



Superconducting Technologies: Exploring the Evolution of Superconducting Technology, from Applications in Particle Accelerators to Cutting-Edge Advancements in Quantum Computing

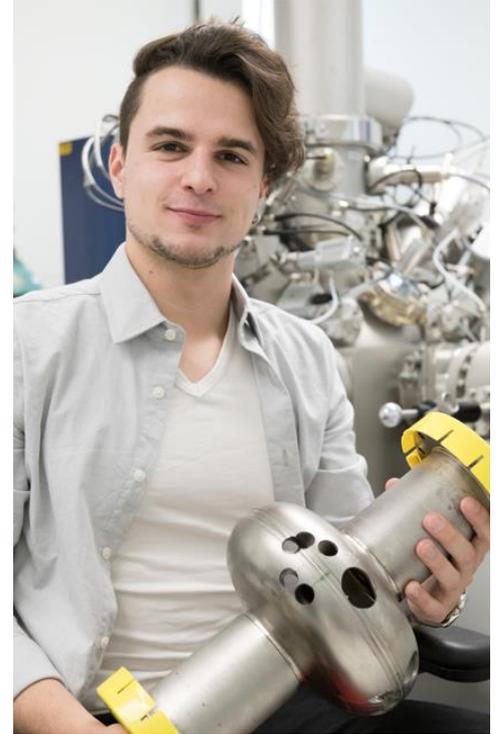
Daniel Bafia

February 28th, 2025

FERMILAB-SLIDES-25-0064-SQMS

About Me

- Associate scientist at Fermilab since 2021
 - Particle Accelerator hat: Lead the “Performance Frontier” group
 - Quantum computing hat: lead the RF characterization of materials
- PhD in physics obtained from Illinois Institute of Technology in 2020
- Bachelor’s degree in physics from Loyola University Chicago in 2016
- High school experience



Goals for This Seminar

- Explore the fundamental physics of superconductivity
- Examine the significance of superconductors in particle accelerators
- Investigate the applications of superconductors in quantum computing
- Discuss current challenges and future trends in superconductivity research

Outline

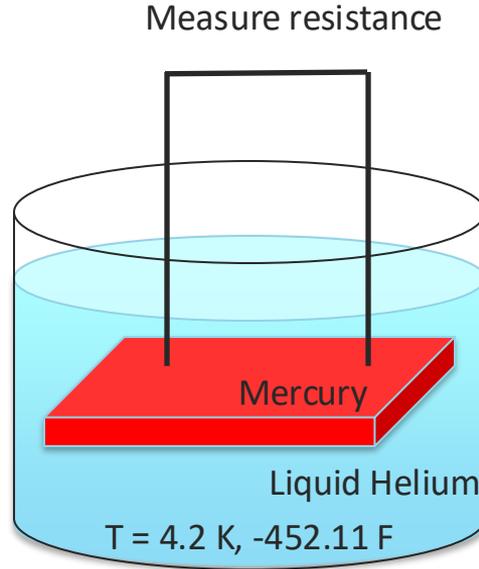
- Fundamentals of Superconductivity
- Particle Accelerators
 - Introduction to Accelerators
 - Introduction to niobium SRF Cavity research and development
- Application of Cavities to Quantum Computing
 - Using Cavities to Identify Sources of Dissipation in Superconducting Qubits
 - Using Cavities as Ultra-Sensitive Detectors
- Conclusion
- Q&A / Open Discussion

Fundamentals of Superconductivity

Superconductivity: The Fourth State of Matter

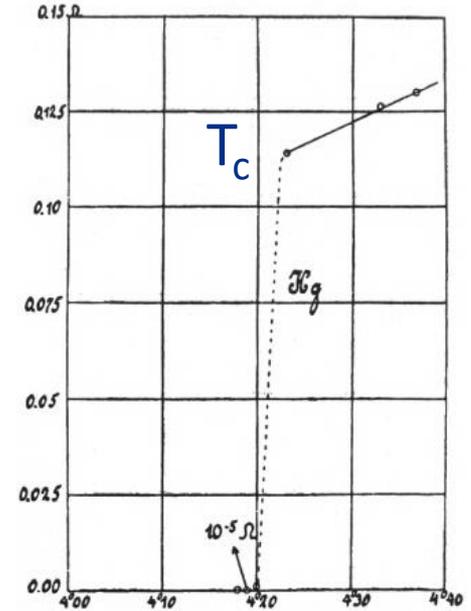


Heike Onnes



Question: How cold is outer space?

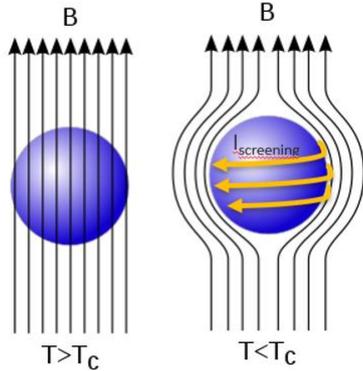
Answer: 2.7 K



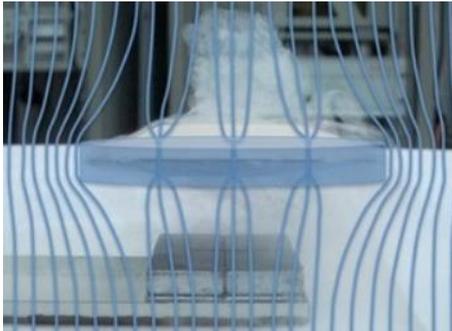
Zero resistance in DC!

H.K. Onnes, Commun. Phys. Lab. Univ. Leiden. Suppl. 29 (Nov. 1911).

Type II Superconductors: Vortices and Vortex Pinning



<http://mriquestions.com/superconductivity.html>



https://en.wikipedia.org/wiki/Flux_pinning#/media/File:Flux_Pinning_Field_Diagram.jpg



<https://quantumlevitation.com/what-is-superconducting-levitation-and-how-does-it-work/>

Our First Understanding of Superconductivity: BCS Theory

Superconductivity is driven by indirect electron-electron interaction



John Bardeen



Leon Cooper



John Schrieffer

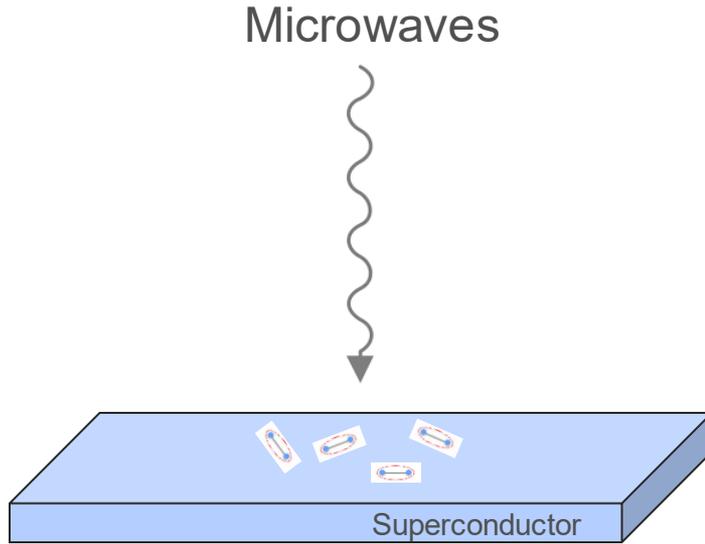


“Cooper Pair”



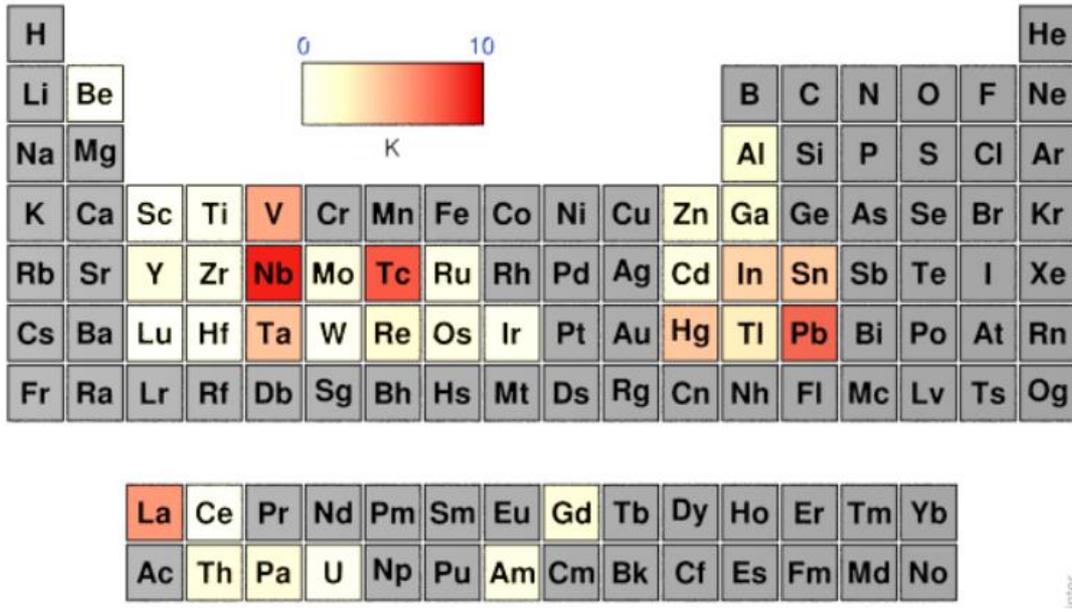
$$\xi_{0,Nb} = 38nm$$

Non-Zero Resistance Under Microwave Fields



- Cooper pairs have mass
 - Takes time to react to applied fields
- This “lag” drives dissipation, called **surface resistance**
 - Just like resistance in an electrical circuit

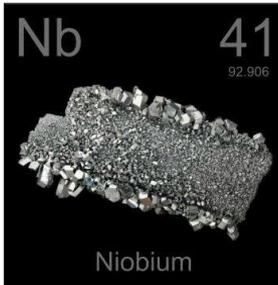
Elemental Superconductors



https://winter.group.shef.ac.uk/webelements/periodicity/supercon_temp/

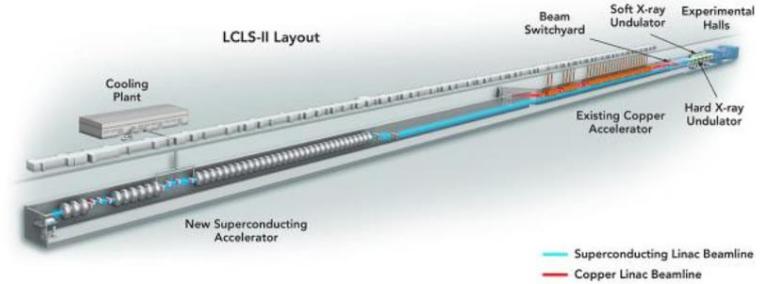
A Key Superconductor: Niobium

- Highest T_c (9.2 K) elemental superconductor
- Easy to form/work with
- Applications in:
 - Particle Accelerator
 - Quantum computers



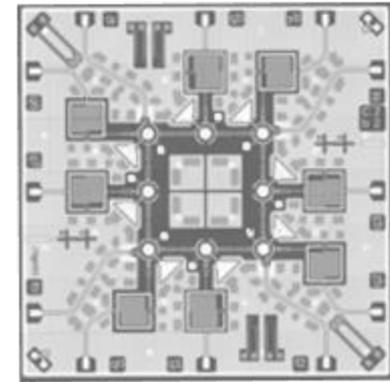
<https://www.rembar.com/applications-for-niobium-metal-in-industry-science-and-medical-fields/>

Accelerators



<https://lcls.slac.stanford.edu/lcls-ii/design-and-performance>

Quantum Computers



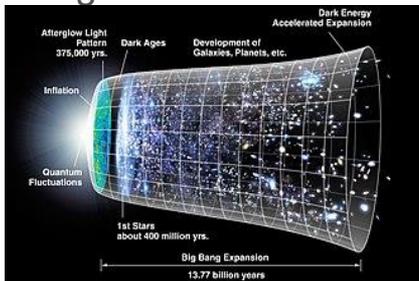
M. Reagor et al, Science Advances, Vol.4, no. 2, (2018)

Introduction to Accelerators

What Are Accelerators and How Are They Helpful?

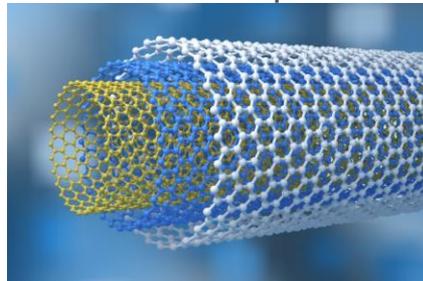
Particle accelerator: a machine which accelerates particles to high energies

Understanding the origins of the universe



https://en.wikipedia.org/wiki/Big_Bang

Materials research and development



<https://www.themandarin.com.au/134215-three-major-materials-science-breakthroughs-and-why-they-matter-for-the-future/>

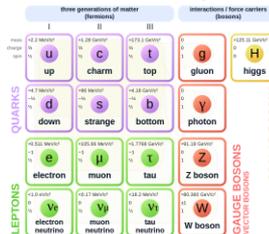
Vaccine Development



<https://www.biospace.com/article/a-timeline-of-covid-19-vaccine-development/>

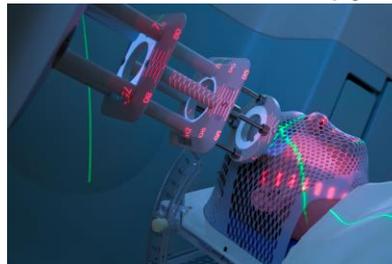
Exploring the composition of matter

Standard Model of Elementary Particles



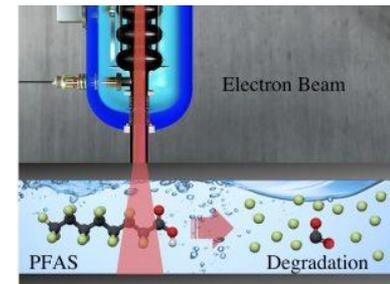
https://en.wikipedia.org/wiki/Standard_Model

Radiation Therapy



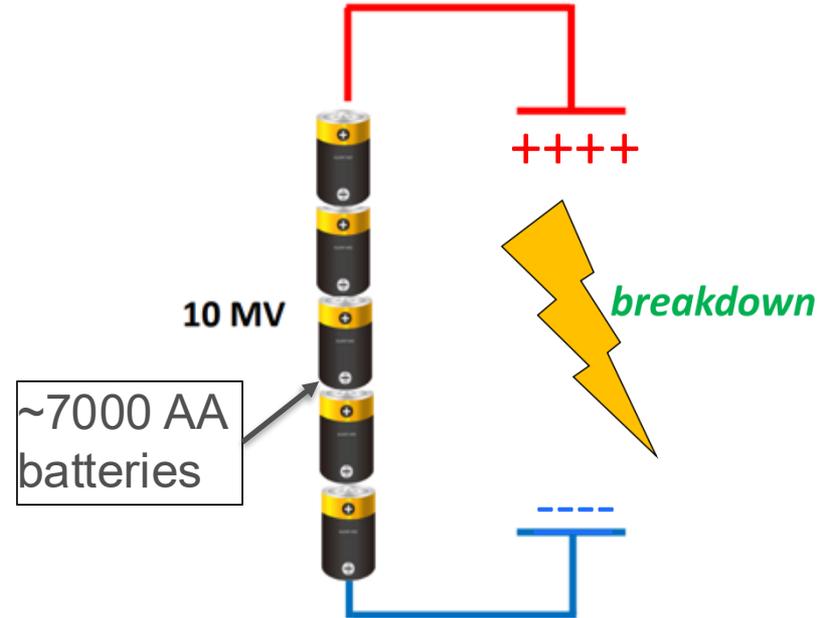
<https://www.itnonline.com/article/prototype-predictions-next-decade>

Environmental



<https://news.stonybrook.edu/newsroom/doe-particle-accelerator-awards-support-clean-water-and-plasma-wave-tech-projects/>

Electrostatic Accelerators



High electrostatic voltage is limited to ~10 MV; we need much higher!

A. Miyazaki, SRF'23 Tutorial

Modern Accelerators Use Radio-Frequency

Circular

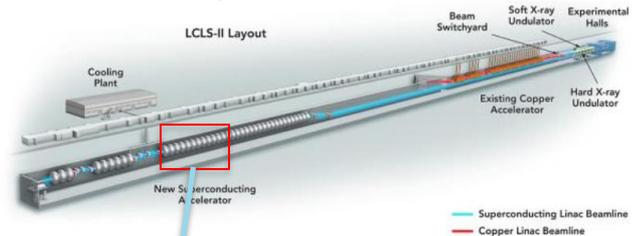
Large Hadron Collider



<https://www.forbes.com/sites/startwithabang/2021/09/07/the-3-reasons-why-cerns-large-hadron-collider-cant-make-particles-go-faster/?sh=70793cac2aae>

Linear

LCLS-II
X-ray Free Electron Laser

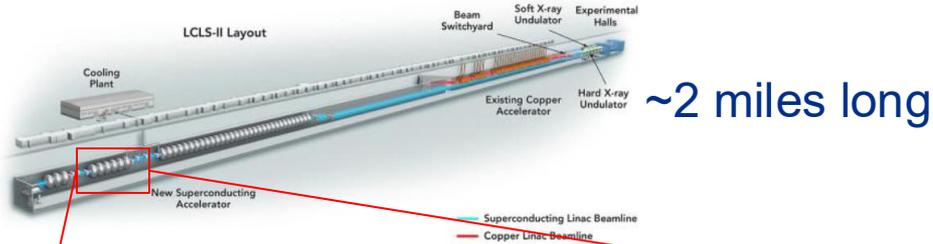


<https://lcls.slac.stanford.edu/lcls-ii/design-and-performance>



Nb Superconducting Radio-frequency (SRF) Accelerating Cavities

<https://lcls.slac.stanford.edu/lcls-ii/lcls-ii-design-and-performance>

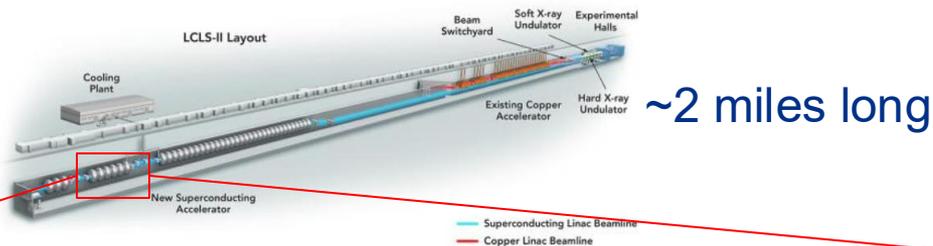


Electromagnetic microwave cavity

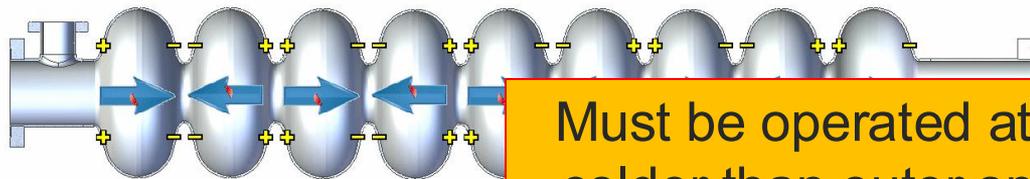


Nb Superconducting Radio-frequency (SRF) Accelerating Cavities

<https://lcls.slac.stanford.edu/lcls-ii/l/design-and-performance>



Electromagnetic microwave cavity



Must be operated at 2 K,
colder than outer space!



“Quality factor”

How efficiently you store microwaves

$$Q_0 = \frac{G}{R_s}$$

“Accelerating gradient”

Strength of kick delivered to particles

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

Cryogenic Systems to Cool Superconducting Accelerators

Cryogenics = branch of physics relating to producing very cold temperatures



Benefit of Superconducting vs Normal Conducting

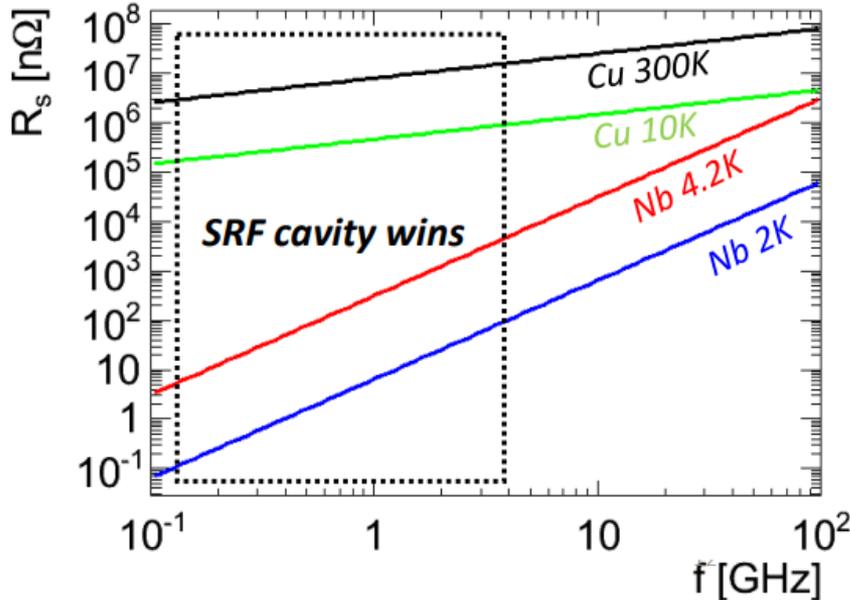
$$Q_0 = \frac{G}{R_s}$$

Comparing Normal Conducting and Superconducting Accelerating Cavities

	Normal Conducting	Superconducting
Q_0	2×10^4	2×10^{10}
$P_{\text{diss}} \text{ (kW)}$	120	1.4

If Newton used a pendulum with this Q_0 in 1700, it would still be oscillating at ~80% amplitude

Superconducting medium cavities dissipate 300x less power than normal conducting cavities! → Copper would melt!



Biggest Problem Facing Accelerators

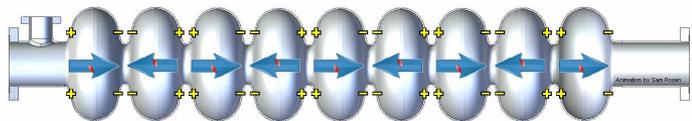
To build a new, impactful particle accelerator:

- Radiofrequency systems
- Cryogenic systems
- Civil engineering
- Project planning
- Material cost
- Accelerating cavities
- Magnets
-



Introduction to Nb SRF Cavity R&D

Key Figure of Merit: Q_0 vs E_{acc}



Goal of accelerator driven SRF

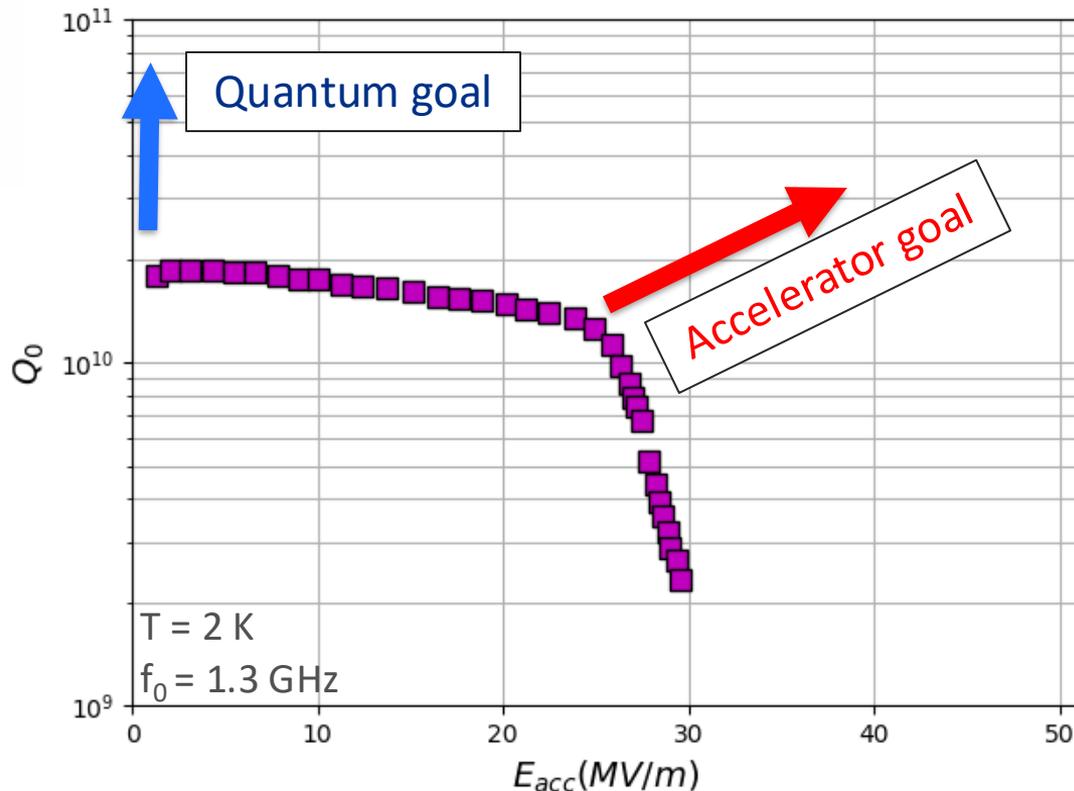
R&D: High Q_0 and E_{acc}

- \$\$\$

Goal of quantum driven SRF R&D:

High Q_0 at low E_{acc}

- Better quantum computer



Cavity Testing

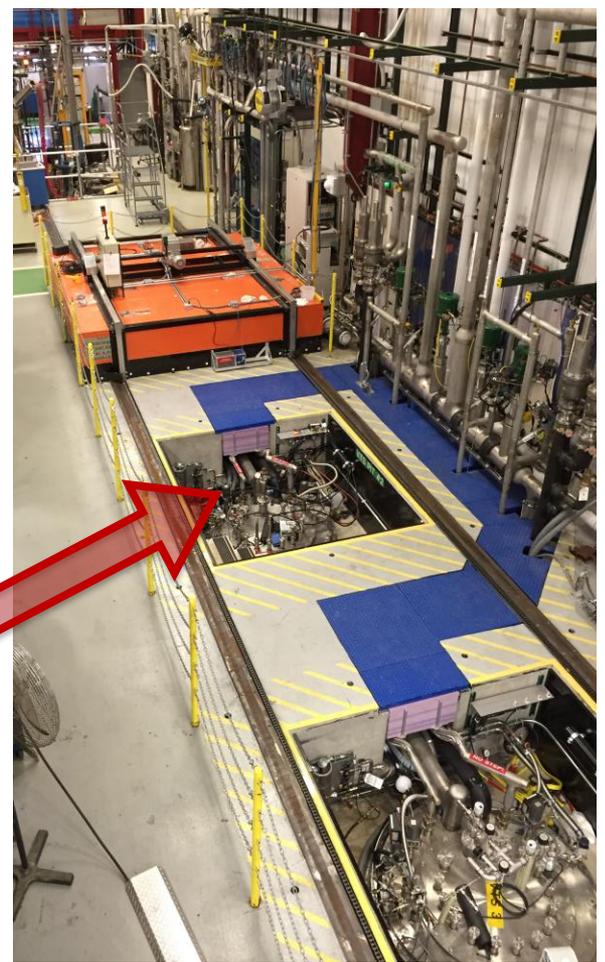
- Cavities installed in large Helium dewars: 2 K
- Power balance measurement: measure power into and out of cavity
 - Question: Why isn't the power coming out of the cavity the same as input power?
 - Answer: power dissipated in cavity as heat

“Quality factor”

$$Q_0 = \frac{G}{R_s}$$

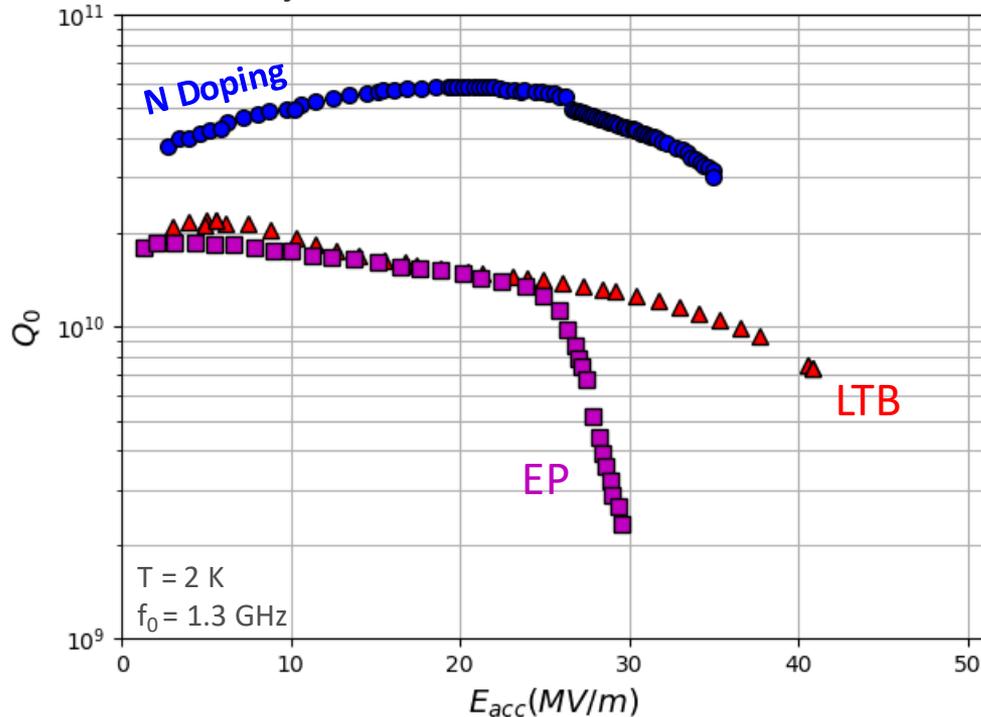
“Accelerating gradient”

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



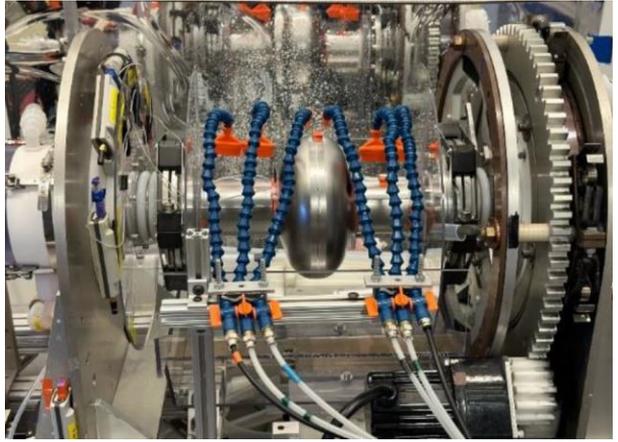
What Limits Cavity Performance?

Performance of Fermilab SRF Cavities
Subjected to Various Surface Treatments



Cooper pair motion limits performance
→ Must change material properties to
minimize dissipation!

Baking and Chemical Polishing Facilities



<https://td.fnal.gov/srf-capabilities/>

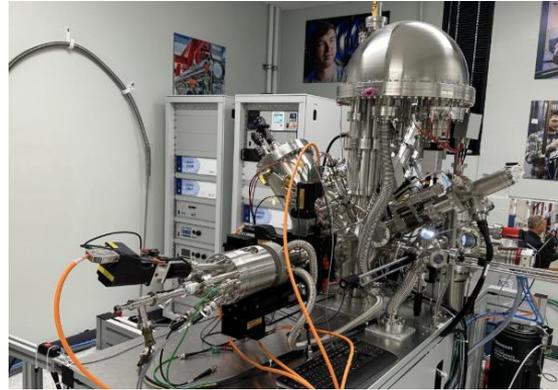
Materials Science Approach and Facilities

Impossible to “see” and study cavity during testing → must recreate surface treatments on samples and analyze in identical conditions! **Materials Science**

Time-of-flight Secondary Ion
Mass Spectrometry



X-ray Photoelectron
Spectroscopy

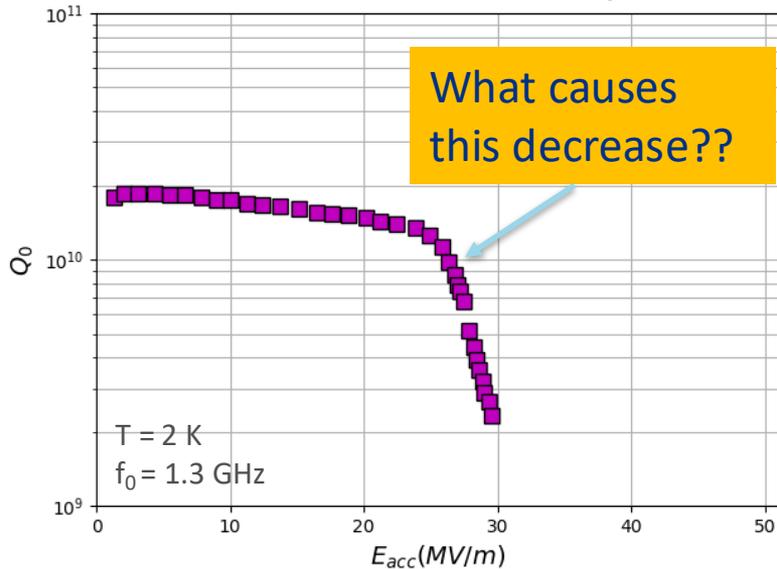


Scanning Electron Microscopy

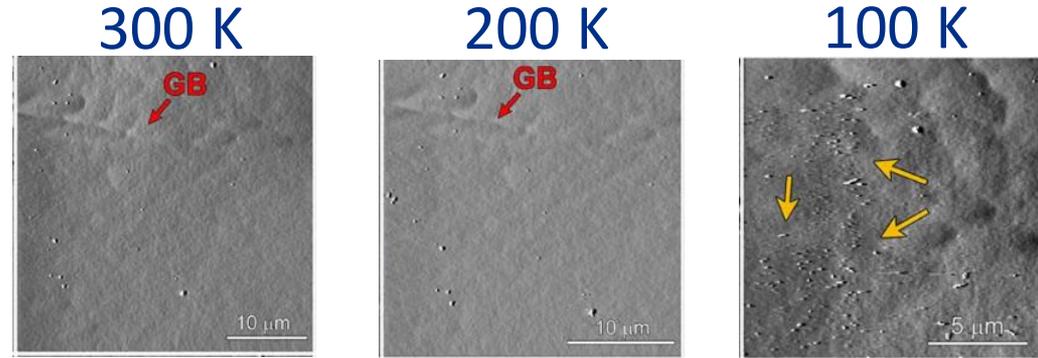


Case Study #1: Nb Hydrides as a Major Limitation in Nb Cavities

Q_0 vs E_{acc} of a
"Standard" SRF Cavity

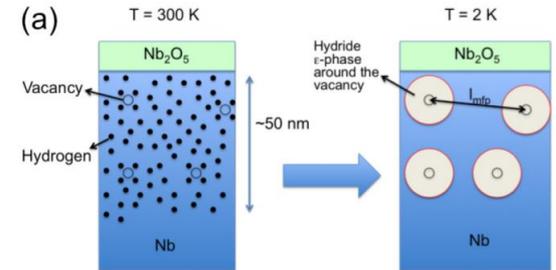


AFM Images Taken on a Nb Cavity Cutout



Z. Sung *et al.* Scientific Report **14**, 26916 (2024)

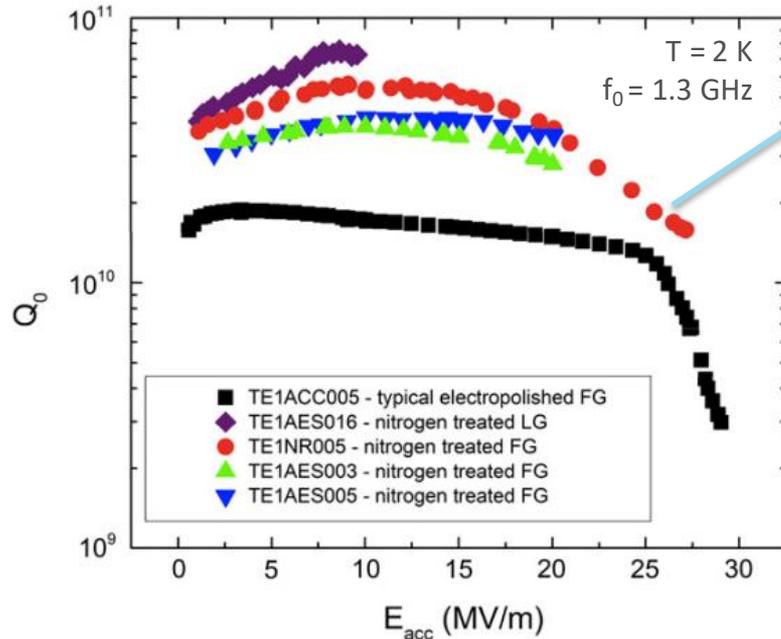
Niobium hydrides
pop up at low
temperatures and
weaken
superconductivity!



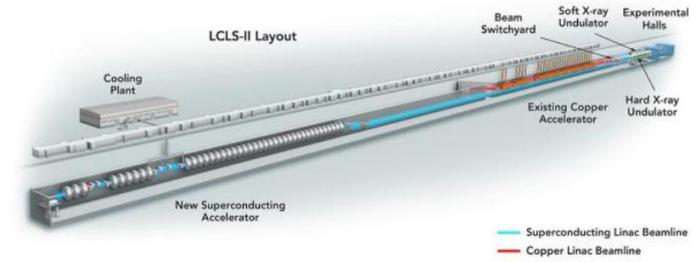
A. Romanenko *et al.* SUST **26**, 035003 (2013)

Case Study #2: Improving Performance with N-Doping

Q_0 vs E_{acc} SRF Cavities Processed with Various Surface Treatments

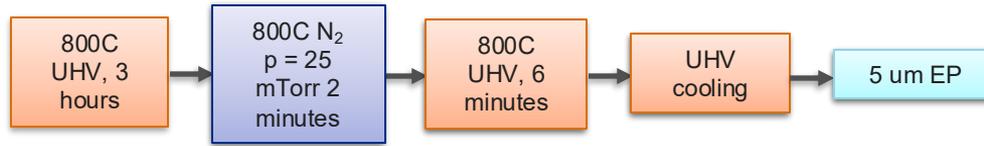


Enabled this accelerator!



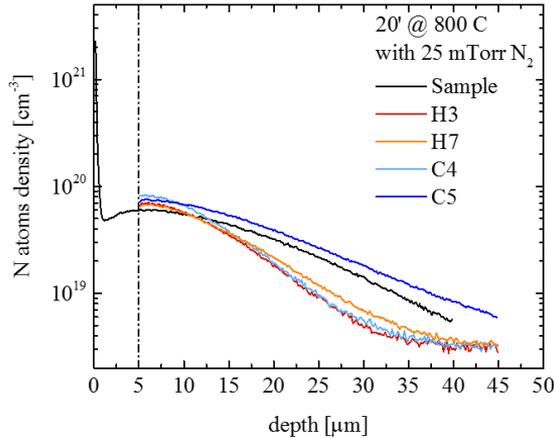
A. Grassellino *et al.* SUST **26**, 102001 (2013)

“2/6” N-doping treatment

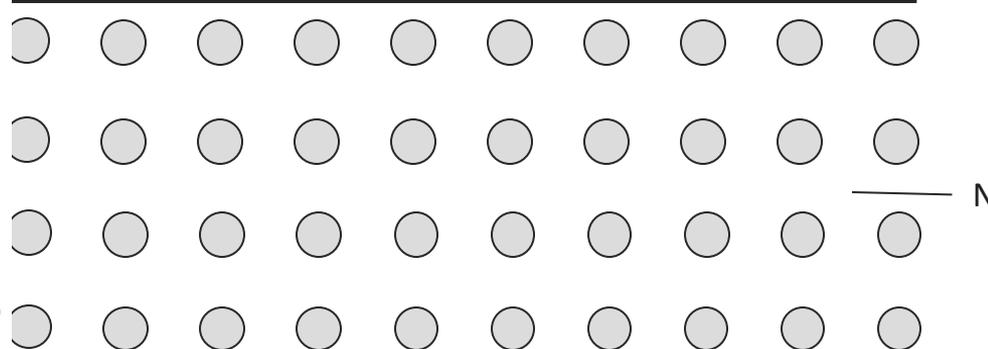


Open question: Why does a uniform layer with ~ 100 ppm of nitrogen allow for record high Q_0 's in SRF cavities?

Depth profile of Nitrogen impurities



Final RF Surface



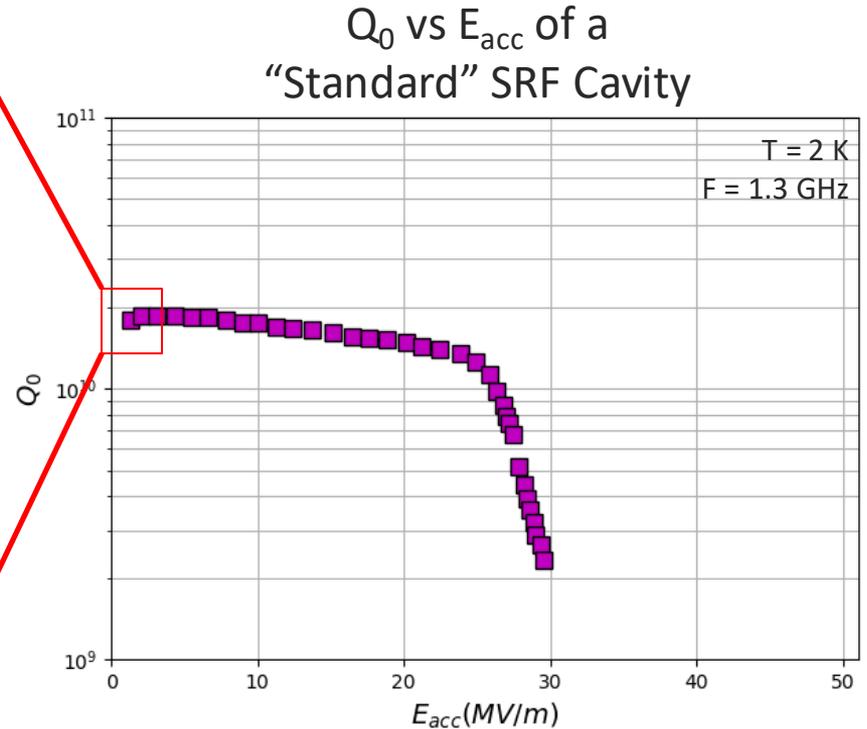
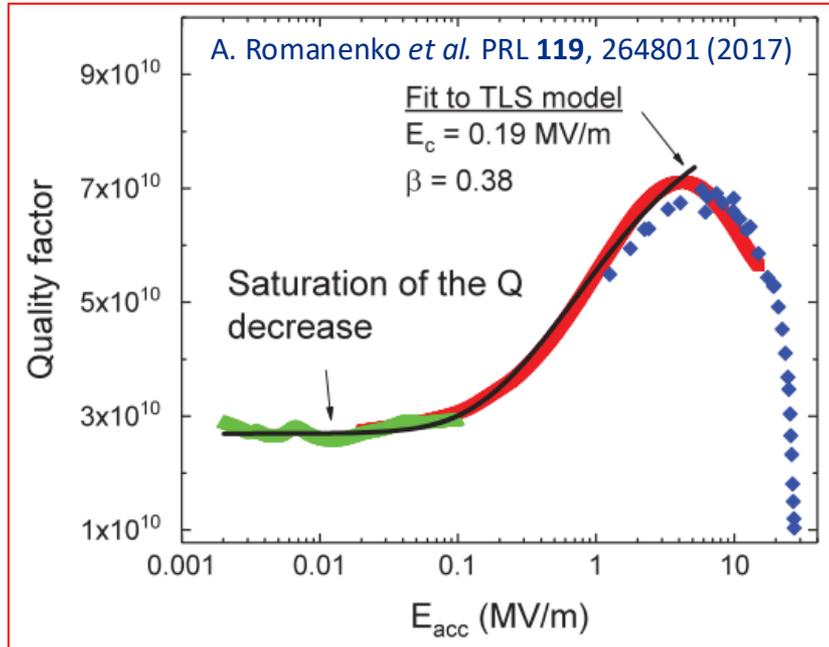
Slides adapted from M. Martinello

Open Questions

- Why do uniform and dilute concentrations of impurities drive such high Q_0 ?
- Is nitrogen the only impurity which enables high Q_0 ? What about oxygen? Carbon?
- How can we *combine* high Q_0 and high gradient?
- Can we realize new geometries which further improve performance?
- Are there alternative materials to niobium?
- Can we eliminate the oxide and maintain ultra-high Q_0 ?
- What is the origin of anti-Q slope?
- How do we industrialize our findings for large scale accelerator applications?

- My group at Fermilab is working on all the above and more!
 - 3 PhD students, 2 postdocs

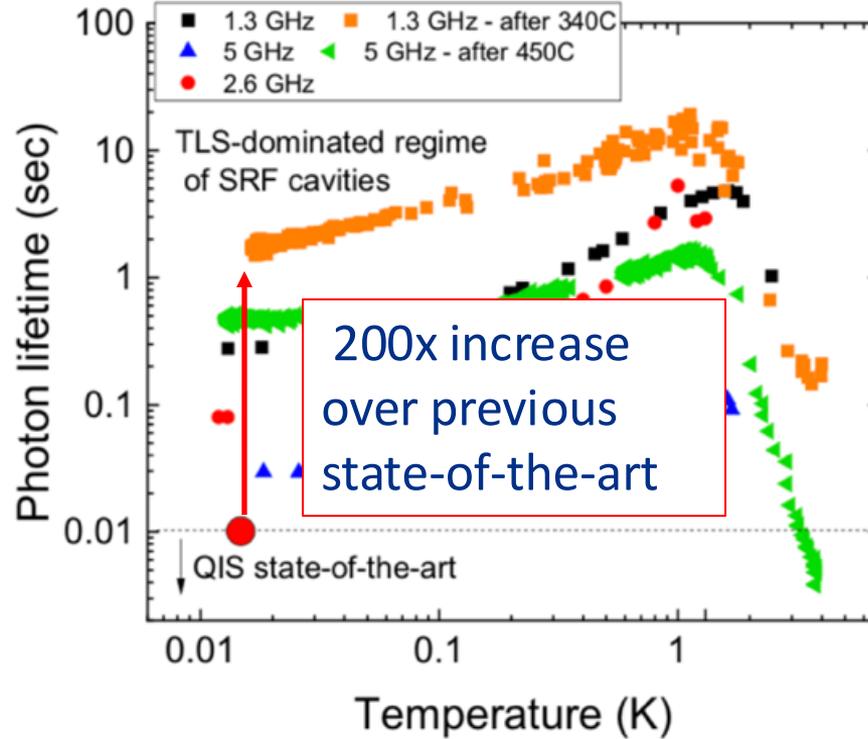
Curiosity: What is Performance Like at Low Fields?



Useful for quantum computing!

Application of Cavities to Quantum Computing

Fermilab Superconducting Cavities: Highest Coherence SC Quantum Resonators Ever Demonstrated



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



A DOE National QIS Research Center

30

Partner Institutions

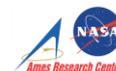
450+

Collaborators



Northwestern
University

rigetti



NIST



Goldman
Sachs



Jefferson Lab



LSU



Stanford



UNIVERSITÀ DI PISA

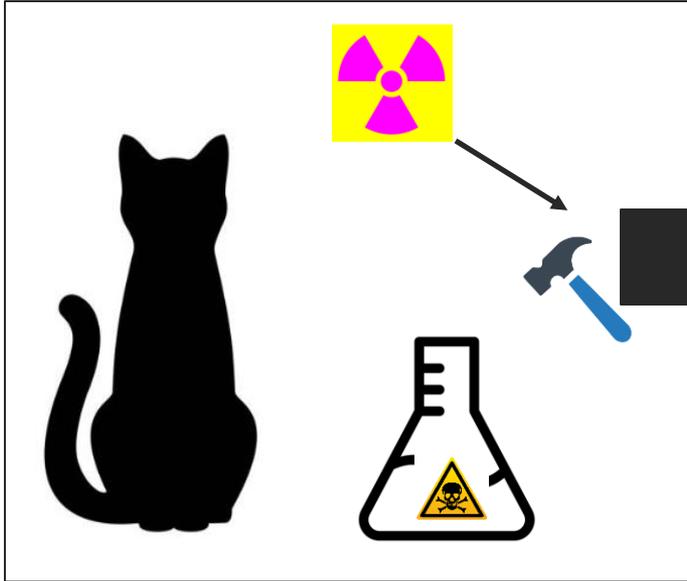


SQMS MISSION

[excerpt]

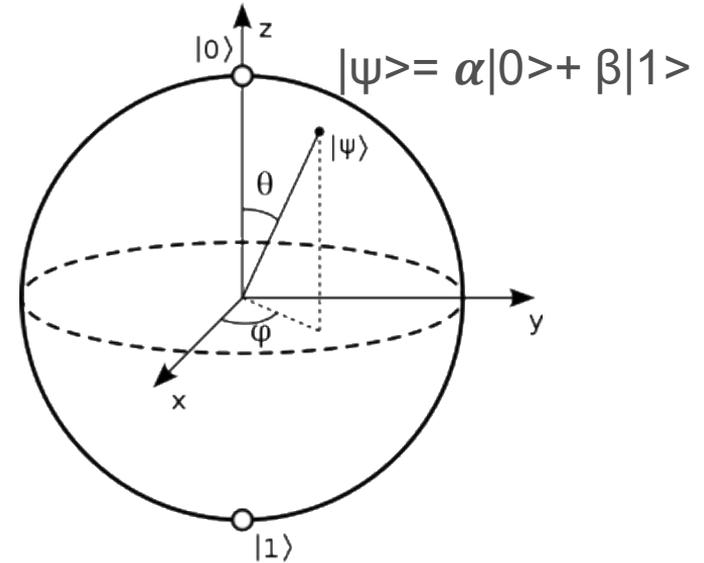
Achieve transformational advances in the major cross-cutting challenge of understanding & eliminating decoherence mechanisms in superconducting devices, enabling construction and deployment of superior quantum systems for computing & sensing.

Key Quantum Mechanics Phenomenon #1: Superposition



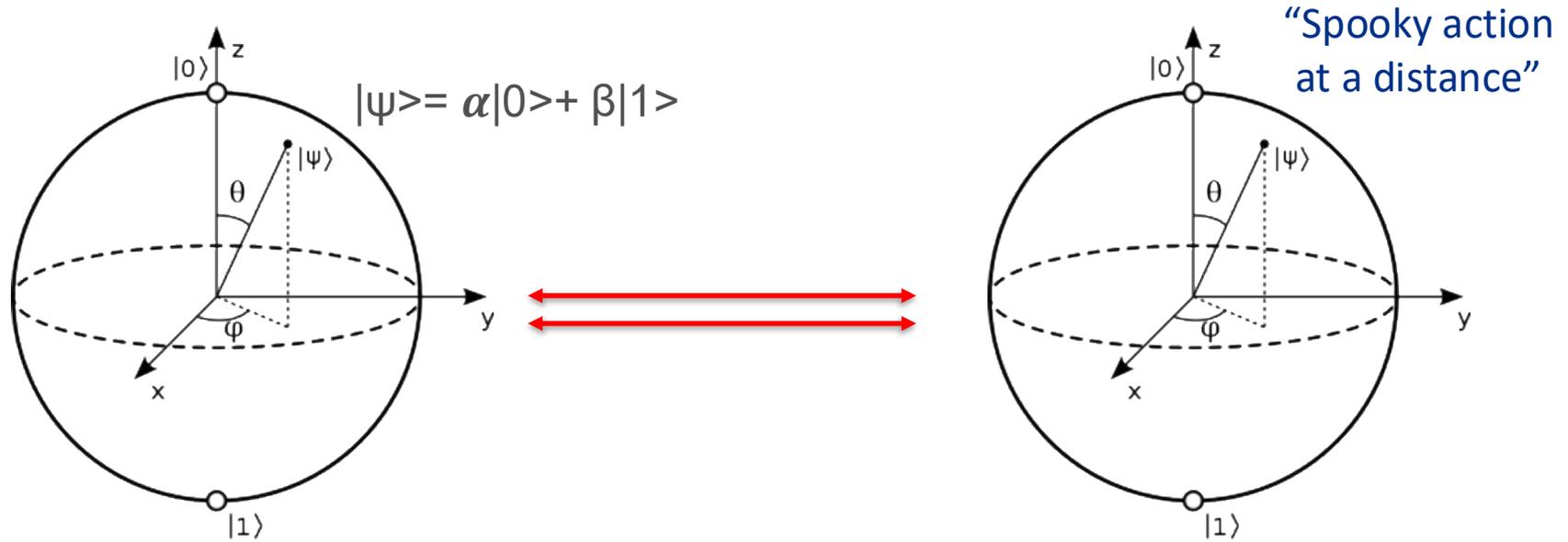
Schrodinger's cat: cat is both alive or N-1 lives until we look inside the box

- $N \leq 9$



A particle can be in two different states at the same time \rightarrow Superposition

Key Quantum Mechanics Phenomenon #2: Entanglement



Define: **qubit** – a quantum bit which utilizes both entanglement and superposition

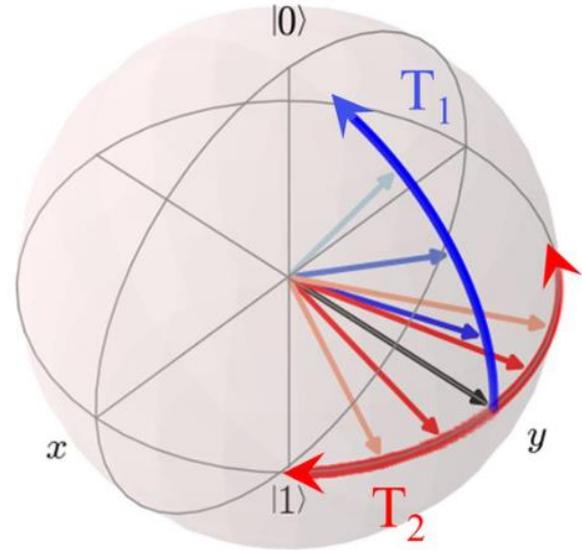
Key Qubit Metrics

Energy Relaxation: T_1

- Quantifies how quickly a qubit loses energy to its environment
- Analogous to cavity Q_0

Coherence Time: T_2

- Timescale over which a qubit maintains its “quantumness”
- How long it can be 0 and 1



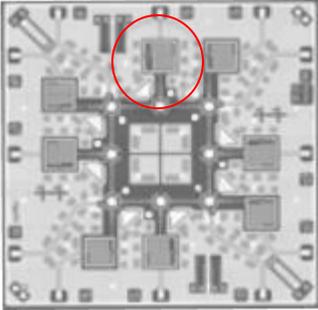
C. Godfrin PhD Thesis, Universite Grenoble Alpes (2017)

Longer T_1 and $T_2 \rightarrow$ More gate operations \rightarrow Better quantum computer!

Realizing a Qubit with Superconducting Devices

1. Resonators (cavities)

2D



Rigetti 8-qubit processor

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

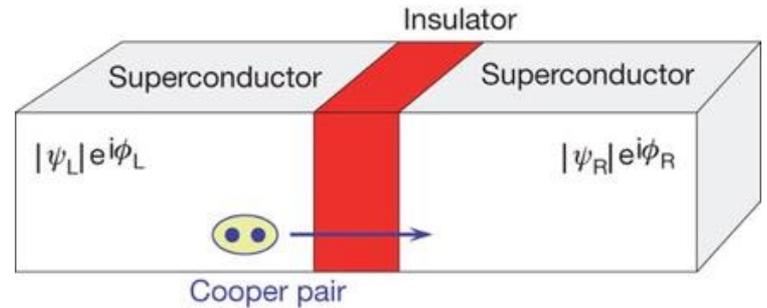
3D



Fermilab SRF resonators

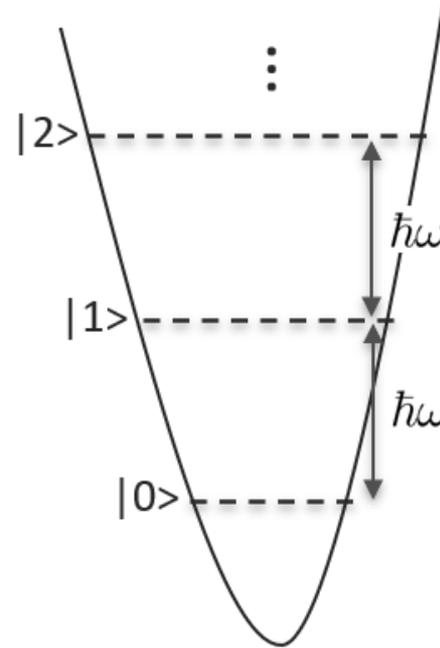
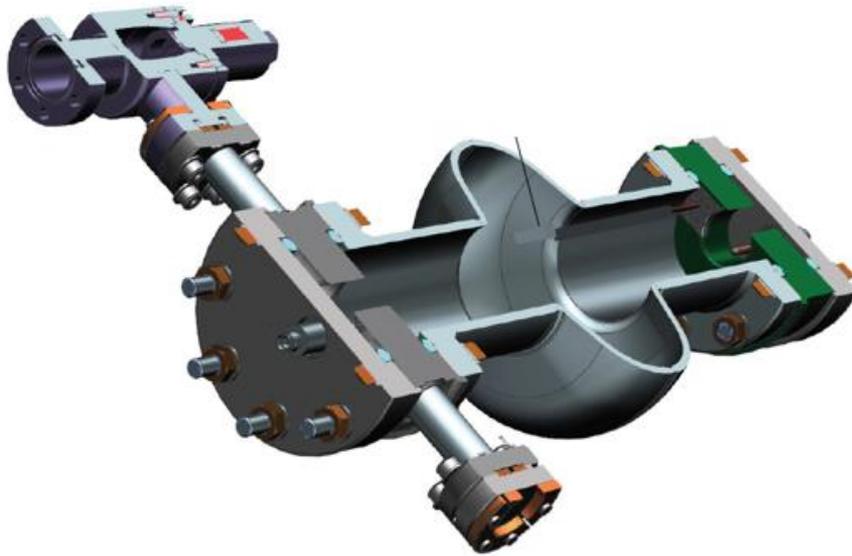
A. Romanenko et al, Phys. Rev. Appl. 13, 134052 (2020)

2. LC circuit with Josephson Junction

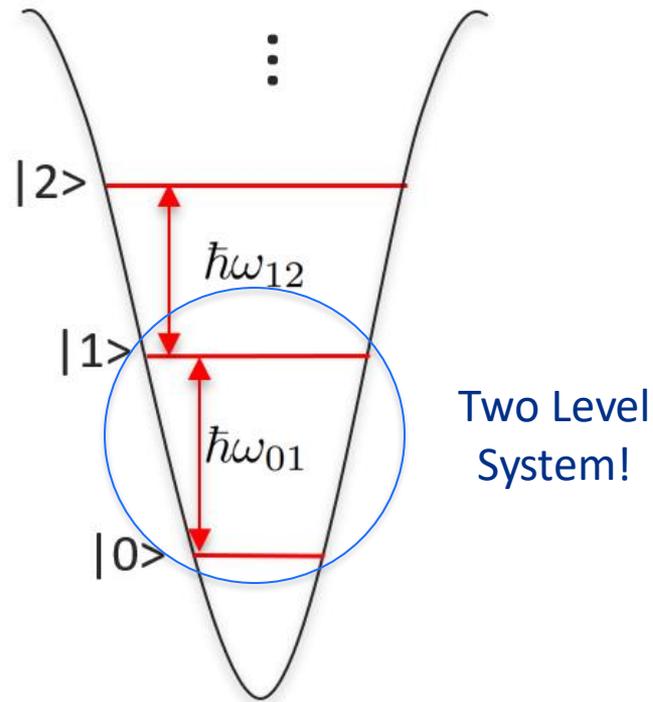
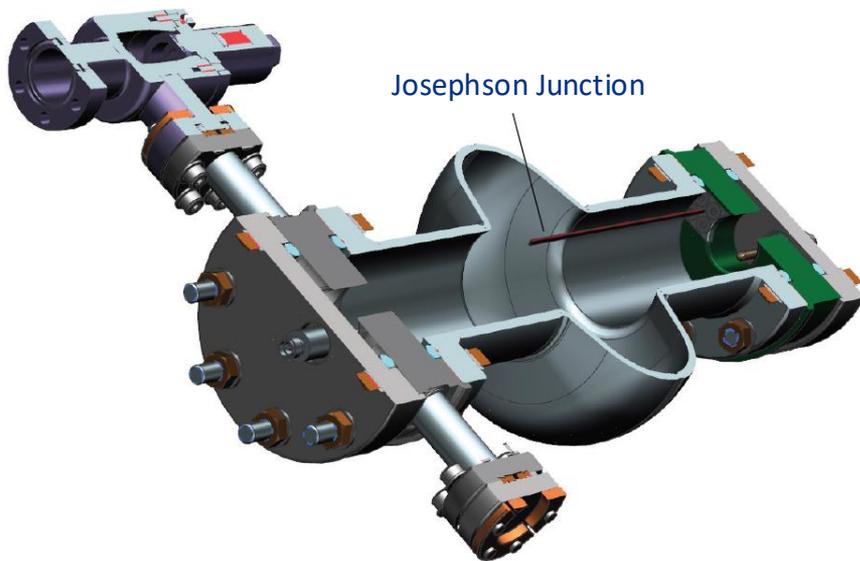


J. Koch et al, Phys. Rev. A 76, 042319 (2007)

Realizing a 3-D Superconducting Qubit

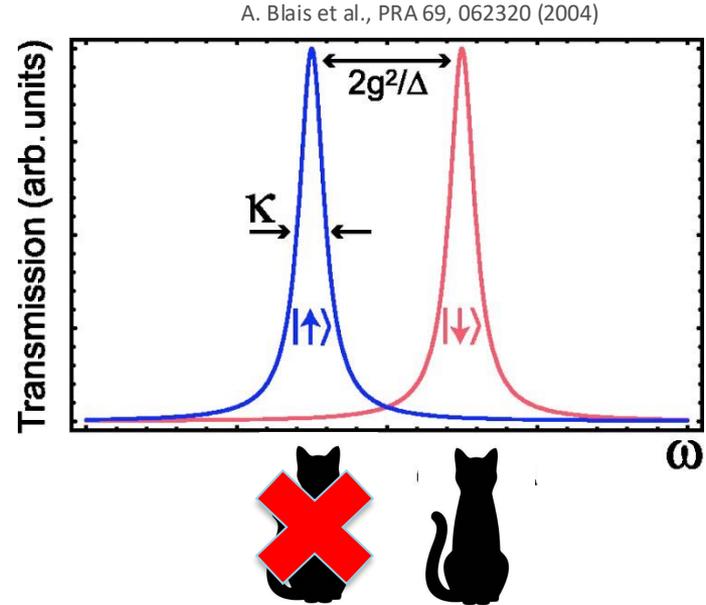
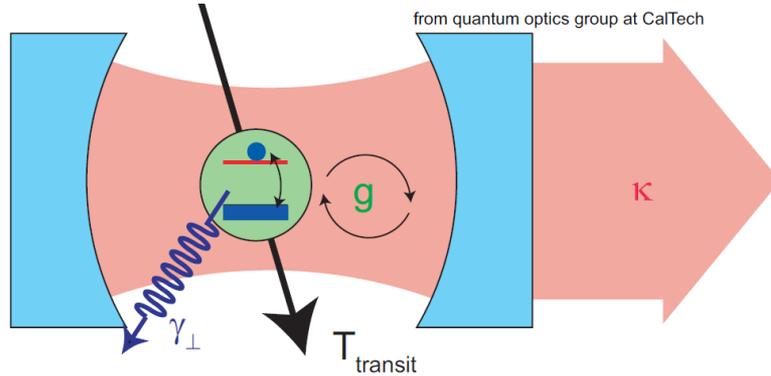


Realizing a 3-D Superconducting Qubit



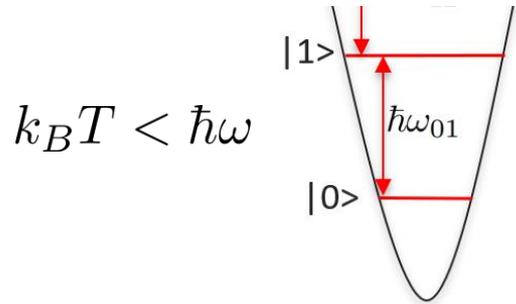
Cavity Quantum Electrodynamics (cQED)

Qubit read-out based on frequency shift of coupled resonator



Ultra-low Temp Needed for Superconducting Quantum Computing

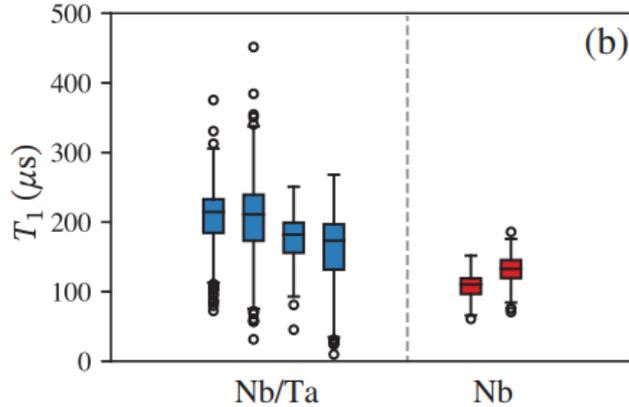
- Very low temperature (milli-Kelvin) required to avoid thermal excitation of qubits
- Experiments are typically carried out at $T \sim 20$ mK



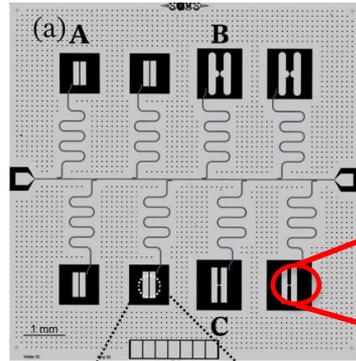
Dilution Refrigerator



Current Limitations for Qubits



- Can routinely achieve $T_1 = 400 \mu\text{s}$
- Key limitation: dissipative materials

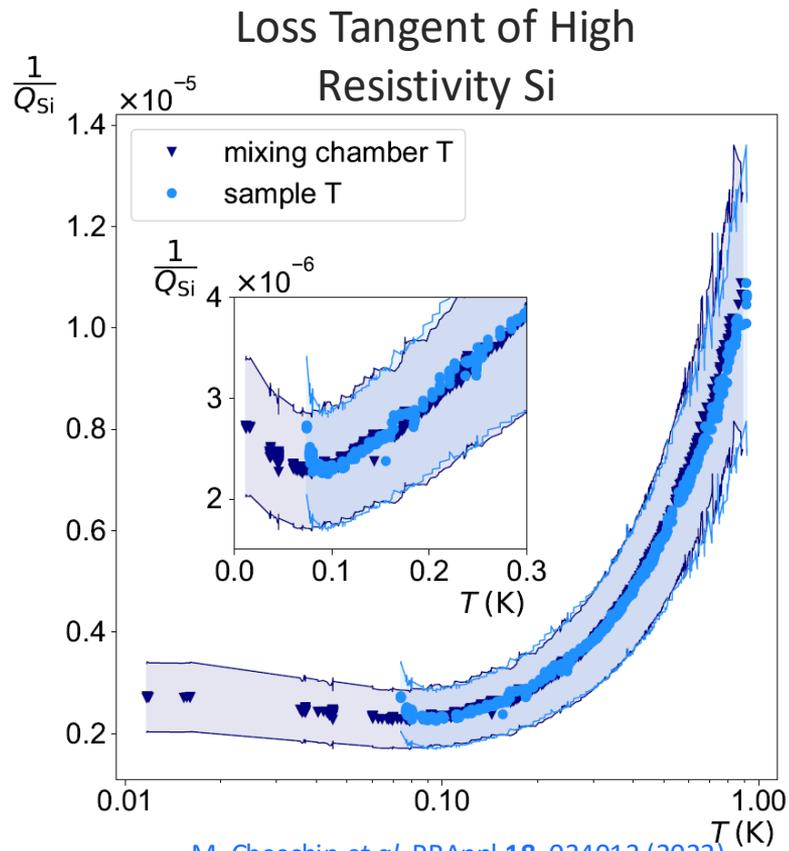
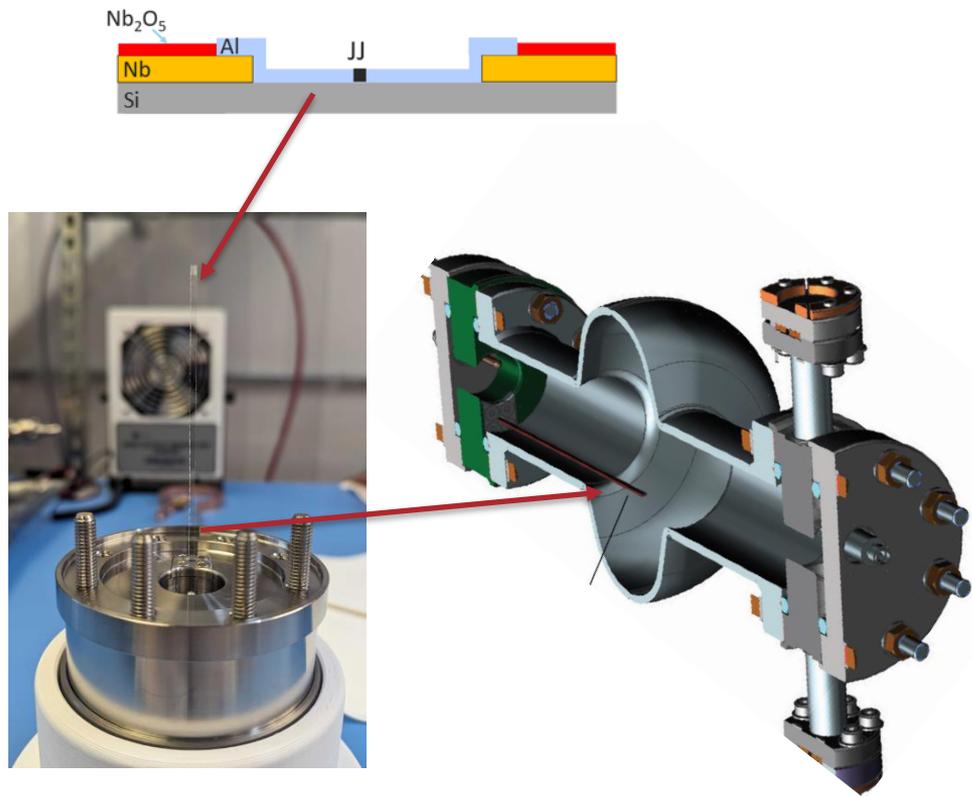


M. Bal *et al.* npj Quantum Information **10**, 43 (2024)



Using Cavities to Identify Sources of Decoherence in Superconducting Qubits

Case Study #1: Substrate Losses as a Key Qubit Limitation

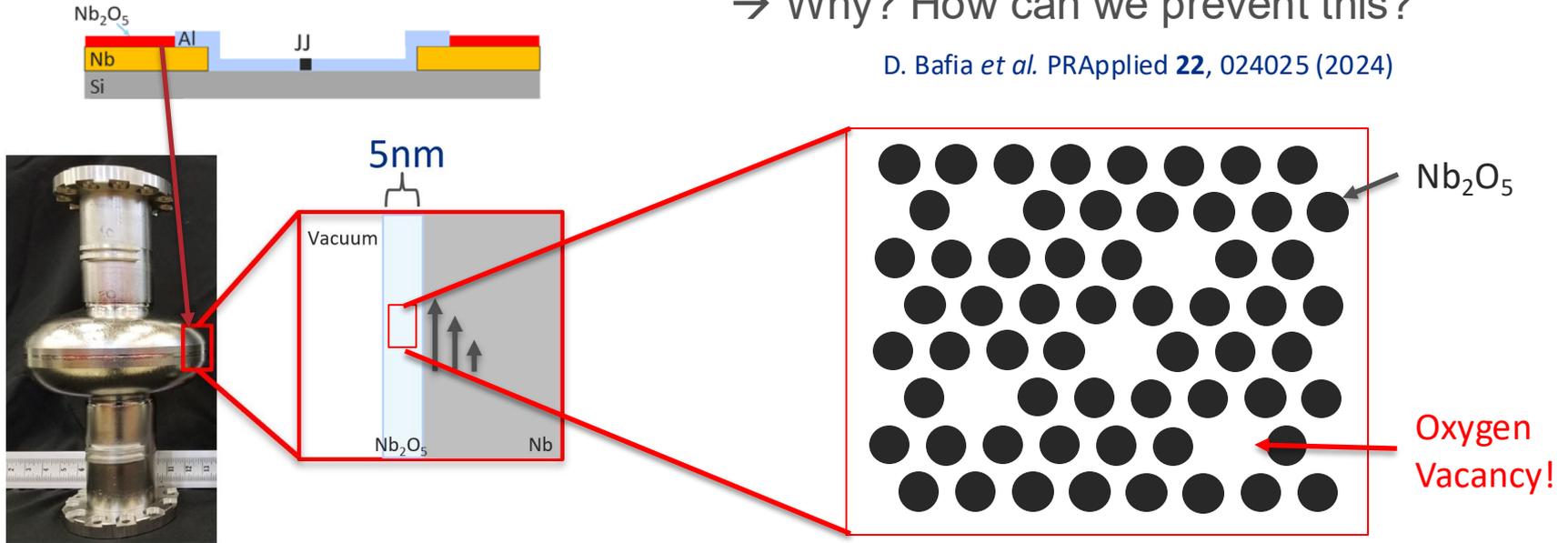


M. Checchin *et al.* PRAppl 18, 034013 (2022)

Case Study #2: Niobium Pentoxide as a Key Qubit Loss

Niobium oxide found to limit performance
→ Why? How can we prevent this?

D. Bafia *et al.* PRApplied **22**, 024025 (2024)



A. Romanenko *et al.*, PRA **13**, 034032, 2020

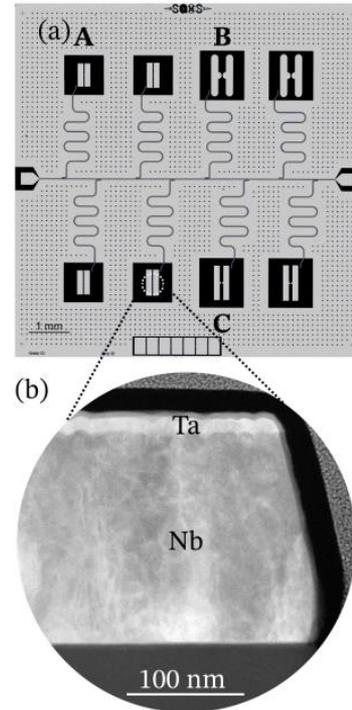
Found that varying the # of oxygen vacancies altered performance!

Case Study #3: Using Findings to Create Improved Qubits

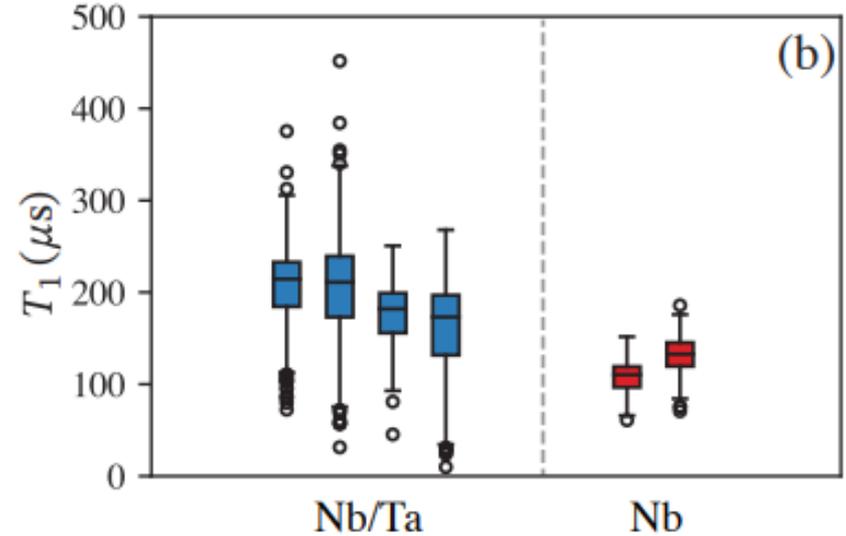
Fermilab fabricated qubits on sapphire substrates

Also developed encapsulation scheme to prevent formation of lossy oxides

Qubits made with encapsulation



Observed Improvement in Qubits!

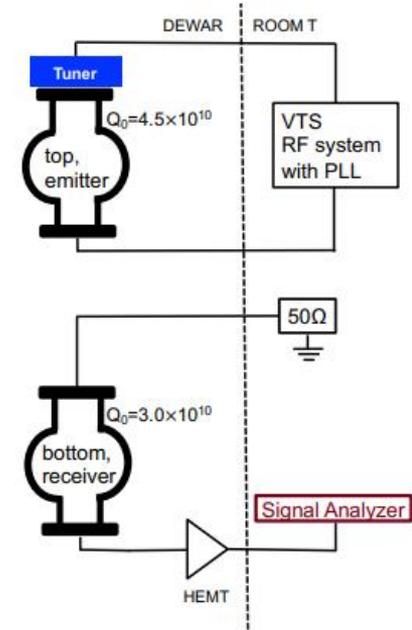


M. Bal *et al.* npj Quantum Inf **10**, 43 (2024).

Using Cavities as Ultra-Sensitive Detectors

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

- Dark matter: theorized to make up most of the universe, hard to measure
- One potential way of: **dark photons**
- “Light shining through wall experiment”



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

Open Questions/Challenges

- **Device performance improvements**
- Scalable qudit architecture
- Quantum error-correction
- Large scale cryogenics for mK
- Quantum communication

Conclusion

- Exciting time to be a part of world-wide efforts in the accelerator and quantum computing fields, enabled by superconducting materials
- Current SRF R&D has the potential of making further dramatic advancements in many disciplines
 - Superconducting qubits and sensors
 - Materials
 - Algorithms
 - Quantum communication
 - Hardware development
 - Cryogenics
 - RF design and engineering
- We look forward to presenting the world's best quantum computer