Advancing SRF cryomodules performance for modern particle accelerators

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Accelerator Physics/Engineering Seminar at MSU/FRIB

Outline

- Fermilab Overview
- Introduction to Accelerator and SRF Technology
- Overview of SRF Cryomodules
  - Static Heat Load of SRF cryomodules
  - Use of Finite Element Analysis in crryomodule design
  - Alignment of beamline elements
  - Dynamic Behavior in Transportation
  - Robot-assisted technology for SRF cleanroom assembly

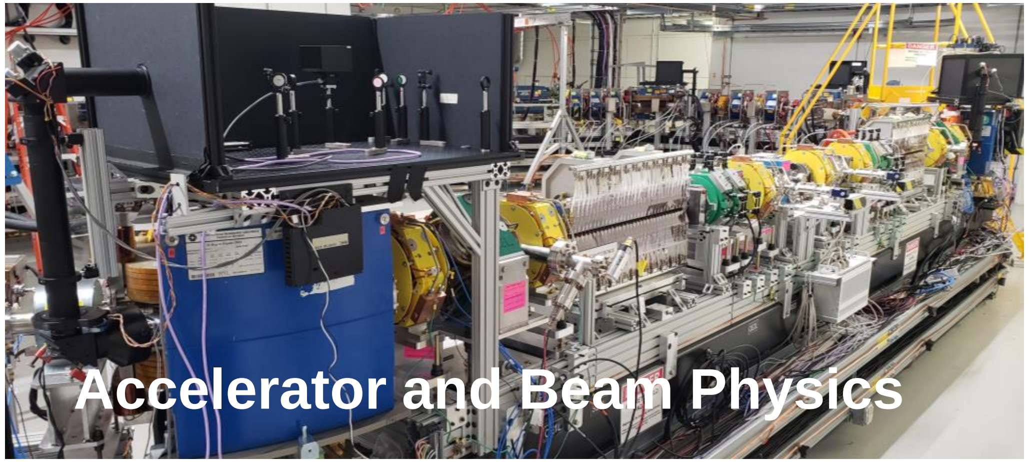
Fermilab at a Glance

- America's particle physics and accelerator laboratory
- Operates the largest US particle accelerator complex
- ~1,900 staff and ~$600M/year budget
- 6,800 acres of federal land
- Facilities used by 4,000 scientists from >50 countries

As we move into the next 50 years, our vision remains to solve the mysteries of matter, energy, space, and time for the benefit of all.

Accelerator Science & Technology

Vision: Fermilab is a world-leader in Accelerator Science & Technology R&D that enables the next generation of particle accelerators and advances the HEP and Office of Science mission. Fermilab is an essential partner of choice to future large-scale accelerators.



Fermilab is addressing the needs of many SC program offices

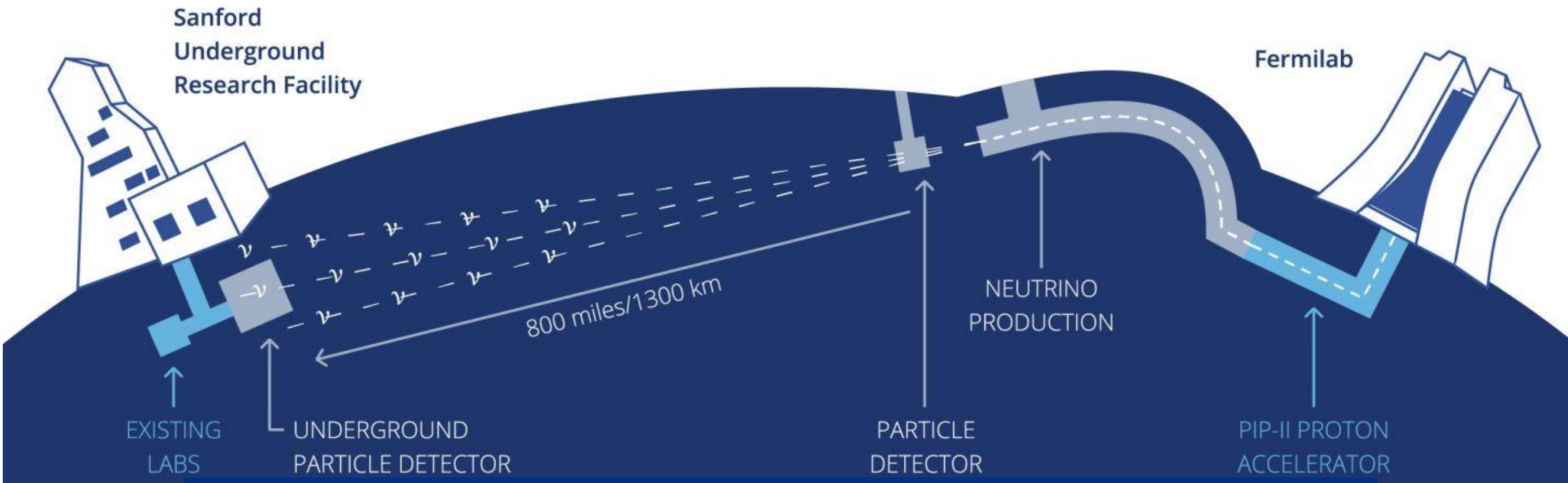
Fermilab

Neutrino Science

DUNE: “Best in Class” neutrino experiment, driven by LBNF and PIP-II

Vision for Neutrino Science

U.S. is universally acknowledged as the world leader in neutrino science for decades to come



Delivering on LBNF/DUNE is Fermilab’s highest priority

PIP-II Project at Fermilab

Proton Improvement Plan II (PIP-II) is an upgrade to Fermilab accelerator complex to enable the world's most intense beam of neutrinos to LBNF/DUNE.

PIP-II Scope

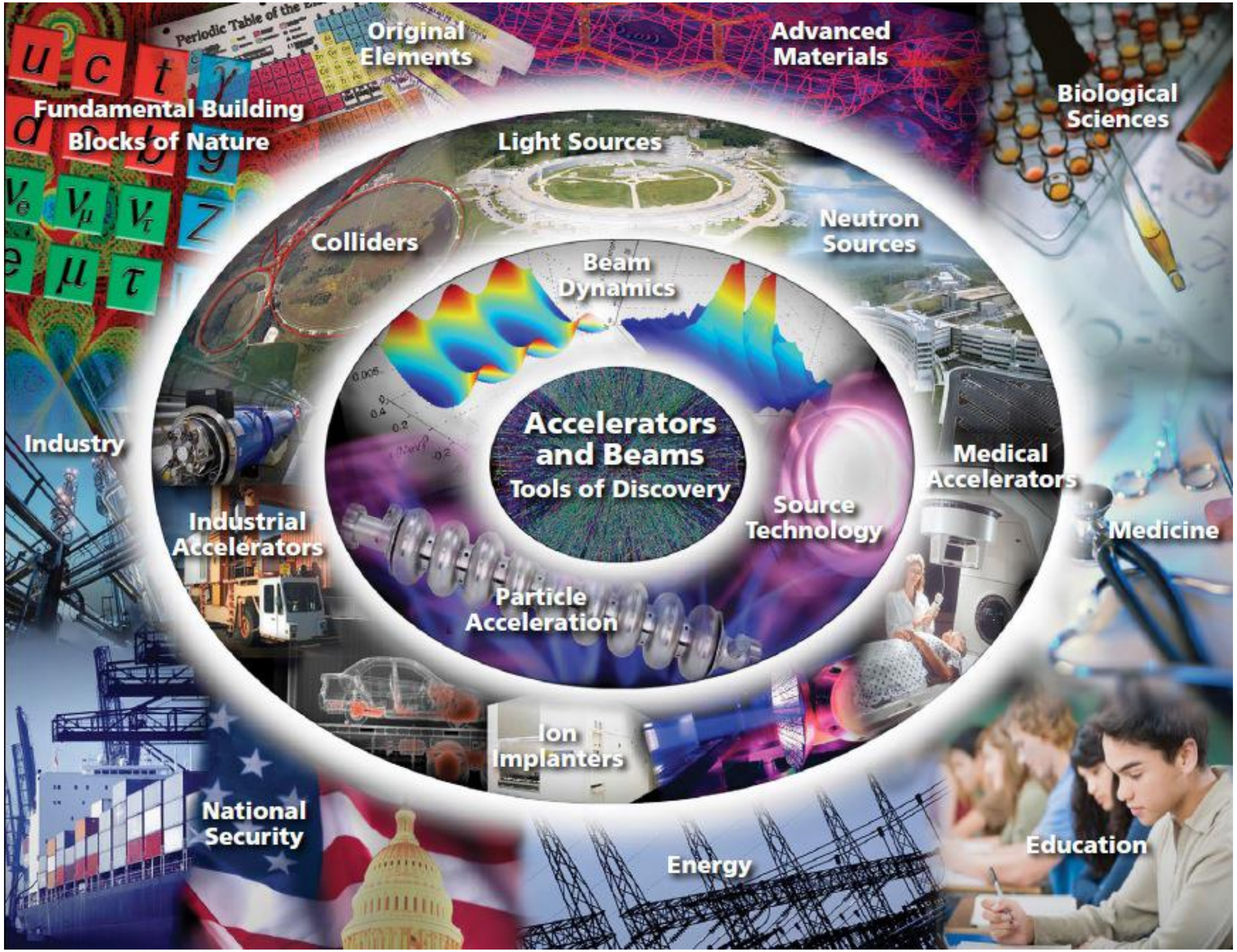
- 800 MeV, 2mA H− SRF linac, CW RF Operations
- Linac-to-Booster transfer line
- Accelerator Complex Upgrades
  Booster
  Recycler
  Main Injector
- Conventional Facilities

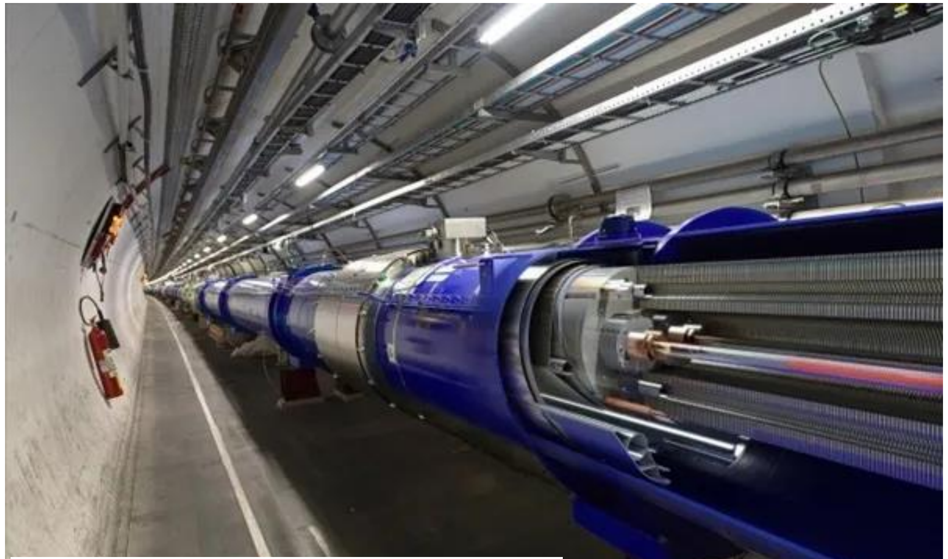
PIP-II Beam Power

- 1.6 MW H− beam
- Upgradeable to multi-MW

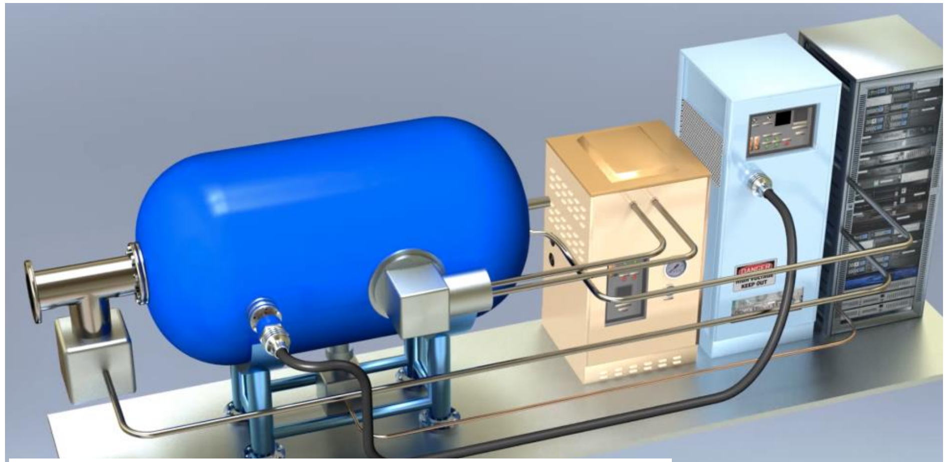
Introduction to Accelerator and SRF Technology

Particle Accelerators





Large Hadron Collider (CERN)



Compact SRF accelerator (Fermilab)

SRF accelerators around the world - Global view

Distribution of superconducting particle accelerators using SRF structures for electrons (orange), protons (purple) and heavy ions (pink). More than 30 SRF accelerators are in operation (circles), approximately 15 are presently under construction (triangles) and more than 10 future projects are under consideration (squares).

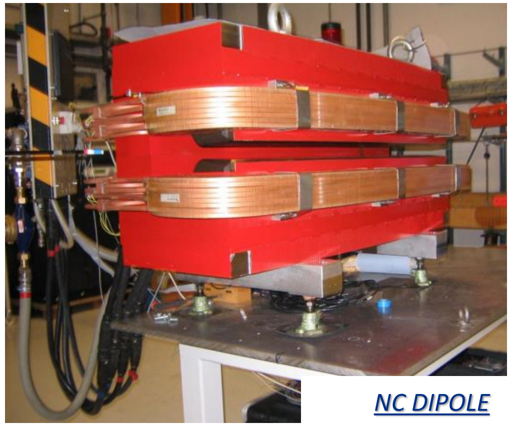
Credit: CERN

SRF accelerators around the world

Linac	Laboratory	Application	Acc. Particle	Operation
SNS	ORNL, USA	Neutron Source	H^-	pulsed
ESS	ESS, Sweden	Neutron Source	p	pulsed
MYRRHA	SCK-CEN, Belgium	ADS	p	CW
CIADS	IMP, China	ADS	p	CW
ISNS	Indore, India	Neutron Source	p	pulsed
ADSS	BARC, India	ADS	p	CW
JADS	JPARC, Japan	ADS	p	CW
PIP II	FNAL, USA	Nuclear physics	H^-	CW
FRIB	MSU, USA	Nuclear physics	Ions	CW
RAON	RISP, S.Korea	Nuclear physics	Ions	CW
CEBAF	JLAB, USA	Nuclear physics	e^-	CW
XFEL	DESY, Germany	FEL	e^-	pulsed
SHINE	SINAP, China	FEL	e^-	CW
LCLS II	SLAC, USA	FEL	e^-	CW

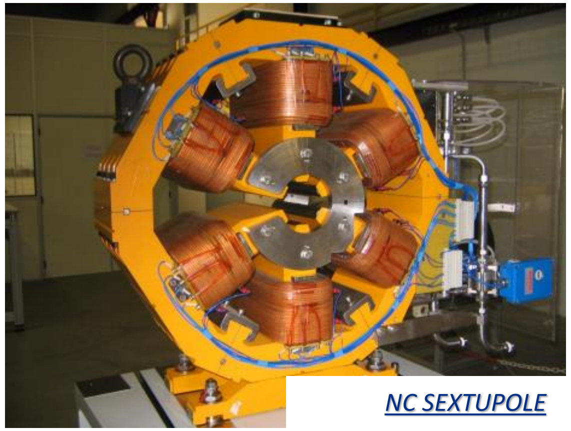
Magnets for Particle Accelerators

- Magnets are employed in particle accelerators for steering, focusing and correcting the beam.
  - Normal conducting magnets (NC) work at room temperature and water cooled (limited magnetic field)
  - Super conducting magnets (SC) works at cryogenic temperature

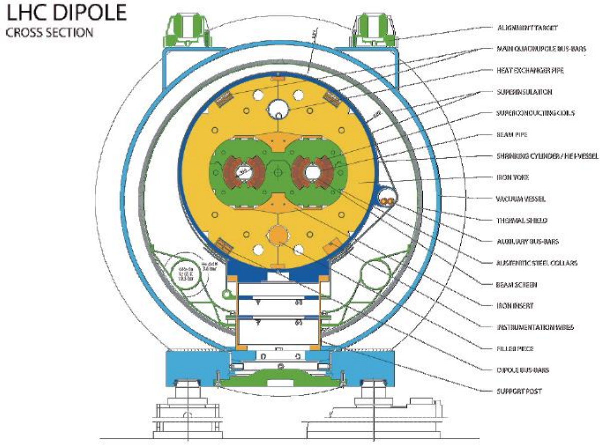


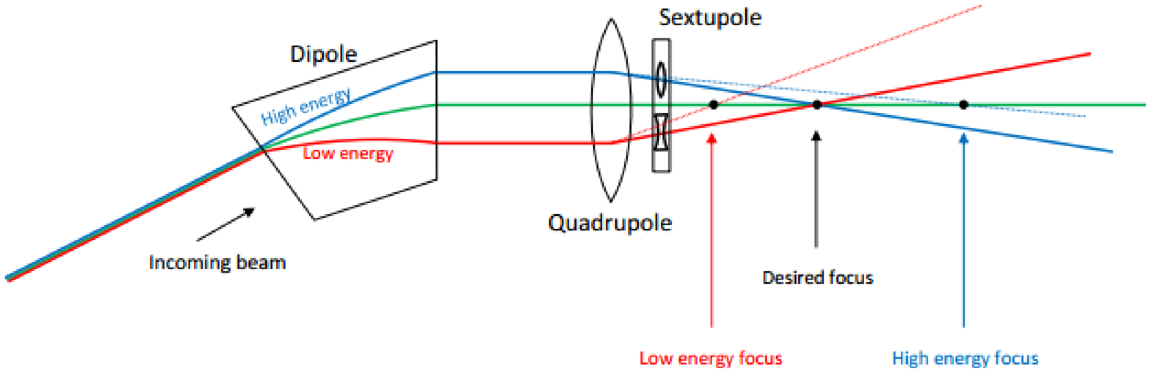
NC DIPOLE

NC QUADRUPOLE



NC SEXTUPOLE





SC MAGNET ASSEMBLY

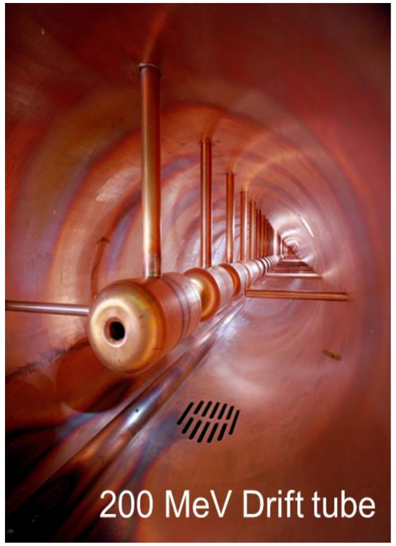
RF cavities for Accelerators

In all modern RF accelerators, the beam acceleration take place in a resonance wave (standing or travelling) electromagnetic field excited in an RF cavities.

RF cavities types:

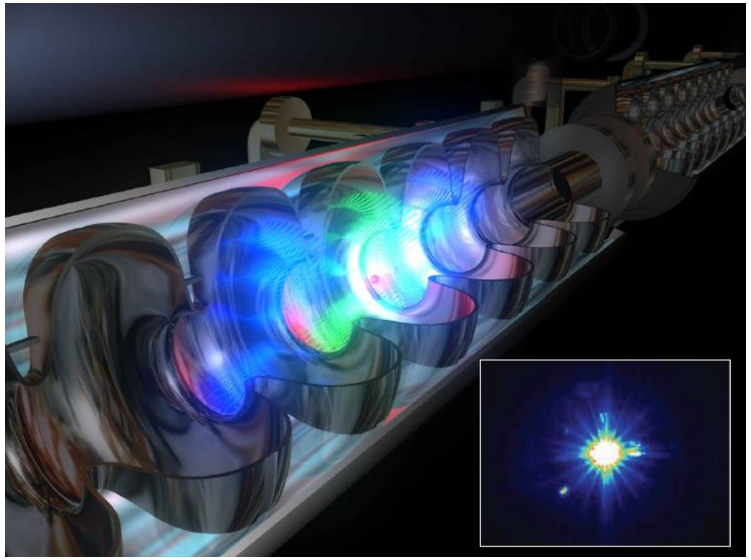
- Normal conducting RF cavities (NRF) work at room temperature and water cooled but with limited powers.
- **Superconducting RF cavities (SRF)** works at cryogenic temperature enabling very high efficiency.

Copper RF cavities (NRF)



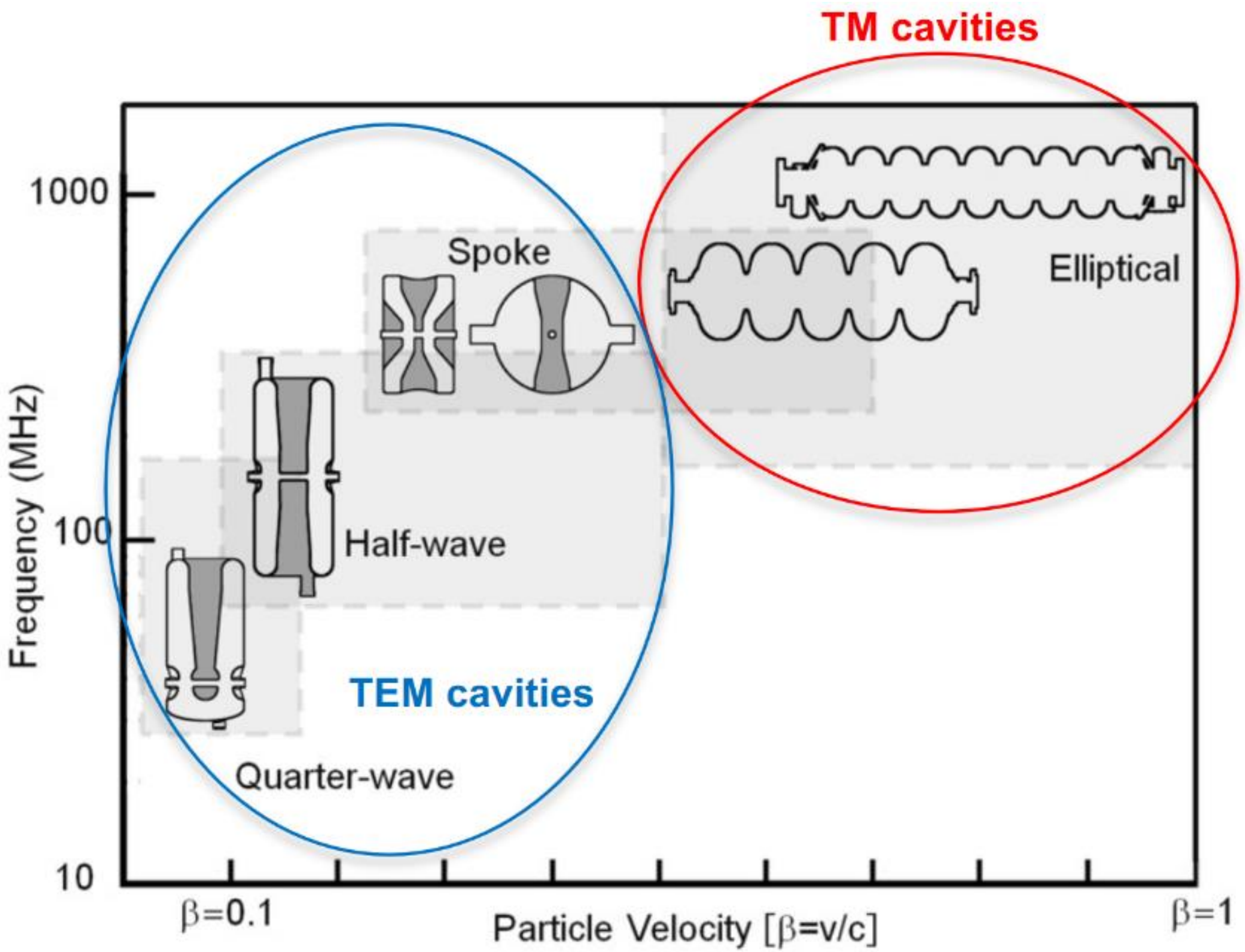
Niobium RF cavities (SRF)

High β:
mostly various elliptical shape structures.



Low β:
a zoo of structures (QWR, RFQ, HWR, spoke, crab cavities)

SRF cavities types

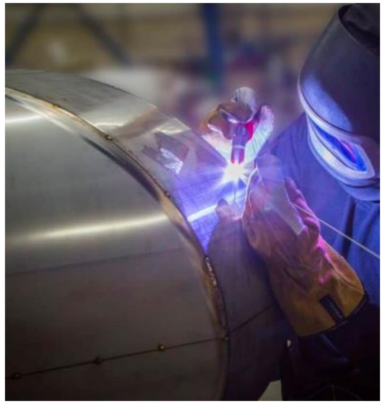
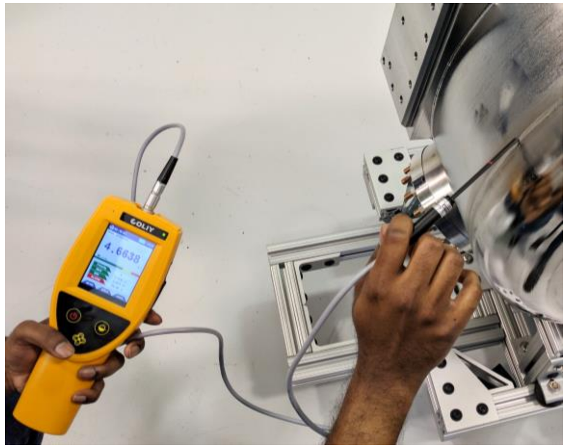
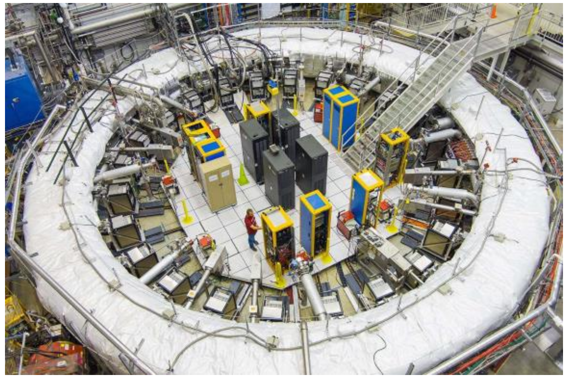
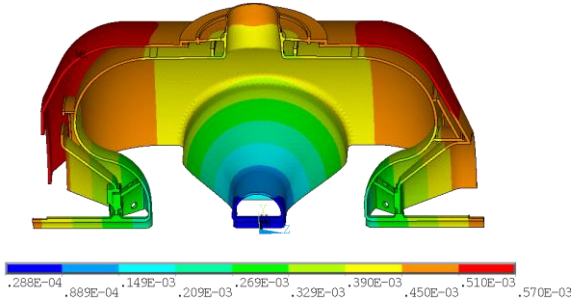


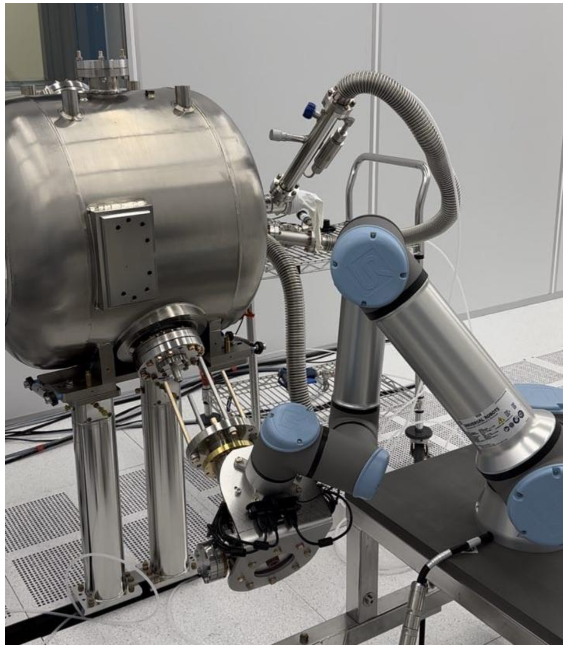
Some practical geometries for different particle velocities

SRF science & technology for particle accelerators

List of disciplines and skills that are relevant in SRF

- Superconductivity
- Vacuum science
- Surface science
- Materials science
- Beam physics
- Cryogenics
- Surface treatment techniques
- Cavity test methods
- RF/microwave engineering
- Mechanical engineering
- Cleaning technology

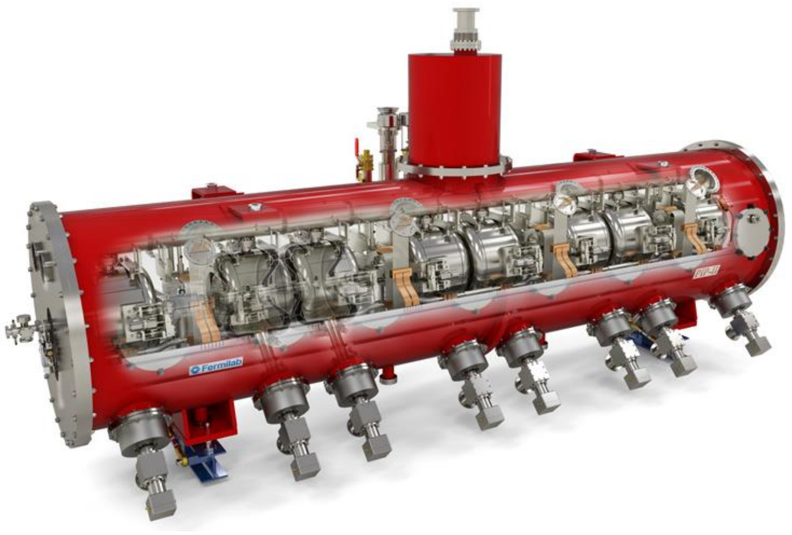





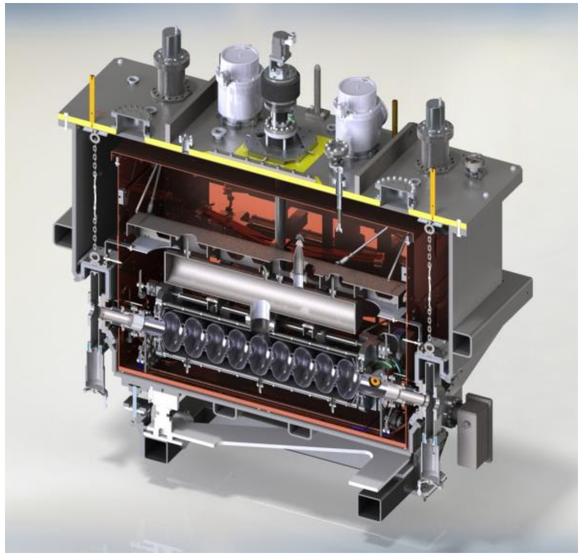


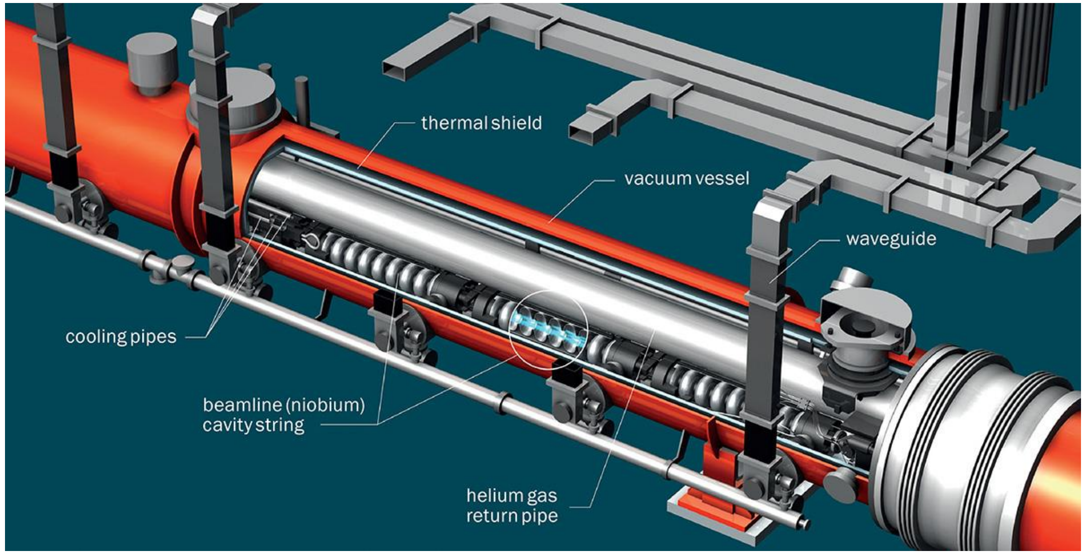
Overview of SRF Cryomodules

SRF Cryomodules

- SRF cryomodules are essential components in modern particle accelerators like linear accelerators (Linacs) and circular accelerators (Synchrotrons).
- They play a crucial role in providing the necessary conditions to superconducting cavities and magnets for accelerating charged particles to very high energies.

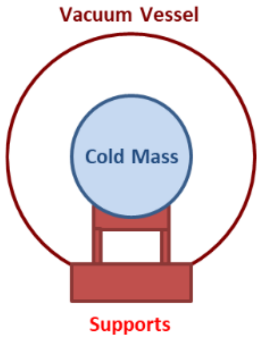






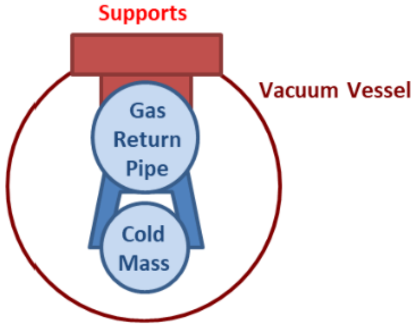
Main layout of SFR cryomodules

- Bottom support



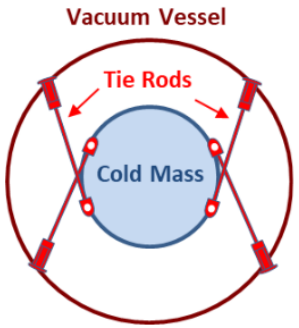
Example: PIP-II, FRIB, SRILAC

- Use the Gas Return Pipe (GRP) as a backbone



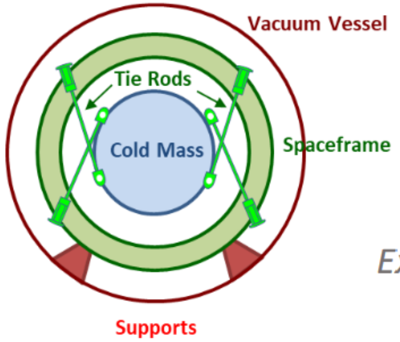
Example: XFEL, LCLS-II

- Use of tie rods
  - Antagonist tie rods



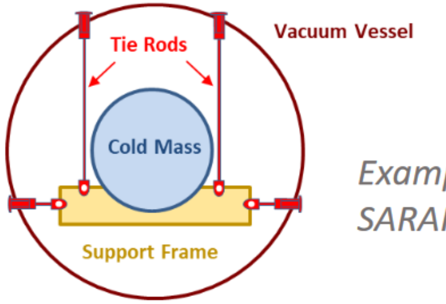
Example: Spiral 2

  - Use an intermediate structure: the “spaceframe”



Example: SNS, ESS

  - Use of a support frame attached to the top of the vacuum vessel



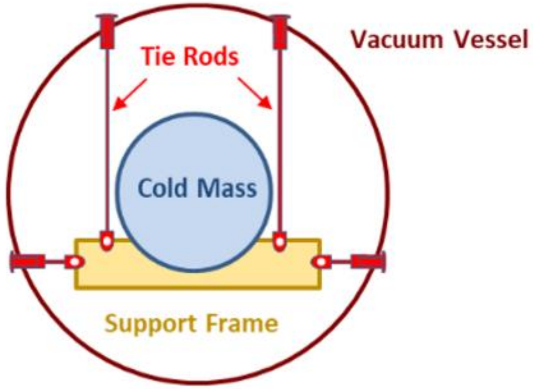
Example: ARIEL, IFMIF, SARAF Phase 2

- Each concept has its specific advantages and drawbacks. The choice depends on many parameters: the type of cavity, the assembly methods, the alignment process, transportation, the experience of the design and assembly teams …

SRF cryomodules shape

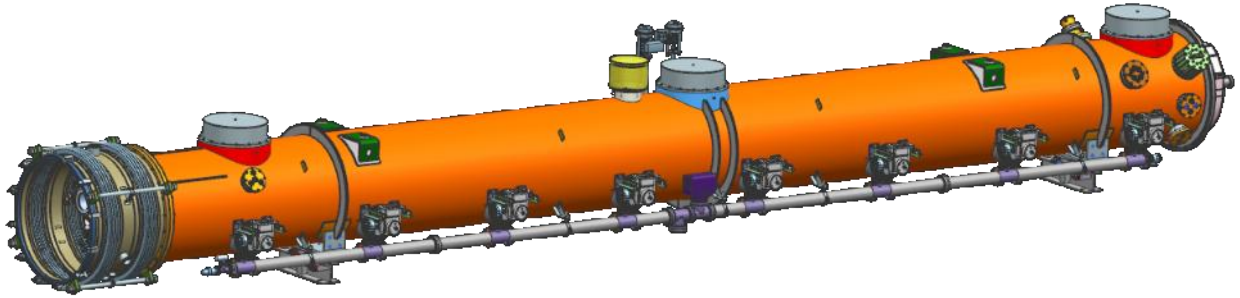
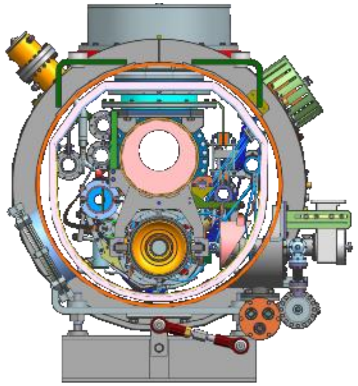
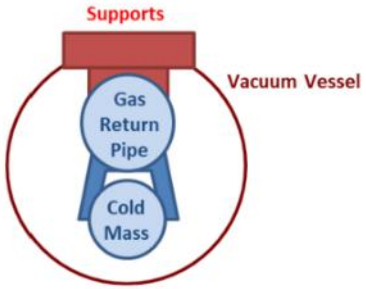
Cryomodules with quarter and half wave cavities use generally a support frame attached to the top plate of the vacuum vessel.





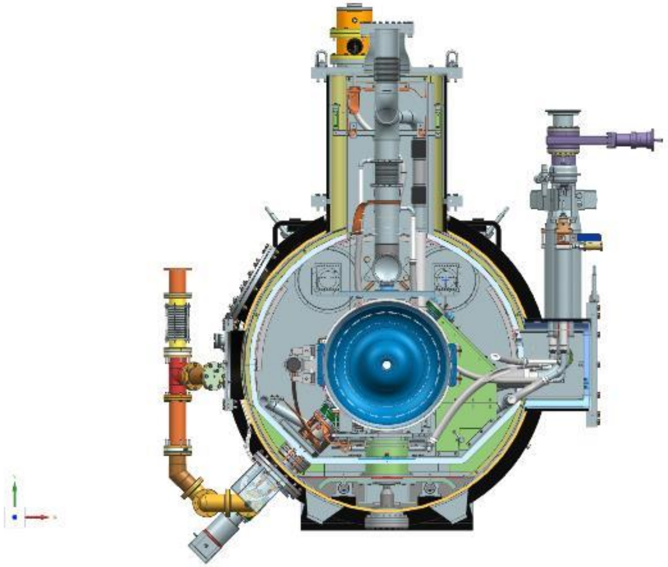
Spoke and elliptical cryomodules can be designed by many ways.

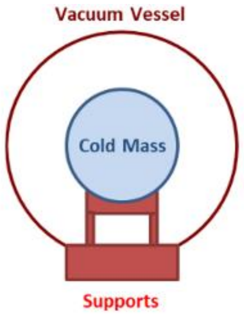
- **LCLS II 1.3 and 3.9 GHz Cryomodule (elliptical)**

Fermilab Style Cryomodule – bottom supported

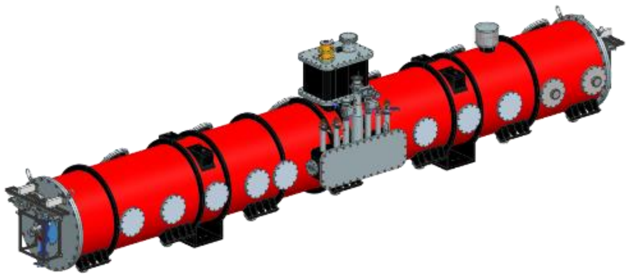
- **PIP-II SSR cryomodules (spoke)**

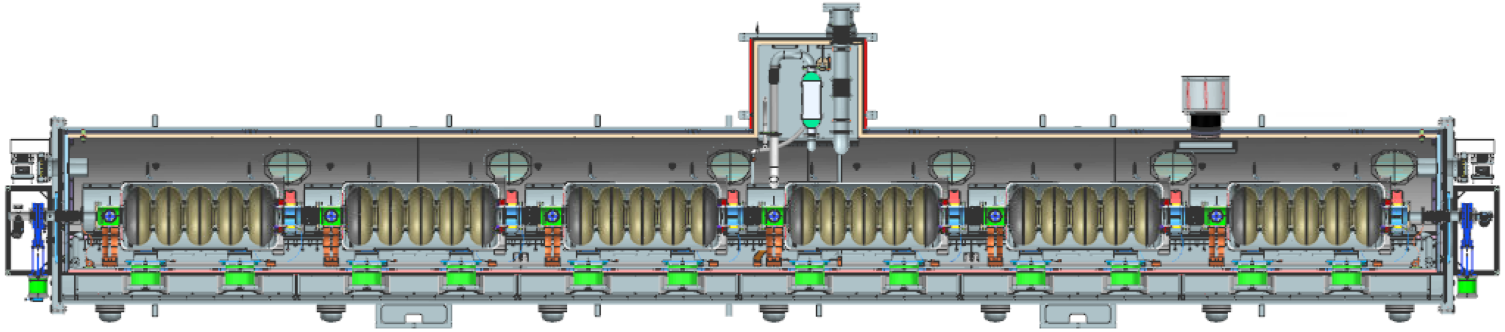


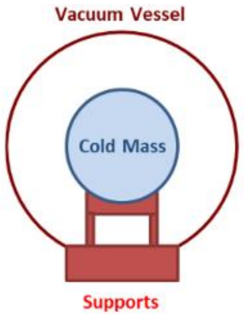


Fermilab-style Cryomodule

- **PIP-II 650 cryomodules (elliptical)**



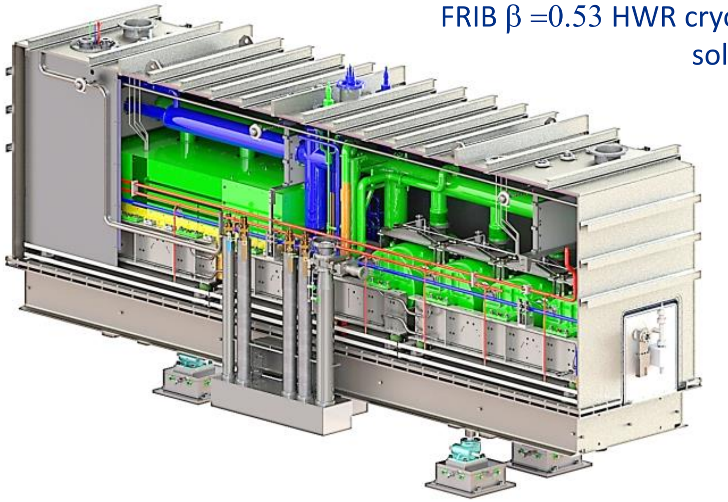




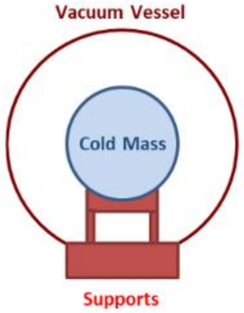
Fermilab-style Cryomodule

FRIB Style Cryomodule – bottom supported

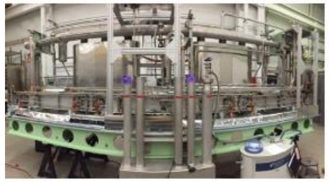
- Total four types cavities (QWR, HWR) and six types of modules
- Total 324 cavities and 46 modules
- Room temperature strong back and machining tolerance to guarantee the alignment
- Local Magnetic shielding around cavities
- Two wind FPC and Mechanical slow tuner
- Two helium saturated bathes 2K for SRF cavity and 4K focusing solenoids
- Cryo system is supported from top and decoupled from cold mass

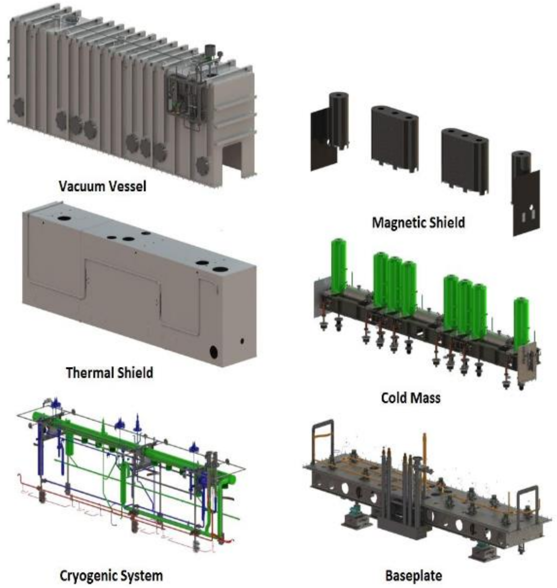


FRIB $\beta = 0.53$ HWR cryomodule, 8 cavities and 1 solenoid



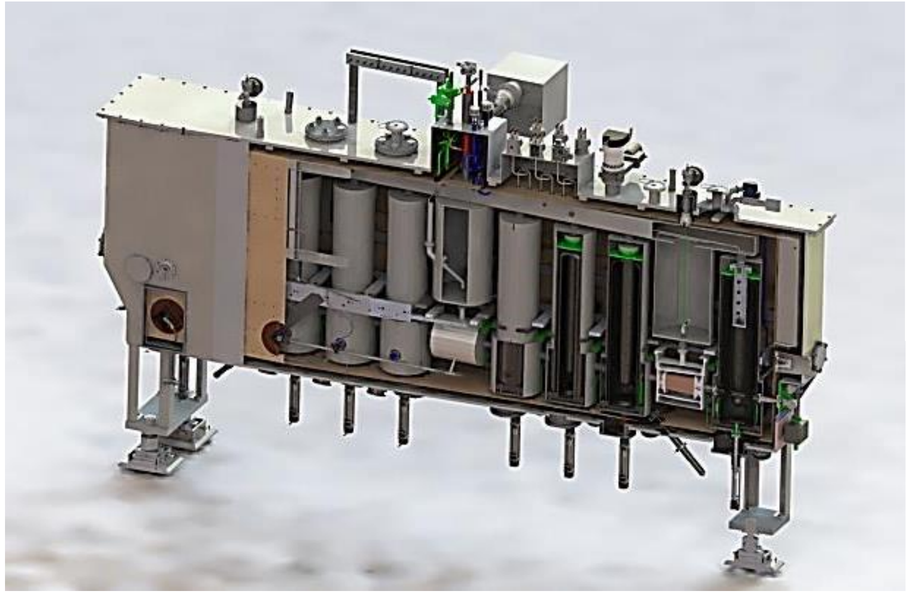
Beta=0.085 cold mass

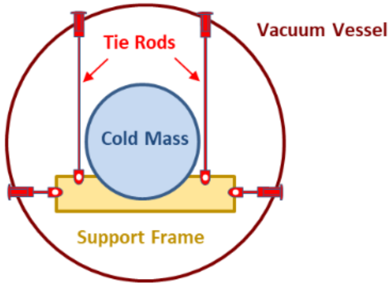


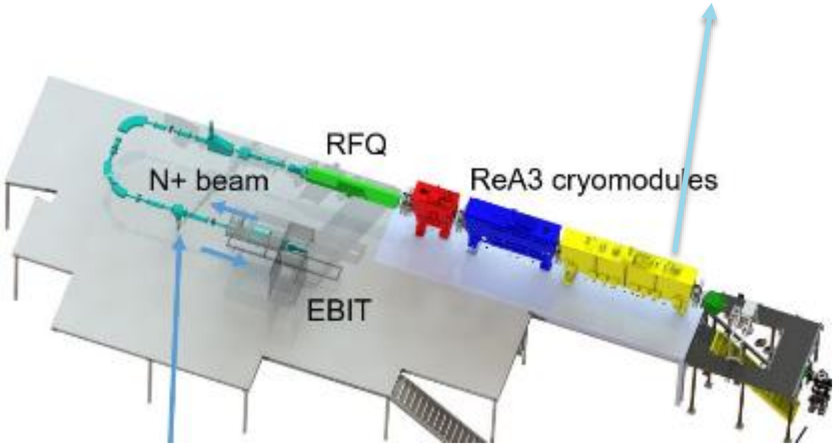


FRIB ReA Cryomodule – top supported by the VV plate

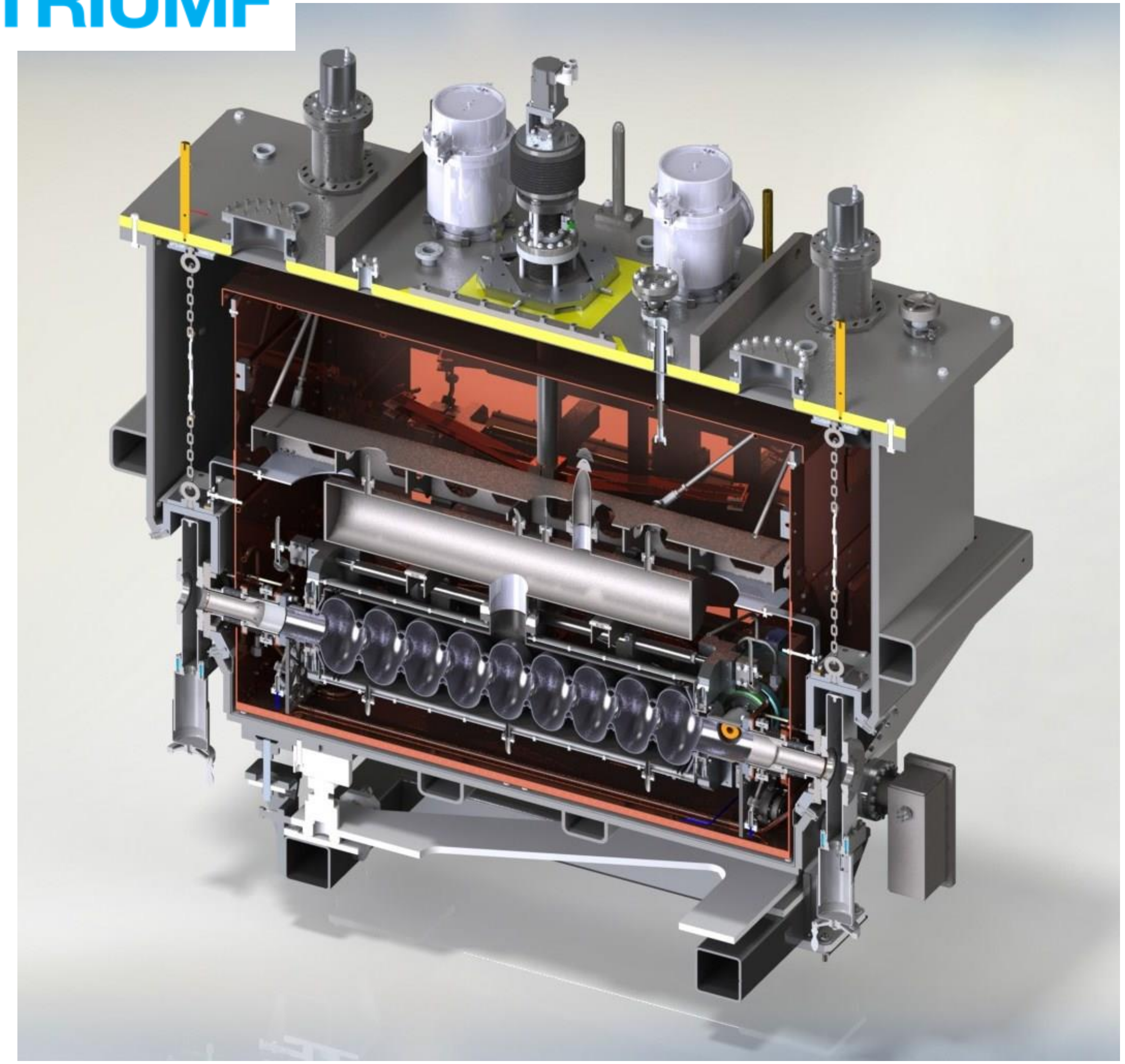
- Eight 80.5 MHz QWR and 3 focusing solenoids
- Ti Rail for cavity string and suspend from the top lid
- Cold alignment adjustment using links
- Local Magnetic shielding around cavities
- Additional iron shielding around focusing solenoids with shield coils
- 4K helium bath for both cavity and magnets
- Cryo system is supported from top and decoupled from cold mass

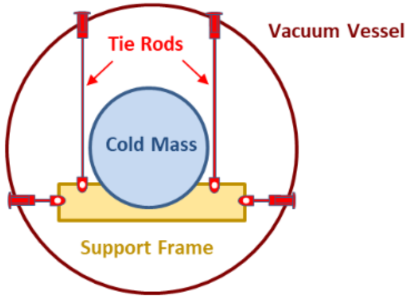






Injector Cryomodule – TRIUMF





Houses

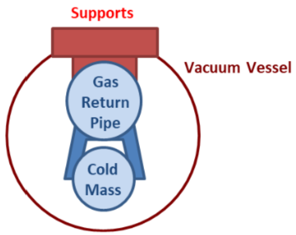
- one nine-cell 1.3GHz cavity
- Two 50kW power couplers

Features

- 4K/2K heat exchanger with JT valve on board
- Scissor tuner with warm motor
- LN2 thermal shield – 4K thermal intercepts via syphon
- Two layers of mu-metal
- WPM alignment system

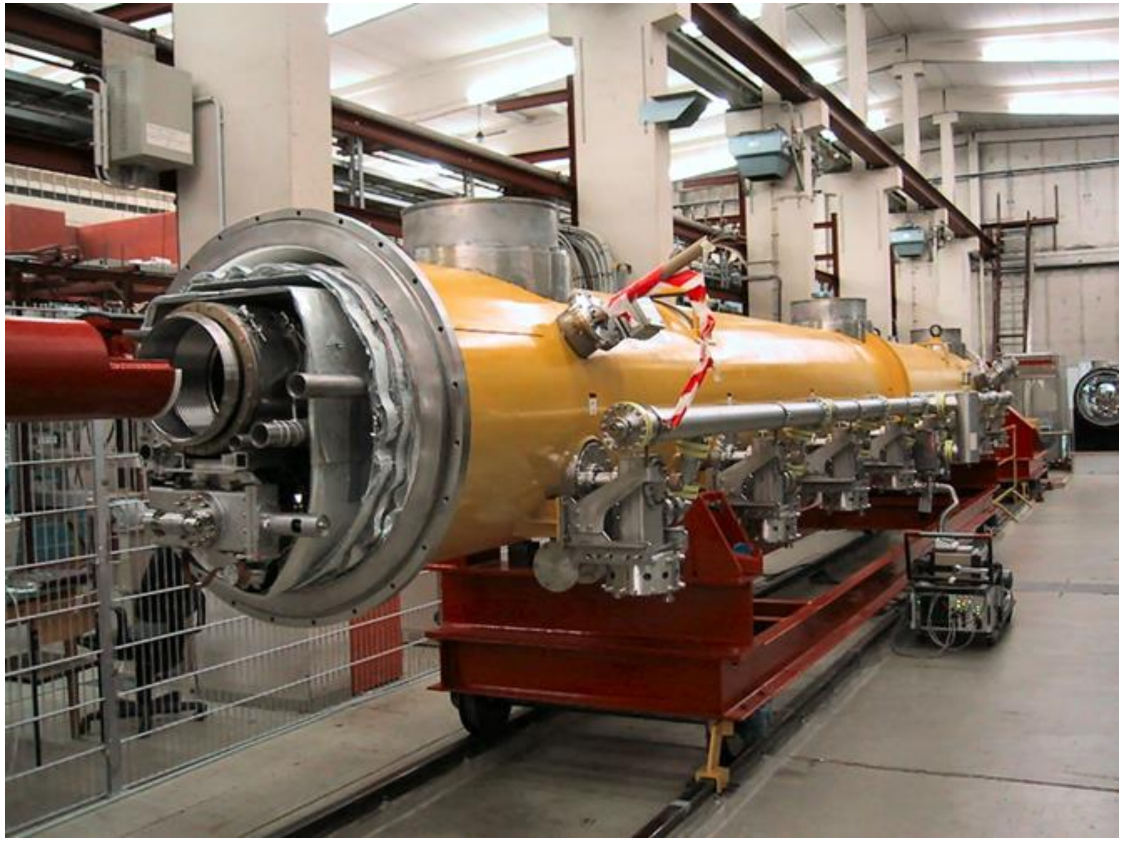
1.3 GHz Cryomodules: XFEL, LCLS-II

- Use the Gas Return Pipe (GRP) as a backbone



Example: XFEL, LCLS-II

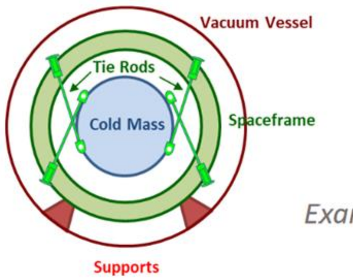
XFEL 1.3 GHz cryomodule at DESY



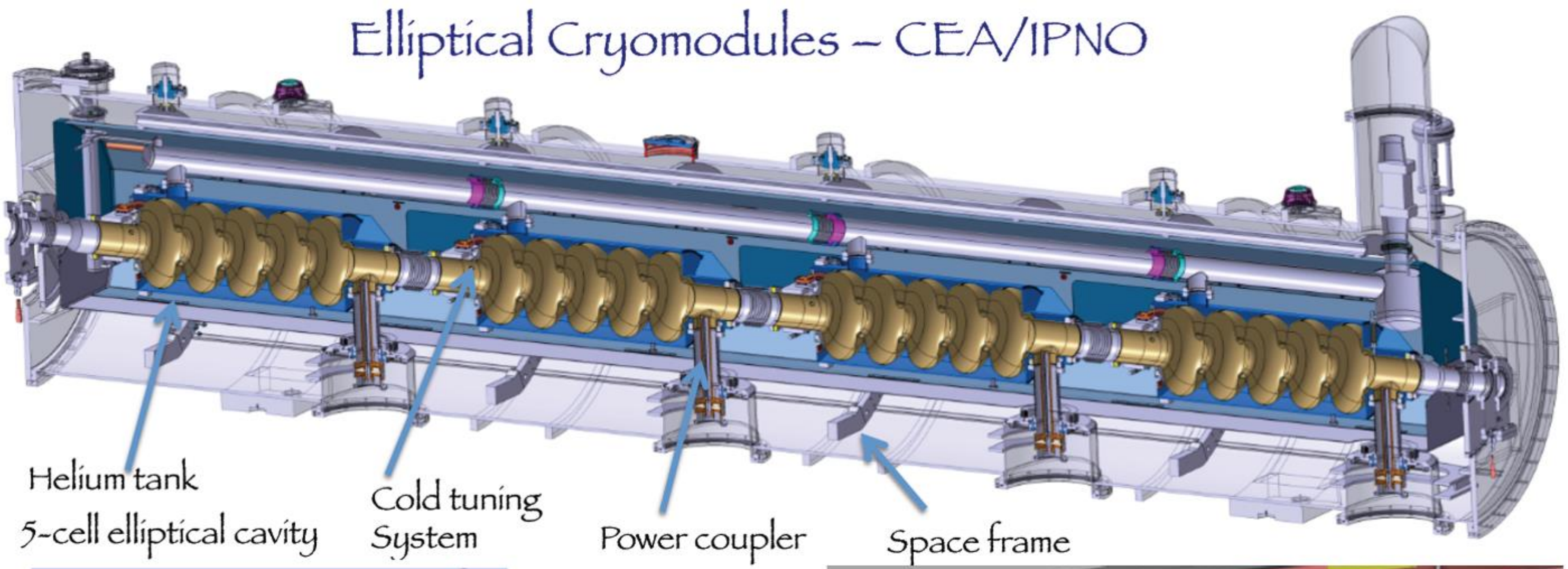
Fermilab 1.3 GHz CM for LCLS-II at SLAC

ESS Space Frame cryomodule – Elliptical cavities

- Use an intermediate structure: the "spaceframe"



Example: SNS, ESS



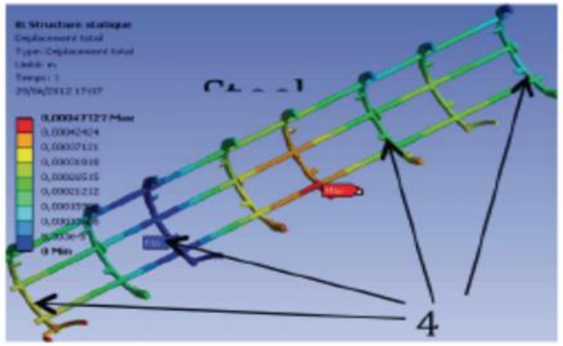
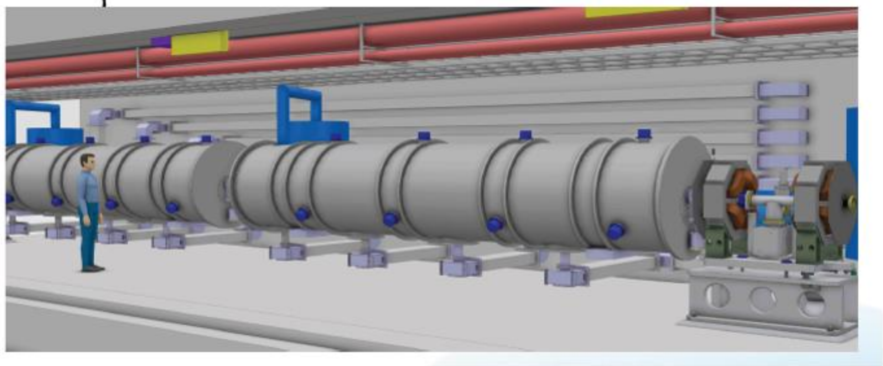
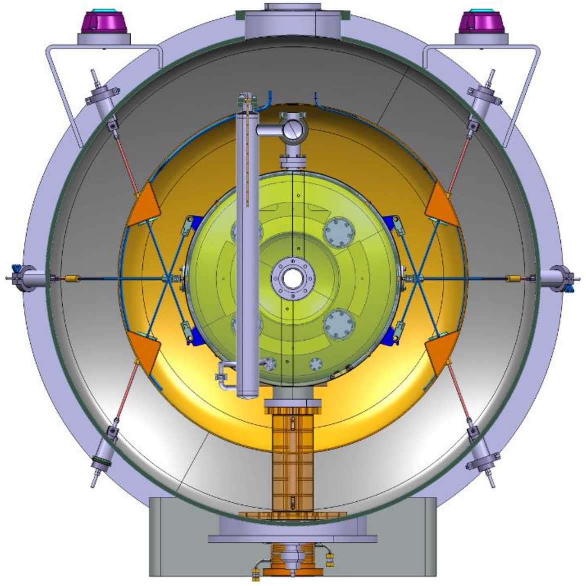


Figure 4.120: Helium vessel with hanging rod





SRF Cryomodule Performance: Static Heat Load

Introduction of the Static Heat Load (SHL)

- The **static heat load** of a cryomodule refers to the **cryogenic power** required to maintain all its components at their nominal operating temperature conditions in the absence of RF power supplied to cavities. This load is distributed across various cooling lines:
  - 2K (or 4K) static heat load
  - Low-temperature thermal shield (5-10K) static heat load
  - High-temperature thermal shield (40-80K) static heat load

SHL Estimation

- Accurate estimation of heat loads is crucial as these values serve as the basis for designing the cryogenic plant that supplies helium to the cryomodules.
  - While Finite Element Analysis (FEA) can be employed for such estimations, analytical calculations are often sufficient, given the well-known equations for conduction and radiation.
- Regardless of the method used, the primary challenge lies in appropriately identifying all sources of heat loads.
  - Conducting a full FEA of the cryomodule is often impractical. Instead, assumptions need to be made about factors such as emissivity, temperature, parts in contact or not, and dimensions (length, surface area, etc.). This process involves a careful consideration of various parameters to arrive at accurate and practical estimates for effective cryogenic plant design
- Control of the cryomodule assembly process is extremely important to check that things are done according to the head loads assumptions…

Comparison of CM 2K static heat load (from TTC 2023)

Serial #	CM type	Static heat load@ 2K				Project/ Lab
		Pstat [W]	Uncertainty [W]	Method	Measurement range	
1	1.3GHz 9-cell CM	~ 18 W	~1 W	Helium Pressure rising(ΔP/Δt) *Not a viable measurement for connected LCLS-II CMs	LH pressure 18 - 33 torr	LCLS II/JLab * Calculate from typical measurement
2		--	--	Liquid level method (ΔLL/Δt)	LH level 95%-90%	LCLS II/JLab
3		Good correlation shown with ΔP/Δt method	--	flow rate reading @ cold	--	LCLS II/JLab
4	1.3GHz 9-cell CM (LO-L2)	9	~10%	Liquid level method (ΔLL/Δt)		LCLS II/ SLAC
5	1.3GHz 9-cell CM (L3-UPSTREAM)	17	~10%			LCLS II/ SLAC * with Additional Pump
6	1.3GHz 9-cell CM (L3-DOWNSTREAM)	16	~10%			LCLS II/ SLAC
7	1.3GHz 9-cell CM	5.5	~10%	flow rate reading @ RT	--	FLASH and XFEL / DESY
8	1.3GHz 9-cell CM (BCP)	23.4	~1W	Liquid level method	--	SHINE/SARI
9	1.3GHz 9-cell CM (High-Q)	21.0	~1W		LH level 90%-85%	
10	1.3GHz 9-cell CM (1st production)	14.5	~1W		HL level 85%-75%	
11	1.3GHz 9-cell CM (mid-T)	28.6	±0.4	flow rate reading @ RT	HL level 80%-75%	DALS /IHEP
12		27.5	±0.8			
13		25.8	±1.3			

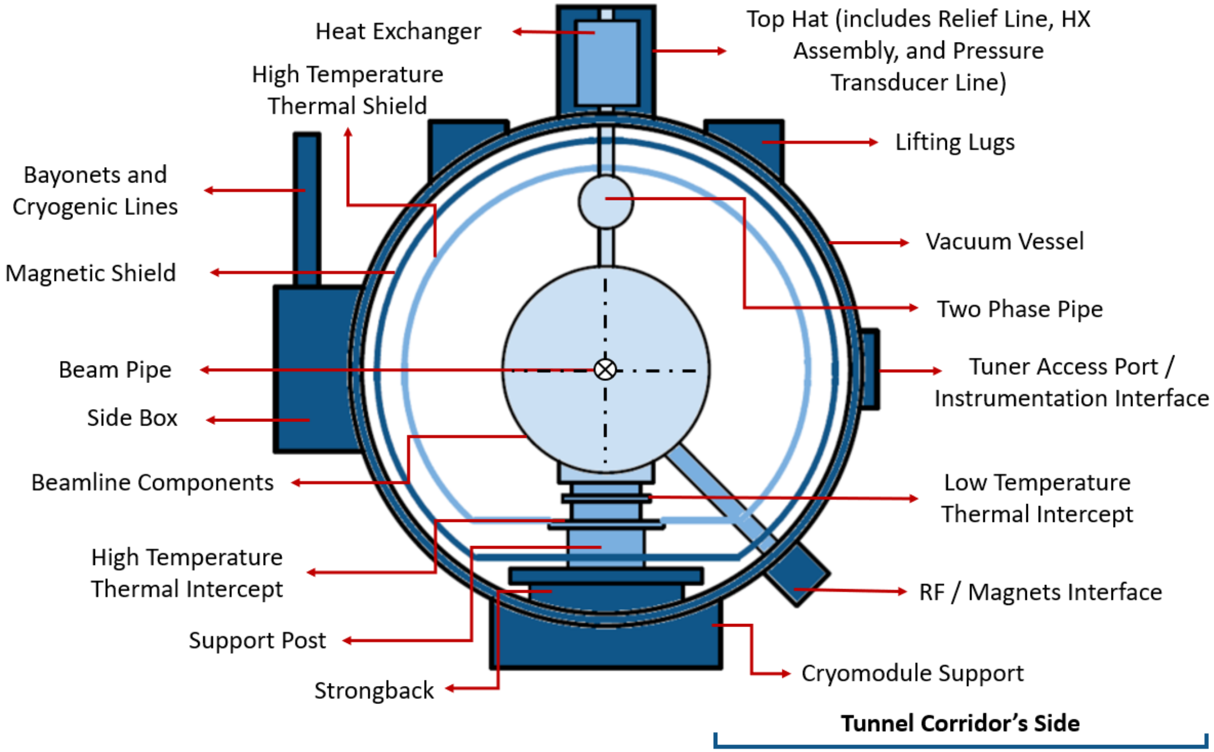
LINK

Comparison of CM 2K static heat load (from TTC 2023)

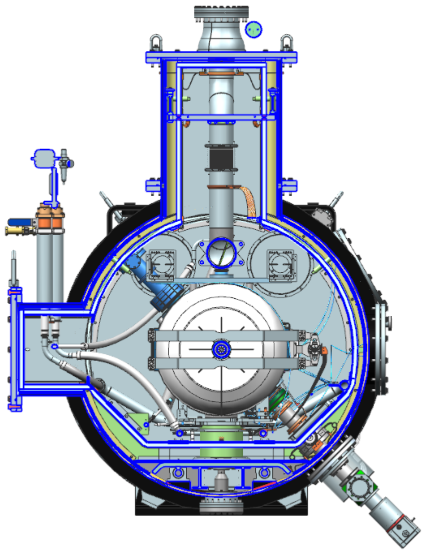
Serial #	CM type	Static heat load@ 2K				Project/ Lab
		Pstat [W]	Uncertainty [W]	Method	Measurement range	
14	MBL CM (include 6-cell *4 cavities)	16.8	~30%	flow rate reading @ RT	HL level 93.2%-84.1%	ESS/ESS
15		16.84	~ 1W	Helium Pressure rising(ΔP/Δt)	HL level 85.4%	
16		17.36	~ 1W	Liquid level method	HL level 93.2%-84.1%	
17	HB650 Prototype CM	38.2	--	flow rate reading @ RT	--	PIP II /FNAL
18	2-cell injector CM (include 3 cavities)	11	10%	flow rate reading @ RT	HL level 77%-67%	cERL / KEK
19	9-cell main Linac CM (include 2 cavities)	11	10%		HL level 28%-18%	cERL / KEK
20	1.3 GHz 9-cell CM (4+8 cavities)(1.5 module)	32.6	10%		HL level 55%-51%	STF / KEK
21	704MHz CM	~ 18	--	flow rate reading @ RT	--	ESS /CEA
22	Medium Beta CM	~ 25	--	Heat vs %JT opening	--	SNS/ ORNL
23	High Beta CM	~ 28	--		--	
24	PPU CM	~ 25	--		--	

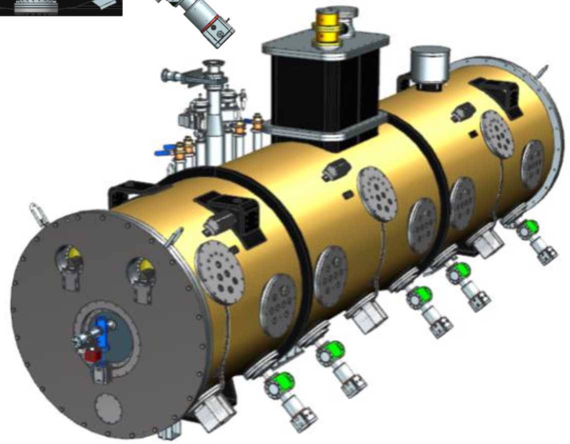
Use of Finite Element Analysis in CM design

Design of the PIP-II SSR2 cryomodule

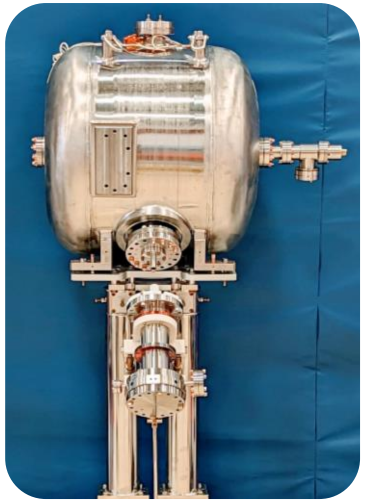


The Fermilab-style Cryomodule

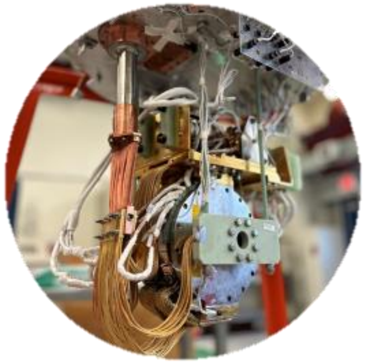




Pre-production SSR2 cryomodule



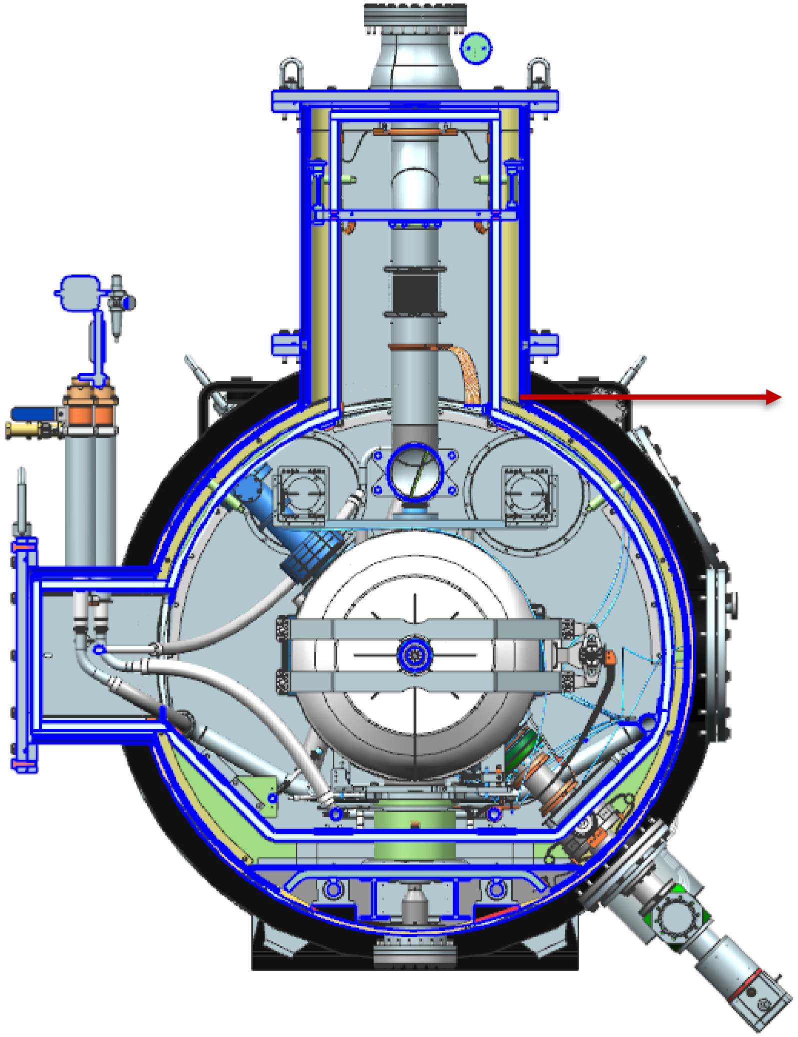
SRF cavities



SC magnets

SSRs Cryomodule Cross-section

Pre-production SSR2

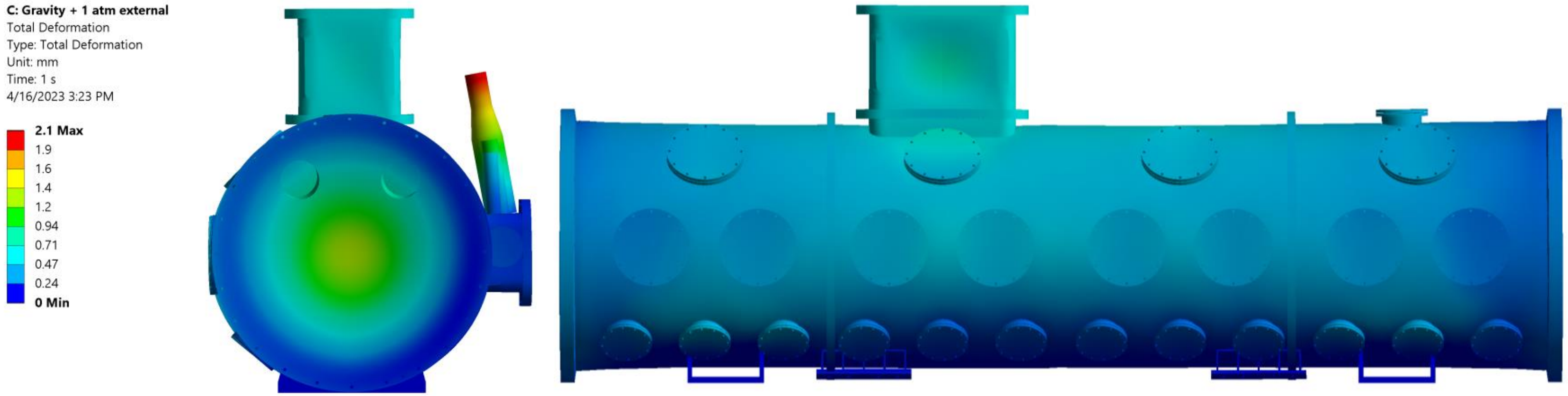


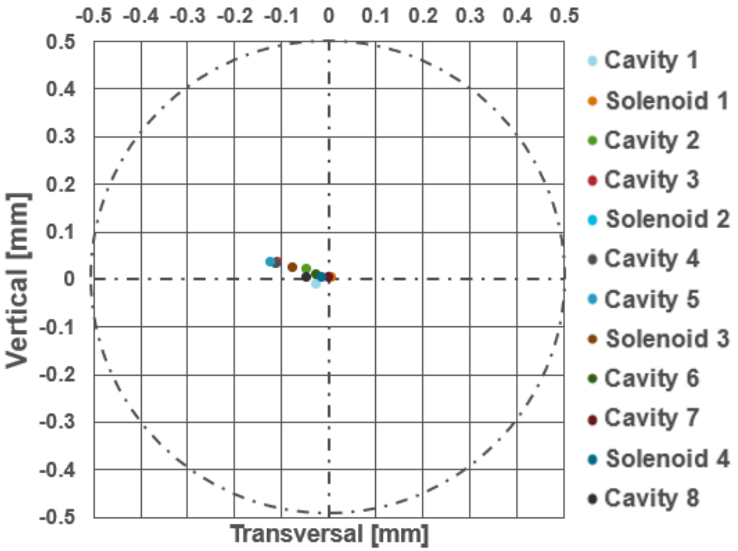
Vacuum Vessel:
It houses all the internal components which operate in a moderate to high vacuum service.

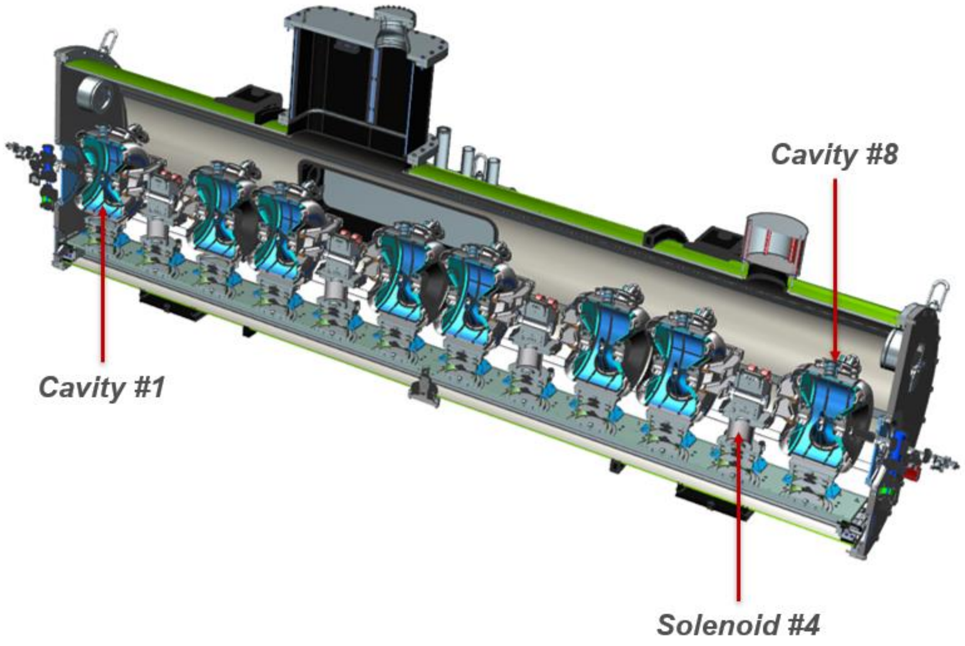
Structural analyses:

- Internal and external overpressure.
- Buckling.
- Lifting.

FEA examples: Vacuum Vessels



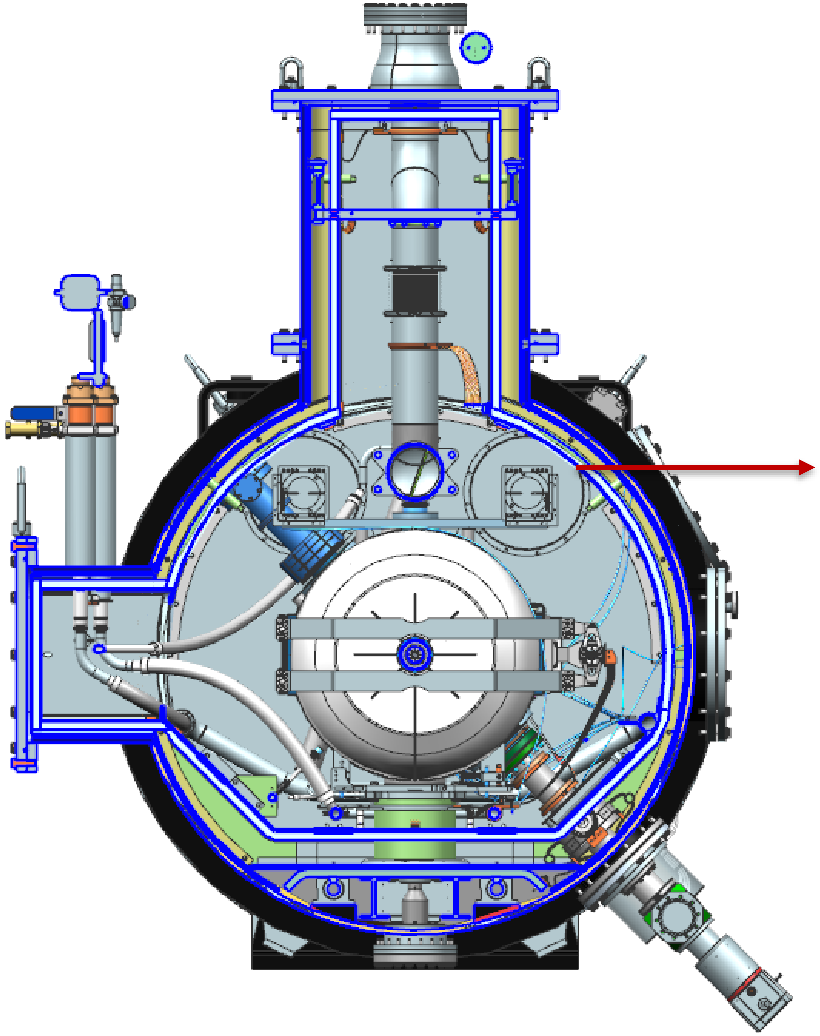




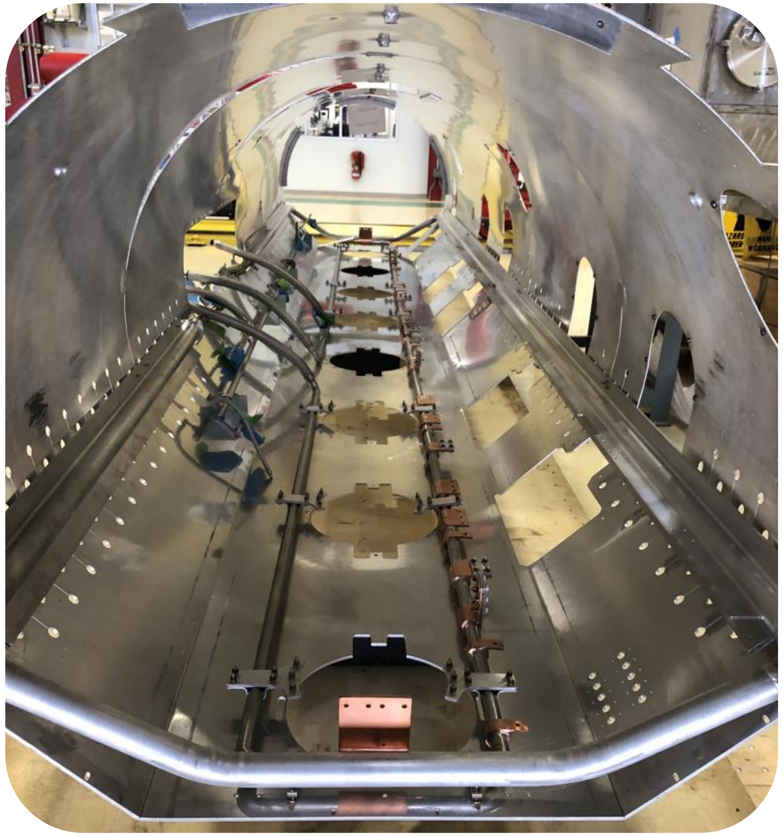
- Goal of the analysis: study the impact of external pressure on cavities and solenoids alignment.
- Probed Parameters: The position of the center of mass for each cavity and solenoid is examined under two different loading scenarios:
  - Gravity-Only Loading.
  - Gravity + External Atmospheric Pressure Loading.
- Alignment Process: the pressure induced misalignment is accounted for and eliminated during the alignment process.

SSRs Cryomodule Cross-section

Pre-production SSR2 (F10138829)



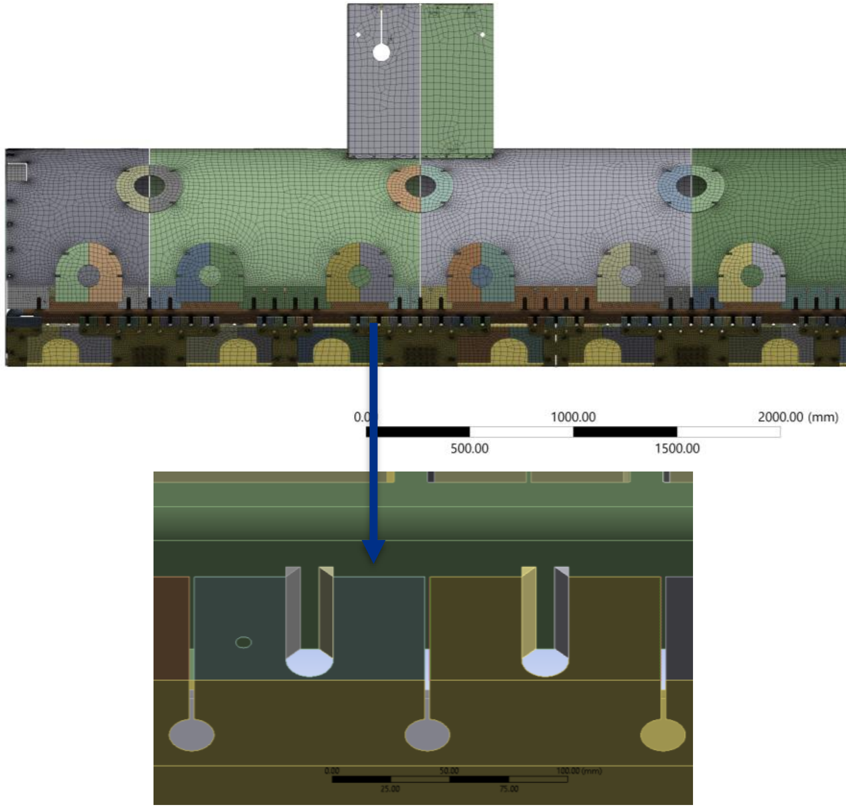
Thermal Shield:
It provides cooling and thermal insulation for the superconducting RF cavities and magnets (coldmass components).

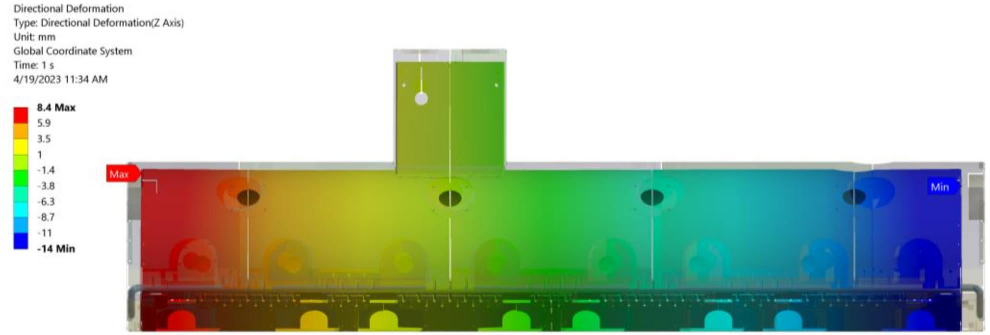


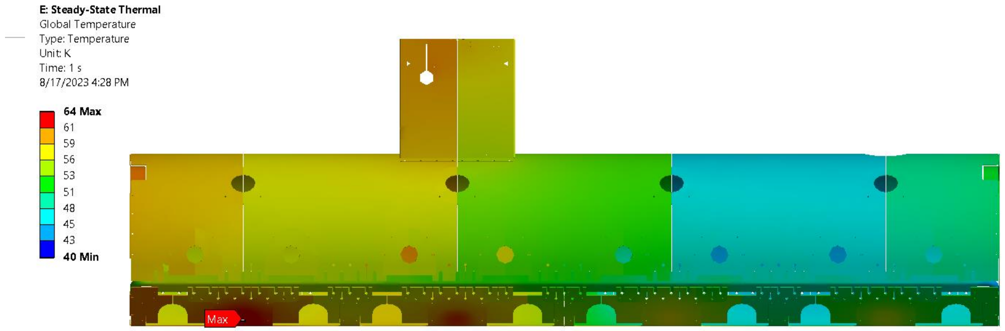
Thermal and structural analyses:

- Steady state temperature distribution.
- Temperature gradient during cooldown.
- Stresses and displacements at steady state and during cooldown.

FEA examples: Thermal Shield





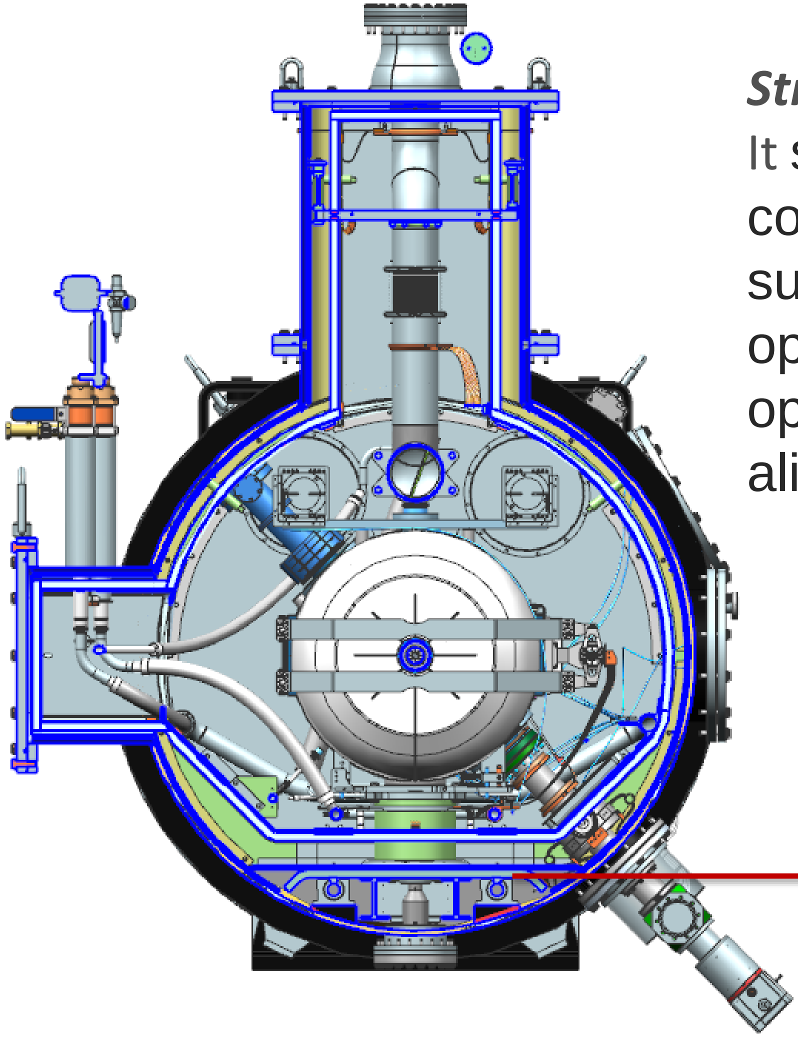


Contacts between upper / lower shields and extrusion are imposed only through the welds.

- Goal of the analysis: determine S-S temperature distribution and maximum allowable cooldown rate.
- Boundary conditions: Helium inlet temperature, pressure, and mass flow rate. Conductive and radiative heat loads from warmer components.
- Probed Parameters: Temperature and displacement at the interface with CM components. Stresses in welded connections.

SSRs Cryomodule Cross-section

Pre-production SSR2

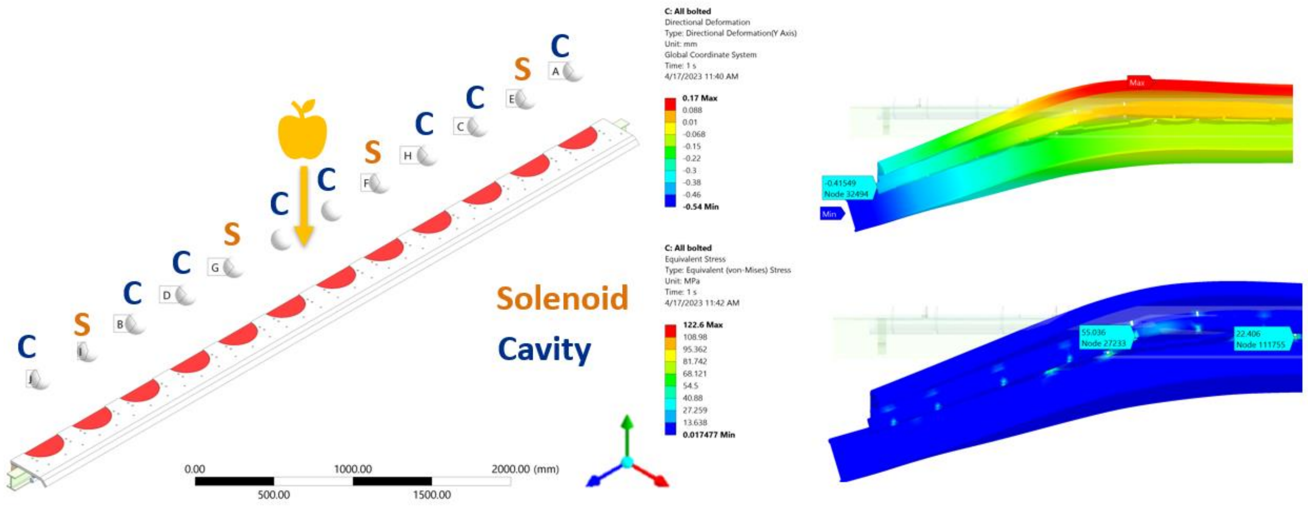


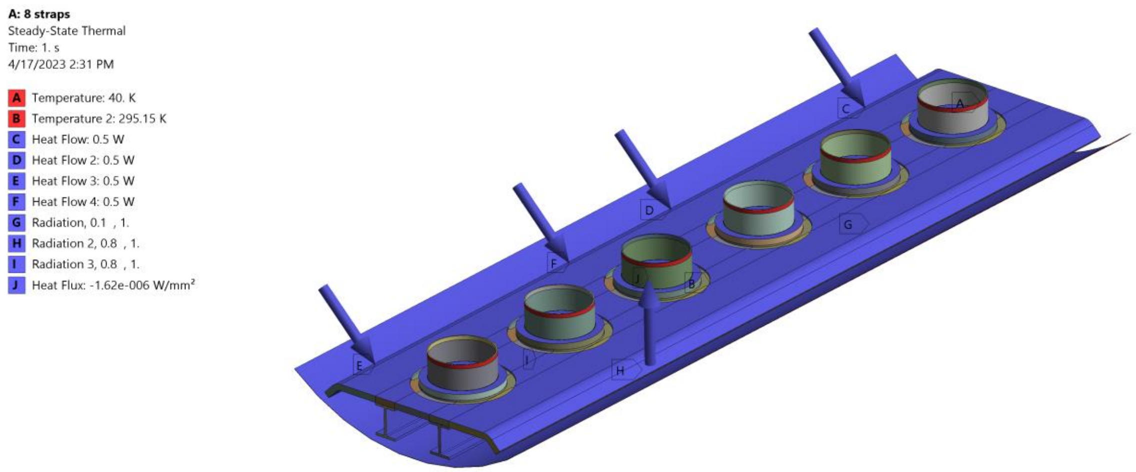
Strongback:
It serves as the backbone of the coldmass: provides a structural support during assembly and operations – stays warm during operations and maintains the alignment of the string components.

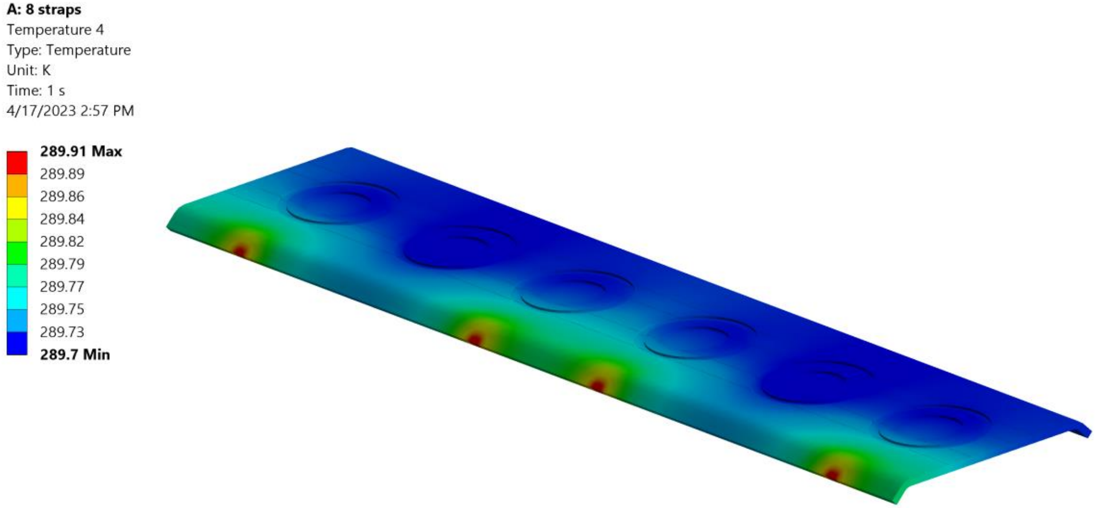
Thermal, structural, and modal analyses:

- Steady state temperature distribution.
- Stresses and deformations during assembly and operations.
- Natural frequencies.

FEA examples: Strongback



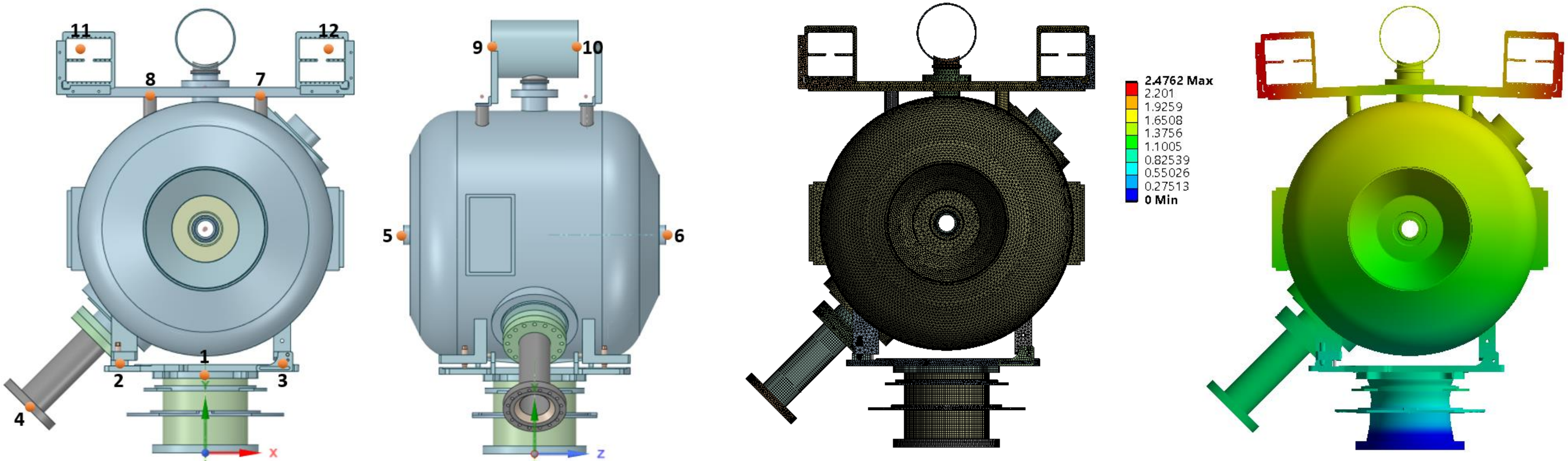




- Goal of the analysis: determine the feasibility of sliding the coldmass into the vacuum vessel. Make sure the strongback stays warm in operations
- Boundary conditions: coldmass weight. Conductive and radiative heat loads from surrounding components.
- Probed Parameters: displacement and stresses during coldmass insertion. Strongback minimum equilibrium temperature and temperature gradient.

Alignment of SRF Cavities

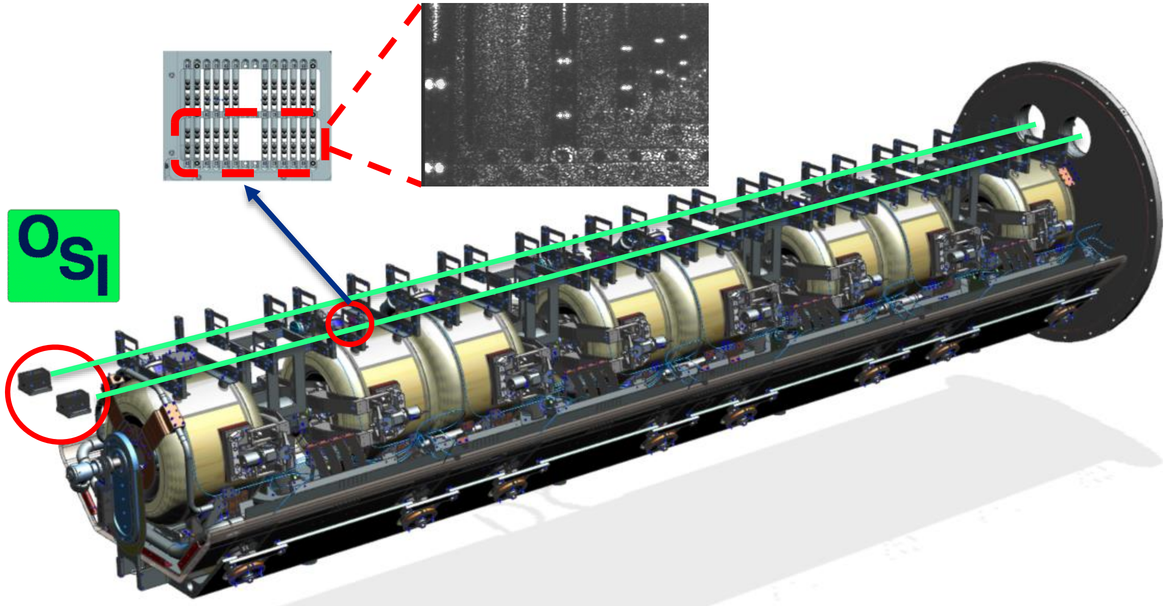
FEA examples: Cavity on support post

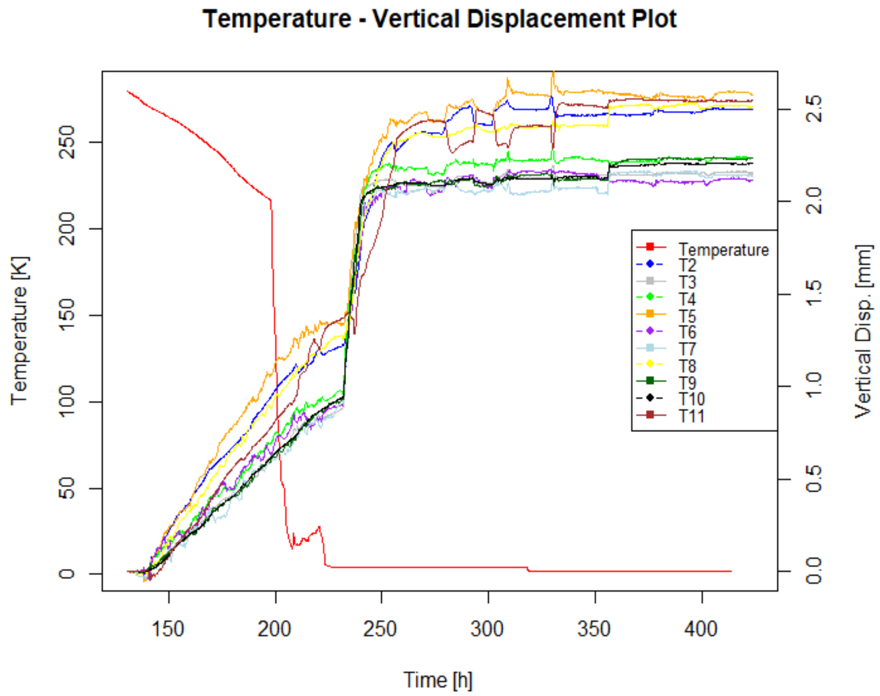


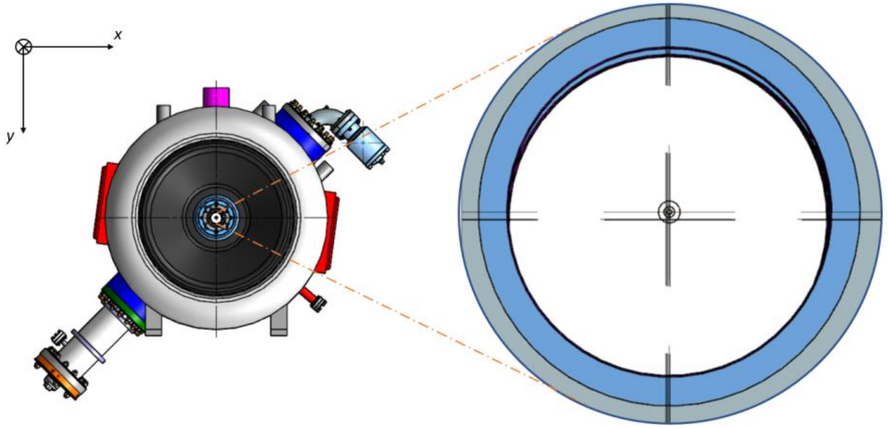
Points	Δx [mm]	ΔY [mm]	ΔZ [mm]
1	≈ 0	-1.08	≈ 0
2	0.18	-0.89	+/-0.14
3	-0.20	-0.87	≈ 0
4	0.31	-1.00	≈ 0
5	-0.07	-1.34	-0.48
6	-0.07	-1.34	0.46
7	-0.12	-1.66	-0.16
8	-0.08	-1.68	-0.16
9	-0.1	-1.68	≈ 0
10	-0.1	-1.68	≈ 0
11	-0.43	-2.23	-0.06
12	0.20	-2.13	-0.06

- Goal of the analysis: determine cooldown induced misalignment between string components.
- Boundary conditions: temperature on the cavity He tank and at the interface with thermal intercepts.
- Probed Parameters: displacement of discrete points from ‘1’ to ‘12’.
- Outcome: correlate displacement of points 11 and 12 to points ‘5’ and ‘6’. Measure the displacement of points 11 and 12 with H-BCAMs.

H-BCAMs system

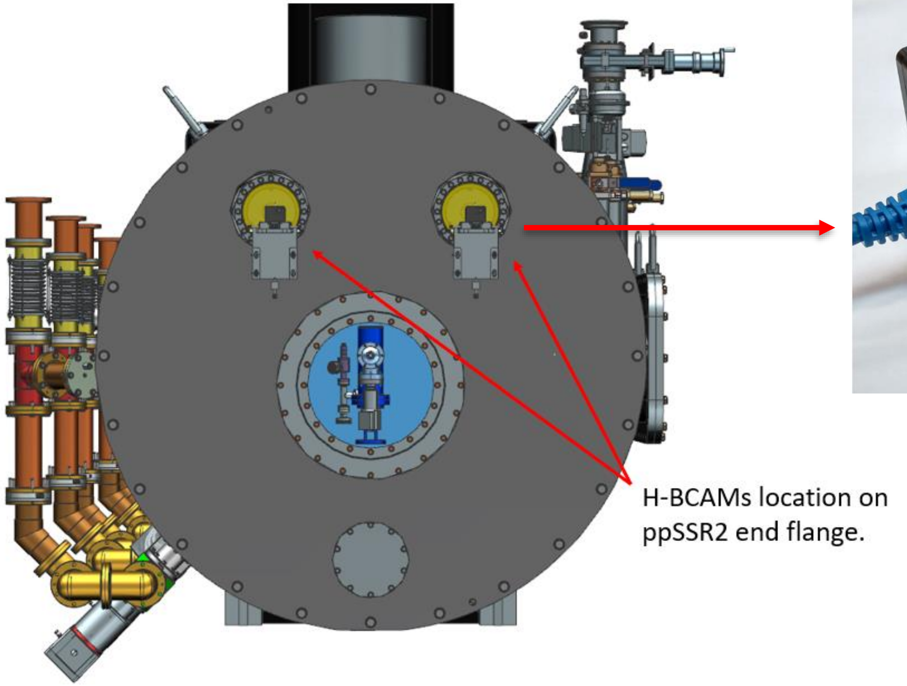


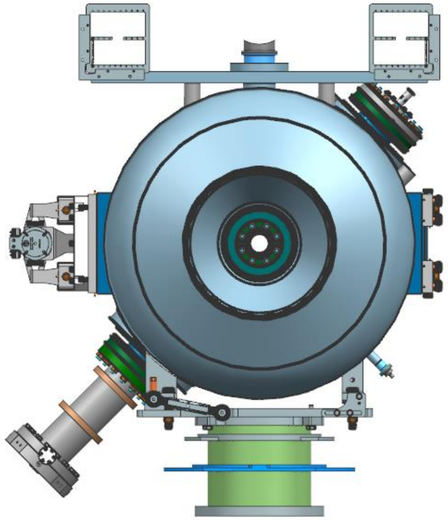


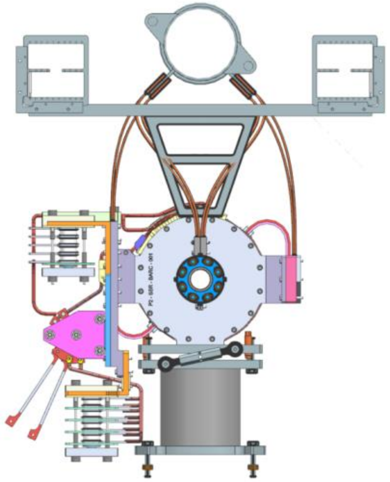


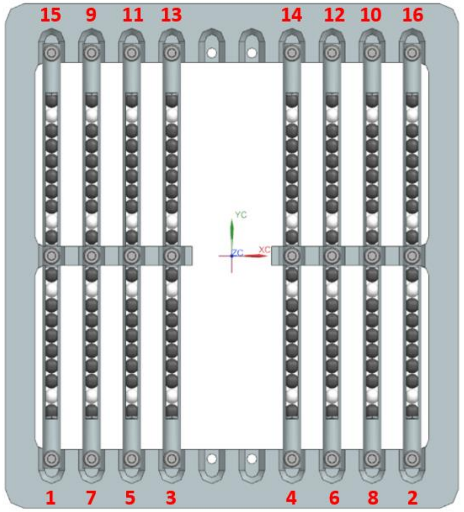
- Open-Source optical instrument developed by Brandeis University;
- Technology already adopted in the field of High Energy Particle Accelerators (HIE-ISOLDE at CERN);
- Technology successfully deployed at Fermilab to monitor Prototype SSR1 and HB650 string components' alignment during Assembly, Transportation, and Cooldown.

H-BCAMs system



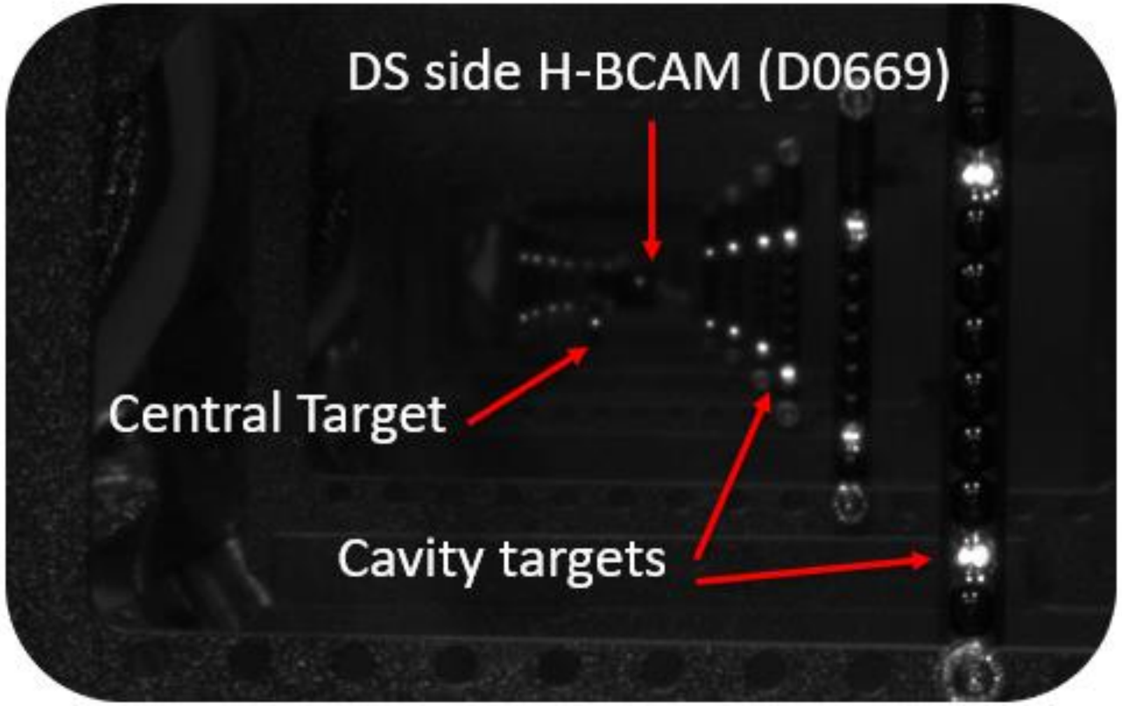






- 4 H-BCAMs for each cryomodule (2 US and 2 DS).
- 4 targets frames for each cavity and solenoids.
- 2 glass balls targets for each frame.
- Images acquired in sequence by each H-BCAM with 2 different led light sources .

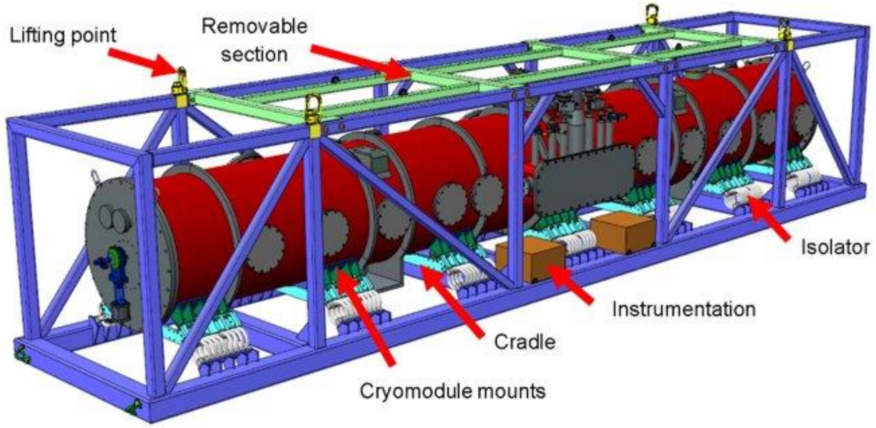
H-BCAMs system



- The acquisition script make the H-BCAMs (from 1 to 4) sequentially acquire 11 images for each visible target and draw rectangles around the targets. Results are written in a .txt file.
- The MATLAB script arrange data from the .txt file into a structure and perform the data analysis.

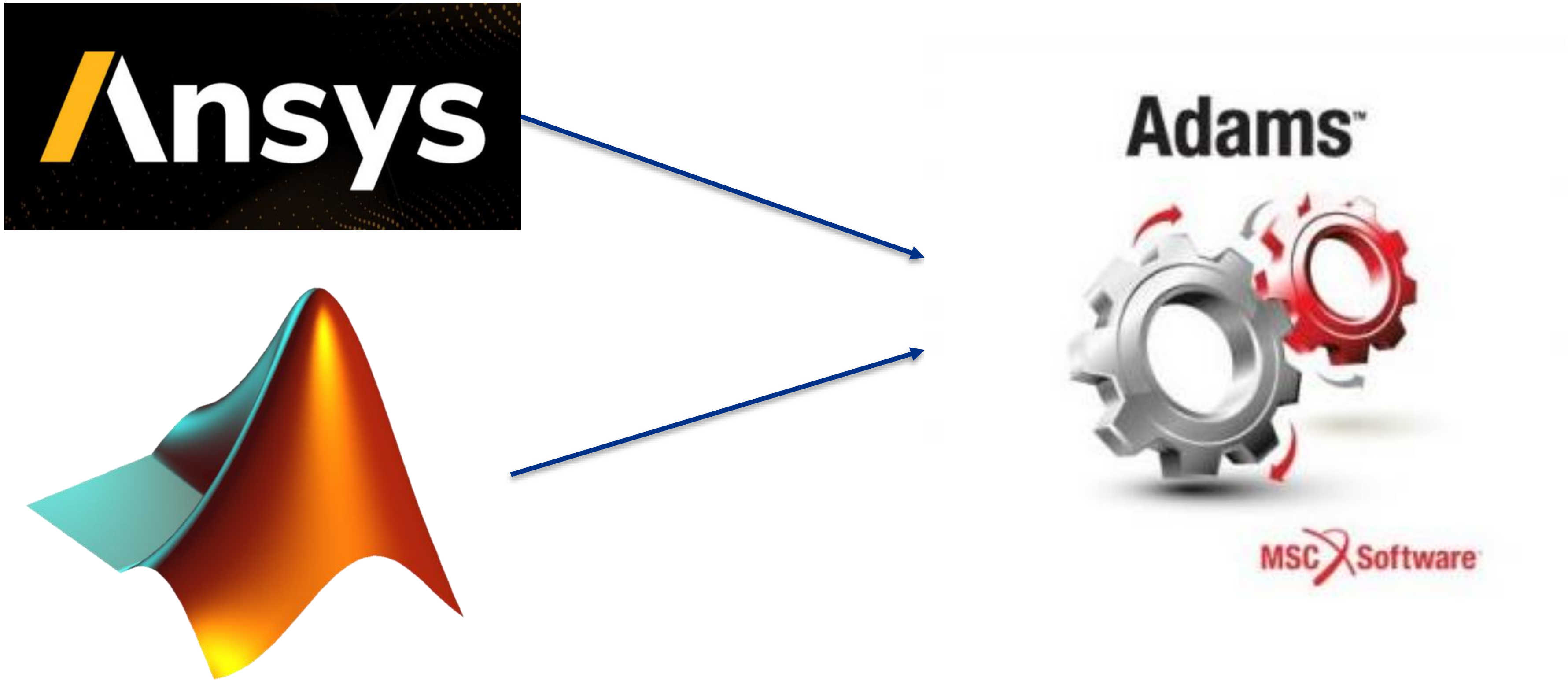
Dynamic Behavior in Transportation

SRF Cryomodules Transportation

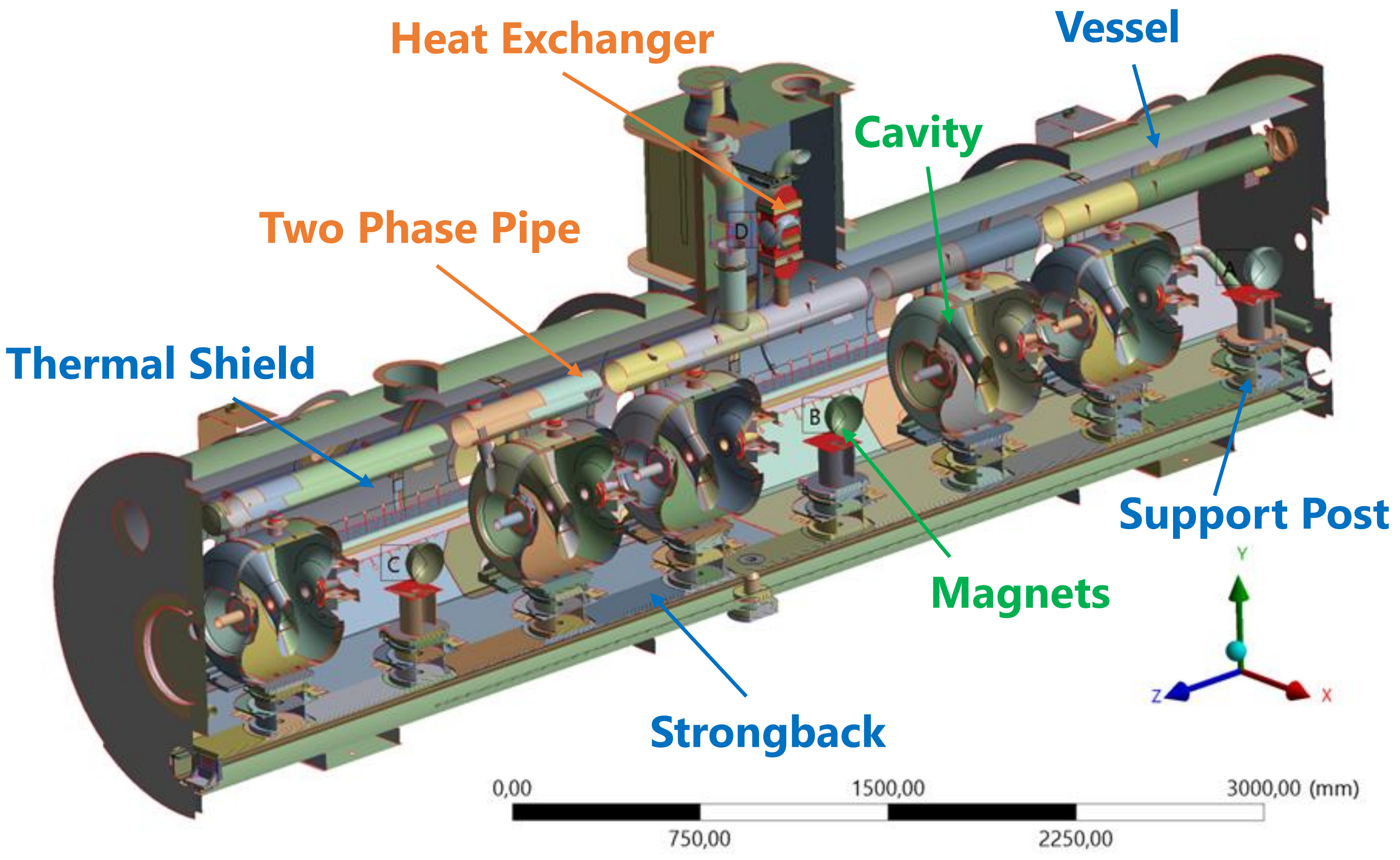


Introduction

Main Aim of the thesis: Develop a model of the cryomodule SSR2 with a Transporting Tool to simulate its transport



FE model – SSR2 Cryomodule



Group 1

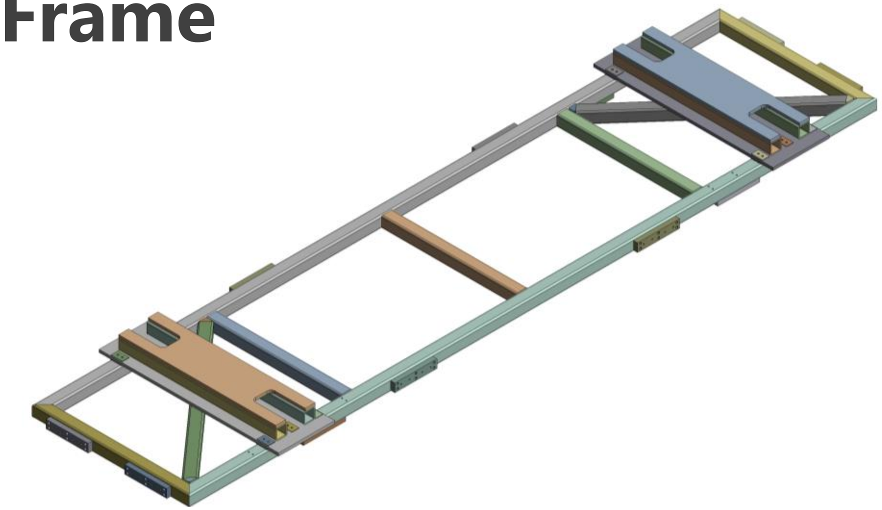
- Vacuum vessel
- Thermal Shield
- Strongback
- Support Post

Group 2

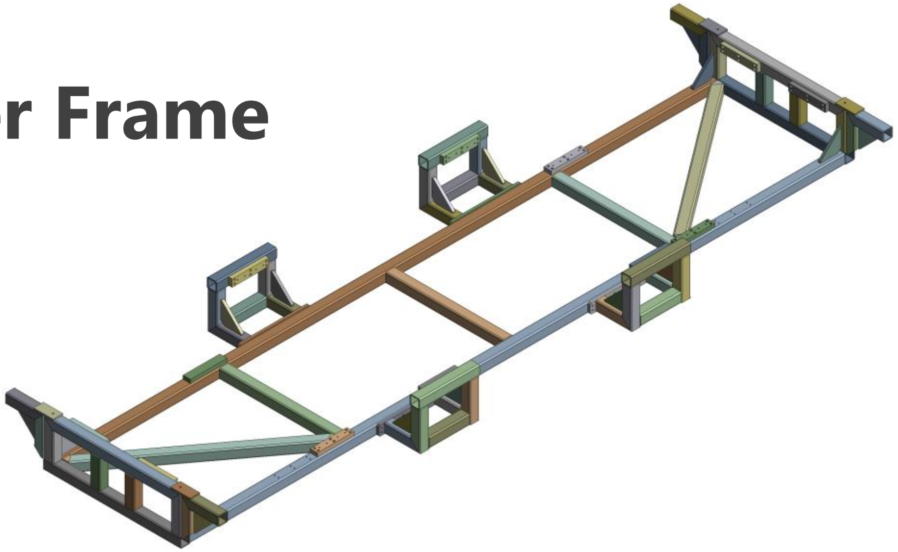
- Two Phase Pipe
- Heat Exchanger

FE model – Transporting Tool

Inner Frame



Outer Frame



- The **Inner Frame** is attached to the **cryomodule**.
- The **Outer Frame** lies on the bed of the truck.
- The **Inner** and **Outer Frame** are connected with 12 **wire rope isolators**.

FE model – MNF files

The exportation has been done using the **Craig-Bampton** reduction method, the main steps are:

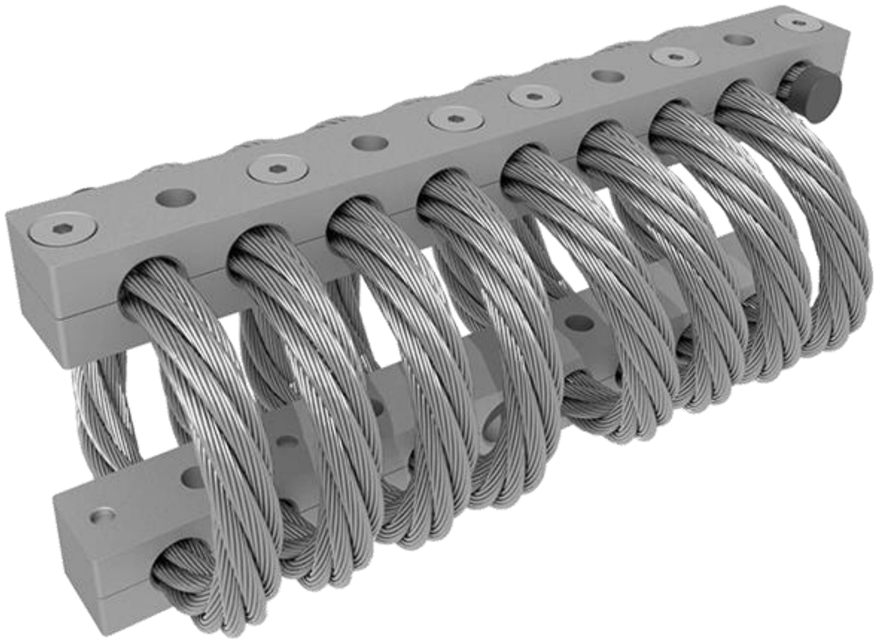
- Decide the **interface points** and place a remote point in these places.
- Decide the **number of modes** to consider in the reduction method.
- Use the command **ADAMS** in Ansys to create the files.

Wire Rope Isolators

Non-linear spring used to connect the **inner** and the **outer frames**.

Enhanced Bouc-Wen equations

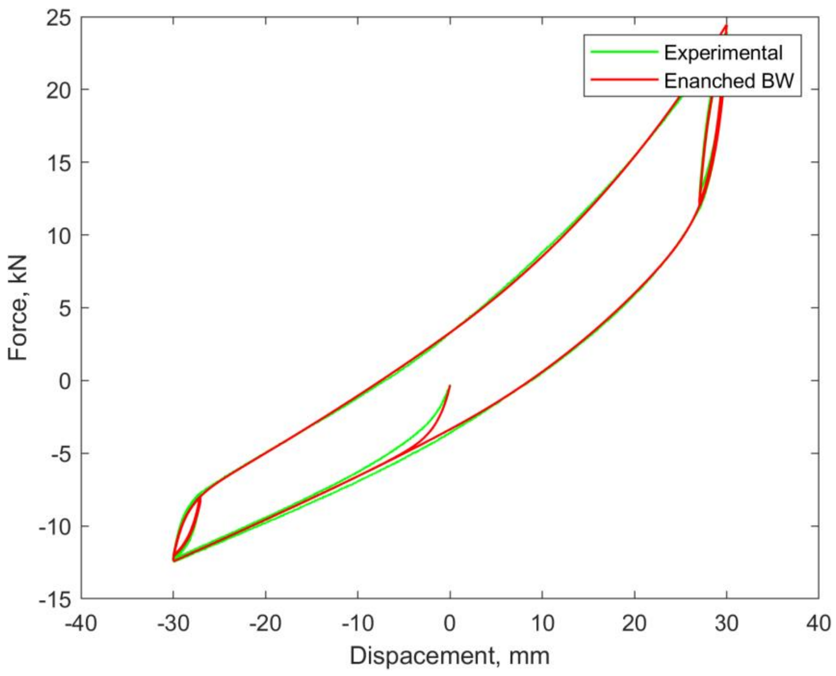
$$F = F_2(z + F_1)$$
$$F_1 = k_1 x + k_2 sign(x) x^2 + k_3 x^3$$
$$F_2 = b^{cx}$$
$$\dot{z} = \dot{x}\,(\alpha + \delta x) - (\gamma + \beta sign(\dot{x}\,) sign(z))|z|^n$$



Wire Rope Isolators - Experimental Tests

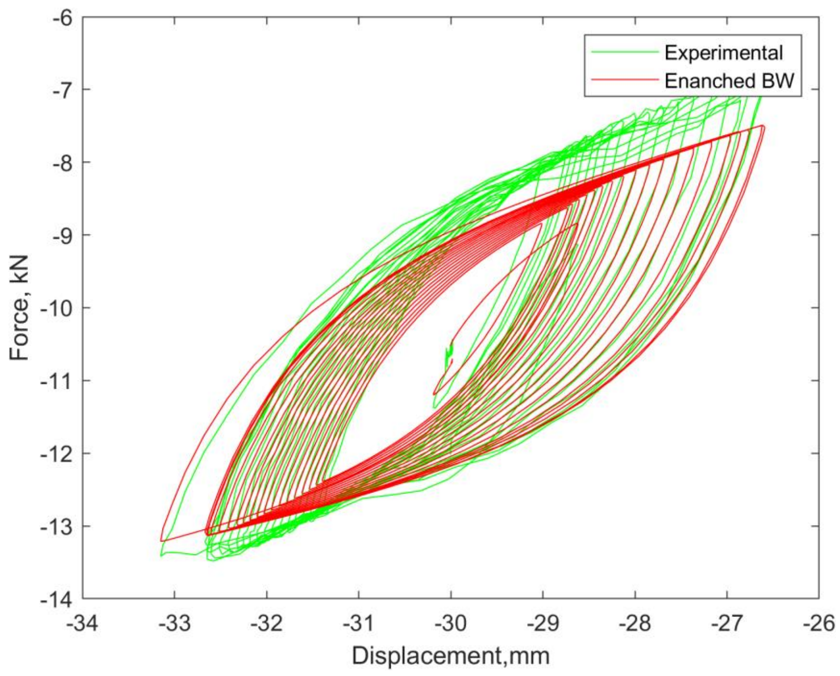
Wire Rope Isolator Axial Tests

Axial direction test



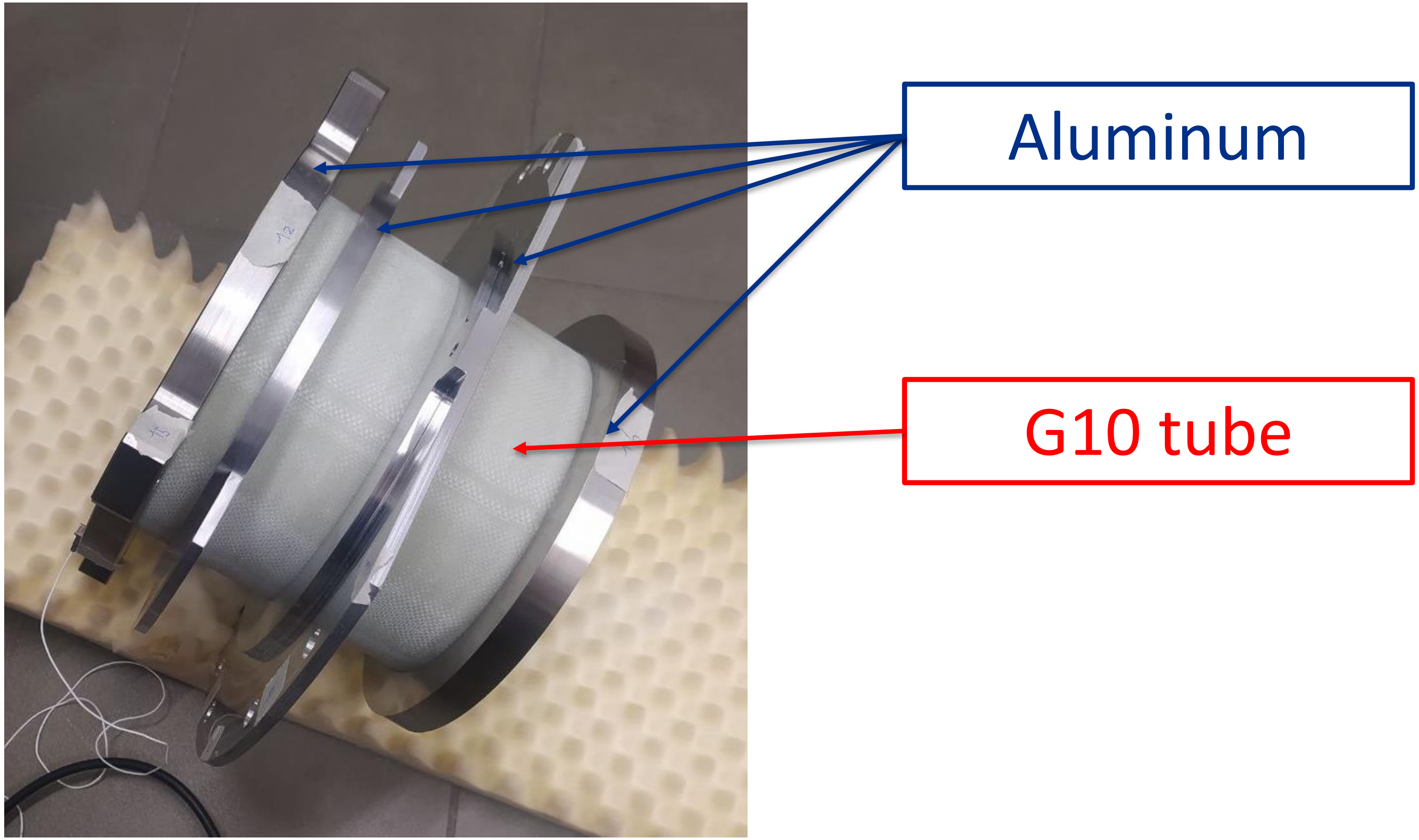
Main test

Used to find the parameters of the **Bouc-Wen** eq.



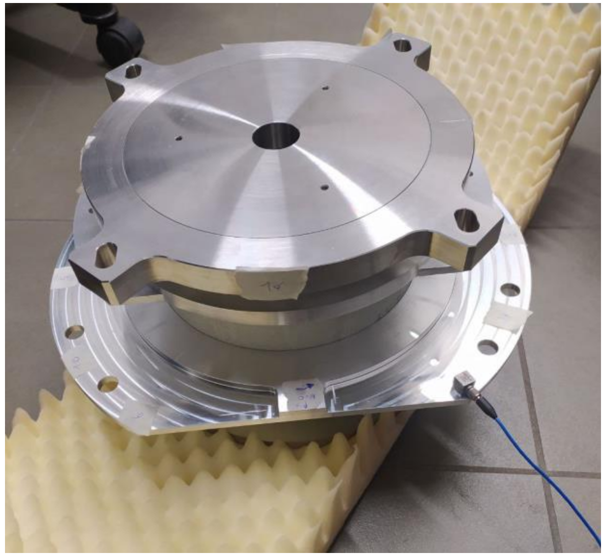
Sinusoidal validation test

Support Post

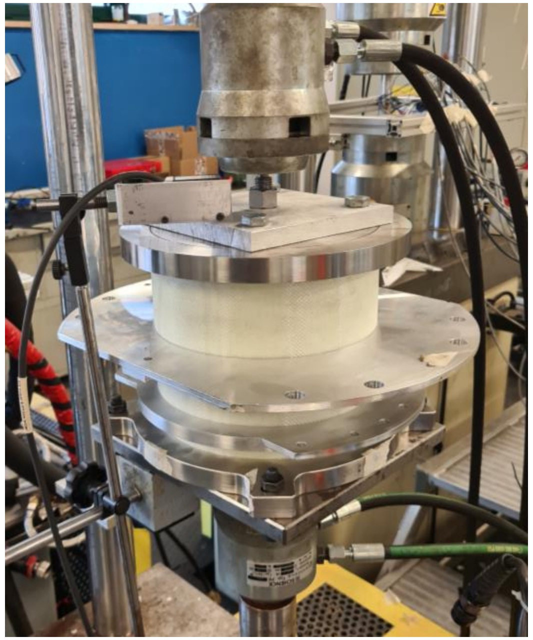


Support Post – Experimental Characterization

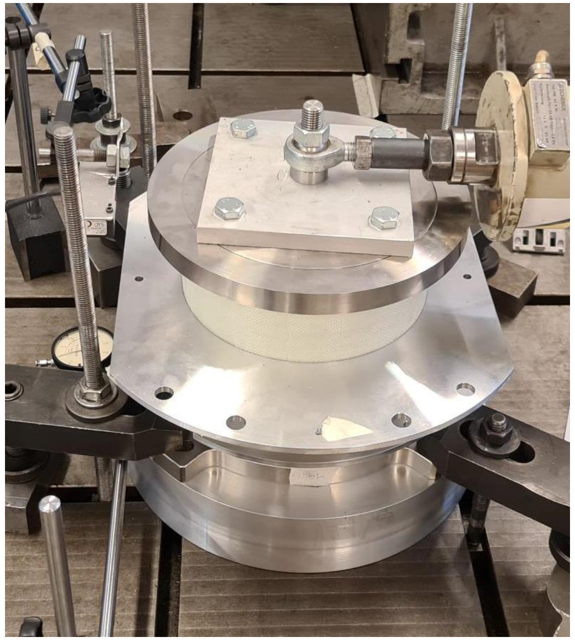
An experimental campaign on the support post has been carried out at UNIPI



Modal analysis
Impact test
I test



Static analysis
Axial test
A test



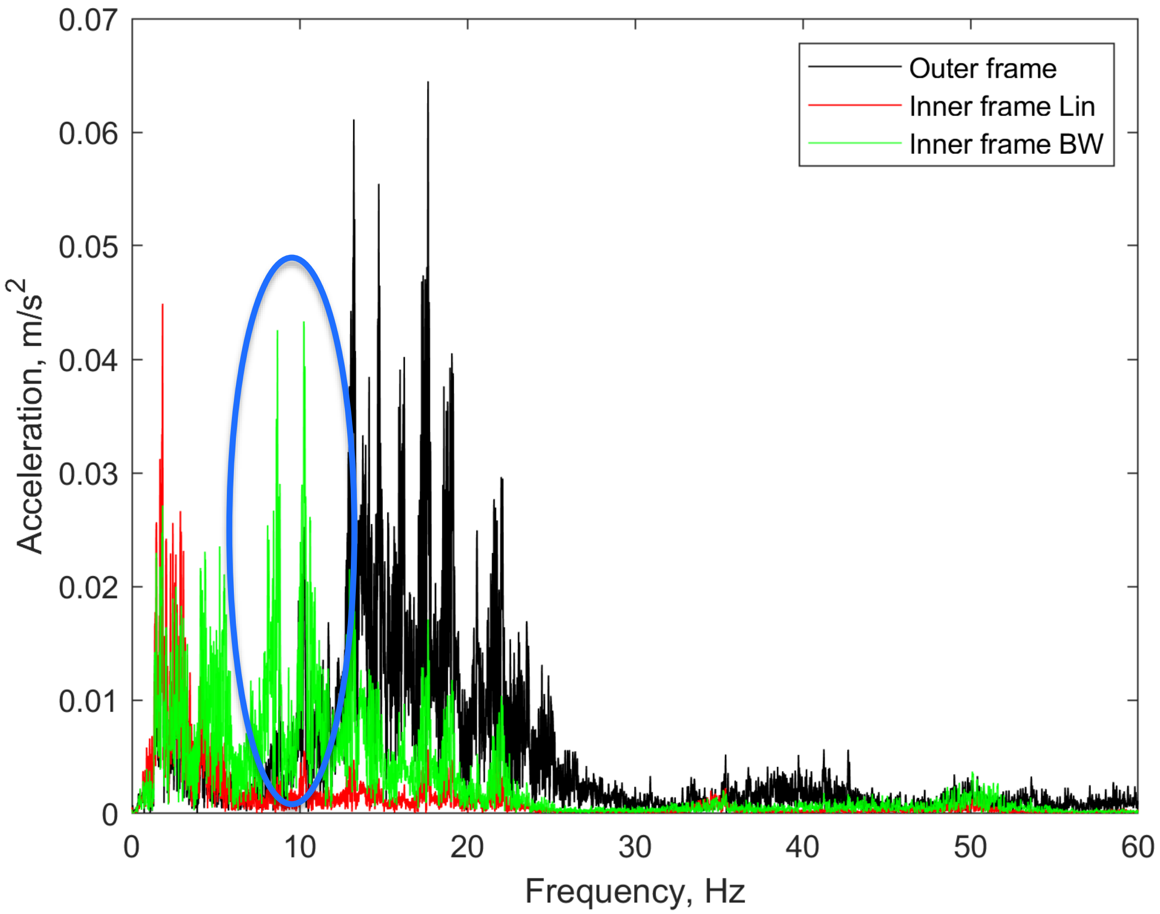
Static analysis
Shear test
S test

MultiBody model

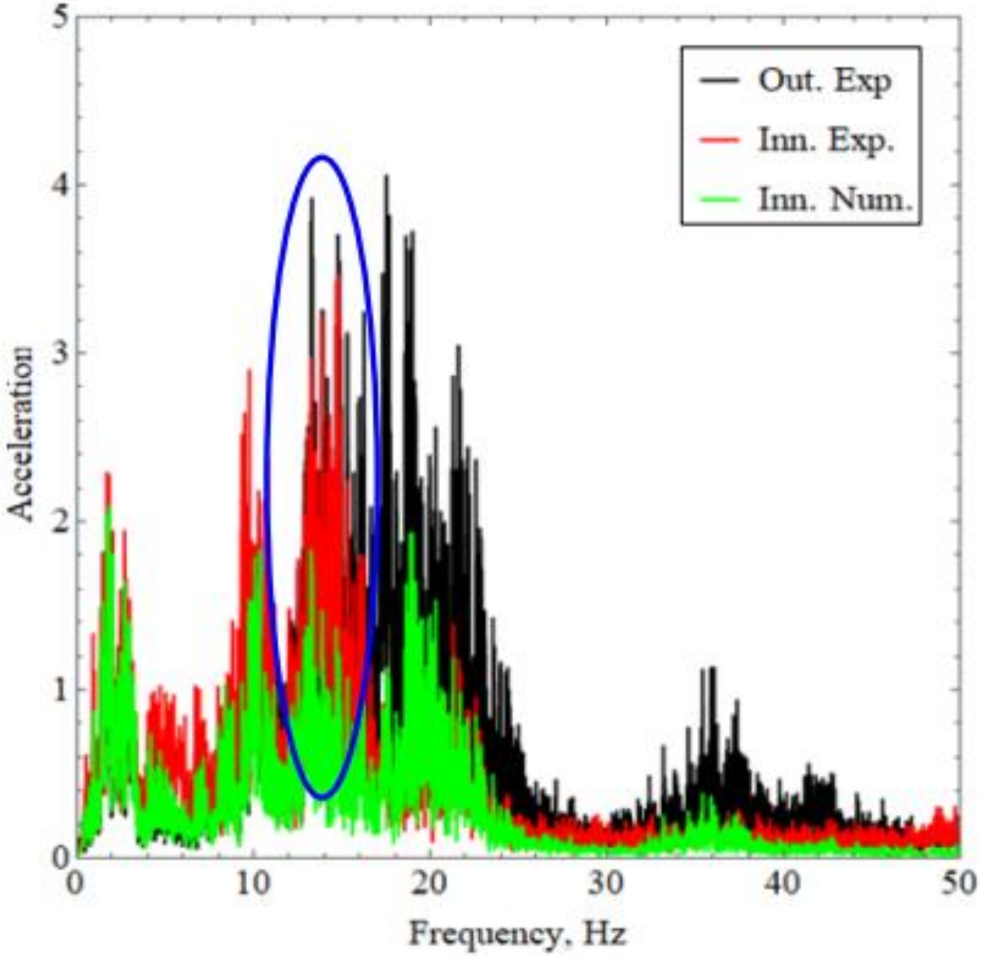
- The **cavities** are considered rigid bodies.
- The **solenoids** are created inside Adams as rigid bodies.
- All the bodies are linked together using the **interface points**.
- The **Wire Rope Isolators** are modeled as **linear** springs with **k** and **c**, and as **nonlinear** using the **dll file**.

Numerical Results

SSR2 Numerical Analysis



SSR1 Proto Transportation



Robot-assisted technology for SRF cleanroom assembly

Manual assembly in cleanroom

- Performance highly depend on operator ability, experience and commitment
- Operators are among the main sources of contamination

Robot-assisted assembly

- The assembly process is more efficient, systematic, and repeatable over time.
- Reduce the risk of chemical and particulate contamination during critical assembly steps

Fermilab

Teamwork is essential for Success!

Building Fermilab's Future

PIP-II Particle Accelerator Project

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