DECEMBER 2, 2024

2024 NP Accelerator R&D PI Exchange Meeting

Argonne NATIONAL LABORATORY

A PRACTICAL Nb_3Sn CAVITY FOR ATLAS

TROY PETERSEN

Speaker: MIKE KELLY

YANG ZHOU

MARK KEDZIE

TOM REID

BEN GUILFOYLE

PAUL DAVIS

Fermilab

GRIGORY EREMEEV

BRAD TENNIS

SAM POSEN

RadiaBeam

SERGEY KUTSAEV

RONALD AGUSTSSON

ED SPRANZA

ALESSANDRO SCHILLACI

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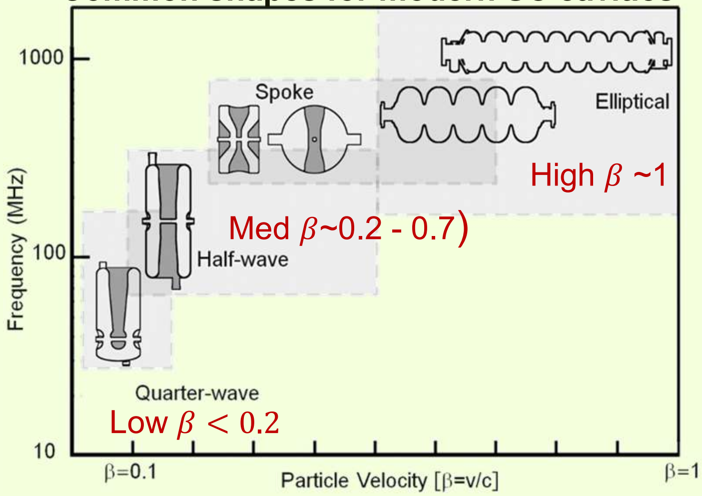
OUTLINE

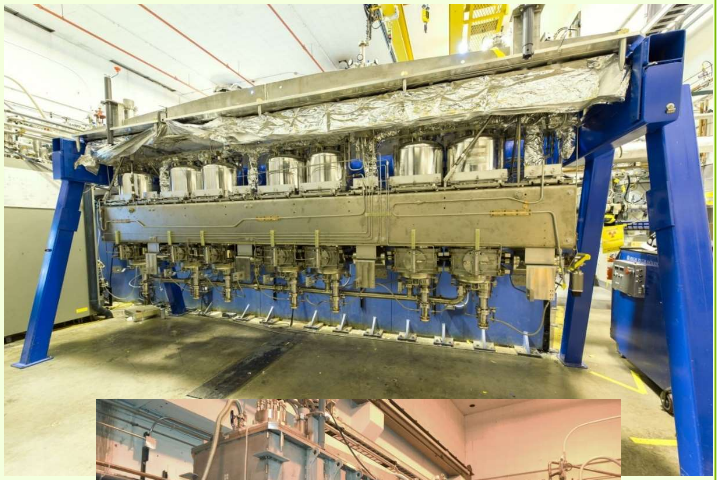
Our Aim is to Change the Way Ion Linacs Like ATLAS Are Built

Large niobium cavity sizes/shapes/operating modes derive directly from properties of niobium

Common shapes for modern SC cavities



ATLAS Quarter-wave (2014)

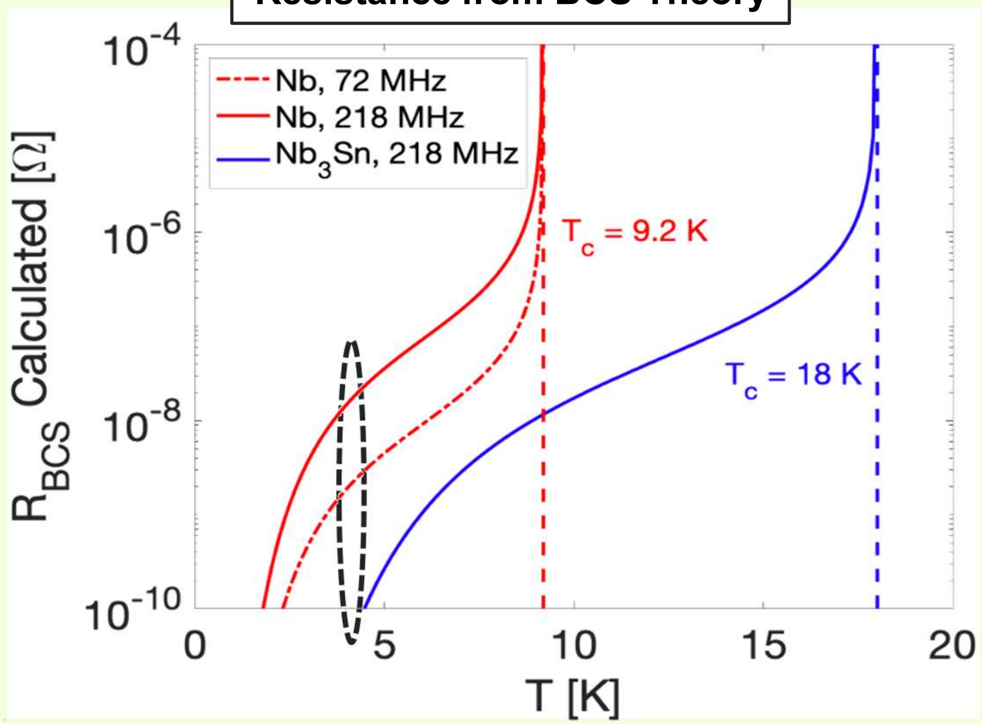


2014 ATLAS Energy and Intensity Upgrade Cryomodule

Nb_3Sn is Very Different From Niobium at Practical Cryogenic Temperatures

RF Heating into the 4.5 K He bath can be practically eliminated even at higher frequencies

Niobium and Nb_3Sn Resistance from BCS Theory



Nb_3Sn Can Enable Transformation Improvements for Ion Linacs

Approach is two-fold: (1) Smaller, higher frequency cavities (2) Coupling to new large cryocoolers

Nb_3Sn Quarter-wave

“10 W” Sumitomo Cryocooler

SUMMARY OF EXPENDITURES BY FISCAL YEAR (FY):

	FY22 ($)	FY23 ($)	Totals ($)
a) Funds allocated	619,000	639,000	1,258,000
b) Actual costs to date	548,915	516,965	1,065,880

***new FOA R&D funds for FY24-25 are of similar scale**

MAJOR DELIVERABLES AND SCHEDULE

Deliverable	Forecast Schedule	Status	Additional Comment
a) Coat 1st low-beta niobium cavity	March 2023	Complete June 2023	Re-coated and tested
b) Complete final design of 2nd cavity	June 2023	Complete June 2023	Adding gusset based on 218 MHz results
c) Testing on the 1st niobium-tin cavity	July 2023	Complete Sept. 2023	Tested again Jan. 2024
d) 2nd cavity parts complete	November 2023	Complete January 2024	
e) Coat 2nd low-beta cavity	January 2024	Complete Nov. 2024	Delayed by leak in niobium part
f) Cryocooler testing complete	September 2023	Tested April 2024	Tested twice RadiaBeam/ANL, working on liquefaction

STATUS OF ALL LOW BETA Nb_3Sn CAVITIES 2021 TO PRESENT

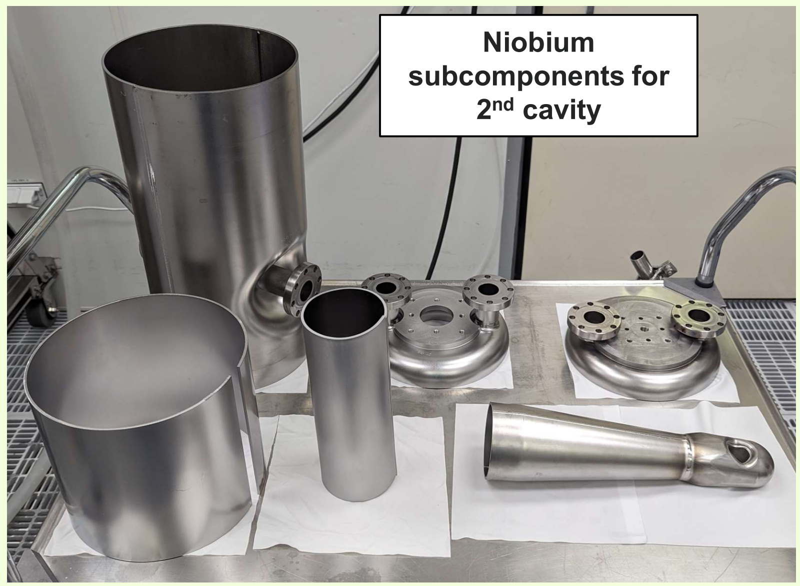
Cavity	Status	Additional Comment
Cavity #1: 218 MHz	Coated twice; tested several times; new results here	R&D cavity → HF rinsing likely next step
Cavity #2: 145 MHz	Coated November 2024	Test Dec. 2024; install into ATLAS 2026*
Cavities #3, #4: 145 MHz	Niobium parts in fabrication	Cold test coated 2-cavity superstructure Dec. 2025
LDRD cavity: 1 GHz	Testing September 2024	1st results; testing ongoing

*FOA funds for cavity fabrication, coating, testing; Funds for ATLAS installation from other sources

TECHNICAL APPROACH: VAPOR DIFFUSION OF TIN INTO A NIOBIUM CAVITY

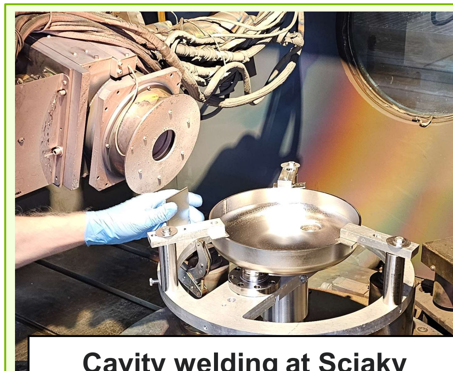
Step 1: A good “defect-free” niobium cavity is the starting point

Hydroforming press at Stuecklen



Niobium subcomponents for 2nd cavity

RadiaBeam performs Nb machining



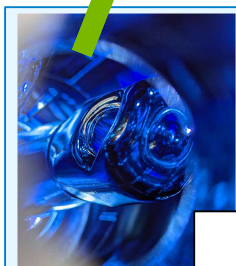
Cavity welding at Sciaky

Argonne electropolishing (EP) for low-beta cavities

2nd Cavity Coating at Fermilab (Nov. 2024)

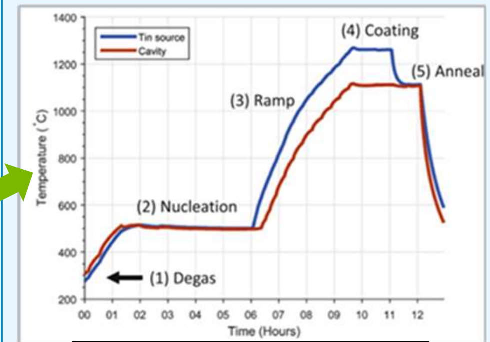
Particular attention to possible sources of contamination (NbTi flanges, semi-trapped volumes, threads)

Cavity with two tin sources before coating



EP, cleaned, anodized cavity

Tin and tin-chloride in crucible



Coating process

Comment: New ANL furnace so far for H_2 degassing → learning from FNAL, convert to Nb_3Sn

Cavities Tested at ANL In 24” Diameter ‘Dunk’ Dewar

All cavities tested pre- and post coating

Cavity and 24” diameter dewar

2nd cavity (145 MHz) and 1 GHz cavity (Oct. 2024)

- **Cavity:** Immersed in 1-meter deep bath of 4.5 K liquid helium
- **Refrigeration:** By ANL test facility model 1630 helium refrigerator
- **Diagnostics:**
  - Si-Diode thermometers
  - 3 Fluxgate magnetometers
  - Helium pressure, level
  - Heaters

Cavity #1 (218 MHz) Test Results for Two Rounds of Coating

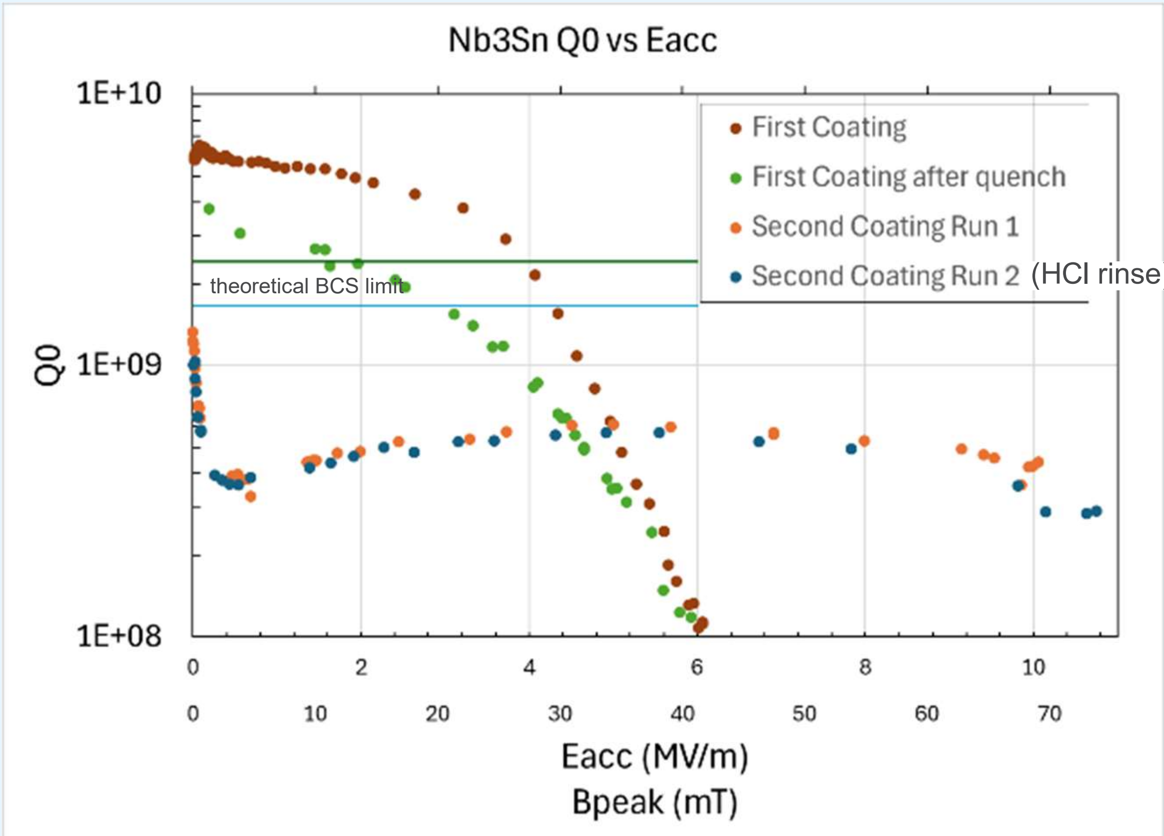
Different results for the two rounds of coating

Upper curves

- Quality factor in first round of coating exceeds niobium by 3-4 times
- Strong Q slope from plastic deformation during pump down
- Quench induced Q-drop is recoverable; we are not overly concerned

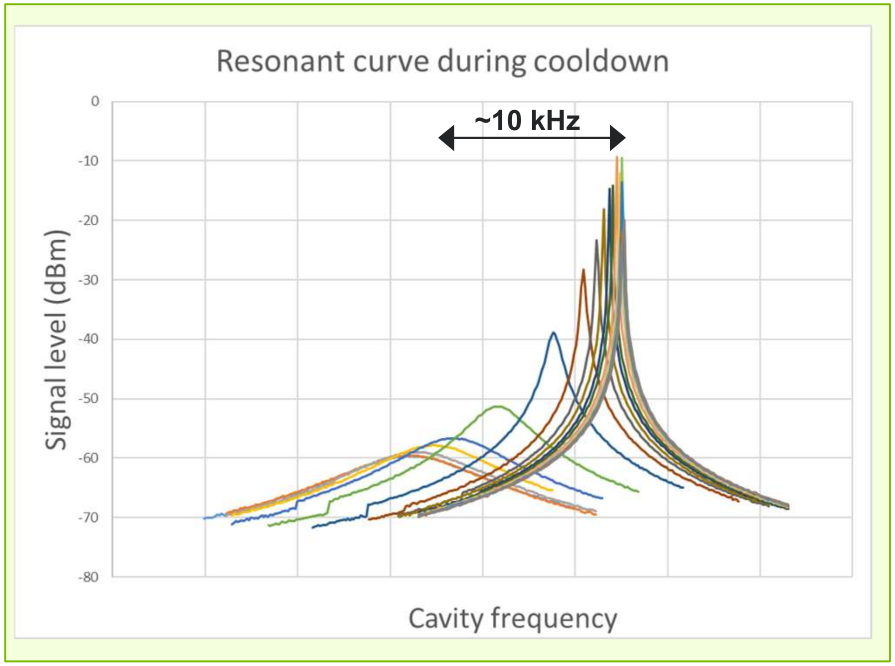
Lower curves - new re-enforcement stiffening added to cavity

- Low field Q much reduced as from a “weak-link”
- Q slope not present and exceeds 1st round at high fields

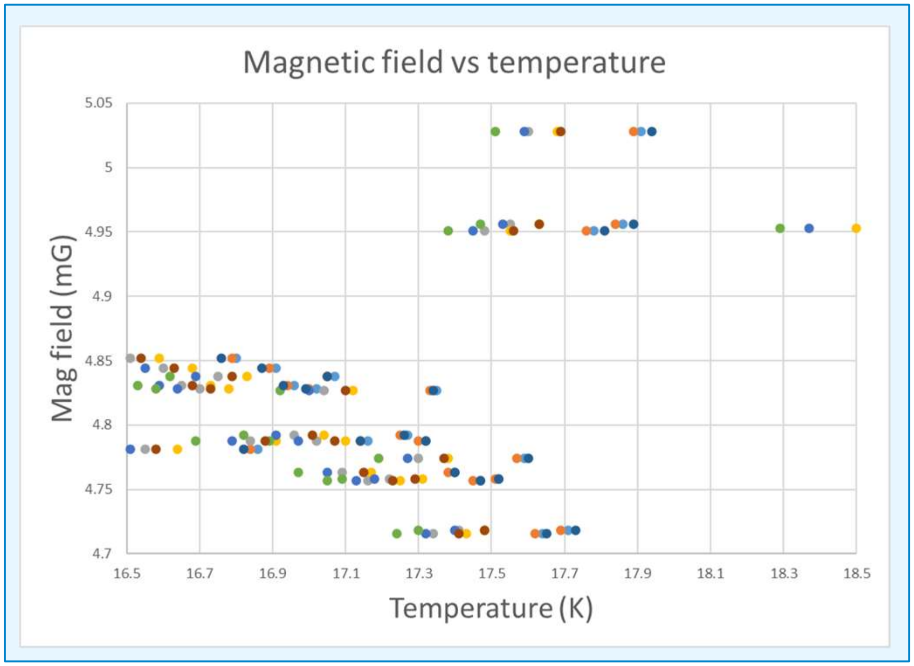


Cavity #1 (218 MHz) Temperature and Magnetic Field Data Near Tc

Superconducting transition clearly visible near 18 K but systematically ~400 mK below 18 K



Cavity quality factor and Q change through Tc



Magnetic flux rearrangement at transition through Tc

Nb_3Sn Cavities: Issues and Solutions

Practical solutions for mechanical and thermocurrents seem in hand; coating purity/quality is the focus

Issue and impact

- **Plastic deformation after coating:** Nb_3Sn film damage leading to Q drop

- **Seebeck effect:** Thermocurrents produced during cooldown produce magnetic fields that reduce Q
- **Thermometry uncertainties:** Doubts at level of ~400 mK on thermometers near 18 K → misinterpretation of temp. gradients or value of Tc
- **Coating quality/purity:** Possible issues → NbTi flanges, contamination in threads or trapped volumes, non-optimal amounts Sn/$SnCl_2$, water, incomplete Sn incorporation

Solution or approach

- **Integral or detachable stiffening after coating:** Must account for all scenarios (pumping, cooling, tuning)
- **Slow uniform cooldown through Tc:** More than ½ dozen cooldowns; no evidence for impact on Q; (Q drop can be induced for externally applied field)
- **Calibrated thermometry:** New purchase with calibration better than 100 mK
- **Study and control of contamination:** Niobium sample analysis from coated cavities, elimination of tapped holes, newest cavities are 100% Nb, no NbTi

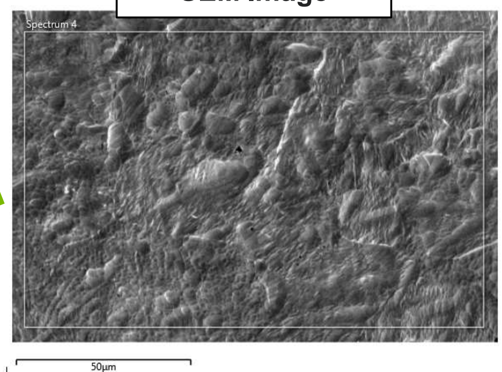
Using Sample Analysis to Improve Coating Quality

SEM/EDS analyses of samples show indications of impurities in some cases

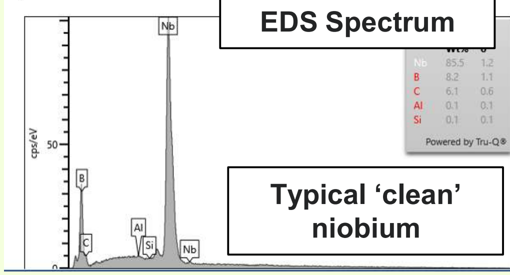
Sample through ANL furnace at 600 °C

Nb 2.5 cm²

SEM Image

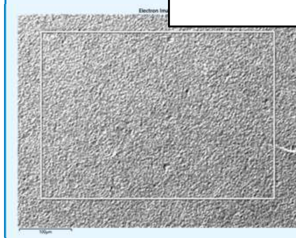


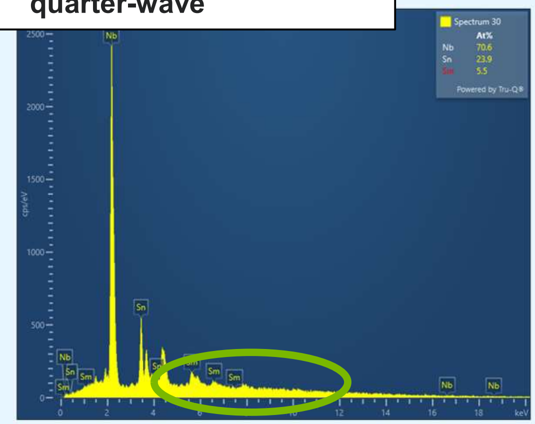
EDS Spectrum



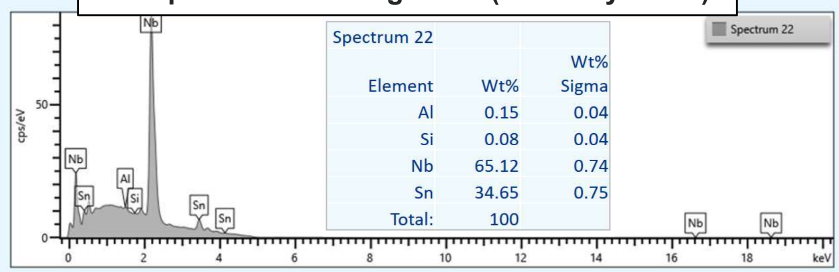
Typical 'clean' niobium

Sample from 2nd coating of 218 MHz quarter-wave





Comparison from single-cell (relatively clean)

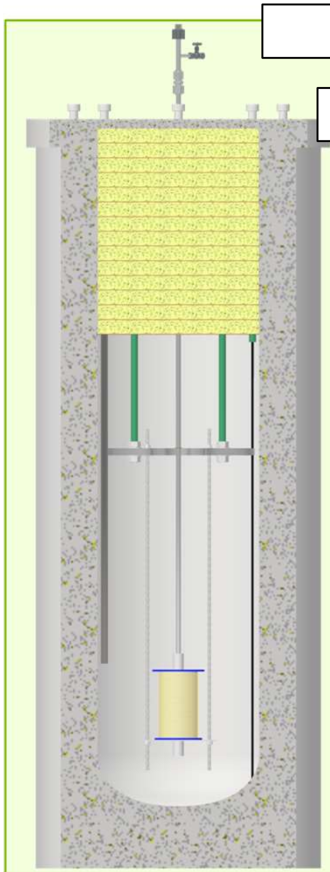


Spectrum 22		
Element	Wt%	Wt% Sigma
Al	0.15	0.04
Si	0.08	0.04
Nb	65.12	0.74
Sn	34.65	0.75
Total:	100	

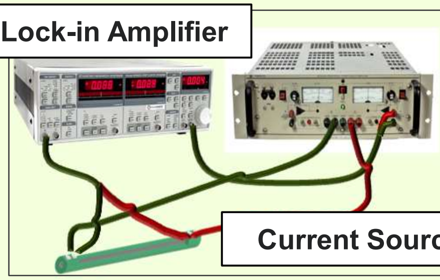
After 20 years Restarted In-house Checks on Niobium Purity

4-wire AC and DC Measurements of Residual Resistivity Ratio support no Issues with niobium

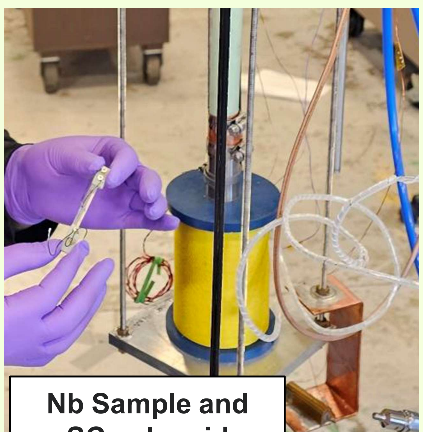
Apparatus



Lock-in Amplifier

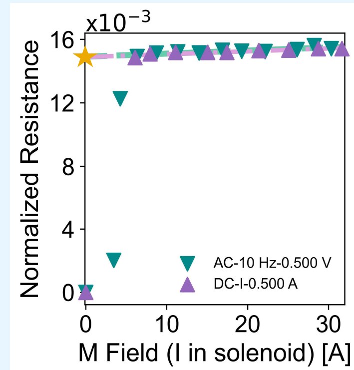


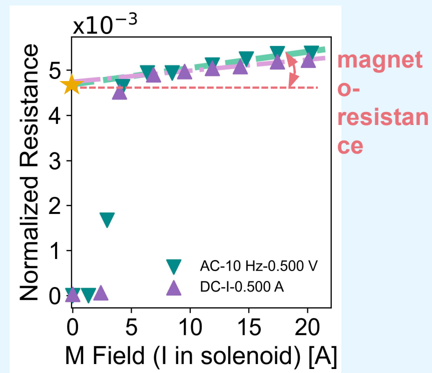
Current Source



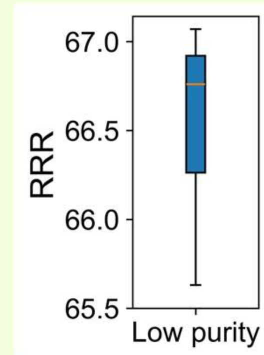
Nb Sample and SC solenoid

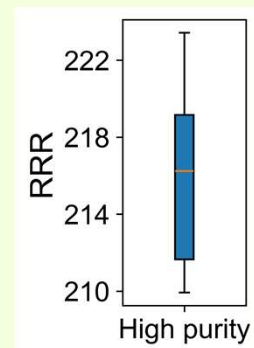
Data





Results

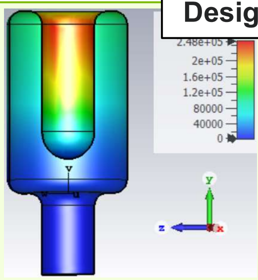


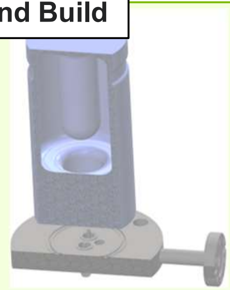


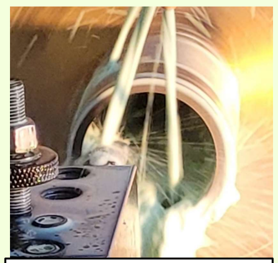
1 GHz Nb_3Sn Cavity Quarter-wave Cavity (ANL LDRD)

Postdoc 8-month project of Yang Zhou to demonstrate proof-of-principle for Nb_3Sn low-beta at high frequency

Design and Build

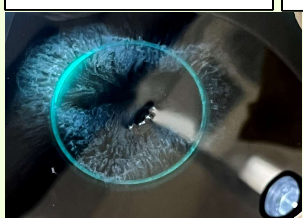






Machining at RadiaBeam

Welding at Sciaky

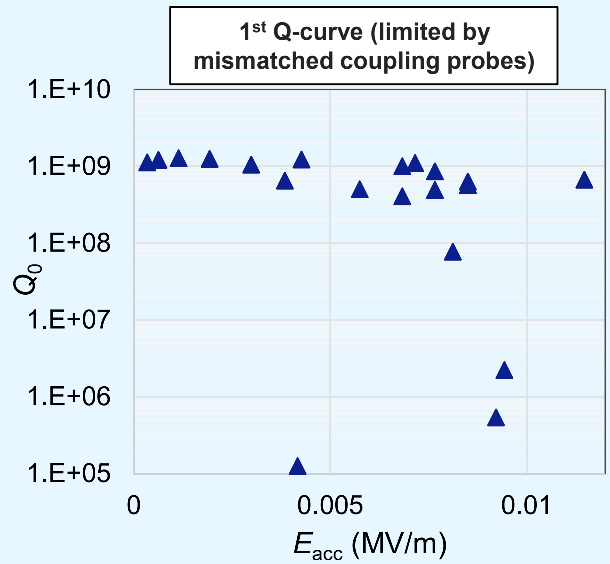


Chemistry

Cavity after EP

Data

- **Tc = 17.7 K** about 0.1 K higher than for larger cavities
- **Q_0~10^9** nearly 10X higher than for a pure niobium cavity at this frequency

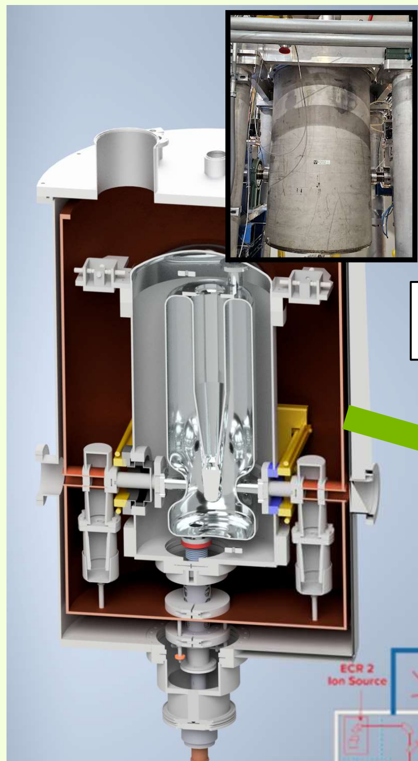


Prep and Testing

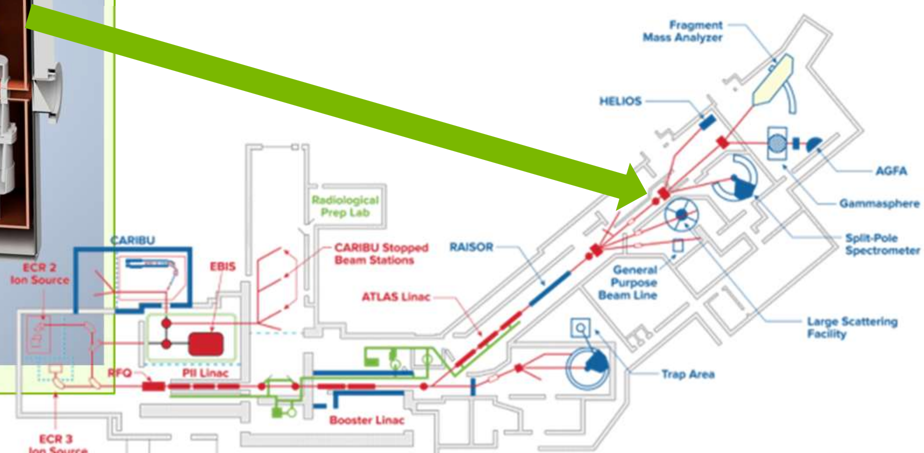
Revised Plan: Installing a Nb_3Sn coated cavity in ATLAS

The 2nd Cavity (145 MHz) is a better match to the end of ATLAS and will be installed in the last buncher cryostat

- **Re-buncher test bed:** Re-bunching does not require the highest performance but forces us to address practical issues
- **Major decision:** Commit to use of 10-Watt cryocooler or use ATLAS refrigerator
- **10-Watt cryocooler:** Tested looks promising, but want to show we can make liquid helium
- **Mechanical slow tuner:** Novel design tested at room temp, also looks promising
- **Helium vessel/cryostat/coupler:** Large effort outside scope of FOA R&D; Requires ATLAS support
- **Timescale:** 2026

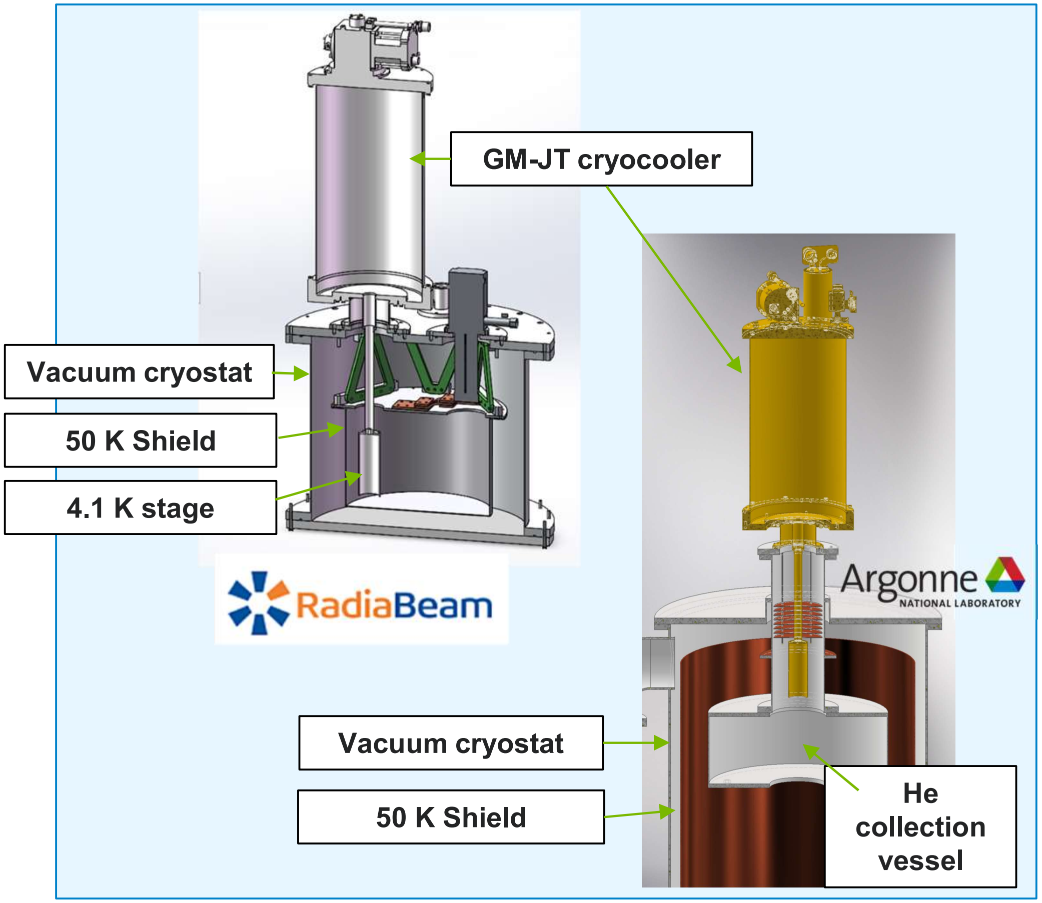


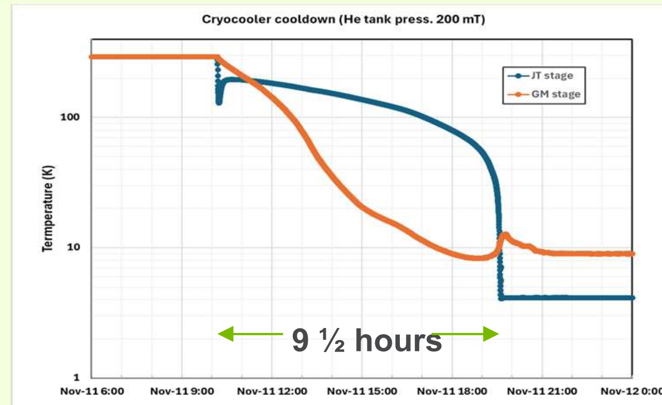
Preliminary engineering design as of April 2024

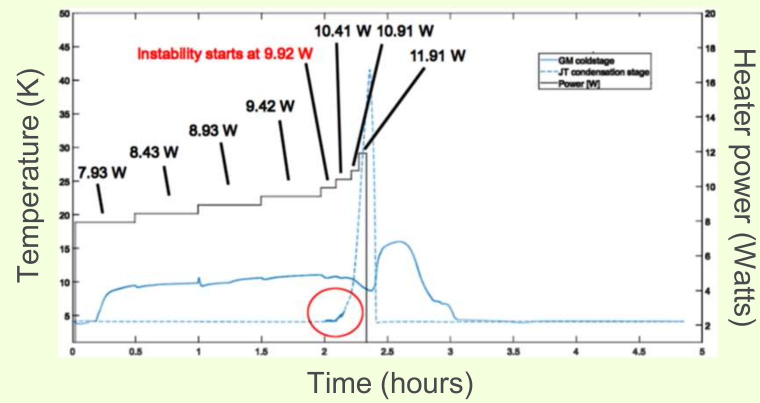


Sumitomo 10 W Cryocooler Testing at RadiaBeam and Argonne

Cryocooler cooled nicely to 4.1 K at RadiaBeam and Argonne, supports > 9.5 W load; Needs more work on ANL cryostat to make liquid

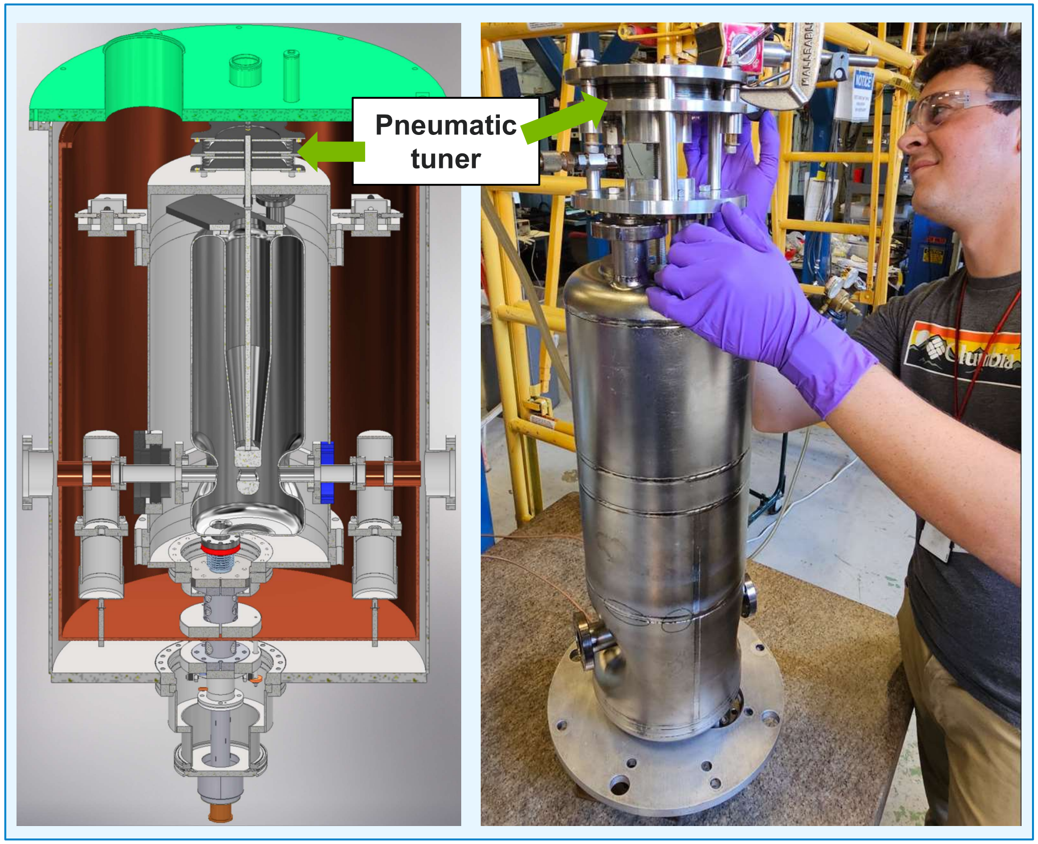




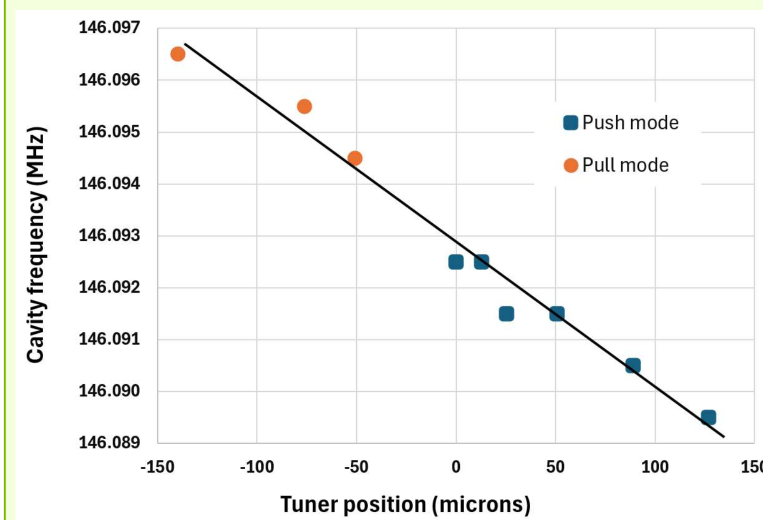


New Top-mounted Slow Tuner

Beam port located tuners only squeeze. The top-mounted tuner operates in push/pull allowing us to aim directly at the frequency "bullseye"



Data (room temp)



Final Comments

- The team of Argonne, Fermilab and RadiaBeam is four years into an effort to prove Nb_3Sn on low-beta cavities, such as those for ATLAS upgrades or other future ion linac applications
- We have coated and tested one cavity twice with encouraging results including, a transition temperature Tc close to 18 Kelvin, high quality factor, and high gradient, but the latter two not (yet) simultaneously
- A second 145 MHz cavity intended for ATLAS has been coated and is scheduled for testing before the end of 2024.
  – Additional lab LDRD investment was secured to build and test a 1 GHz quarter-wave cavity.
  – The team has initial test results for a new 10-Watt cryocooler and a top-mounted pneumatic tuner, which they believe can be made "accelerator ready" in a short time.
- Challenges encountered creating a practical and high-performing Nb_3Sn cavities for ion accelerators are not a surprise. History tells us that only through a sustained and determined program of building, testing, learning, and improving are we likely to make the type of transformative breakthrough that RF superconductivity itself was five decades ago.

Backup