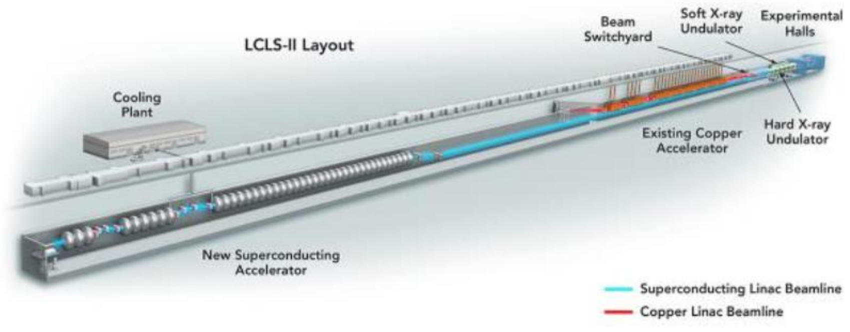
Daniel Bafia

MSU/FRIB Seminar

October 18th, 2024

Particle Accelerators & Quantum Computers?

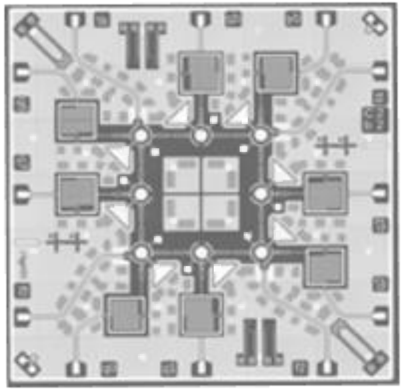
LCLS-II
X-ray Free Electron Laser



https://lcls.slac.stanford.edu/lcls-ii/ldesign-and-performance

- Material analysis
- Exploration of fundamental matter
- Medical applications
- …

Superconducting Qubit

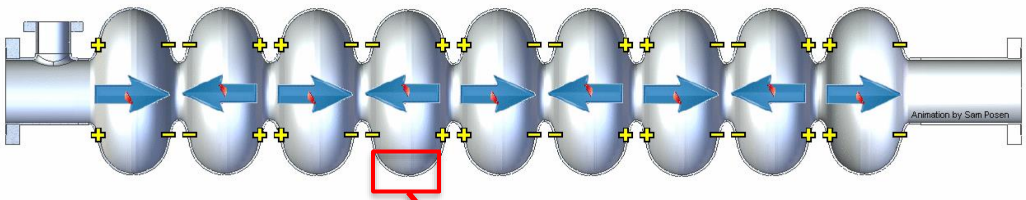


M. Reagor et al, Science Advances, Vol.4, no. 2, (2018)

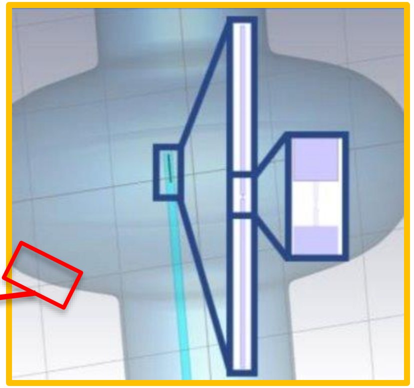
- New platform for advanced computing
- Prime number factorization
- Atomic simulations

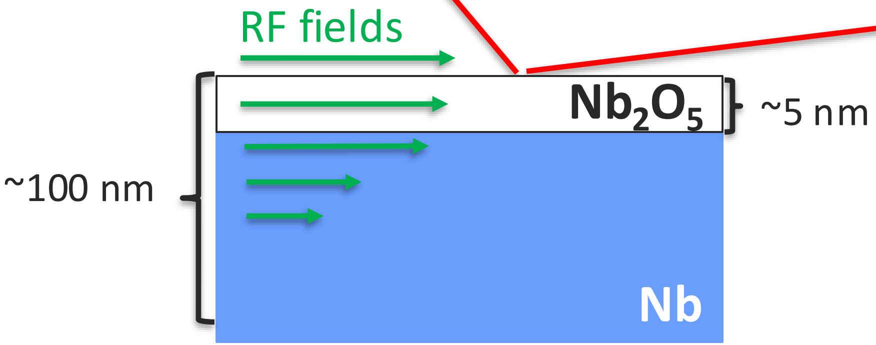
The Common Factor: Nb Superconducting RF Cavities

High Energy Particle Acceleration



Low Energy Quantum Computing





Performance is governed by properties within the first ~100 nm from inner surface

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Overview

Introduction to SRF Cavities

- Basics of RF superconductivity
- Intro to Cavity Testing

Part I: SRF R&D for High Energy Accelerator Applications

- Investigating Mechanisms for Ultra-High Quality Factors
- Investigating Mechanisms for Ultra-High Quality Factors Post N-Doping

Part II: SRF R&D for Low Energy Quantum Computing Applications – SQMS

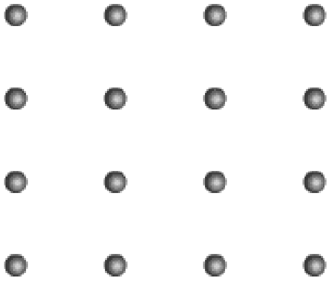
- SRF Cavities for Quantum Bits
- Dissipation in Quantum Devices

Summary

Basics of RF Superconductivity

BCS Theory of Superconductivity

Below T_c, conduction electrons (e) interact via virtual phonons to pair up and form bosonic Cooper Pairs (CP) that propagate with zero resistance



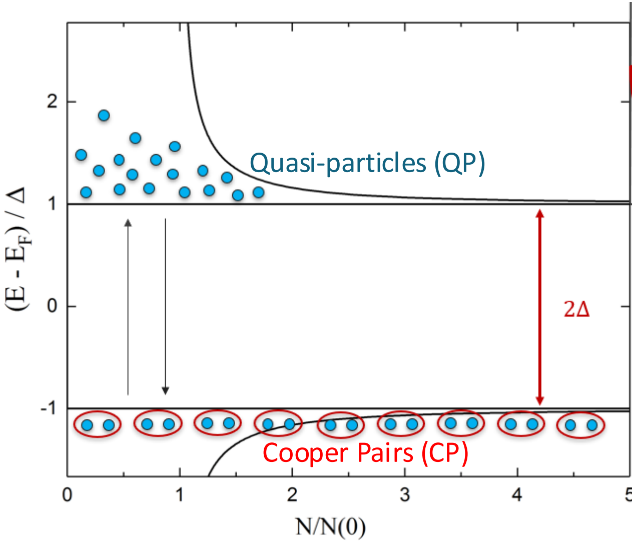
$\xi_{0,Nb} = 38nm$

Size of CP

Attractive e-e interaction leads to a gap in energy spectrum

- $\Delta_{0,Nb} \approx 1.5 - 1.62$ meV
- Singularity in DOS:

$$\frac{N}{N_0} = \frac{E}{\sqrt{E^2 - \Delta^2}}$$



Plot adapted from M. Martinello, TTC Topical Workshop @ FNAL, 2017

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Surface Resistance in SRF Cavities

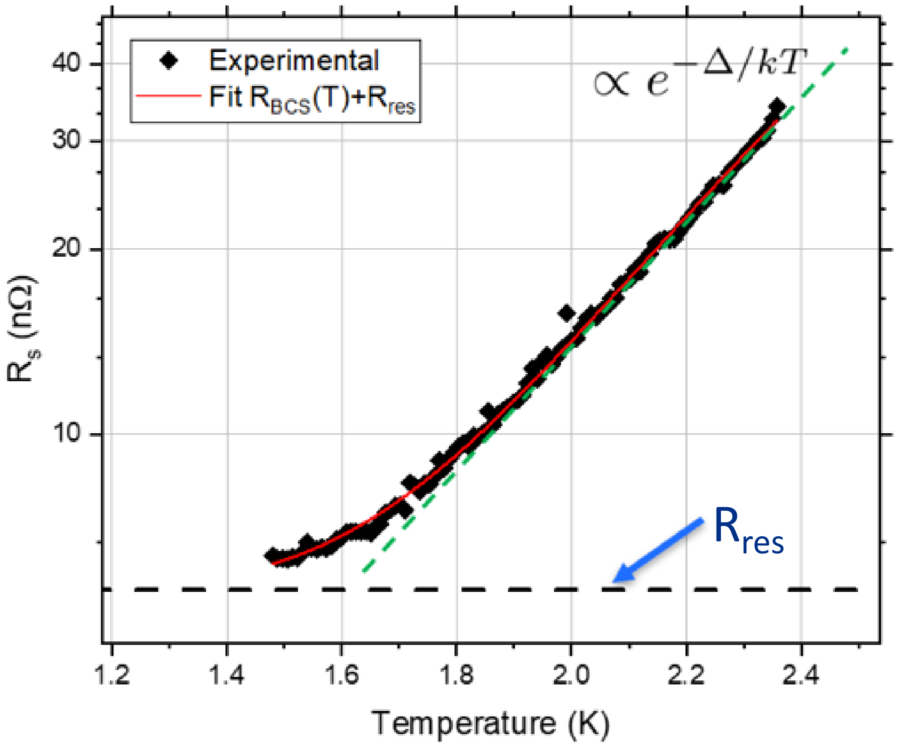
$$R_s(\omega, T) = A(l)\frac{\omega^2}{T}e^{-\frac{\Delta}{k_B T}} + R_{res}$$

Temperature dependent "BCS" resistance driven by single state quasi-particles (QP):

- Thermal excitation (T > 0K)
- Pair-breaking of CPs by photon absorption

Temperature independent residual resistance

- Trapped magnetic flux
- Sub-gap states
- Proximity coupled inclusions
- Material properties
- …..



Intro to SRF Cavity Testing

Cavity Testing

- Cavities instrumented with temp. sensors, fluxgates, installed in large He dewars
  - Cooled to 2 K
- Power balance measurement used to obtain:

"Quality factor"

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

"Accelerating gradient"

$$E_{acc} = \frac{V_c}{L_g}$$

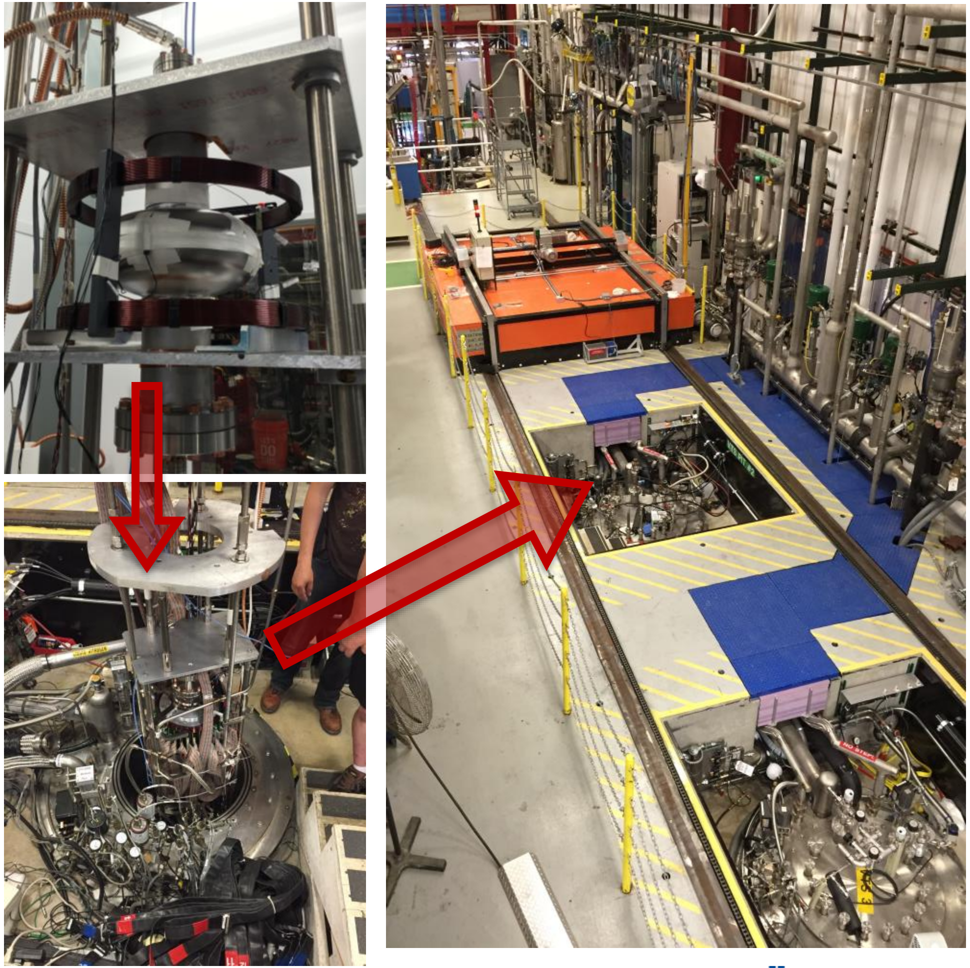


Figure of Merit and Motivations for Different Thrusts of R&D

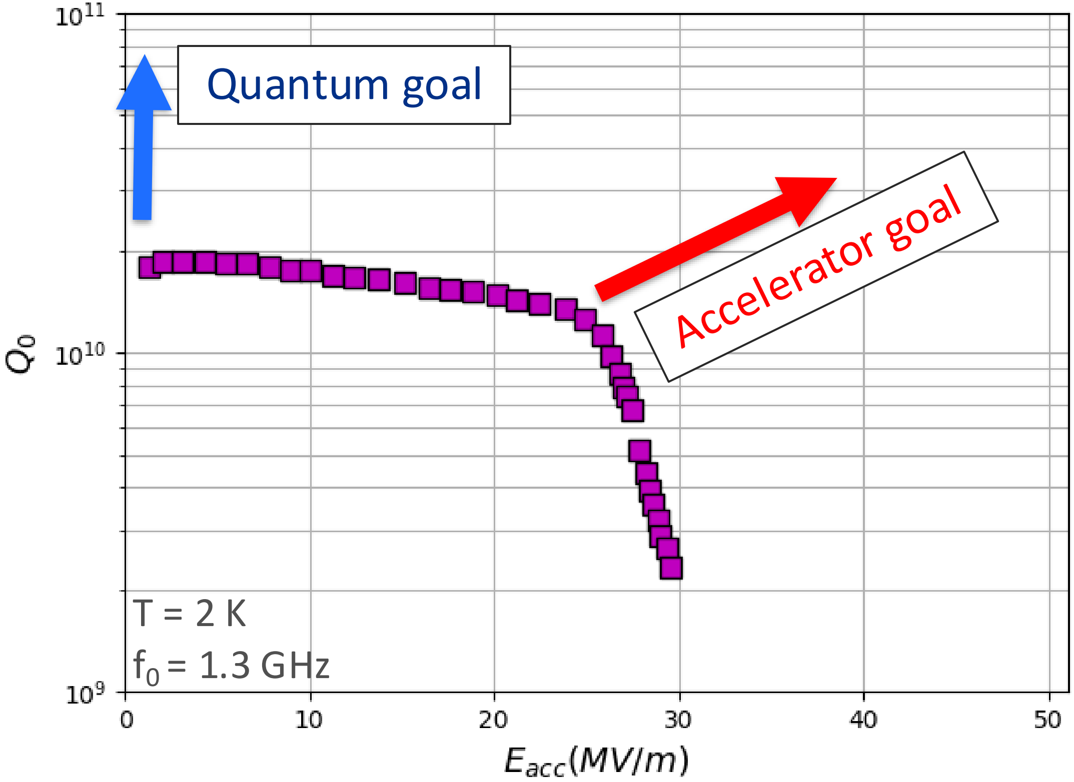
- Q_0 limited by R_s
- E_{acc} limited by:
  - Available RF power
  - Quench: thermal breakdown of SC

Goal of accelerator driven SRF research: Higher Q_0 and E_{acc}

- Cheaper accelerators/higher energy

One goal of quantum computing driven SRF research: Higher Q_0 at low E_{acc}

- Longer photon lifetimes = better quantum computer



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Part I: SRF R&D for High Energy Accelerator Applications

Q_0 vs E_{acc} of Cavities Post State-of-the-Art Surface Treatments

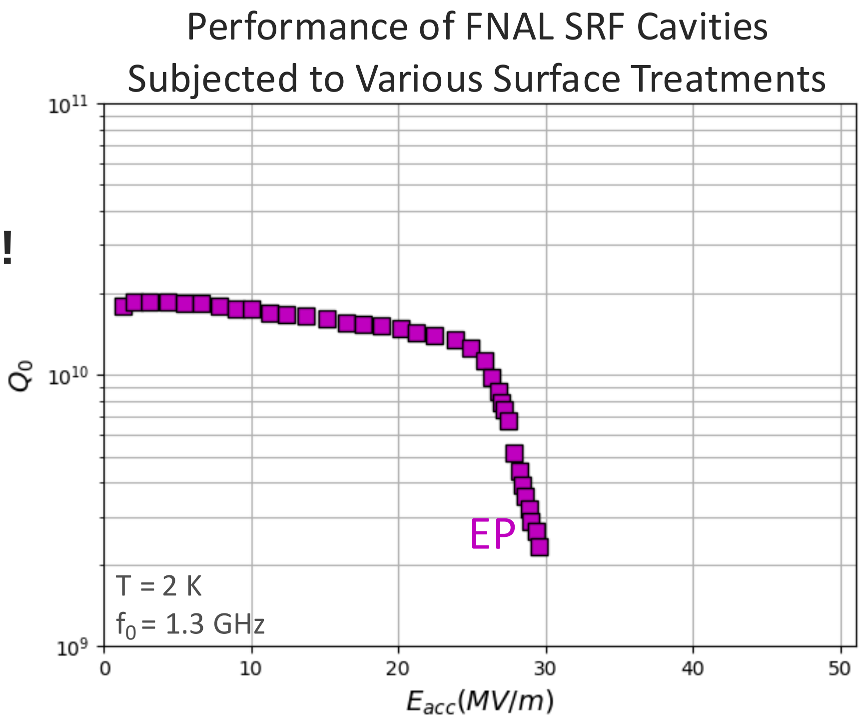
Near surface impurity structure affects RF performance

- Surface processing techniques – “recipes”
  - Baking/chemical treatments

Higher Q_0 and E_{acc} ➔ cheaper accelerators!

Key state-of-the-art surface treatments:

- Electropolishing (EP)



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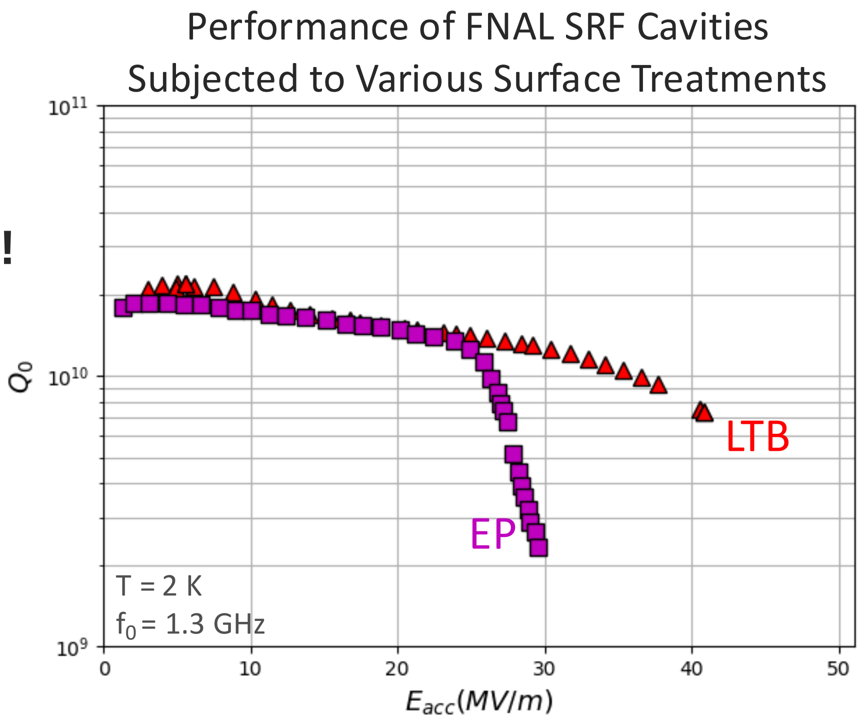
- Low T baking (LTB)



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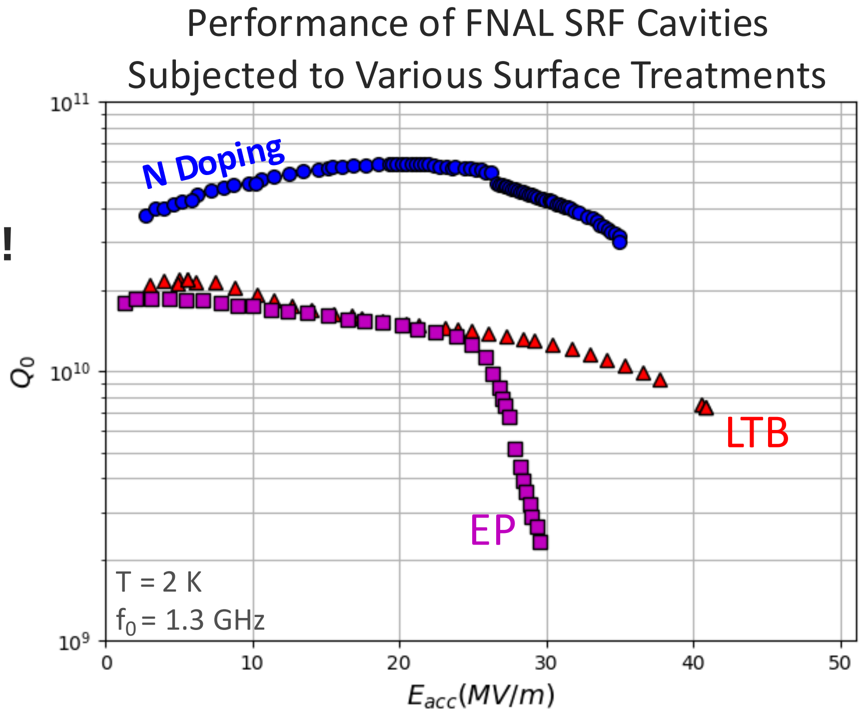
Key state-of-the-art surface treatments:

- Electropolishing (EP)
- Low T baking (LTB)
- Nitrogen Doping

Not understood how impurities vary the interface to allow for these phenomena



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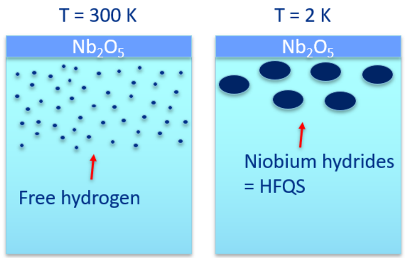
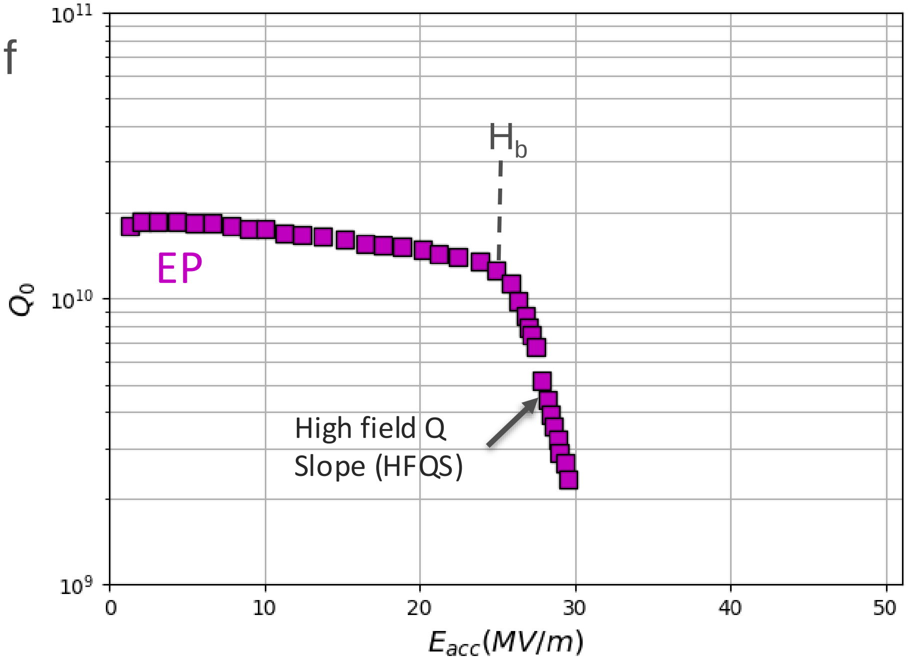
Mechanisms for High Gradients in Cavities Post LTB

Overcoming High Field Q Slope (HFQS) in LTB Cavities

EP cavities:

- High Field Q Slope (HFQS): sharp Q_0 degradation driven by the breakdown of proximity coupled Nb nano-hydrides





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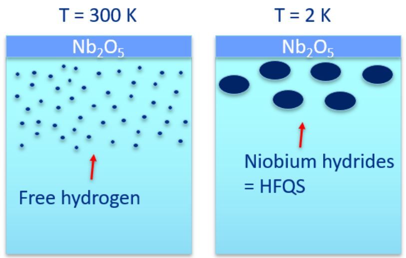
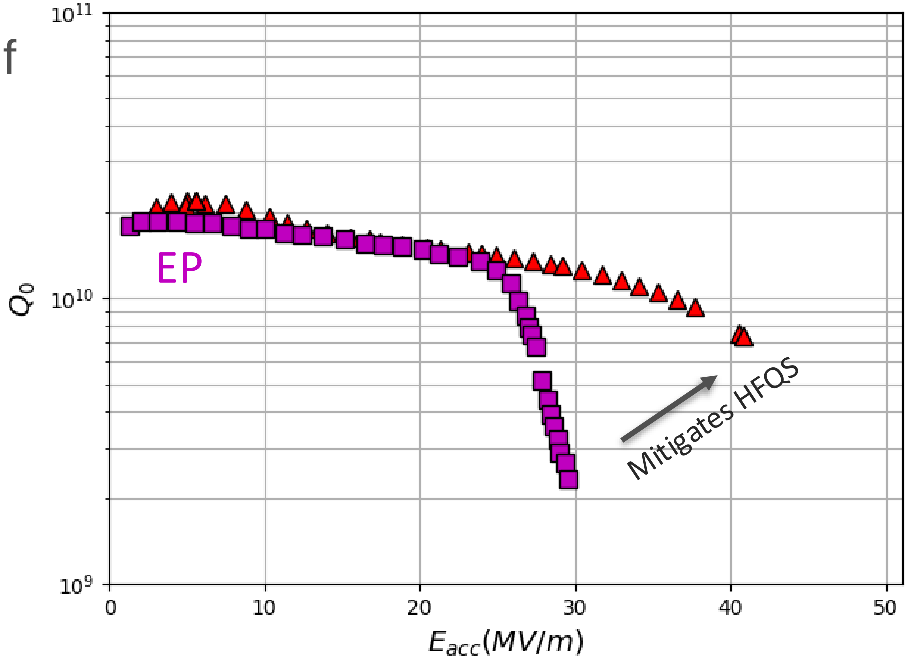
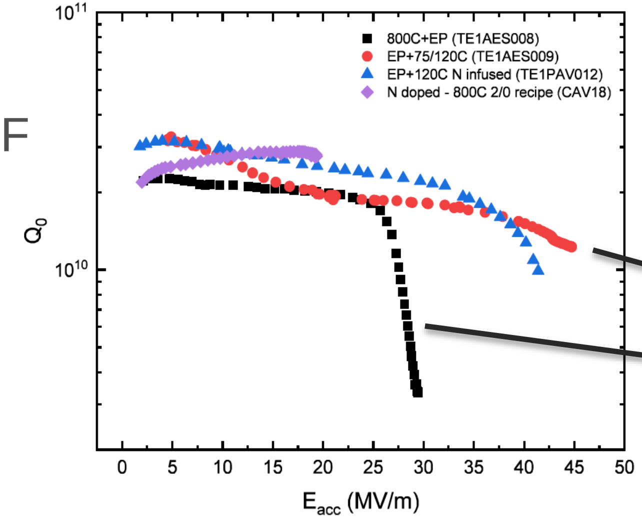


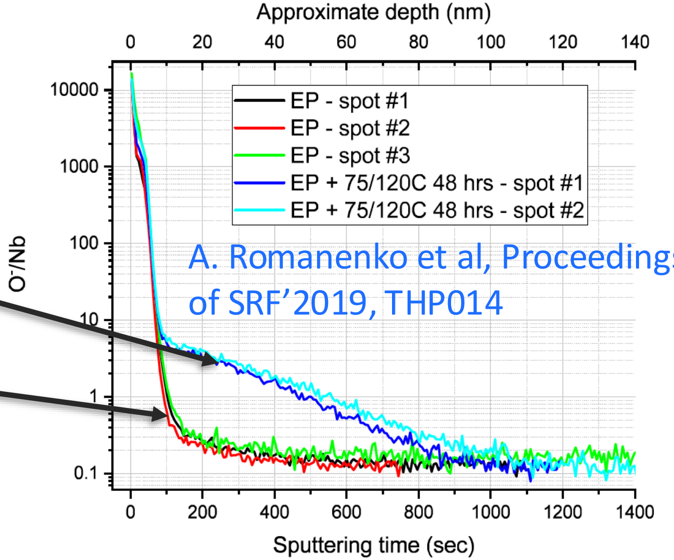


- Empirically derived fix: **low temperature bake (LTB)** cavity under vacuum at 120 C for 48 hours
  - "120 C baking effect"

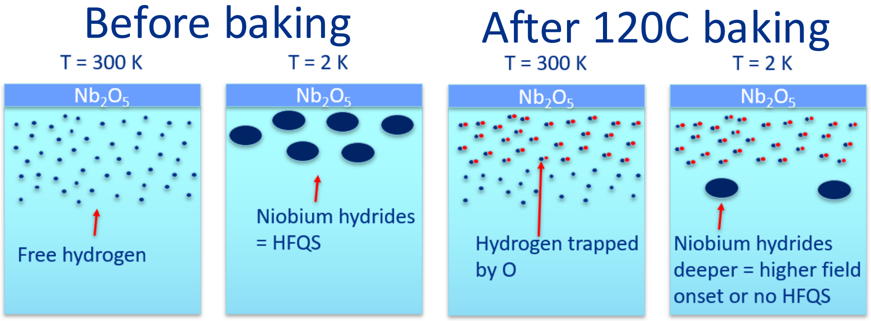
Role of Oxygen Diffusion in the 120C Baking Effect

Recent SIMS measurements on SRF cavity cutouts has highlighted the role of oxygen in enabling ultra-high gradients





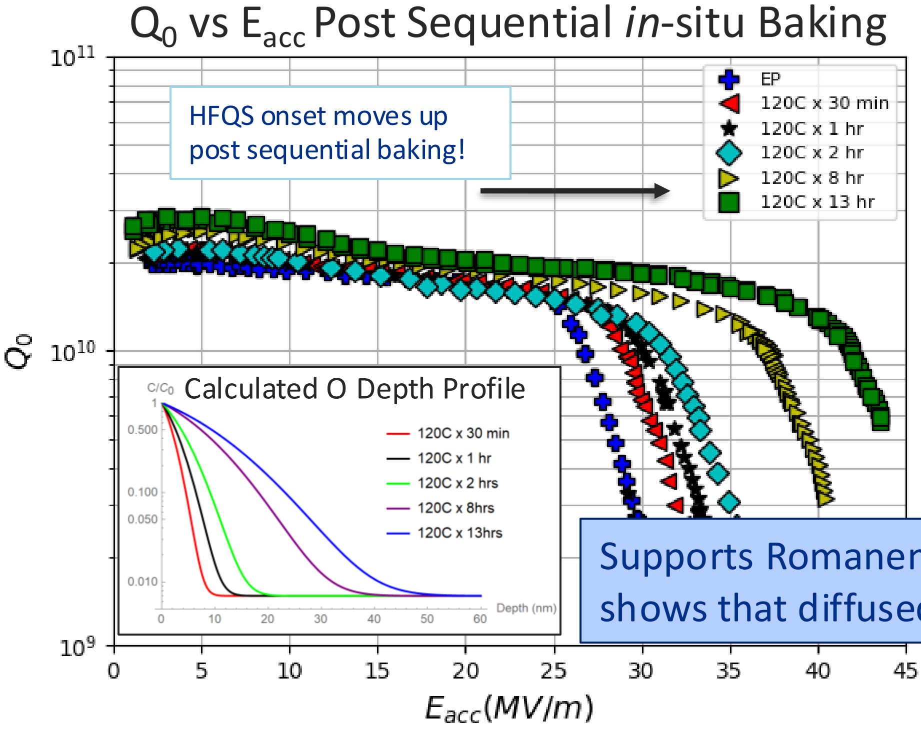
A. Romanenko et al, Proceedings of SRF'2019, THP014

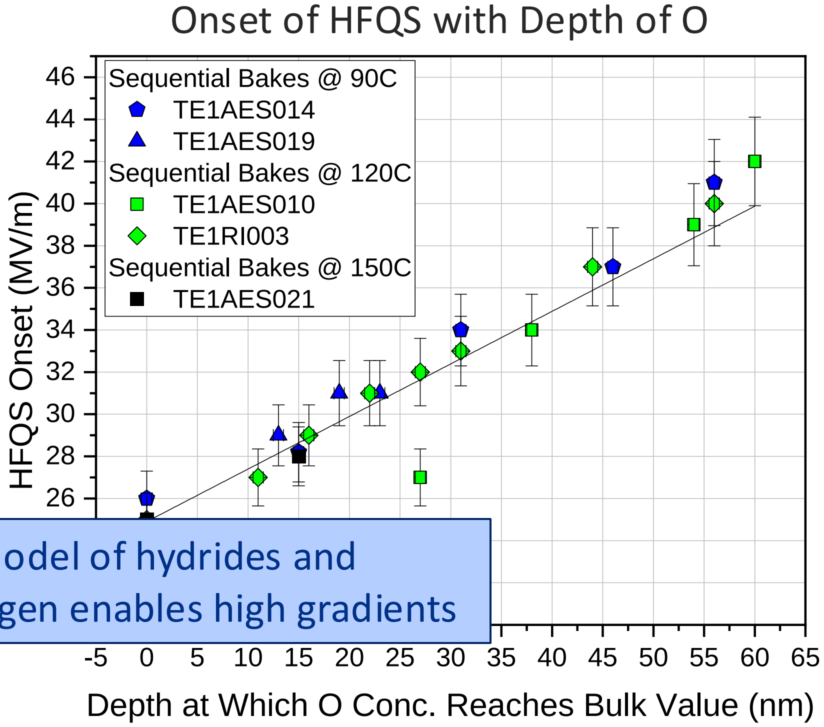


Implication: able to tune performance by diffusing oxygen from the native oxide via LTB

Solidifying the Role of O in the Mitigation of HFQS

Subjected a cavity to sequential rounds of LTB treatments, gradually diffusing O deeper





Supports Romanenko model of hydrides and shows that diffused oxygen enables high gradients

D. Bafia et al, Proceedings of SRF'2021, THPTEV016

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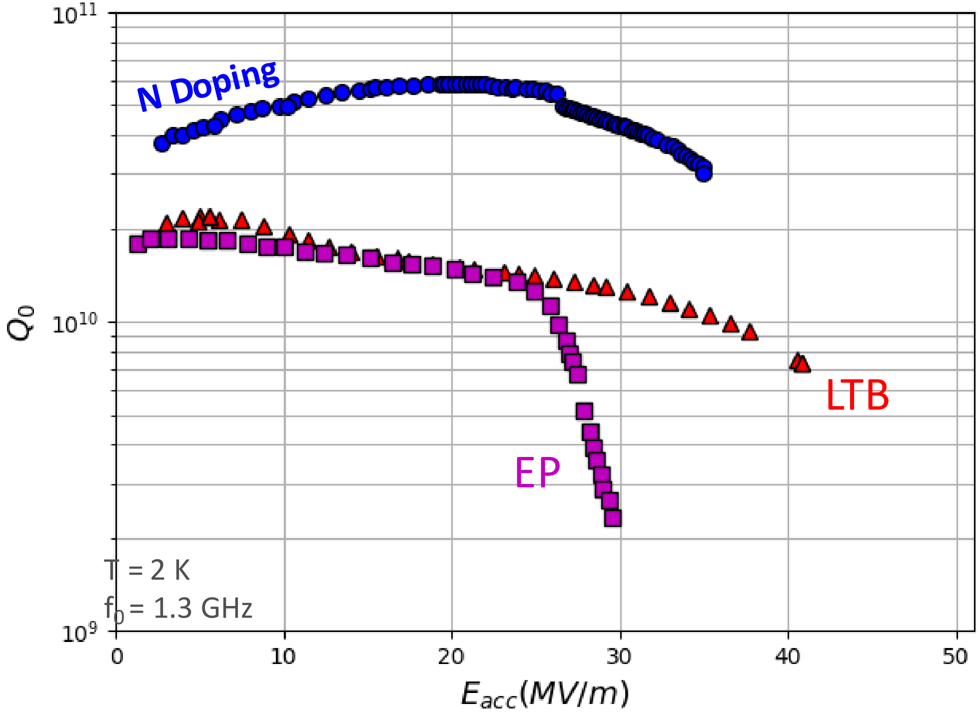
Investigating Mechanisms for Ultra-High Q_0 Post N-Doping

Effect of Nitrogen Doping on Cavity Performance

- **Nitrogen doping**: Cavity surface treatment which introduces uniform concentrations of N interstitial in RF layer

- Yields cavities w/
  - $Q_0 > 5E10$ @ 2 K
  - Puzzling anti-Q slope
  - Early quench

Performance of FNAL SRF Cavities Subjected to Various Surface Treatments



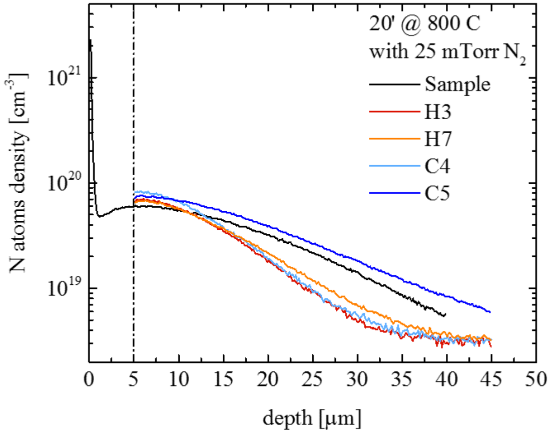
"2/6" Nitrogen-Doping Treatment

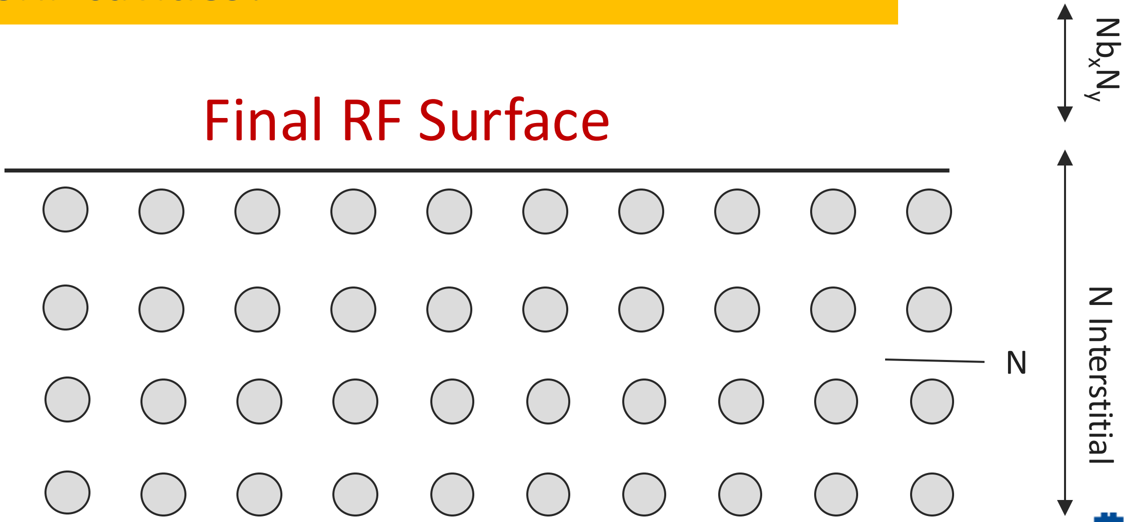
800C UHV, 3 hours → 800C N_2 p = 25 mTorr 2 minutes → 800C UHV, 6 minutes → UHV cooling → 5 um EP

Why does a uniform layer with ~100ppm of nitrogen allow for record high Q_0's in SRF cavities?

N_2

Depth profile of Nitrogen impurities





Slides adapted from M. Martinello

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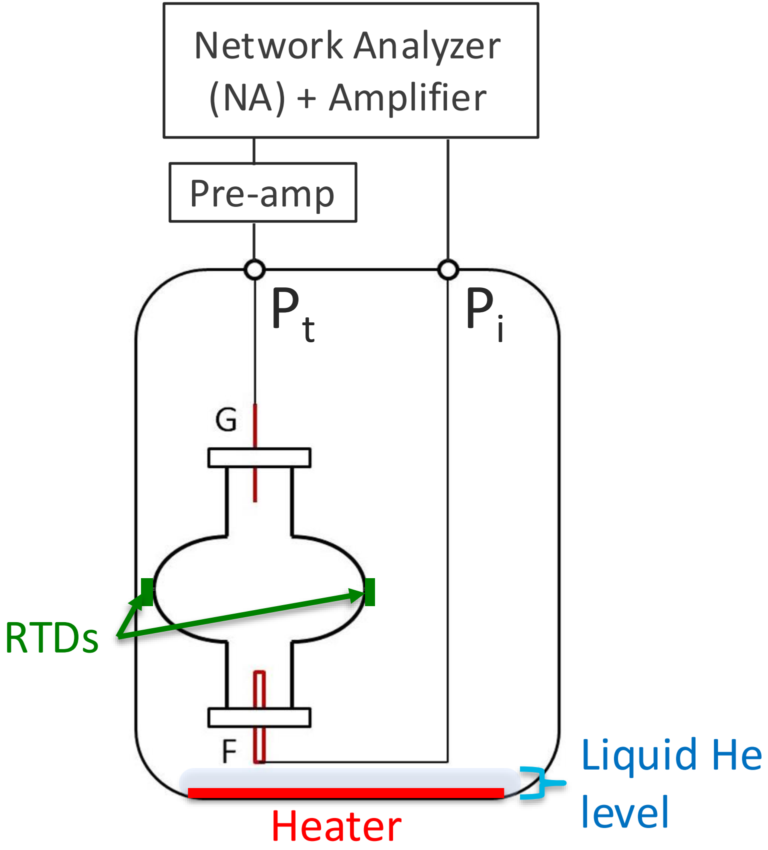
Experimental Setup for Frequency vs Temperature Measurements



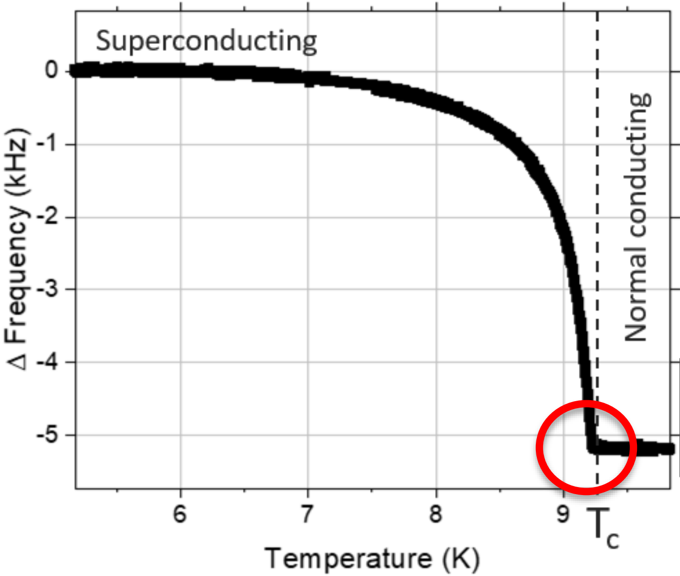
Well known method used to extract avg electronic MFP near the RF surface:

- NA + Amp sends a low signal (10mW) to measure f_0
- Increase temperature *slowly* (< 0.1 K/min) w/ heaters at bottom
- TFM:

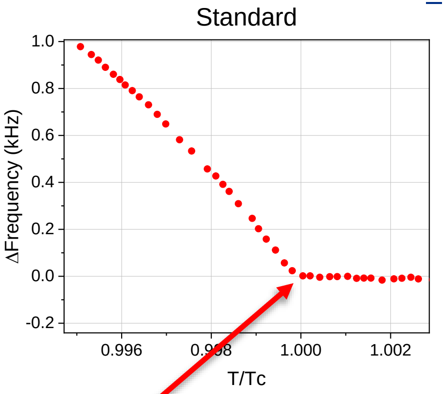
$$\lambda(T) = \frac{\lambda_L}{\sqrt{1 - \left(\frac{T}{T_c}\right)^4}}$$

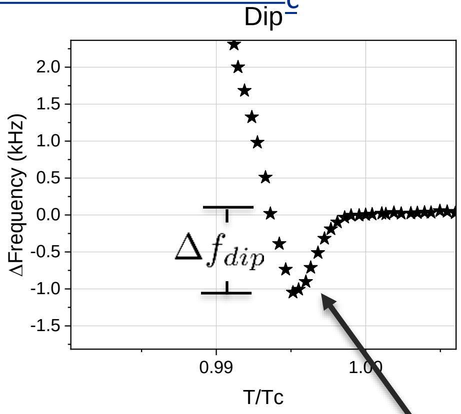
- Increase in effective RF volume = decrease in f_0

Discovery of Δf_0 vs T Features Near T_c

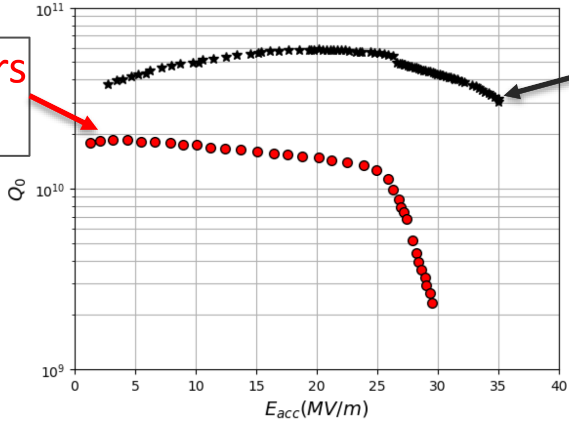


Zoology of Δf_0 vs T feature near T_c





Typically occurs in EP cavities



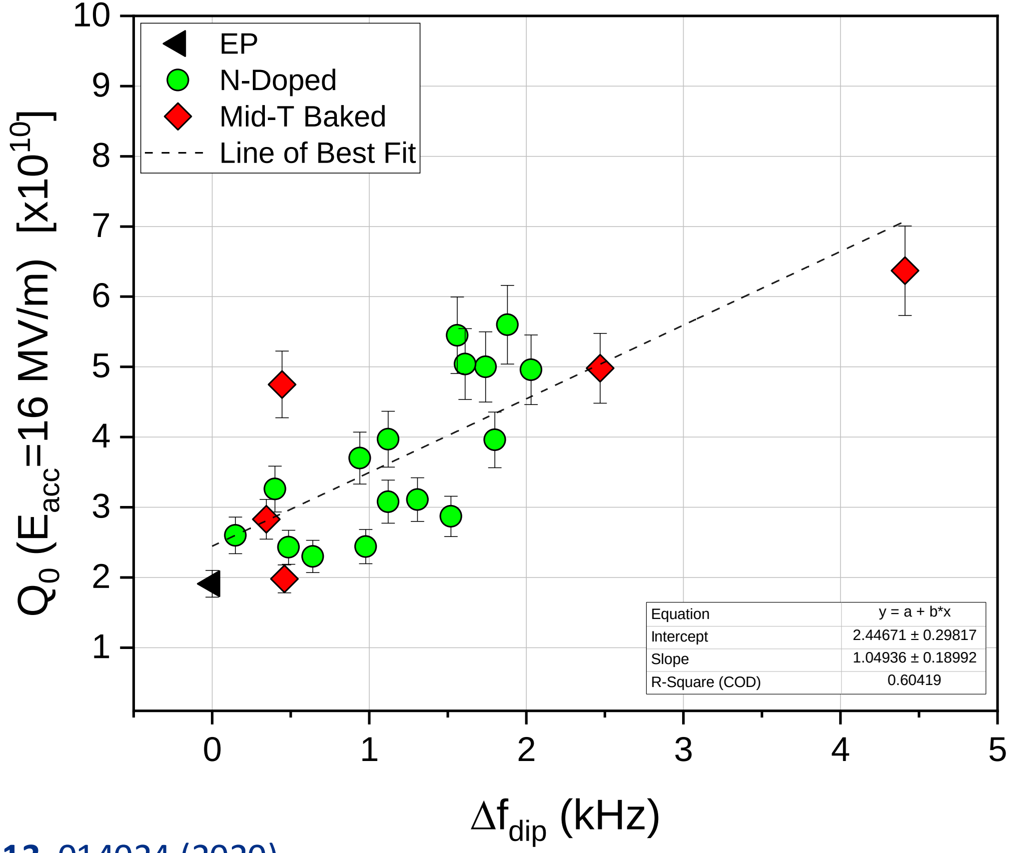
Occurs in N-Doped cavities

Quality Factor Correlates with Magnitude of Frequency Dip

Linear relationship between quality factor and dip magnitude!

Both Q_0 and dip magnitude tied to **same interface properties**

A full model of the frequency dip would give insight on mechanisms responsible for high Q_0

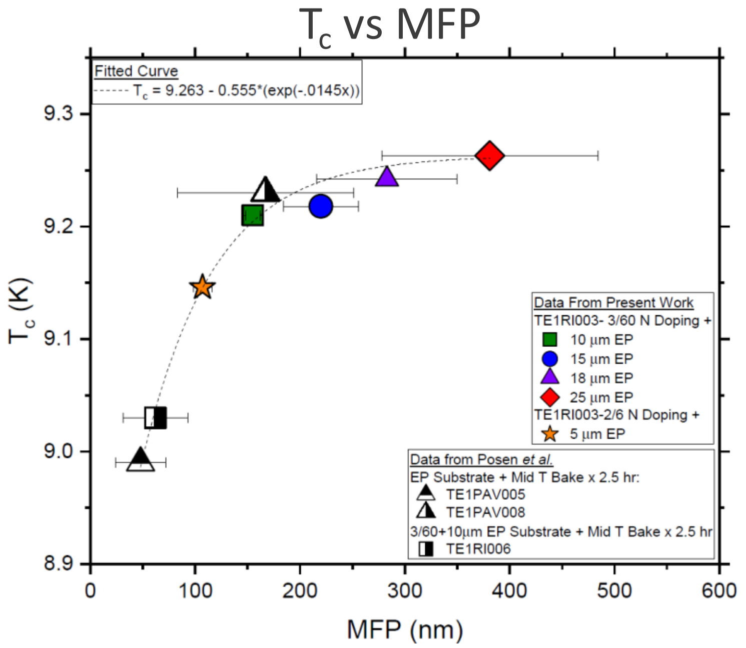


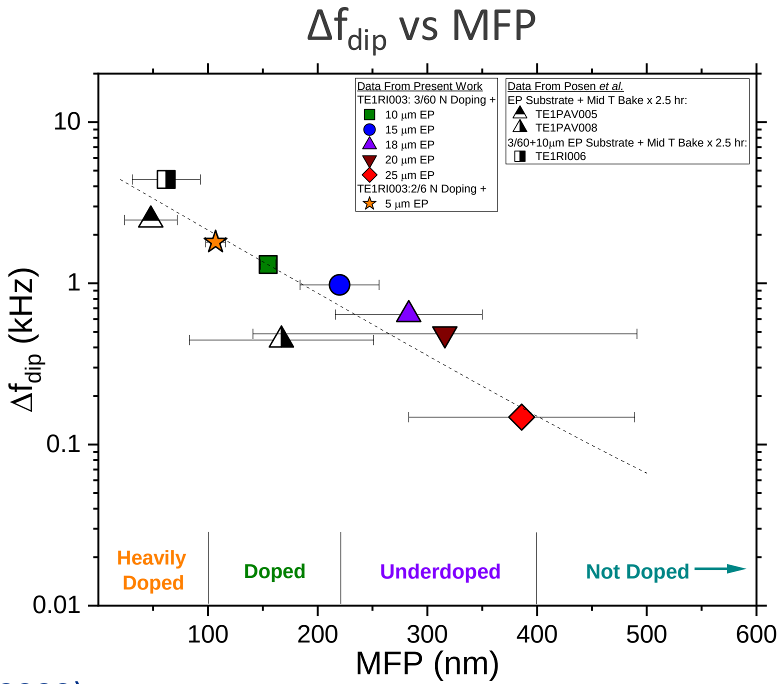
Mid-T bake data comes S. Posen *et al.* Phys. Rev. Appl. **13**, 014024 (2020)

Tracking Δf_{dip} and T_c with Average MFP (or Concentration)

Varied the concentration of interstitial N in cavities and found that both frequency dip magnitude and transition temperature followed some exponential relationship with the MFP (concentration)

- Dip is tied to fundamental properties within the interface





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

Study: Implications of the Dip on 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

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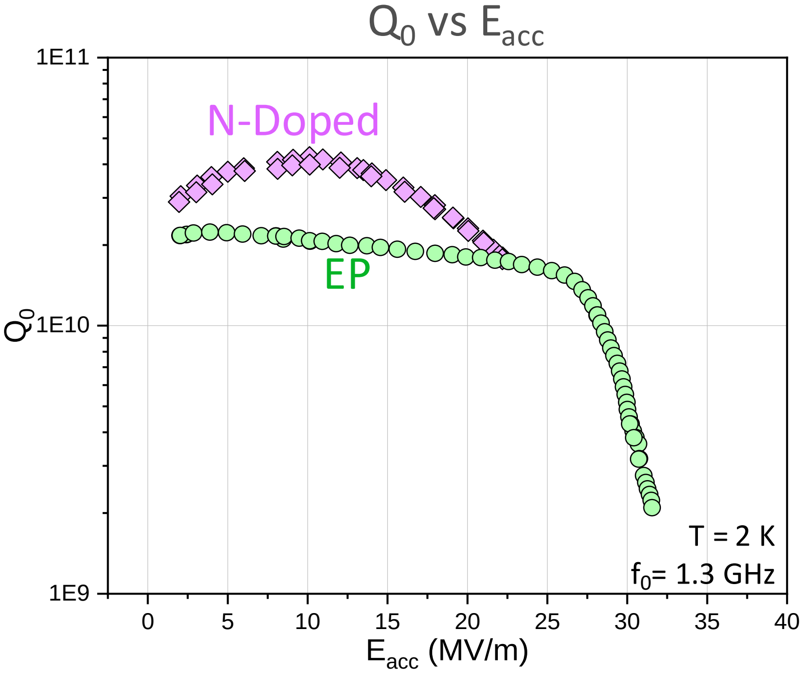
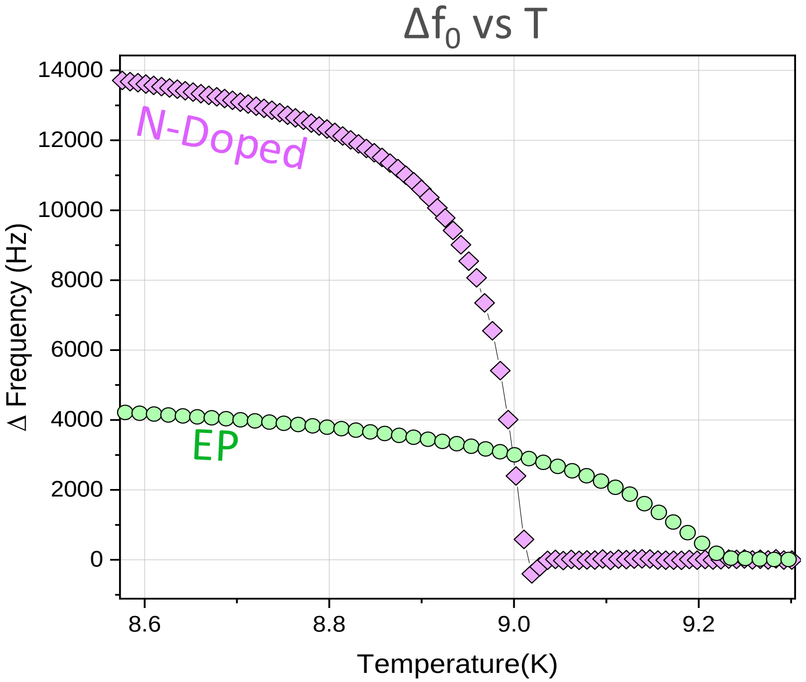
RF Performance of N-Doped and EP Cavities





EP: HFQS

N-Doped: High Q_0/anti-Q slope

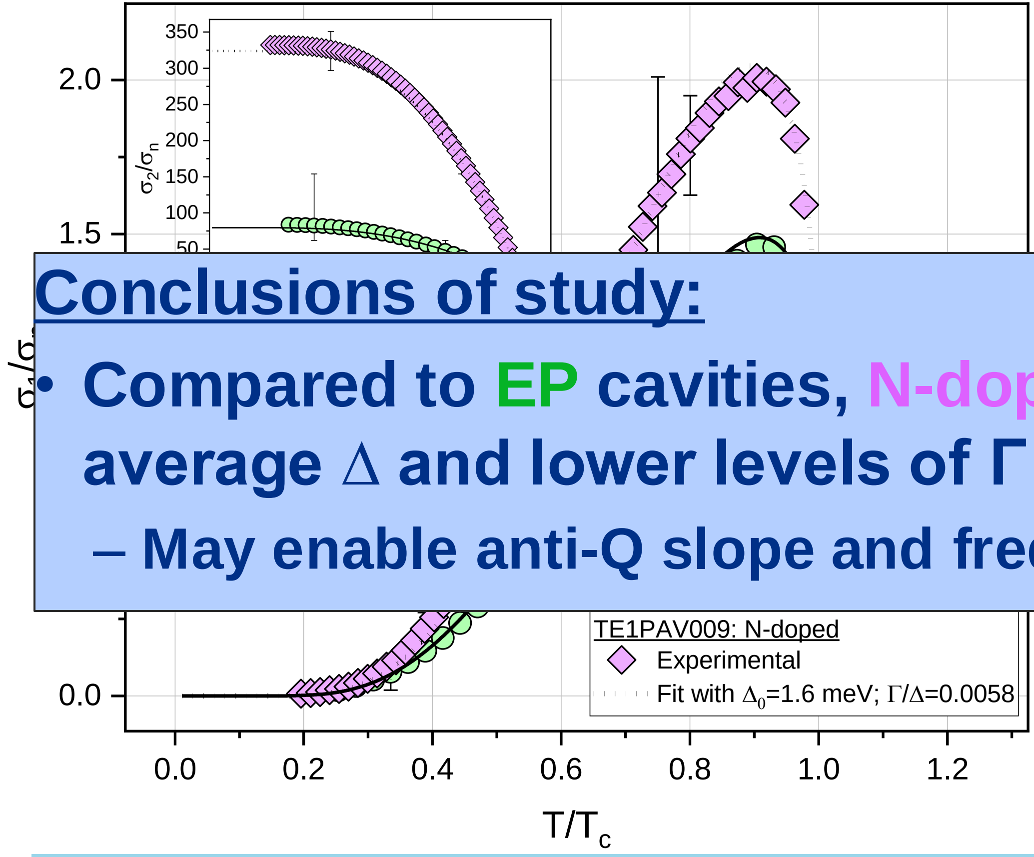
EP: Standard feature near T_c

N-Doped: Prominent dip near T_c

Conclusions of study:

- **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**

Conductivity of N-Doped and EP Cavities



Model Fitting Parameters

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

…ed cavity cutouts arXiv:1805.06359

- Herman PRB **104,** 094519 (2021)
- Kubo PRAppl **17**, 014018 (2022)

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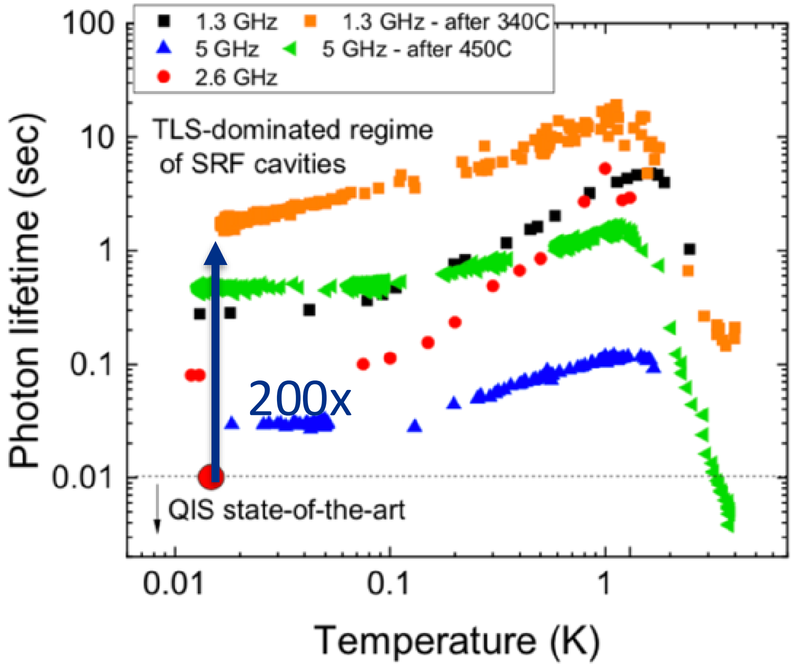
Part II: SRF R&D for Low Energy Quantum Computing Applications

Why Use SRF Cavities in the Quantum Regime?

SRF cavities provide a technological advantage for many applications in the quantum regime

- Qubit readout
- Materials studies
- Quantum memory
- Particle detection

A. Romanenko et al, Phys. Rev. Applied **13**, 034032, 2020



SQMS

A DOE National QIS Research Center

30
Partner Institutions

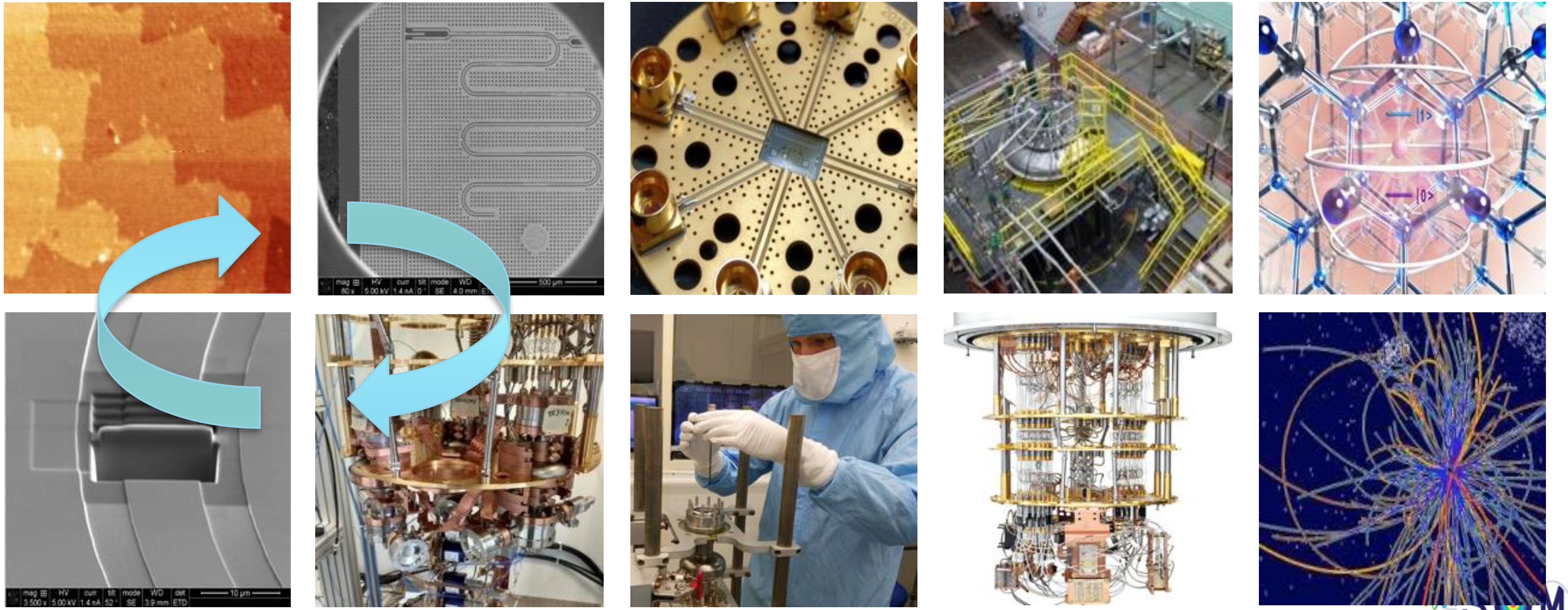
450+
Collaborators

SQMS MISSION [excerpt]

Achieve transformational advances in the major cross-cutting challenge of understanding & eliminating decoherence mechanisms in superconducting devices, enabling construction and deployment of superior quantum systems for computing & sensing.

SQMS S&T Innovation Chain: from material discovery to quantum advantage

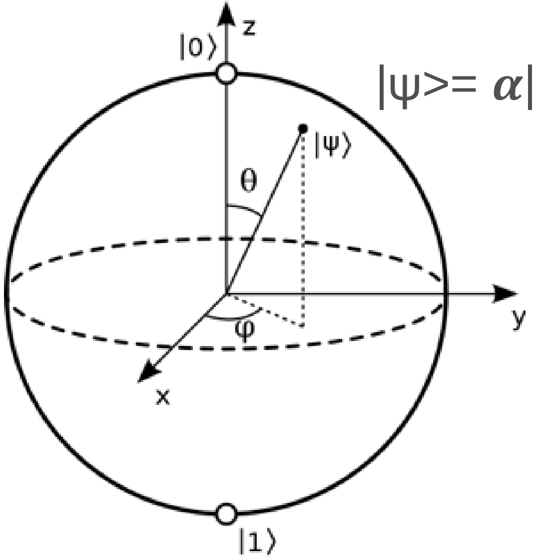
Materials Discovery → High Coherence Devices → Systems Integration → New quantum computing and sensing platforms → Quantum Advantage



What is a Qubit?

<u>Qubits</u>: basic unit of quantum information → Two (energy) level system

Superposition



$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

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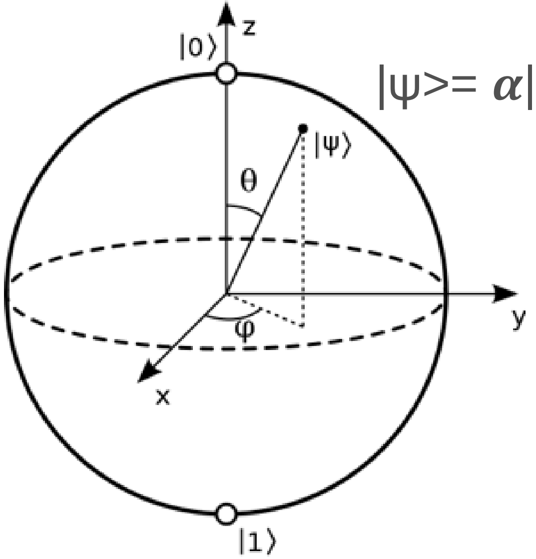
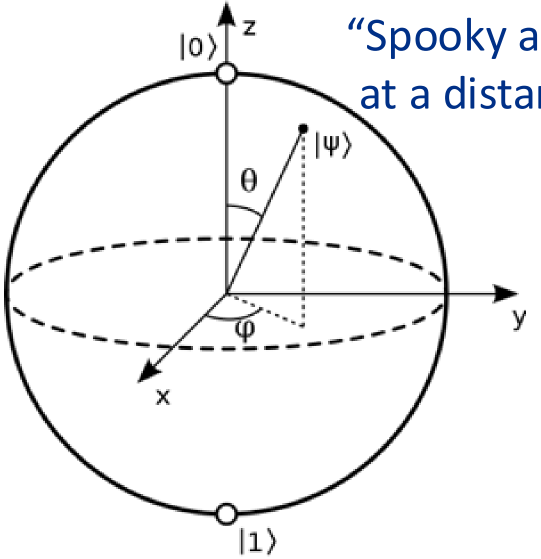


$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

Entanglement

"Spooky action at a distance"

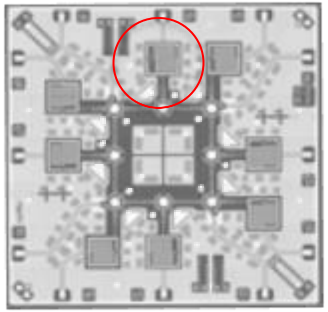


Phenomena give a quantum computer the potential to provide computational capacity for dramatic speedups in several high impact areas

Superconducting Qubits

1. Resonators (cavities)

2D



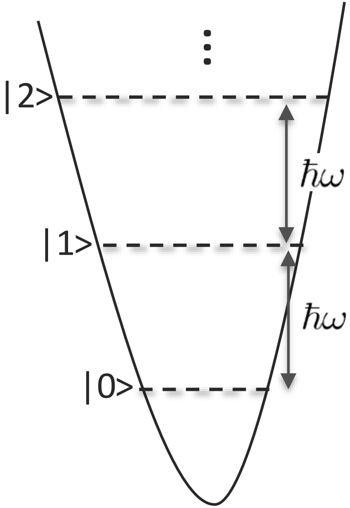
Rigetti 8-qubit processor

3D

Fermilab SRF resonators

M. Reagor et al, Science Advances, Vol.4, no. 2, (2018)

A. Romanenko et al, Phys. Rev. Appl. 13, 134052 (2020)



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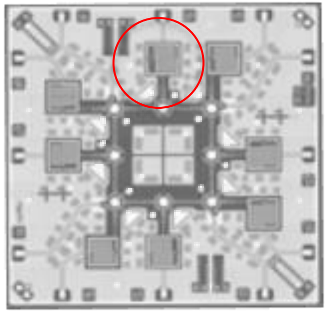
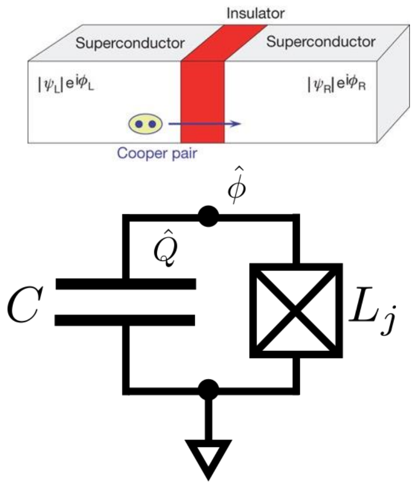


Rigetti 8-qubit processor

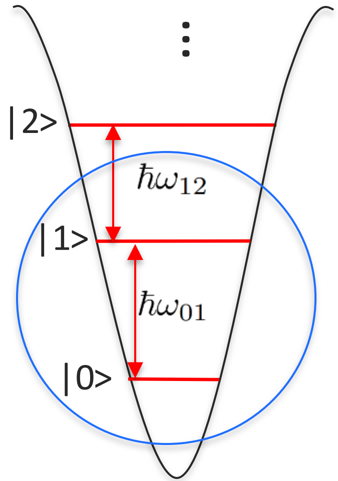
3D

Fermilab SRF resonators

2. LC circuit with Josephson junction



SC qubit based on Josephson junctions



Two Level System!

M. Reagor et al, Science Advances, Vol.4, no. 2, (2018)

A. Romanenko et al, Phys. Rev. Appl. 13, 134052 (2020)

J. Koch et al, Phys. Rev. **A** 76, 042319 (2007)

Need long **quantum coherence** for both resonator and JJ

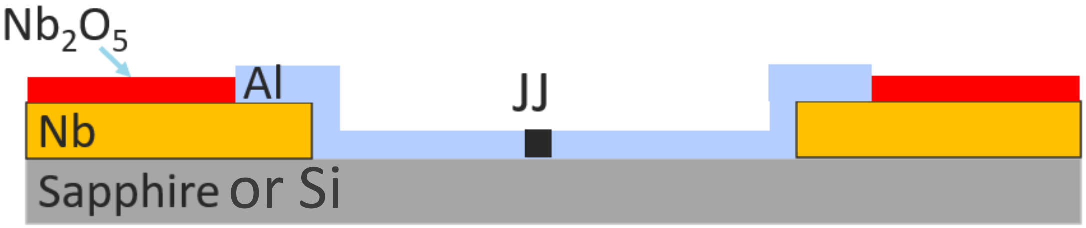
→ Need a qubit that you can manipulate and not confuse with other states

Dissipation in Quantum Devices

Dissipation in quantum regime given by lifetime of the quantum information (or photons) (T_1) stored in the device

$$Q_0 = \omega T_1$$

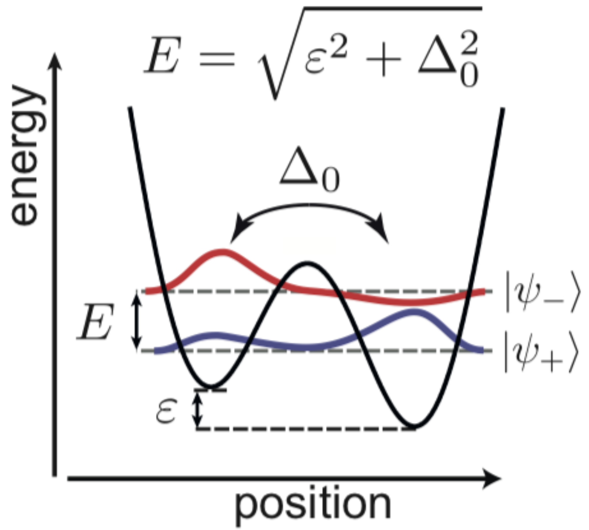
$$\Gamma_1 = \frac{1}{T_1} = \omega \sum_i \frac{p_i}{Q_i}$$

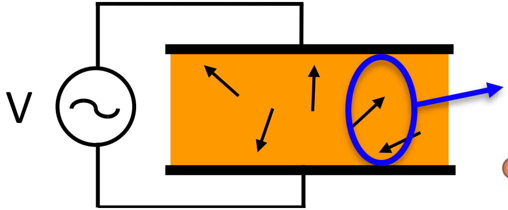


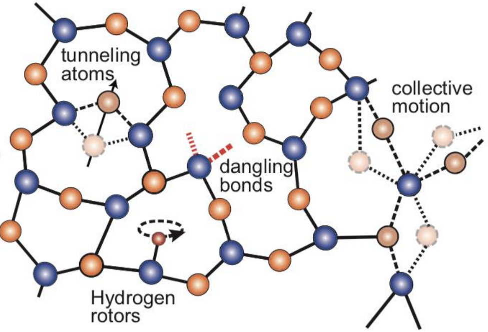
Qubits are limited by the worst component in the system → which materials/interfaces are the worst?

TLS Dissipation

- Catch-all mechanism used to describe losses with a particular loss behavior
- Induce noise in quantum devices introducing charge, flux, I_c noise
- If TLS couple directly to qubit transition, may allow for direct relaxation channel
- **Quantum coherence is negatively affected**



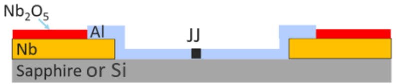




Images from C. Muller *et al.* Rep. Prog. Phys. **82**, 124501 (2019)

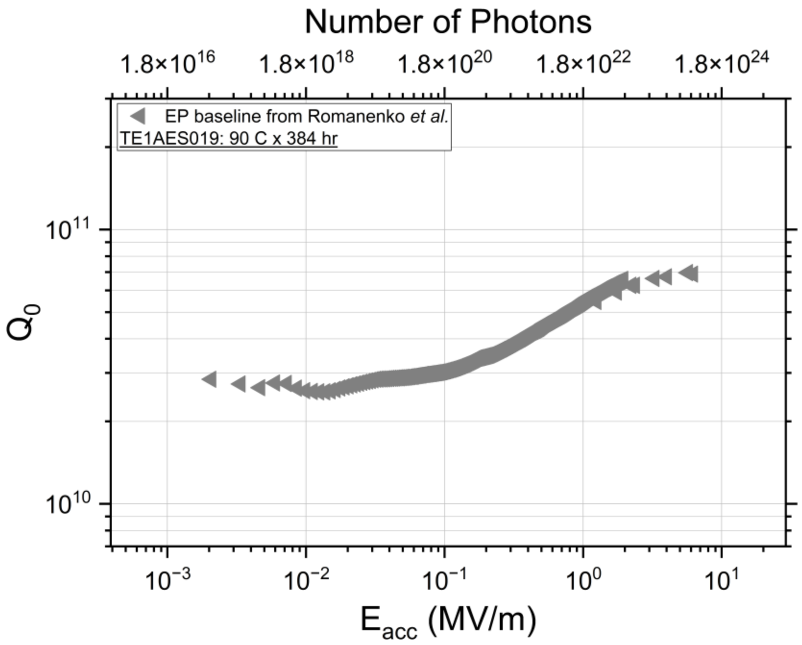
Identifying Sources of Decoherence in the Quantum Regime

Lossy Element #1: Native Niobium Oxide?

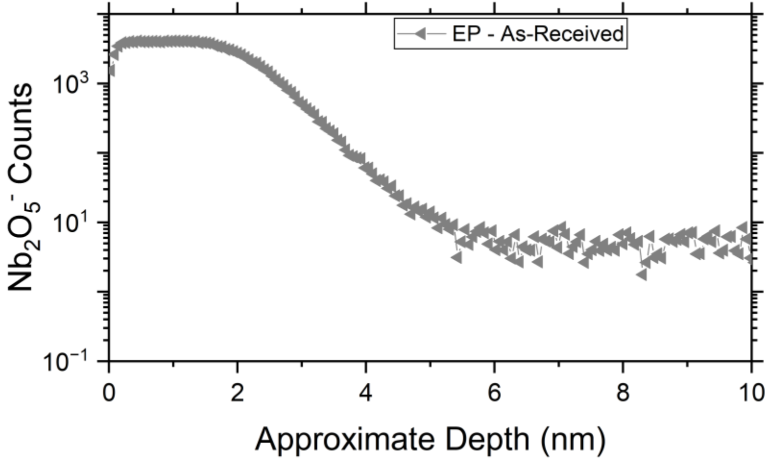


D. Bafia *et al.* PRAppl **22**, 024035 (2024)

Q_0 of Sequentially Baked Nb Cavity



Nb_2O_5 Signal of Nb Cutout Sample Post Baking in ToF SIMS



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D. Bafia *et al.* PRAppl **22**, 024035 (2024)

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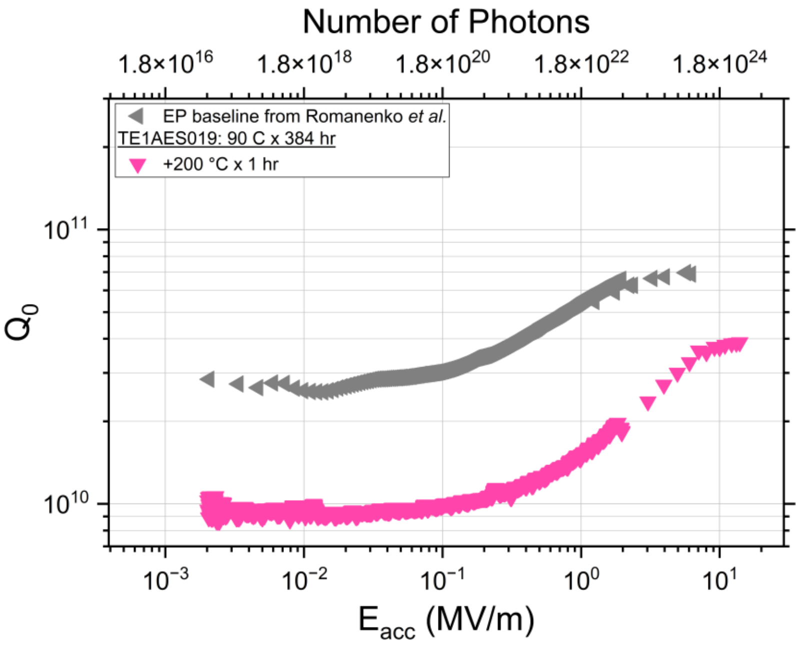

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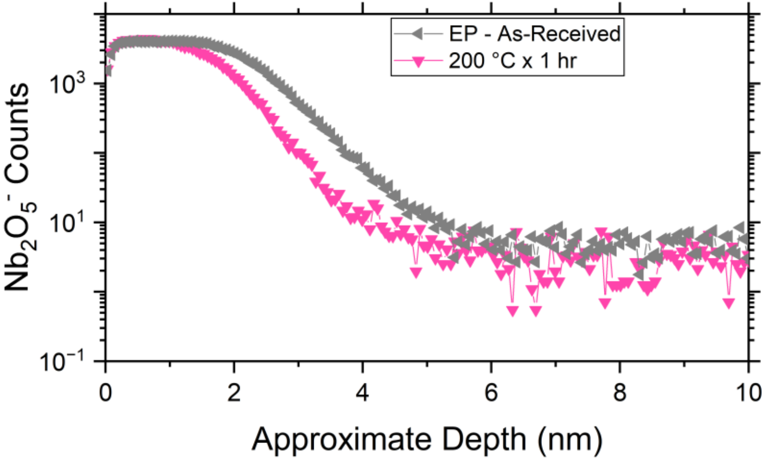

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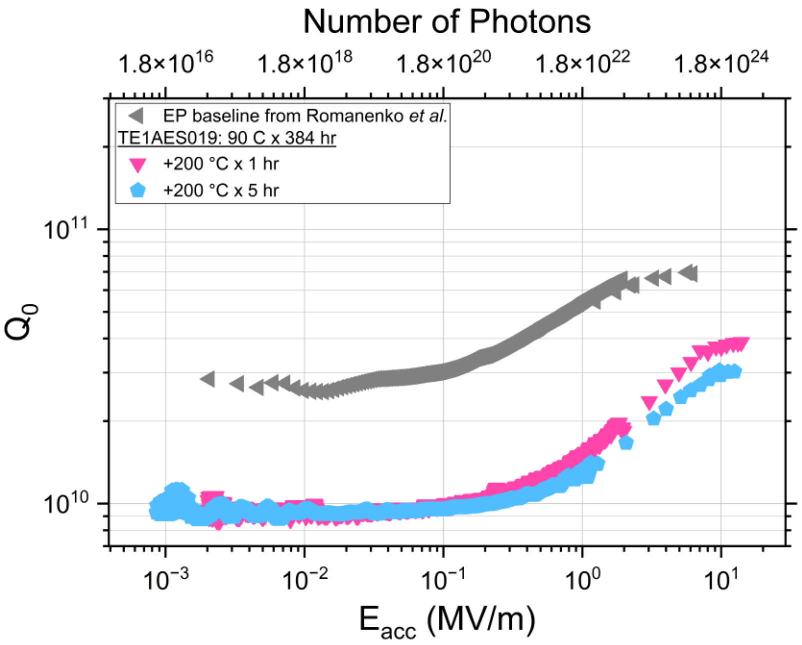

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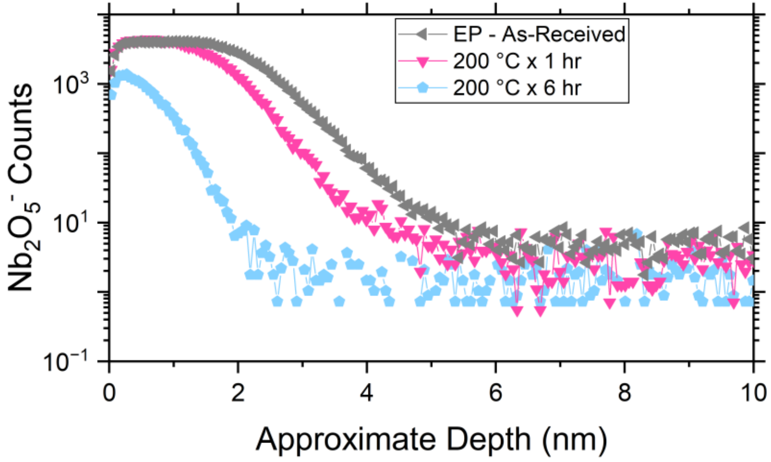

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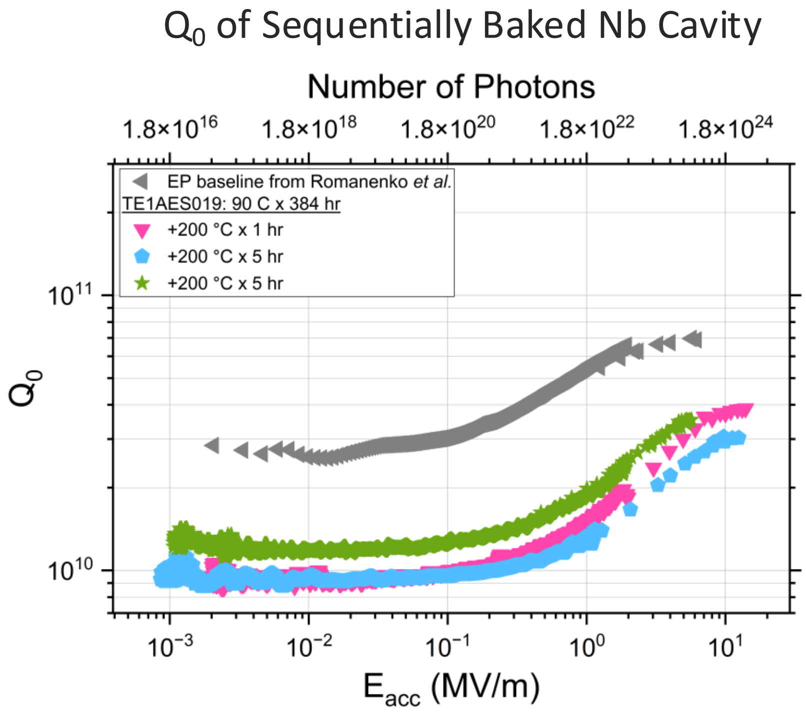
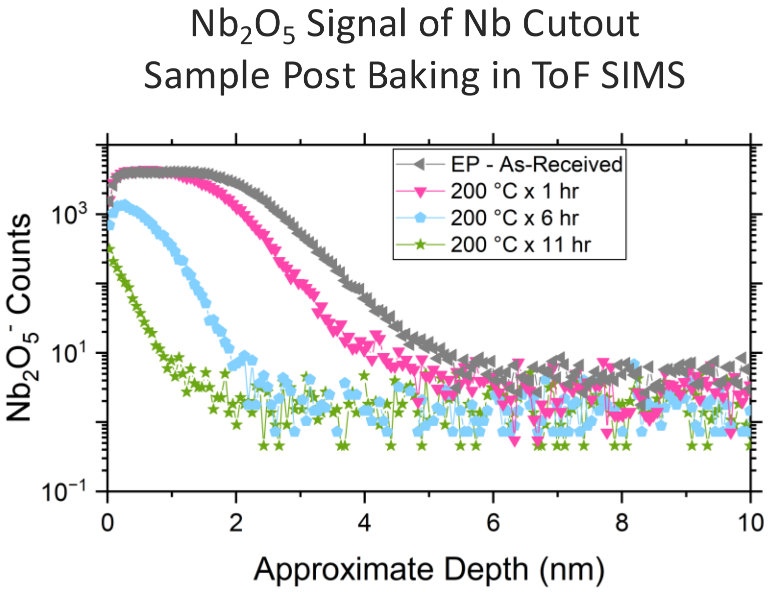
D. Bafia *et al.* PRAppl **22**, 024035 (2024)





Lossy Element #1: Native Niobium Oxide?

D. Bafia *et al.* PRAppl **22**, 024035 (2024)

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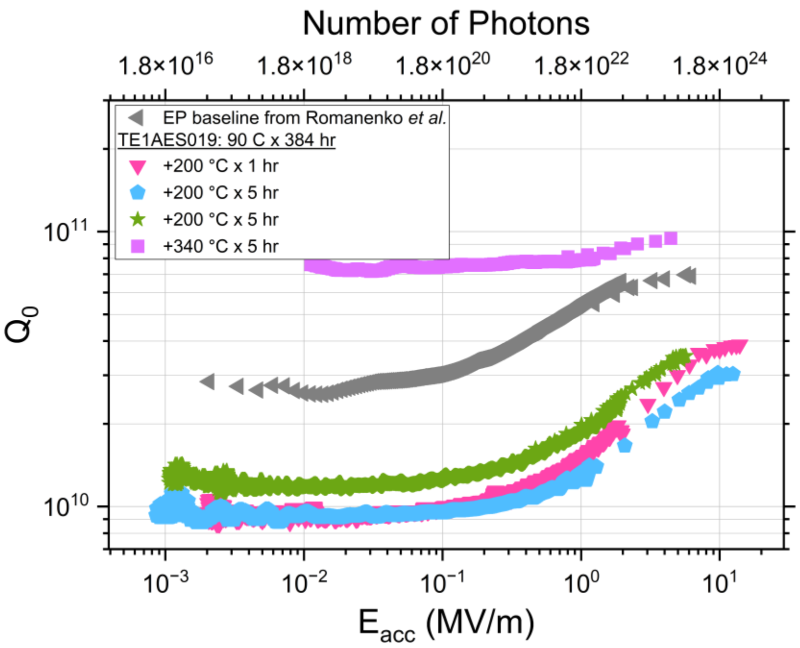

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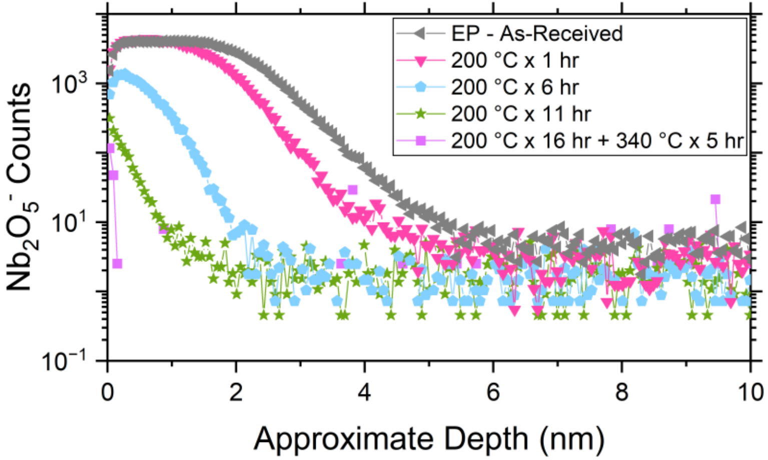
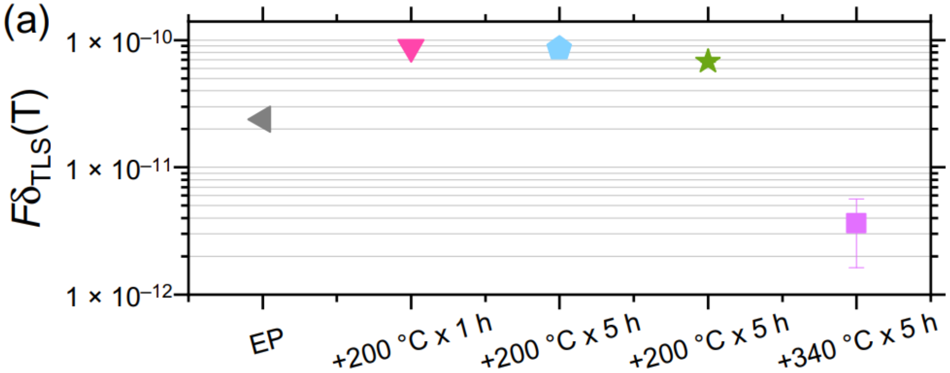


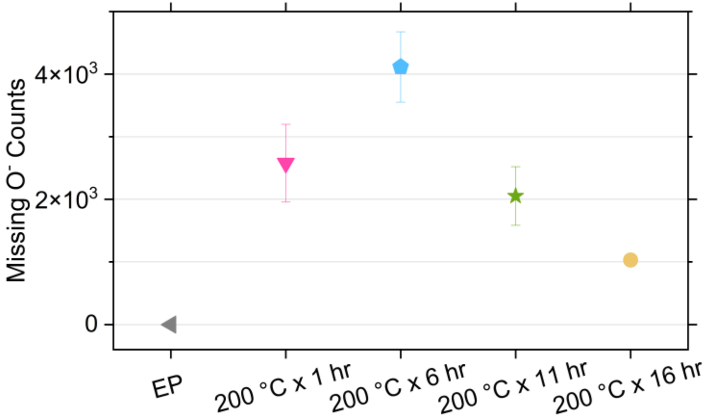
Lossy Element #1: Native Niobium Oxide?

D. Bafia *et al.* PRAppl **22**, 024035 (2024)

TLS Loss of Sequentially Baked Nb Cavity



Missing O Counts in Nb_2O_5 of Nb Cutout Sample Post Baking in ToF SIMS



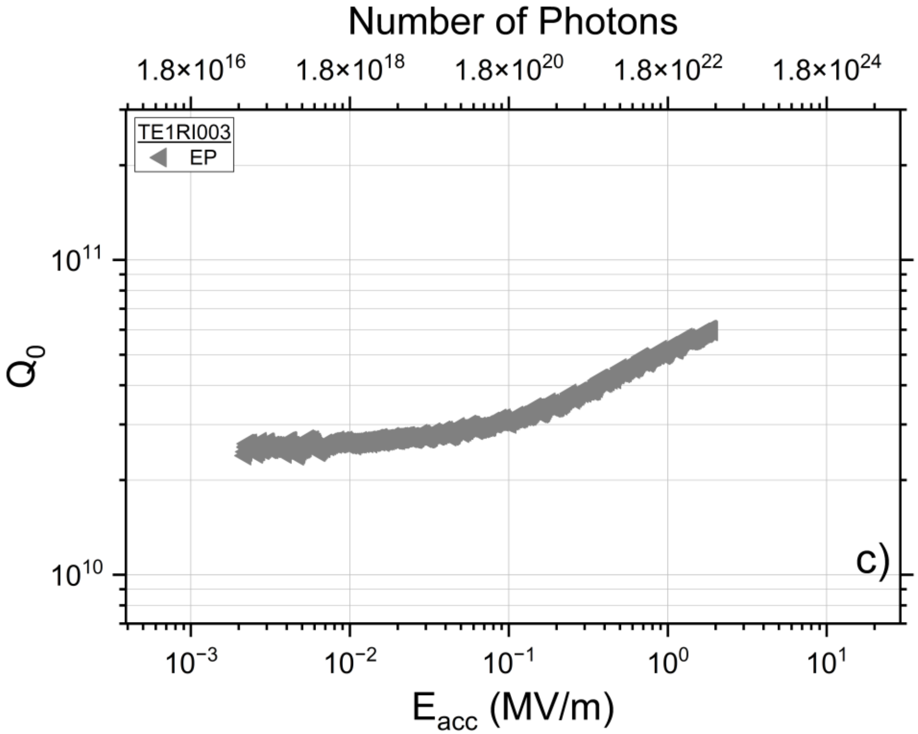
- TLS loss is aggravated when # of missing O atoms increases
  - O vacancies likely host magnetic impurities (agrees with PCTS studies by Proslier)

Yes, niobium oxide is lossy!

Lossy Element #2: O Impurities in Nb?

D. Bafia *et al.* PRAppl **22**, 024035 (2024)

Q_0 of Sequentially Treated Nb Cavity



Lossy Element #2: O Impurities in Nb?

D. Bafia *et al.* PRAppl **22**, 024035 (2024)

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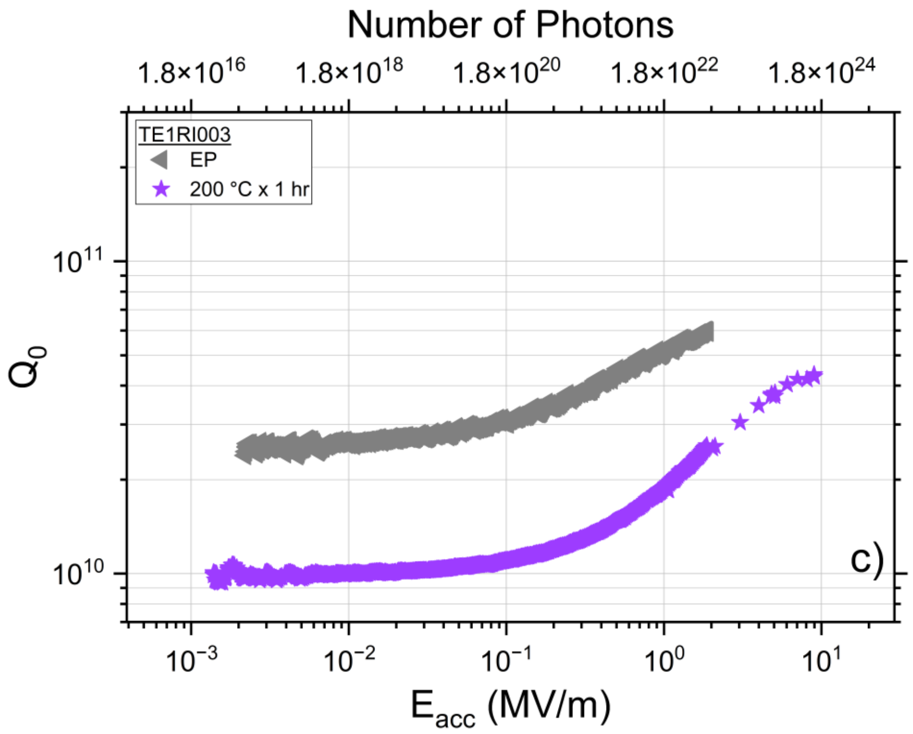

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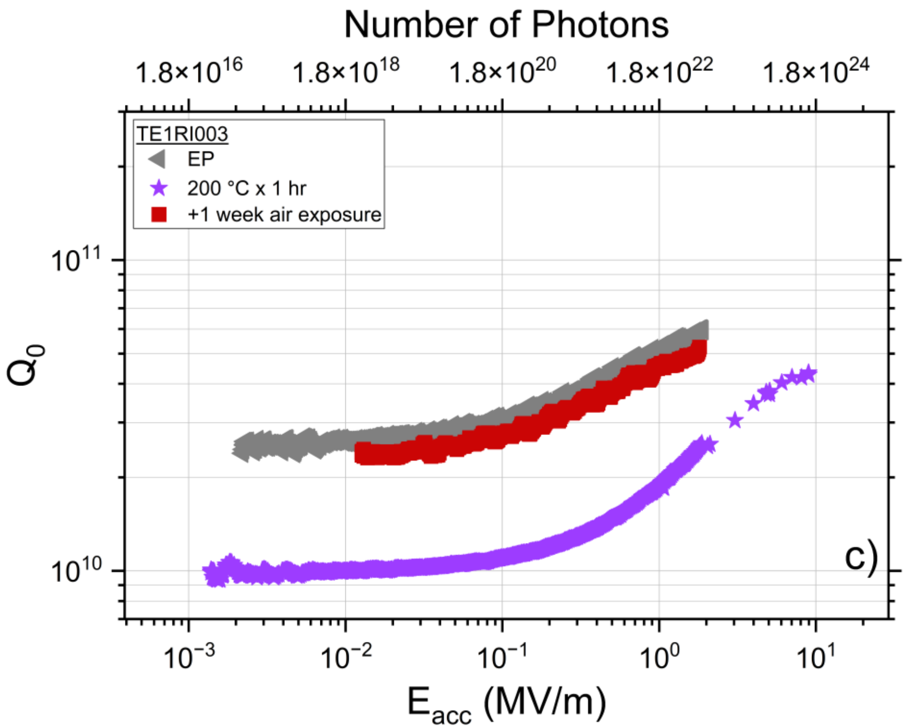
Lossy Element #2: O Impurities in Nb?

D. Bafia *et al.* PRAppl **22**, 024035 (2024)

Q_0 of Sequentially Treated Nb Cavity



Performance at low fields with and without interstitial O is identical

Interstitial O does not contribute to additional TLS (yet?)

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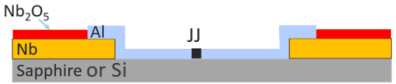
Lossy Element #3: Nb Film Quality?

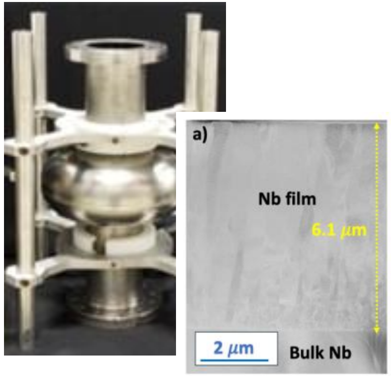


B. Abdisatarov *et al* arXiv:2407.08856, to be published in APL

Bulk Nb

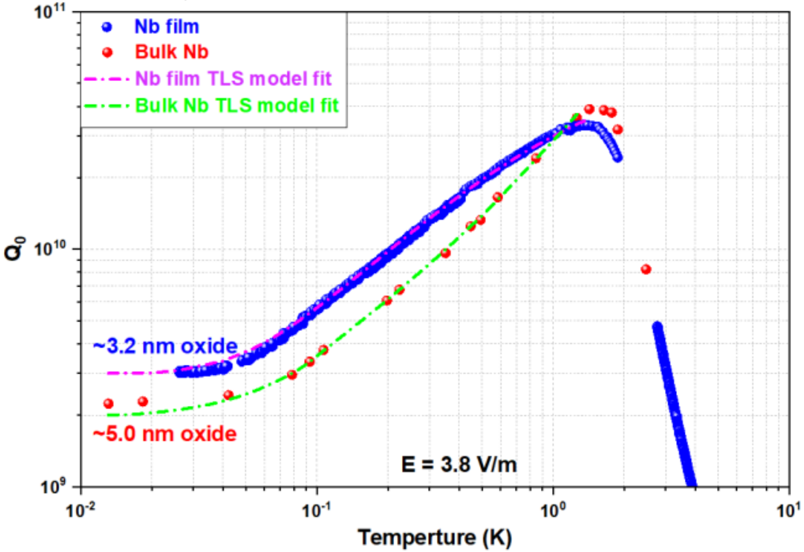
RRR ~ 300

HiPIMS Nb Film



RRR ~ 50

Q_0 vs T of Bulk and Nb Film Cavities



Nb Film quality does not limit T_1 (yet?)

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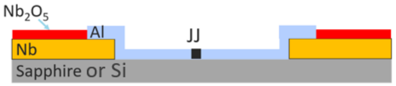
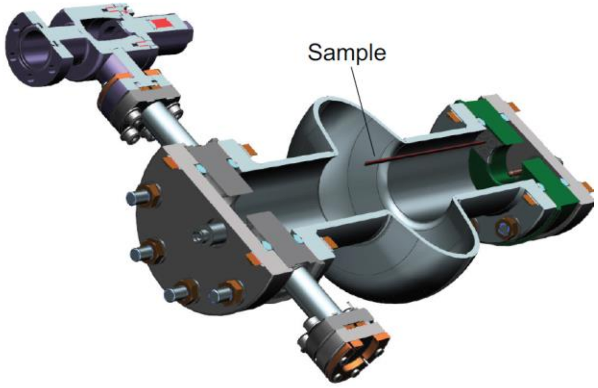
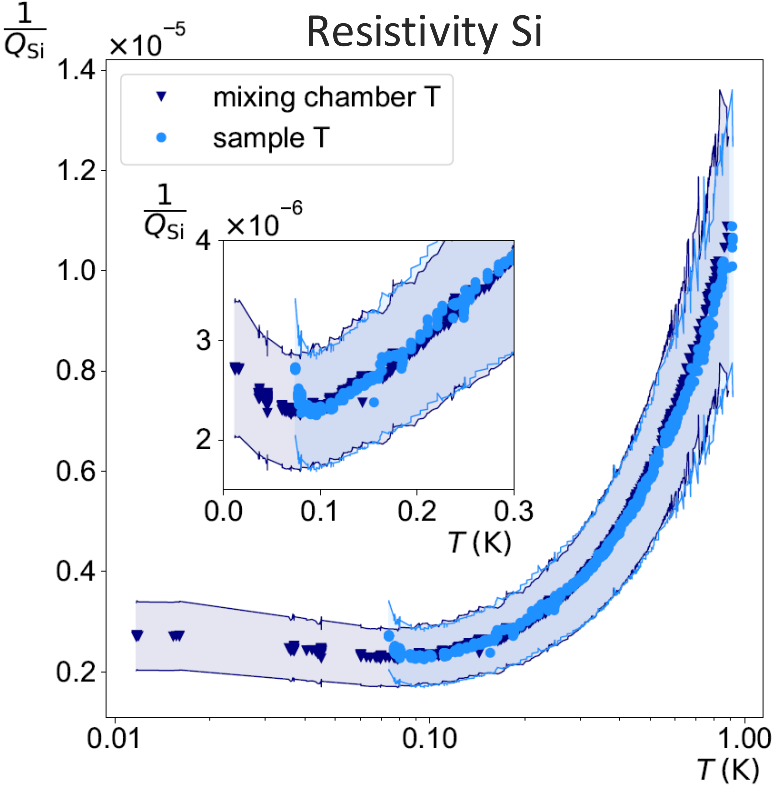
Lossy Element #4: Substrate?





M. Checchin *et al.* PRAppl **18**, 034013 (2022)

Loss Tangent of High Resistivity Si



- Higher than expected loss tangent for Si

Yes, Si substrates are presently limiting T_1!

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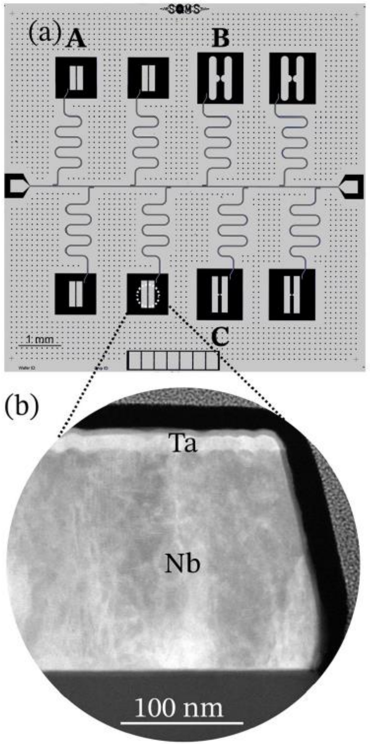
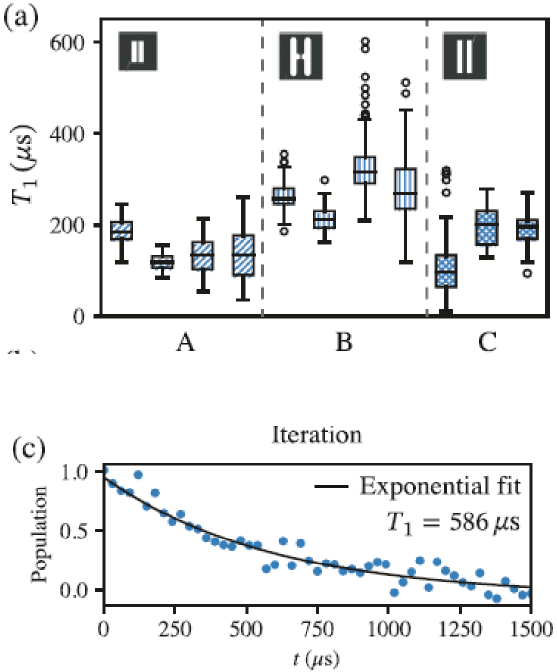
Using Findings to Develop New Qubits Which Push Performance

M. Bal *et al.* npj Quantum Inf **10, 43** (2024)

Biggest limiting factors for T_1

- Si Substrate
  - Sol'n: use Sapphire
- Niobium Oxide
  - Sol'n: encapsulate with other materials to prevent formation





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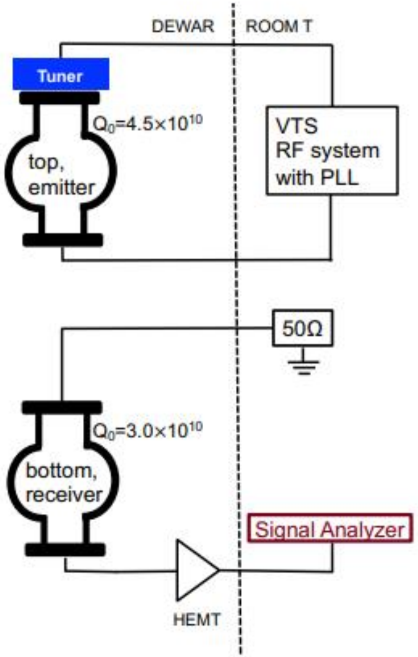
Ultra-Sensitive Measure of Dark Photons with 3-D Nb Cavities

A. Romanenko, et al., PRL **130**, 261801 (2023)

- Dark matter: theorized to make up most of the universe, hard to measure
- One potential way of: **dark photons**
  - Weakly interacts with matter, very hard to measure
- "Light shining through wall experiment"
  - High Q increases number of photons in the emitter & allows to resonantly enhance signal in receiver cavity (combining high energy and low energy regime)



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Summary

Summary

- Exciting time to be a part of world-wide efforts in the accelerator and quantum computing fields
- Current SRF R&D has the potential of making further dramatic advancements in many disciplines
  - Superconducting qubits and sensors
  - Materials
  - Future accelerators
  - Hardware development
  - Cryogenics
  - RF design and engineering
- We are continuing to push forward SRF technology and looking forward to the breakthroughs it will bring in the accelerator and quantum communities

Thank you for your attention!