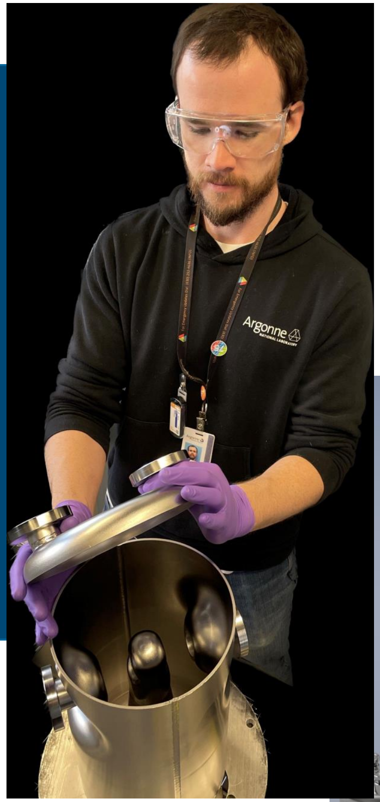
Development of Practical Niobium-Tin Cavities for Ion Linacs



Michael Kelly Accelerator Development Group Leader, Physics Division

Argonne Accelerator Development Group: **Ben Guilfoyle, Mark Kedzie, Troy Petersen, Tom Reid, Gongxiaohui Chen (moved to HEP)**

Fermilab Technical Lead: **Sam Posen** RadiaBeam Technical Lead: **Sergey Kutsaev**

2022 NP Accelerator R&D and AI-ML PI Exchange Meeting

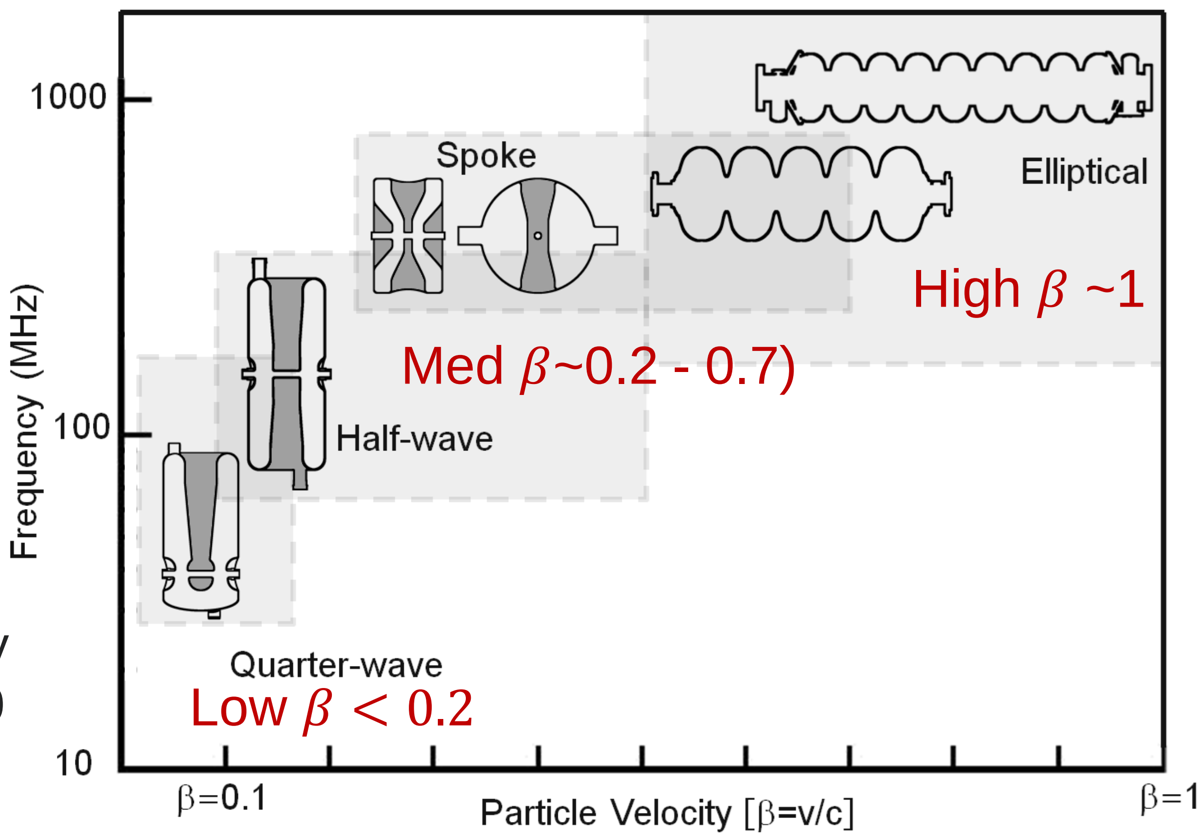
November 29, 2022

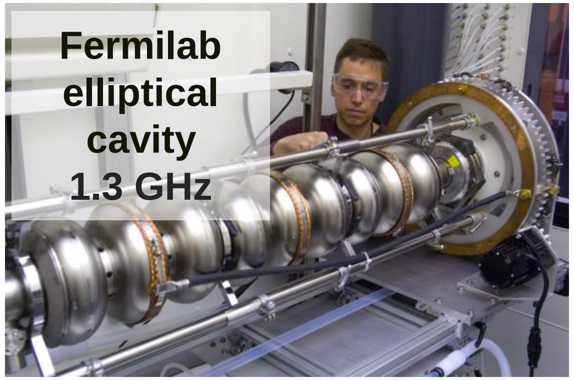
The present paradigm for CW Accelerators like ATLAS

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





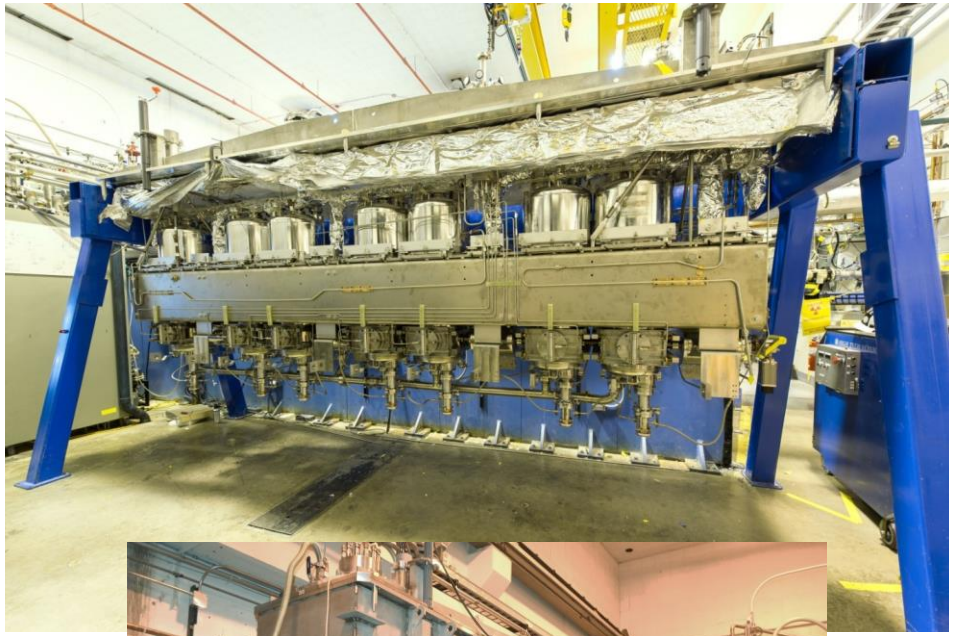
Motivation for this work

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

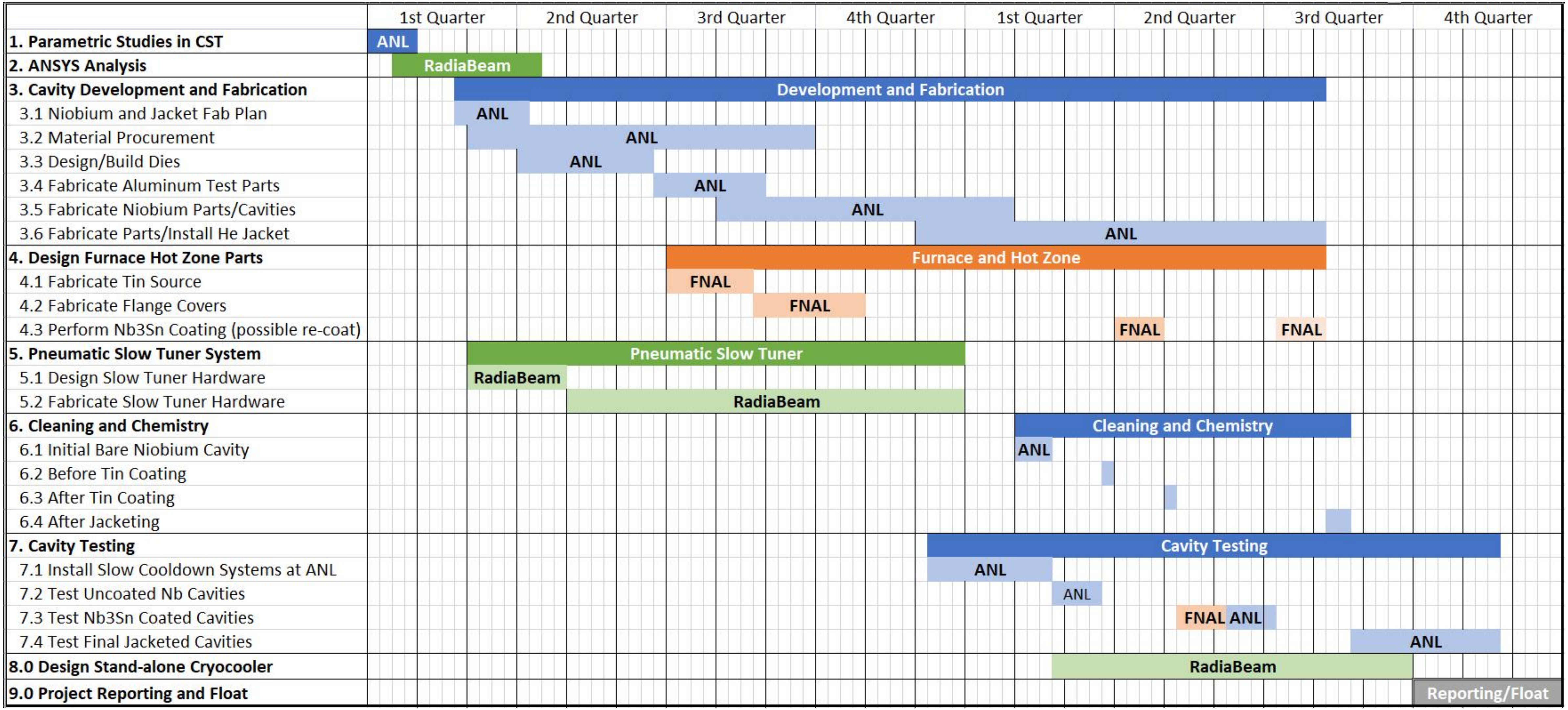
- A foundationally new approach to the design, fabrication and operation of ion linear accelerators
- Ion linacs several times smaller, cheaper and less complex than today's niobium based accelerators
  - *Implications of successful niobium-tin are different than for elliptical cavities*
    1. "2 Kelvin" performance at 4.5 Kelvin is one advantage in terms of cryogenics
    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

Summary of expenditures by fiscal year (FY):

	FY20 ($)	FY21 ($)	Totals ($)
a) Funds allocated	598,185	592,885	1,191,070
b) Actual costs to date	444,738	548,915	993,653

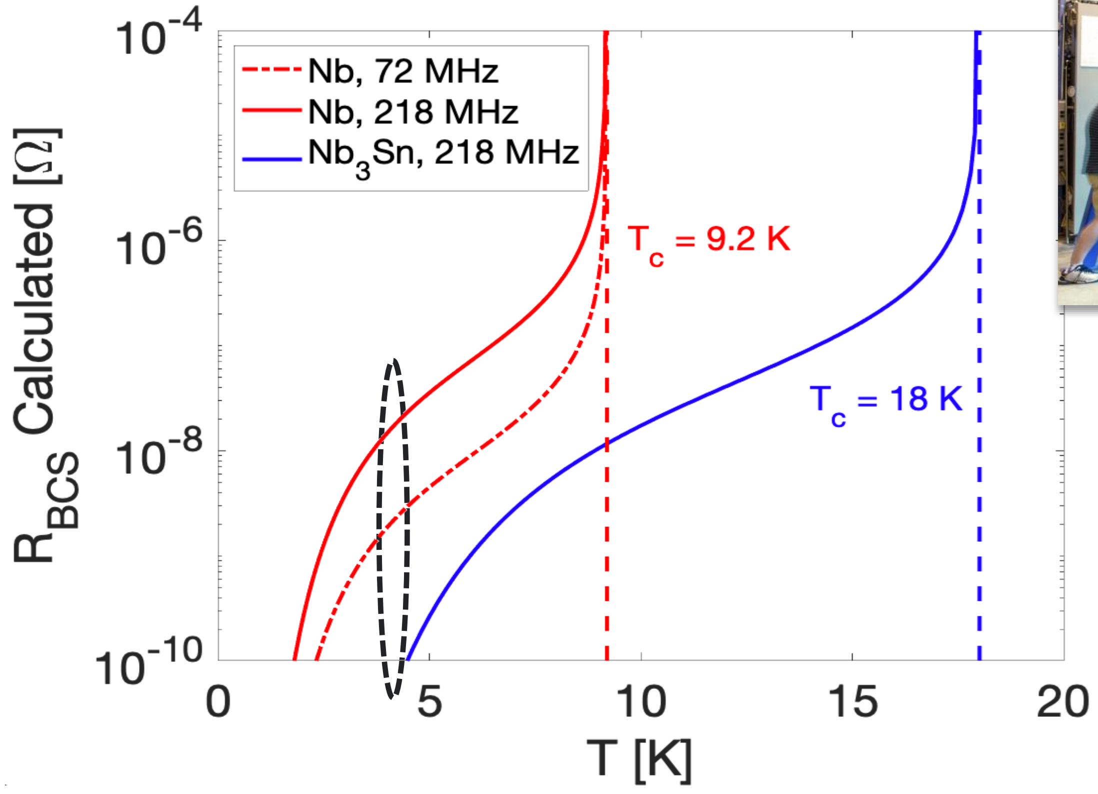
Major Deliverables and Schedule

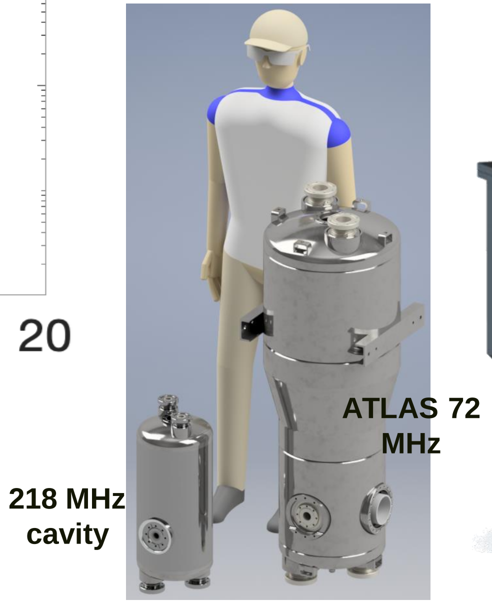


Technical Description and Current Status

‘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 nΩ → 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

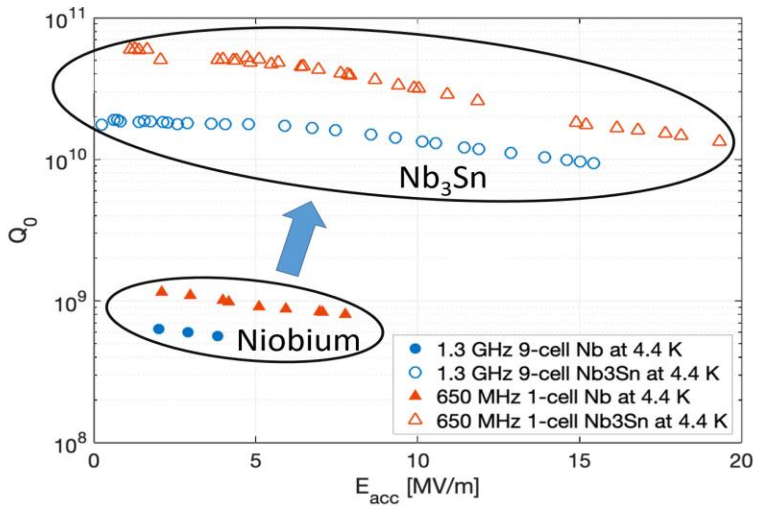




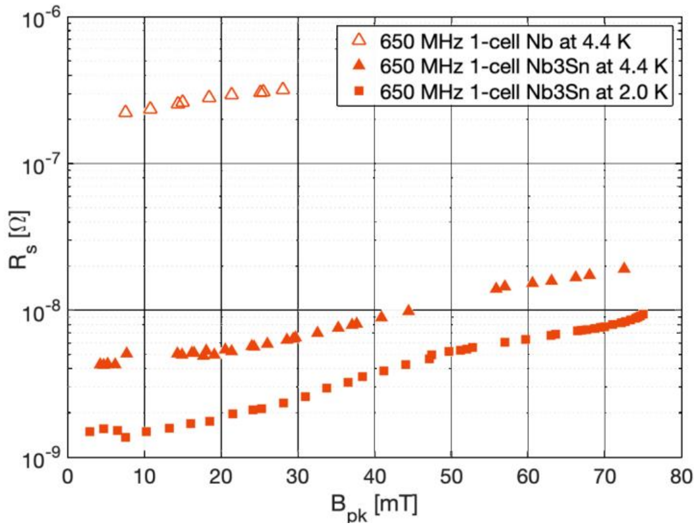
Size for a two-cavity module

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

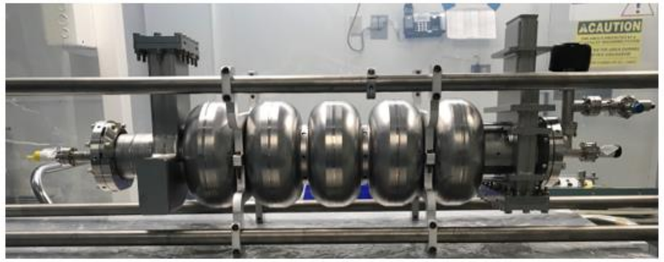
Cavity quality factors before and after coating

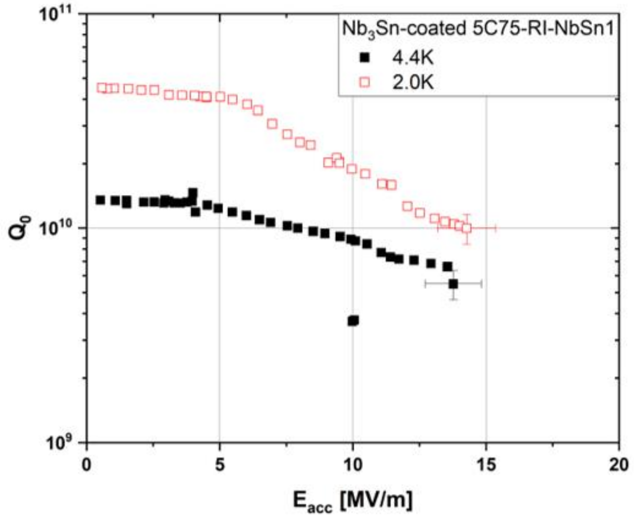


Associated surface resistance before/after coating



Five-cell CEBAF cavity with integral waveguides successfully coated with Nb3Sn



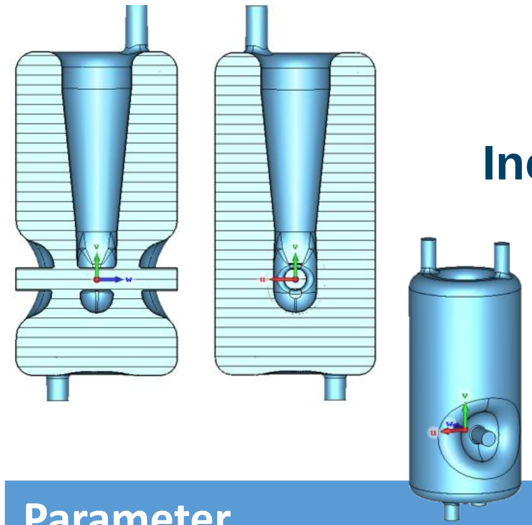


Message: Fermilab and others are producing Nb3Sn cavities with useful performance

Final Electromagnetic Design

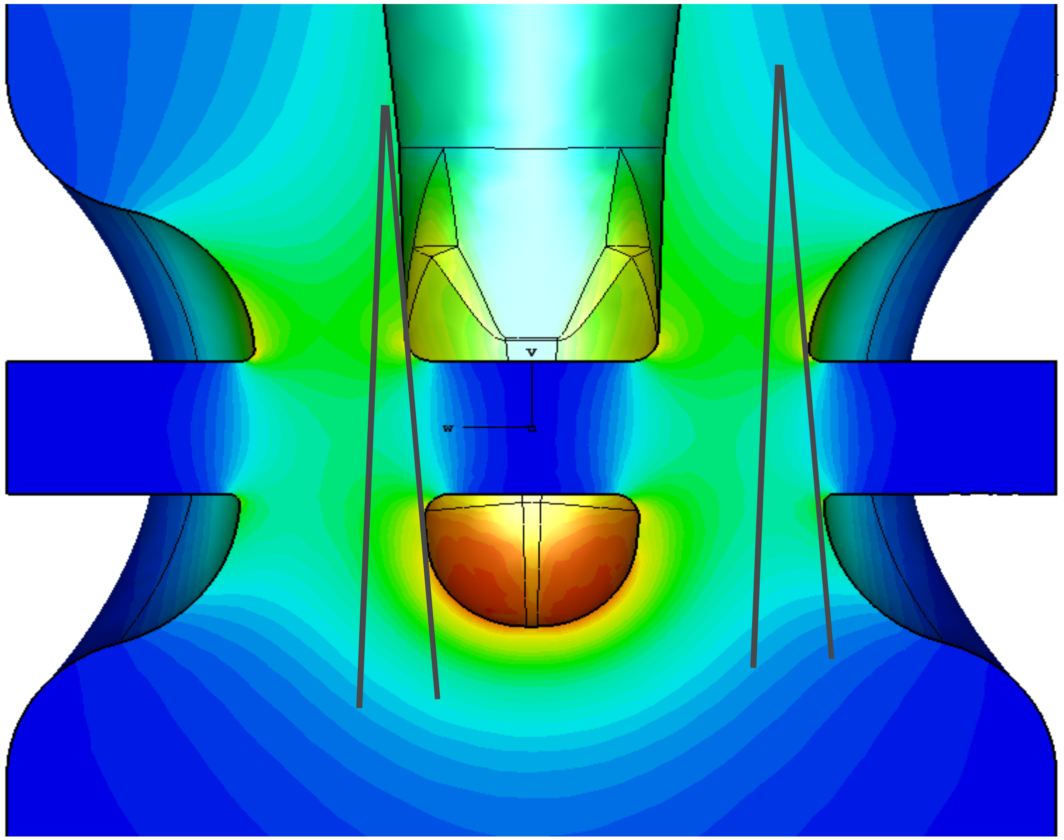
Deliverable 1

Includes quarter-wave steering correct need 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

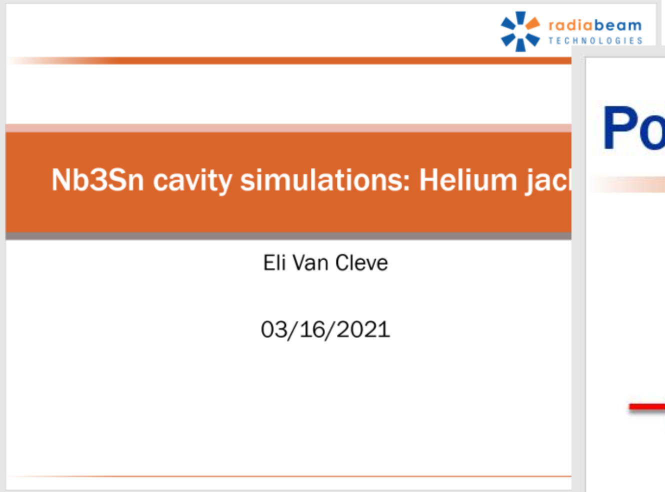


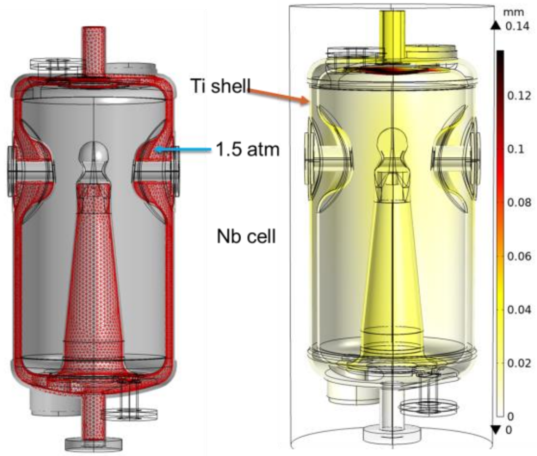
5 degree tilt on drift-tube faces produces transverse electric field that cancels on-axis magnetic field steering

Mechanical Analysis

Deliverable 2

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

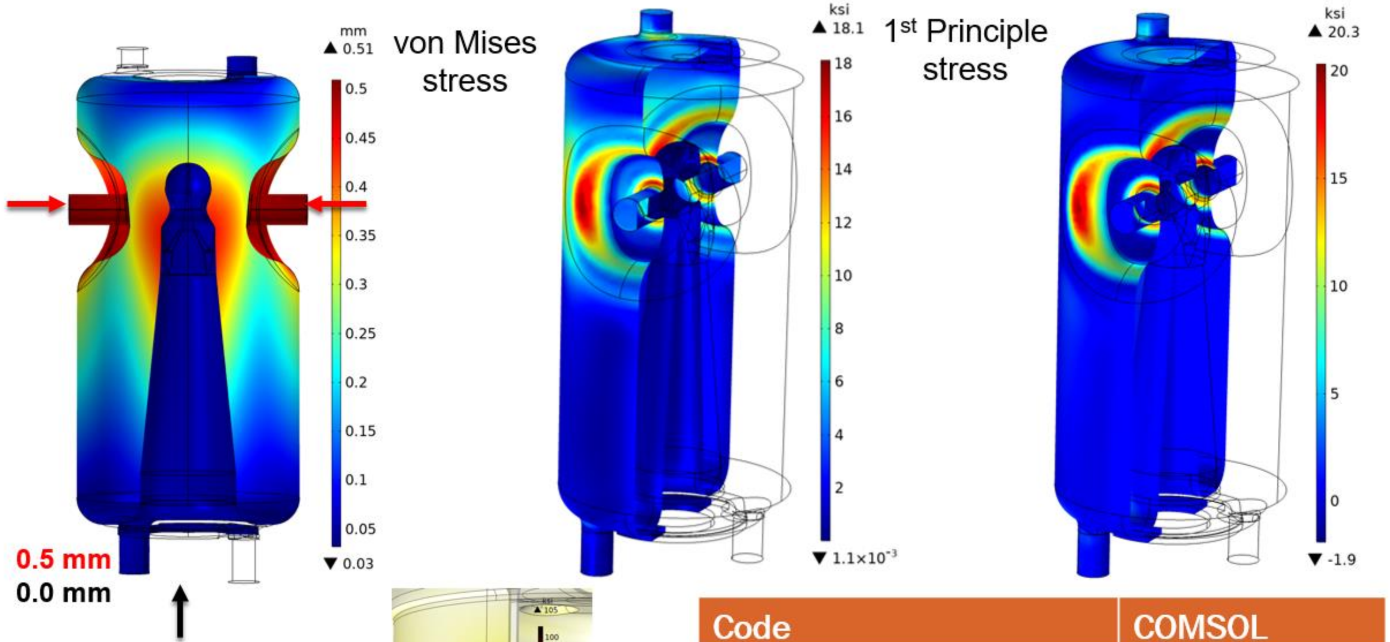


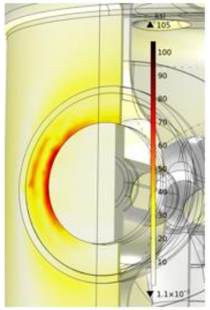


Working model

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

Cavity Development and Fabrication

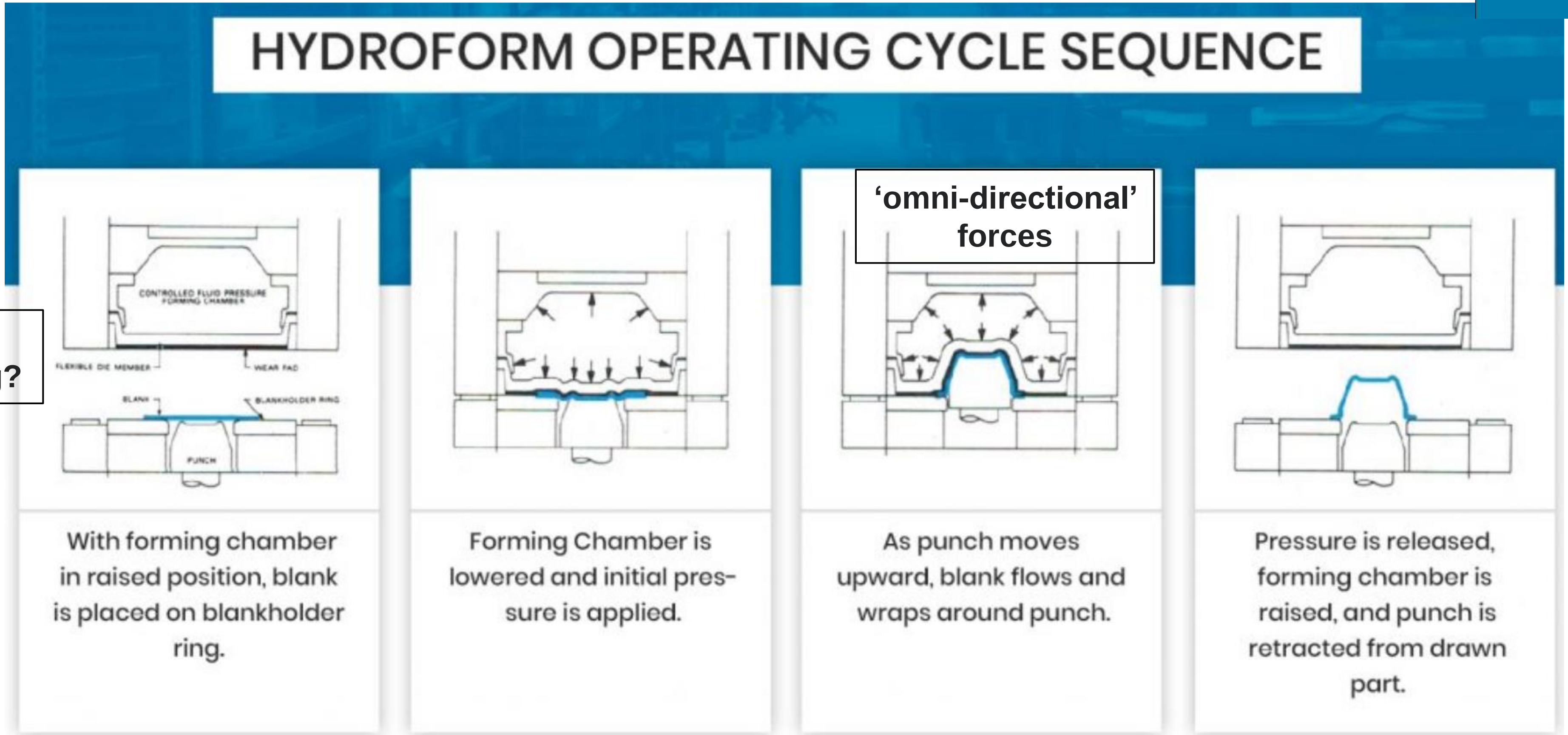
Deliverable 3

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 have developed and qualified 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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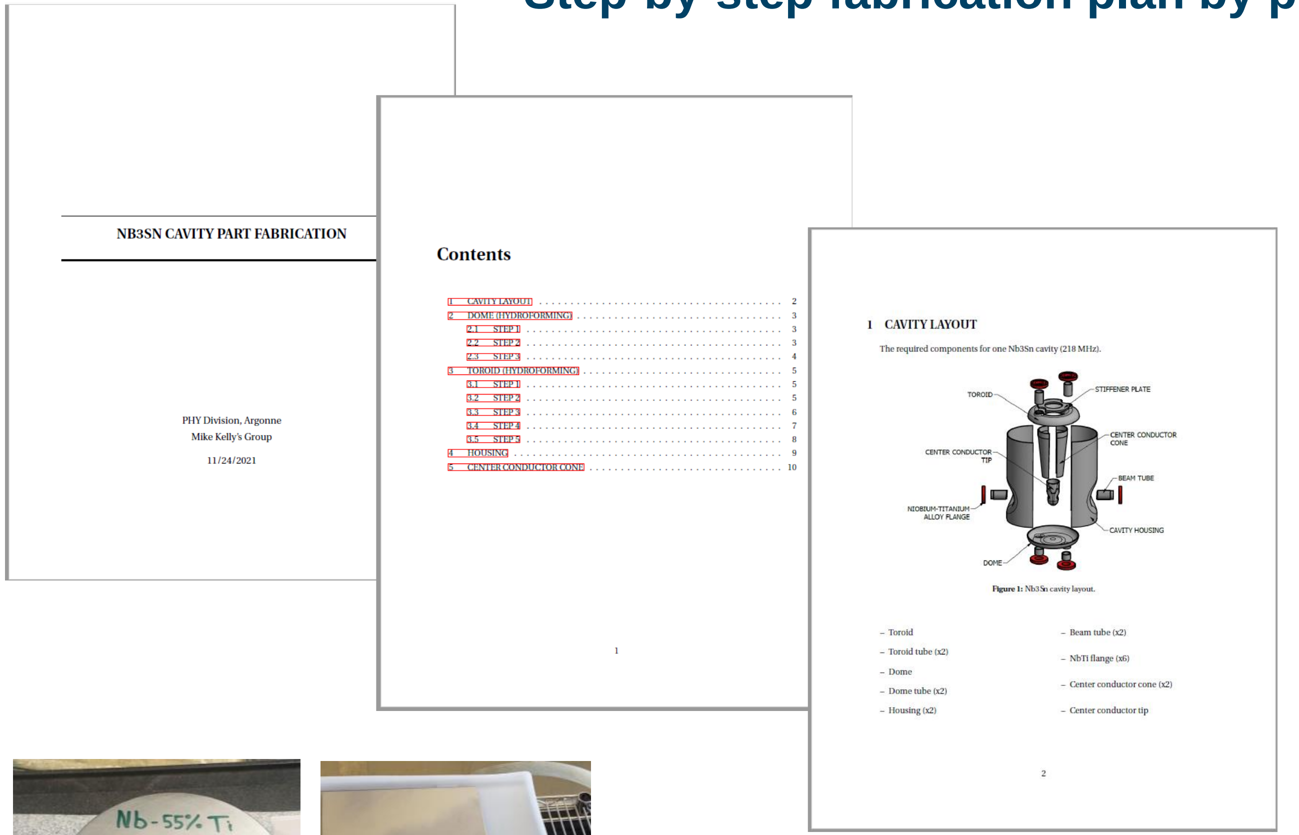
Cavity Development and Fabrication

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

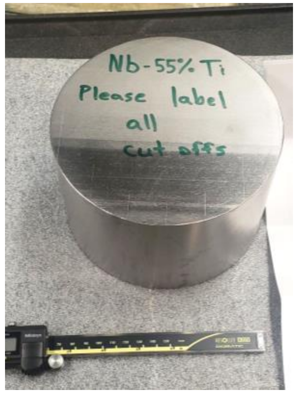
1 CAVITY LAYOUT

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

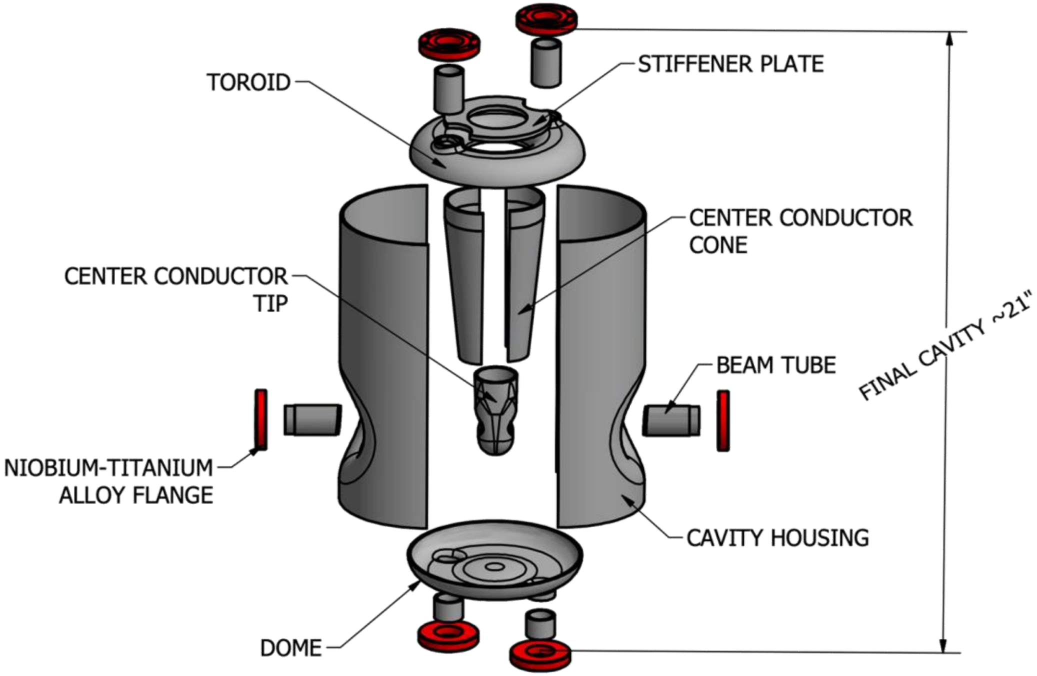
Figure 1: Nb3Sn cavity layout.

- 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

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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.

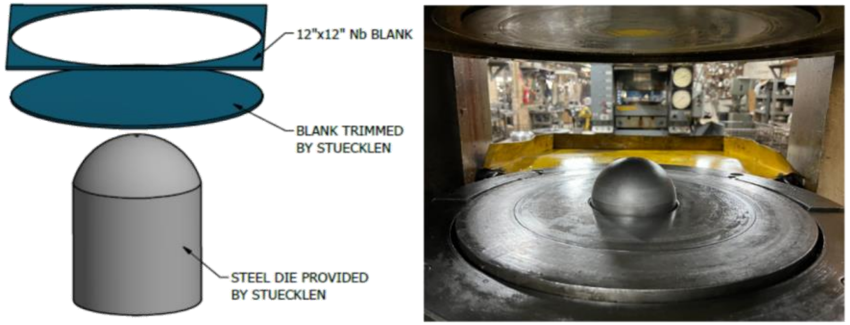


Figure 5: Step 1 forming.

3.2 STEP 2

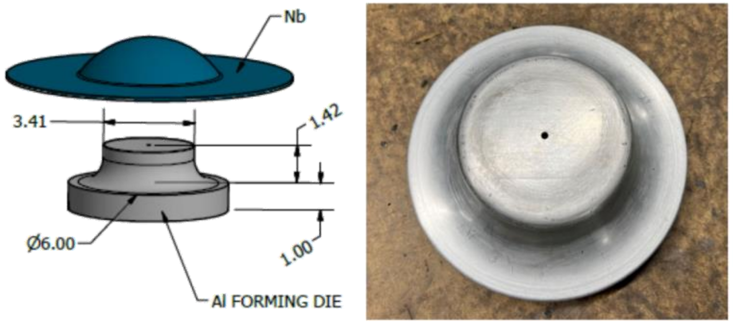


Figure 6: Step 2 forming.

3.3 STEP 3

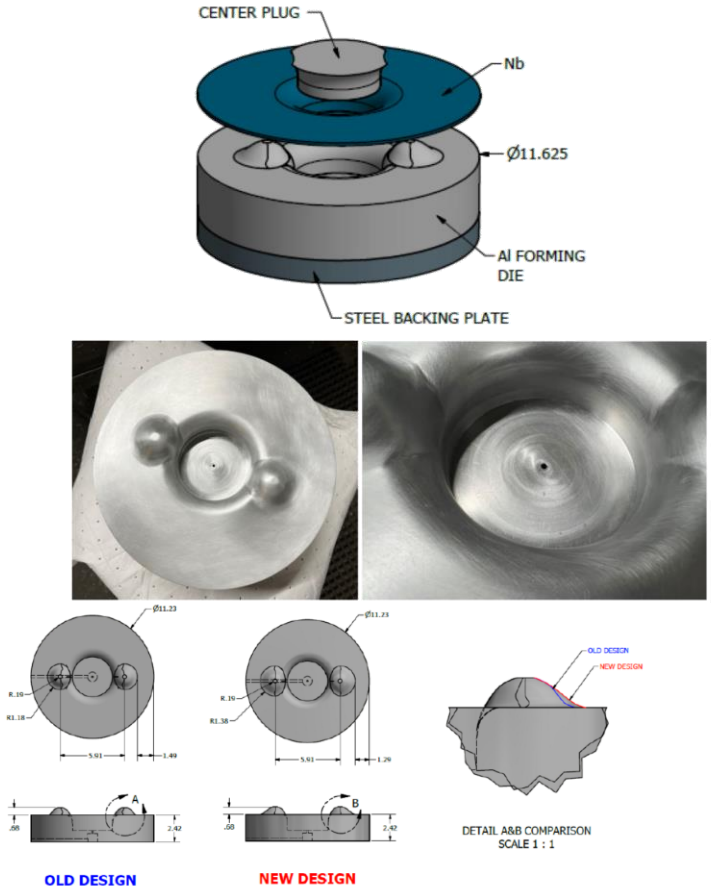


Figure 7: Step 3 forming. Note: the nub shown in the old design follows the profile of the nub used in the dome. The new design was adopted in the final toroid die.

Cavity 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.

3

2.3 STEP 3

Figure 4: Step 3 coining.

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

Cavity toroid hydroforming

Deliverable 3

3.4 STEP 4

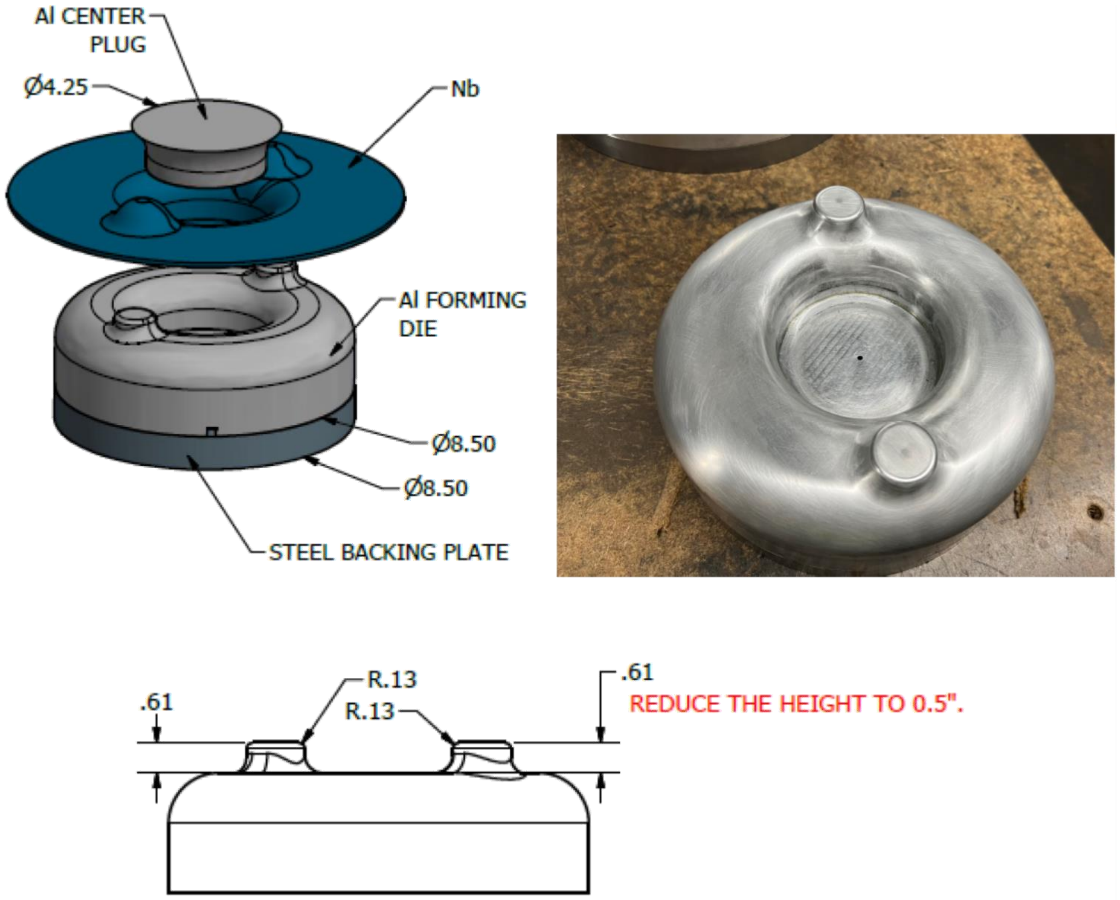


Figure 8: Step 4 forming. Note: the Al die was modified later at ANL Central Shops on 9/28/2021

3.5 STEP 5

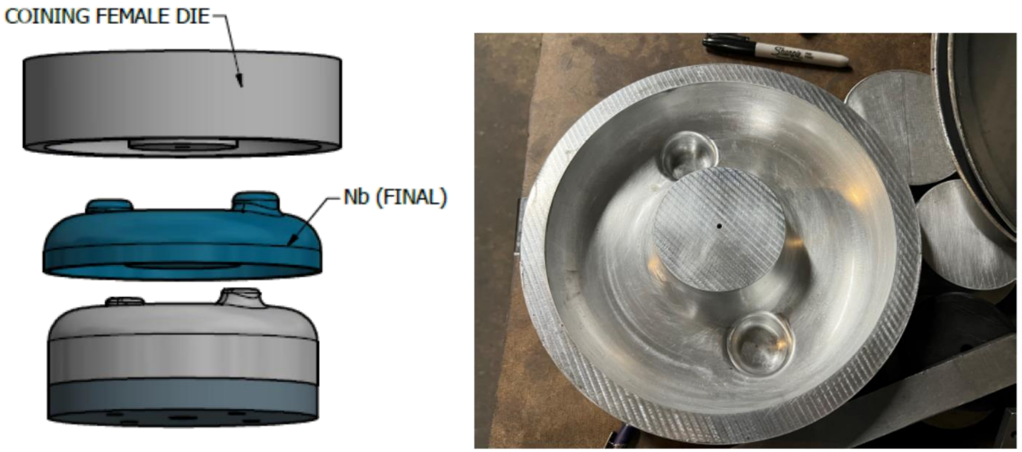


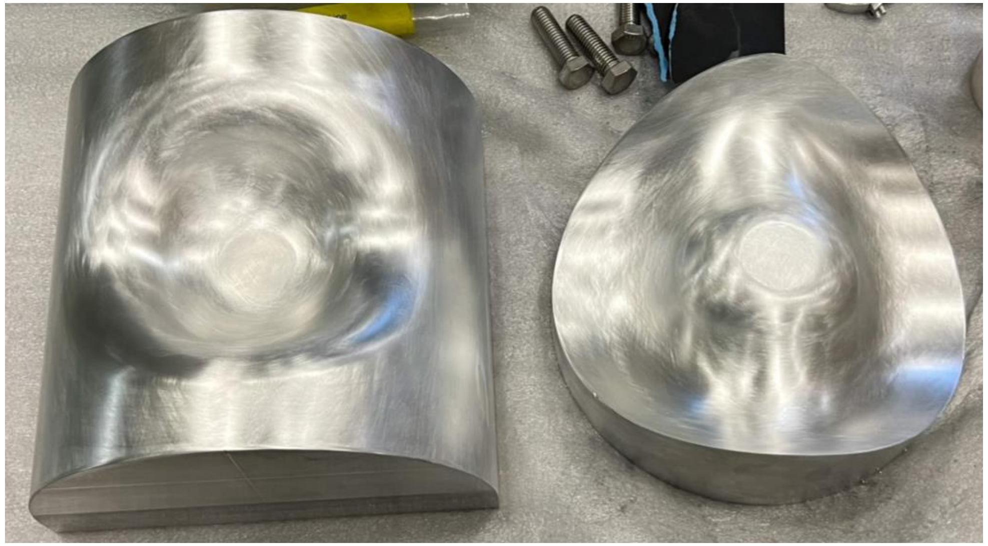
Figure 9: Step 5 coining.

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

Cavity Outer Housing Deep Drawing

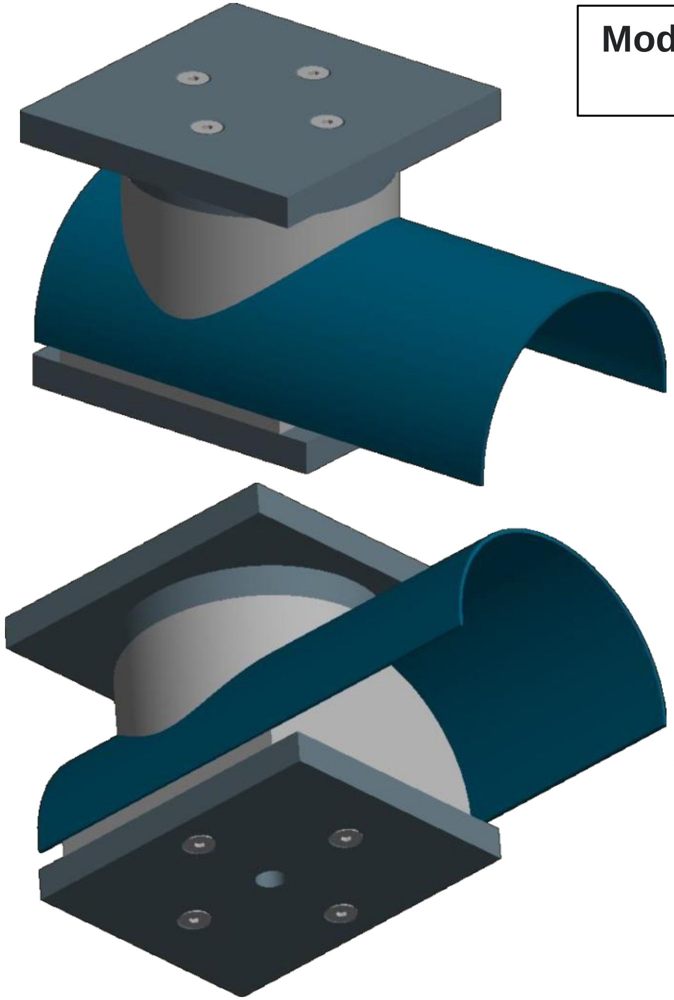
Deliverable 3

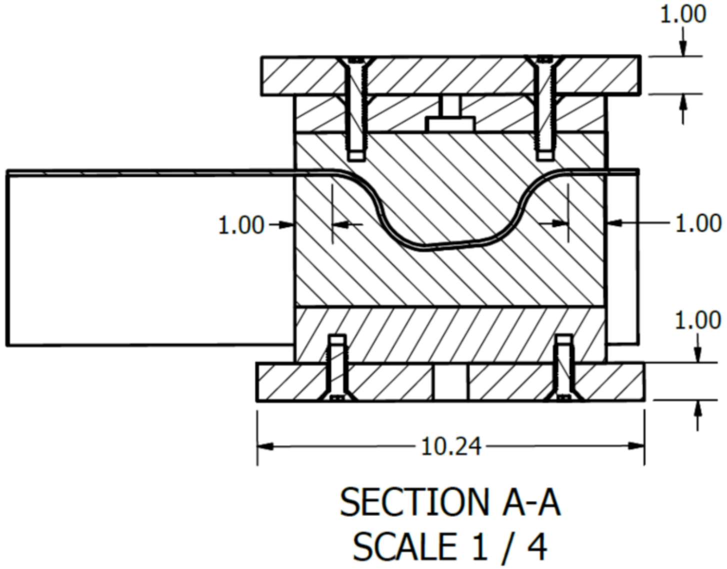
A 'simple' half cylinder with a re-entrant nose is easier by this method



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

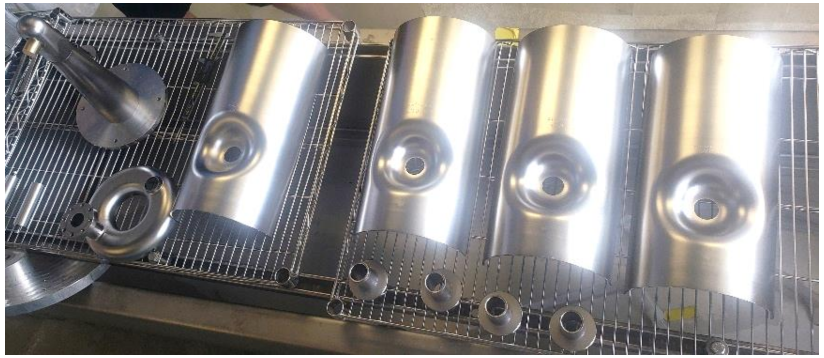
Model of deep draw tooling





Cavity Tuning and Electron Beam Welding

Deliverable 3



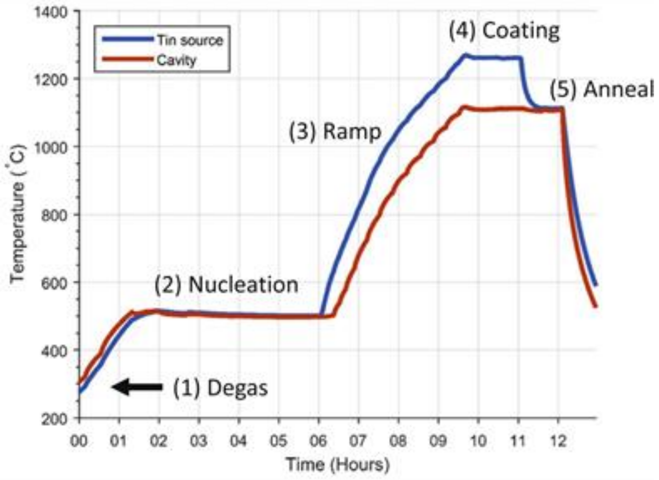
(Top left) 3D niobium machining of drift tube at RadiaBeam and final assembly for e-beam welding (bottom left and middle)

Cavity port welding at Sciaky

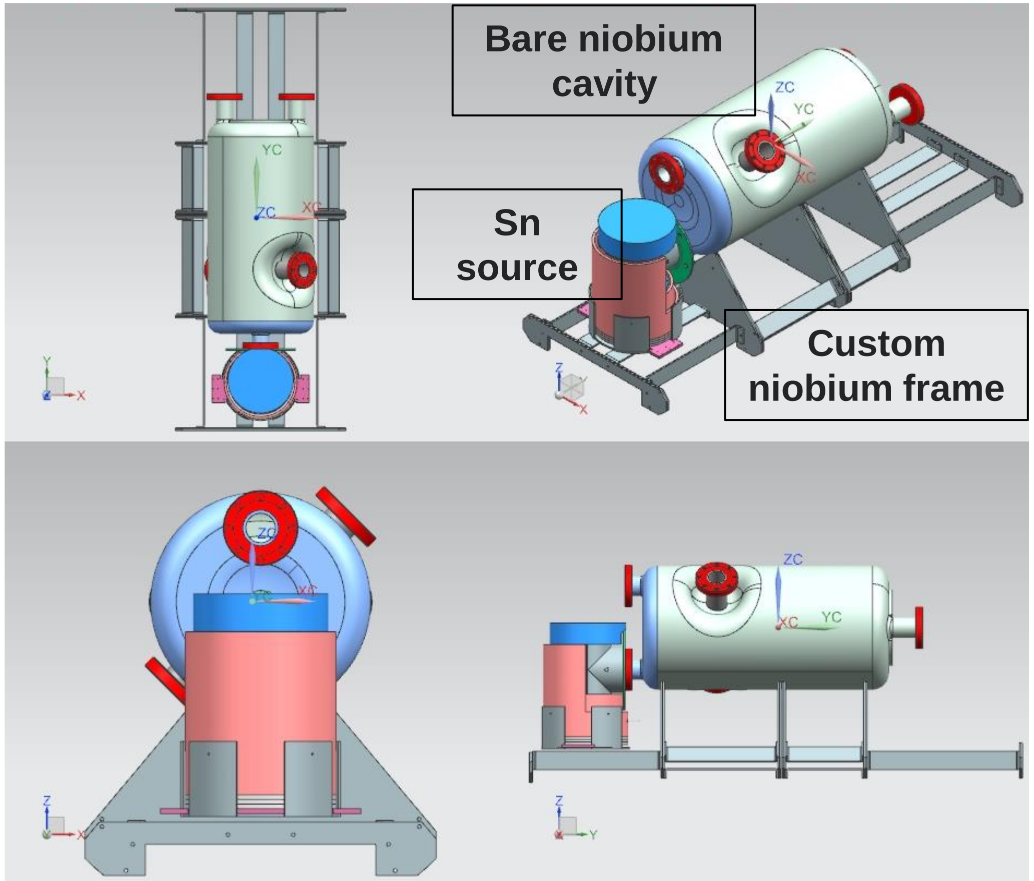
Plan for Coating a Quarter-wave Cavity

Deliverable 4

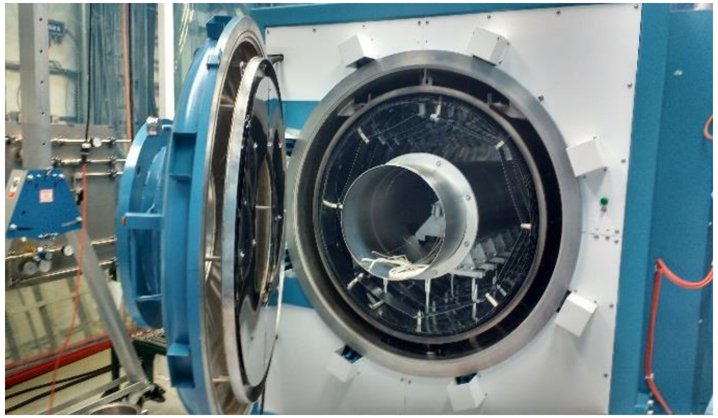
Fermilab



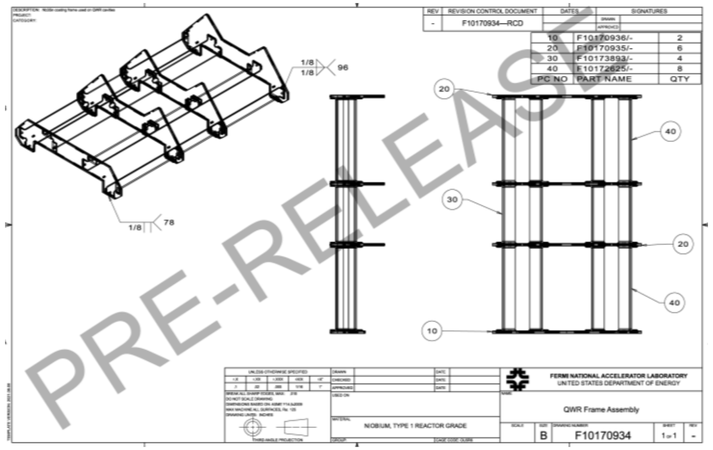
coating process



Hardware design for quarter-wave cavity in furnace



Nb_3Sn coating furnace at Fermilab



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Final coarse tuning and QA before chemistry

Deliverable 3

1 Year Look Ahead

- Complete electropolishing of niobium cavity (week of 11/28/22) **Deliverable 6**
- Cold test bare niobium cavity at Argonne (Dec. 2022) **Deliverable 7**
- Fermilab has fabricated components required for the coating process; port/flange covers are being test fit (week of 11/28/22) **Deliverables 4**
- Argonne will supply the cavity to Fermilab for coating early in calendar 2023 **Deliverables 4**
- RadiaBeam carrying forward work on two cryocoolers
  - The one supported by this work is a novel 10 Watt nominal GMJT cryocooler for Sumitomo
- Continuing effort will be to deploy one of these cavities as rapidly as possible into ATLAS in order to gain experience with the technology