Development of Practical Niobium-Tin Cavities for Ion Linacs

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2021 NP Accelerator R&D and AI-ML PI Exchange Meeting

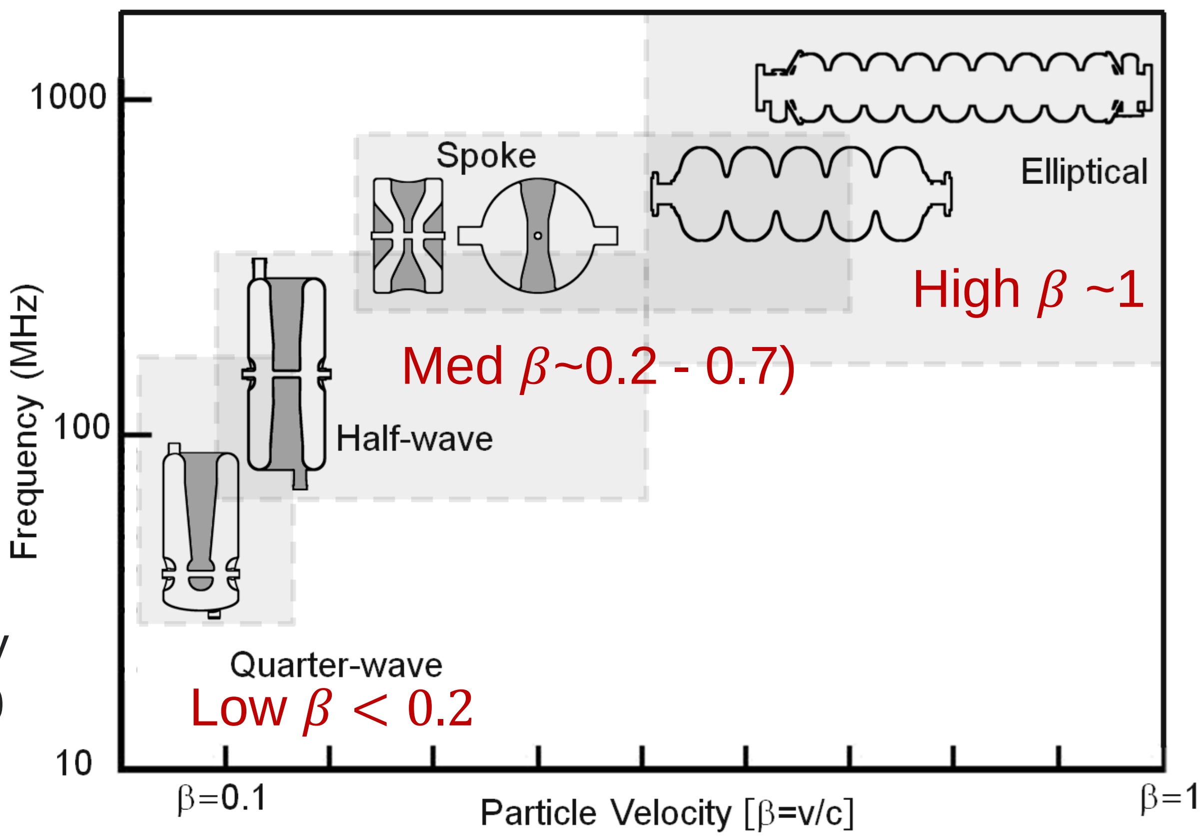
November 30, 2021

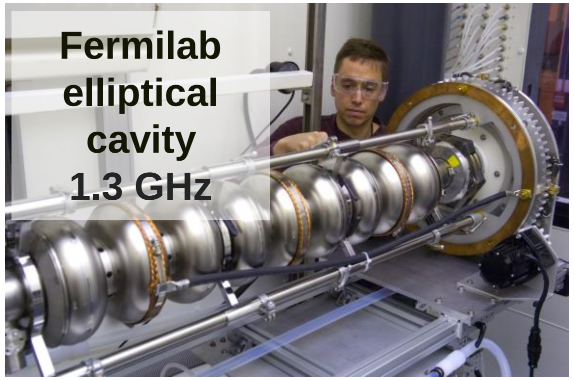
The Present Paradigm for CW Accelerators like ATLAS

Modern linear accelerators based on cavities fabricated from high purity Nb

- Cavity designs flow from:
  - Specific accelerator needs (particle energy, desired voltage, current etc.)
  - Material properties of niobium
- For our interest → Low-β acceleractors
  - QWR is generally the most efficient geometry
  - Niobium → large, ~100 MHz

Common shapes for modern SC cavities





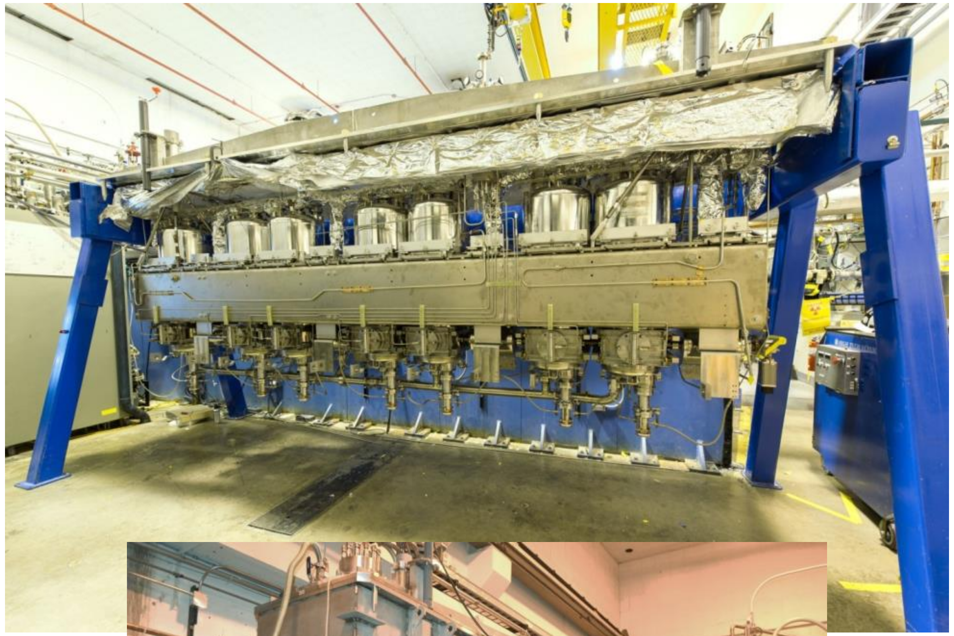
Motivation for this work

Low-beta cryomodule with 100 MHz cavities are large, module cost of order ~$10M in low quantity

- Goal: *Transformational cost reductions*
- Higher gradient? Niobium is near limits; ***and*** even with new materials, improvements difficult due to field emission (dirt)
- Future ATLAS upgrades, applications like medical isotopes much more attractive if $↓

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

2009 ATLAS Energy Upgrade Cryomodule



2014 ATLAS Energy and Intensity Upgrade Cryomodule

Main goal of the project

Demonstration of high-frequency ion linac cavity from Nb_3Sn

- A foundationally new approach to the design, fabrication and operation of ion linear accelerators
- Ion linacs several times smaller, cheaper and less complex than today's niobium based accelerators
  - *Implications of successful niobium-tin are different than for elliptical cavities*
    1. "2 Kelvin" performance at 4.5 Kelvin is one advantage in terms of cryogenics (much smaller helium refrigerators or cryocoolers)
    2. ***However, for ion linacs, the combination of negligible (BCS) surface resistance (RF losses), while simultaneously using higher cavity frequency by 2-4 times, can be used to achieve a transformational reduction in cavity, cryomodule, subsystem costs***

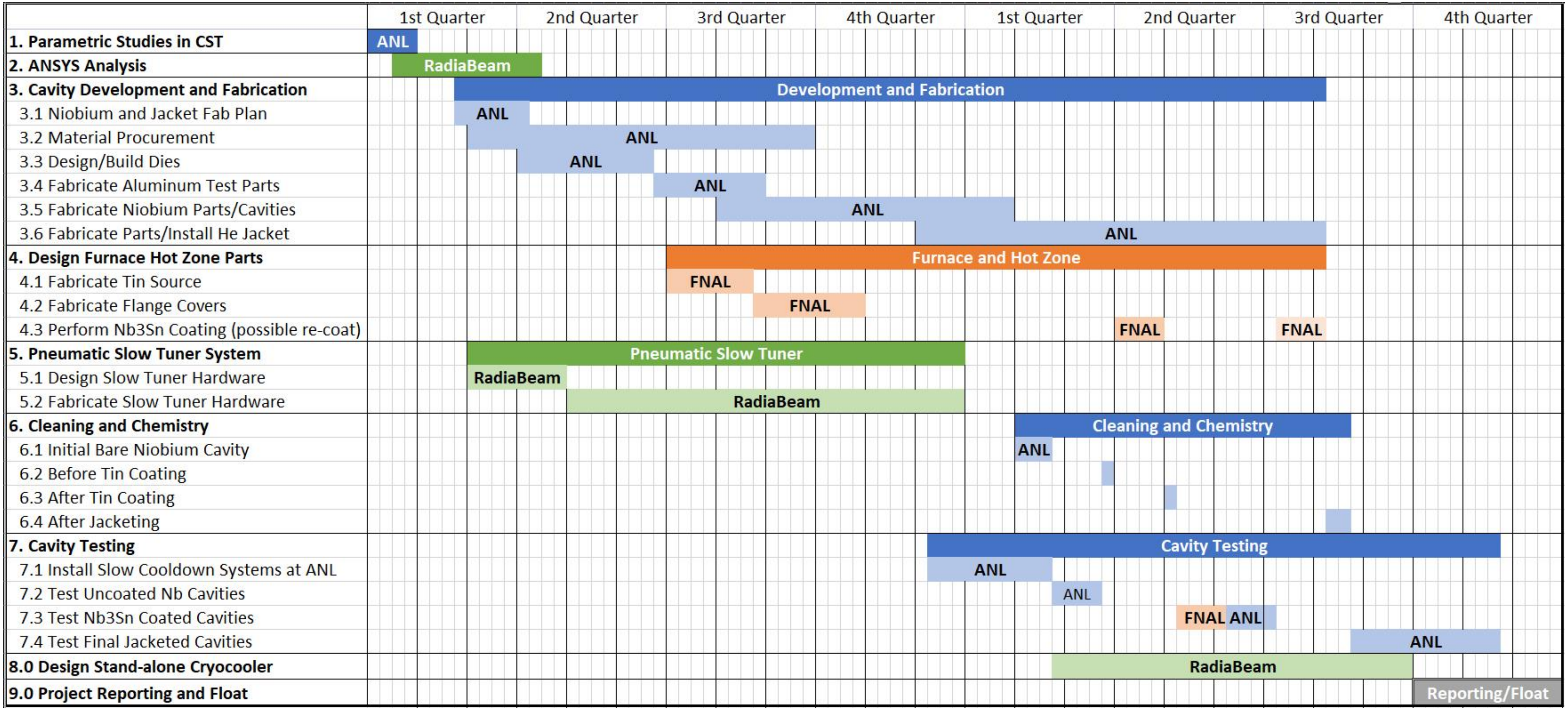
New 218 MHz QWR and existing ATLAS 72 MHz cavity

Annual budget and the total received to date

	FY21 ($)	FY22 ($)	Totals ($)
a) Funds allocated	598,185	598,185*	1,196,370
b) Actual costs to date	444,738	172,904	617,642

*Based on planned FY22 RadiaBeam invoices of $80K

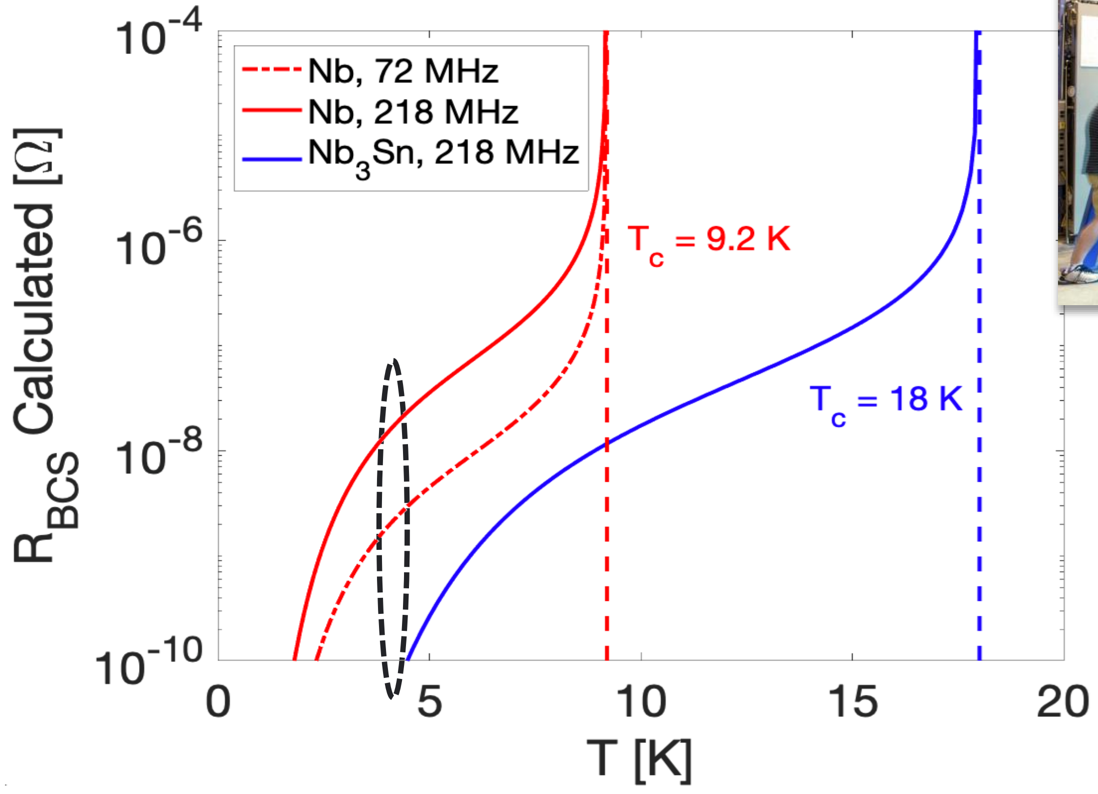
Major Deliverables and Schedule

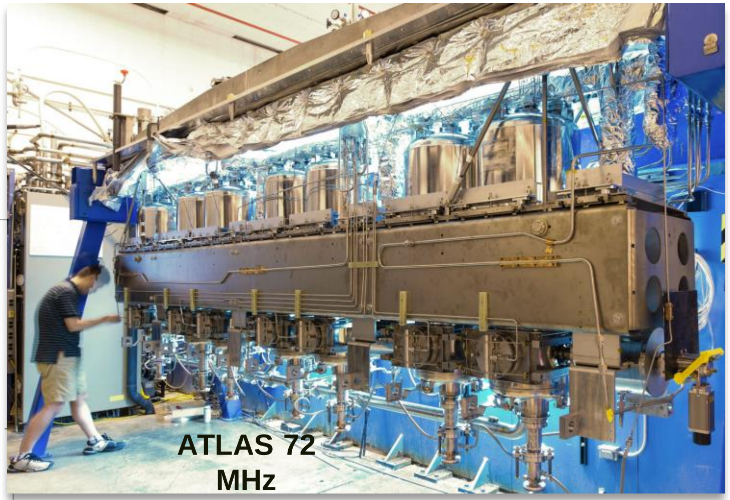


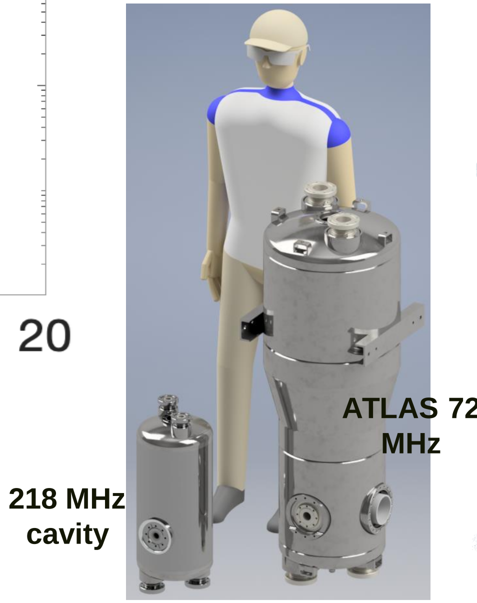
Technical Description and Current Status

'Why use Nb_3Sn and what does it offer for a quarter-wave?'

- Present state: *Ion linacs are built from large ~1+ meter long niobium cavities*
  - Niobium $R_s \approx$ several 10's $n\Omega \rightarrow$ Cryomodule loss ~100 Watts in 4.5 K helium (dot-dash red curve)
- Small (high frequency) niobium cavities would have very high losses into helium (solid red)
- Cavities from niobium-tin can be simultaneously small (>200 MHz) and have low RF losses (solid blue)



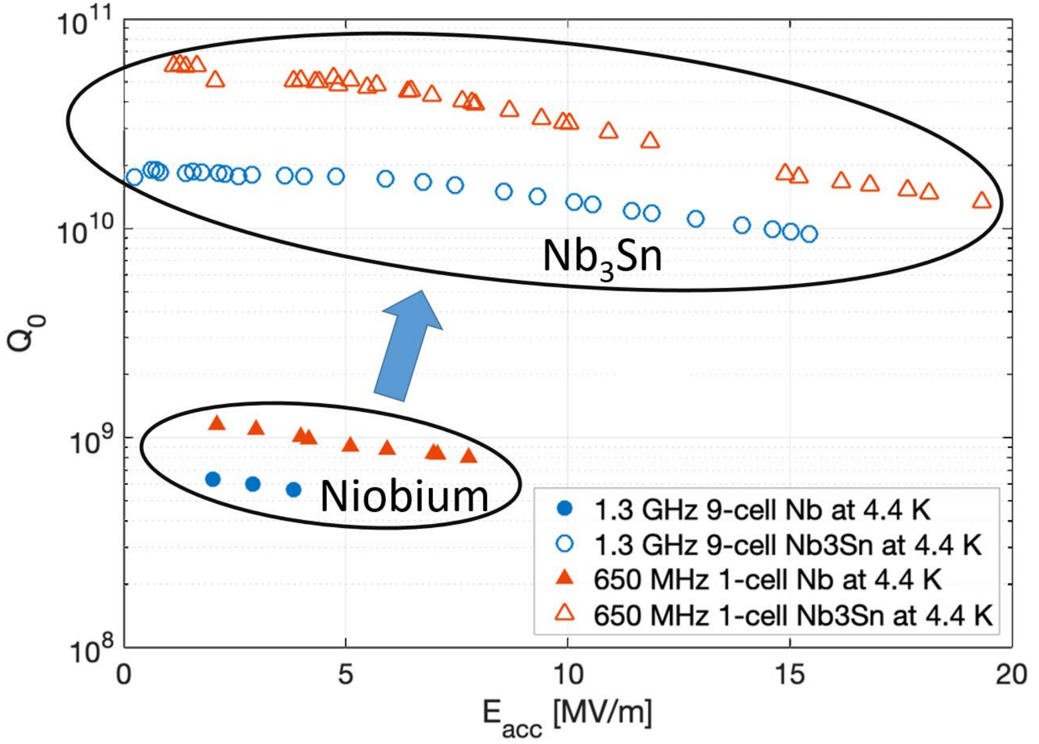




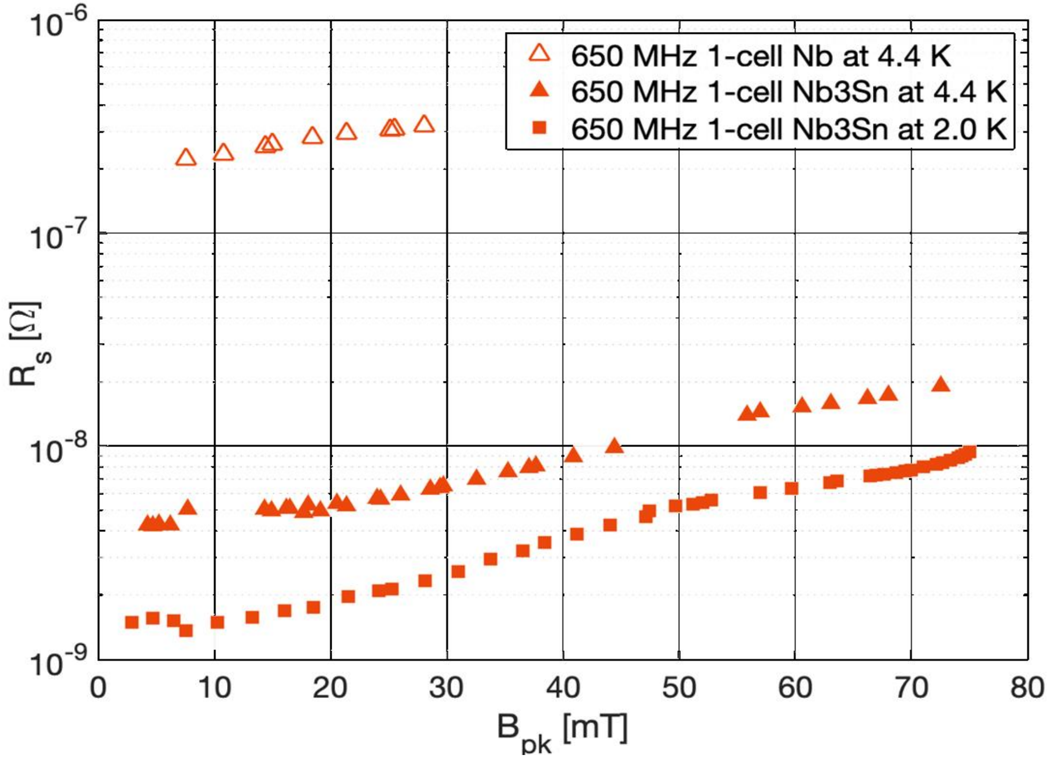
Size for a two-cavity module

This work has been going on for 10+ years, what's to show? Results of Nb_3Sn cavities coated at FNAL

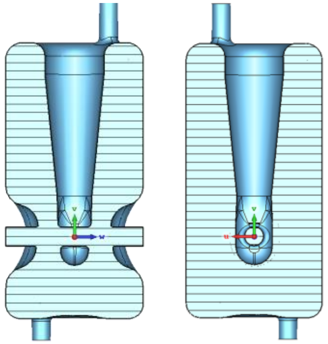
Cavity quality factors before and after coating

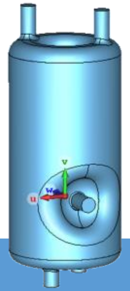


Associated surface resistance before/after coating



Message: Fermilab and others are producing Nb_3Sn cavities with useful performance





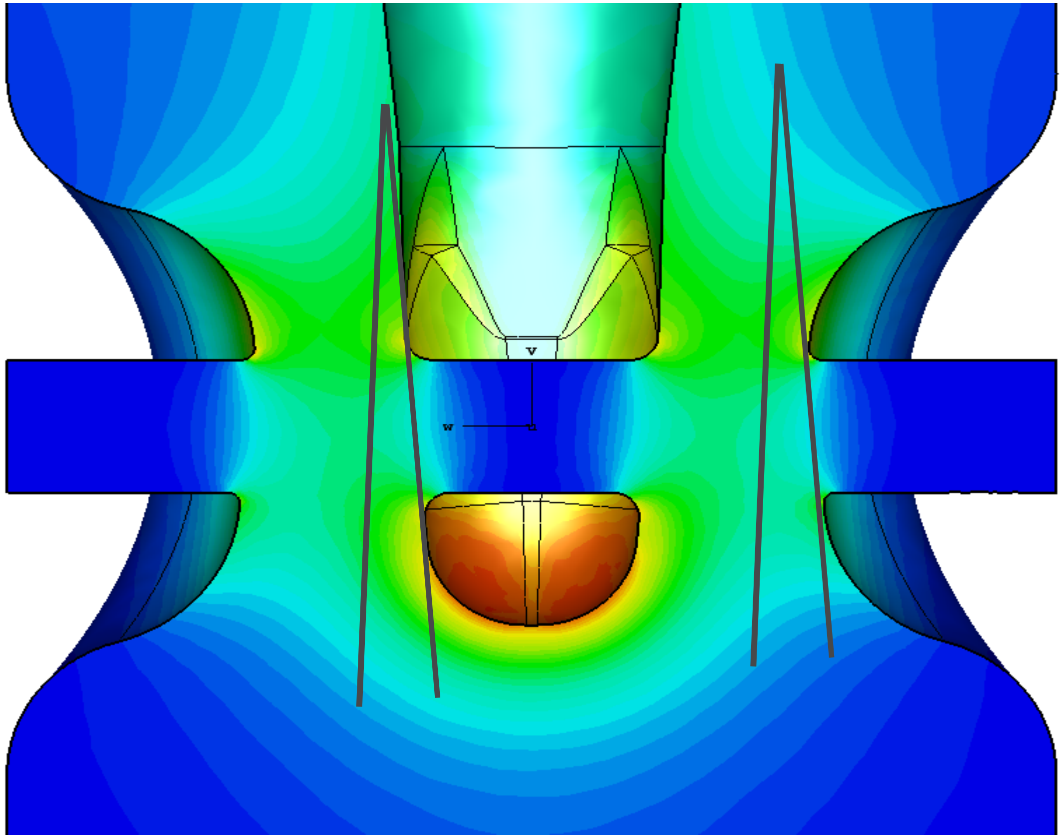
Final Electromagnetic Design

Deliverable 1

Includes all features, including steering correction, needed for useful cavity

Parameter	Value	Unit
Frequency (as simulated)	217.9	MHz
Beta (peak)	0.12	
Planned Voltage	1.3	MV
R/Q	445	Ohm
G	44	Ohm
E_{PEAK}	45	MV/m
B_{PEAK}	***54***	***mT***
$P_{dissipated}$ @ Q=1e10	0.39	Watts

Reasonably achievable goal

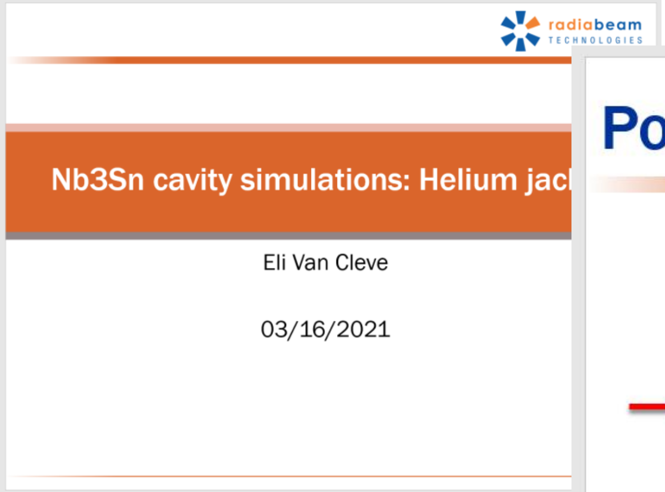


5 degree tilt on drift-tube faces produces transverse electric field that cancels on-axis magnetic field steering

Mechanical Analysis

Deliverable 2

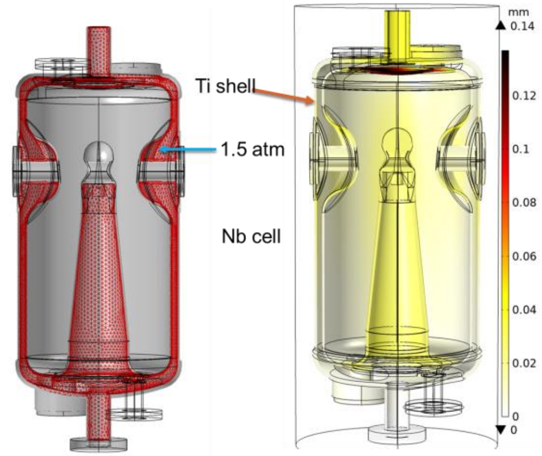
Similar as for standard niobium, combination of helium pressure and mechanical tuner


radiabeam TECHNOLOGIES

Nb3Sn cavity simulations: Helium jac

Eli Van Cleve

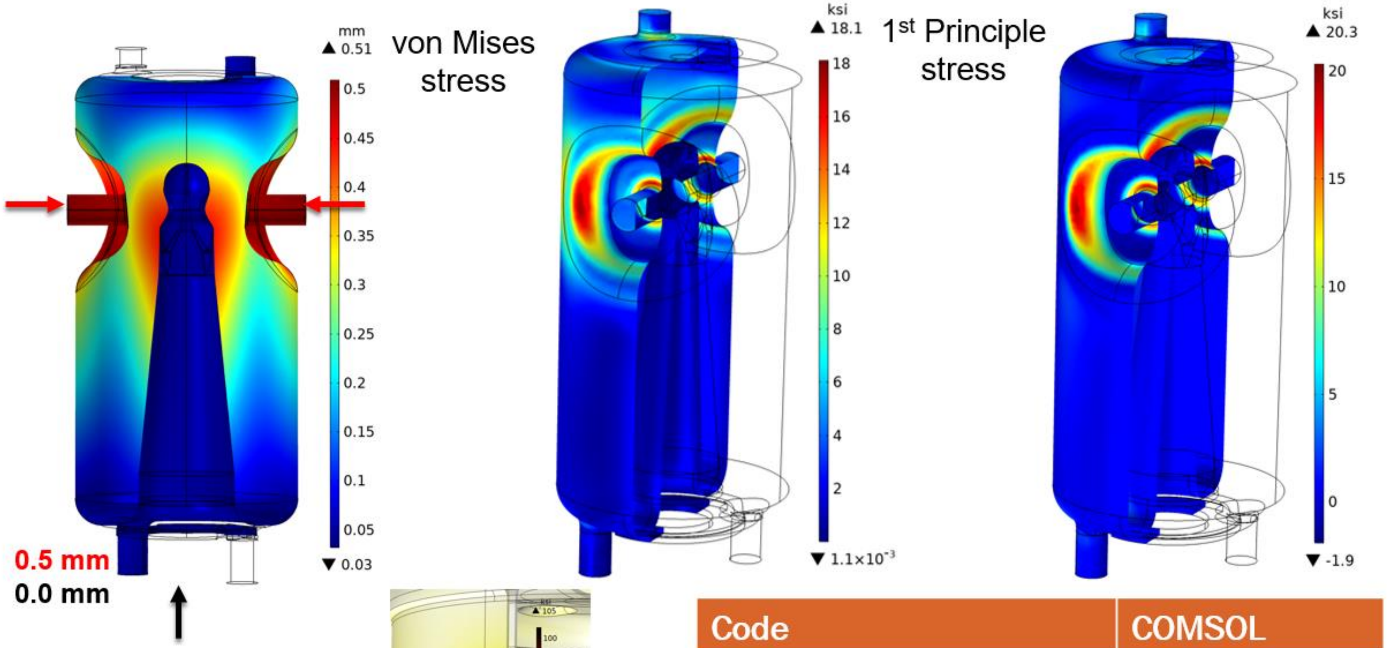
03/16/2021

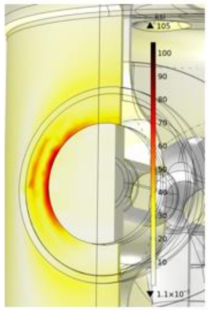


Working model

Port deformation: 1.5 atm + 0.5mm

radiabeam TECHNOLOGIES





Code	COMSOL
Max. von Mises, ksi	18.1
Max. principal, ksi	20.3
Frequency shift, kHz	-277.06
Max. deformation, mm	0.51

Stresses are tolerable and with a large useable tuning range

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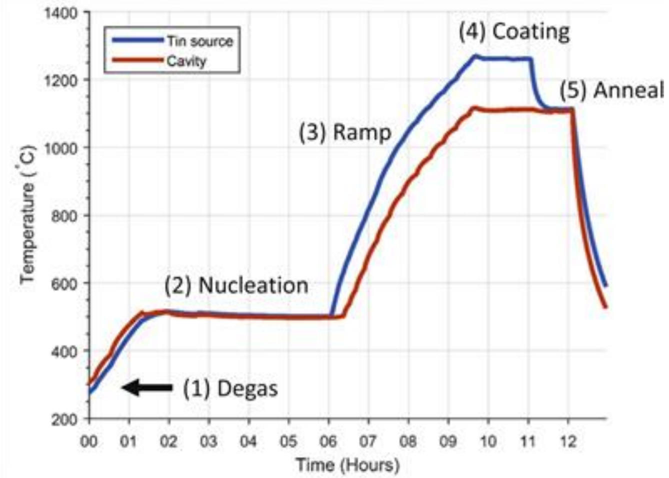
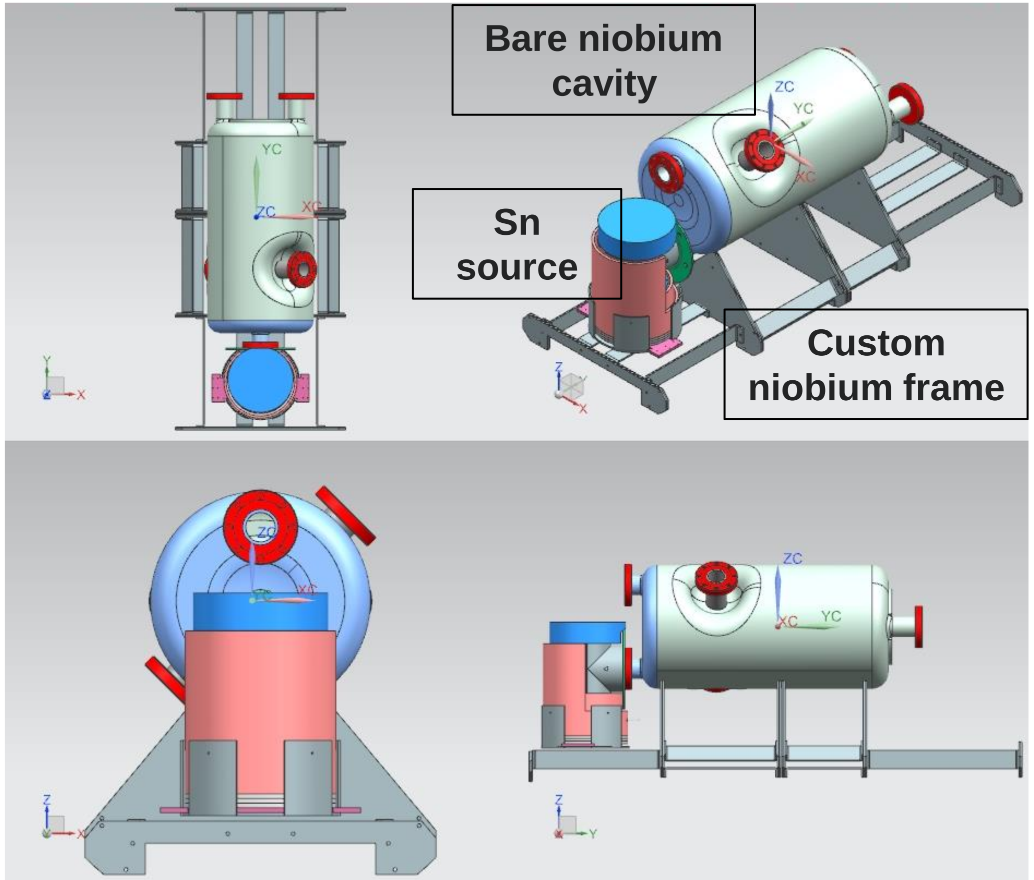
Plan for Coating a Quarter-wave Cavity

Deliverable 4

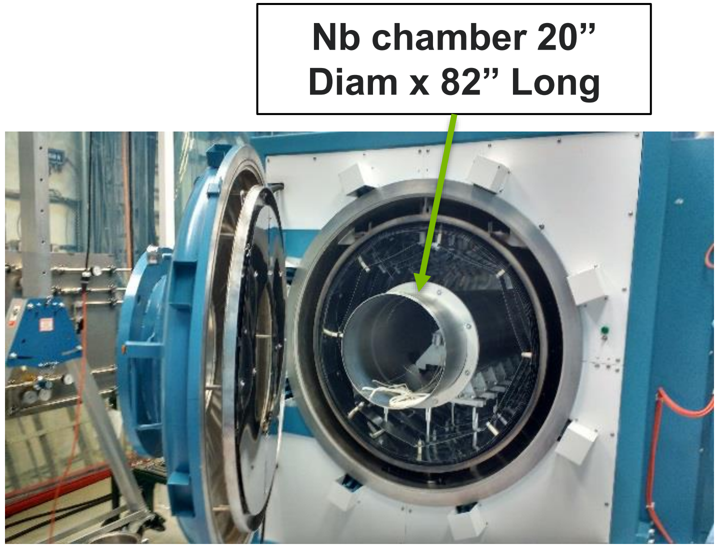
Fermilab



Typical coating process



Hardware design for quarter-wave cavity in furnace (most recent plan will use two Sn sources, post-coating optical/visual inspection good preliminary indicator of success)



Nb_3Sn coating furnace at Fermilab

Cavity Development and Fabrication

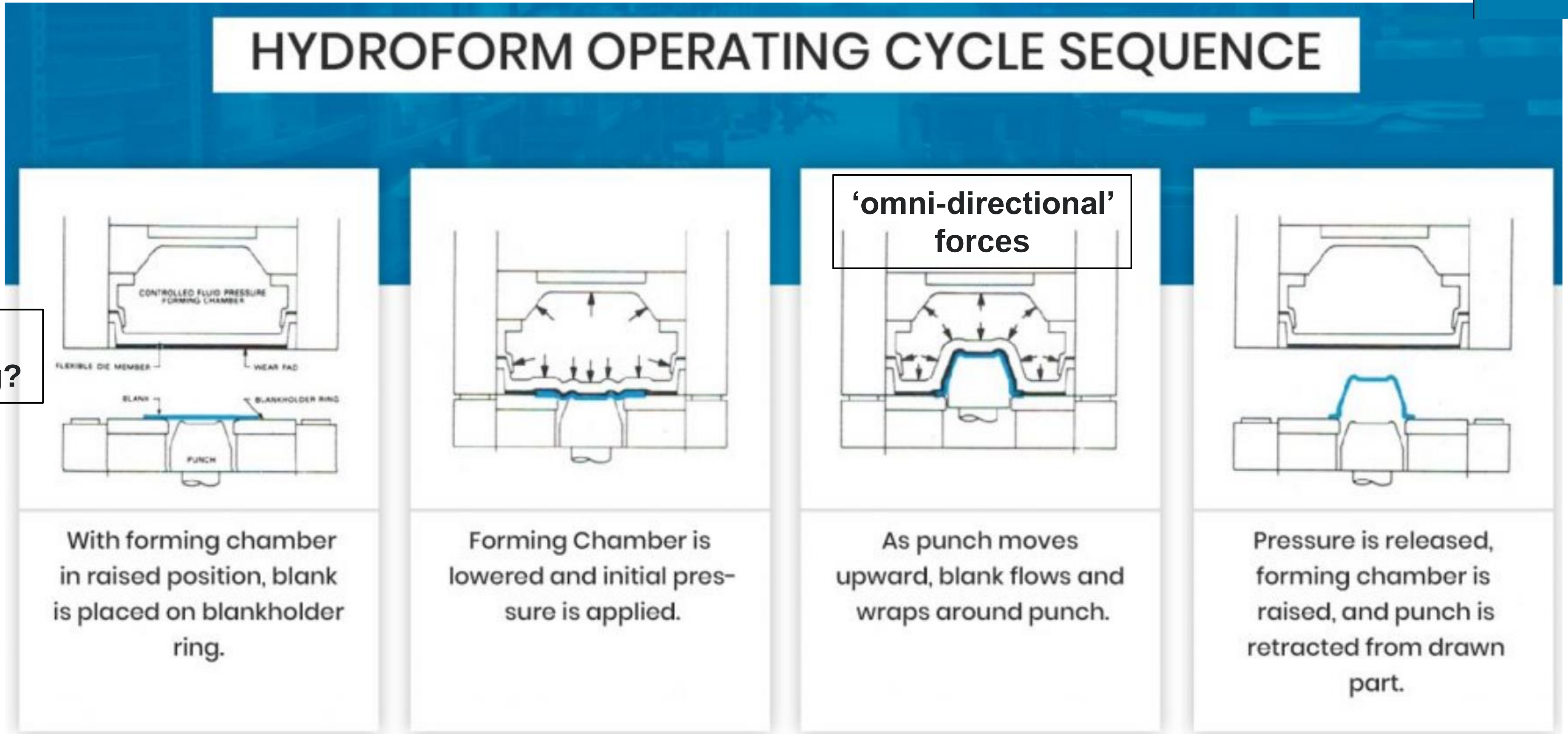
Deliverable 3

No present U.S. vendors for finished niobium cavities

- Situation: AES out of business, Roark has some, but not all capabilities, European vendors costly/slow
- Approach: In the tradition of ANL development of US partners for accelerators (Meyer Tool, Sciaky, Andersen Dahlen) ***we are working with a new U.S. vendor for niobium cavity parts***

Stuecklen MFG. CO.

Why hydroforming?



'omni-directional' forces

Answer: to form complex niobium parts as efficiently as possible

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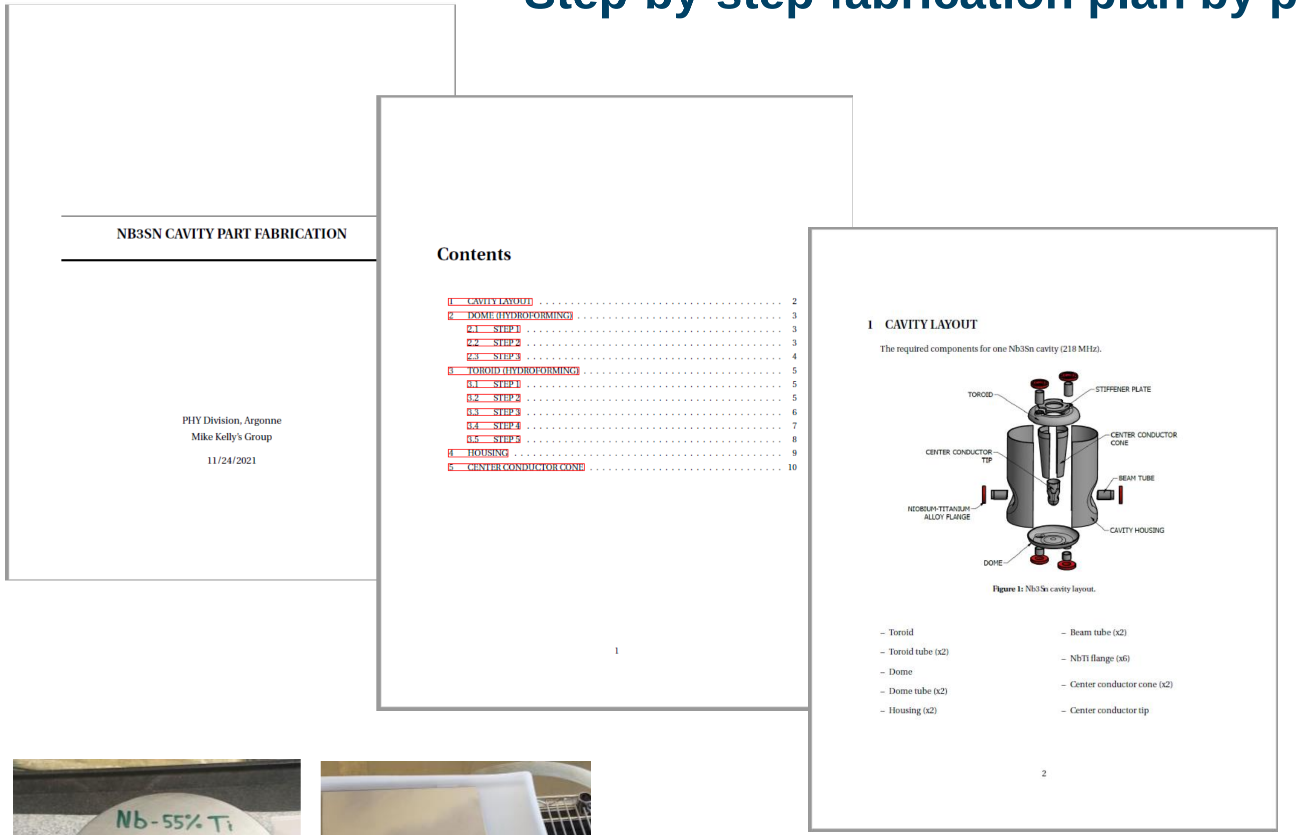
Cavity Development and Fabrication

Deliverable 3

Step-by-step fabrication plan by postdoc Gongxiaohui Chen



NB3SN CAVITY PART FABRICATION

PHY Division, Argonne
Mike Kelly's Group

11/24/2021

Contents

1

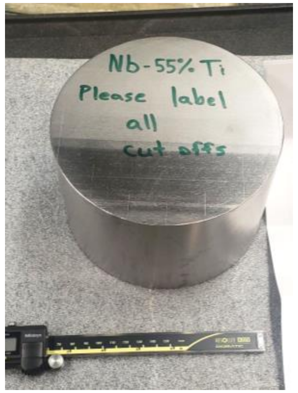
1 CAVITY LAYOUT

The required components for one Nb3Sn cavity (218 MHz).

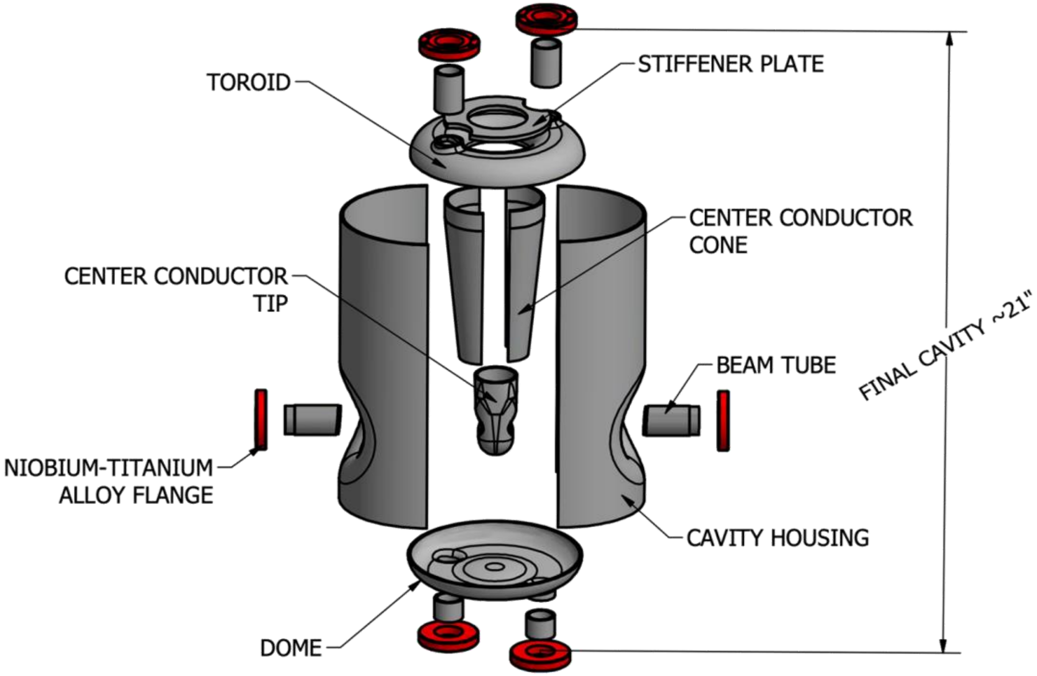
Figure 1: Nb3Sn cavity layout.

- Toroid
- Toroid tube (x2)
- Dome
- Dome tube (x2)
- Housing (x2)
- Beam tube (x2)
- NbTi flange (x6)
- Center conductor cone (x2)
- Center conductor tip

2



NbTi and niobium ordered, received March 2021



- ☑ Beam/port tubes (wire EDM)
- ☑ NbTi flanges (wire EDM)
- ☑ Dome (hydroforming + coining)
- ☑ Toroid (hydroforming + coining)
- ☐ Housing
- ☐ Center conductor cone
- ☐ Center tip

Cavity bottom dome hydroforming

Deliverable 3

(Only niobium hydroforming in U.S. today)

2 DOME (HYDROFORMING)

The dome of the Nb3Sn cavity was made by using the hydrofroming technique, and was fabricated at a local machine shop- Stuecklen Manufacturing Co. (10020 Pacific Ave, Franklin Park, IL 60131).

The following subsections demonstrate the detailed forming process of the cavity dome. A 12" by 12" square Nb blank was prepared for the dome fabrication.

2.1 STEP 1

Figure 2: Step 1 forming.

ANL-designed aluminum hydroforming dies

2.2 STEP 2

Figure 3: Step 2 forming.

2.3 STEP 3

Figure 4: Step 3 coining.

3

'low RRR' test (left), production parts (middle), test dome w/ ports (right) – September 2021


One of three large hydroforming presses at Stuecklen

Cavity toroid hydroforming

Deliverable 3

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.

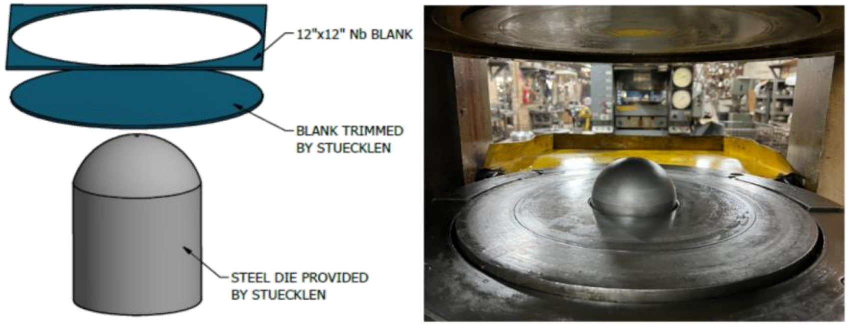


Figure 5: Step 1 forming.

3.2 STEP 2

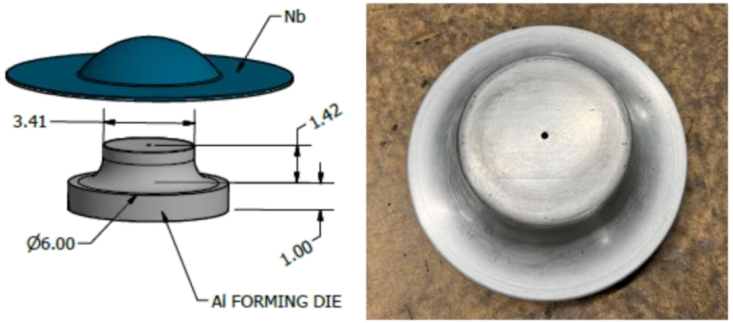


Figure 6: Step 2 forming.

3.3 STEP 3

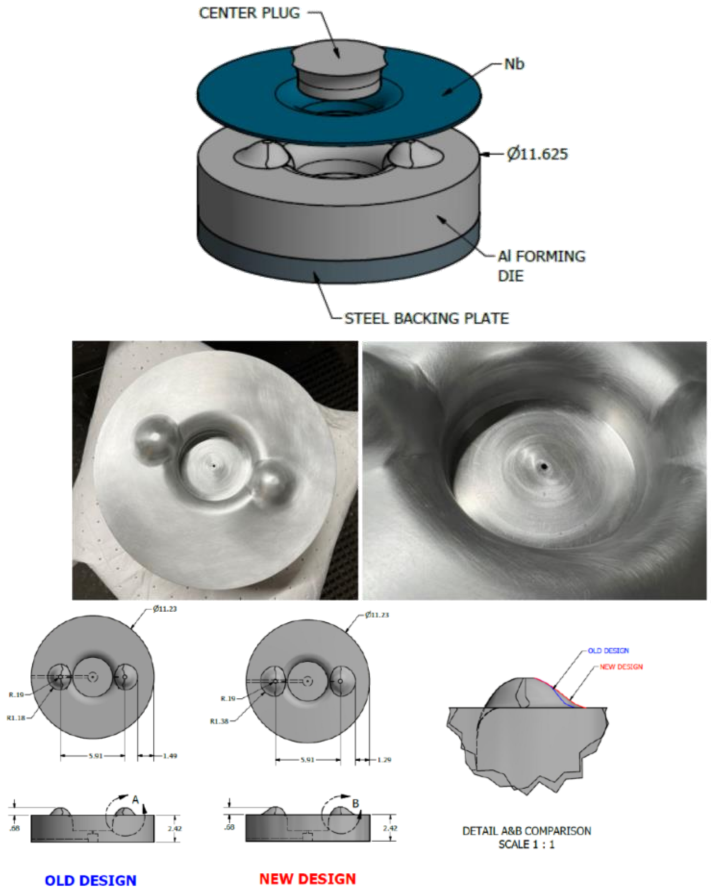


Figure 7: Step 3 forming. Note: the nub shown in the old design follows the profile of the nub used in the dome. The new design was adopted in the final toroid die.

Cavity toroid hydroforming

Deliverable 3

3.4 STEP 4

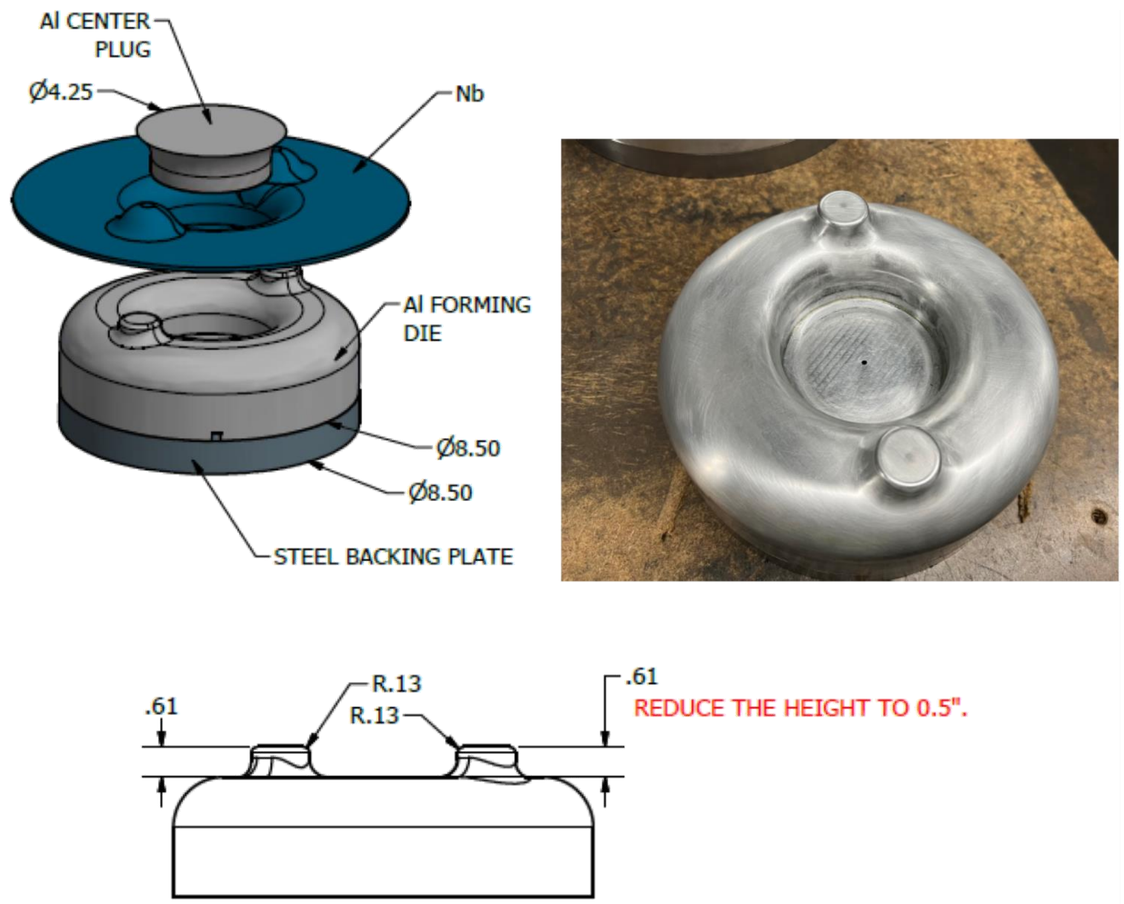


Figure 8: Step 4 forming. Note: the Al die was modified later at ANL Central Shops on 9/28/2021

3.5 STEP 5

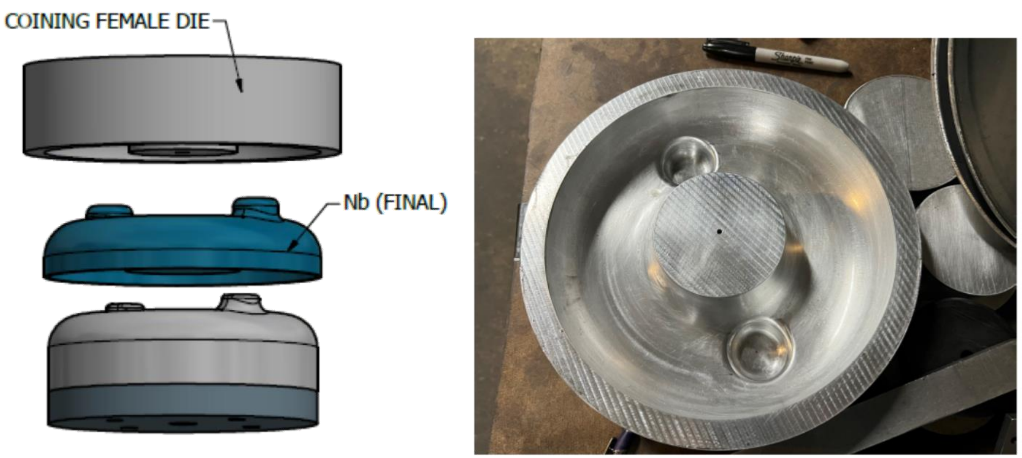


Figure 9: Step 5 coining.

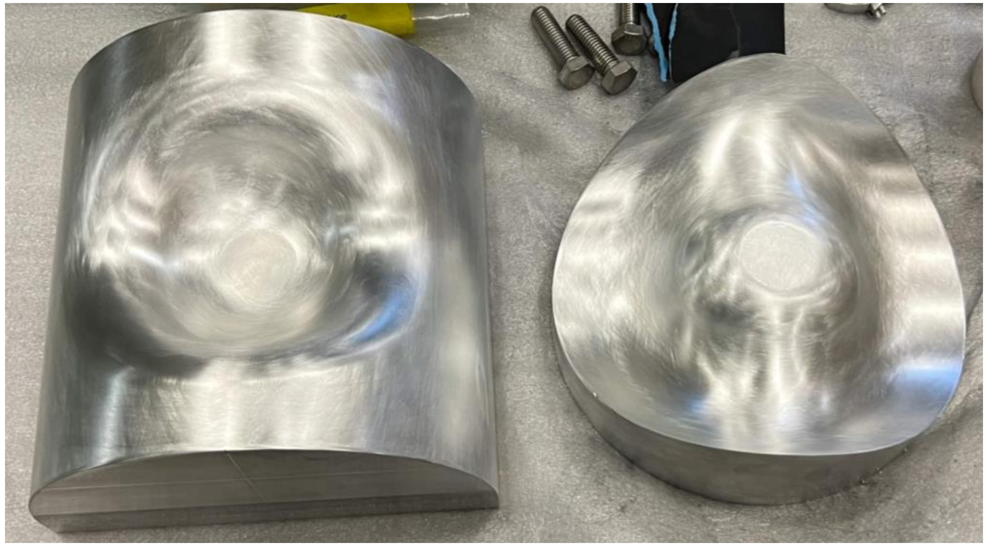
Aluminum, low RRR and final niobium toroids (left to right) – November 2021

Cavity Outer Housing Deep Drawing

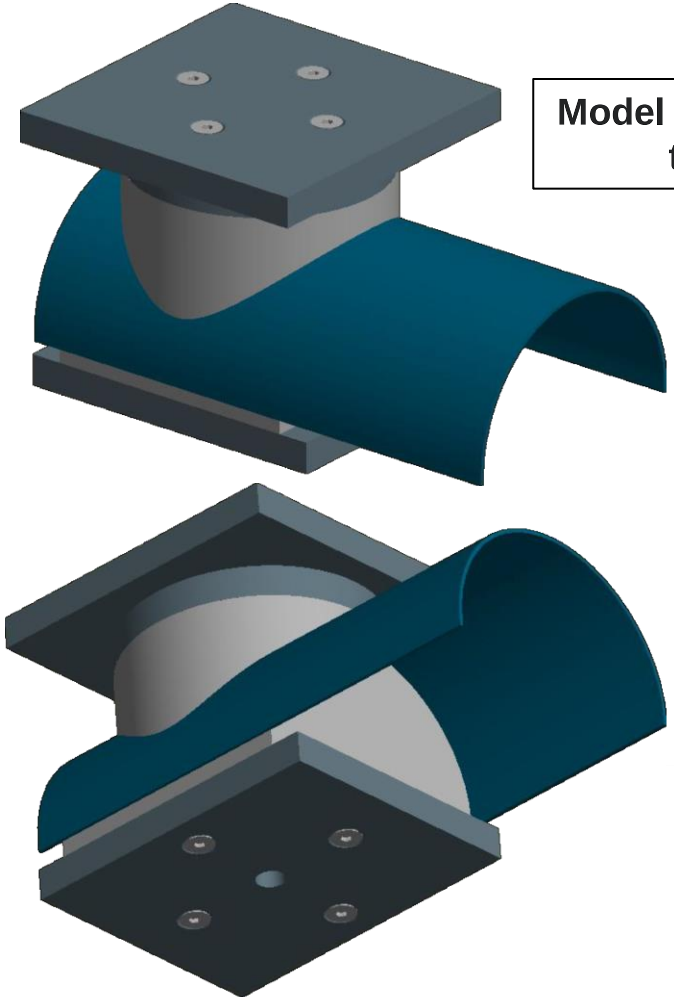
Deliverable 3

A ‘simple’ half cylinder with a re-entrant nose is easier by this method

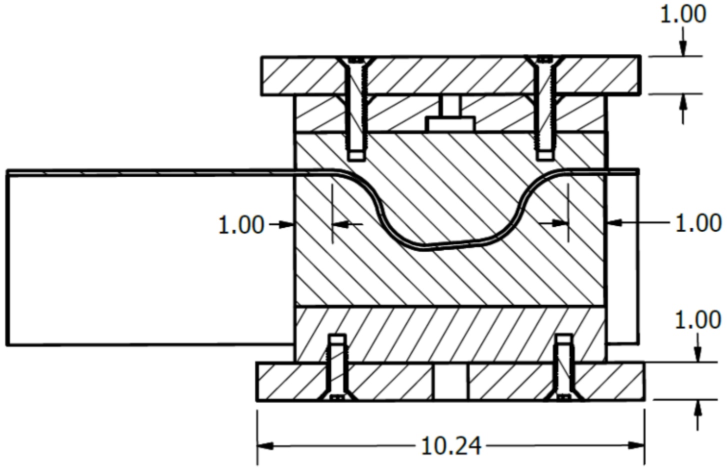
This is our present activity as of Nov./Dec. 2021



Aluminum dies for the noses and ‘practice’ aluminum 6061-O half shells



Model of deep draw tooling



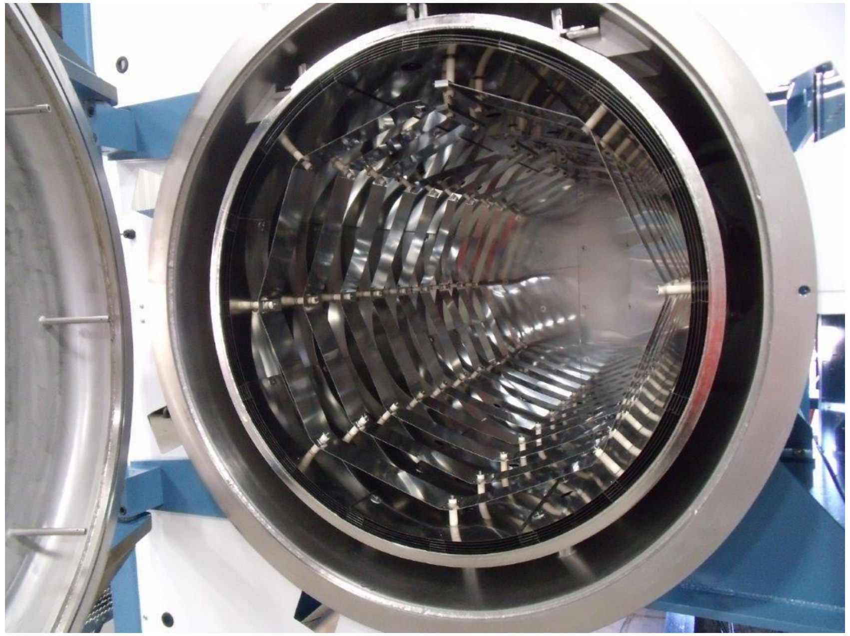
New Argonne Furnace

Deliverable 3

Key missing component from ANL cavity processing facility

- Present workflow requires large number of SRF cavity shipments (100-200 per year between ANL, FRIB, Fermilab)
- Furnace cost $1.05M, support infrastructure $400K
  - Support from ANL (2/3) and direct DOE/SC (1/3)
- Hydrogen degassing required for all of modern niobium cavities
- Future for next generation technologies, nitrogen infusion, Nb_3Sn
- Acc. group installed new compressor for helium recovery; providing expertise on helium purifier

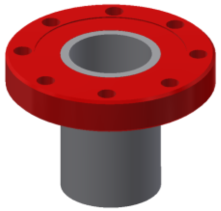
Furnace external cooling building 208



New ANL furnace will be ready for hydrogen degassing

6 Month Look Ahead

- Ensure these two cavities, if successfully coated, are useable
  - RadiaBeam has received cavity and tuner models and will design tuner hardware for the new cavity **Deliverable 5**
  - However, RadiaBeam, rather than fabricating the tuner now, will focus on helping ANL finish the cavities (ports and niobium center conductor) **Deliverable 3 →**
- Fermilab will fabricate niobium support frame and port/flange covers required for the coating process **Deliverable 4**
- Argonne will complete the cavity housing, center conductor and electron beam weld niobium assembly and perform electropolishing **Deliverables 4, 6**
- The team is working together on the test plan (bare cavity, then coated cavity) **Deliverable 7**



Niobium port with NbTi flange

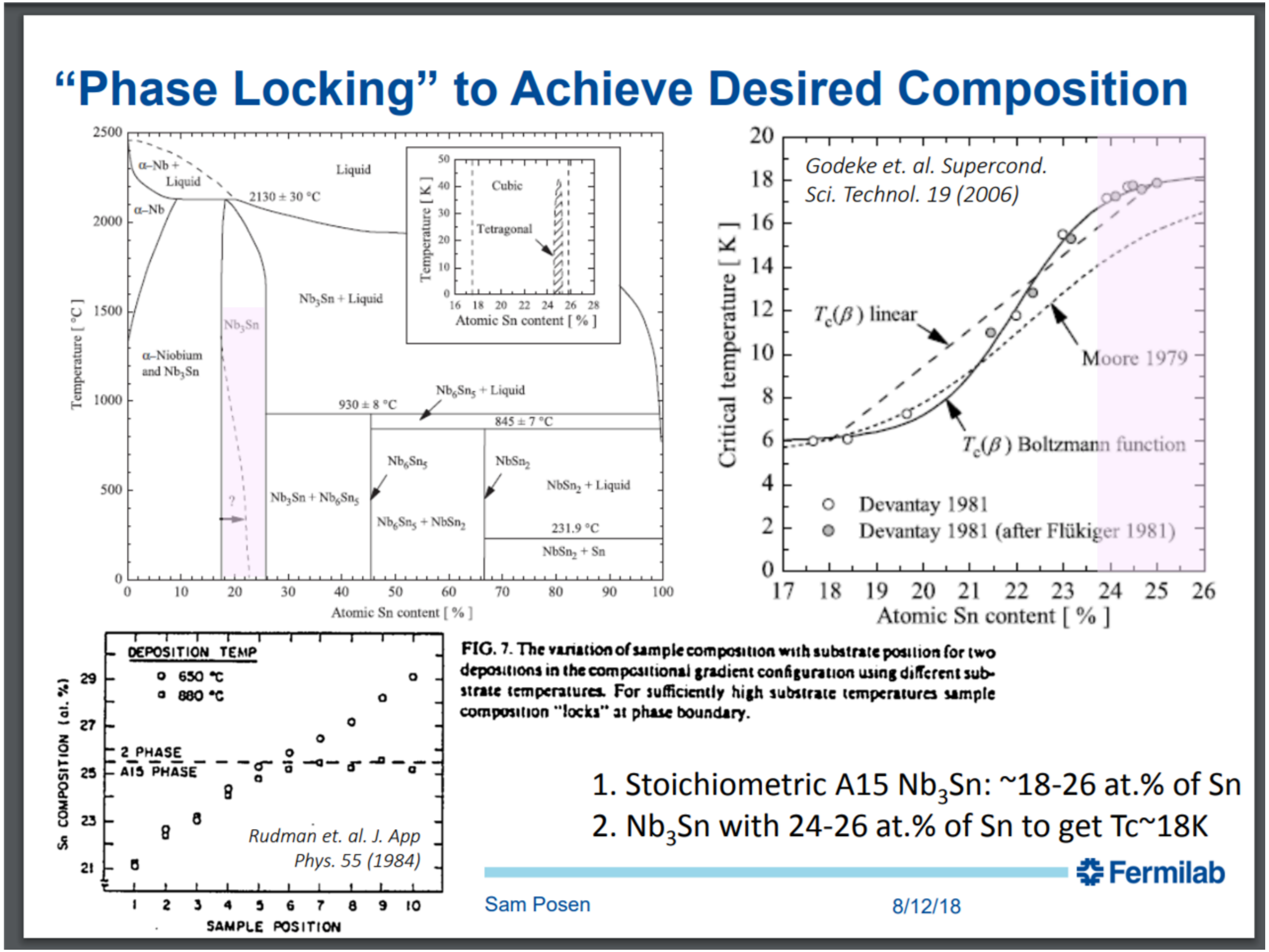
End of QWR center conductor

Thank you to collaborators and DOE/SC NP

ASME U-stamped helium vessel built with collider funds 2010

Backup

Backup



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