Applications of SRF Cavities Other than Big Accelerators

Sam Posen

Tutorial for the SRF Conference 2023

June 24, 2023

1) Compact SRF Accelerators
2) Quantum Computing
3) Quantum Sensing

Fermilab Postdoc Opportunities

1. The Applied Physics and Superconducting Technology (APS-TD) Directorate is seeking a **postdoctoral Research Associate**. This individual will conduct cutting-edge research of both superconducting radiofrequency resonator cavities for accelerator applications as well as superconducting qubits for quantum information science through the use of **surface characterization techniques** as part of the Superconducting Quantum Materials and Systems (SQMS) center. They are expected to complete scientific publications based on their research. **Expertise in surface characterization is preferred, including: XPS, ARPES, ToF-SIMS and/or TEM.** The position is for a period of up to three (3) years, with the potential for extension considered on a yearly basis thereafter, and subject to continued funding.

   Contact Akshay Murthy, amurthy@fnal.gov, for more information.

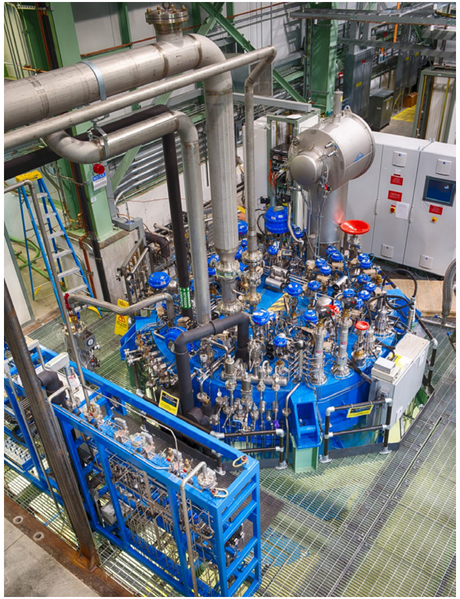
2. The Applied Physics and Superconducting Technology Directorate seeks a motivated **postdoctoral Research Associate** to join the SRF Performance Frontier group. The successful candidate will lead **R&D efforts on the performance improvement of superconducting radio-frequency cavities**. They will pursue **novel processing techniques** of bulk niobium as well as deposition of various **thin films** on top of metallic substrates for high energy particle accelerating applications. The individual will couple materials science, SRF testing, and RF engineering to aid in the development of these treatments and processes.

   Contact Daniel Bafia, dbafia@fnal.gov, for more information.

The **Fermilab SQMS Physics and Sensing group** is looking for a **graduate student/postdoc** interested to **join our group** and work on searches for new physics!

Compact SRF Accelerators: Introduction to Nb_3Sn and the importance of high Q_0 >4 K

Cryogenic Plant vs Cryocooler



e.g. Fermilab CMTF cryoplant has cooling capacity of 500 W at 2 K

Big Cryoplant

- High cooling capacity
- For **large** cooling requirements, good cost
- About as power efficient as it gets
- Requires expert team to maintain/operate
- Great for big accelerators

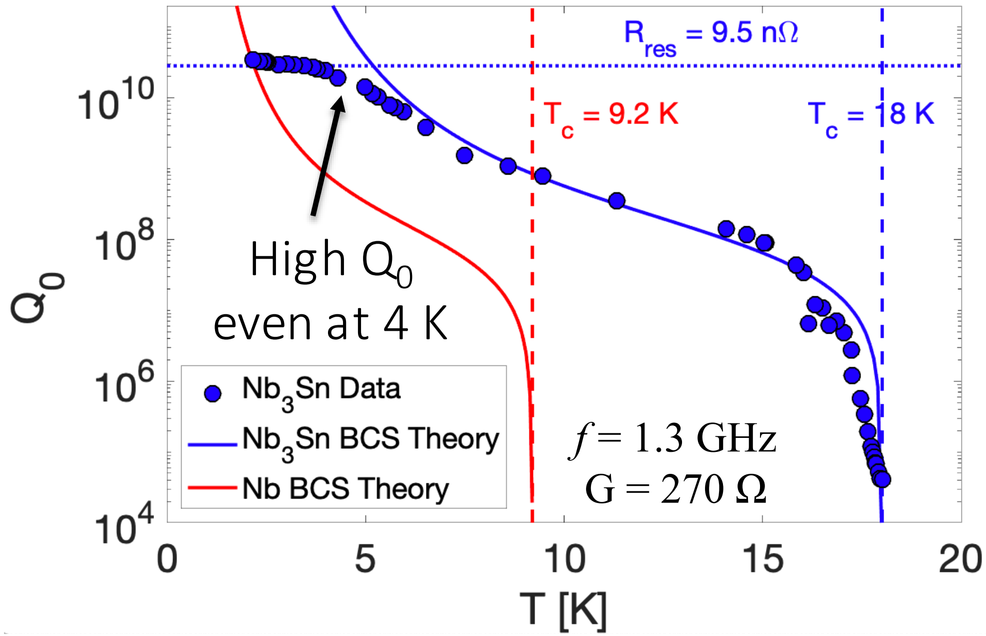
Cryocooler

- Few watts cooling capacity at 4 K, but much smaller at 2 K
- For **small** cooling requirements, good cost
- Small footprint, high reliability, low maintenance, minimal operator training

e.g. Cryomech PT420 has cooling capacity of 2.0 W at 4.2 K

Key Advantage of Nb_3Sn Cavities: Higher Q_0 at High Temperature

- Nb_3Sn has substantially higher T_c than Nb (18 K vs 9 K)
- High Q_0 at relatively high temperatures
  - Potential for high $Q_0 > 10^{10}$ in ~4.5 K operation in liquid helium
  - Potential for replacing cryoplant with cryocoolers
  - Even eliminating liquid helium via conduction cooling
- Impacts for high duty factor applications, especially small and medium-scale



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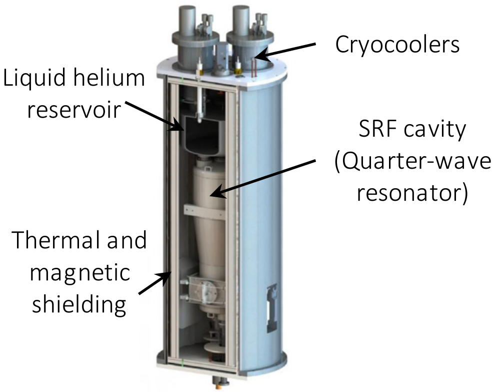
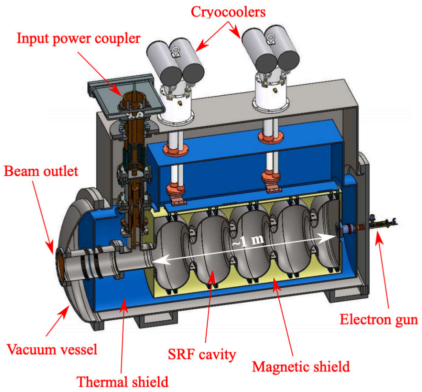
Potential Near-Term Applications of Nb_3Sn Cavities

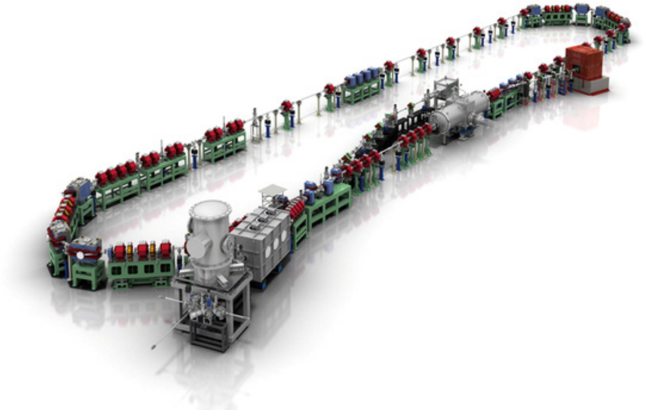
- Nb_3Sn is a potentially enabling technology for CW accelerator applications that could be realized in the near future:
  - Stand-alone cryomodules (e.g. isotope separator, harmonic cavities)
  - Compact high power accelerators (e.g. water treatment)
  - Turnkey/high MTBF energy recovery linacs (e.g. isotope production, EUV sources)



S. Kutsaev et al, *IEEE Trans. App. Superc.* 30, 8, 2020



R.C. Dhuley et al, *Phys. Rev. Accel. Beams.* 25, 041601 (2022).

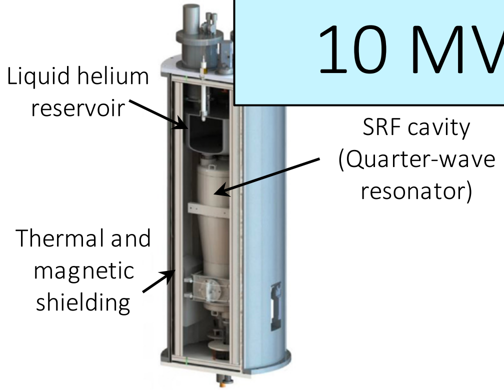


Y. Morikawa et al, New industrial application beamline for the cERL in KEK, IPAC'19, THPMP012

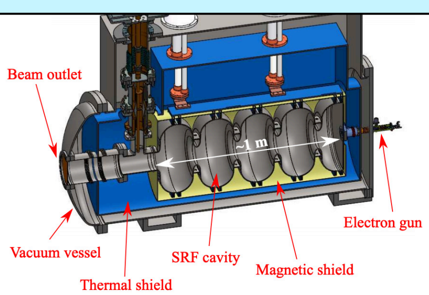
Potential Near-Term Applications of Nb_3Sn Cavities

- Nb_3Sn is a potentially enabling technology for CW accelerator applications that could be realized in the near future:
  - Stand-al
  - Compac
  - Turnkey/)

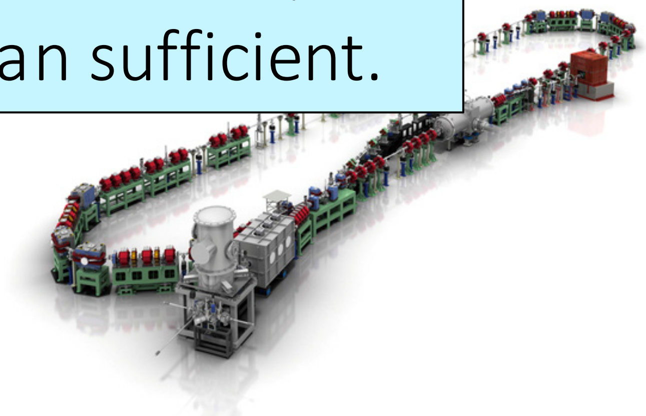
For useful early accelerator applications like these, we don't need to reach 100 MV/m. 10 MV/m would be more than sufficient.



S. Kutsaev et al, *IEEE Trans. App. Superc.* 30, 8, 2020



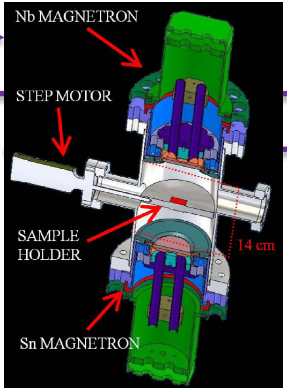
R.C. Dhuley et al, *Phys. Rev. Accel. Beams.* 25, 041601 (2022).

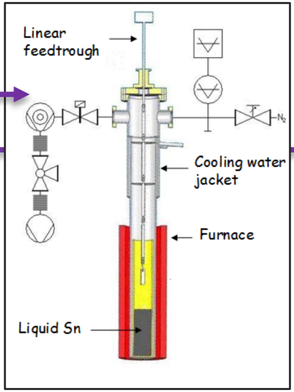


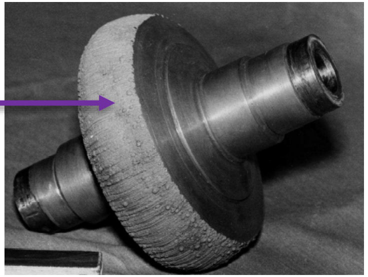
Y. Morikawa et al, New industrial application beamline for the cERL in KEK, IPAC'19, THPMP012

Methods for Fabricating Nb_3Sn Coatings

- Many different manufacturing methods attempted for Nb_3Sn SRF cavities, including:
  - Multilayer sputtering
  - Liquid tin dipping
  - Molten salts electrodeposition
  - Mechanical plating
  - Metal-organic CVD
  - E-beam co-evaporation
  - Bronze Process
  - Cold evaporation



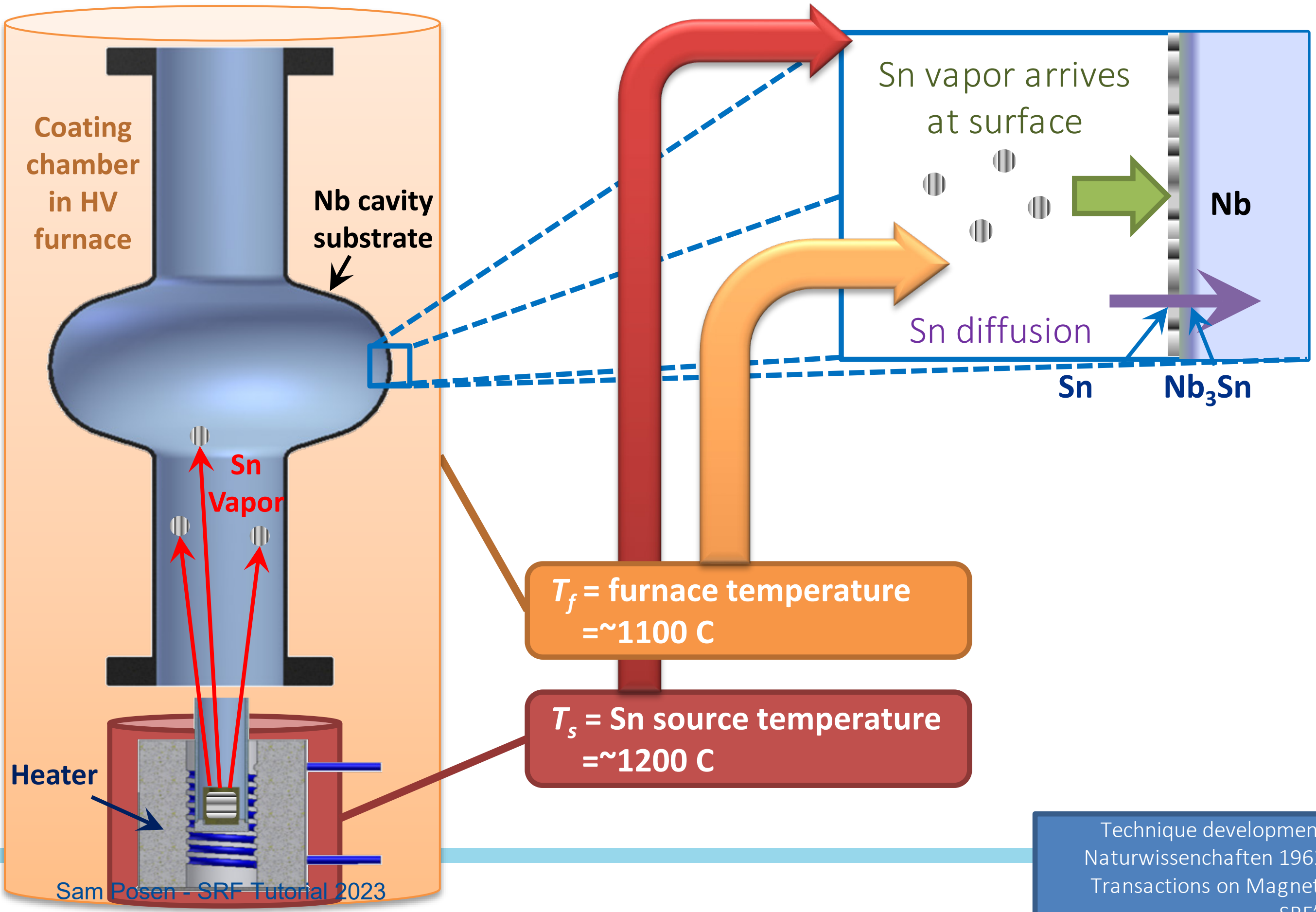




Preliminary r.f. results were not encouraging. A low-power Q value of 1.6×10^7 was obtained at 4.2 K when the method was applied to a single-cell

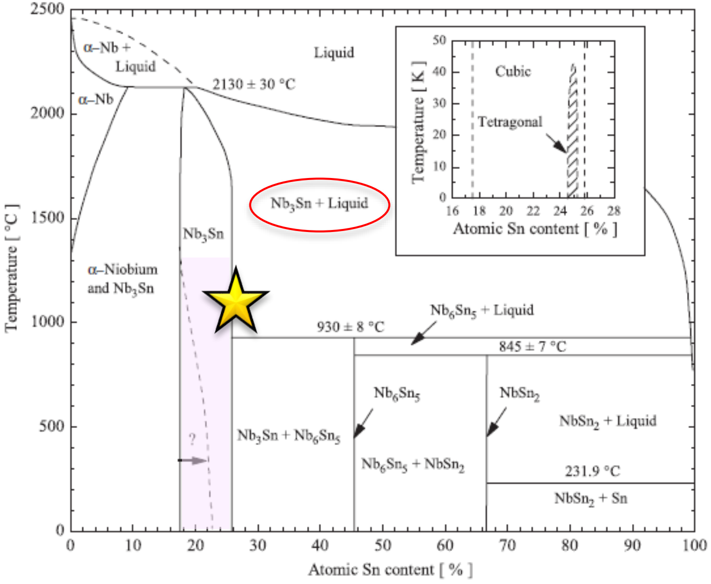
- Work continues on these, but so far no good RF results
- The **only** method to have produced promising RF results so far is Vapor Diffusion

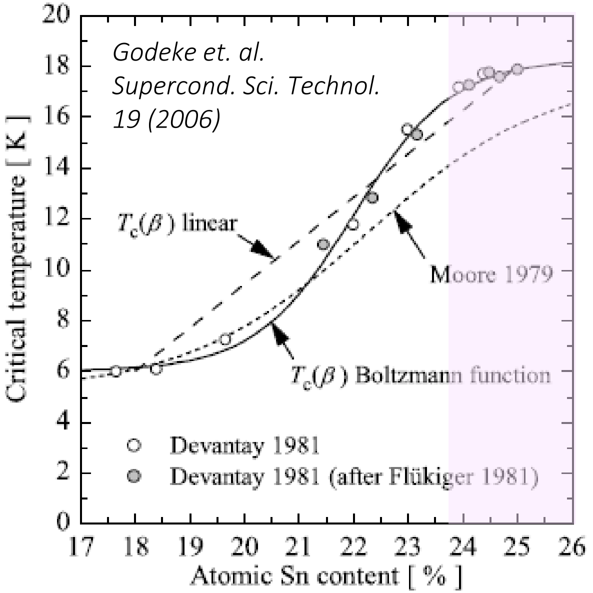
Coating Mechanism: Vapor Diffusion



Technique development: Saur and Wurm, Die Naturwissenchaften 1962, Hillenbrand et al. IEEE Transactions on Magnetics 1977, Peiniger et al, SRF'88.

"Phase Locking" to Achieve Desired Composition





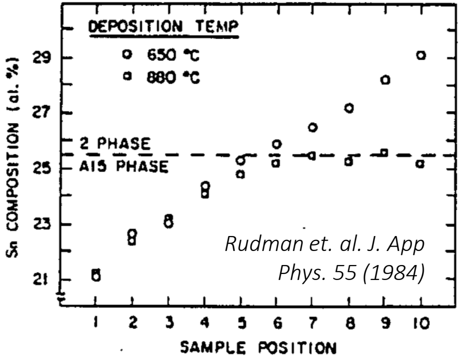


FIG. 7. The variation of sample composition with substrate position for two depositions in the compositional gradient configuration using different substrate temperatures. For sufficiently high substrate temperatures sample composition "locks" at phase boundary.

1. Stoichiometric A15 Nb_3Sn: ~18-26 at.% of Sn
2. Nb_3Sn with 24-26 at.% of Sn to get Tc~18K

Diffusion Limited Growth and Large Cavity Geometries

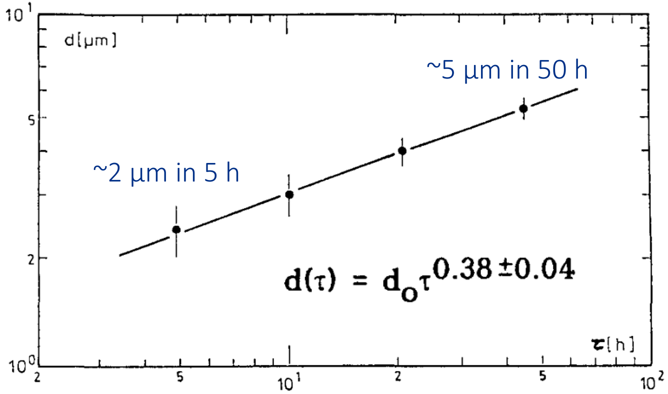
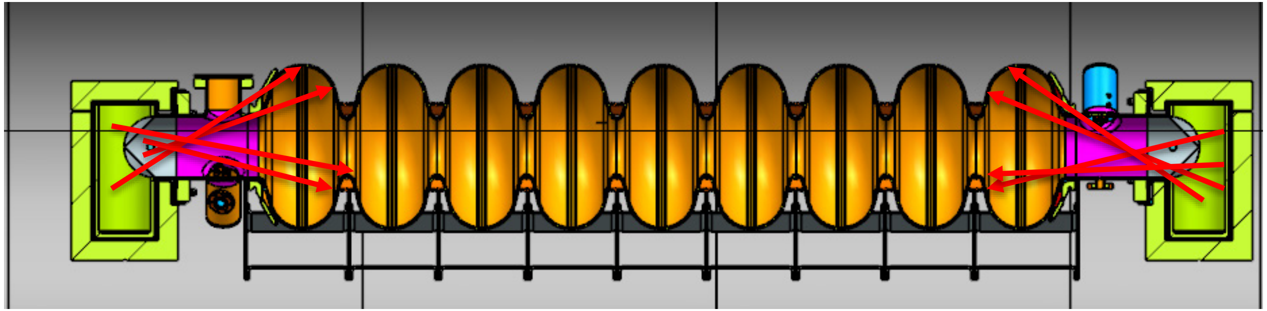


Fig. 6: Thickness of a Nb_3Sn layer formed by the vapor diffusion technique as a function of time (reaction temperature 1160° C and tin vapor pressure about 10^{-3} Torr).

M. Peiniger et al., "Work on Nb_3Sn cavities at Wuppertal" Proceedings of The Third Workshop on RF Superconductivity (1988)

- Coating mechanism is diffusion limited – as film becomes thicker locally, less tin is consumed, more re-evaporates and moves to other areas
- Another "self regulating" feedback mechanism to help with uniformity



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Coherence Length

- Superconductor's coherence length ξ: length scale for wavefunction of cooper pairs
- Disorder with size > ξ can cause interruption of superconductivity
  - Nb ξ ~ 30 nm
  - Nb_3Sn ξ ~ 3 nm
  - HTS ξ can be <nm!
- Expect Nb_3Sn is less "forgiving" than Nb for surface defects
- For current state-of-the-art Nb_3Sn, expect this to be gradient limit – working on reducing defects

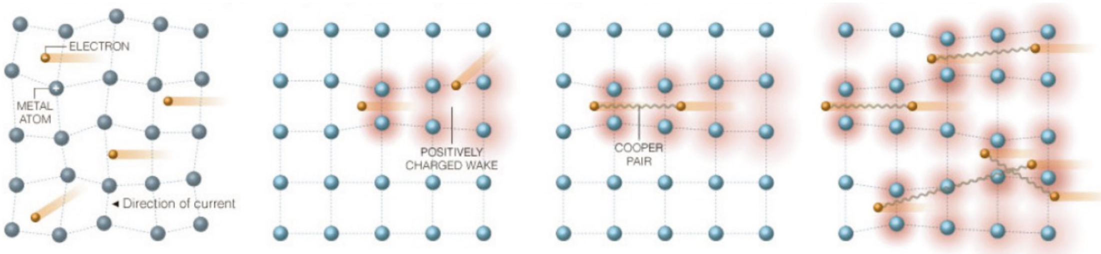
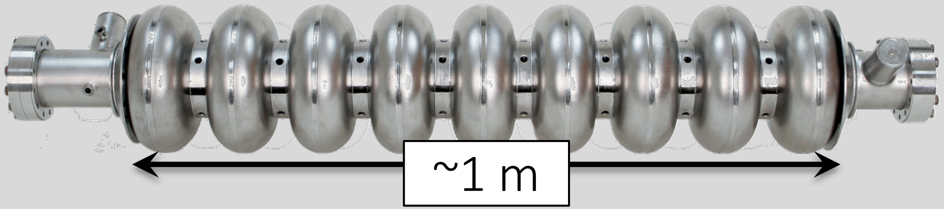
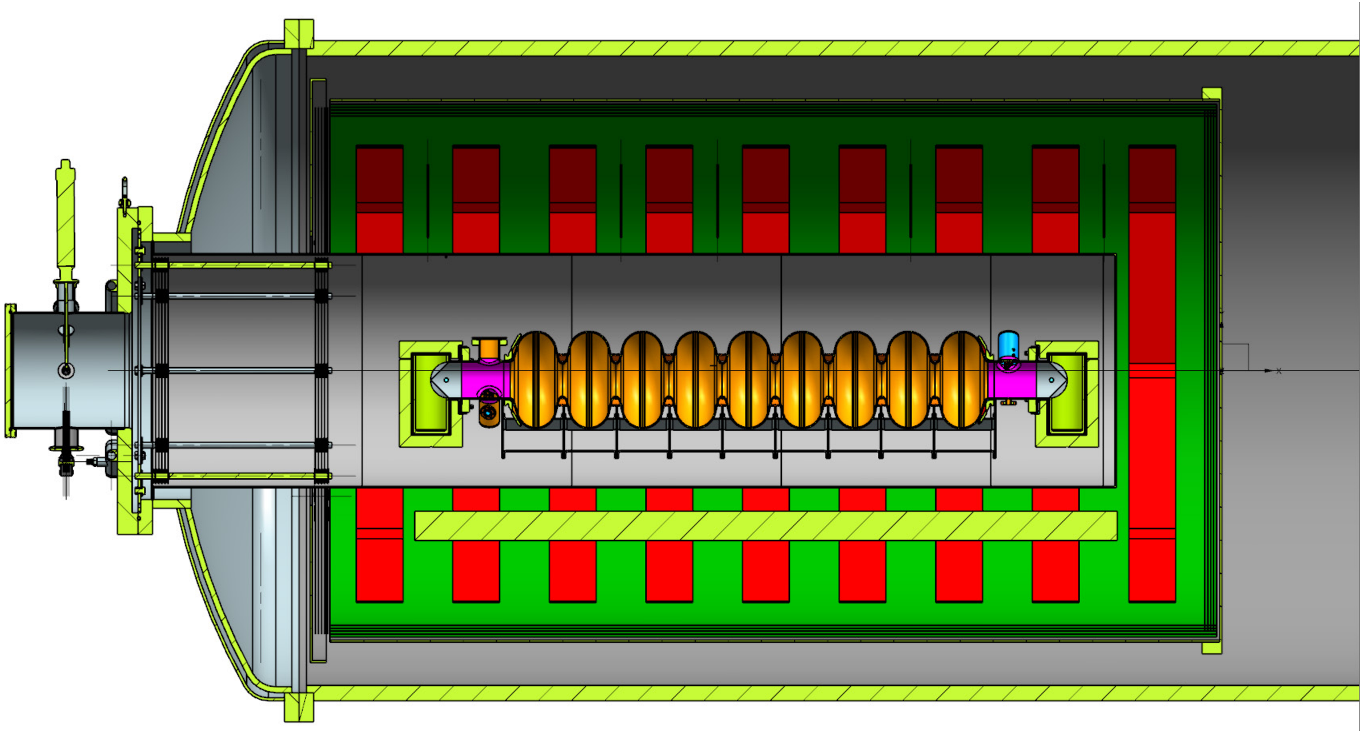


Image from The New York Times

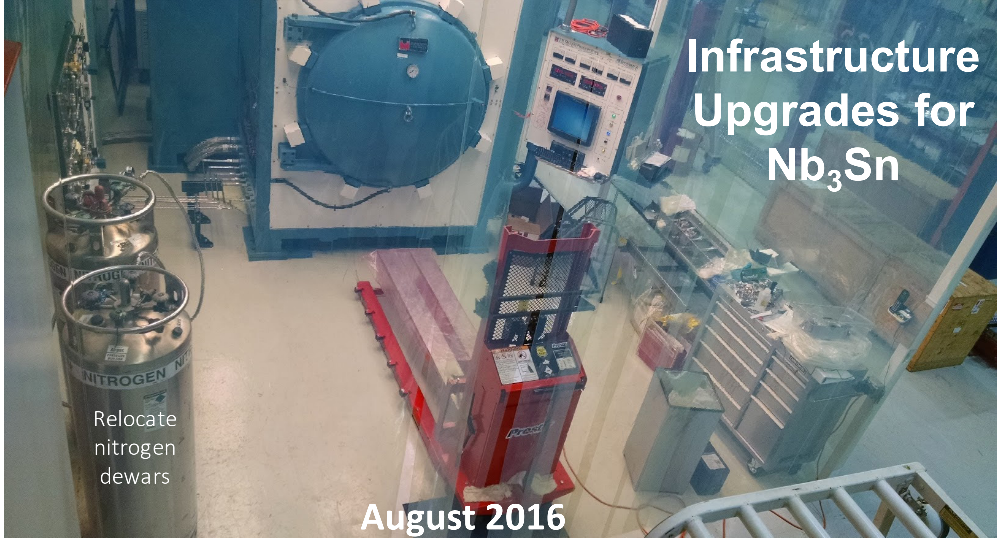
Especially helpful to have "self-regulating" coating mechanism considering length scales. ξ ~3 nm but cavity size is ~1 m. Self-regulation helps to reduce likelihood of defects that can degrade performance.



Fermilab Nb_3Sn Coating System



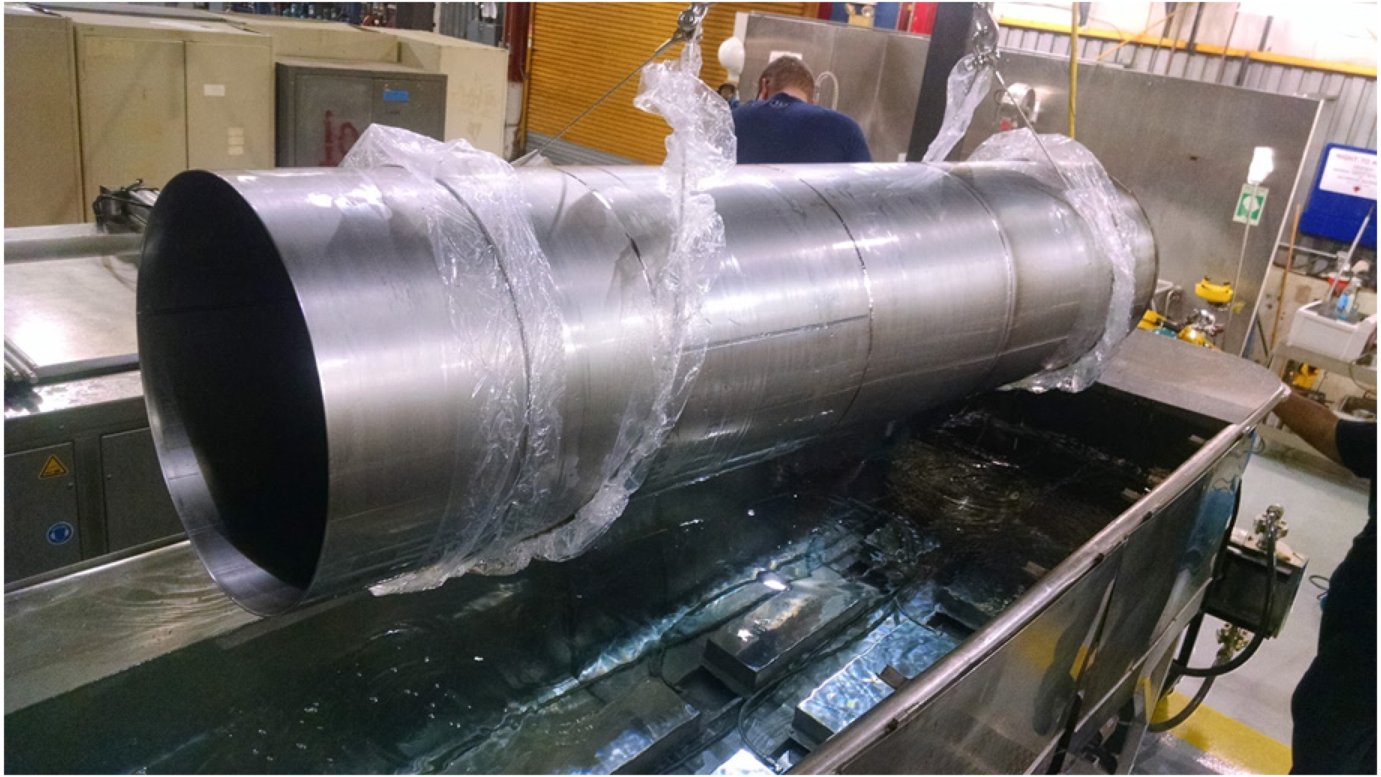
First and only Nb_3Sn coating chamber capable of coating 1.3 GHz 9-cell cavities or 5-cell 650 MHz cavities



Infrastructure Upgrades for Nb_3Sn
Relocate nitrogen dewars
August 2016

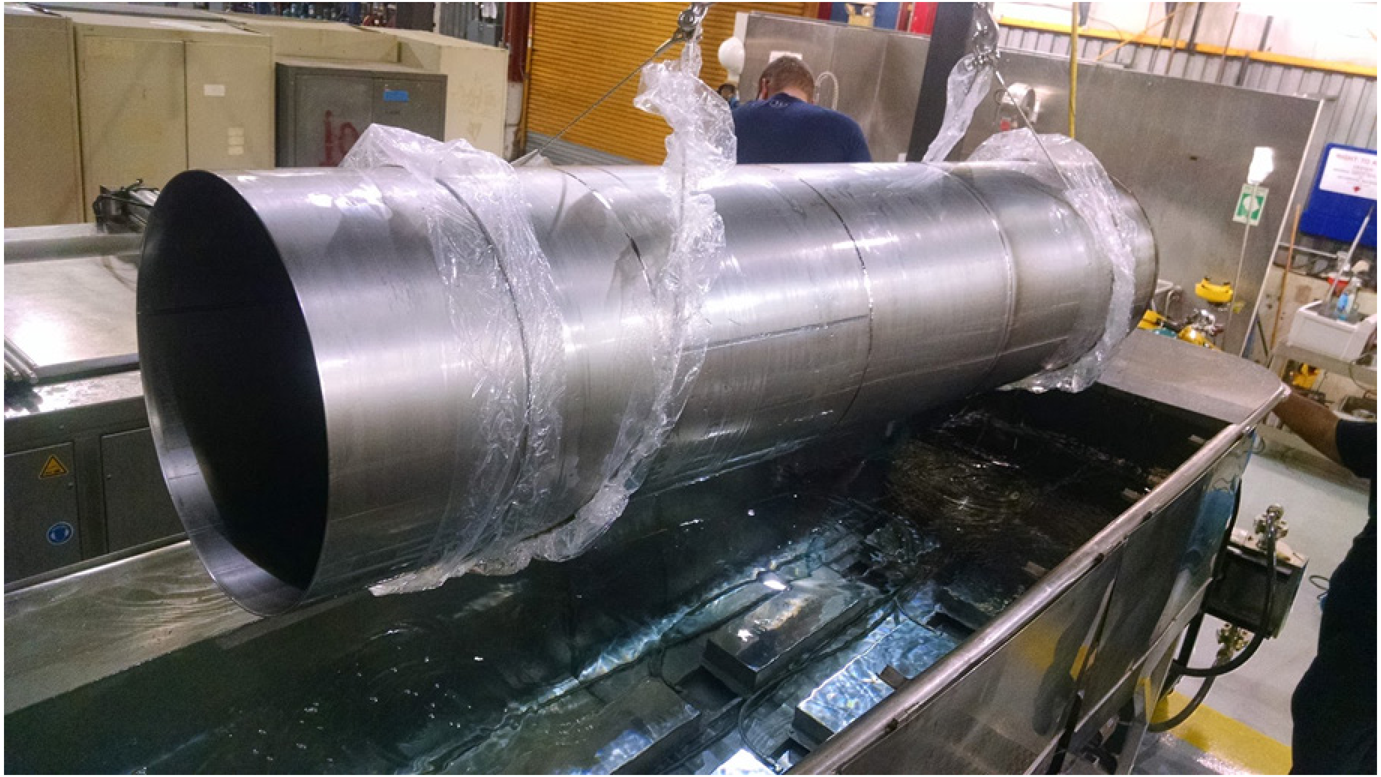
New door with 31” flange
Slow pumpdown system added
Heater power supply rack
Feedthroughs, heat shields
Coating chamber w/ support frame
Nb_3Sn parts storage
$SnCl_2$ prep area
New rail system for precision insertion to furnace
Cleanroom garments added
After Upgrades

Nb Coating Chamber (protects furnace from Sn)



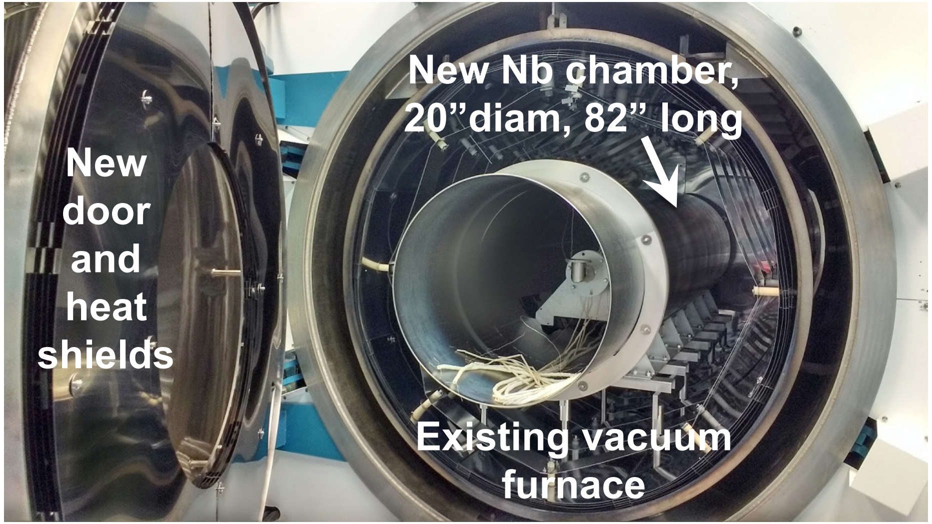
Nb Coating Chamber (protects furnace from Sn)

Chemical polishing done by M. Kelly's group at ANL



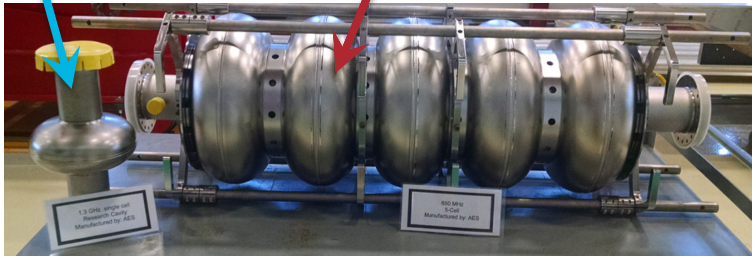
Installation of New Door

Fermilab Nb_3Sn Coating Furnace



1.3 GHz 1-cell (previous state of Nb_3Sn R&D)

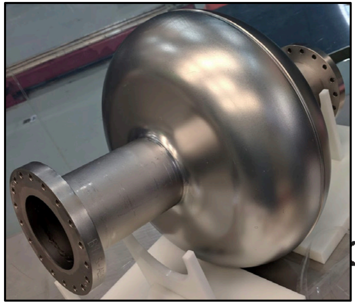
650 MHz 5-cell (new furnace size)

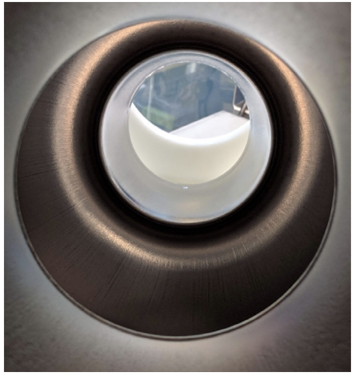


Compact SRF Accelerators: Nb_3Sn Performance Demonstrations

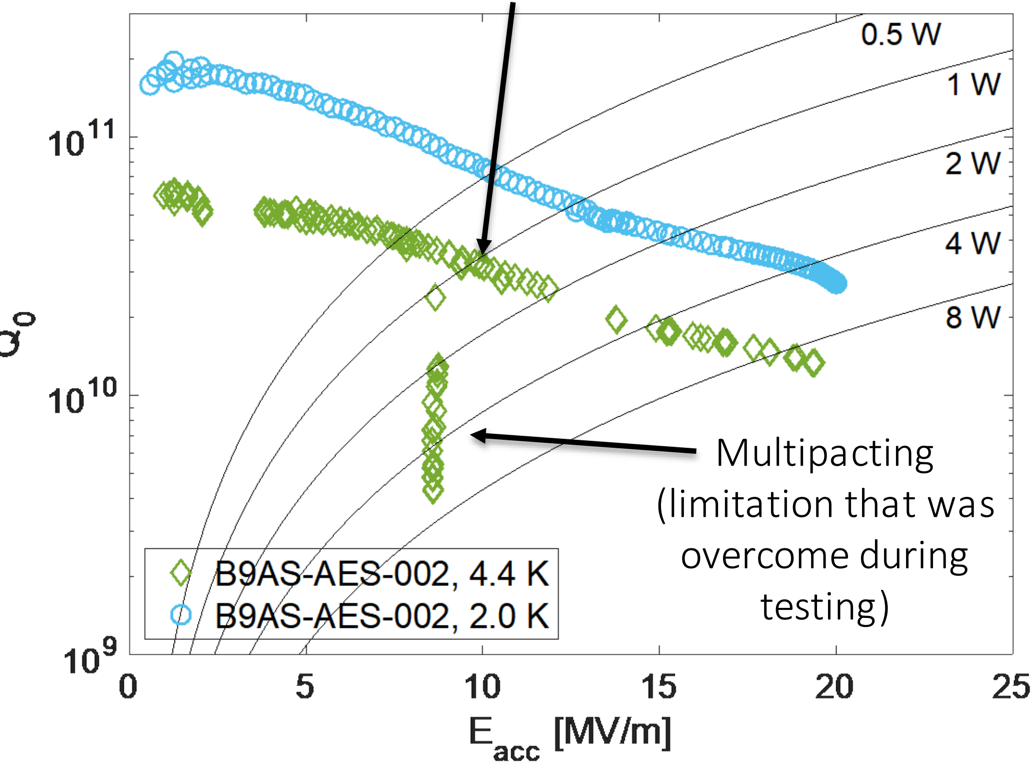
High Q at 4 K – Nb_3Sn 650 MHz Single Cell

650 MHz cavity B9AS-AES-002





~1 W dissipation at 10 MV/m, 4.4 K



Multipacting (limitation that was overcome during testing)

PAPER • OPEN ACCESS

Advances in Nb_3Sn superconducting radiofrequency cavities towards first practical accelerator applications

S Posen[1], J Lee[1,2], D N Seidman[2,3], A Romanenko[1], B Tennis[1], O S Melnychuk[1] and D A Sergatskov[1]

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Superconductor Science and Technology, Volume 34, Number 2
Citation S Posen *et al* 2021 *Supercond. Sci. Technol.* **34** 025007

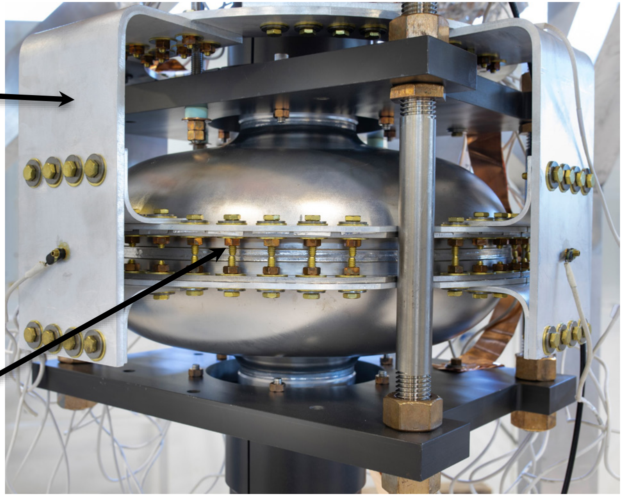
e.g. Cryomech PT420 has cooling capacity of 2.0 W at 4.2 K

Cryocooler-Based Cooling

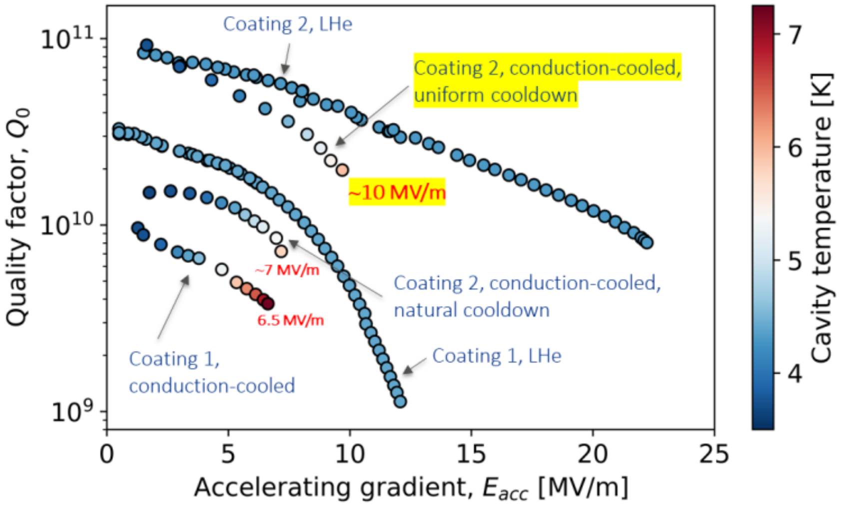
- Nb_3Sn-coated 650 MHz single cell cavity reaches gradient ~10 MV/m with a single cryocooler
- No liquid helium – conduction cooling only

R. Dhuley

High purity aluminum cooling links between cavity and cryocooler



Nb_3Sn-coated cavity with welded Nb rings for attaching cooling links

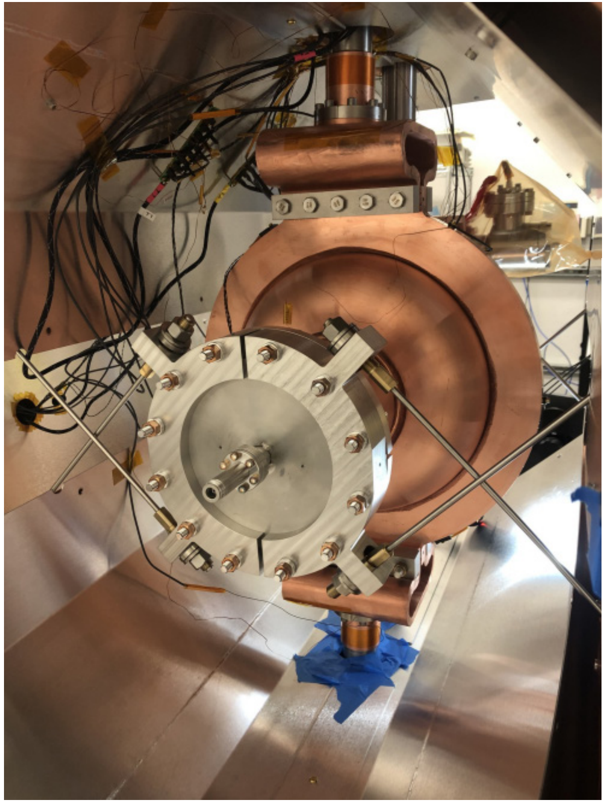


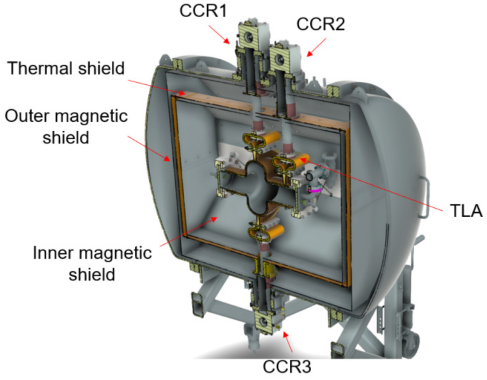
LETTER • OPEN ACCESS
First demonstration of a cryocooler conduction cooled superconducting radiofrequency cavity operating at practical cw accelerating gradients
R C Dhuley[1], S Posen[1], M I Geelhoed[1], O Prokofiev[1] and J C T Thangaraj[1]
Published 20 April 2020 • © 2020 IOP Publishing Ltd
Superconductor Science and Technology, Volume 33, Number 6
Citation R C Dhuley *et al* 2020 *Supercond. Sci. Technol.* 33 06LT01

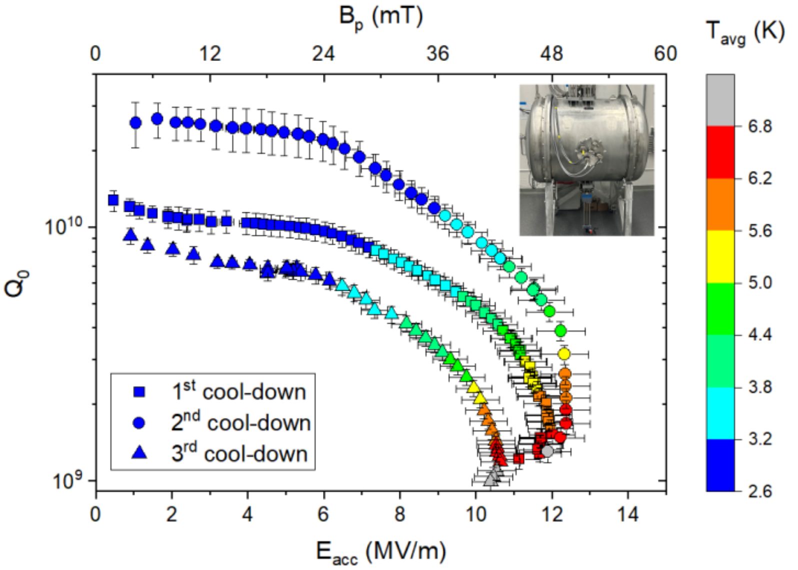
Physics > Accelerator Physics
[Submitted on 20 Aug 2021]
Development of a cryocooler conduction-cooled 650 MHz SRF cavity
R.C. Dhuley, S. Posen, M.I. Geelhoed, J.C.T. Thangaraj

JLab Cryomodule Demonstration

- Different approach, using thick copper coating on outside of Nb cavity instead of welded Nb rings
- G. Ciovati et al., arXiv: 2302.07201 (2023)







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Cryocooler-Based Cooling

- Different labs seem to think that it is time for this technology: Fermilab, Cornell, and Jefferson Lab all have successfully operated Nb_3Sn cavities conduction cooled by cryocoolers

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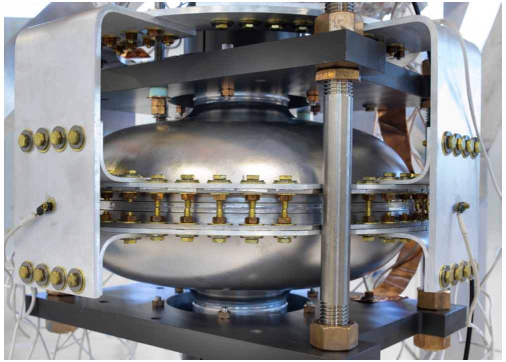
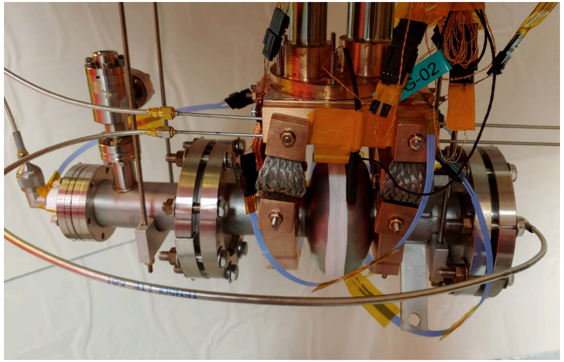


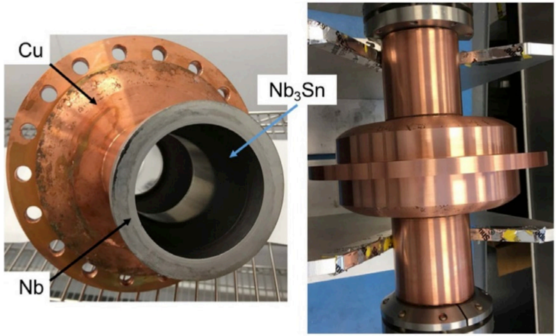
R.C. Dhuley et al, *Supercond. Sci. Technol.* 33 06LT01 (2020)

Cornell University



N. Stilin et al, arXiv:2002.11755v1 (2020)

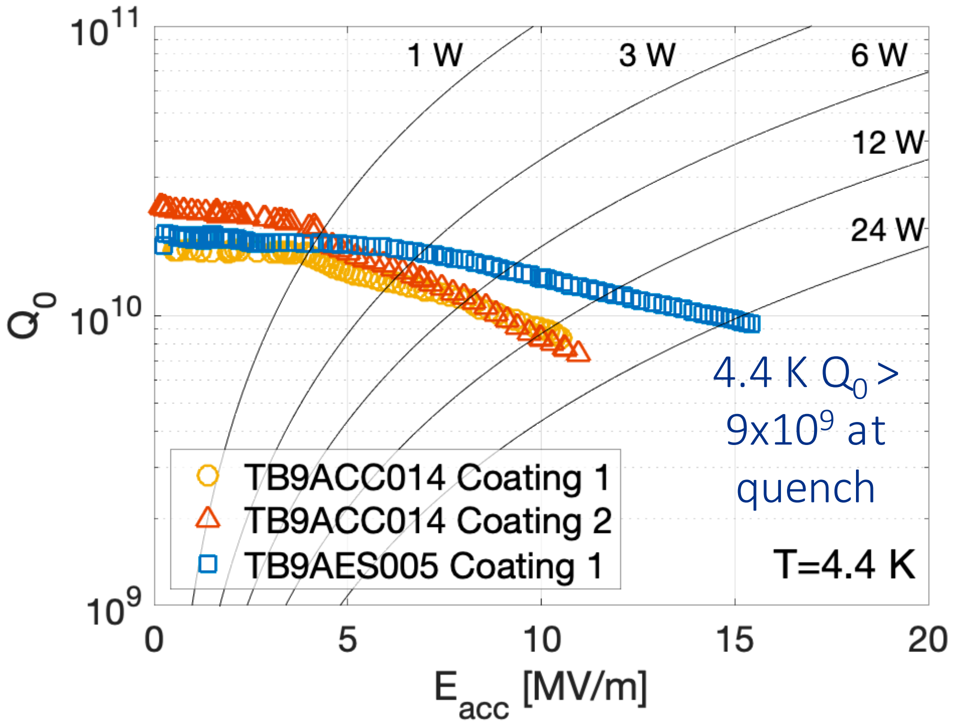
Jefferson Lab



G. Ciovati et al, *Supercond. Sci. Technol.* 33 07LT01 (2020)

Coating Multicell Cavities

Nb_3Sn-coated 9-cell cavities TB9ACC014 and TB9AES005



4.4 K Q_0 > $9x10^9$ at quench

PAPER • OPEN ACCESS

Advances in Nb_3Sn superconducting radiofrequency cavities towards first practical accelerator applications

S Posen[1], J Lee[1,2], D N Seidman[2,3], A Romanenko[1], B Tennis[1], O S Melnychuk[1] and D A Sergatskov[1]

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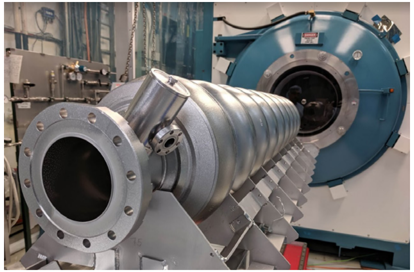
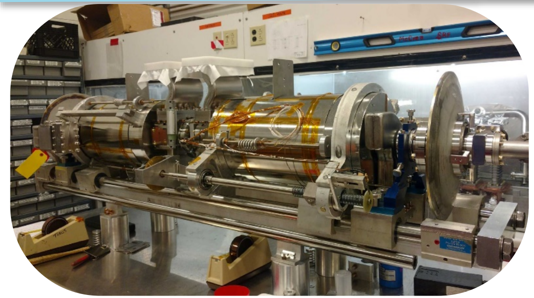
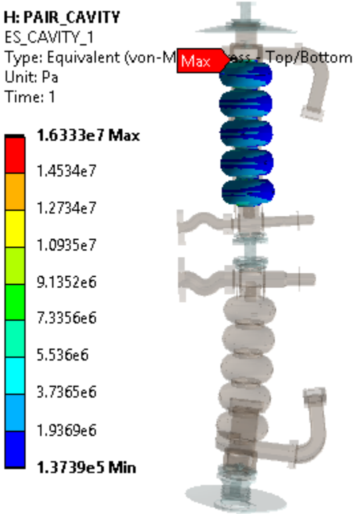


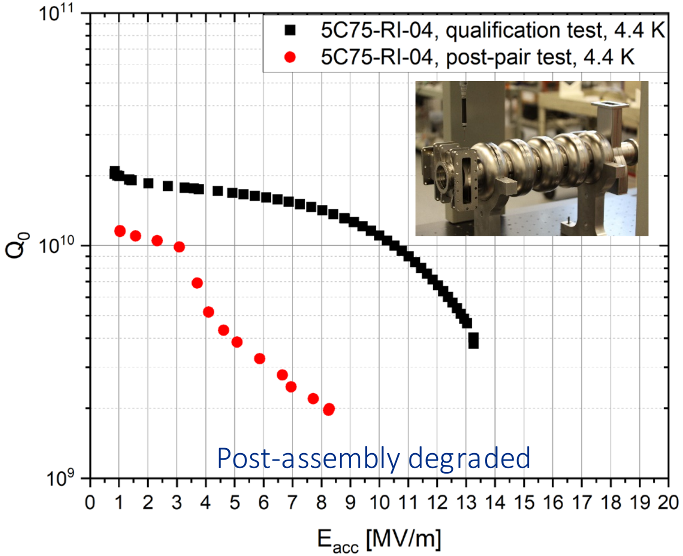
Includes correction for stainless steel flanges 2x0.8 nΩ

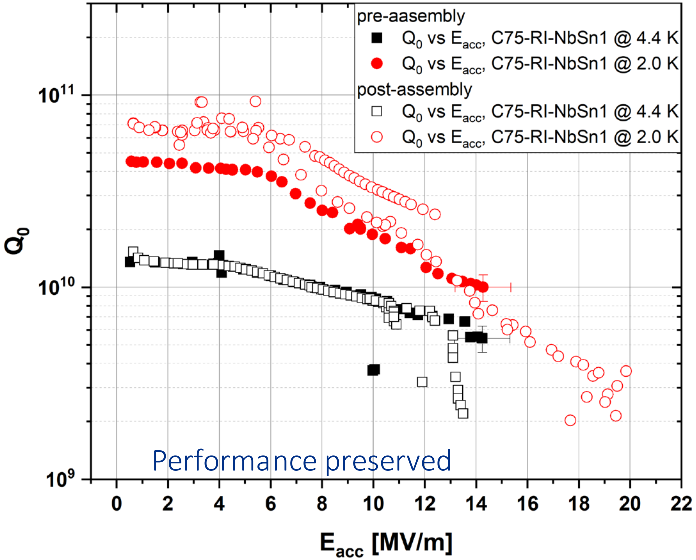
Preservation of the high quality factor and accelerating gradient of Nb3Sn-coated cavity between VTS and string assembly



Two 1.5 GHz 5-cell accelerator cavities have been coated with Nb3Sn film using the vapor diffusion technique. One cavity was coated in the Jefferson Lab Nb3Sn cavity coating system, and the other in the Fermilab Nb3Sn coating system. Both cavities were measured at 4 K and 2 K in the vertical dewar test in each lab and then assembled into a cavity pair at Jefferson Lab. Previous attempts to assemble Nb3Sn cavities into a cavity pair degraded the superconducting properties of Nb3Sn-coated cavities. This contribution discusses the efforts to identify and mitigate the pair assembly challenges and will present the results of the vertical tests before and after pair assembly. Notably, one of the cavities reached the highest gradient above 80 mT in the vertical test after the pair assembly.

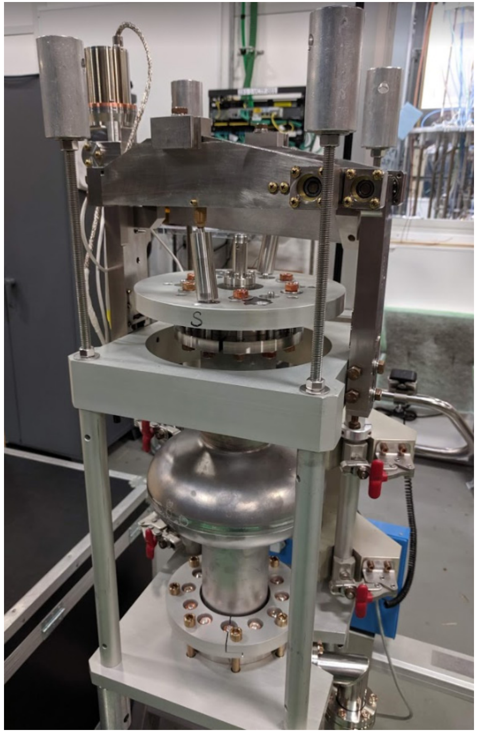


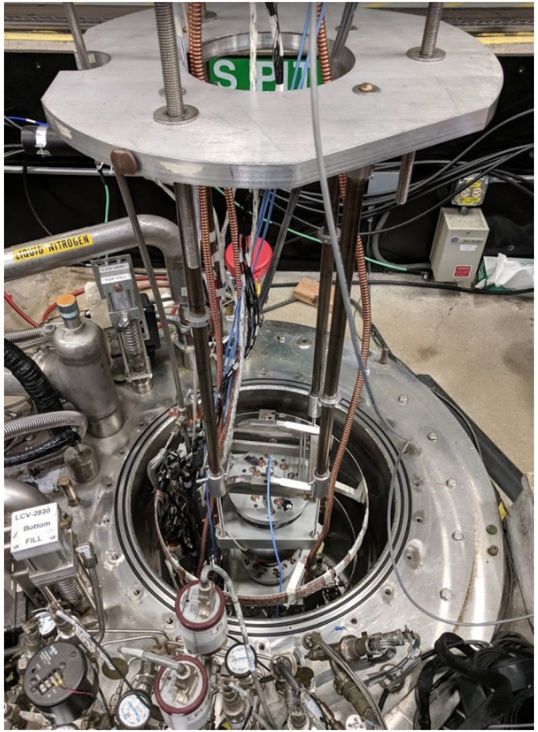




Grigory Eremeev, Sergey Cheban, Sam Posen, Brad Tennis, Uttar Pudasaini, Anthony Reilly, Robert Rimmer

Frequency Tuner Test





Special thanks to Y. Pischalnikov and J.-C. Yun

Frequency Tuner Test

- Why worry about frequency tuning with Nb_3Sn?
- Nb_3Sn wires show degradation under strain
- Is tuning enough strain to degrade cavity performance?

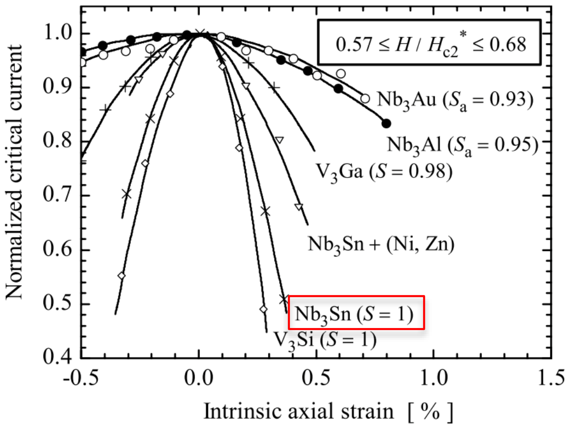
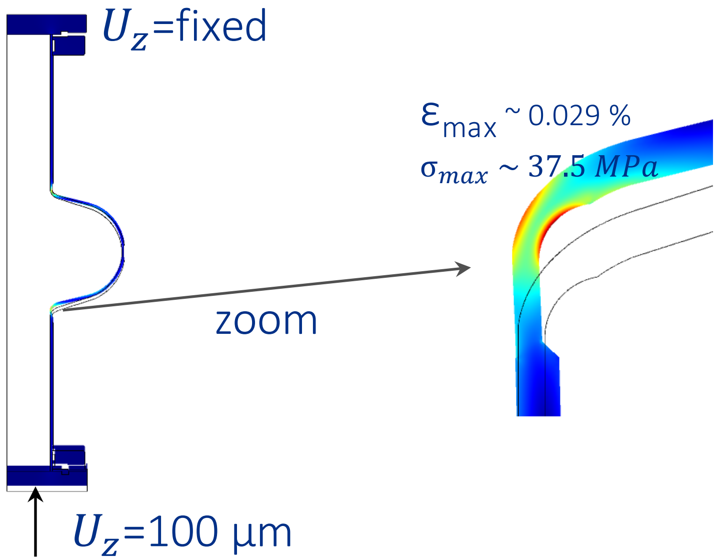
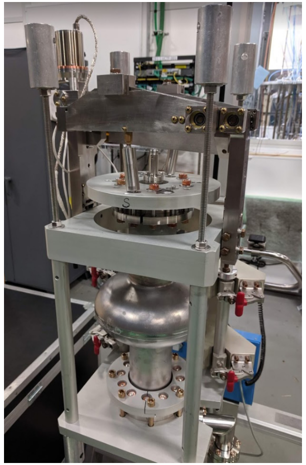


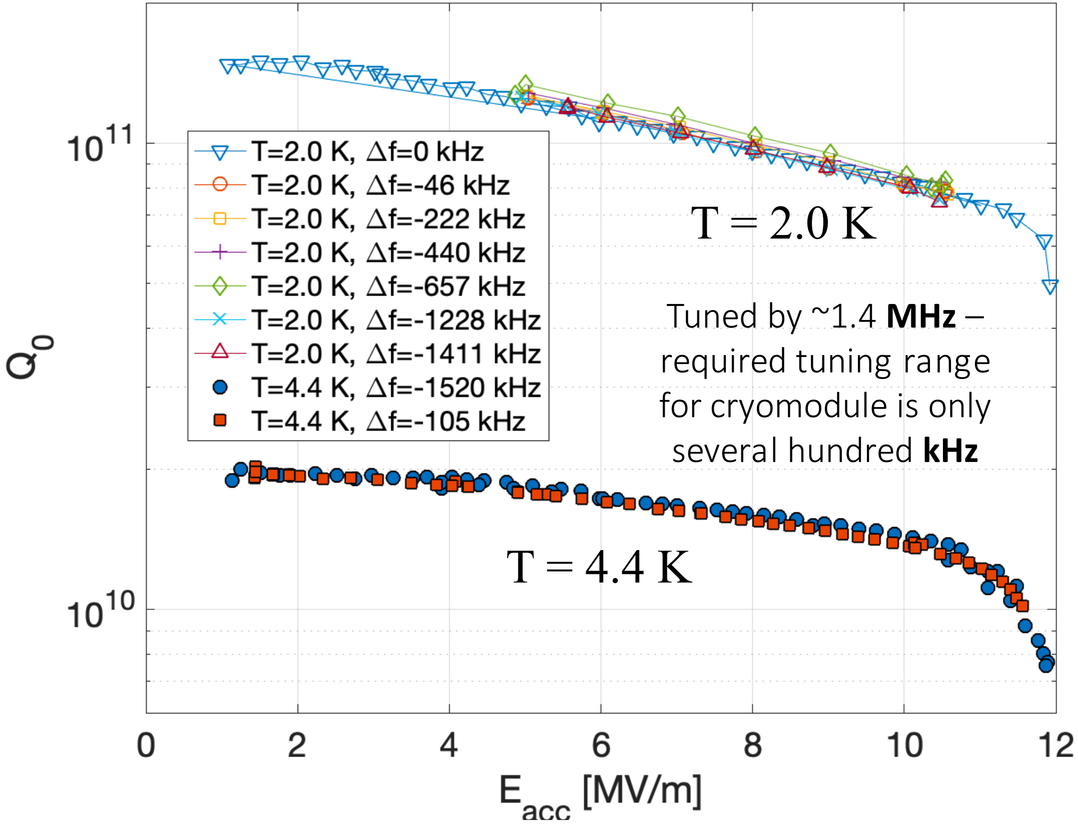
Figure 11. Strain sensitivity of the critical current for different A15 superconductors with varying amounts of disorder, after Flükiger *et al* [26] (*©1984 Plenum Press. Adapted with kind permission of Springer Science and Business Media and R Flükiger*).

A Godeke 2006 *Supercond. Sci. Technol.* **19** R68



Frequency Tuner Test



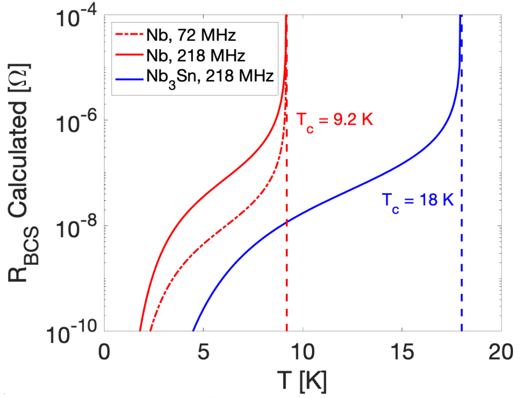


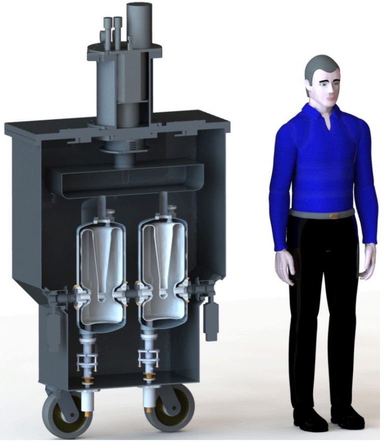
Tuned by ~1.4 **MHz** – required tuning range for cryomodule is only several hundred **kHz**

Compact SRF Accelerators: Towards First Prototypes

Nb_3Sn for Nuclear Physics (Collaboration ANL/FNAL/Radiabeam)

- Project aims to build cavities for Argonne's ATLAS Multi-User Upgrade – could be implemented in energy adjustment cryomodule without connection to cryoplant
- Nb_3Sn allows the use of higher frequency (smaller) cavities and low enough dissipation for cryocooler-based cooling
- Under this project we will Nb_3Sn-coat quarter cavities – optimistic after experience with 9-cell cavities
- Success would be promising for future NP work, e.g. a dedicated U.S. accelerator-based isotope production facility
- Led by ANL, support from DOE NP





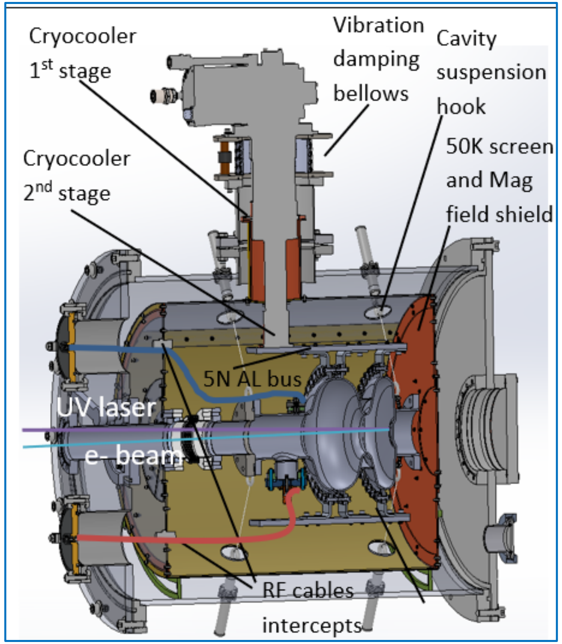
Argonne NATIONAL LABORATORY — Lead lab; PI: Mike Kelly

Fermilab — FNAL Lead: Sam Posen

RadiaBeam — RB Lead: Sergey Kutsaev

Nb_3Sn for Industrial Accelerators (Collab. Euclid/FNAL/BNL)

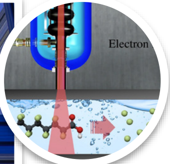
- Funded by DOE SBIR Phase II, DE-SC0018621 (BES)
- Ultra-compact & -efficient ultrafast electron diffraction
- Led by Euclid, with FNAL and BNL partners
- Cavity at FNAL for SRF work, incl. Nb_3Sn coating



euclid BEAMLABS
Fermilab
BROOKHAVEN NATIONAL LABORATORY

Emerging E-beam Applications

E-beam accelerator used for proof-of-concept studies and development of new applications and technologies at Fermilab



Destruction of PFAS — Addressing one of the biggest contamination concerns in the world

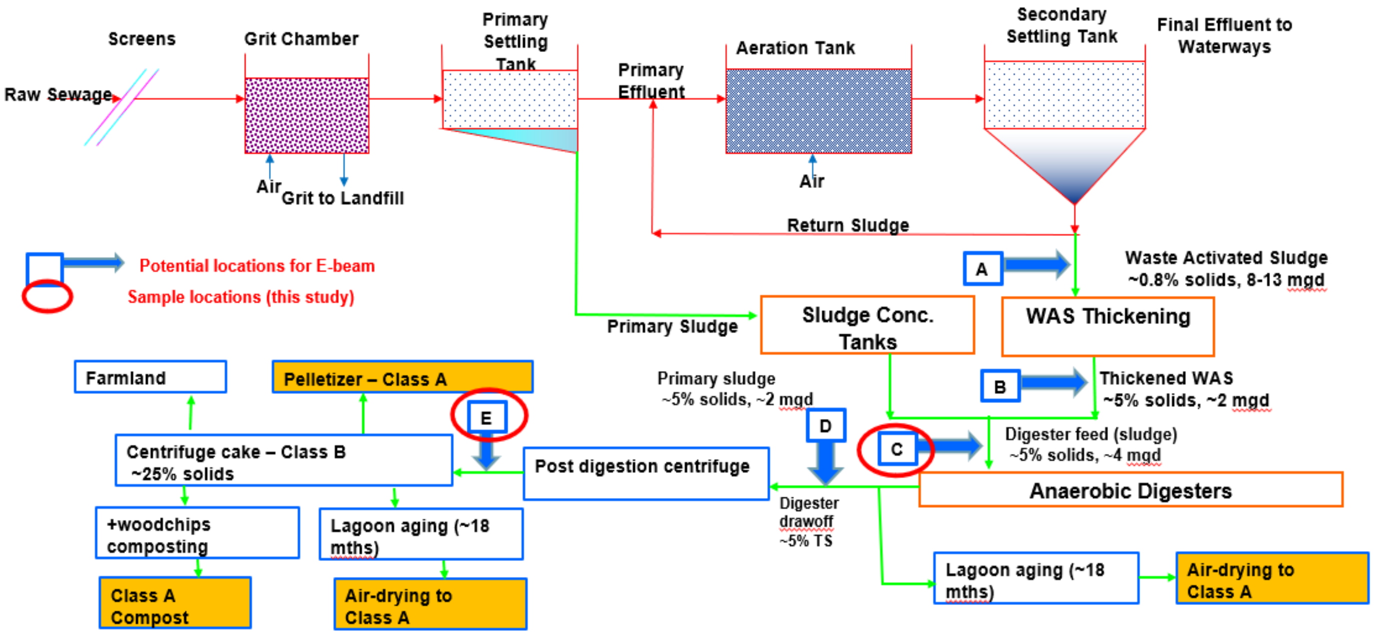
Municipal water treatment — On-demand sterilization of water

Ballast water treatment — Mitigating problem of invasive species

Destruction of toxins in soil — Helping DOE/DOD manage legacy waste

Curing of pavement — Developing new and improved pavements

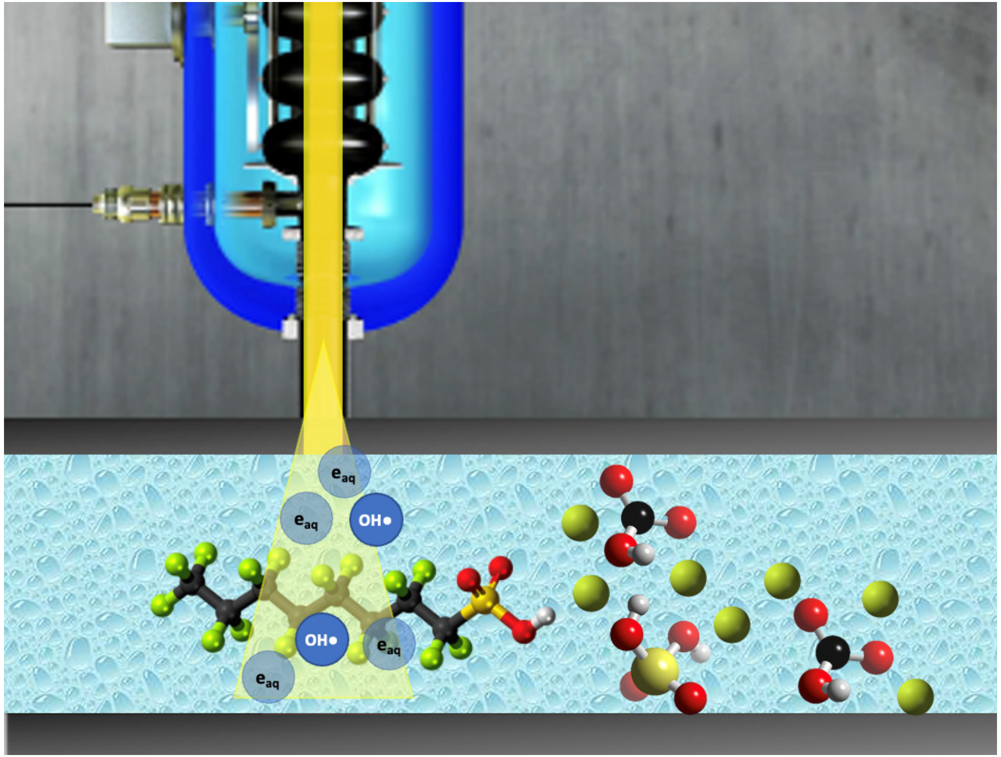
Water Treatment – MWRD Chicago



- Greater than 4 log reduction of fecal coliform
- Enhanced phosphorous recover
- Substantial increased energy recover
- Decreased smell
- Operating costs = economical

Treatment of PFAS in water – EERE 3M

- Office of Energy Efficiency & Renewable Energy funding
- Fermilab & 3M has been evaluating the overall effectiveness of electron beam accelerators in the degradation of a group of environmental contaminants (PFAS) in water.
- Have found complete destruction of PFOA and PFOA homologs and 99.7% destruction of PFOS.



What are "Forever Chemicals"? – *PFAS*

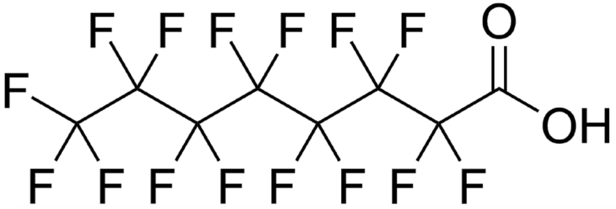
- these days used synonymously with forever chemicals
- per- and polyfluoroalkyl substances

  ↪ de facto (long) chains of C atoms, many F's & a functional group

- recent proposed drinking water restrictions by EPA (*US*)
  - PFOA, PFOS, PFNA, PFHxS, PFBS, HFPO-DA (GenX)
  - proposed limits basically as low as detection limits
- big challenge for wastewater treatment plants

  ↪ current approach often filter & concentrate (GAC) → deal with filter (incinerate …?)

  ↪ cost & energy intensive



https://www.youtube.com/watch?v=9W74aeugsiU

©HBO

How does ebeam treatment of water work?

- don't attack contaminants directly

  → "activate" water with beam

$$e^- \Rightarrow \quad H_2O \rightarrow e^-_{aq} + HO^{\cdot} + H^{\cdot} + HO_2 + H_3O^+ + OH^- + H_2O_2 + H_2$$

↪ create oxidants **and** reductants (*not just any, some of the strongest*)

→ those react with contaminants

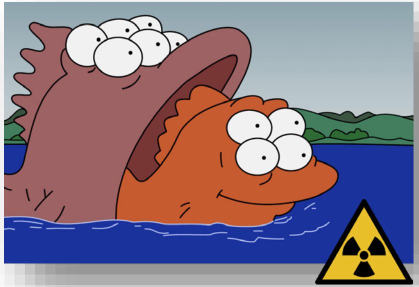
- big benefit → no addition of further chemicals required

  ↪ very cost-effective generation of free radicals

- And no, we don't (radio)activate your water!

  ↪ stay below 10 MeV ↔ neutron activation threshold

  - *Yet, public acceptance oft an issue – "**treatment**" vs "irradiation"*



Jefferson Lab

What is our approach? – *10 MeV concept*

©Buena Vista Television

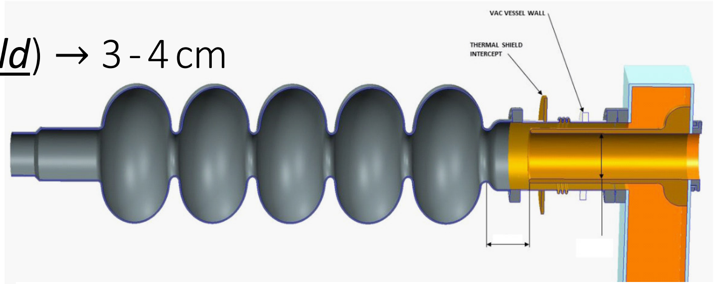
- 1 MeV penetration depth e^- in water ~ 3 - 4 mm

  ↪ not very practical

- move to 10 MeV (***remember threshold***) → 3 - 4 cm

- single cell → multi-cell cavity

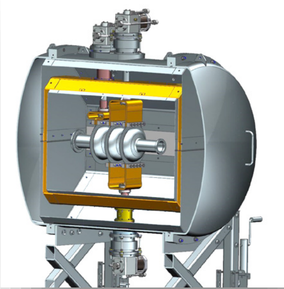
  ↪ not new for SRF but for CC

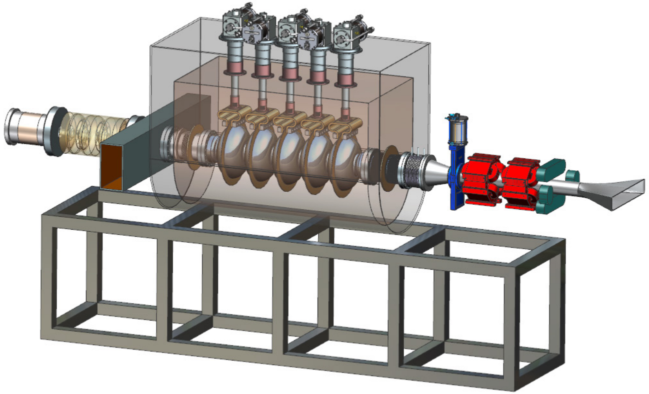


- develop multi-cell cavity (RF parameters, FPC etc.) & update design of compact accelerator

- test CC concept with 3-cell

  in horizontal cryostat



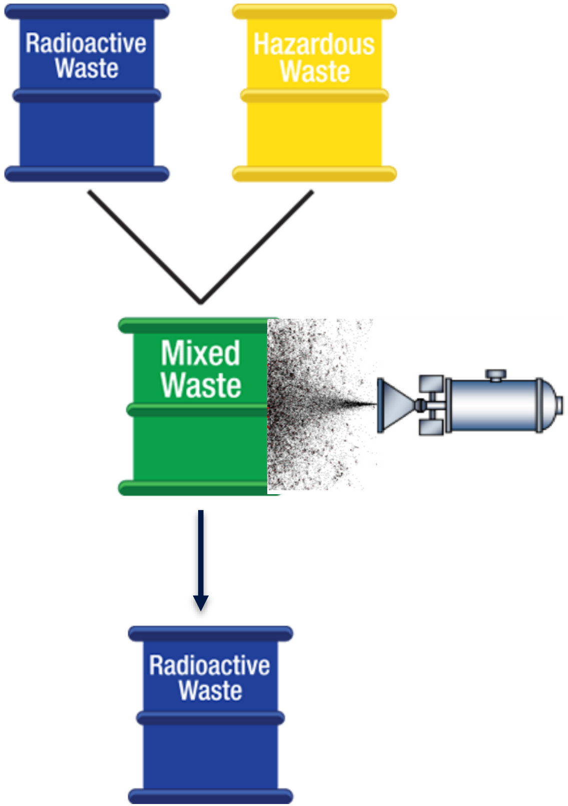


Treatment of MLLW – FUSRAP

- U.S. government had a large stockpile of mixed waste created during the production and use of radioactive material.
- Treatment and disposal of mixed wastes has received much attention with no viable solutions so far.
- Common process today is to simply store. Sometimes with vitrification (turn in to glass).

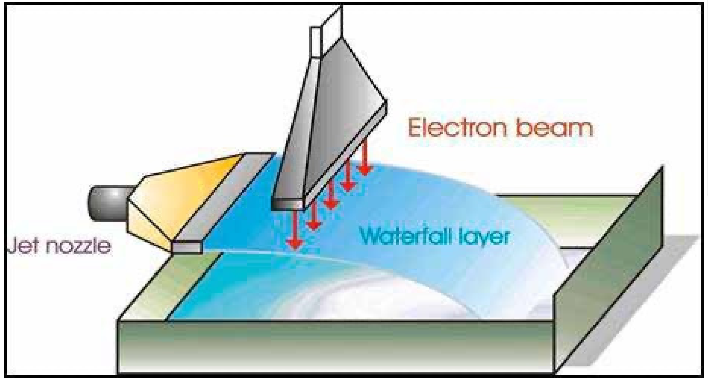
E-beam can

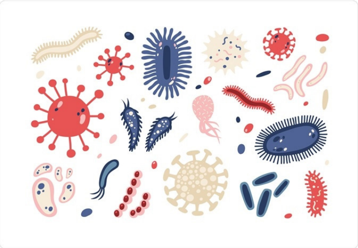
- Remediate the toxic component of mixed waste, leaving it only radioactive.
- Reduce cost and regulation and simplify transport of the waste
- Improve safety of handling waste

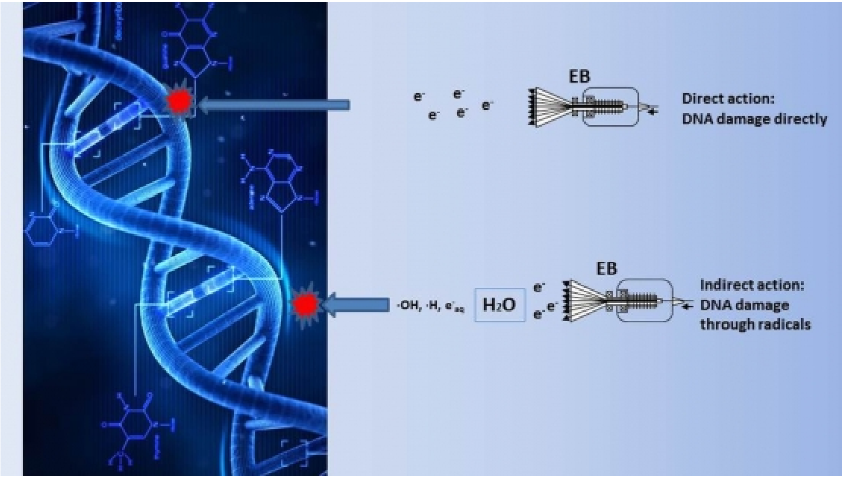


Management of Ballast Water – UW Superior

- Ballast water is one of the major pathways of biological invasion throughout the world.
- Using high energy electron beams directly into ballast water to generate highly reactive species in the ballast water that rapidly damage and destroy the cells of harmful marine organisms, including viruses, bacteria and algae.

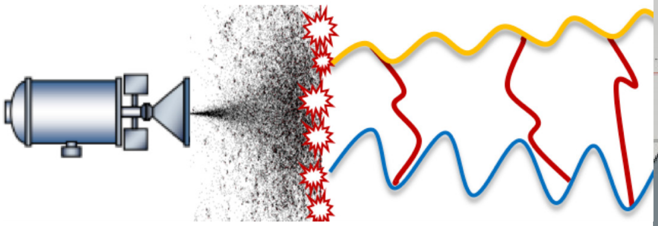


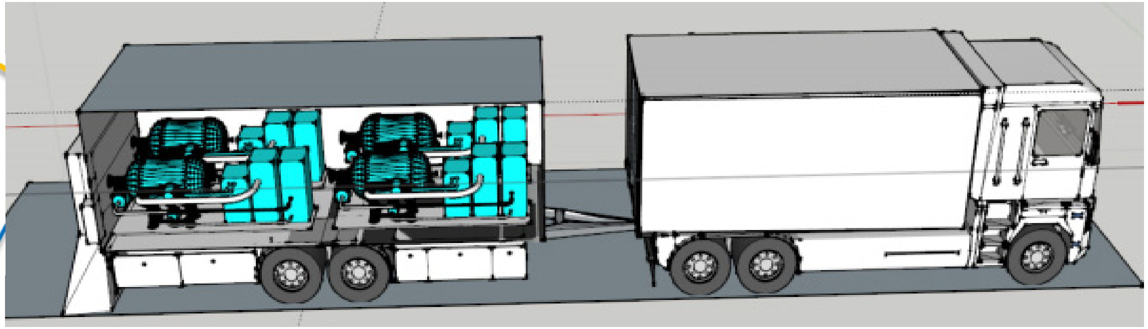




E-beam crosslinking of bitumen – ERDC

- Electron beams are used to polymerize a mixture of reactive monomers, colorants, surfactants and other additives
- Enhancing strength properties of bitumen by means of electron beam induced polymer modification could reduce or prevent crack initiation and propagation in pavements due to various weather conditions and heavy loads .
- The electron penetration depth in asphalt is around 2 cm (for a 10 MeV beam).
- While the initial energy deposited is important, further electron interactions within the polymer would promote additional chemistry to be driven deeper in the system.



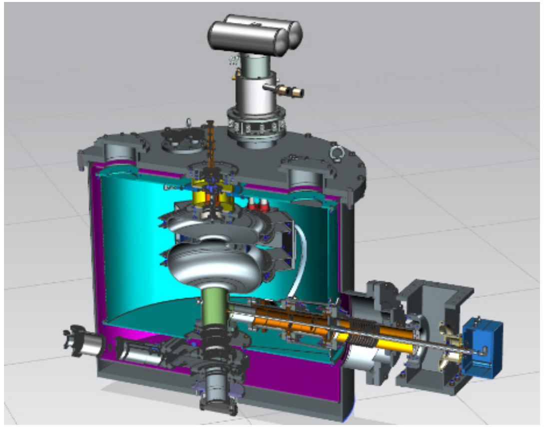


Fermilab

SRF 2023 GRAND RAPIDS

Medical Device Sterilization - NNSA

- **Medical Device Sterilization**
  inactivation of microorganisms with no effect on med devices
  - NNSA – Replace Co-60 irradiators with electron or X-ray beams from compact SRF accelerator that has equivalent capacity as commercial facilities

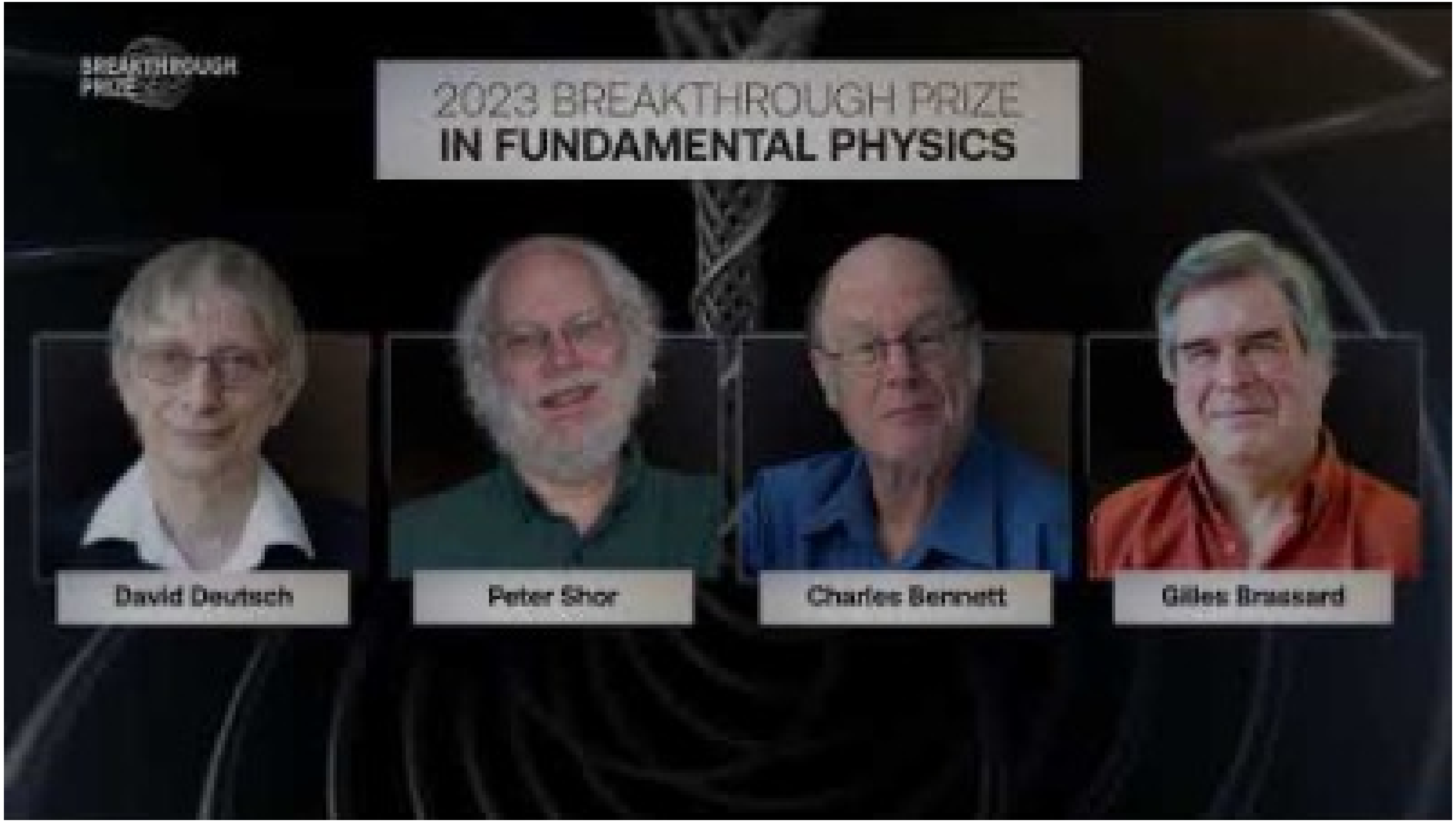


Quantum Computing: Introduction

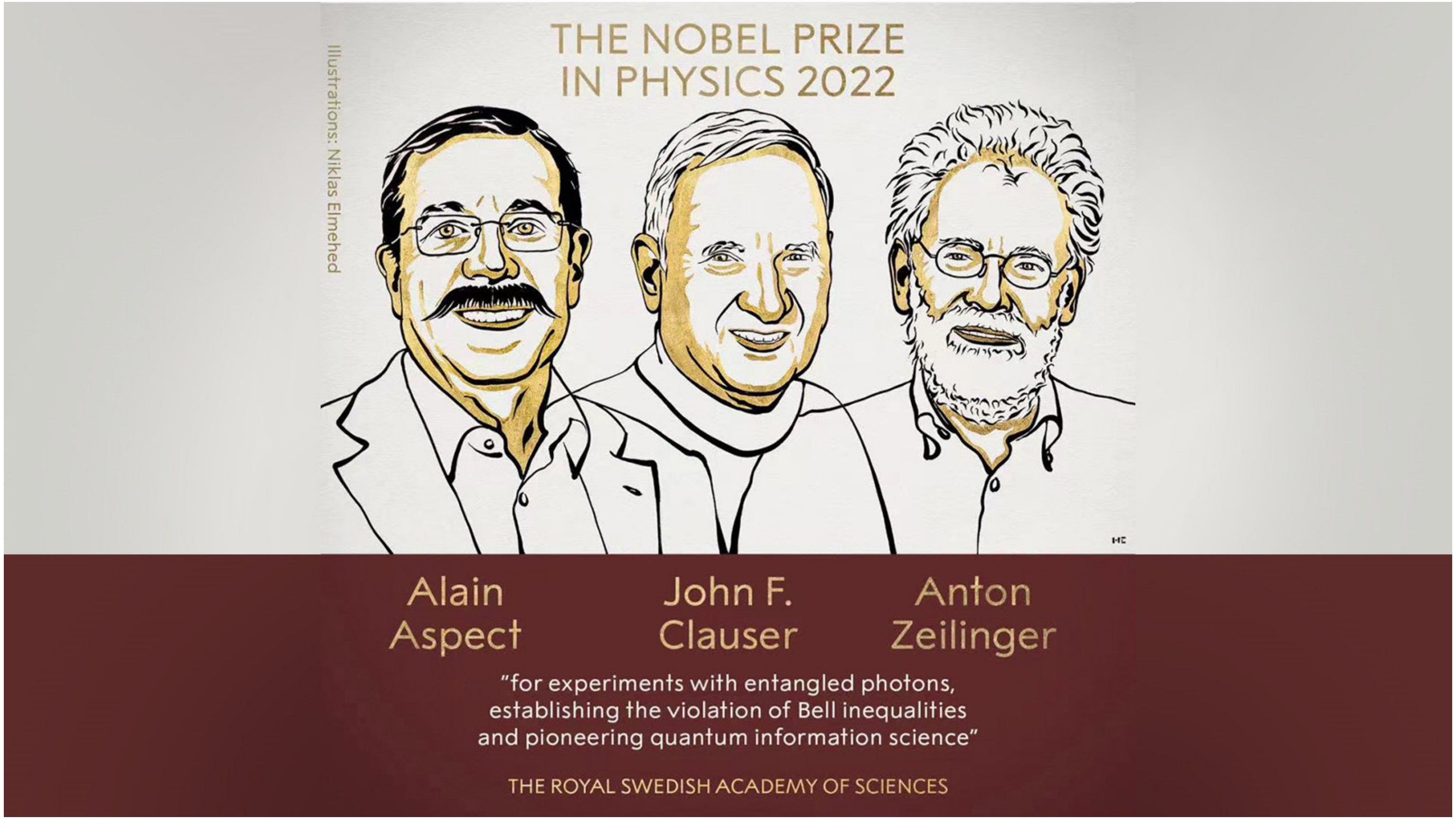
The world is excited about QIS

Grassellino - Quantum

The world is excited about QIS

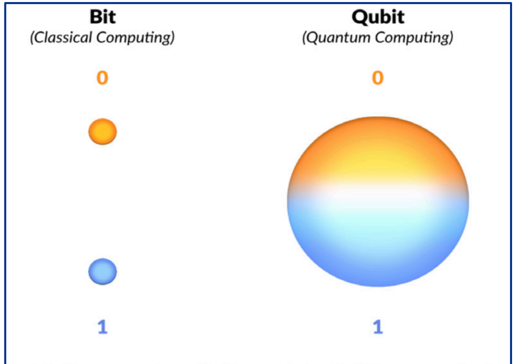


The world is excited about QIS

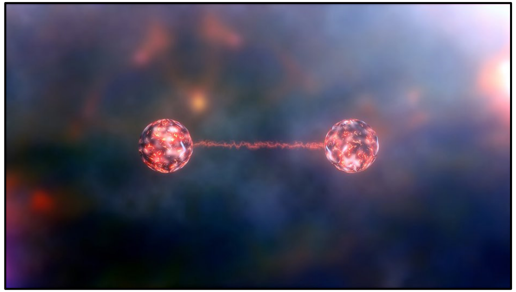


Quantum Information Science

- Growing field of science and technology, combining and drawing on the disciplines of physics, mathematics, computer science, and engineering
- Its aim is to understand how certain **fundamental laws of quantum physics** – **superposition, entanglement** - can be harnessed to dramatically improve the acquisition, transmission, and processing of information
- The exciting scientific opportunities offered by QIS are attracting the interest of a growing community of scientists and technologists, and are promoting **unprecedented interactions across traditional disciplinary boundaries**



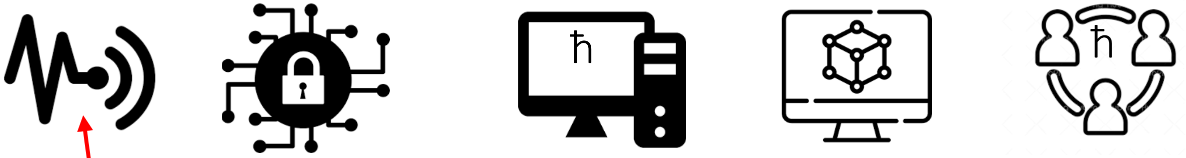
Classical qubits are zero or one: two possible states, represented as points. Qubits are a superposition of zero and one: a continuum of possible states, represented as the surface of a sphere (the Bloch sphere).



Fermilab SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Quantum Information Science

Quantum Sensing & Metrology | Quantum Cryptography | Quantum Computing | Quantum Simulation | Quantum Communication



Superconducting materials and RF cavities

Cryogenics

Electronics and Microwave Controls

Precision Timing

…

Leveraging HEP technologies
for advancing quantum information science

The accelerator community has advanced technologies that are now critical for QIS;
we have the responsibility and the fortune to contribute to the important field of QIS

Quantum Information Science

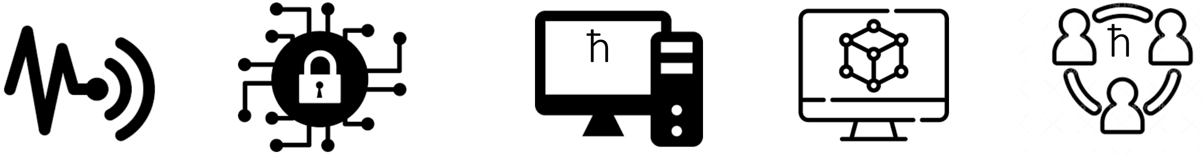
Quantum Sensing & Metrology

Quantum Cryptography

Quantum Computing

Quantum Simulation

Quantum Communication



Foundations of Quantum Mechanics

Physics beyond Standard Model

Dark Matter

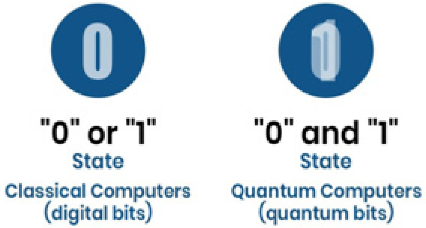
Simulation of quantum field theories…

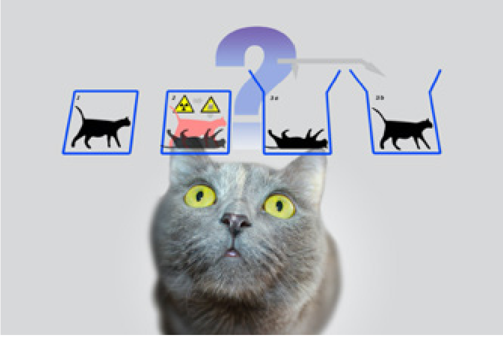
Leveraging quantum technologies for studying particle physics

QIS in turn will advance technologies that can become critical for fundamental physics discovery; we have the fortune and the responsibility to explore their full potential for particle physics

Quantum computing

- Basic idea is to build a computer which uses “qubits” instead of bits
  - Utilize very special quantum mechanics principles: two states of the quantum system, which can be also prepared in any “**superposition**”
  - Also utilize “**entanglement**” between the qubits
- A quantum computer can provide potentially computational capacity for dramatic speedups in several very high impact areas, such as:
  - Finding large prime number multipliers, database search, simulating and predicting molecules behavior and interactions, modeling financial markets, simulating particle collisions etc



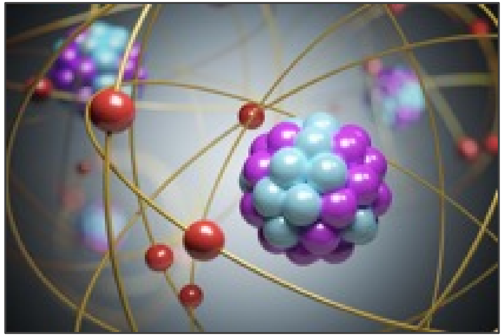


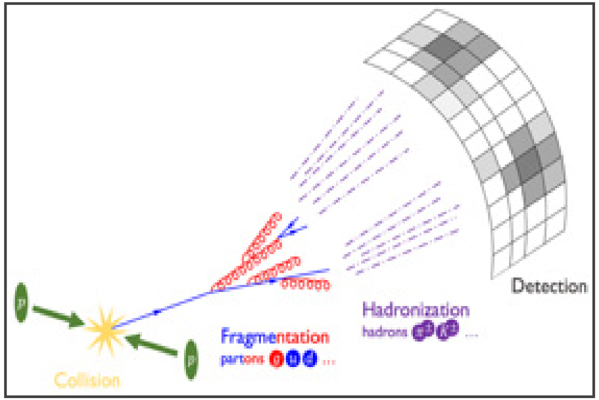
Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981





"Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy" – Richard Feynman

"The pursuit of a quantum computer can be thought of as a way to improve current computer technology, as a way to simulate quantum mechanics, or simply as a universal quantum problem stimulating interaction between disparate scientific disciplines." – Dave Schuster

Physics, Chemistry, Medicine…

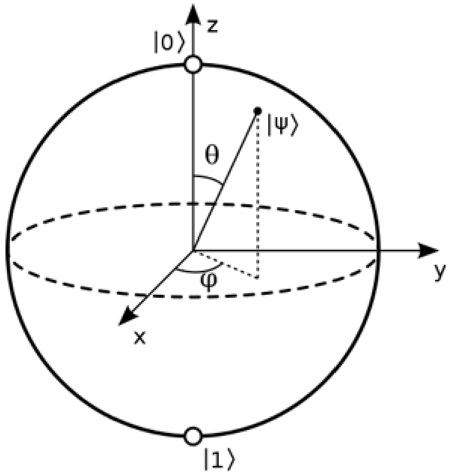
Quantum Computing: Qubits and SRF Cavities

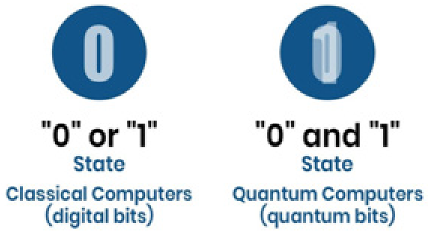
Qubits

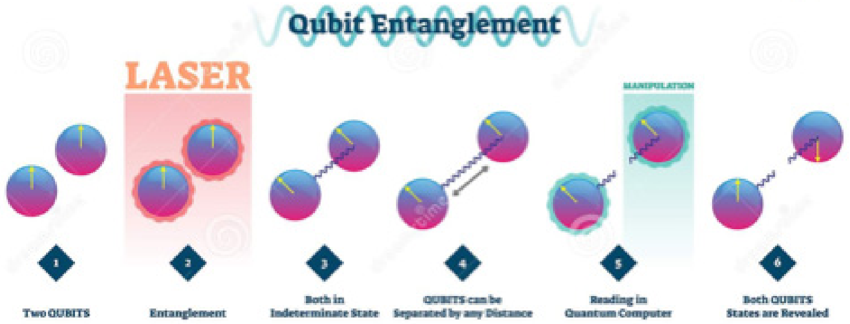
- Basic unit of quantum information
- Two levels quantum mechanical system
- Utilize very special quantum mechanics principles: two states of the quantum system (|0>, |1>), which can be also prepared in any "**superposition**" :

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

- Also utilize "**entanglement**" between the qubits







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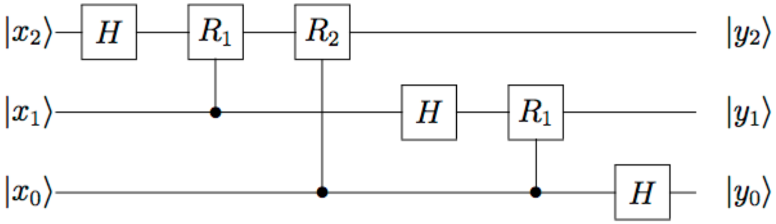
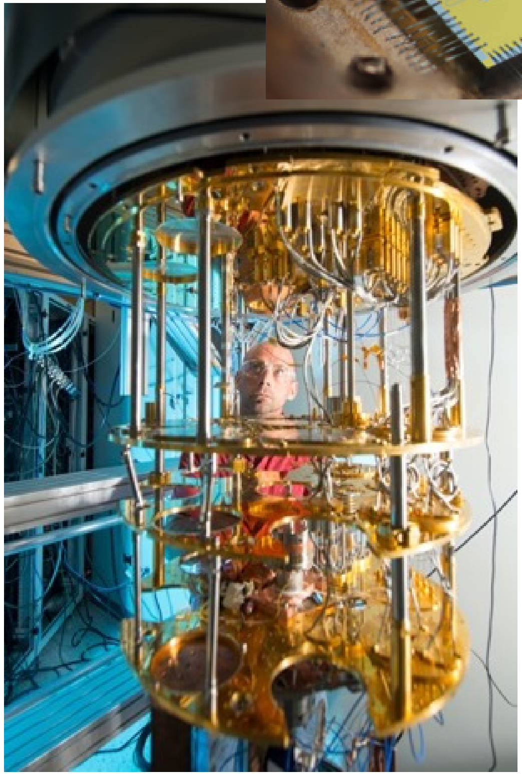
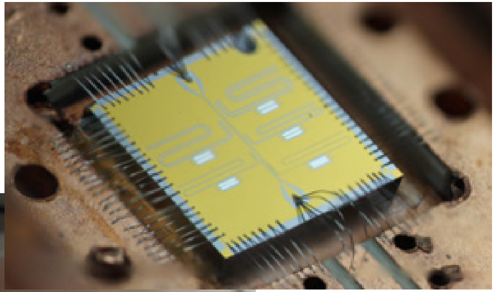
Qubits main challenges

- Need a qubit that you can manipulate and not confuse with other possible states of the system
- Maintain the **quantum coherence** of superpositions long enough to perform a large number of gate operations

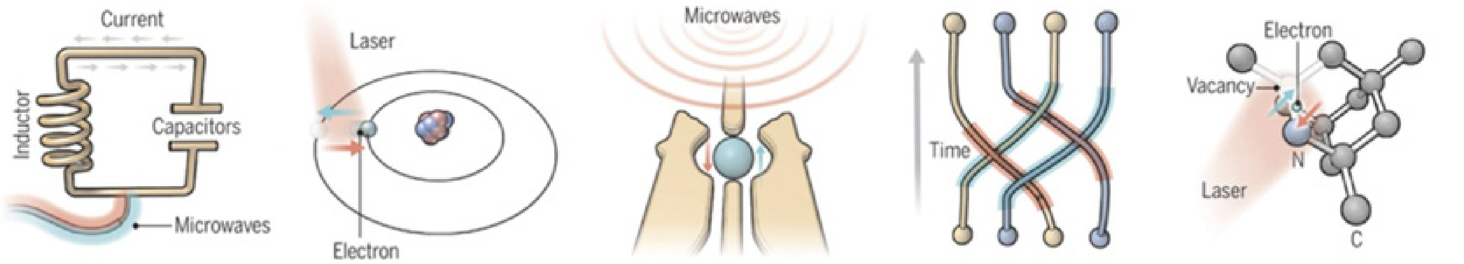






Qubit platforms

Qubit technologies overview. From: Forbes, *Quantum Computer Battle Royale: Upstart Ions Versus Old Guard Superconductors*



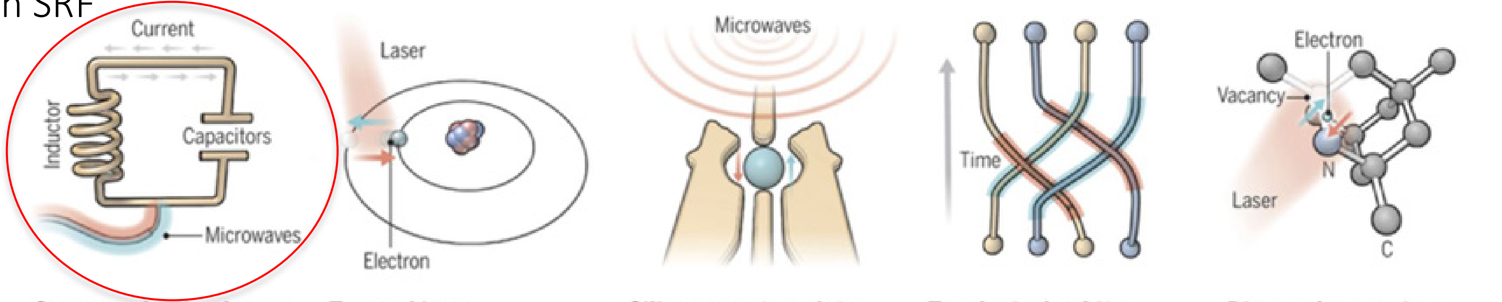
Superconducting loops	Trapped ions	Silicon quantum dots	Topological qubits	Diamond vacancies
A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into super-position states.	Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.	These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	Quasiparticles can be seen in the behavior of electrons channeled through semi-conductor structures. Their braided paths can encode quantum information.	A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.
Longevity (seconds)				
0.00005	>1000	0.03	N/A	10
Logic success rate				
99.4%	99.9%	~99%	N/A	99.2%

"The tech giants, IBM , Google , and Intel , all have staked out their quantum computing claims with superconducting qubits. Rigetti Computing, a recent but impressive California start-up, also uses superconducting qubits"

Qubit platforms

Qubit technologies overview. From: Forbes, *Quantum Computer Battle Royale: Upstart Ions Versus Old Guard Superconductors*

Can we make this out of an SRF cavity?



	Superconducting loops	Trapped ions	Silicon quantum dots	Topological qubits	Diamond vacancies
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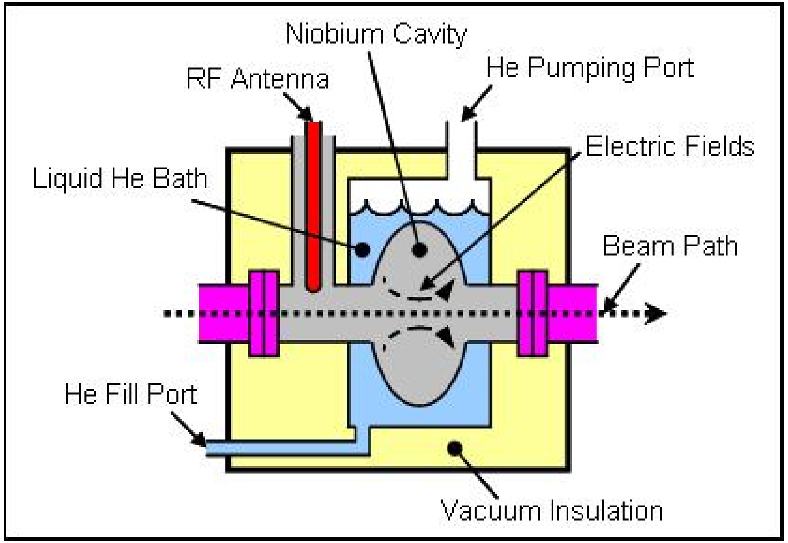
"The tech giants, IBM , Google , and Intel , all have staked out their quantum computing claims with superconducting qubits. Rigetti Computing, a recent but impressive California start-up, also uses superconducting qubits"

Photos from: Disney, BlueFors

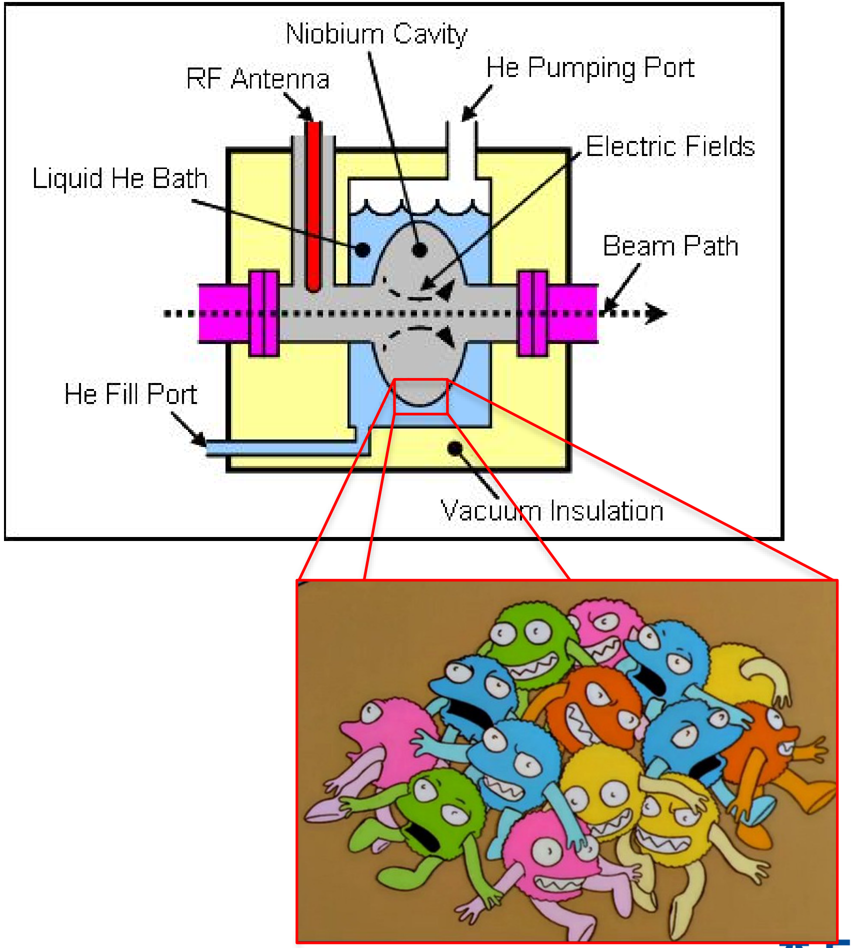
SRF Cavity in Liquid Helium

- Can this be the basis for a qubit?



Images from: Hasan Padamsee, 20th Century Fox

SRF Cavity in Liquid Helium



- Can this be the basis for a qubit?
- Well, there's a problem – the cavity might seem cold at 4 K or 2 K, but it's still teeming with thermal photons
- Thermal photons can turn |0> to |1> and cause decoherence

Images from: Hasan Padamsee, 20th Century Fox

T ~ 400 C

n_T ~ 7x10^4

How many photons of added thermal noise at f = 1.3 GHz?

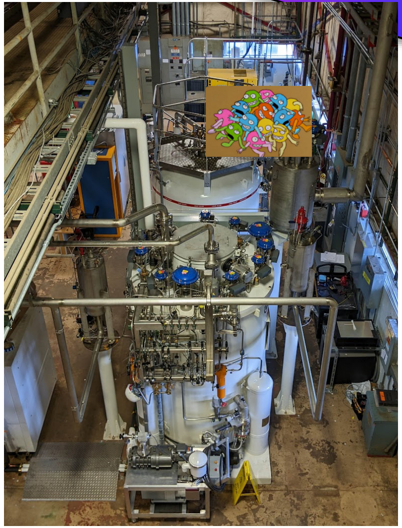
$$n_T \sim \frac{k_B T}{\hbar\omega}$$

T = 20 C

n_T ~ 3x10^4

T ~ 77 K

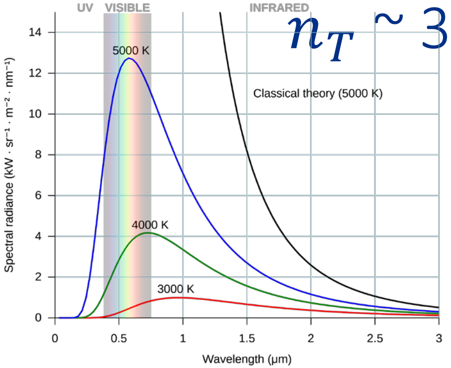
n_T ~ 8x10^3



T = 2 K n_T ~ 201

T = 20 mK

n_T ~ 2

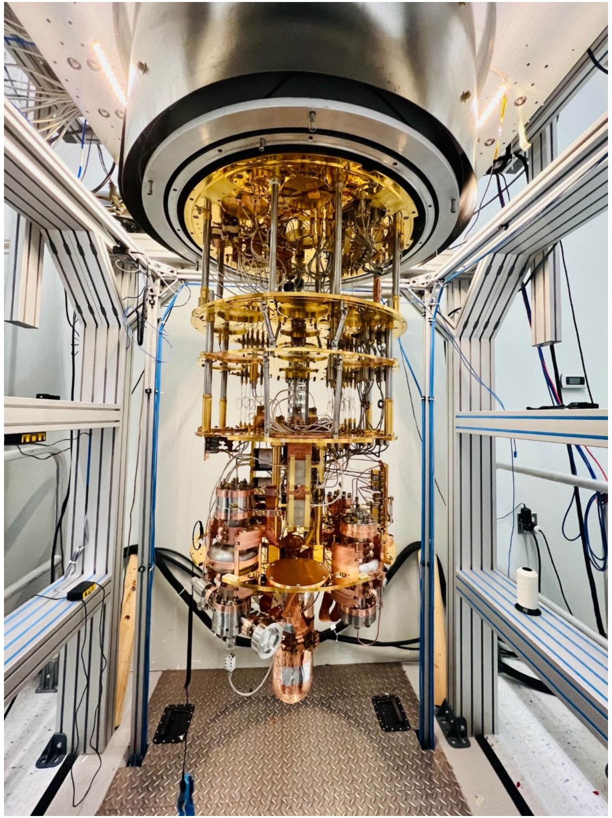


$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1},$$

Images from: Wikipedia, freefoodphotos.com, 20th Century Fox

SRF Cavity in ~~Liquid Helium~~ Dilution Refrigerator

- Are our SRF-based qubits protected from thermal photons in a dilution refrigerator at 20 mK?



SRF Cavity in ~~Liquid Helium~~ Dilution Refrigerator

- Are our SRF-based qubits protected from thermal photons in a dilution refrigerator at 20 mK?
- We still need to be very careful – for example, the RF input lines can be low impedance connection to room temperature that can transport thermal photons into our nice cold cavity

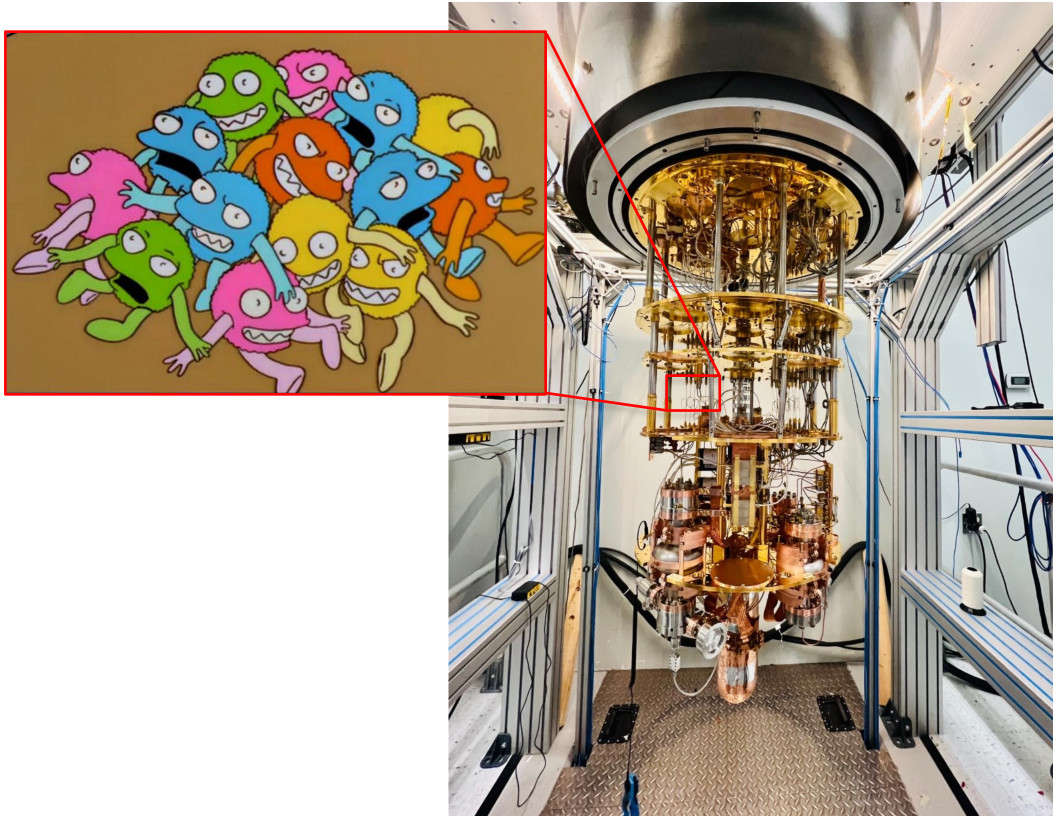
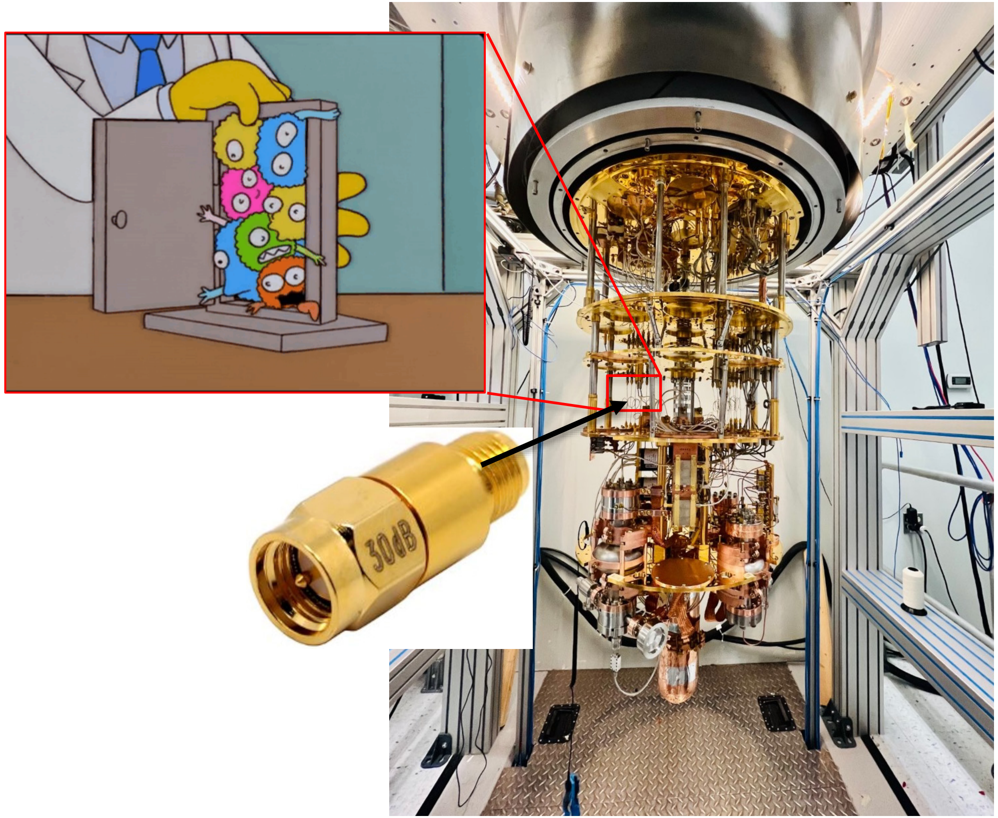


Image from: 20th Century Fox

SRF Cavity in ~~Liquid Helium~~ Dilution Refrigerator

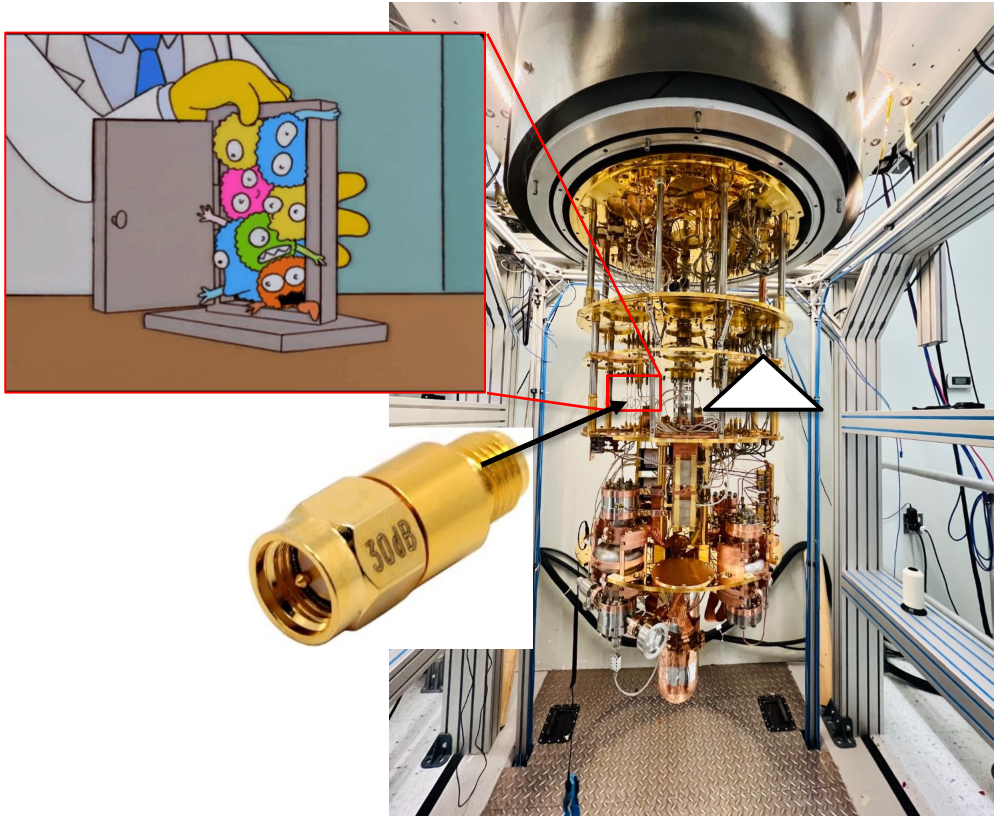
- Are our SRF-based qubits protected from thermal photons in a dilution refrigerator at 20 mK?
- We still need to be very careful – for example, the RF input lines can be low impedance connection to room temperature that can transport thermal photons into our nice cold cavity
- Cold attenuators on the input line will help block thermal photon
- We can increase the input power to still have a strong signal at the cavity even with the attenuation



Images from: 20th Century Fox, Amazon

SRF Cavity in ~~Liquid Helium~~ Dilution Refrigerator

- We also have to be careful with the transmitted power line
- If we send a few photons to room temperature, they'll get washed out by thermal photons
- Cold amplifiers will raise the transmitted power signal above the thermal background



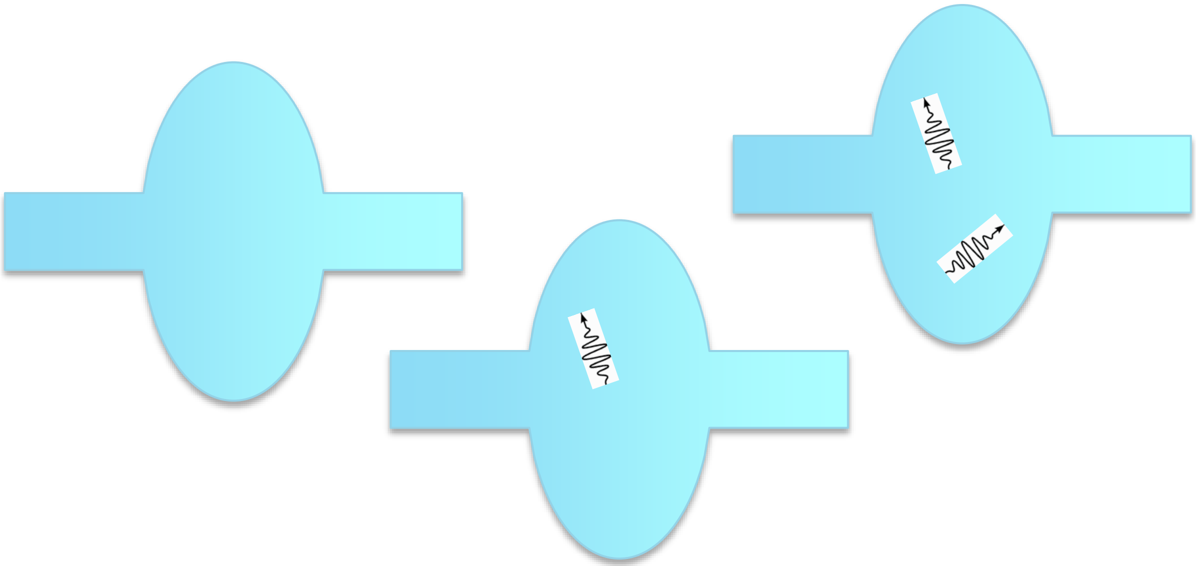
Images from: 20th Century Fox, Amazon

Fermilab

SRF 2023 GRAND RAPIDS

Nonlinearity

- We still don't have a qubit yet
- Need to distinguish different quantum states
- E.g. having 0, 1, or 2 photons in the cavity looks really similar to our diagnostics



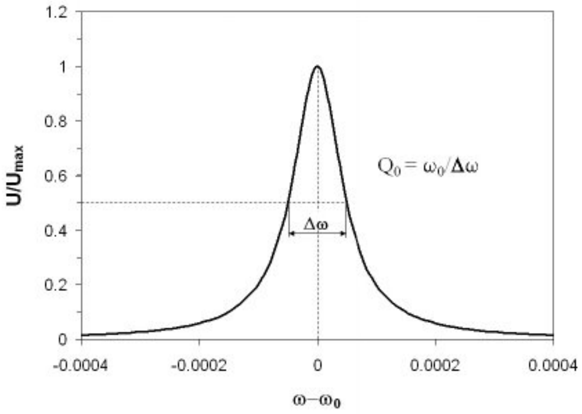
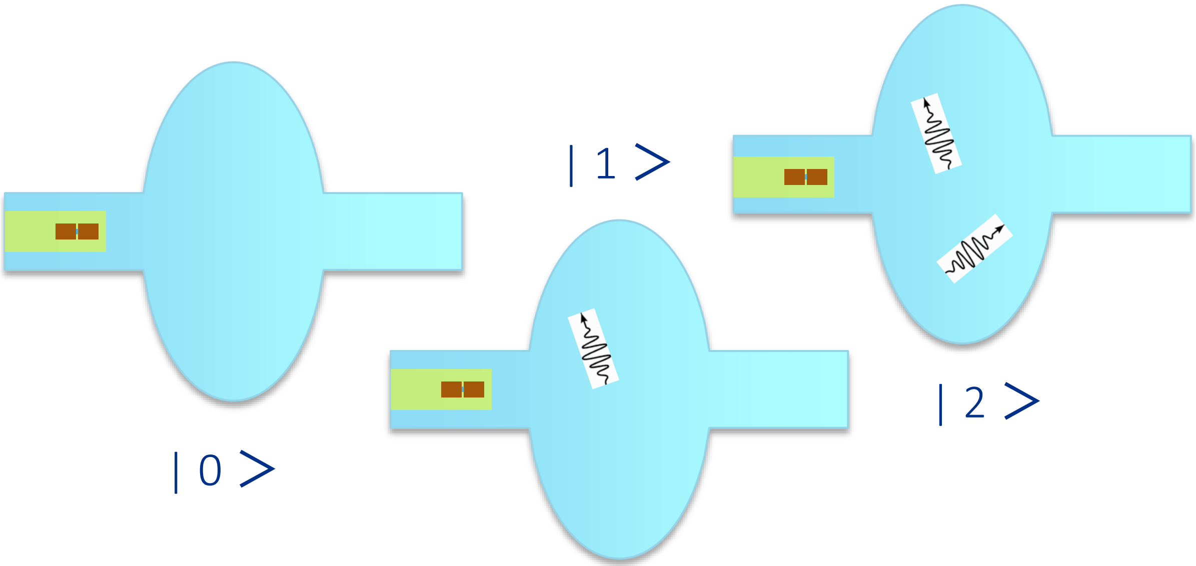
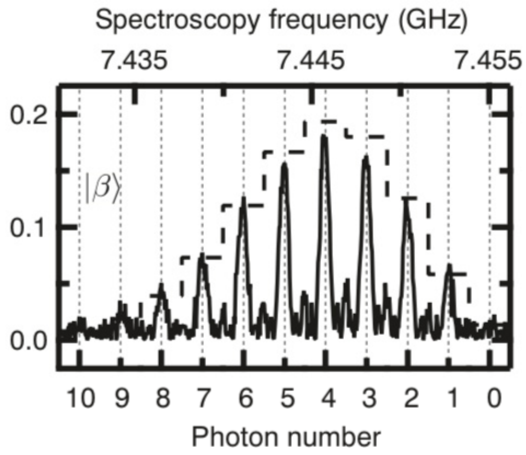


Image from: G. Ciovati

Nonlinearity

- Now let’s add a nonlinear element: a Josephson junction! (aka JJ)
- Frequency of readout mode is now dependent photons in storage mode
- Even better: it’s a quantum non-demolition (QND) measurement
- Can use multiple modes as multiple qubits, and entangle their states





B. Vlastikas, *Science*, Vol 342, Iss 6158, pp. 607-610 (2013).

Photos from: Disney, BlueFors

Quantum Computing: Surface Treatment of SRF Cavities in the Quantum Regime

Can we translate high Q expertise in SRF cavities to the 'quantum regime'?

Can we translate high Q expertise in SRF cavities to the ‘quantum regime’?

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- **First question:** What is the cause of the low field Q slope and what happens with Q as we decrease the field further?

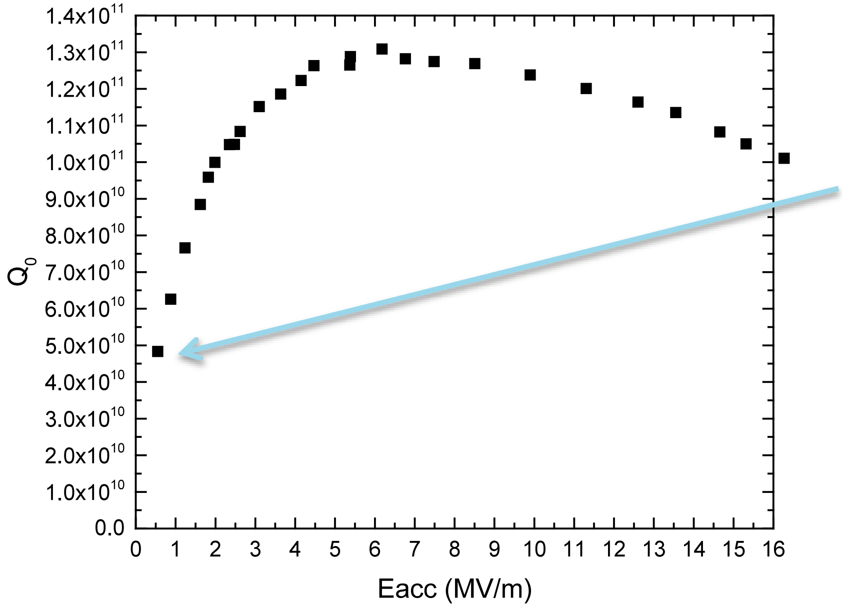
Can we translate high Q expertise in SRF cavities to the 'quantum regime'?

- **First question:** What is the cause of the low field Q slope and what happens with Q as we decrease the field further?

- **Second question:** What happens at lowest T < 20 mK and at low photon numbers?

Low field Q slope

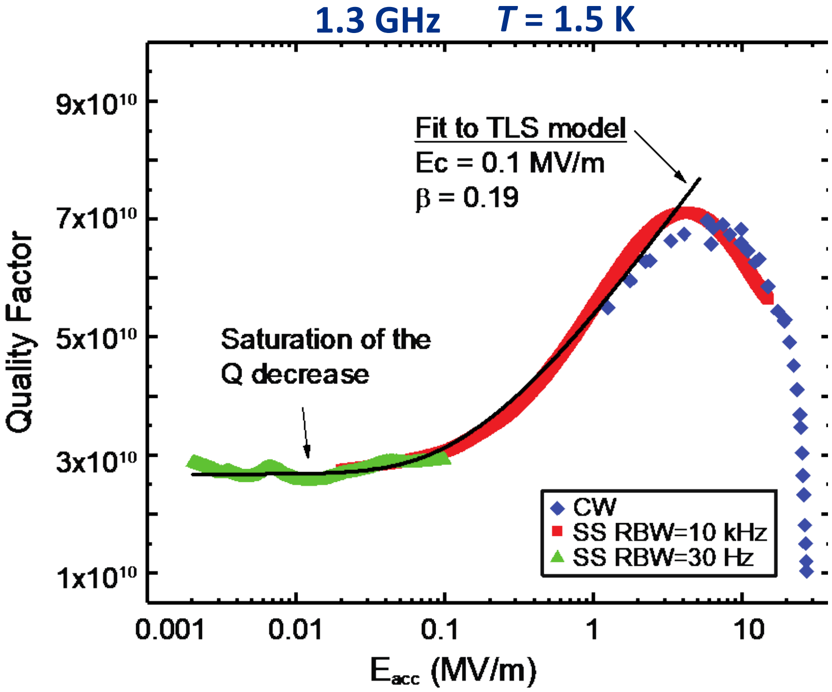
The ultralow field and temperature limit was not explored it in SRF before as it is inconsequential for accelerator applications



Where does the "low field Q slope" end?

What is the Q at single-photon field levels?

First experiment: extend the measured fields to record low fields



Good news: low field Q saturates at Q > **3 x 10^{10}**

Now measured down to <N> < 1000 photons

A. Romanenko and D. I. Schuster, *Phys . Rev. Lett.* **119**, 264801 (2017)

What is the effect of surface treatments on low field Q?

TABLE I. Summary of results for investigated 1.3 GHz elliptical shape cavities.

		R_s (nΩ)		ΔR_s (nΩ)	TLS fit	
Cavity	Treatment	5 MV/m	< 0.001 MV/m		E_c(MV/m)	β
AES012	Bulk EP	2.7	9.0	6.3	0.19	0.38
AES012	+100 nm oxide by anodizing	5.0	17.0	12.0	0.02	0.25
AES012	+EP 5 μm	3.0	7.0	4.0	0.19	0.38
AES014	Bulk EP + 120 °C 48 hrs	2.6	8.6	6.0	0.14	0.41
AES015	N infusion 800/120 °C 48 hrs	2.0	5.2	3.2	0.21	0.33
AES015	N infusion 800/160 °C 48 hrs	1.8	4.4	2.6	0.18	0.29
RDTTD004[a]	N doping + condensed 10^{-4} Torr of N_2	1.5	6.6	5.1	0.09	0.28
AES011	800 °C 2 hrs +120 °C 48 hrs	1.4	5.5	4.1	0.17	0.35
AES011	N infusion 800/160 °C 96 hrs	2.3	5.2	2.9	0.11	0.26
AES016[a]	800 °C 2 hrs +120 °C 48 hrs	1.7	5.6	3.9	0.10	0.28
PAV008[b]	800 °C 3 hrs +120 °C 48 hrs	9.8	17.0	7.2	0.12	0.37
PAV010	N infusion 800/120 °C 48 hrs	2.1	6.7	4.6	0.26	0.35
PAV010	N infusion 800/200 °C 48 hrs	6.6	10.8	4.2	0.20	0.42

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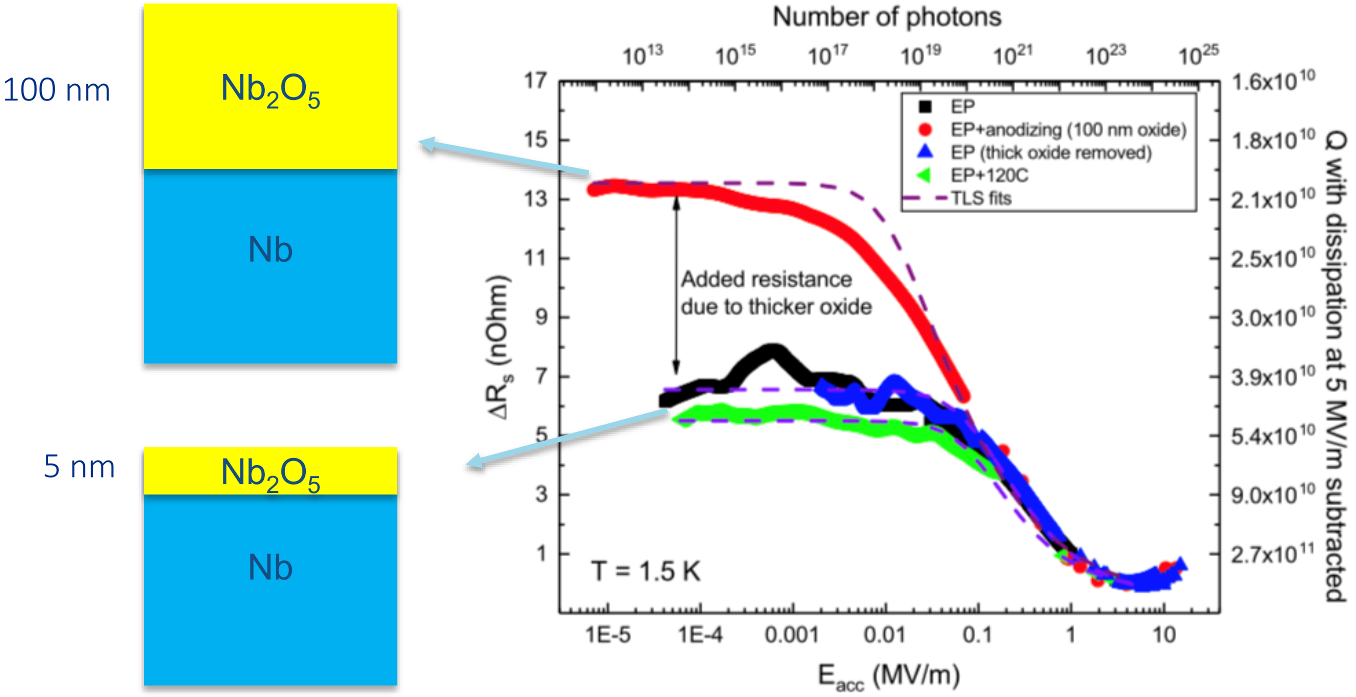
Changes within penetration depth have little effect

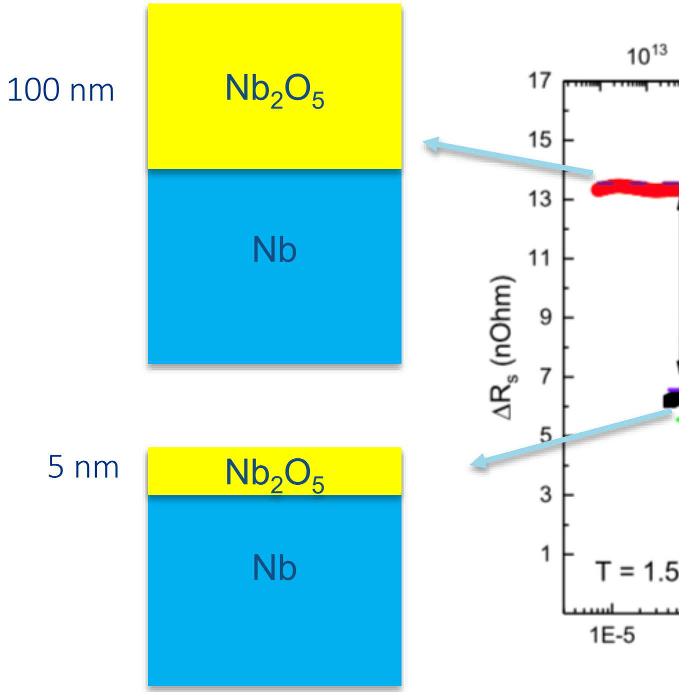
Oxide growth/change -> strong increase in very low field dissipation

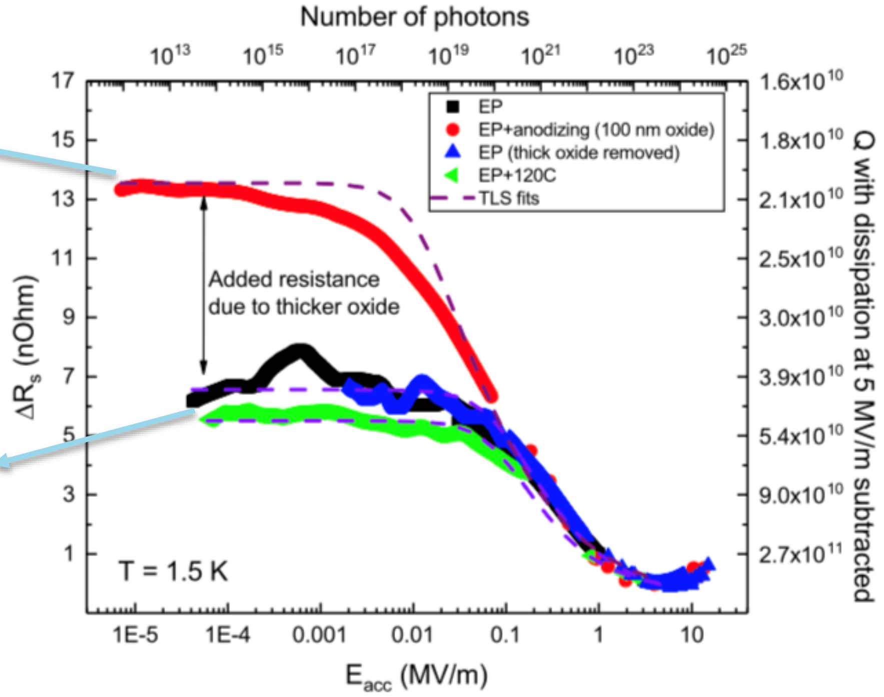
Growing natural niobium oxide → low field Q degrades



A. Romanenko and D. I. Schuster, *Phys . Rev. Lett.* **119**, 264801 (2017)

Growing natural niobium oxide → low field Q degrades





A. Romanenko and D. I. Schuster, *Phys . Rev. Lett.* **119**, 264801 (2017)

Growing natural niobium oxide →
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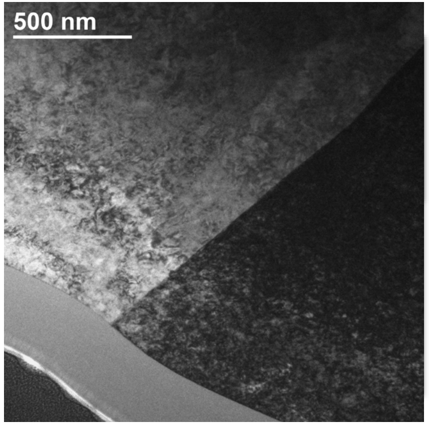
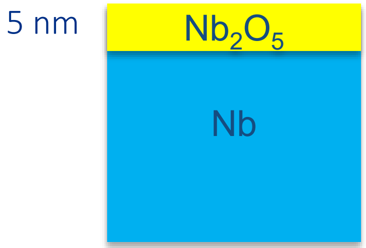
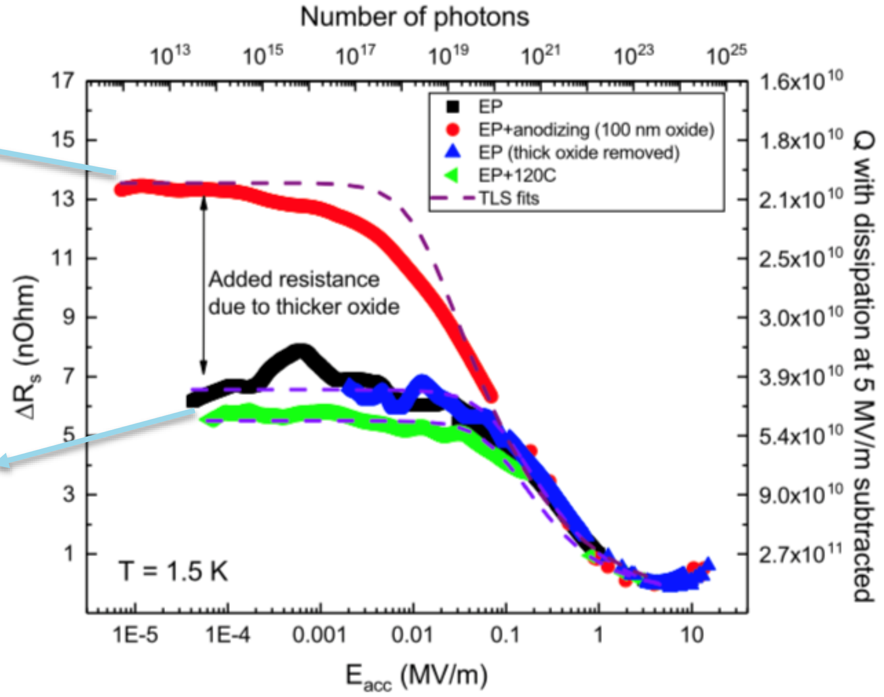


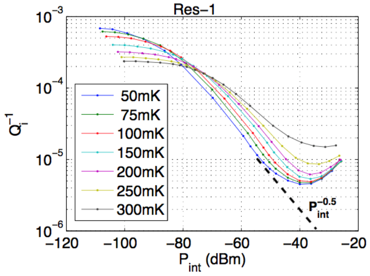




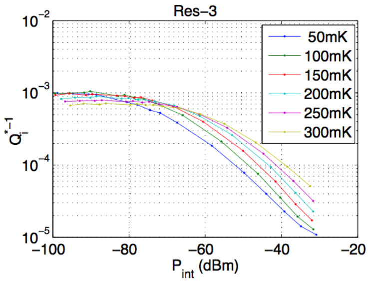
A. Romanenko and D. I. Schuster, *Phys . Rev. Lett.* **119**, 264801 (2017)

Fermilab SRF 2023 GRAND RAPIDS

From 2D resonator world → low-field increased losses

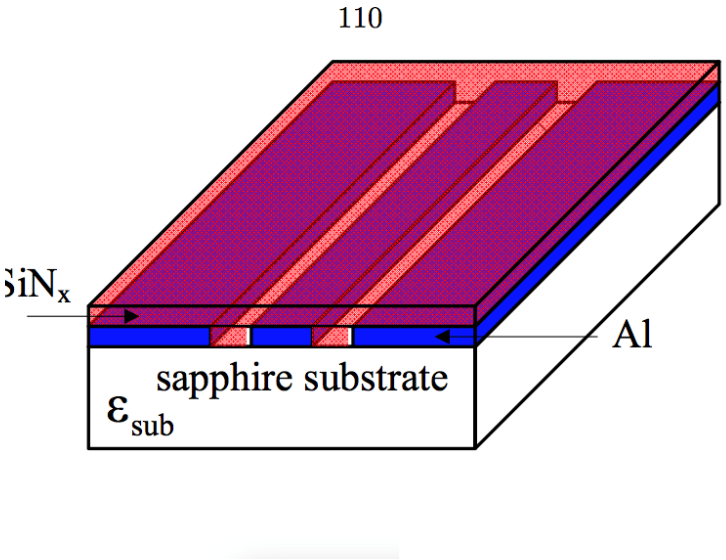


(a)



(c)

Two level systems in the dielectric as a cause

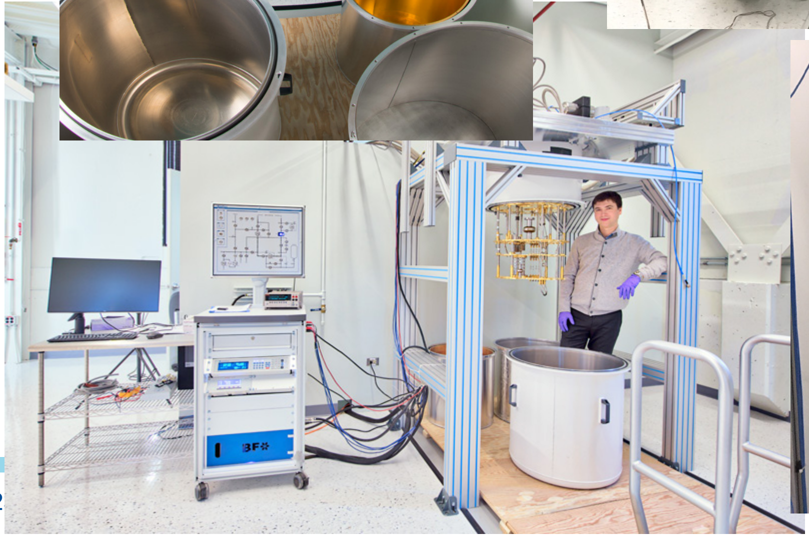


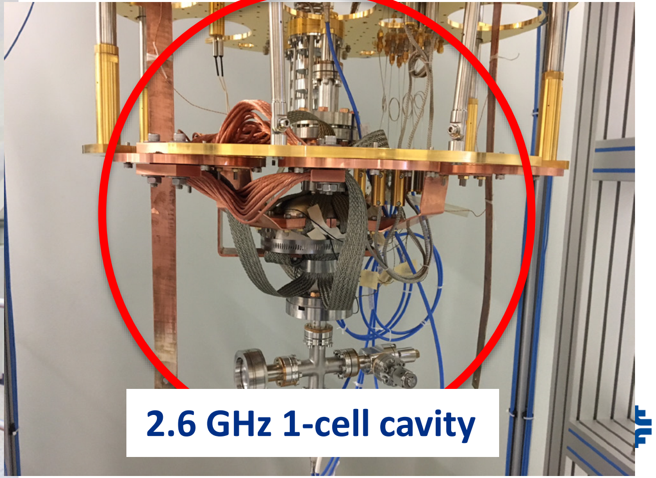
J. Martinis et al, *Phys. Rev. Lett.* **95**, 210503 (2005)

J. Gao, PhD Thesis, Caltech, 2008

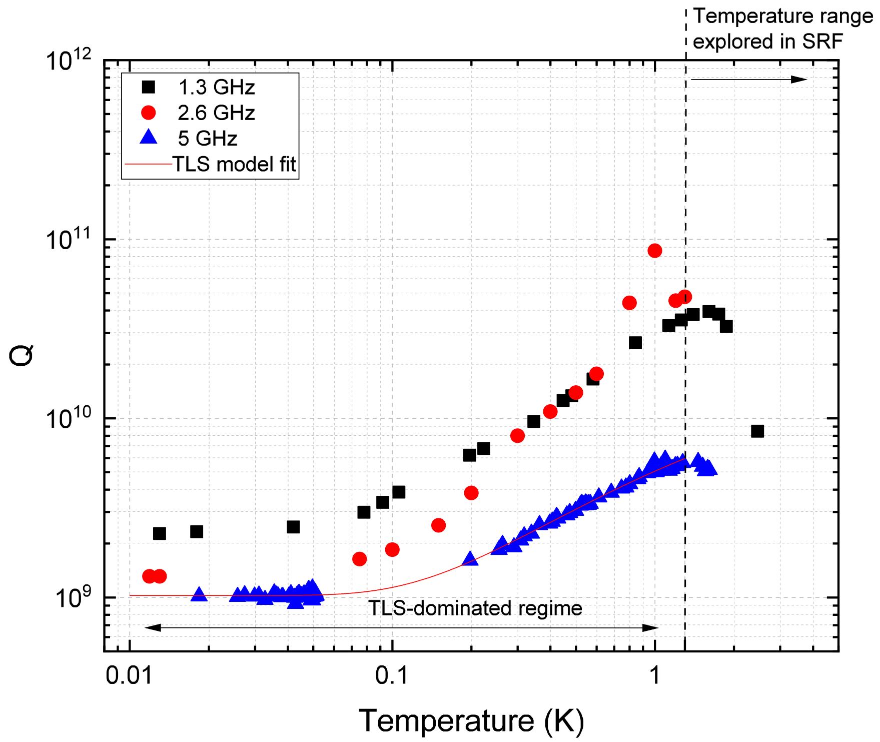
J. Zmuidzinas, *Annu. Rev. Condens. Matter Phys.* 2012

What happens in the “quantum regime”? (T < 20mK, low photon number)


BF

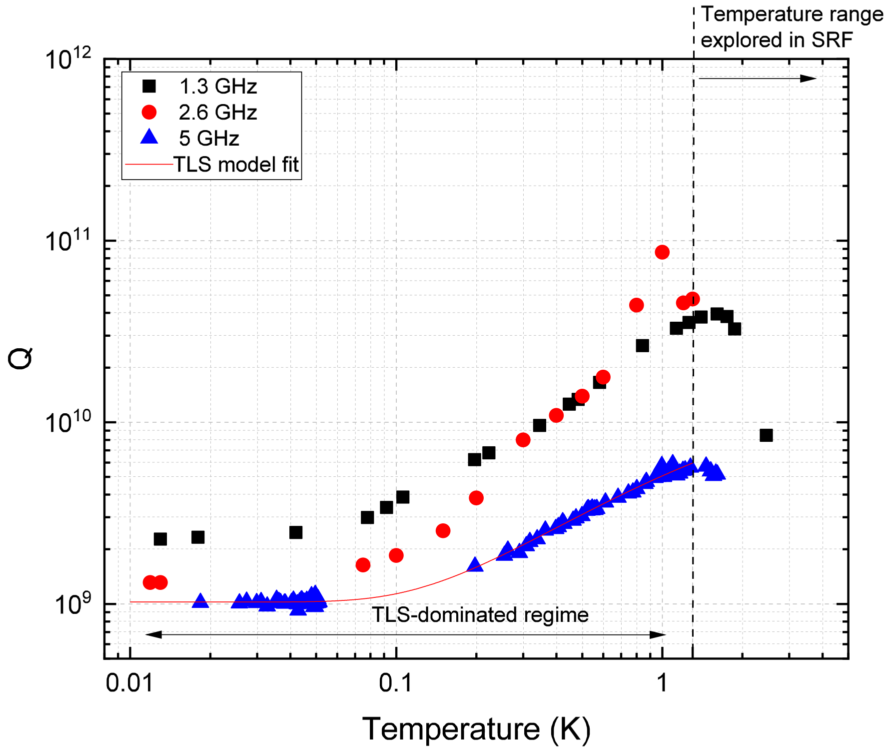

2.6 GHz 1-cell cavity

Record high Q in quantum regime at first run



A. Romanenko, R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Posen, A. Grassellino, arXiv:1810.03703

Material treatment to suppress TLS dissipation



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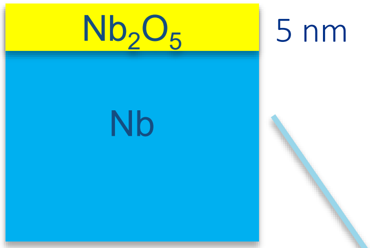

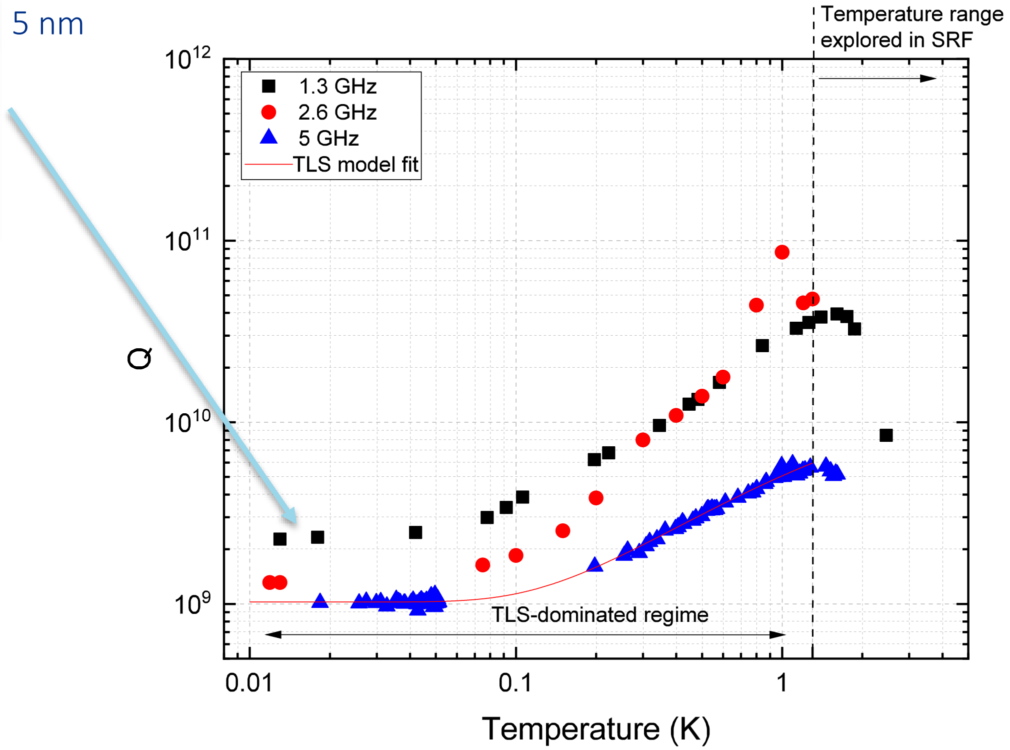

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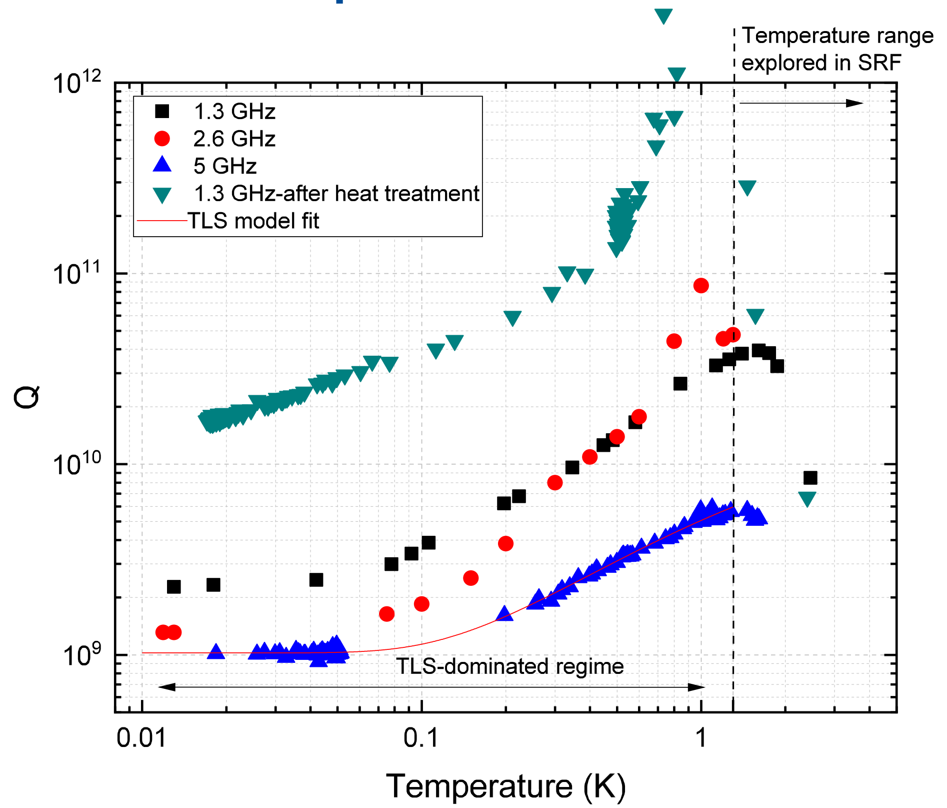

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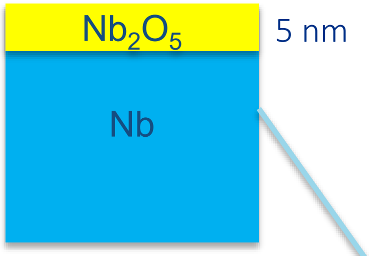

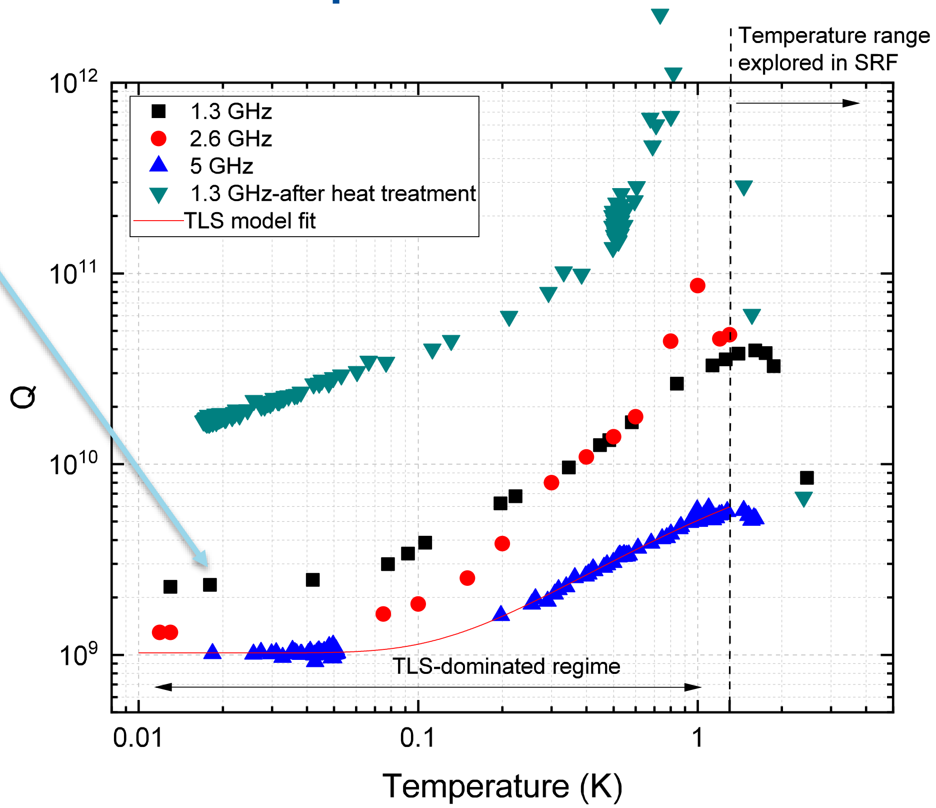

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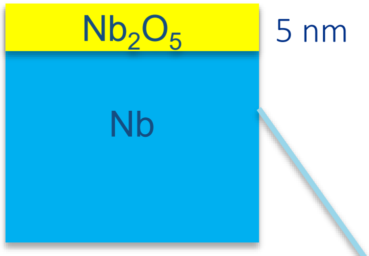

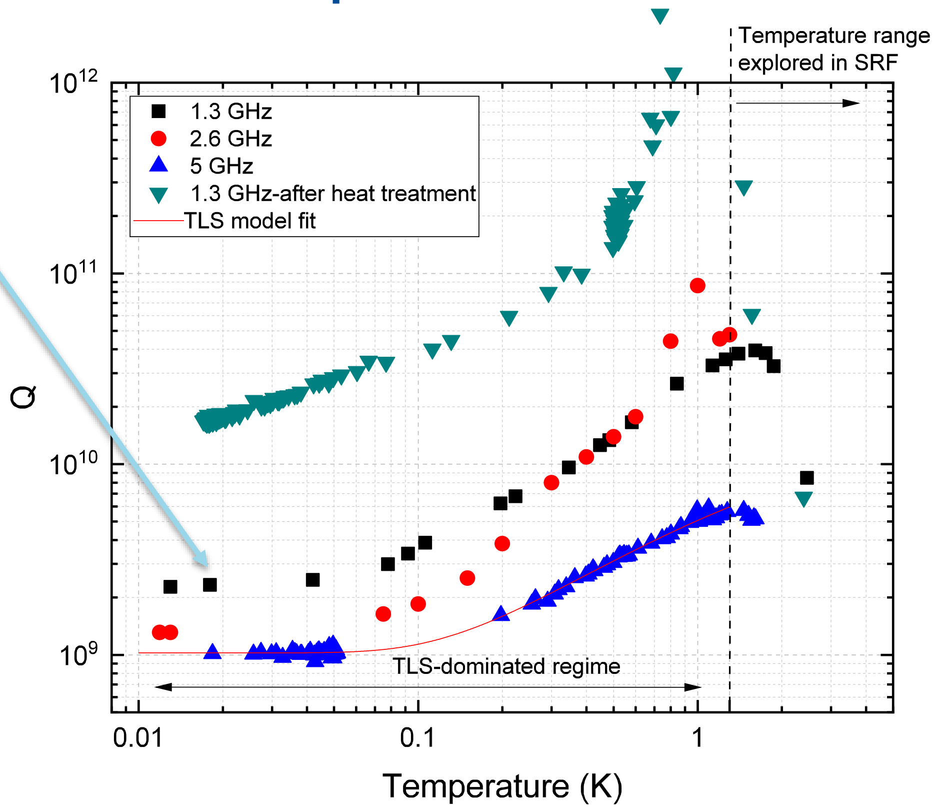

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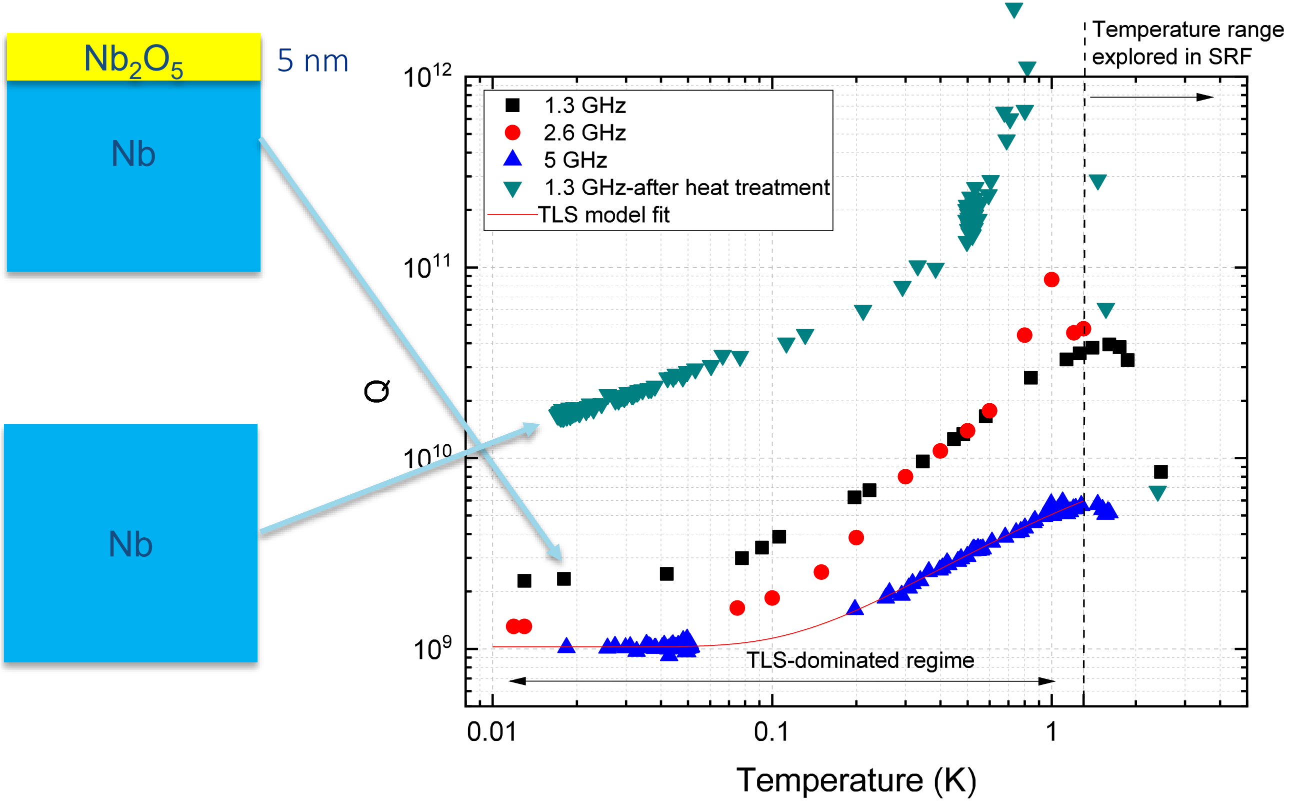
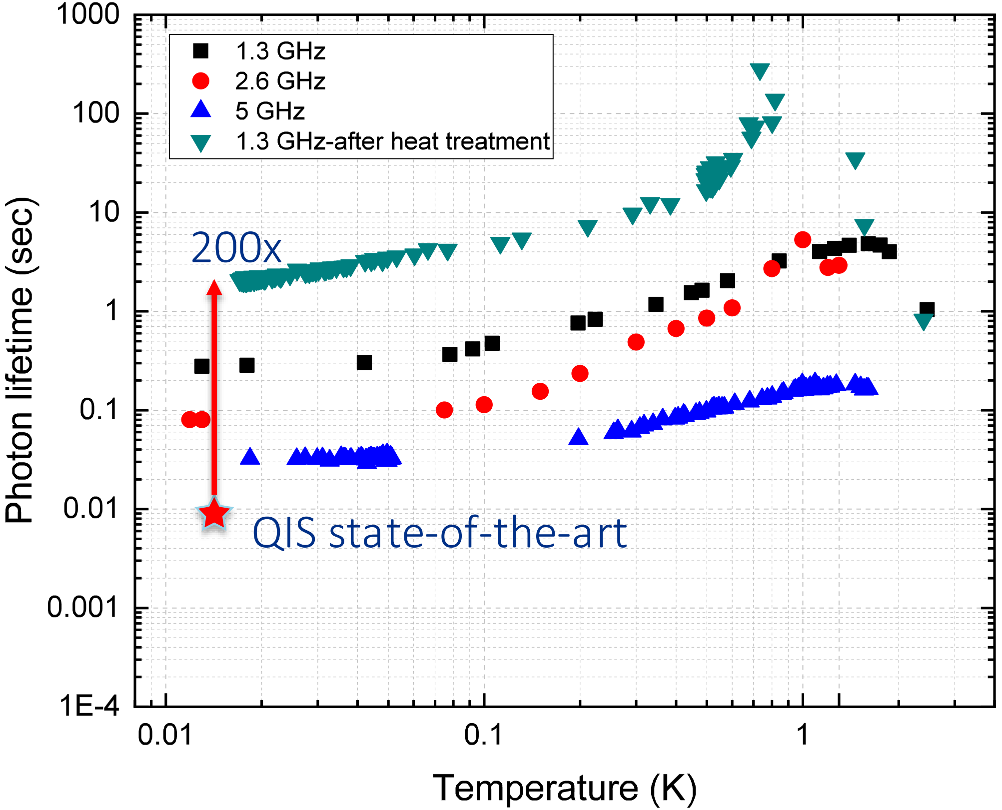


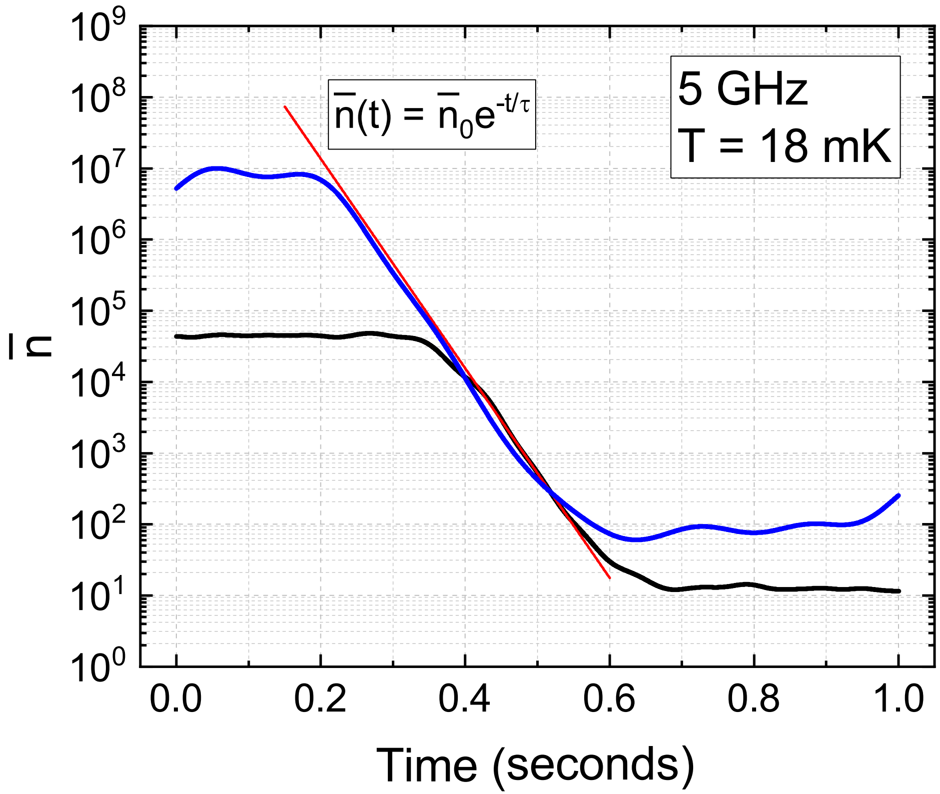
A. Romanenko, R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Posen, A. Grassellino, arXiv:1810.03703

Record high photon lifetimes achieved



A. Romanenko, R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Posen, A. Grassellino, arXiv:1810.03703

Decays show no Q(n) dependence



Quantum Sensors: “Beyond-the-Standard-Model” Physics

Searching for Tiny Signals with SRF Cavities

- We’ve done a lot of work relevant to studying tiny signals
  - Suppressed thermal photons, achieved high Q at mK temperatures and small photon numbers, developed quantum tools for studying single photon signals
- It turns out that this is useful for more than just quantum computing
- High energy physics wants this type of thing for detectors
- That’s right! SRF cavities have long been a means of accelerating particles so that people with detectors can do science with the beams – but we can use the cavities themselves as high sensitivity detectors
- What high energy physics motivation is there to look for small microwave signals?

Image from: BestClipArt

Searching for Tiny Signals with SRF Cavities

- The Standard Model of Physics describes our best understanding of the universe based on experimental evidence (e.g. from colliders)
- Beyond-the-standard-model (BSM) physics theories address questions not addressed by the Standard Model, like what is the origin of dark matter, and why is there so much more matter than antimatter in the universe?
- Theorists have developed a number of ideas for BSM physics that would result in a signal that is detectable but still small enough that it wouldn't have yet been observed

Image from: BestClipArt

Searching for Tiny Signals with SRF Cavities

- Theories of BSM physics are designed to solve key problems (they aim to be “well-motivated”) but there is so little information to base theories on that many possibilities can fit the data
- BSM theories sometimes involve many orders of magnitude of parameter space to search through (e.g. axions)
- High value experiments in BSM physics **exclude** a wide range of parameter space with high sensitivity (they “search wide and deep”)
- Exclusion is a good result! Don’t expect to find something, and in fact expect NOT to! If you see something, your first instinct should be that it’s probably a false signal

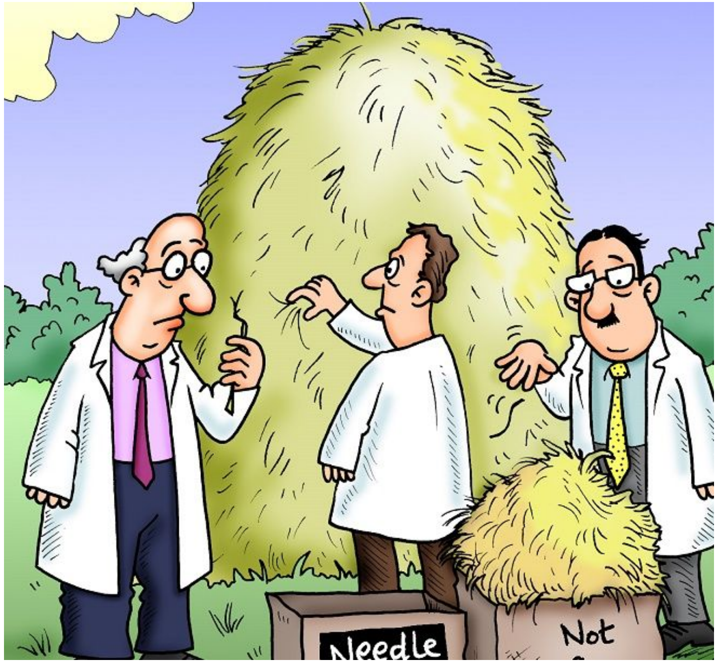
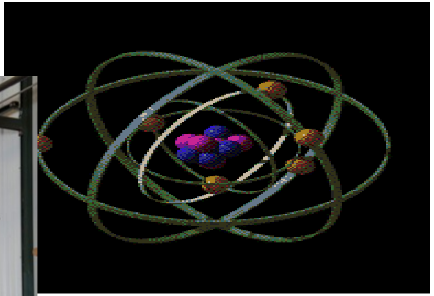


Image from: triz.co.uk

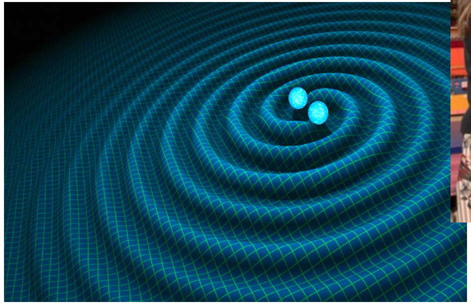
Quantum Sensing: new windows into fundamental physics

Dark Matter

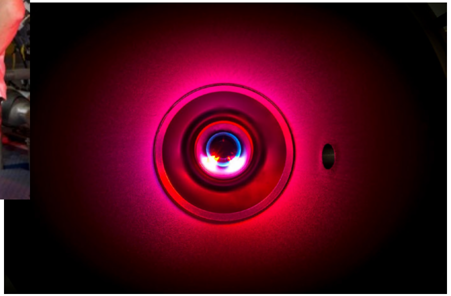
Fermilab DarkSRF experiment



Precision Measurements



Gravitational Waves

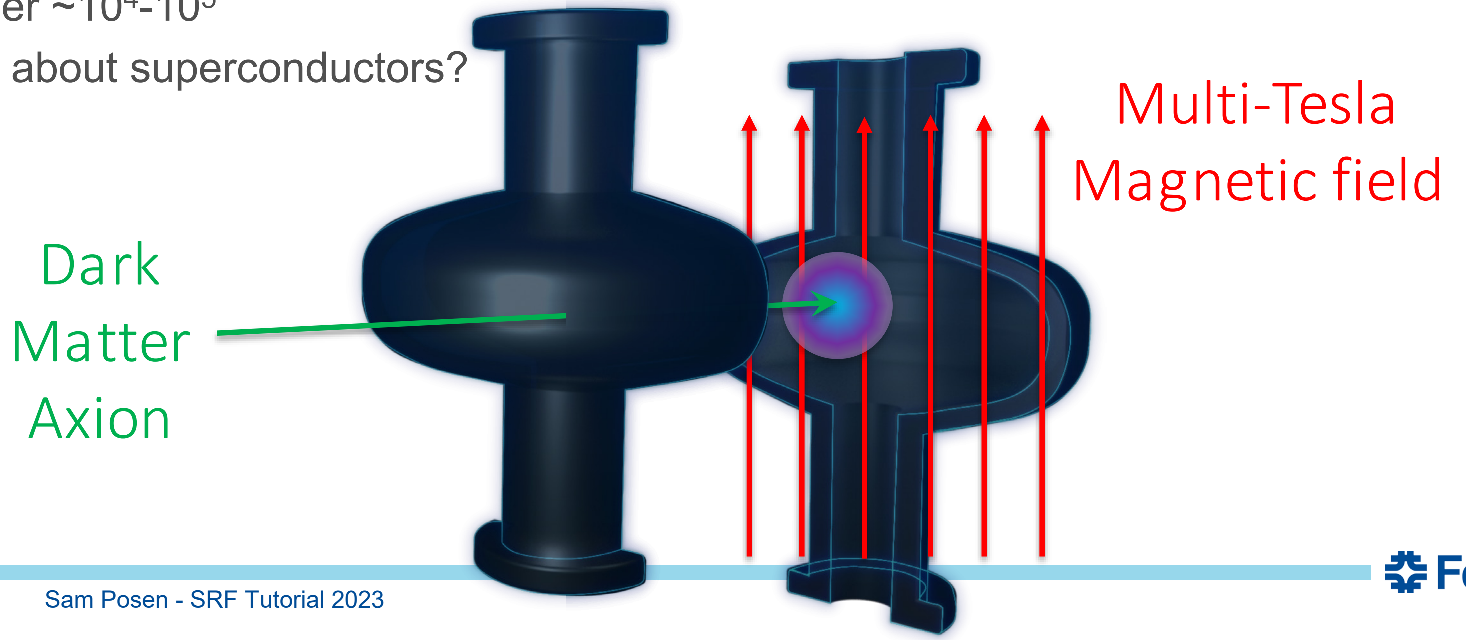


Quantum Physics

Quantum devices are extremely sensitive to small effects – sensors!
New ways to search for dark matter?
Searches for new BSM particles?
Precision tests of the SM or of QM?
New ways to look for gravitational waves?

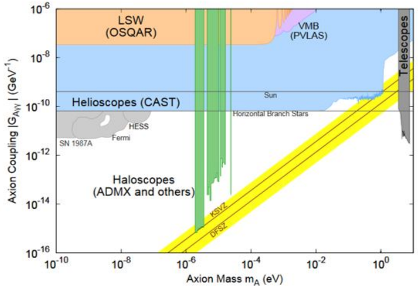
Conversion of Axion in Magnetic Field to Microwave Photon

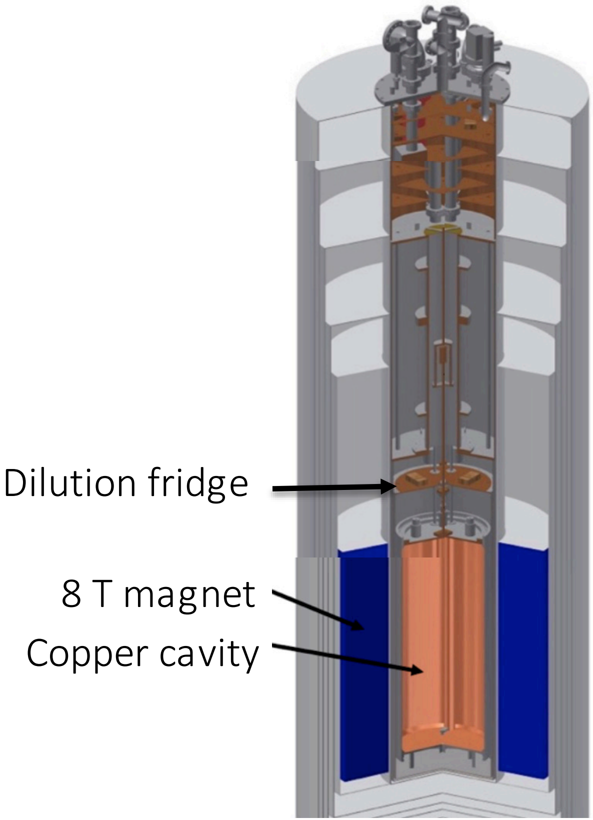
- Axion haloscope: axion converts to photon in magnetic field; if cavity frequency matches axion mass it can detect it
- Sensitivity improves with higher magnetic field, higher cavity Q_0
  - **Need a cavity that maintains high Q_0 in a multi-tesla magnetic field**
  - Copper ~10^4-10^5
  - What about superconductors?



Current State of the Art Axion Searches

- Operating haloscopes like ADMX use normal conducting cavities (typically copper)
- They have reached desired exclusion limit for a small range of masses, but a very wide mass range remains
- Scan rate scales as $dv/dt \propto B^4V^2Q/2T_{sys}$
  - B (magnetic field), V (cavity volume), Q (cavity quality factor), T_{sys} (system noise temperature)
- Q improvement is promising path to improving rate of scanning substantially
- **Nb_3Sn is well suited due to its very high upper critical field, ~30 T** (for comparison: Nb ~0.4 T, NbTi ~15 T)

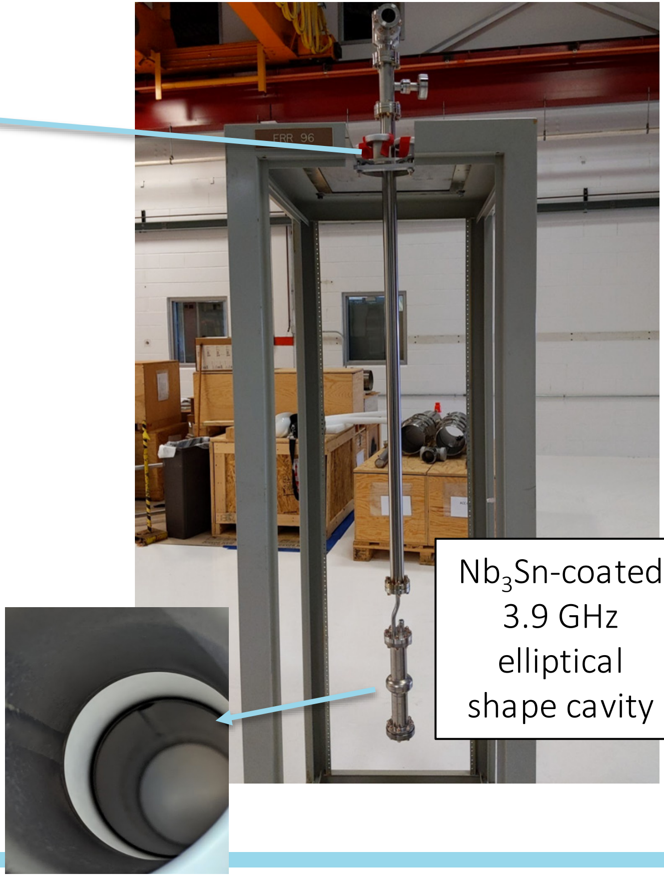




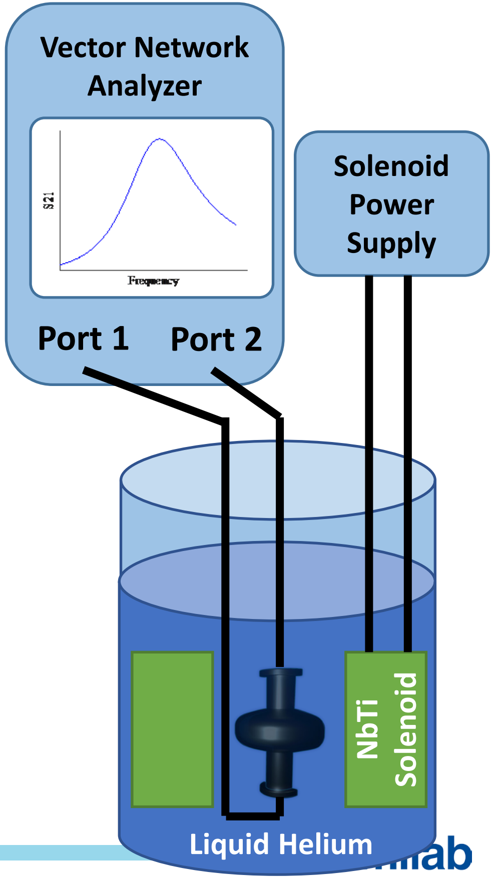
From ADMX

https://arxiv.org/pdf/1405.3685.pdf & https://indico.cern.ch/event/606690/contributions/2655459/attachments/1498473/2332791/Axion_Overview_TAUP_2017_Final.pdf

First Test – Put Existing Cavity into 6 T Field and Measure Q_0

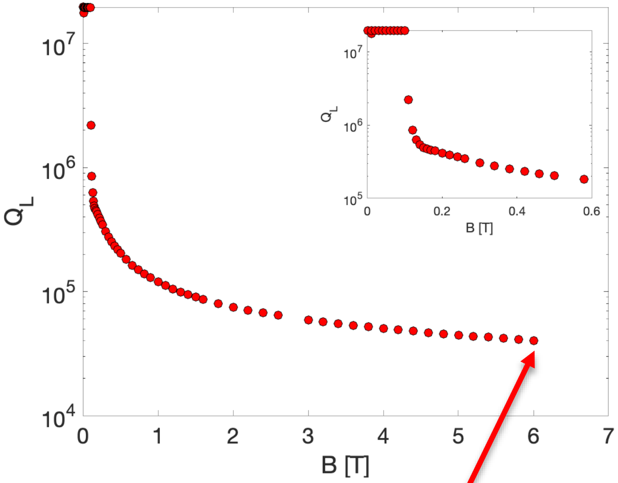


Nb$_3$Sn-coated 3.9 GHz elliptical shape cavity

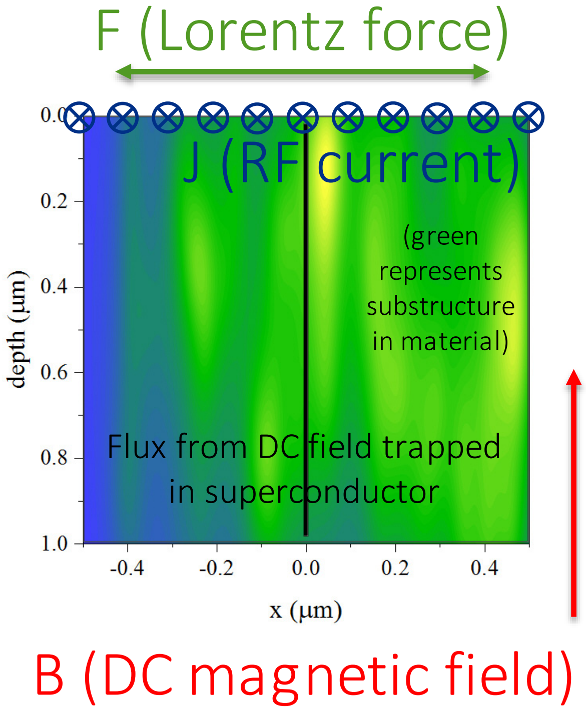


Results from First Cavity (Accelerator Type Cavity)

- Q_0 ~4x10^4 at 6 T
- Q_0 lowered due to flux dissipation – Lorentz force **F ~ J × B**
- Not expecting best possible results from first test due to geometry – cavity walls highly perpendicular to applied field



Q_0 of 4x10^4 at 6 T, 4.2 K, 3.9 GHz



M. Checchin and A. Grassellino, "Vortex Dynamics and Dissipation under High-Amplitude Microwave Drive," Phys. Rev. Applied *14, 044018 (2020)*

M. Checchin et al. "Frequency dependence of trapped flux sensitivity in SRF cavities," Appl. Phys. Lett. *112, 072601 (2018)*

Flux motion analysis by Mattia Checchin
Details in arXiv:2201.10733 (2022)

Figure of Merit

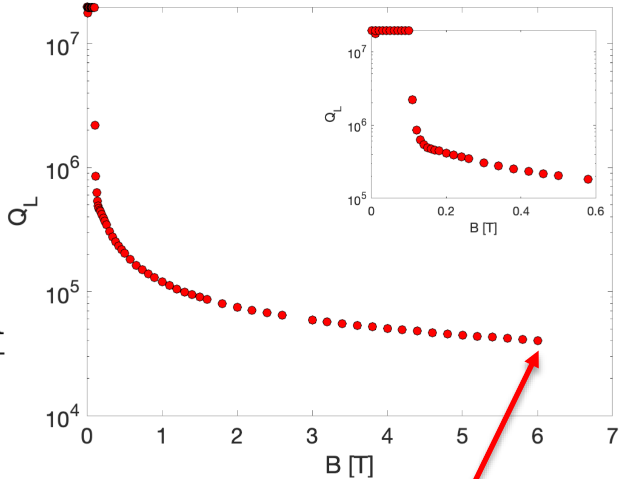
$$P_c = \frac{1}{2\mu_0^2}\int R_{fl} B_s^2 \, dA.$$

$$Q_0 = \frac{\omega W}{P_c},$$

$$\mathrm{FoM} = \frac{\int \mathbf{B}\cdot\hat{\mathbf{n}}\, |\mathbf{B}_{\mathrm{RF}}|^2 \, dA}{B_0 \int |\mathbf{B}_{\mathrm{RF}}|^2 \, dV}$$

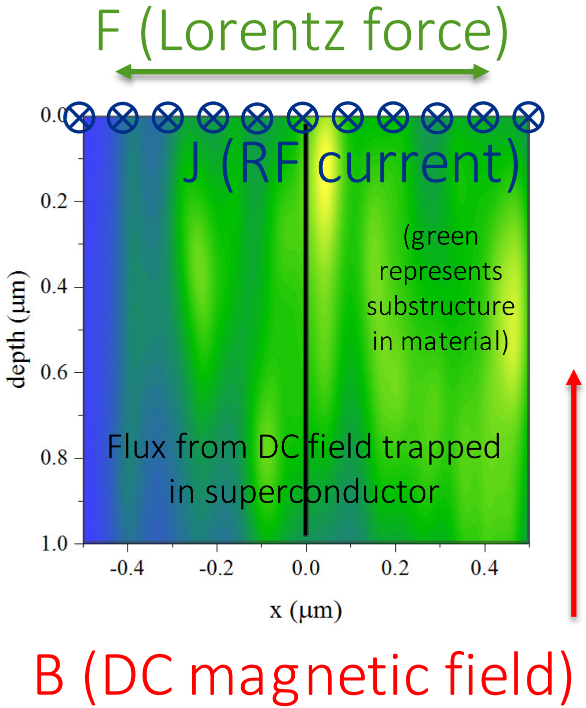
Different behavior than copper cavities – specialized superconducting cavity geometry will be different

Details in S. Posen et al., arXiv:2201.10733 (2022)



Q_0 of 4x10^4 at 6 T, 4.2 K, 3.9 GHz

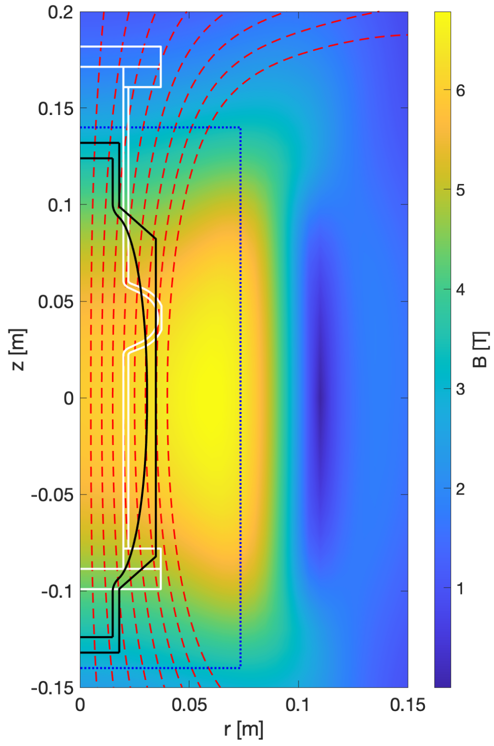
M. Checchin et al. "Frequency dependence of trapped flux sensitivity in SRF cavities," Appl. Phys. Lett. *112, 072601 (2018)*



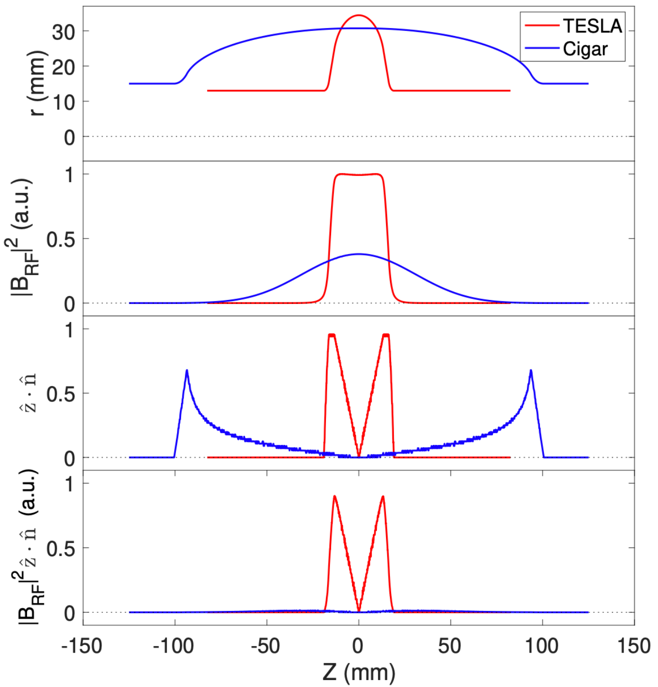
Flux motion analysis by Mattia Checchin

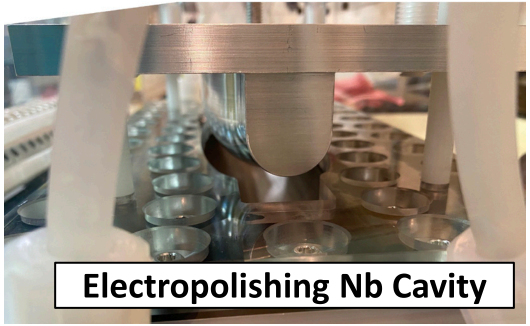
Details in arXiv:2201.10733 (2022)

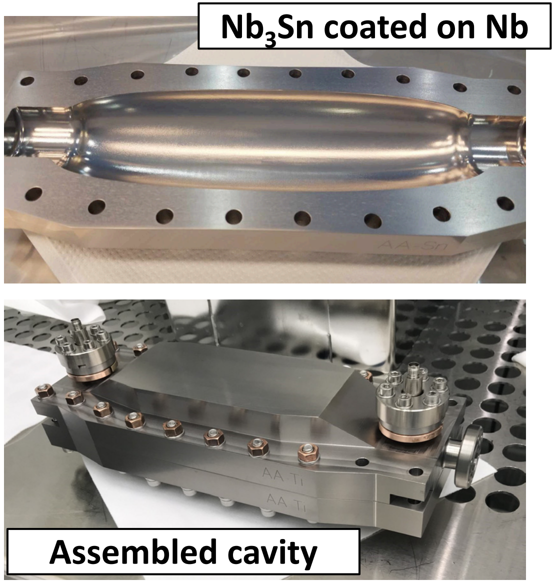
Second Cavity – Specialized Geometry



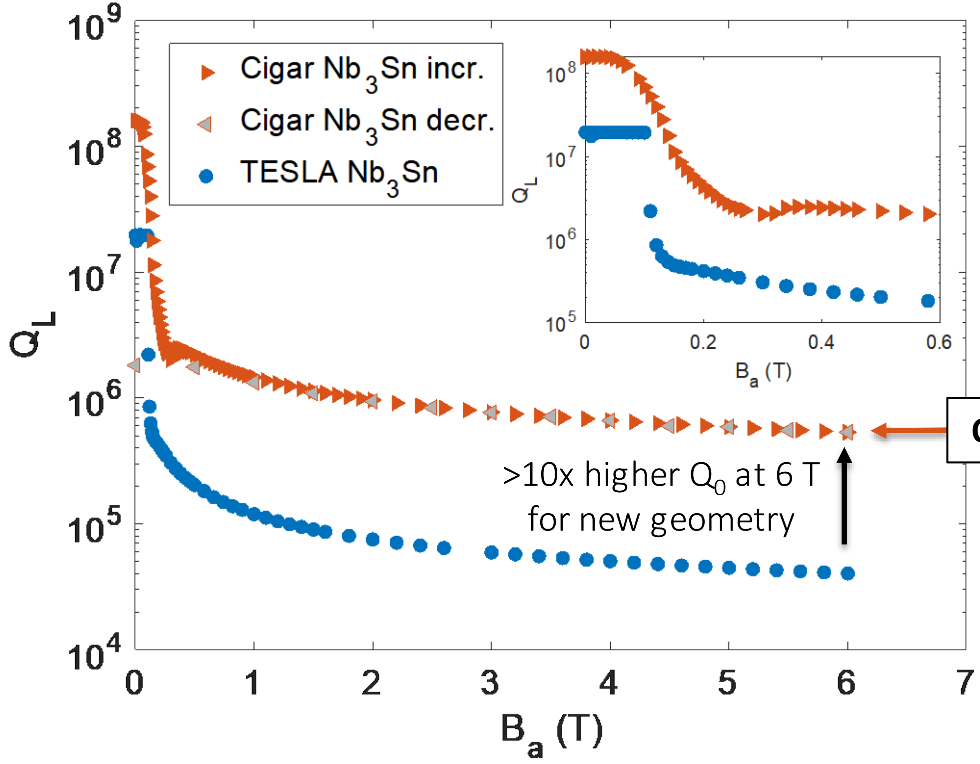
- Second cavity designed to minimize $\hat{\mathbf{z}} \cdot \hat{\mathbf{n}} |\mathbf{B}_{\mathrm{RF}}|^2$







Results of Second Cavity

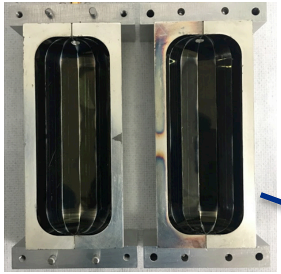


Q_0 of $5x10^5$ at 6 T, 4.2 K, 3.9 GHz

Details in '**Measurement of high quality factor superconducting cavities in tesla-scale magnetic fields for dark matter searches**'
S. Posen et al., arXiv:2201.10733 (2022)

Comparison to Previous Results

- Challenging to compare to other cavities due to different frequencies and fields, but clearly much better than copper, and among the highest Q_0 measured in multi-tesla fields
- Superconducting cavities from other groups (table) also show promising results – SRF cavities have potential for axion searches



Source	Material	*f* (GHz)	B_a (T)	*T* (K)	Q_0
This work	Nb_3Sn	3.9	6.0	4.2	$(5.3\pm0.3)\times10^5$
[1]	NbTi/Cu	9.08	5	4.2	2.95×10^5
[2]	Nb_3Sn	9	8	4.2	6×10^3
[2]	REBCO	9	11.6	4.2	7×10^4
[3]	YBCO	6.93	8.0	4.2	3.2×10^5

[1] D. Alesini *et al.*, "Galactic axions search with a superconducting resonant cavity," *Phys. Rev. D*, vol. 99, no. 10, 101101, (2019).
[2] J. Golm *et al.*, "Thin Film (High Temperature) Superconducting Radiofrequency Cavities for the Search of Axion Dark Matter," 3–7, (2021).
[3] D. Ahn *et al.*, "Superconducting cavity in a high magnetic field," *arxiv:2002.08769*, (2020).

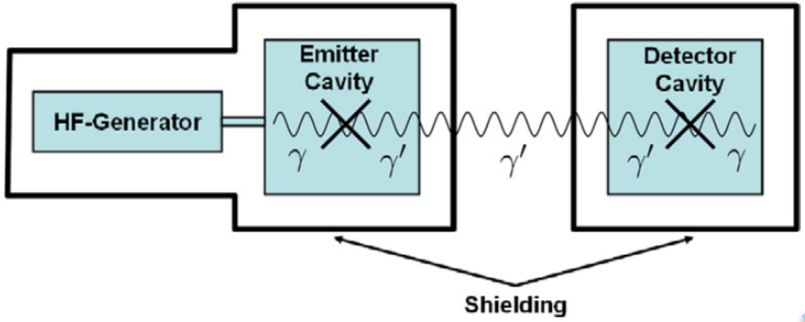
Recently reported Q_0 of 1e7 with HTS tapes, fixed frequency – not yet published to my knowledge

Dark Photon Search

S. R. Parker *et al.*, Phys. Rev. D 88, 112004 (2013)
J. Hartnett *et al.*, Phys. Lett. B 698 (2011) 346
J. Jaeckel and A. Ringwald, Phys. Lett. B 659, 509 (2008)

Q_{DET}, Q_{EM} < 10^5
so far used

Looking for hidden paraphotons

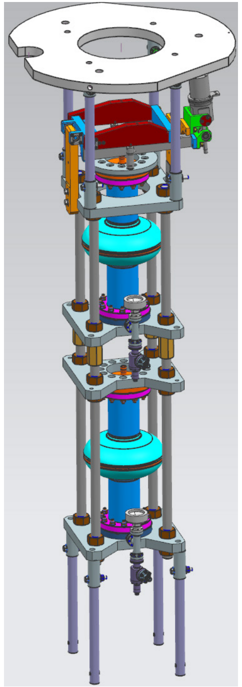


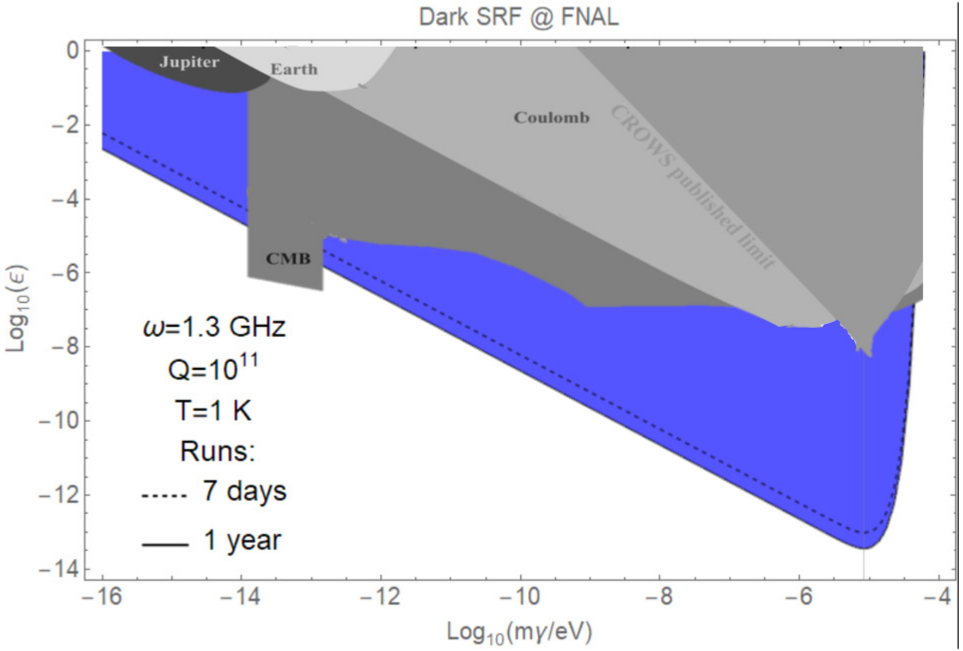
$$\frac{P_{DET}}{P_{EM}} = \chi^4 Q_{DET} Q_{EM} \left(\frac{m_{\gamma'} c^2}{\hbar\omega_\gamma}\right)^8 |G|^2$$

Q_{DET}, Q_{EM} > 10^{10} SRF can offer several orders of magnitude improvement in sensitivity to χ

"Dark SRF" experiment at Fermilab

- First search for dark photons with SRF cavities





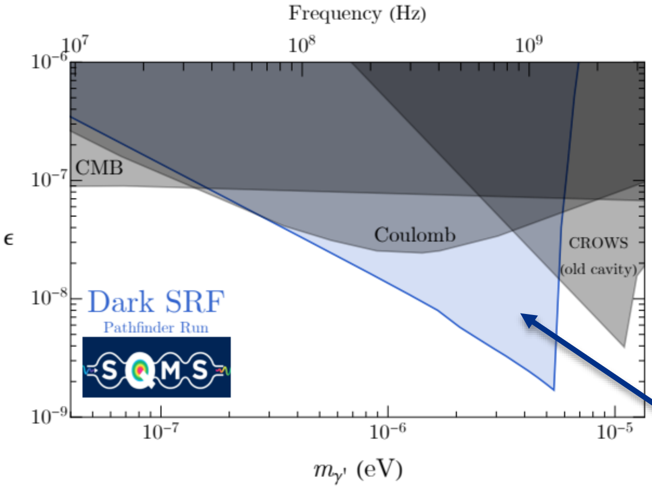
First test run has been accomplished

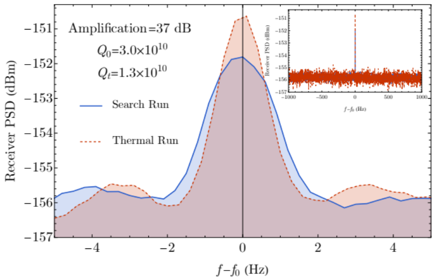
Dark SRF: Pathfinder Run has been successful

More in Bianca Giaccone's talk Thursday!

Everything worked!

- ✓ Design
- ✓ Tuner operation
- ✓ Microwave scheme for matching the frequencies
- ✓ New exclusion limits





Previously unexplored!

arXiv > hep-ex > arXiv:2301.11512

High Energy Physics - Experiment

[Submitted on 27 Jan 2023]

New Exclusion Limit for Dark Photons from an SRF Cavity-Based Search (Dark SRF)

A. Romanenko, R. Harnik, A. Grassellino, R. Pilipenko, Y. Pischalnikov, Z. Liu, O. S. Melnychuk, B. Giaccone, O. Pronitchev, T. Khabiboulline, D. Frolov, S. Posen, A. Berlin, A. Hook

Fermilab

SRF 2023 GRAND RAPIDS

Summary

Summary

- Nb_3Sn SRF cavities can operate several MV/m at >4 K with only a few watts of dissipation, within range of cryocoolers: enabling for industrial applications
  - Wastewater treatment, medical isotopes, extreme UV, cargo scanning, and more
- Nb SRF cavities can achieve high Q at tens of mK and small photon numbers: high coherence qubits for quantum computing are in development
- High Q SRF cavities can substantially enhance searches for beyond-the-standard-model physics
  - Axions, dark photons, gravitational waves

The **Fermilab SQMS Physics and Sensing group** is looking for a **graduate student/postdoc** interested to **join our group** and work on searches for new physics!

Fermilab Postdoc Opportunities

1. The Applied Physics and Superconducting Technology (APS-TD) Directorate is seeking a **postdoctoral Research Associate**. This individual will conduct cutting-edge research of both superconducting radiofrequency resonator cavities for accelerator applications as well as superconducting qubits for quantum information science through the use of **surface characterization techniques** as part of the Superconducting Quantum Materials and Systems (SQMS) center. They are expected to complete scientific publications based on their research. **Expertise in surface characterization is preferred, including: XPS, ARPES, ToF-SIMS and/or TEM.** The position is for a period of up to three (3) years, with the potential for extension considered on a yearly basis thereafter, and subject to continued funding.

   Contact Akshay Murthy, amurthy@fnal.gov, for more information.

2. The Applied Physics and Superconducting Technology Directorate seeks a motivated **postdoctoral Research Associate** to join the SRF Performance Frontier group. The successful candidate will lead **R&D efforts on the performance improvement of superconducting radio-frequency cavities**. They will pursue **novel processing techniques** of bulk niobium as well as deposition of various **thin films** on top of metallic substrates for high energy particle accelerating applications. The individual will couple materials science, SRF testing, and RF engineering to aid in the development of these treatments and processes.

   Contact Daniel Bafia, dbafia@fnal.gov, for more information.