Status of the SLAC/MSU SRF Gun Development Project

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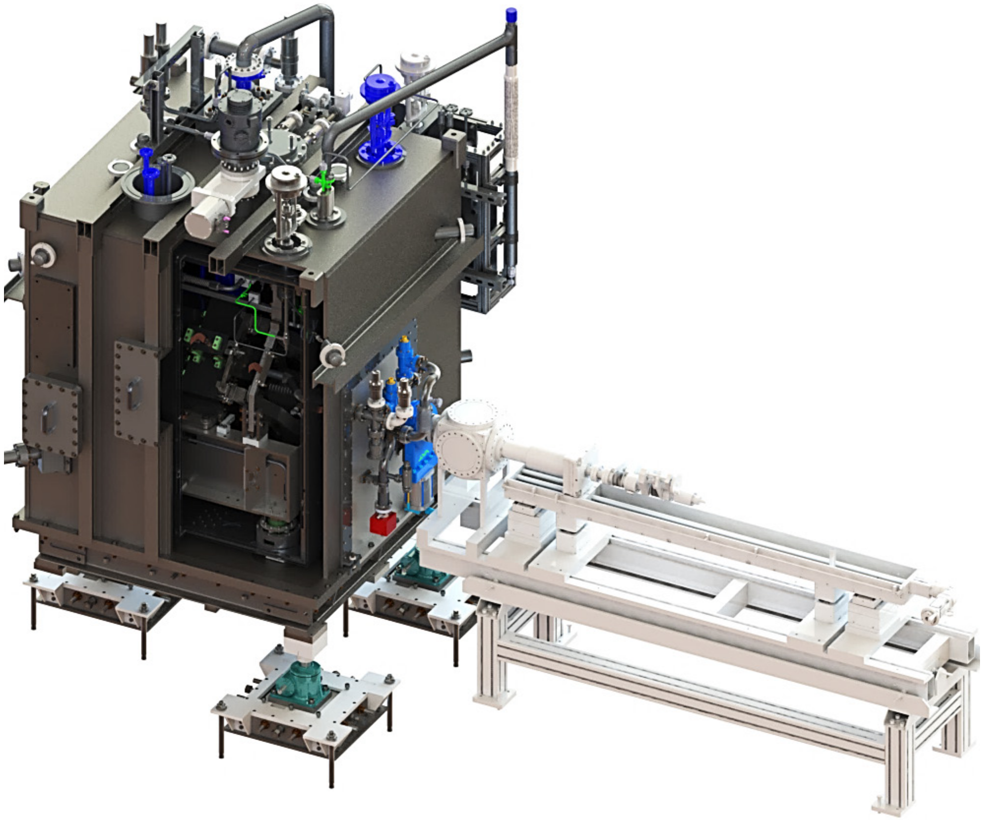
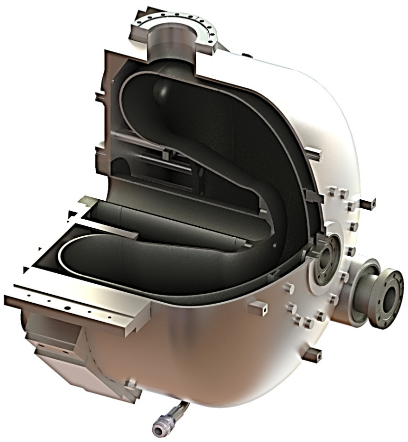
Outline

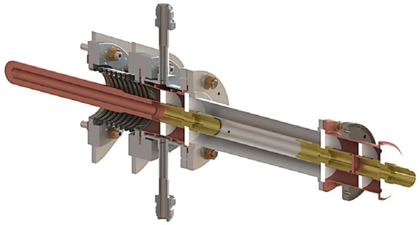
- This talk will focus on:
  - SRF Gun Project Overview
  - SRF Gun Cryomodule Performance Goals
  - SRF Gun Cryomodule Design
  - SRF Gun Cryomodule Fabrication Plans/Status
  - SRF Gun Cryomodule Testing Plans
  - Summary

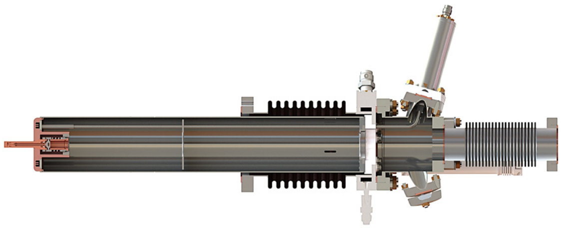


SRF Gun Project Overview

- SLAC established a collaboration to design, construct and test a quarter-wave SRF gun within four years with FRIB at MSU
- Two versions of the RF cavity are to be manufactured, one with a cathode plug port and one without it
- Fundamental power coupler (FPC): The FPC(s) should be multipacting and field emission free, and not produce significant asymmetric fields in the cavity
- Cavity tuner: Slow and fast tuners should be designed to ensure the gun operates at the nominal frequency within the detuning budget
- Cathode stalk and load lock: The cathode stalk is to be designed to provide an RF short while minimizing the heat load to the helium bath
- Emittance compensation solenoid: the specified solenoid magnet location is close to the gun anode

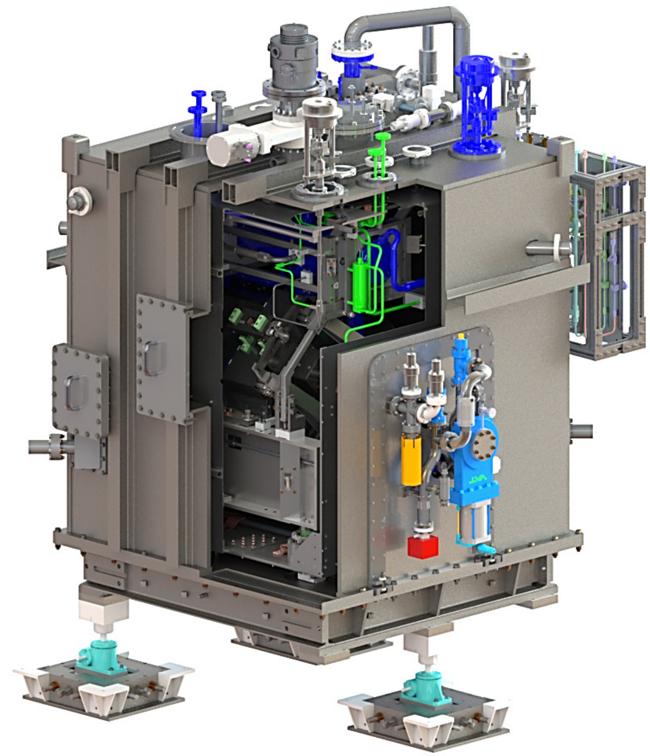






SRF Gun Cryomodule Performance Goals

Parameter	Units	Value
Operating Temperature	K	4.2
Cavity Frequency at 4.2K, 1 bar	MHz	185.7
Cathode Gradient (Nominal/Maximum Operating)	MV/m	> 30/35
Integrated E_z Field at 30 MV/m Gradient	MV	> 1.6
Captured Dark Current at 30 MV/m Gradient	nA	< 10
Distance from Cathode to Anode*	mm	70
Length of Solenoid Magnetic Yoke*	mm	124
Exit Beam Pipe Radius	mm	20
Cavity Q_0		$> 1 \times 10^9$
RF Coupler Q_{ext}*		10^7
Static Heat Load at 4.5 K	W	< 25
Cavity Vacuum Pressure at Room Temperature	torr	$< 1 \times 10^{-9}$
Helium Vessel Leak Rate at Room Temperature	torr-liter/sec	$< 1 \times 10^{-7}$
*SLAC Design Values		



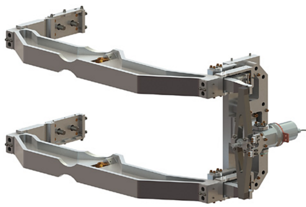
Scope Between Partners

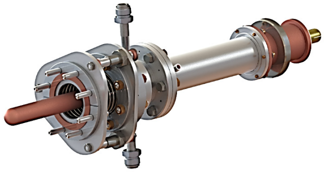
Final Cryomodule and Load Lock System will be Assembled and Delivered by MSU

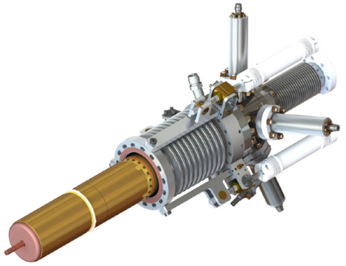
Scope	FRIB	ANL	HZDR	SLAC
Overall Project Management and Coordination	✓			
SRF Component and Cryomodule Design	✓	✓		
Magnet Package Design and Testing	✓			
Cathode Stalk Design, Fabrication, RF/DC Testing	✓	✓		
Cathode, Load-lock, Insertion/Transport Design			✓	
Cathode Stalk Particulate Testing			✓	
Cryomodule Major Component Procurement and Assembly	✓			
Load-Lock Major Component Procurement and Assembly	✓			
Cavity Processing and Cold Testing	✓	✓		
Integrated Cavity Test (Tuner/FPC)		✓		
Cavity Bunker Test	✓			
Beam Dynamics	✓	✓		✓

Challenges and Lessons Learned from Existing Systems

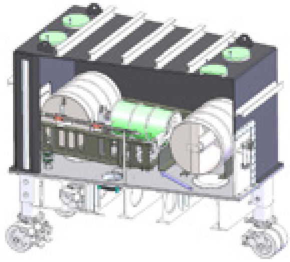
Challenge	Design/Processing/Validation Impact
Field Emission Limits Performance and Produces Dark Current	• Four Rinse Ports • Make Cathode System as Clean as Possible • Make FPC Adjustable ▪ High Peak Power Pulsed Processing • Plasma Processing if Needed
Multipacting Limits Performance	• DC Dias for Cathode Stalk and FPC • Design Systems for MP Avoidance • Apply FRIB Conditioning Experience
SRF Auxiliaries: Couplers and Tuners are Critical Elements	• Existing Gun Projects Developed Unique Solutions ▪ Dedicated Development • Adapt Proven Technology where Possible
Cathode and RF Choke Critical Performance	• Extra RF Pickup in Choke • Sub-System Testing • Iteration as Needed
FPC on Beam Port: Complex System and Downstream Focusing	• Separate Off-Axis Port for FPC
RF Pickup on Beam Port Results in Systematic RF Amplitude Error	• Pickup Loop in Rinse Port



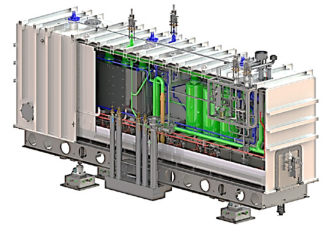




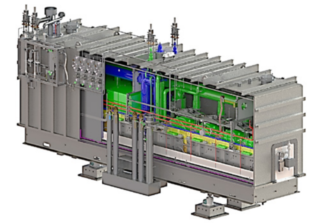
FRIB Cryomodule Road Map
Modular Design to Used on All FRIB Cryomodule Types



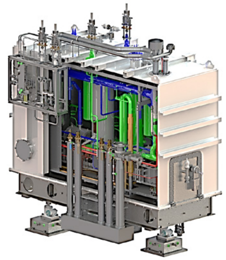
ETCM, tests completed in 2013



FRIB β=0.085 QWR
design complete 2015

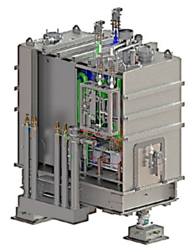


FRIB β=0.53 HWR
design complete 2016

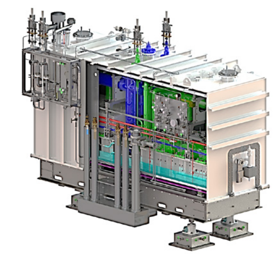


Jefferson Lab

FRIB β=0.041 QWR
design complete in 2016

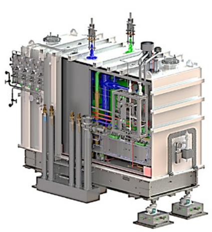


FRIB β=0.085 QWR Rebuncher
design complete in 2016

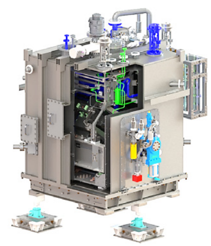


Jefferson Lab

FRIB β=0.29 HWR
design complete 2017

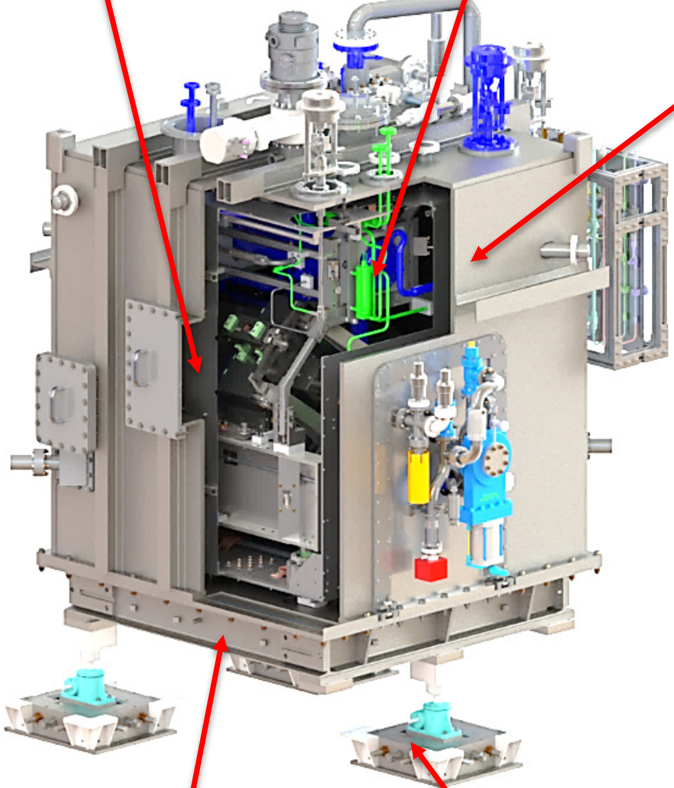


FRIB β=0.53 HWR Rebuncher
design complete 2017

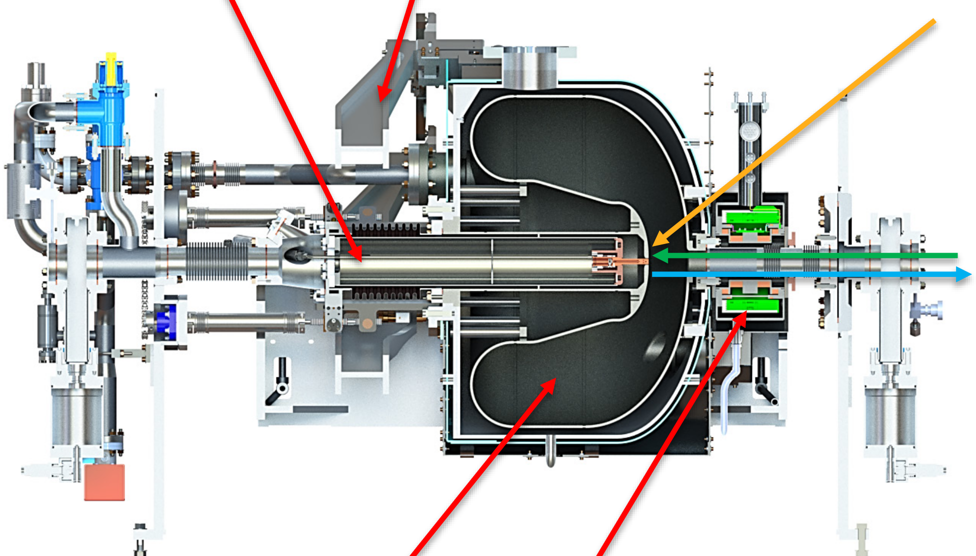


SRF Gun QWR
design complete 2022

3D CAD SRF Gun Cryomodule Overview



Cryomodule Dimensions (in)					
Property	β=0.041	β=0.085	β=0.29	β=0.53	SRF Gun
Length	117	236	143	230	62
Width	61	60	60	60	72
Height	114	114	109	107	102

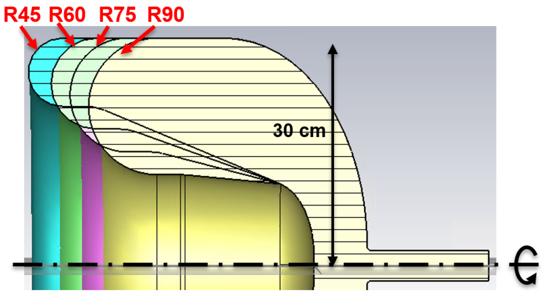


SRF Gun Cryomodule Design: Cavity

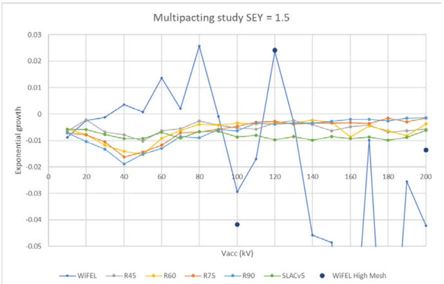
Cavity Parameters	Value
f0 (MHz)	185.75
Geometry Factor (Ω)	84.5
Quality factor Q0 @ 4.4 K[1]	1.3×10^{9}
r/Q (Ω)	131
Ec (MV/m)	30
Stored Energy U (J)	21.4
Bpeak (mT)	52.9
Epeak (MV/m) with cathode	33.7
Cavity wall dissipation power Pw[1] (W)	20
Gap Voltage V0[2] (MV)	1.81
Accelerating voltage Vacc (β=1) (MV)	1.80
df/dP (Hz/Torr)	-3.95
df/dx (kHz/mm)	-435
dF/dx (kN/mm)	44.6
Tuning Force: 60kHz, 15 psi, 4K (kN)	8.4
LFD (Hz/J)	-29
Modes 1-4 (Hz)	157, 182, 191, 227

(1) Estimated 4.4 K R_s is 66 nΩ, no 120 ºC baking case.

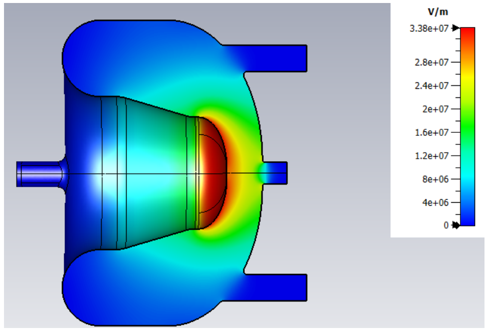
(2) $V_0 = \int E_z(z)dz$, geometric shunt impedance = $\frac{V_0^2}{P_W}\frac{P_W}{\omega_0 U}$



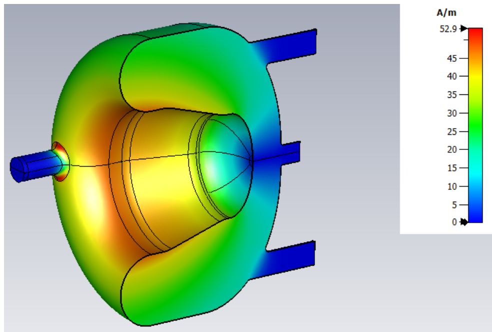
Cavity Shape Optimization



Multipacting Study

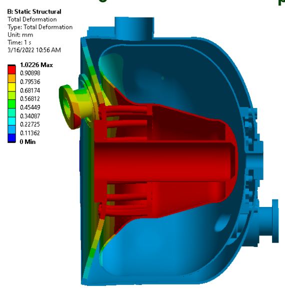


E-field at E_c = 30 MV/m, E_{peak} = 33.7 MV/m



B-field at E_c = 30 MV/m, B_{peak} = 52.9 mT

Cavity Mechanical Model



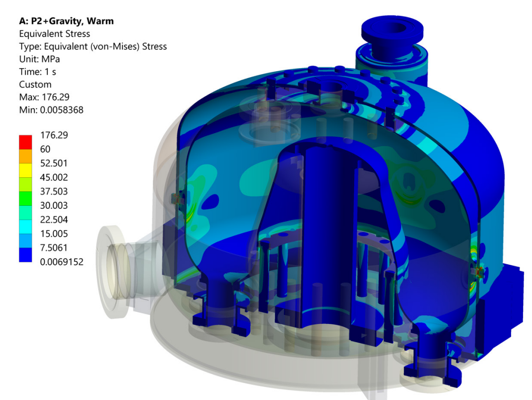
df/dx = -435 kHz/mm

SRF Gun Cryomodule Design: Cavity

Design to be compatible with BPVC Sec VIII, Div.2: Part 5 Limit Load

Temperature	Loads	Description	Load Factor	Limit Load
300 K	Gravity P2=0.227 MPa P1=P3=0 MPa	Warm Pressurization	1.5(P2+Gravity)	Converges
300 K	Gravity P2=0.227 MPa P1=P3=0 MPa T=0.14 mm	Warm Pressurization + Tuner Compression	1.3(P2+Gravity+T)	Converges
4 K	Gravity P2=0.41 MPa P1=P3=0 MPa	Cold Pressurization	1.5(P2+Gravity)	Converges
4 K	Gravity P2=0.41 MPa P1=P3=0 MPa T=0.14 mm	Cold Pressurization + Tuner Compression	1.3(P2+Gravity+T)	Converges

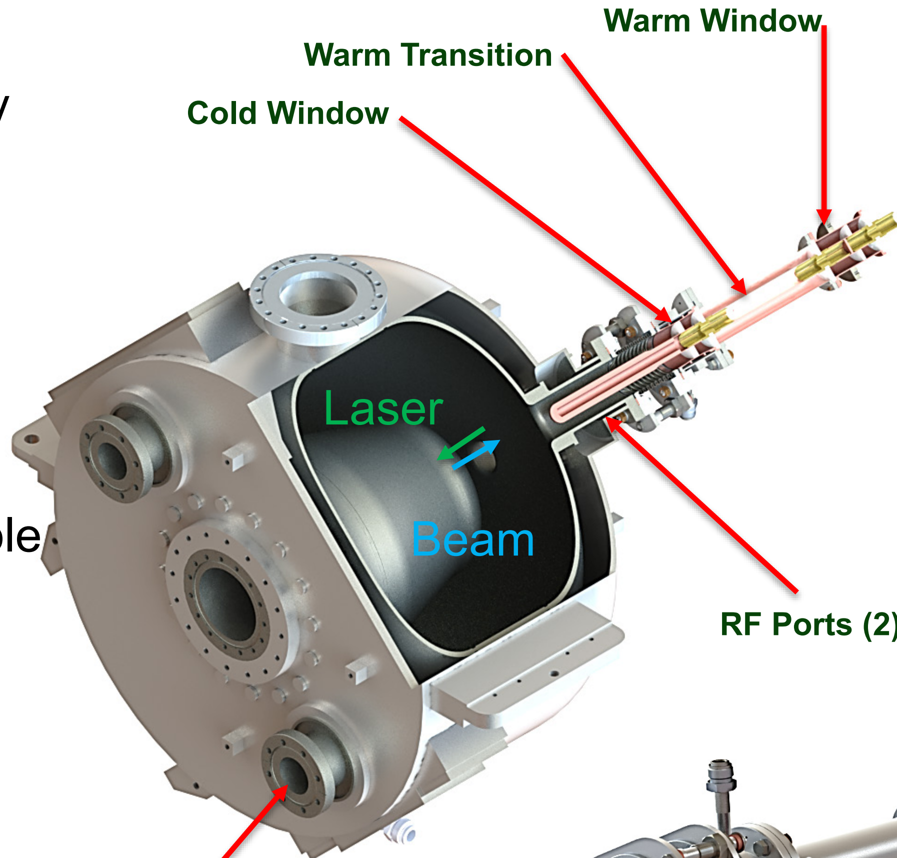
Cavity Mesh



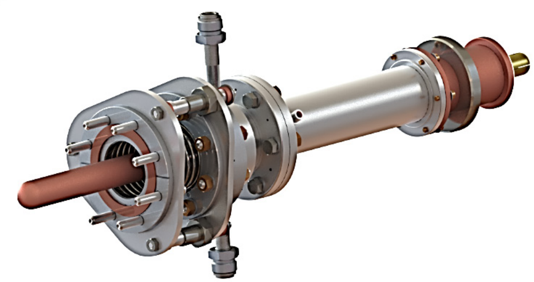
Cavity Stress Analysis Results

SRF Gun Cryomodule Design: Fundamental Power Coupler

- Cavity Design for FPC
  - Low-field multipacting mitigated by design
  - Four access ports for electro-polishing (EP) and high-pressure water rinsing (HPR)
  - Off-beam-axis FPC port to reduce impacts of potential particulate contamination on cavity operation
  - Mechanical design to support stable resonance control at 4 K [*df*/*dP*, Lorentz Force Detuning (LFD), mechanical modes]

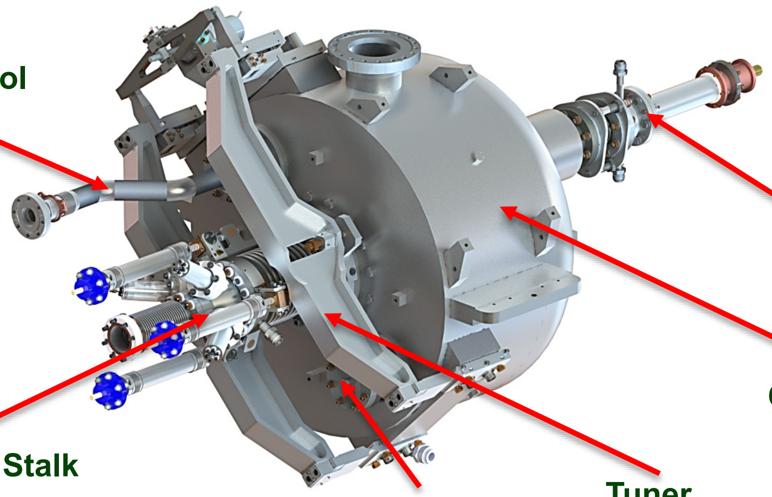


- FPC
  - ANL 162.5 MHz FPC design, validated with the PIP-II HWRs
    - » Designed for assembly without particulate contamination



SRF Gun Cryomodule Design: Tuner

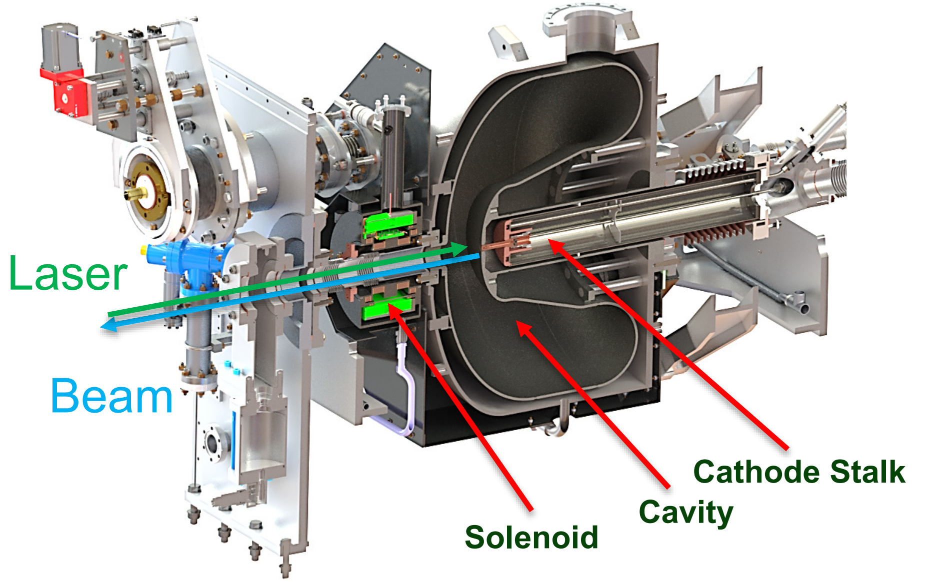
- FNAL tuner design validated on PIPII-SSR1
- Unidirectional tuning to the cathode port
- Design includes a stepper motor based slow tuner and Piezo actuator based fast tuner
  - Stepper: Pythron VSS 52.200.1.2
  - Piezo: PI P-844.20
    - » Fast tuning Piezo actuators have resolution < 1 Hz



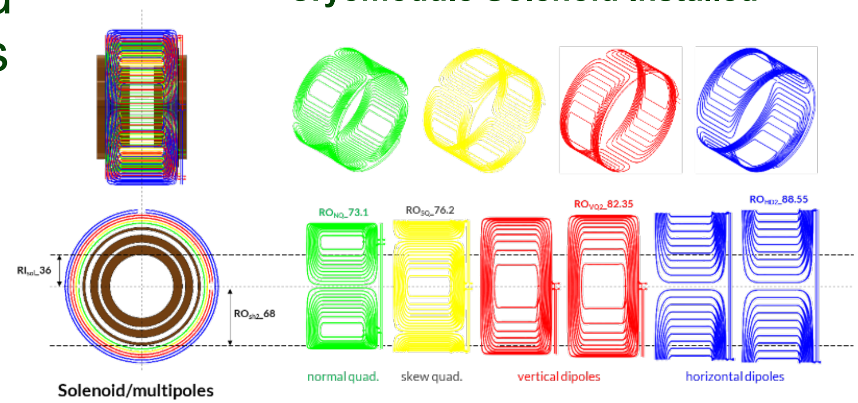
Parameter	Value	Unit
Stepper coarse tuning range	-60	kHz
Tuning sensitivity	-435	kHz/mm
Cavity stiffness	61	kN/mm
Piezo mechanical advantange	2.22	
Stepper mechanical advantage	9.27	
Max tuning displacement	0.138	mm
Max tuning force	8.4	kN
Force on a piezo out of two	1.9	kN
Force on the stepper	0.91	kN
Stepper planary gear ratio	50	
Stepper resolution (motor)	200	rev/step
Stepper shaft pitch	1	mm/rev
Stepper linear resolution (motor)	0.1	um/step
Stepper linear resolution (cavity)	0.011	um/step
Stepper tuning resolution	4.7	Hz/step
Piezo travel range (piezo)	20	um
Piezo travel range (cavity)	9.0	um
Piezo fine tuning range	-3.9	kHz
Piezo resolution (piezo)	0.3	nm/mV
Piezo resolution (piezo)	0.14	nm/mV
Piezo tuning resolution	0.06	Hz/mV

SRF Gun Cryomodule Design: Solenoid

- The emittance compensation solenoid will be utilized for the compensation of adverse space charge effects on the emittance of the electron beam
- The solenoid contains two sets of windings that can be independently powered in addition to bucking coils to minimize the fringe field at the resonator surface
- The package also contains dipole and quadrupole coils to correct field errors due to misalignment and fabrication imperfections
- Adjustors are built into the solenoid package mounts to allow for adjustment within +/0.2 mm



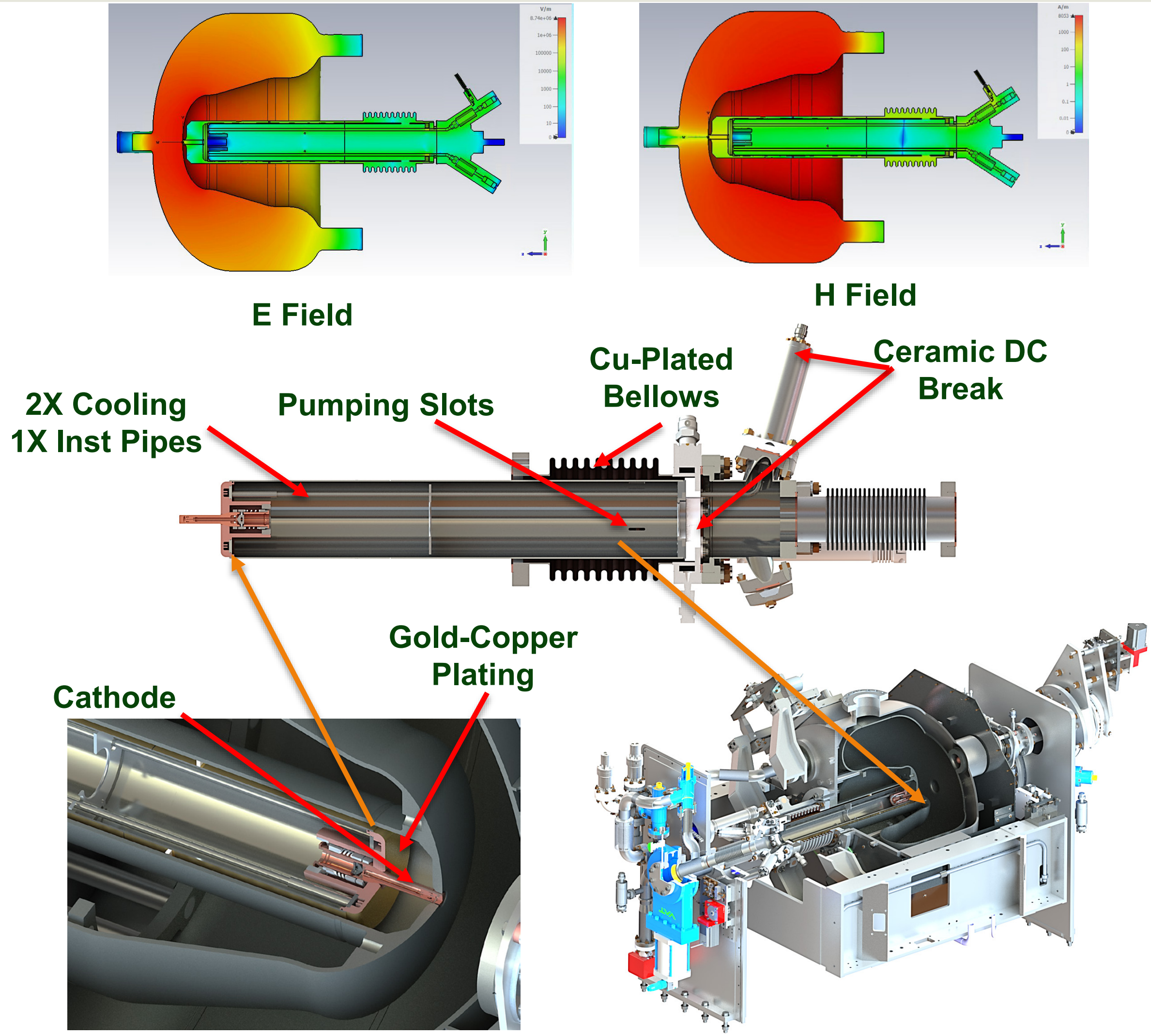
Cryomodule Solenoid Installed



Solenoid Coil Layout

SRF Gun Cryomodule Design: Cathode Stalk

- Precision alignment control of the cathode position
- Bias the coaxial structure of the cathode and cathode stalk up to 5 kV DC to prevent multipacting
- Temperature adjustability of the cathode which can be utilized to improve cathode performance
- Prevent field emission by providing a particle free cathode exchange



SRF Gun Cryomodule Design: Alignment and Fiducialization Plan

- Cathode plug aperture data transferred to HV tabs fiducials
- Cavity placed on alignment rails
- Definition of beamline established based on cavity alignment
- Solenoid adjusts to match cavity beamline
  - If the solenoid magnetic center deviates from the theoretical center by more than +/-0.2mm and +/-5 mrad at z=0, adjustment can be made using the solenoid adjustment system
- Thermal offsets accounted for in placements
- End assemblies evaluated to cavity beamline
- Beamline data transferred to cryomodule baseplate

2 Alignment and Fiducialization Strategy

2.1 SRF Gun Cavity

2.1.1 The cathode aperture placement relative to the beamport is determined by the fabrication of the cavity in accordance to print L10803-MDE-0105-0000.

2.1.2 The clocking of the FPC port is determined by the fabrication of the cavity in accordance to print L10803-MDE-0105-0000.

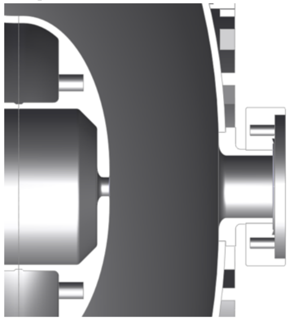


Figure 1: Cathode Aperture Alignment to Beamport

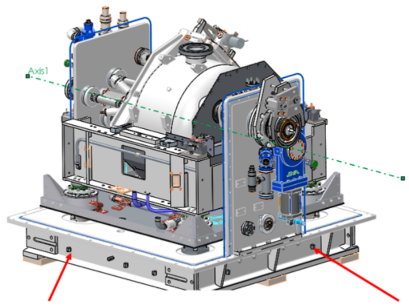


Figure 10: SRF Gun Cryomodule Baseplate Monuments

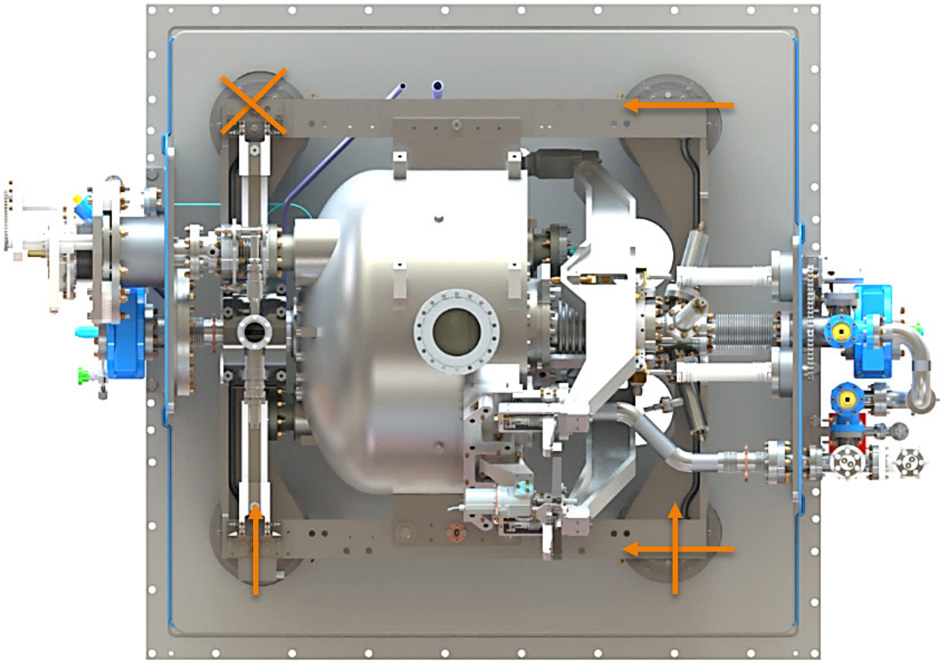
.8 Cryomodule Assembly

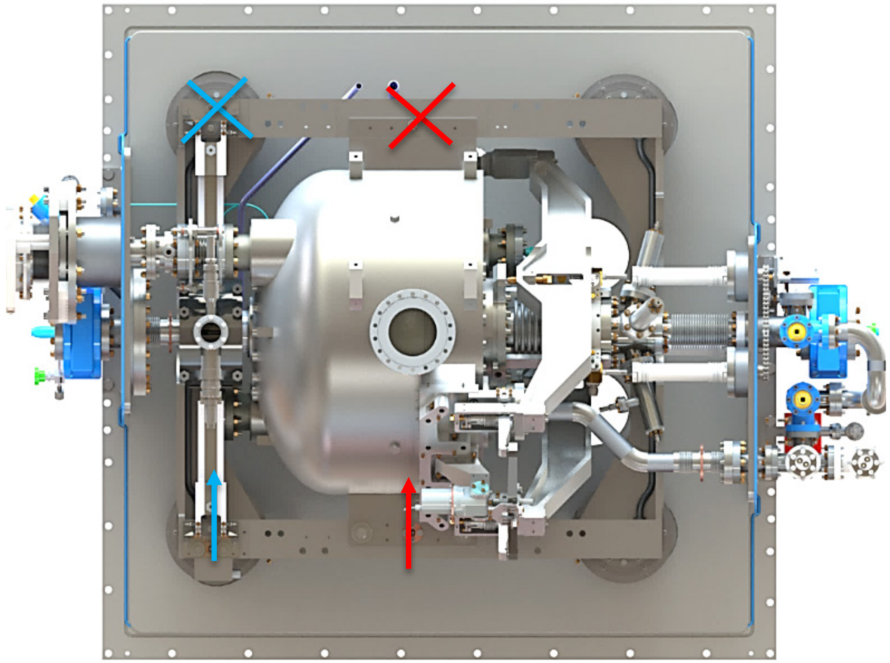
.8.1 The baseplate fiducials now contain the complete information of the component alignment and will be used to align the cryomodule.

.8.2 Using the orthogonal adjusters below the cryomodule, adjust the cryomodule beamline location to the desired location.

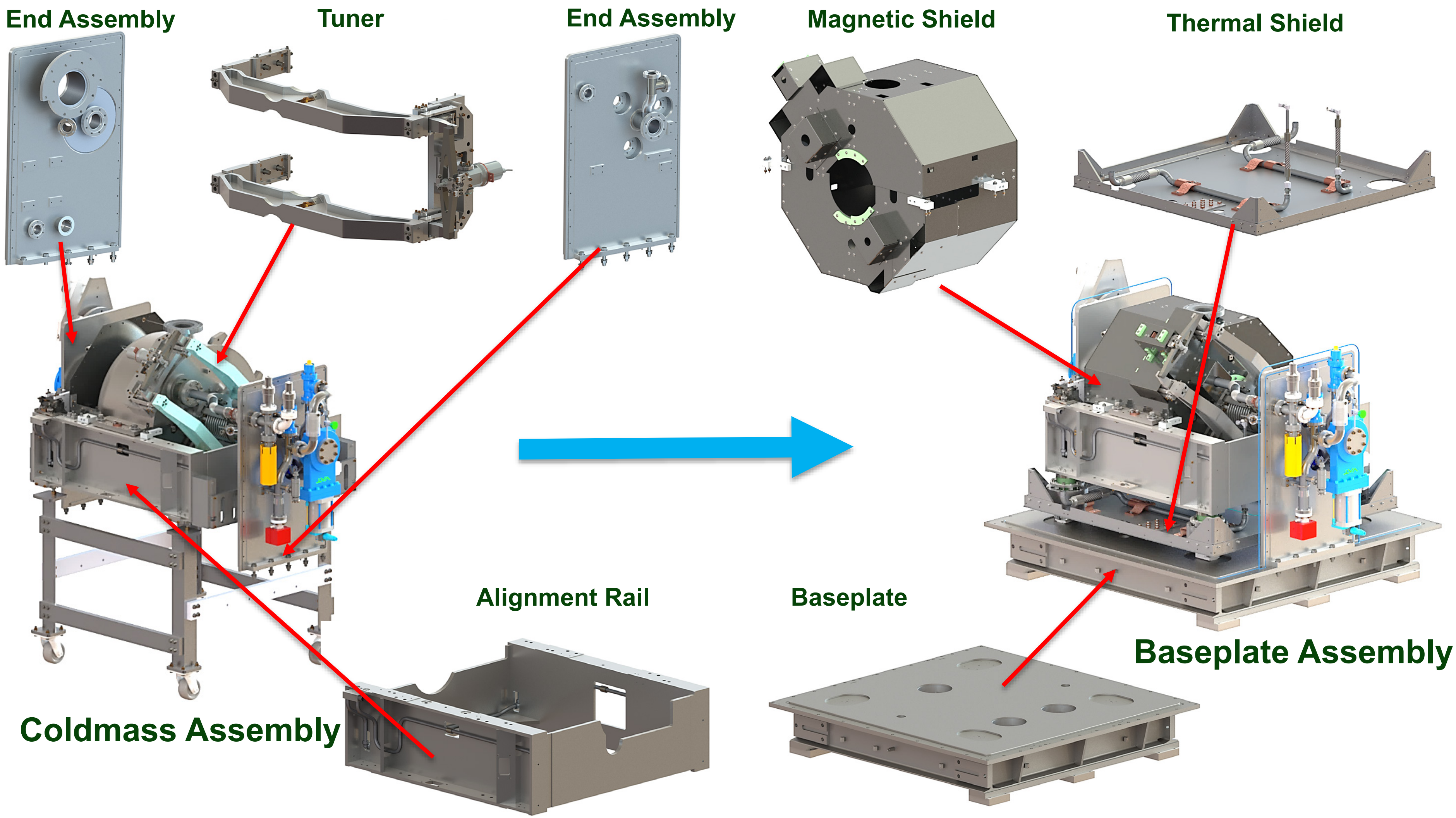
SRF Gun Cryomodule Design: Thermal Contraction and Alignment

- The fixed post and "fixed" side of the cavity are coincident and develop a "fixed" side for all thermal contraction
- The cavity and solenoid independently transversely contract from the "contraction" side to the "fixed" side
  - The contraction is calculated and offset by the cavity and solenoid placement

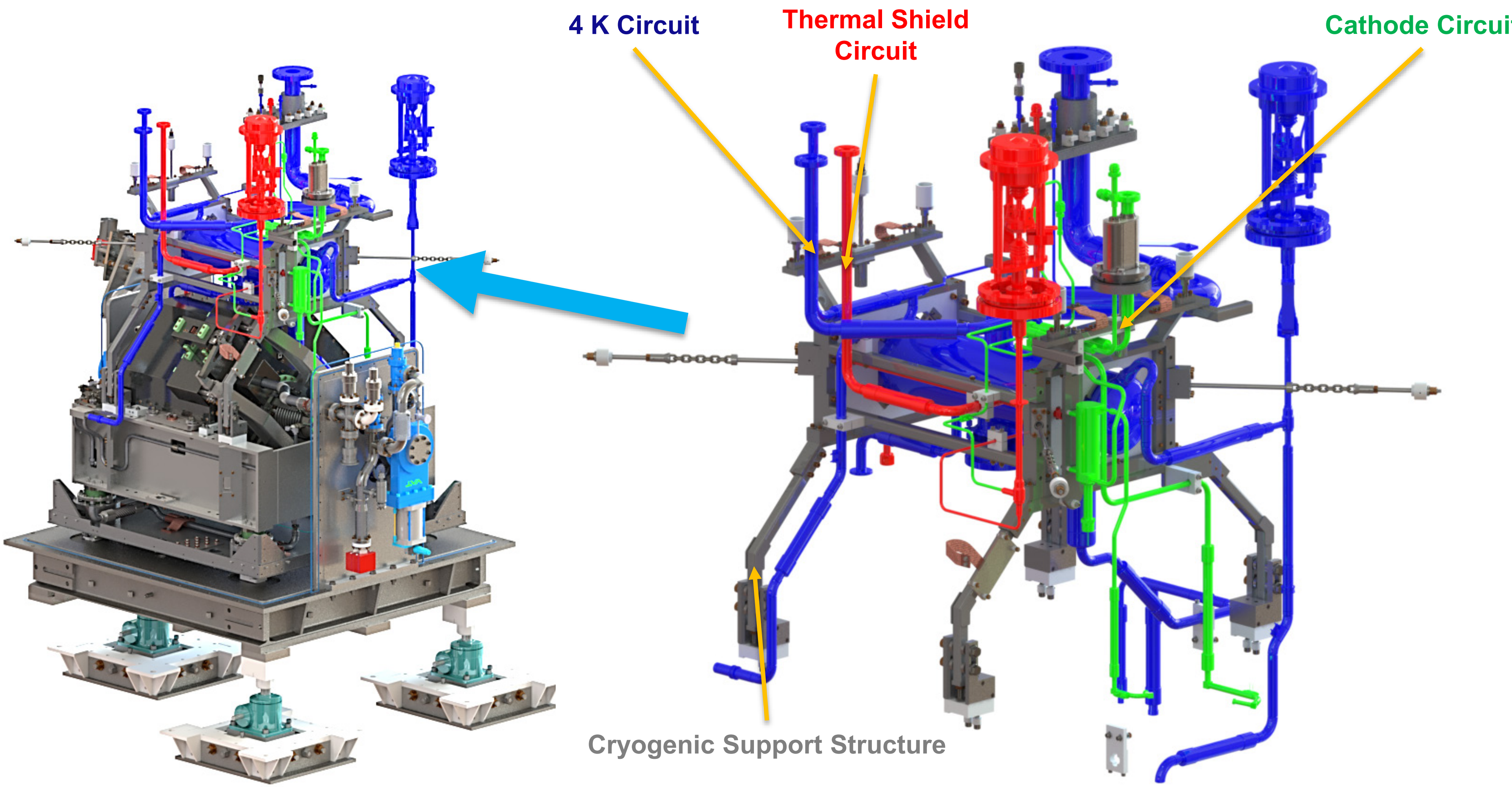




SRF Gun Design: Coldmass Integration

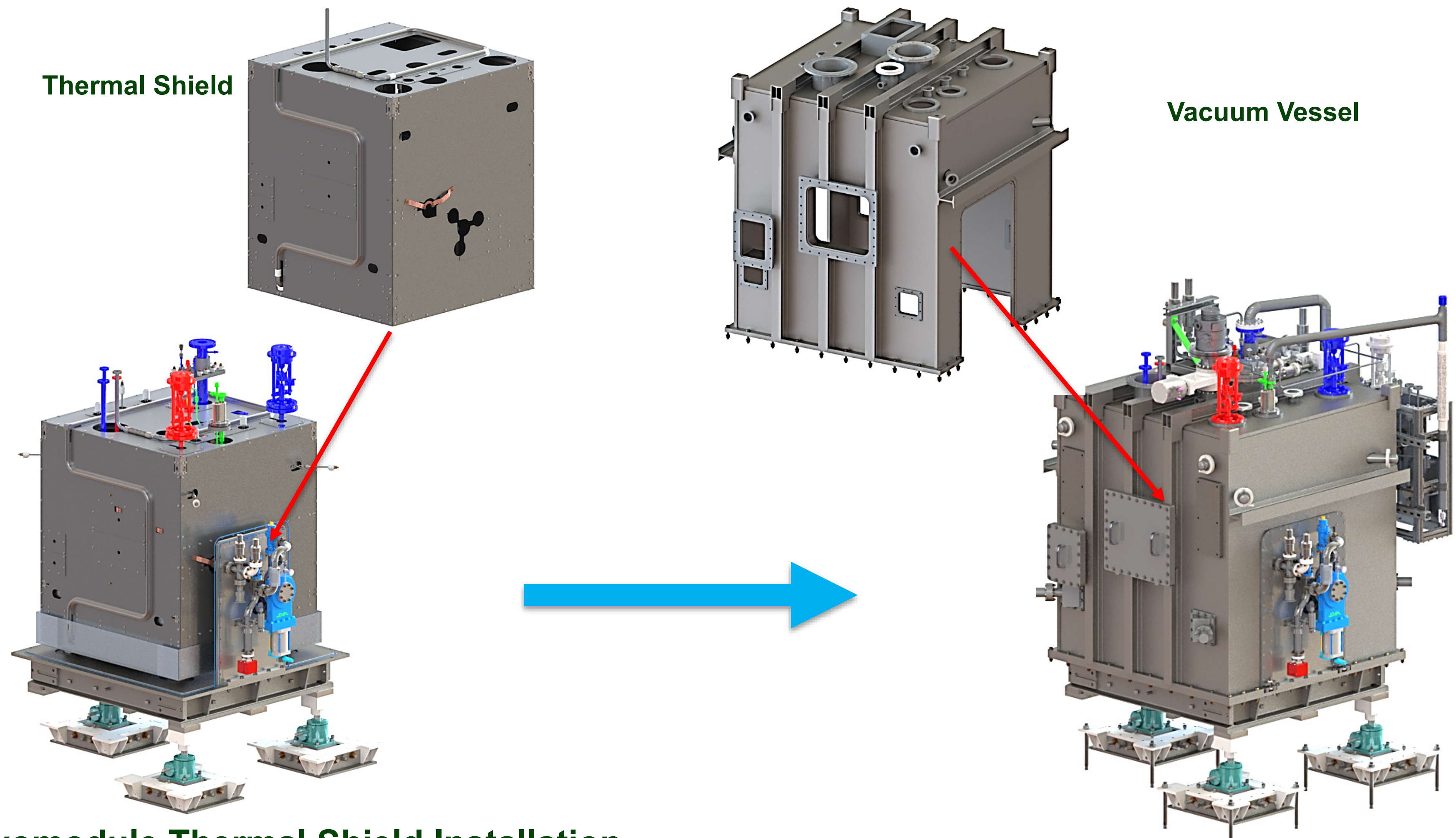


SRF Gun Design: Cryogenic Installation



Cryomodule Cryogenic Installation **Cryogenics System**

SRF Gun Design: Cryomodule Integration



Cryomodule Thermal Shield Installation

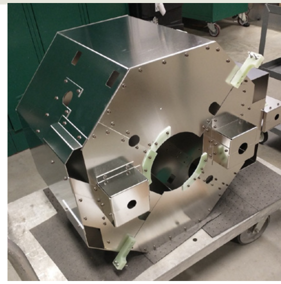
Cryomodule Completion

SRF Gun Cryomodule Fabrication Plans/Status

Part number	Description	Plan	Delivery Date (Planned)	Status
L10803-MDE-0303-0000	SRF GUN LOAD LOCK SYSTEM	Procurement	Oct 2023	After Cathode FDR
L10803-MDE-0304-0000	SRF GUN CATHODE STALK	Procurement	Sep 2023	Started the 2nd cathode stalk based on RF testing
L10803-MDE-0193-0000	SRF GUN CRYOMODULE STANDS	Procurement	May 2023	Test Assembly at Supplier
L10803-MDE-0313-1000	SRF GUN CRYOMODULE SHIPPING FRAME	Procurement	May 2023	Shipment Ready
L10803-MDE-0266-0000	SRF GUN CRYOGENICS	Procurement	July 2023	In-House Fabrication
L10803-MDE-0301-0000	SRF GUN UPPER COLDMASS MLI	Procurement	Mar 2023	Received
L10803-MDE-0275-0000	SRF GUN THERMAL SHIELD	Procurement	May 2023	Shipment Ready
L10803-MDE-0302-0000	SRF GUN UPPER THERMAL SHIELD MLI	Procurement	Mar 2023	Received
L10803-MDE-0260-0000	SRF GUN VACUUM VESSEL COVER	Procurement	May 2023	Inspection Complete/Painting
L10803-MDE-0296-0000	SRF GUN SEAL PLATE	Procurement	Nov 2022	Shipment Ready
L10803-MDE-0299-0000	SRF GUN LOWER COLDMASS MLI	Procurement	Mar 2023	Received
L10803-MDE-0300-0000	SRF GUN LOWER THERMAL SHIELD MLI	Procurement	Mar 2023	Received
L10803-MDE-0253-0000	SRF GUN VACUUM VESSEL BASEPLATE	Procurement	May 2023	Inspection Complete/Painting
L10803-MDE-0278-0000	SRF GUN ALIGNMENT POST	Self-perform	Sep 2023	In-House Fabrication
L10803-MDE-0259-0000	SRF GUN TUNER	Procurement	Aug 2022	Received
L10803-MDE-0261-0000	SRF GUN MAGNETIC SHIELD	Procurement	May 2023	Received
L10803-MDE-0171-0000	SRF GUN ALIGNMENT RAIL	Procurement	May 2023	Shipment Ready
L10803-MDE-0246-0000	SRF GUN END ASSEMBLY	Procurement	May 2023	Shipment Ready
L10803-MDE-0146-0000	SRF GUN FUNDAMENTAL POWER COUPLER	Procurement	Aug 2022	Received 1st article - 2nd/3rd NCR & rework at vendor
L10803-MDE-0174-0000	SRF PICKUP ANTENNA	Procurement	Jul 2022	Received
VENDOR PART	PIEZO AND STEPPER MOTOR	Procurement	June 2023	Partial Received
VENDOR PART	CONTROL VALVES	Procurement	May 2023	Received
VENDOR PART	GATEVALVE	Procurement	June 2023	Contracted
VENDOR PART	INSTRUMENTATION AND FEEDTHRU	Procurement	Mar 2022	Received
MATERIAL	NB & NBTI	Long Lead	Apr 2022	Received

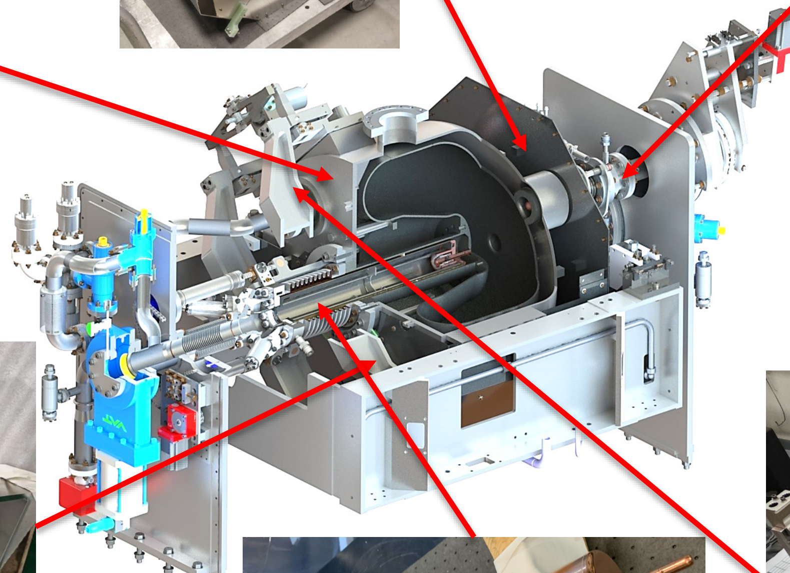
SRF Gun Cryomodule Fabrication Plans/Status- Coldmass

SRF Cavity



Magnetic Shield

Fundamental Power Coupler

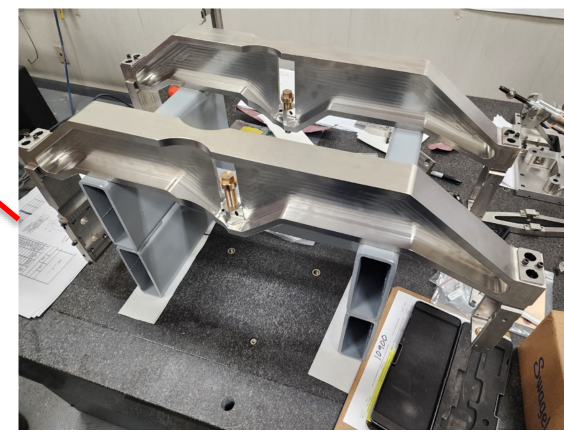


Alignment Rail

Full Stress Relieve to Minimize Distortion During Cool-down

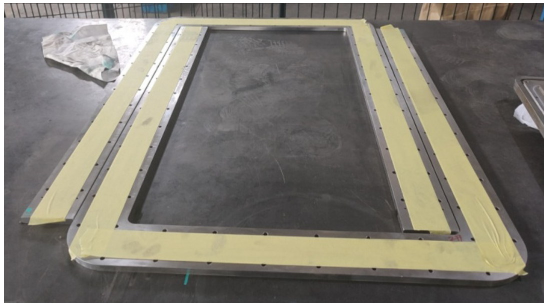
Reset To Austenitic State (Min. Permeability)

Cathode Stalk

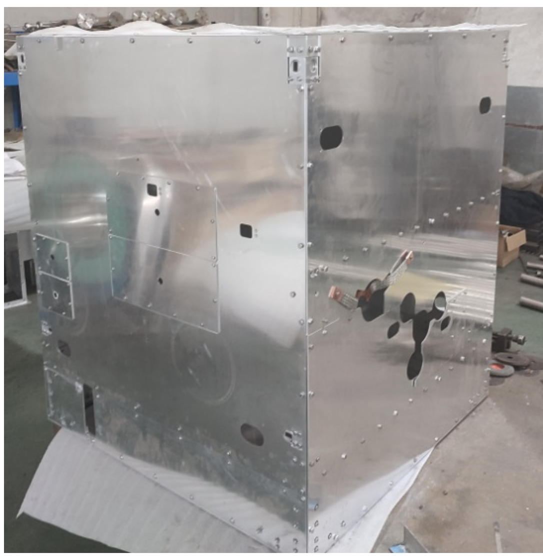


Tuner

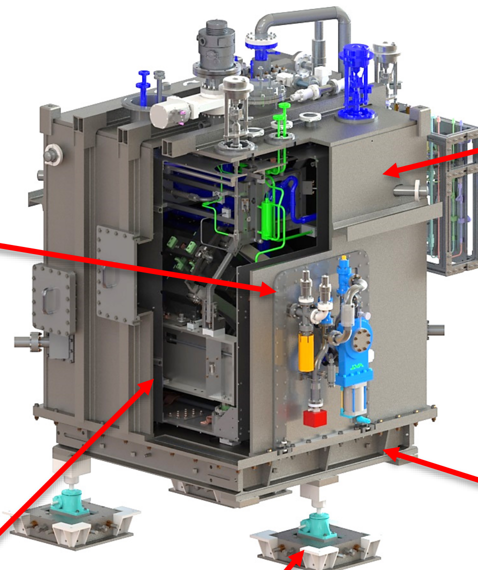
SRF Gun Cryomodule Fabrication Plans/Status- Cryomodule



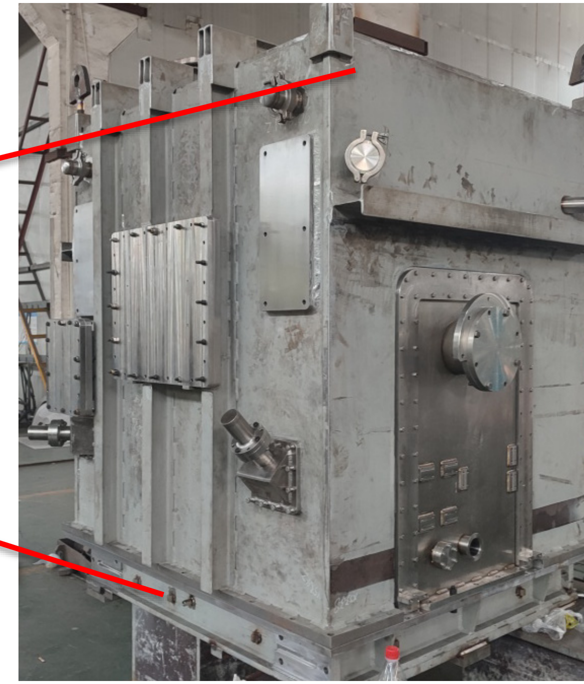
Vacuum Vessel Seal Plate



Thermal Shield



Adjuster Components

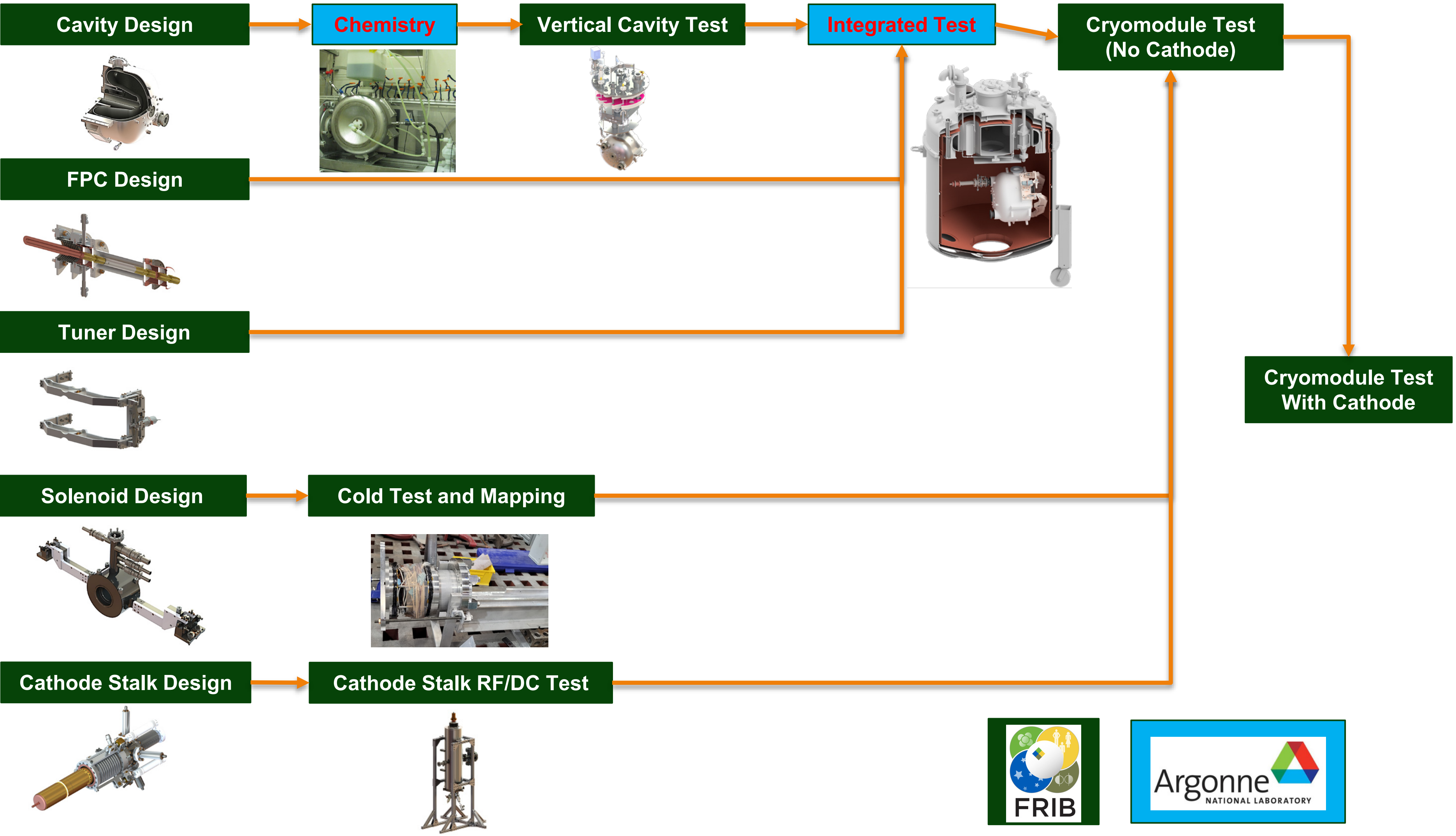


Vacuum Vessel Baseplate & Cover

3 Way O-ring

Separated Cavity/Cryomodule Isolation Vacuum

SRF Gun Cryomodule Testing Plans



Summary and Path Forward

- SRF Gun cryomodule design has been completed to the performance goals/requirements
- Cryomodule component fabrication is ongoing and progressing smoothly
- Validation plans for critical systems are established and where possible proceeding
- The first cavity will be tested in the second half of 2023