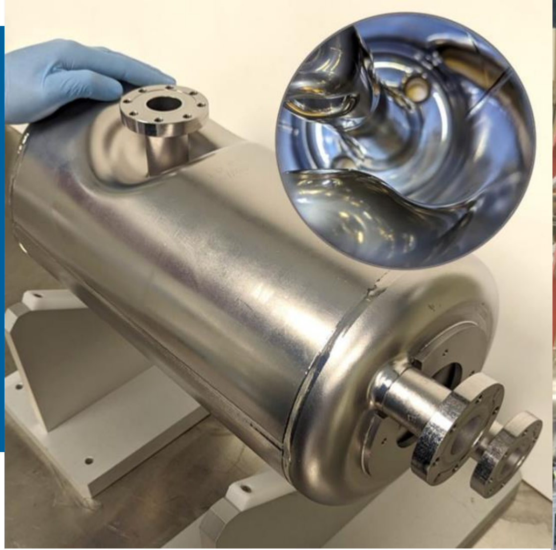
DECEMBER 7, 2023

2023 NP Accelerator R&D PI Exchange Meeting

A PRACTICAL NIOBIUM TIN CAVITY FOR THE ATLAS SUPERCONDUCTING LINAC



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U.S. DEPARTMENT OF ENERGY

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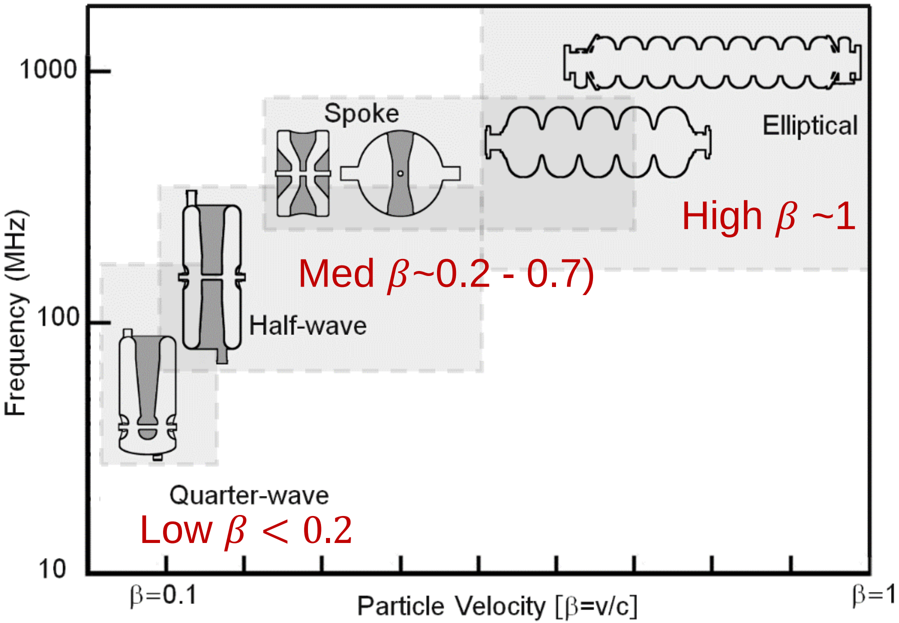
OUTLINE

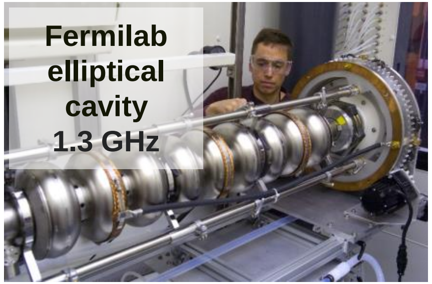
The Present Paradigm for CW Accelerators Like ATLAS

Modern linear accelerator cavities are based on high-purity Nb

- Cavity designs emerge from:
  - Accelerator needs (energy, voltage, current etc.)
  - Intrinsic material properties of niobium
- For our low-β ion acceleractors
  - QWR most efficient geometry
  - Niobium → large, ~100 MHz

Common shapes for modern SC cavities





MOTIVATION

TRANSFORMATIONAL COST REDUCTIONS THROUGH NIOBIUM-TIN COATINGS WITH SIMILAR OR BETTER OVERALL PERFORMANCE RELATIVE TO NIOBIUM

- **Ion accelerator cryomodules are large and costly, of order ~$10M per module**
- **Helium refrigerators, kW scale, are large and costly, of order ~$10M per kW @ 4.5 K**
- **Main goal: (1) Large size/cost reductions for ion linac cryomodules, (2) Elimination of need for cryoplant; cooling within capacity of new larger cryocoolers**

2019 ANL/FNAL half-wave cryomodule for PIP-II

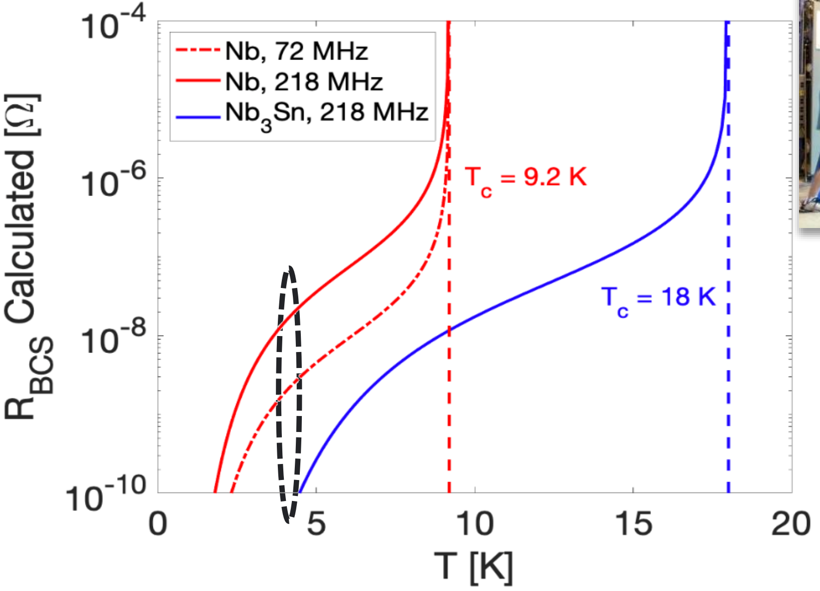
2009 ATLAS Energy Upgrade Cryomodule

2014 ATLAS Energy and Intensity Upgrade Cryomodule

'WHY USE NIOBIUM-TIN FOR A QUARTER-WAVE CAVITY?

TRANSFORMATIONAL COST REDUCTIONS THROUGH NIOBIUM-TIN COATINGS WITH SIMILAR OR BETTER OVERALL PERFORMANCE RELATIVE TO NIOBIUM

- **Present state:** *Ion linacs are built from large ~1+ meter long niobium cavities*
  - Niobium R_s **y** several 10's nΩ → Cryomodule loss ~100 Watts in 4.5 K helium (dot-dash red curve)
- **Future:** Small (high frequency) niobium-tin coated cavities with milliwatt-level heat loads (solid blue)
- **Approach for achieving main goal:**
  1. Complete testing development on 218 MHz cavity
  2. Complete 2nd cavity at 145 MHz suitable for installation into ATLAS



SUMMARY OF EXPENDITURES BY FISCAL YEAR (FY):

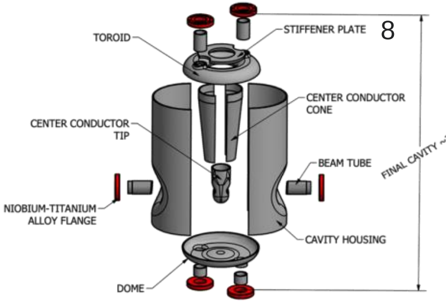
	FY22 ($)	FY23 ($)	Totals ($)
a) Funds allocated	619,000	639,000	1,258,000
b) Actual costs to date	548,915	516,965	1,065,880

MAJOR DELIVERABLES AND SCHEDULE

Deliverable	Forecast Schedule	Status	Additional Comment
a) Coat 1st low-beta niobium cavity	March 2023	Performed June 2023	
b) Complete final design of reduced frequency (buncher) cavity	June 2023	Complete June 2023	Adding gusset based on 218 MHz results
c) Testing on the 1st niobium-tin cavity	July 2023	1st testing Sept. 2023	2 additional tests (one is ongoing)
d) Fabrication of 145 MHz rebuncher cavity parts complete	November 2023	Hydroformed parts complete	Need to fabricate reinforcing gusset
e) Coat 2nd low-beta cavity	January 2024	Revised date April 2024	
f) Cryocooler testing complete	September 2023	Complete at Sumitomo	Delivery to RadiaBeam

NIOBIUM PARTS FORMING IN CHICAGO AREA

Hydroforming press
Stuecklen



3 TOROID (HYDROFORMING)

The toroid of the Nb3Sn was also hydroformed by Stuecklen. A 12" by 12" sqaure Nb blank (thickness of 0.125") was used for the toroid fabrication.

3.1 STEP 1

In Step 1, the steel die was provided by Stuecklen.

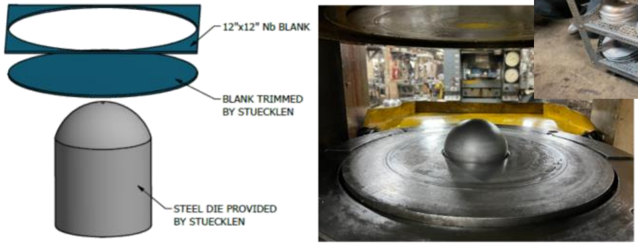


Figure 5: Step 1 forming.

3.2 STEP 2

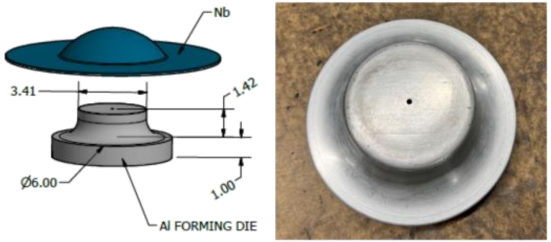


Figure 6: Step 2 forming.

3.3 STEP 3

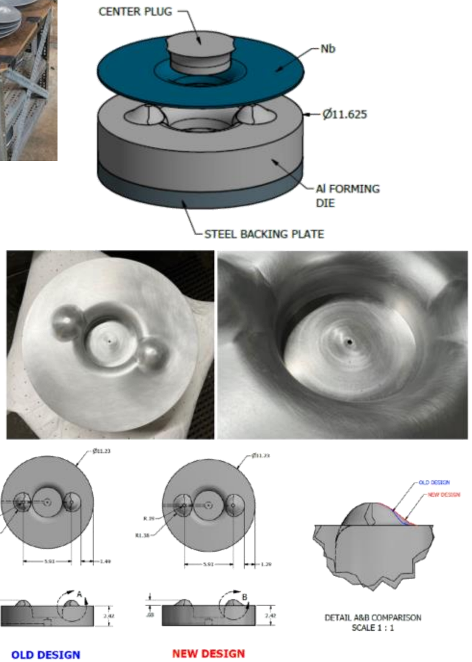
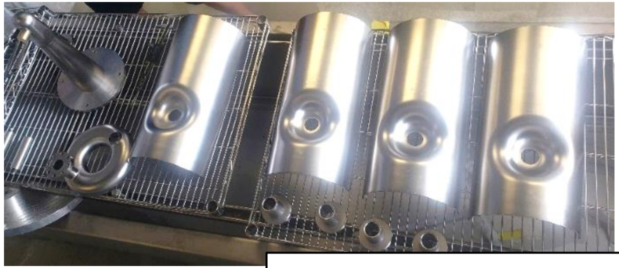


Figure 7: Step 3 forming. Note: the nub shown in the old design follows the profile of the nub used in the dome. The new design was adopted in the final toroid die.

CAVITY TUNING AND ELECTRON BEAM WELDING

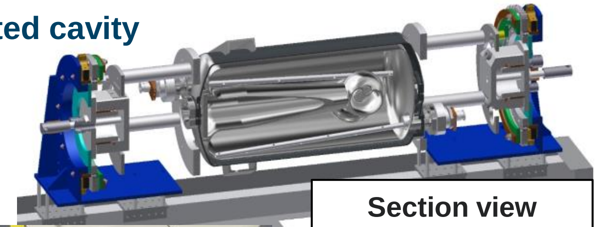


Parts machining and assembly at RadiaBeam and Argonne

Cavity welding at Sciaky

New work since last report

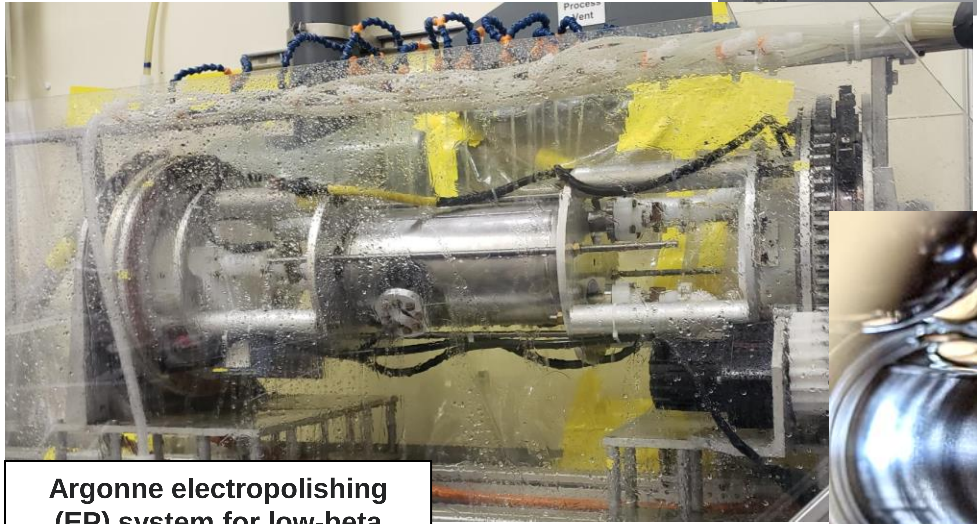
From electropolishing bare niobium cavity to testing coated cavity



Section view

Activities since 2022 PI meeting

- **Electropolishing**
- **Cleaning and testing of bare niobium**
- **Anodization**
- **Coating in Fermilab furnace**
- **Cold testing coated cavity (3 rounds)**



Argonne electropolishing (EP) system for low-beta cavities

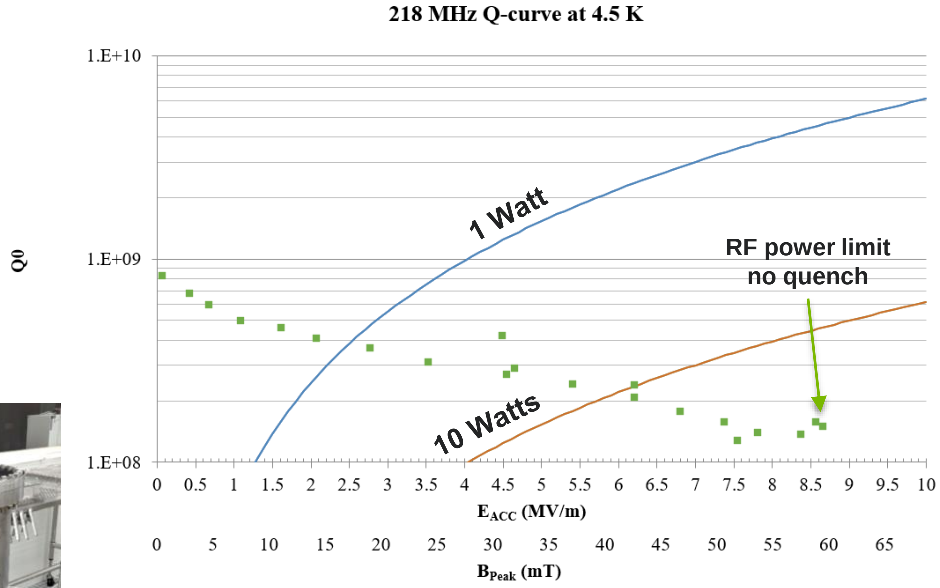
After EP

Verification testing on the bare niobium cavity before coating

Bare cavity meets design goals (Bpeak~60 mT with no quench)

Bare cavity in clean room

Cavity in temporary helium tank



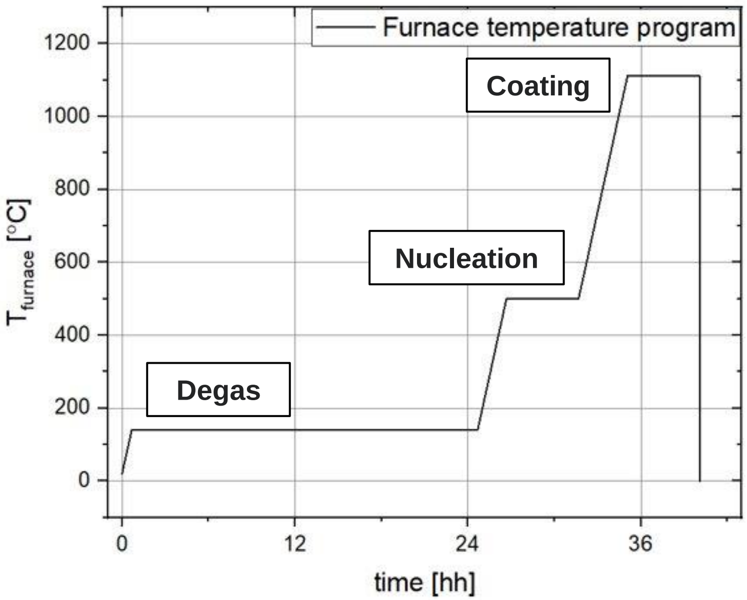
Cavity in primary ANL test cryostat (TC3)

Niobium-tin coating parameters for the quarter-wave cavity

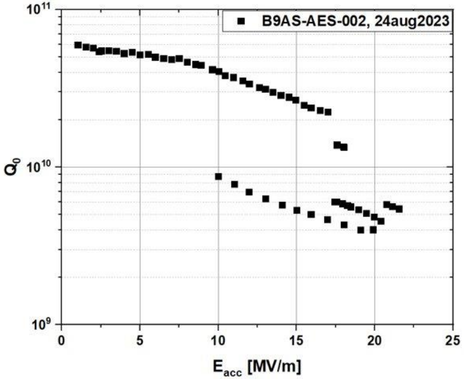
Adapt a successful process from a recent 1-cell 650 MHz cavity with same surface area

- **Nb_3Sn by vapor diffusion:** Most successful method relative to cavity performance
- **Tin quantity:** From cavity surface area and desired thickness
  - QWR surface area=0.46 m^2, E-cell surface area 0.49 m^2 **Y4 grams of tin**
- **Nucleation:** 0.8 grams $SnCl_2$
- **Heaters:** Furnace (1100 ^oC) and tin source heaters independently controlled. Tin source ~100-200 ^oC hotter than furnace

Furnace temperature profile



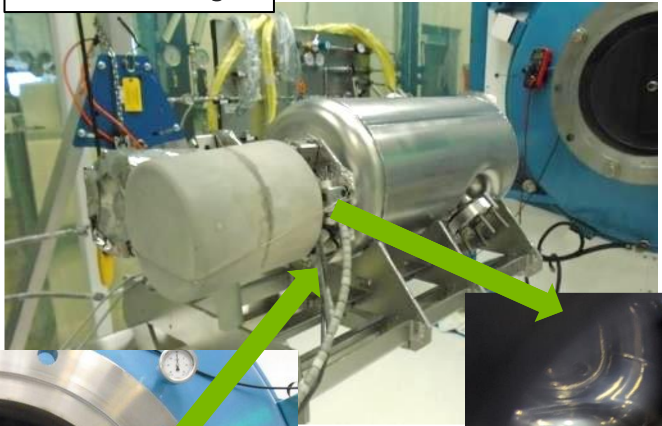
Performance for 1-cell Fermilab cavity @ 4.3 K

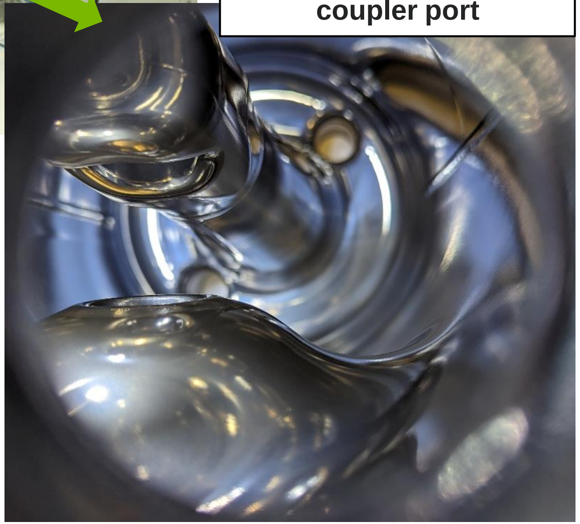


Cavity coating at Fermilab

~1 week process to dress, coat, cool and remove cavity from the furnace coating chamber

After coating

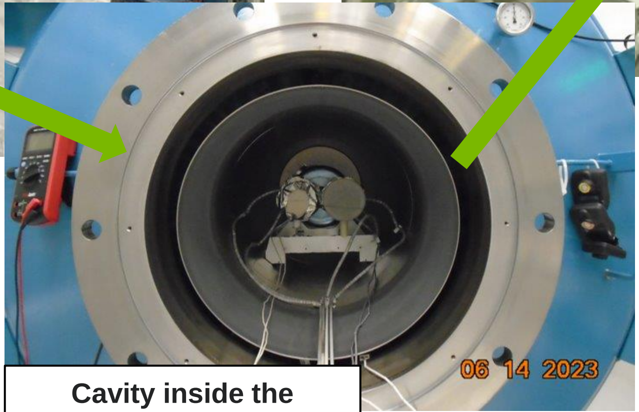




After coating, through coupler port

Cavity with two tin sources before coating

Anodized cavity

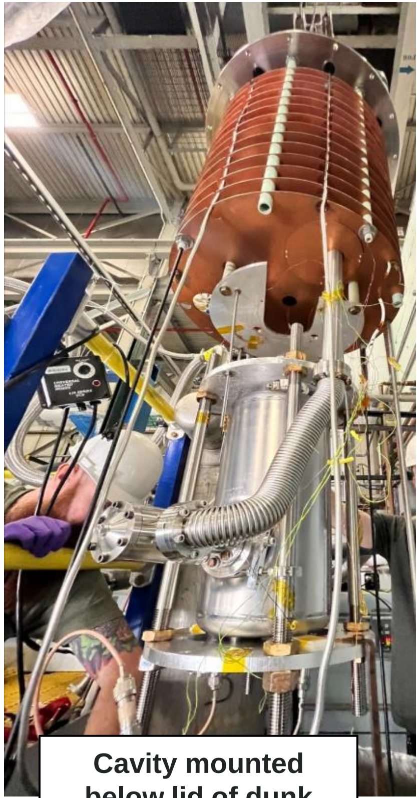


Cavity inside the coating chamber

Experimental Apparatus

24” diameter liquid helium dunk dewar

Cavity and 24” diameter dewar



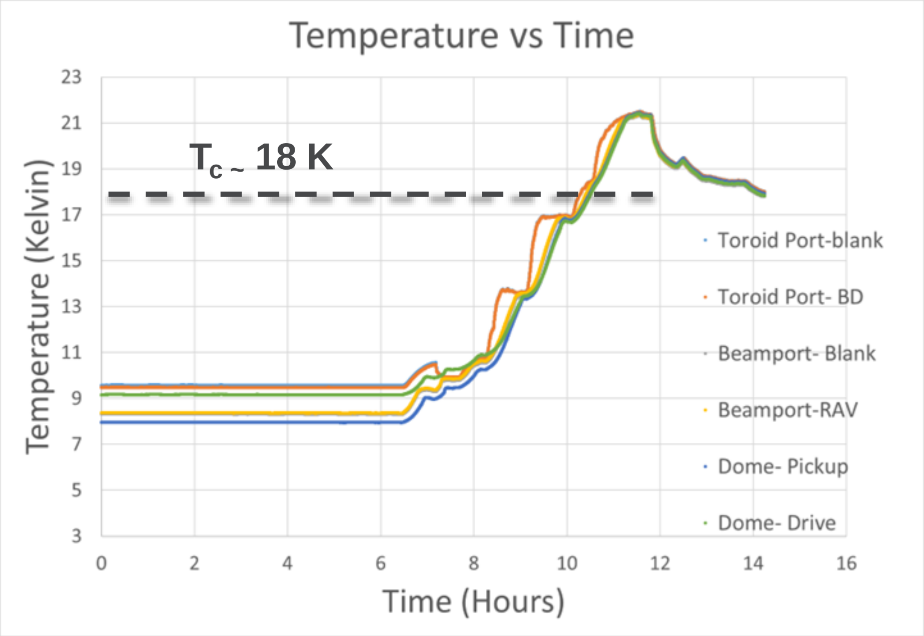
Cavity mounted below lid of dunk dewar

- **New system for ‘dunk testing’:** Adapted our 24” dewar in Sept/Oct 2023
- **Cavity:** Sits in ~1 meter tall bath of 4.5 K liquid helium with active vacuum pumping on the RF volume
- **Refrigeration:** ANL test facility model 1630 helium refrigerator
- **Diagnostics:**
  - 6 channels thermometers
  - 1 magnetic field probe
  - Helium pressure transducer

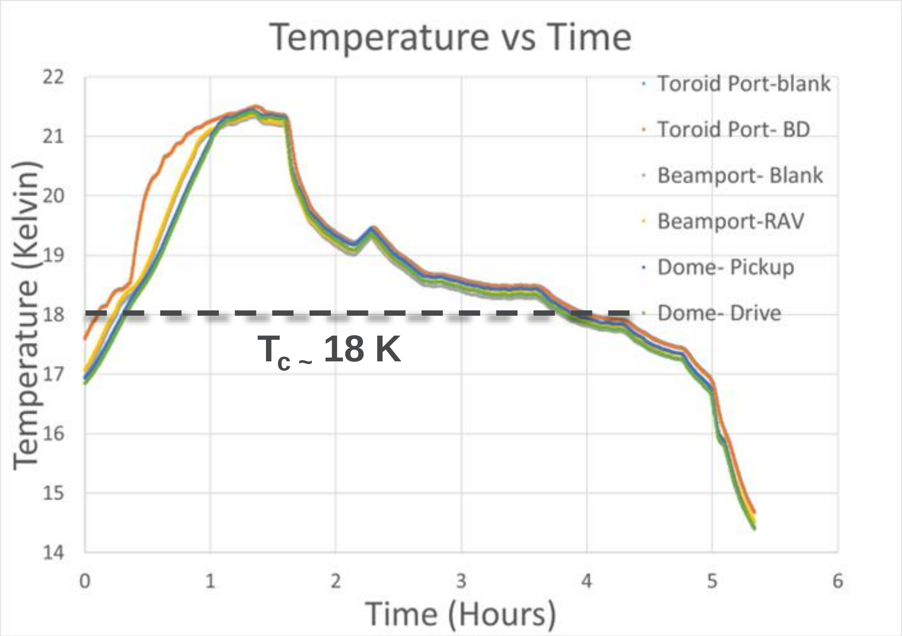
Cooldown through SC Transition, T_c~18 K

The cool down through Tc requires particular care: Seebeck effect known to cause Q drop

Warm up above T_c after initial cooling



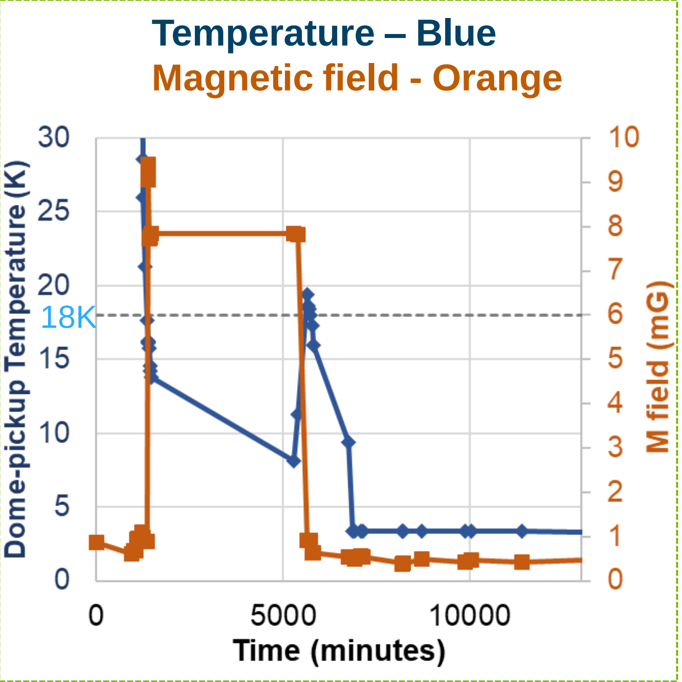
And then, slow (uniform) cooldown through T_c

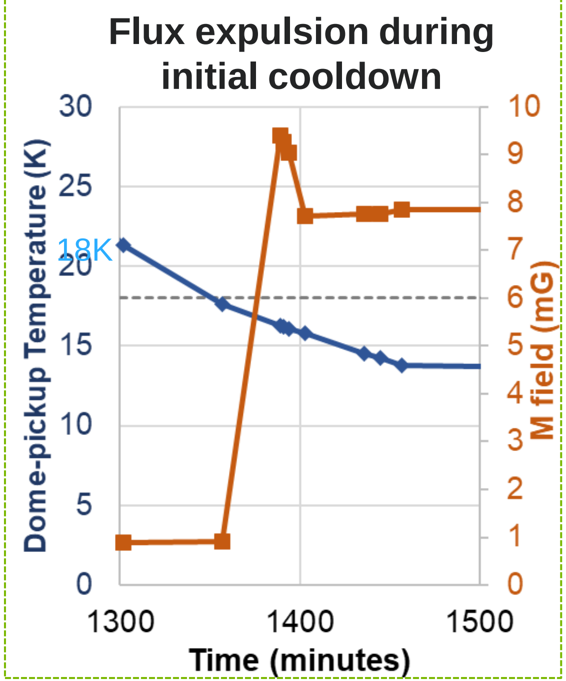


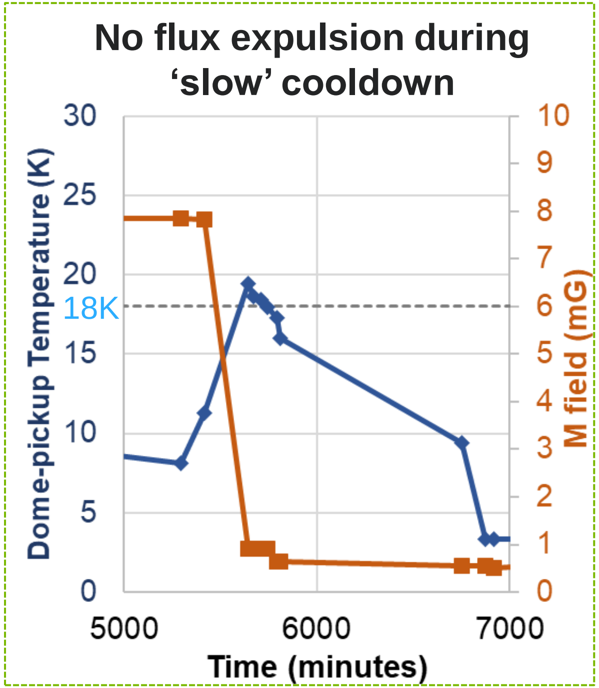
Magnetic fields and the niobium-tin cavity

Trapped magnetic fields lower the Q in Nb_3Sn (similar as for niobium)

- Unlike for niobium, flux expulsion by fast cooldown cannot be used with Nb_3Sn because fast cooldown also creates thermocurrents (Seebeck effect) that lower the Q in Nb_3Sn
- Data show complete flux trapping after the required slow cooldown → **Niobium-tin requires starting with low mag. field**



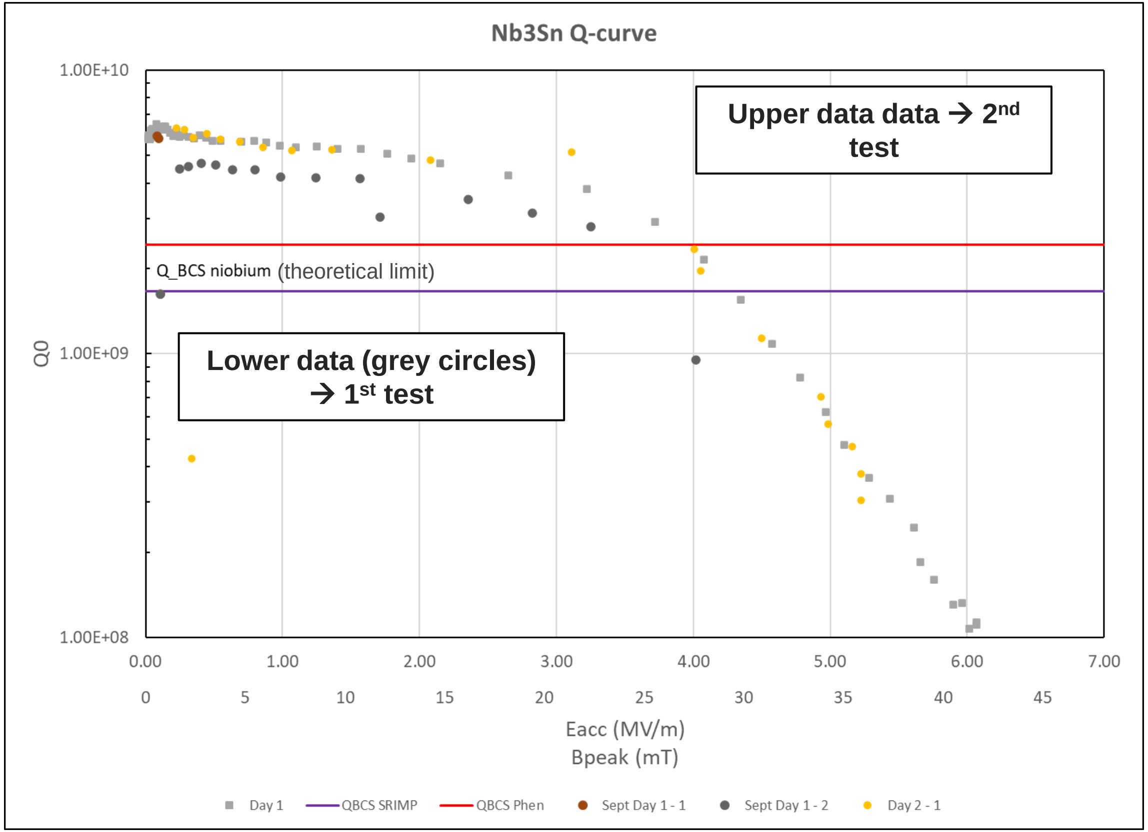




Results from first and second rounds of testing

First round of testing limited by cryogenics issues, second round consistent with third round (ongoing)

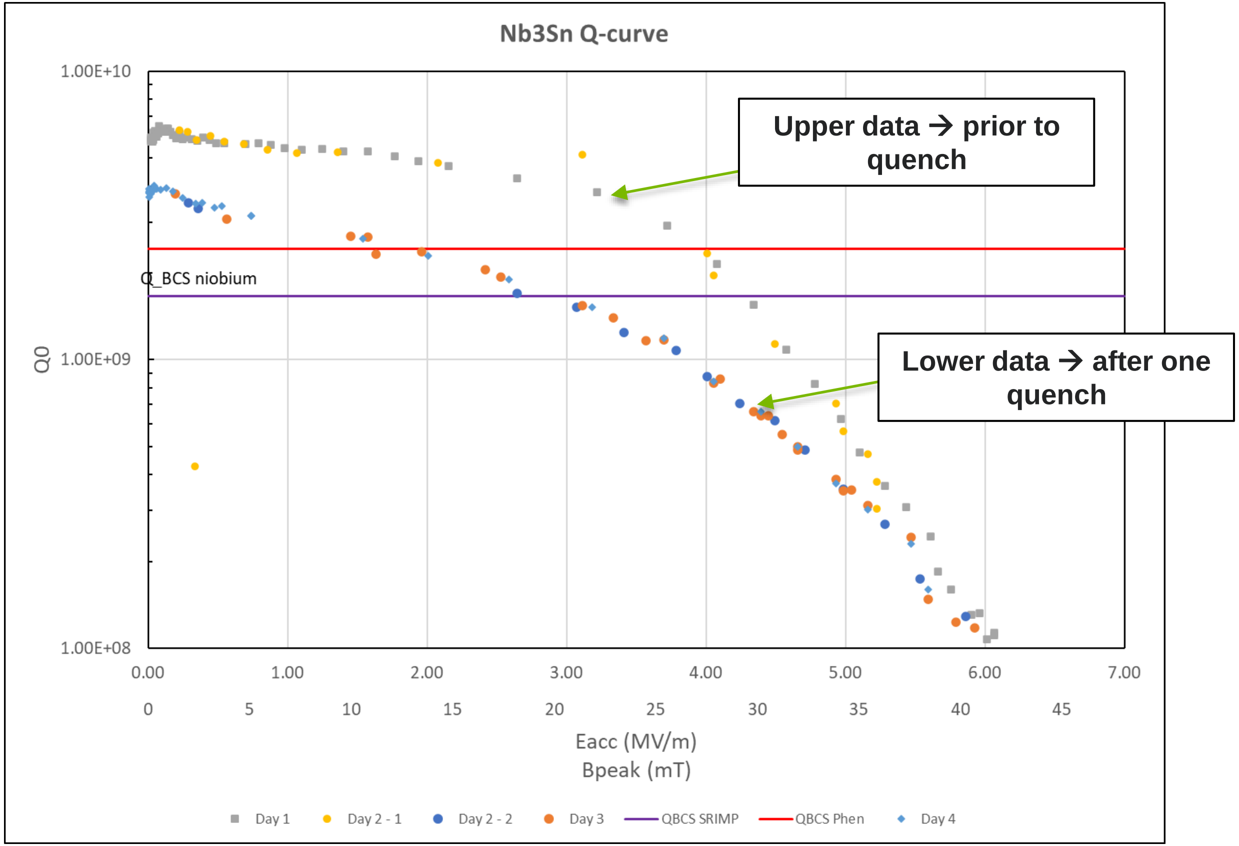
- **Upper curve:** Q vs. E measured after the cooldown of the 2nd testing cycle
- **Lower curve:** Q vs. E measured after the cooldown of the 1st testing cycle (cleaned He refrigerator in between)
- **Quality Factor:** Substantially higher than theoretical limit for niobium up to ~3-4 MV/m
- **Q-slope:** Strong above 4 MV/m
  - Need to find the origin



Quality factor vs accelerating gradient at 4.5 K

Cavity appears to be very sensitive to trapped flux from a simple thermal quench

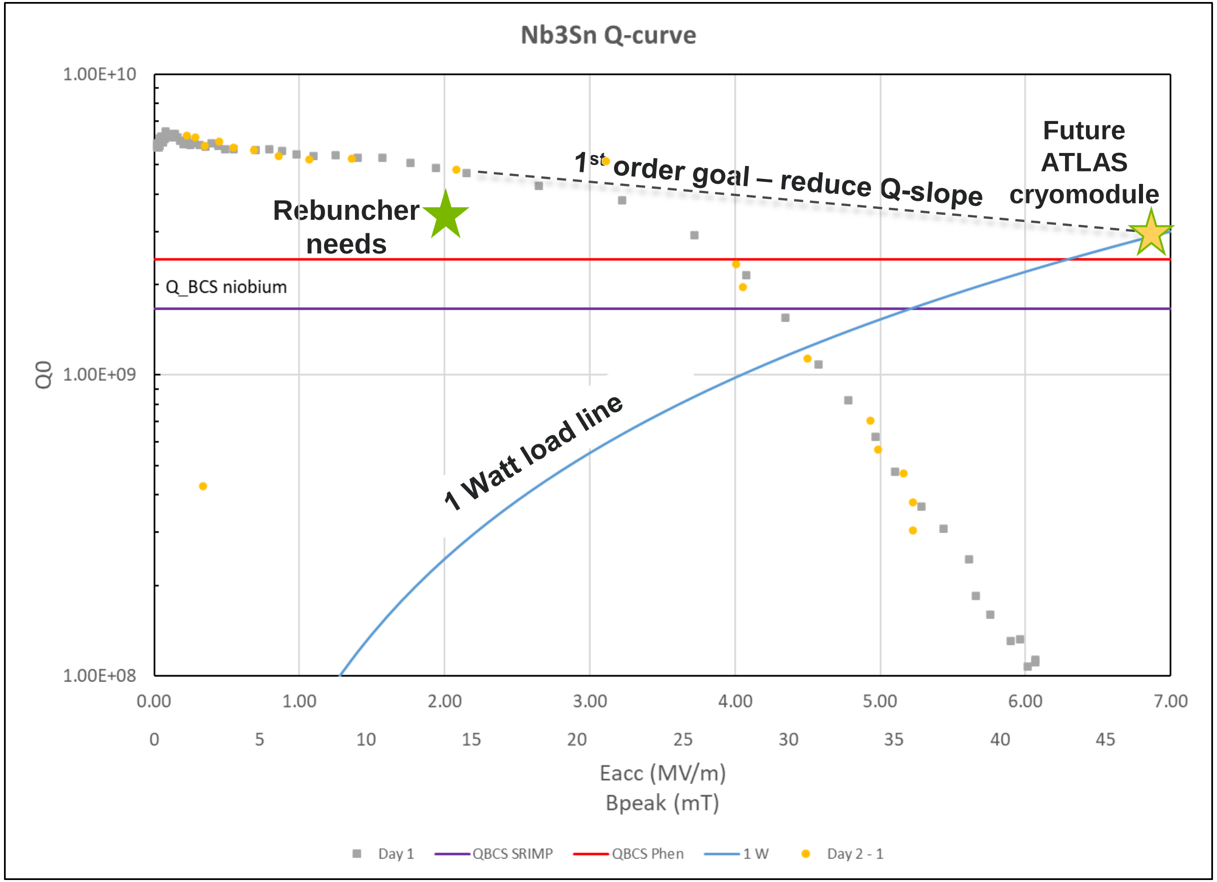
- **Upper curve:** Q vs. E measured after the cooldown of the 2nd testing cycle
- **Lower curve:** Same testing cycle (a couple days later), but after a single observed thermal quench
- **Thermal currents** during the quench are thought to be the cause
  - Cavity recovers if warmed above Tc
- **Significance:** In operations (*e.g.* in ATLAS) probably need to avoid quench



Results to date: Where are we, where do we need to go?

Present cavity performance is already easily good enough for rebuncher; need to resolve Q-slope for future accelerator cryomodules

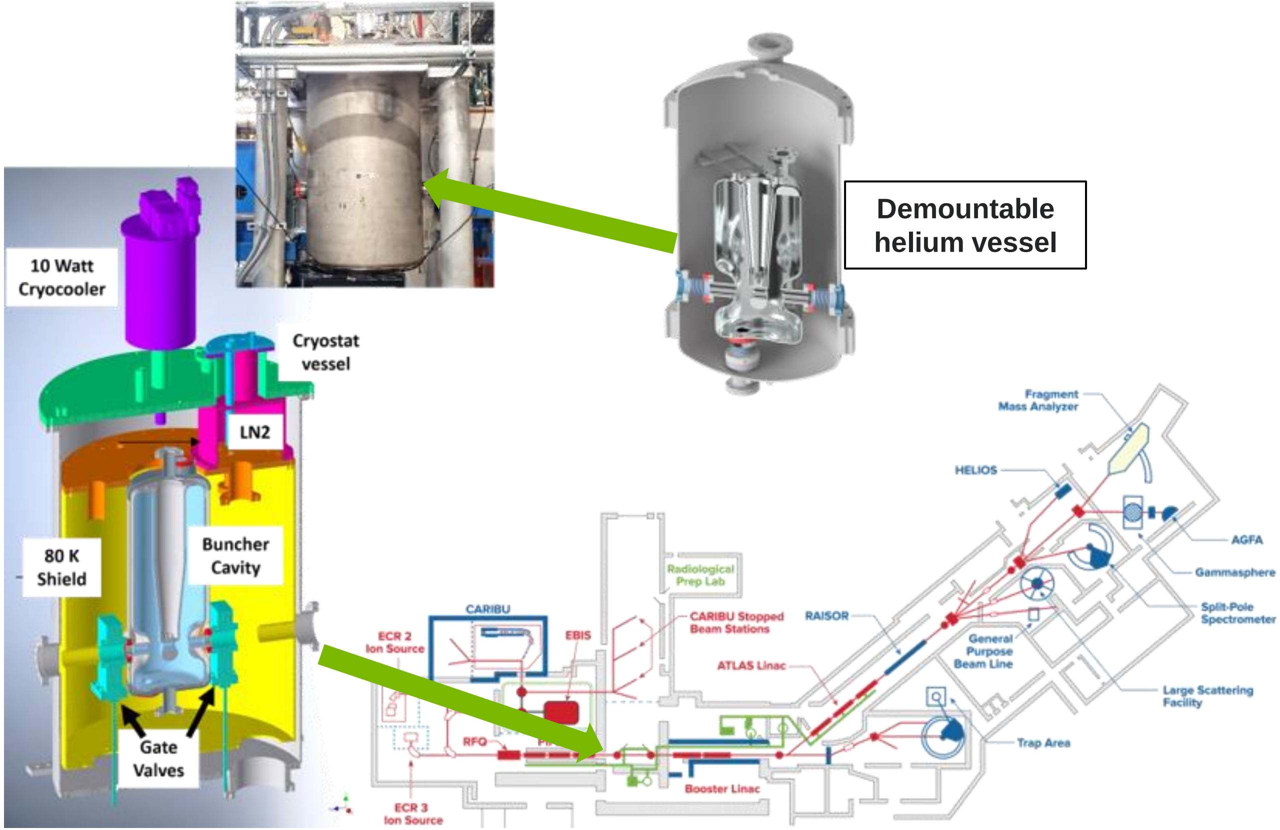
- **Q at low-mid field is high:** Much higher than for niobium, R_s=7 nΩ at 4.5 K
- **ATLAS Rebuncher:** Needs 0.3-0.5 MV → this performance is easily sufficient → high confidence for cavity #2
- **Future accelerator cryomodules:** Need to improve Q-slope
  - Extending flat region of present curve already good
  - Even better to raise Q_o at the same time
- **At minimum two important issues will be addressed for 2nd cavity:** Plastic deformation and contamination



Plans: Installing a niobium-tin coated cavity in ATLAS

A rebuncher in the middle of the ATLAS provides a large benefit for high intensity beams (N=126 factory) with moderate cavity requirements

- **Test bed:** Among the first real use of a niobium-tin coated cavity
- **Existing infrastructure:** Hardware re-use provides some cost reduction
- **10-Watt cryocooler:** Design will include compatibility with this device
- **FY2024 goal:** Develop 145 MHz niobium-tin coated cavity course tuned for ATLAS
  - Module modifications support by ATLAS AIP
- **Challenges:** Slow tuning due to brittle nature of Nb_3Sn
  - Ferroelectric tuner
  - Squeezing as normal but within elastic limits



Plans: Completing work on 2nd cavity at RadiaBeam

The 2nd cavity will include at least a couple of modifications based on experience with the 1st cavity

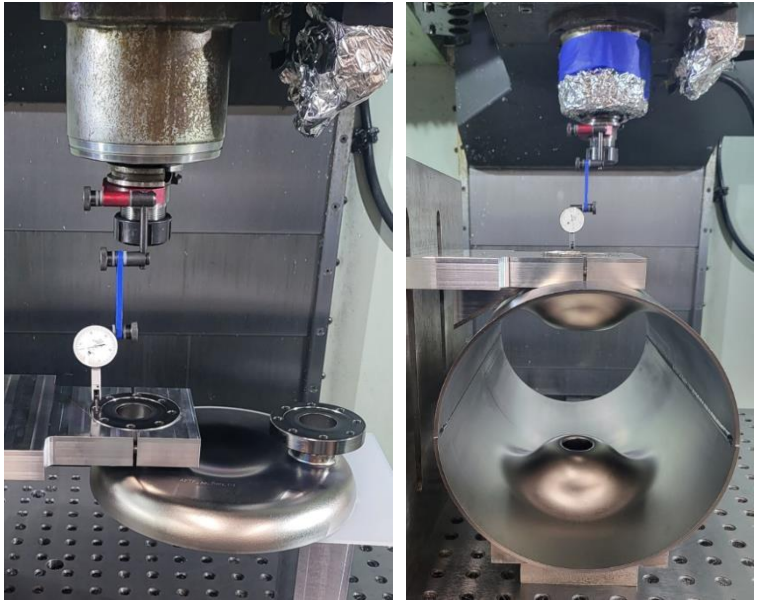
1st cavity used blind tapped holes Y a possible source of contaminants

These two ports need a reinforcing gusset not present in the 1st cavity!

To do list:

- **Removal of blind tapped holes:** Eliminate possible source of contamination
- **Reinforcing gussets:** Need a stiffener plate at both top and bottom of cavity
- **Housing and center conductor spool:** Needed to lower frequency of 2nd cavity to 145 MHz

2nd components at RadiaBeam

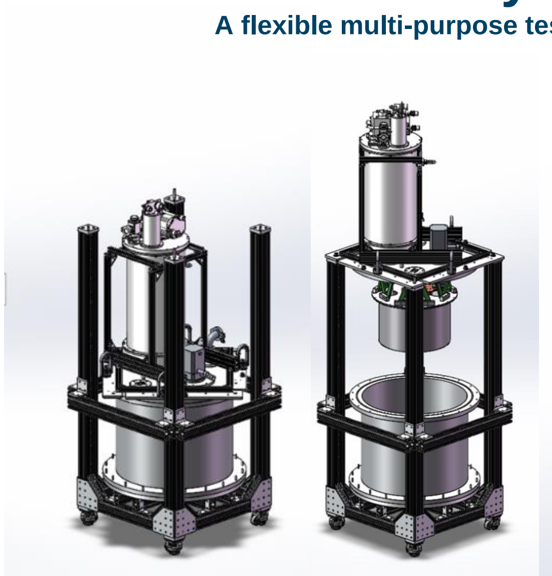


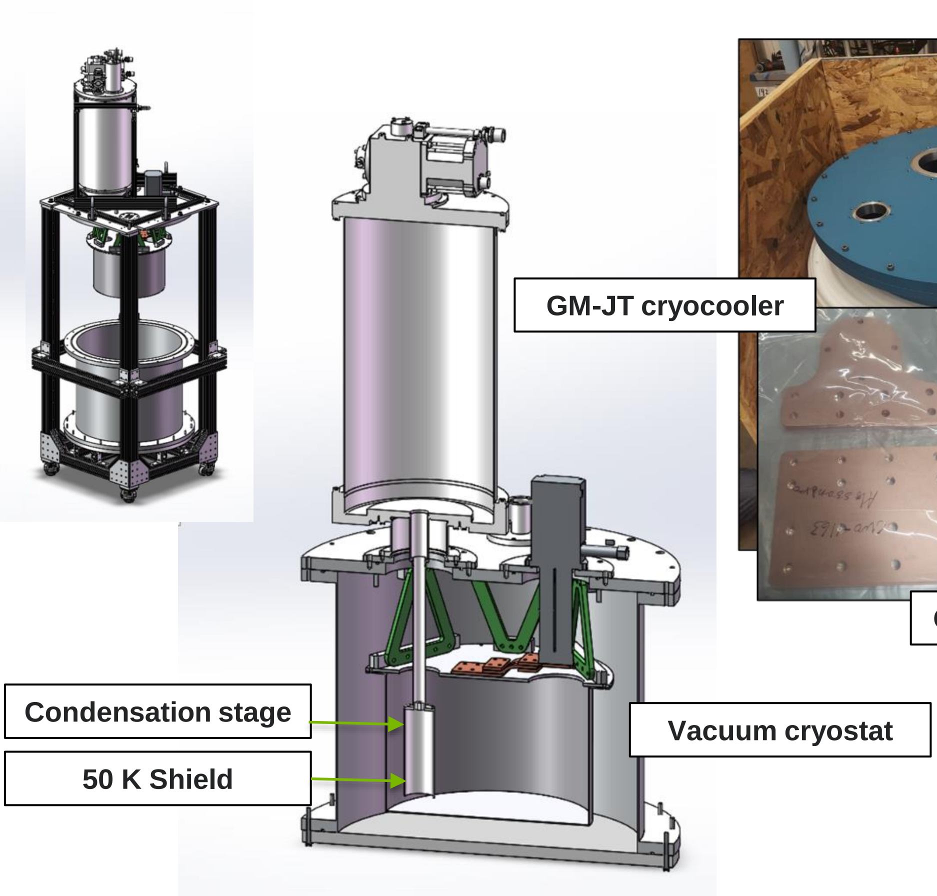
RadiaBeam removing blind holes on all 6 ports

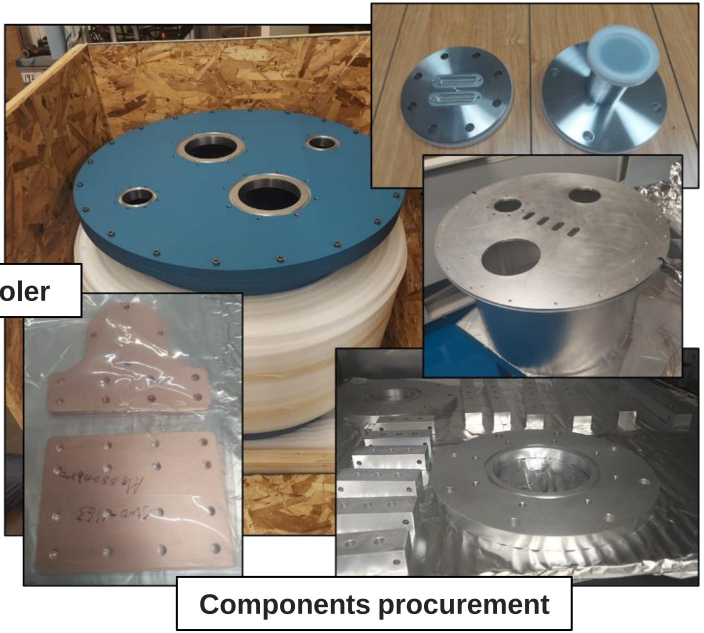
Plans: A cryocooler test bed at RadiaBeam

A flexible multi-purpose test bed suitable for the new GM-JT cryocooler from Sumitomo

RadiaBeam







- **Vacuum cryostat and subsystems:** All in-hand or ordered
- **Sumitomo cryocooler:** Initially planned delivery to RadiaBeam before end of 2023. Revised details in next quarterly report

Summary and Plans

- **The ANL, FNAL, RadiaBeam team has coated a low-beta niobium quarter-wave cavity with Nb_3Sn for the first time:** Performance clearly and significantly exceeds what could be achieved with niobium at this frequency
- **Three rounds of testing complete on first cavity:** Consistent performance in latest two tests after addressing cryogenics issues → We will begin process of re-coating this cavity (strip and re-electropolish, add gusset and re-coat)
  - Aim is to retest 1st cavity by 3rd quarter FY24
- **10-Watt cryocooler:** A lot of testing already at Sumitomo, additional testing with more realistic cryostat set up will take place at RadiaBeam
  - I will request to have this at RadiaBeam in 2nd quarter FY24
- **The second cavity will be tuned to 145 MHz to match ATLAS**
  - Welding of niobium parts 2nd quarter FY24
  - EP and coating in the 3rd quarter
- **The team will continue to set aggressive goals to advance Nb_3Sn for low-beta cavities**
  - The centerpiece of this is to complete the 2nd cavity such that it is ready for ATLAS
  - Our optimism that this will lead to transformative change for low-beta has only increased based on work and results of these last 3 years

Backup

Thoughts on future of Nb_3Sn and low beta

- **The rebuncher cryomodule:** best available way to vet practical subsystems needed to run these cavities in a larger more demanding accelerating cryomodule
- Beyond that, **a two-cavity energy adjustment cryomodule:** for “ATLAS Area II” dovetails nicely with the ATLAS Multi-user Upgrade
  - An aggressive but reasonable goal on a two year timescale would be demonstration of the cavities at gradient
  - Cryomodule would be by AIP
  - Strongly considering testing a “superstructure assembly” → cavities joined in cleanroom at the ports
  - Considering demountable helium vessel → permits rework without cutting off an expensive and complicated vessel
- A beautiful application would be niobium-tin for a **“bunch lengthening cryomodule”** → this could be BES funded/supported work
- Toward **a full cryomodule** → Sweet spot for niobium tin and low beta could be ~300 MHz where cavities are coffee can sized
  - A larger superstructure of four cavities would be ~1 meter long, provide high real estate gradient, small transverse size and still be practical from a cleaning handling standpoint