Cryomodule and Cryogenic Design Overview

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Many thanks to co-workers, colleagues, and collaborators at laboratories around the world and to the cooperative spirit we all share.

Outline

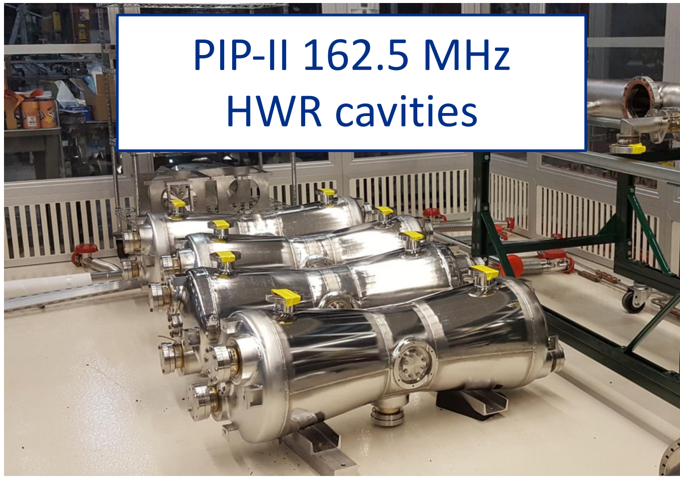
- Cryomodule design overview
- Overall configurations
- Vacuum vessels
- Structural supports
- Thermal shields and insulation
- Magnetic shielding
- Cryogenic piping
- Tuners
- Couplers
- Bellows and Interconnects
- Alignment
- Assembly Techniques
- Transportation
- Summary

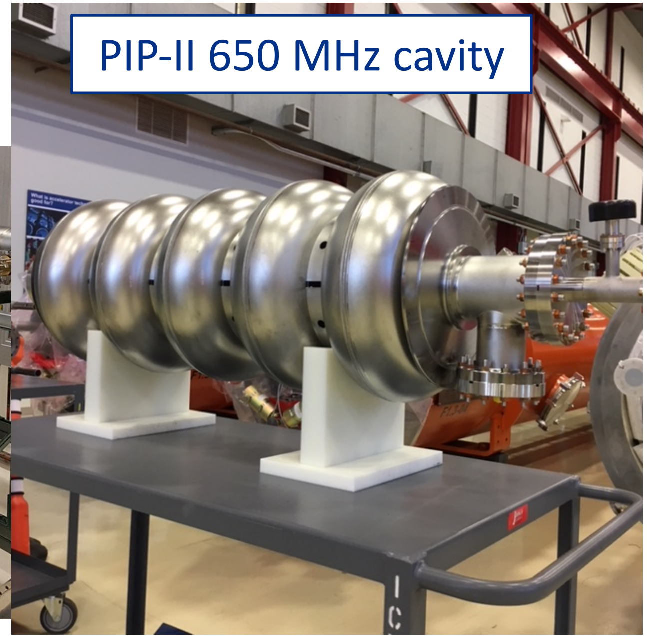
Cryomodule Defined

- “Cryomodule is a term that is most commonly used to refer to cryostats that contain superconducting radio frequency (SRF) cavities. Such cavities are used to accelerate charged particle beams and are a major component of modern particle accelerators. Using the term cryomodule to refer to cryostats containing SRF cavities appears to stem from the original Continuous Beam Accelerator Electron Facility (now Jefferson Lab) machine design in the early 1990s in which cryomodules were defined as cryostats that contained four cryo-units (each with two SRF cavities) and two end cans. Since then, cryomodule has been used more generally to refer to the basic building block of SRF based accelerators that contains the cavities.”

Dr. John Weisend, originally published in the Summer 2011 issue of Cold Facts as part of his series, Defining Cryogenics.

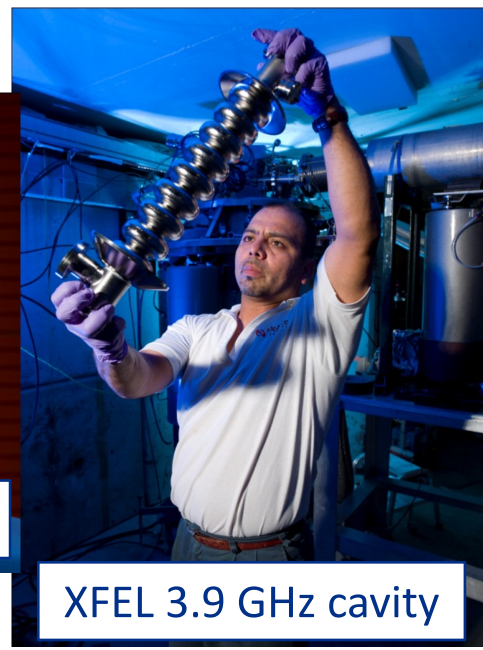
SRF Devices


PIP-II 162.5 MHz HWR cavities


PIP-II 650 MHz cavity


HINS focusing magnet


PIP-II 325 MHz spoke cavity


XFEL 3.9 GHz cavity


ILC 1.3 GHz cavity

Cryomodule Design Overview

- There are lots of cavity types being used in various superconducting RF accelerator designs around the world.
  - Single and multiple spoke
  - Half and quarter-wave
  - Elliptical resonators
  - Operating in pulsed or CW mode
  - Spanning frequencies from a few megahertz to several gigahertz
  - Operating nominally at 4.5 K or 2 K

Cryomodule Design Overview (cont'd)

- In spite of this variety, they contain many common design features. In addition to cavities they all have:
  - Outer vacuum shell
  - Cold mass support system
  - One or more layers of magnetic shielding
  - One or more intermediate thermal shields
  - Multi-layer insulation
  - Cryogenic piping
  - Cavity tuning systems
  - Input and HOM couplers
  - Beam vacuum gate valves
  - Instrumentation

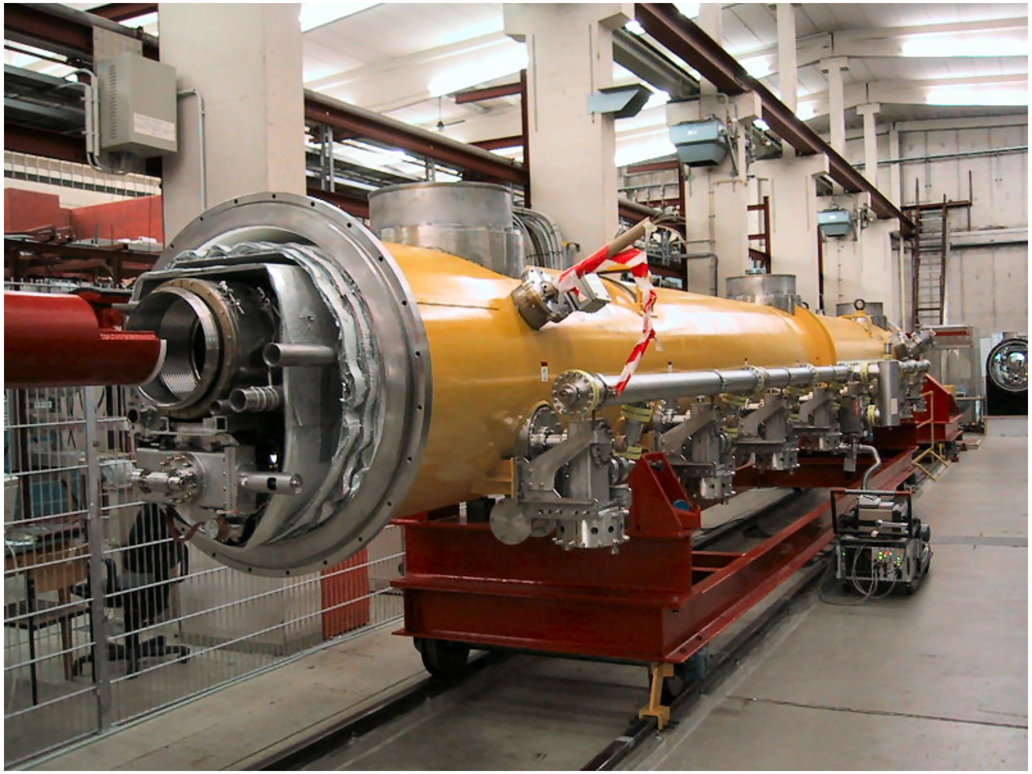
Cryomodule Design Overview (cont'd)

- In addition there are features that may be unique to each design.
  - Alignment systems
  - Cavity position monitoring systems
  - Internal heat exchangers
  - Cold-to-warm-transitions
  - Active magnetic elements
  - Current leads
  - And many others

Cryomodule Design Overview (cont'd)

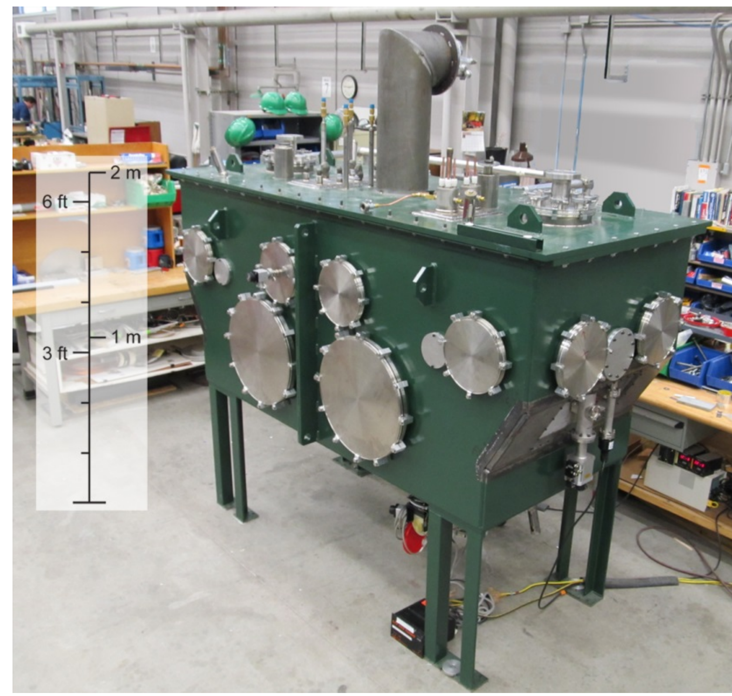
- The goal here is to describe some of the options available to both pulsed and CW mode cryomodule designers, focusing on things that guide the design process and ultimately lead to a design choice. Most of the time there is no right or wrong choice. More often than not, final design features are a compromise between many factors.
- This is not meant to be comprehensive, but an introduction so when you look at superconducting magnets or superconducting RF cryomodules on the production floor where you work or visit, you'll have a better understanding of what you're looking at.

Overall Configurations



1.3 GHz elliptical cavity XFEL cryomodule at DESY

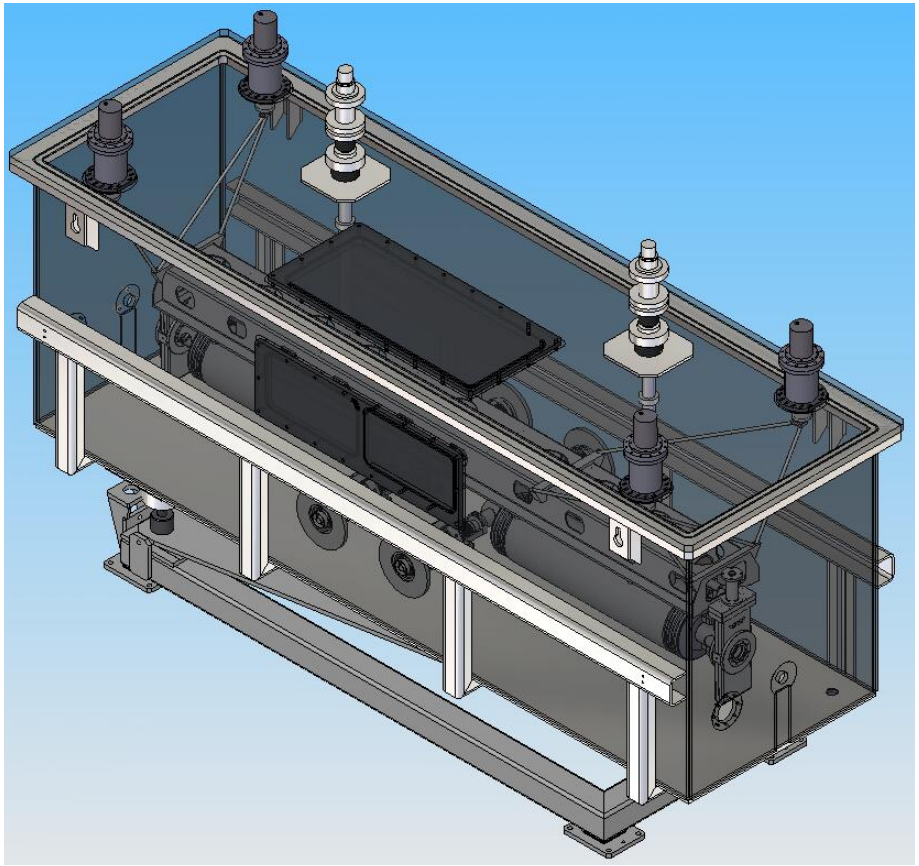
Technology demonstrator cryomodule for FRIB



Overall Configurations (cont'd)

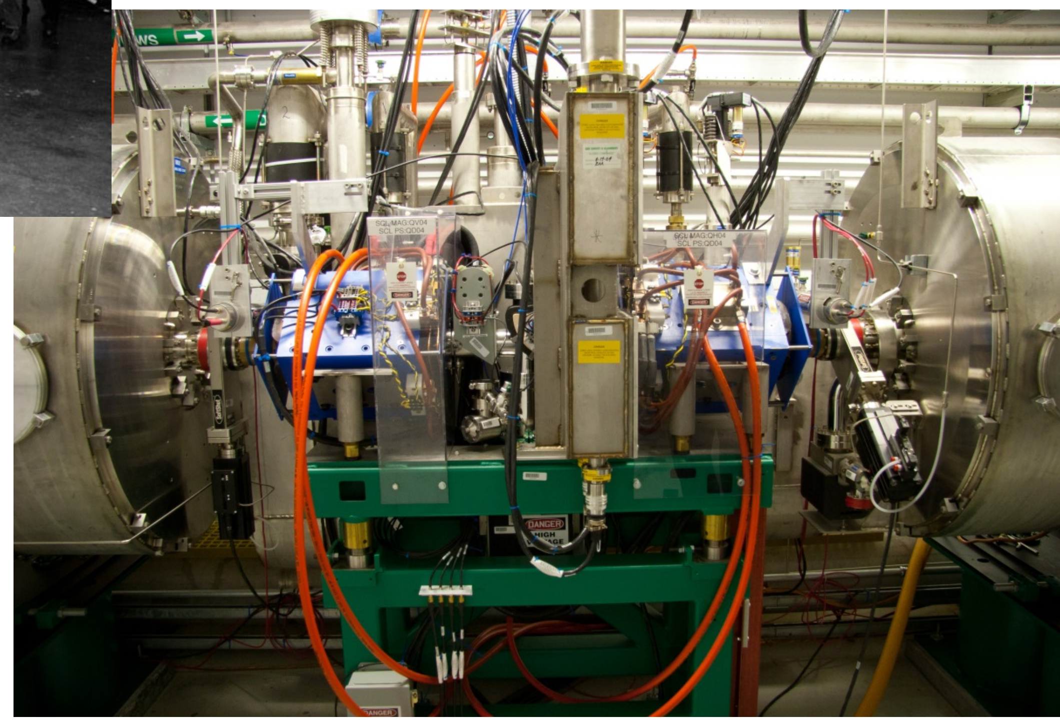
Quarter-wave cryomodule for the Atlas upgrade at Argonne

ARIEL cryomodule at Triumf



Overall Configurations (cont'd)

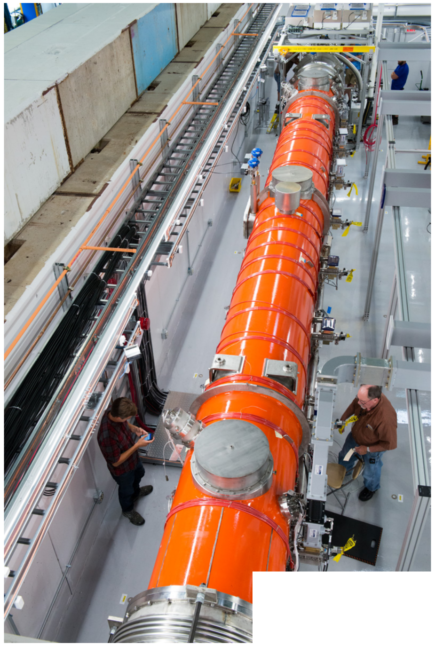
Jefferson Lab cryomodule

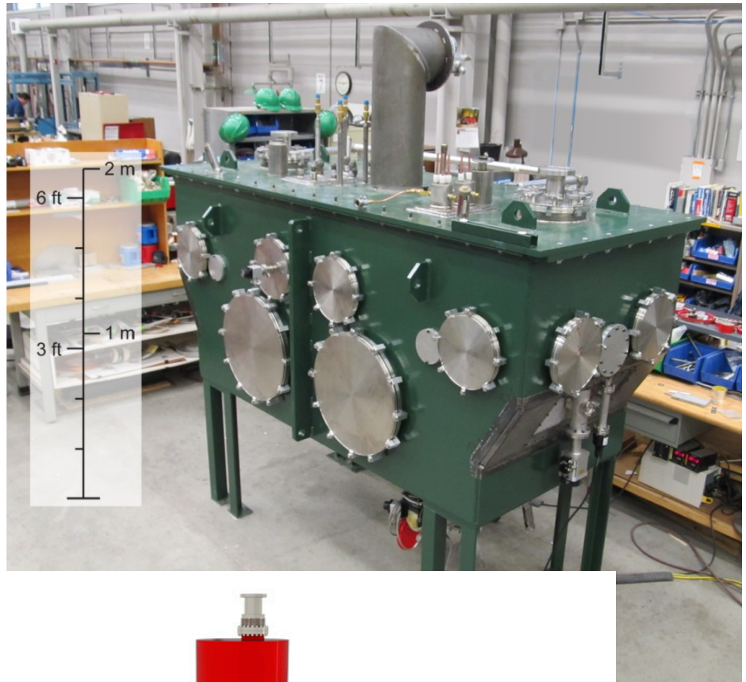


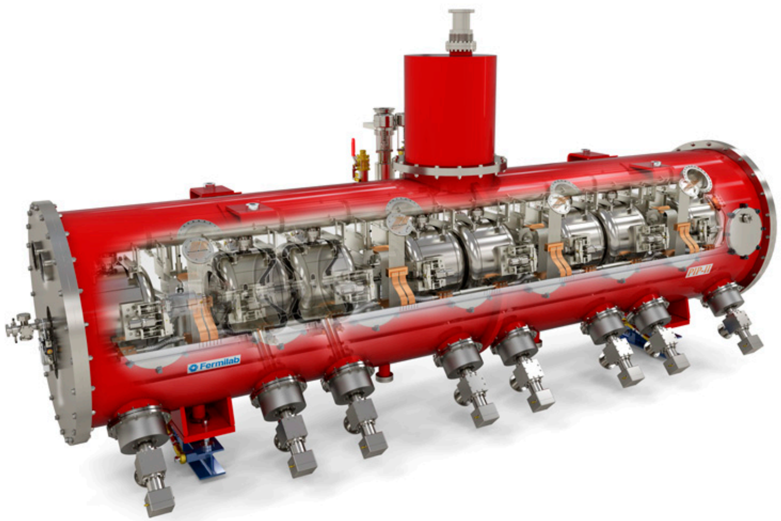
Vacuum Vessels

- The outermost cryostat component that:
  - Contains the insulating vacuum.
  - Serves as the major structural element to which all other systems are attached to the accelerator tunnel floor.
  - Serves as a pressure containment vessel in the event of a failure in an internal cryogen line.
- The design for internal and external pressure are addressed by the ASME Boiler and Pressure Vessel Code, Section VIII, Divisions 1 and 2 and specific workplace codes.
- Insulating vacuum is generally in the $1e10^{-6}$ torr range, but can be as high as $1e10^{-4}$. The lower the better.
- Materials are usually stainless steel, carbon steel, or aluminum, dictated by cost, magnetic permeability, pressure requirements, etc.

Vacuum Vessels (cont'd)







Structural Supports

- Secure internal piping, shields, SRF devices, and focusing elements to the vacuum vessel and, in turn, to the tunnel floor.
- Structural loads are largely due to shipping and handling, cooldown, fluid flow, and ground motion.
- Should constitute a heat load as low as possible.
- Must be reliable and stable over the lifetime of the cryomodule, ensuring that alignment is maintained.
- Materials are often composites or thermal resins, materials like G-10, G-11, filament wound composites, Ultem, PEEK, etc. That is, materials with high strength, but low thermal conductivity and suitable for use at low temperature in a radiation environment. In certain configurations can also be high strength stainless steel or titanium.
- Heat loads can be as low as 30 to 40 mW per support to 4.5 K.
- Configurations include posts, tension members, space frames, and many others

Structural Supports (cont'd)

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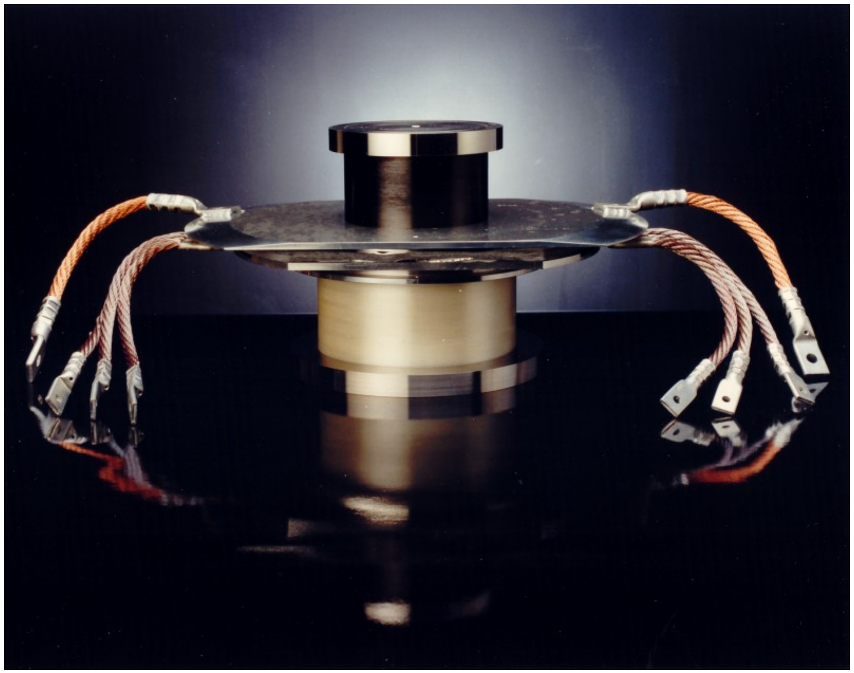
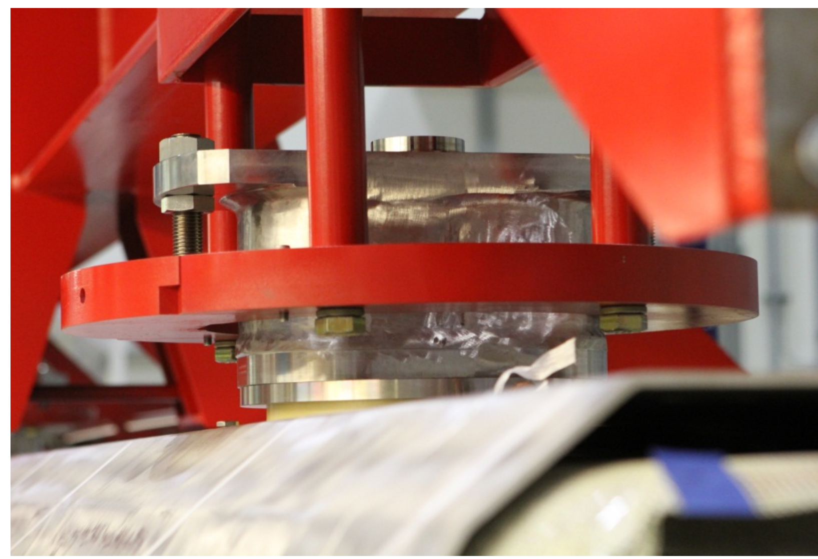
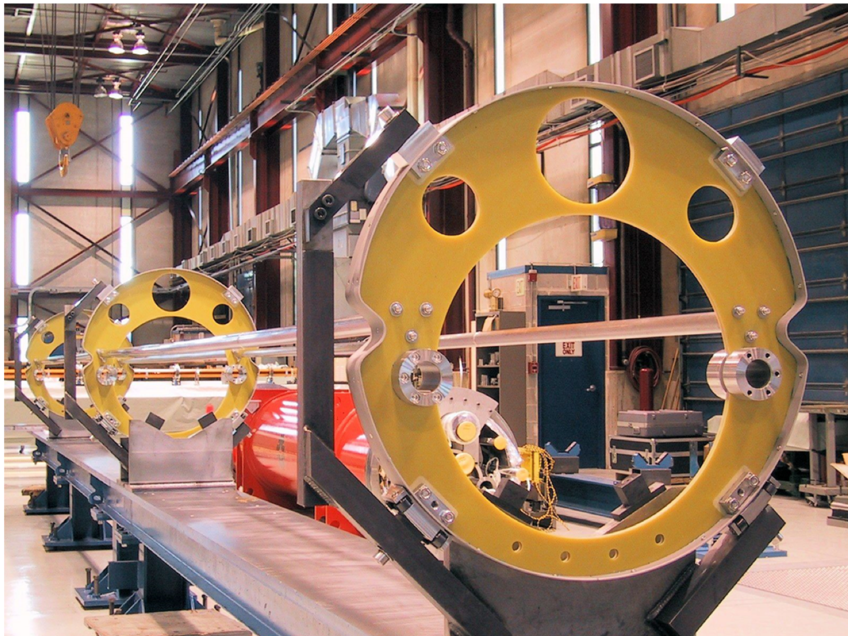


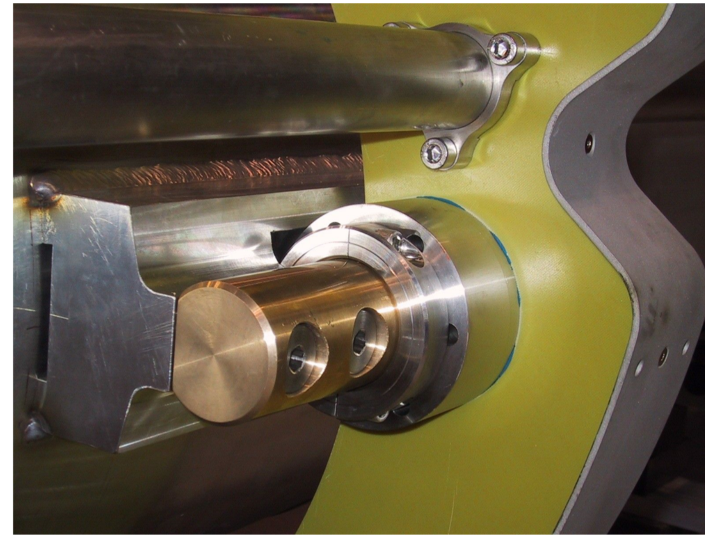
SSC magnet support

ILC cryomodule support

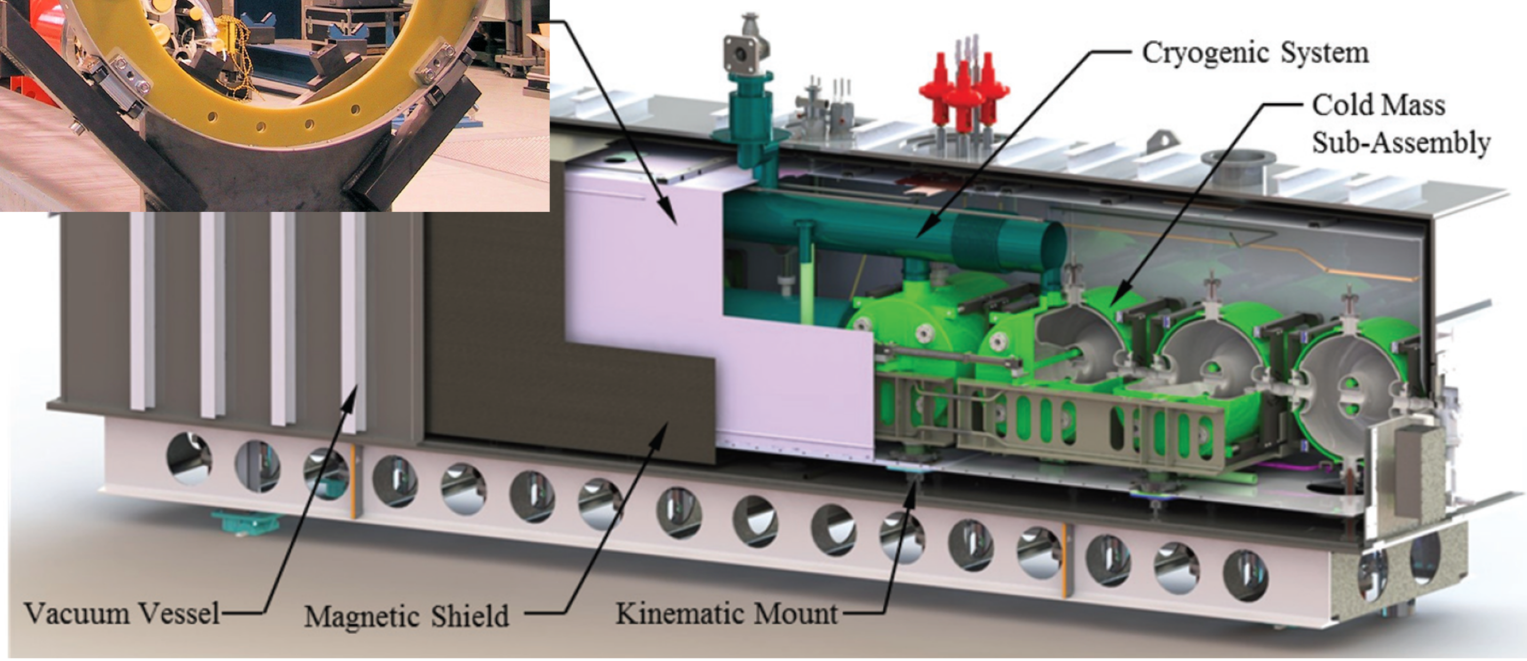


Structural Supports (cont'd)



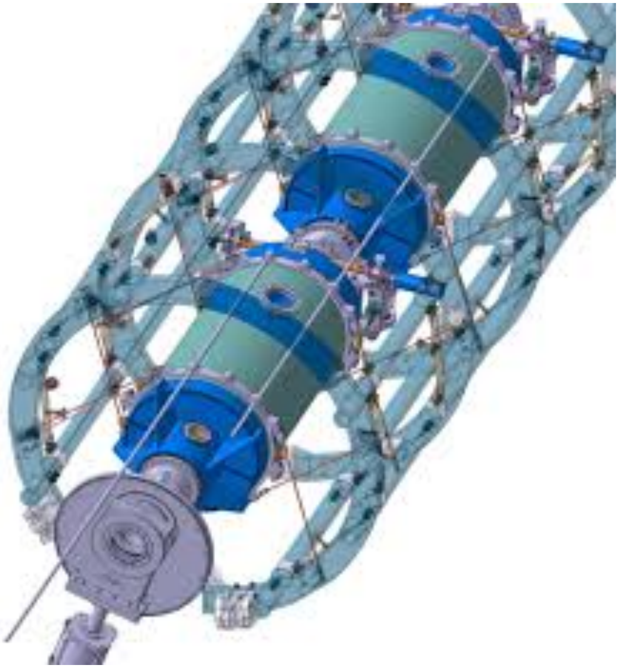


LHC IR quad



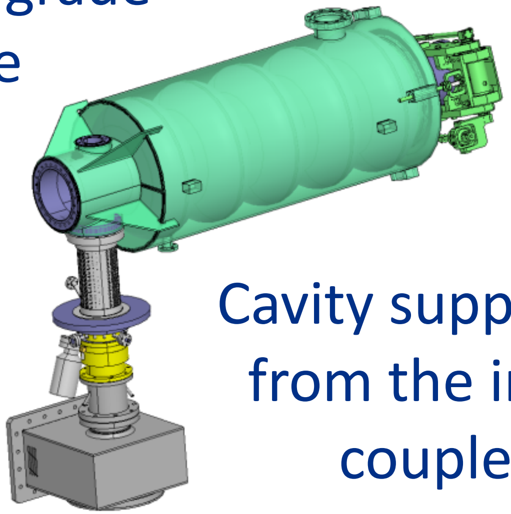
FRIB cryomodule

Structural Supports (cont'd)



ESS magnet support and space frame

Jefferson Lab upgrade cryomodule



Cavity supported from the input coupler

Thermal Shields

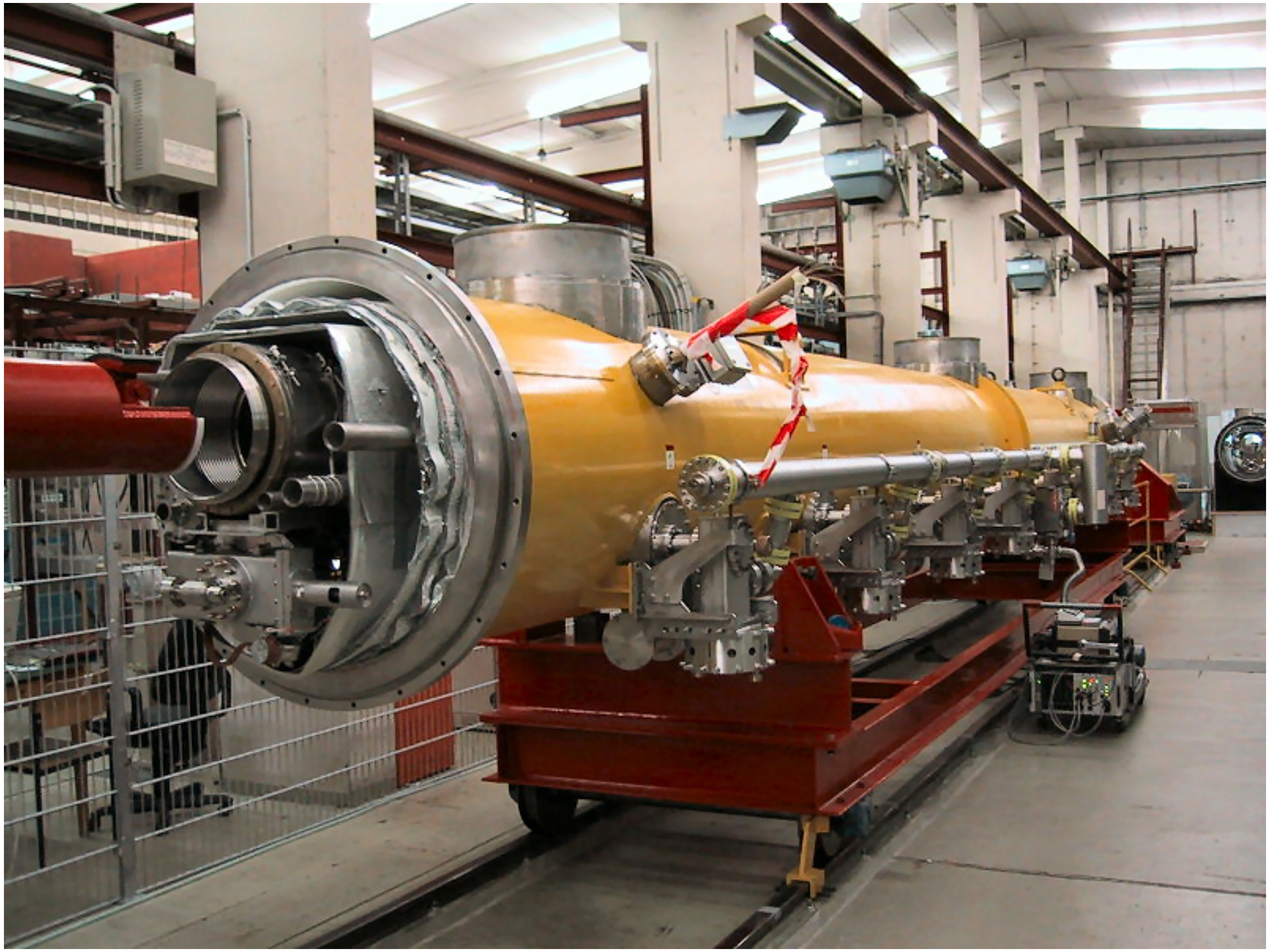
- Intercept heat radiated from the surfaces of the vacuum vessel at temperatures higher than the operating temperature of the SRF devices.
- There is always a thermal shield operating in the 50-80 K range, depending on the details of the cryogenic system.
- There is sometimes a second shield operating in the 5-20 K range, again depending on the details of the system and the operating temperature of the SRF devices.
- Usually segmented to minimize thermal bowing.
- Material is usually aluminum or copper depending on cost, weight considerations, structural strength, ease of fabrication, attachment needs, etc.

Multi-Layer Insulation (MLI)

- Limits radiation heat transfer from the outside world to the internal components.
- It works by providing “n” reflective layers to reflect radiative heat back to its source.
- The first layers are installed on the outside of the outermost thermal shield. At that level, 30-60 layers of reflector are common.
- On lower temperature surfaces, fewer layers are used, e.g. 10. Most of the rationale below about 20 K is to reduce heat load in case of loss of vacuum.
- Material is generally double aluminized mylar with fabric, nylon or spun-bonded material spacers. Some installations use aluminum foil.
- Typical heat transfer rates are ~1 W/m^2 for 30 layers from 300 K to 70 K and 50 to 100 mW/m^2 for 10 layers below 70 K.

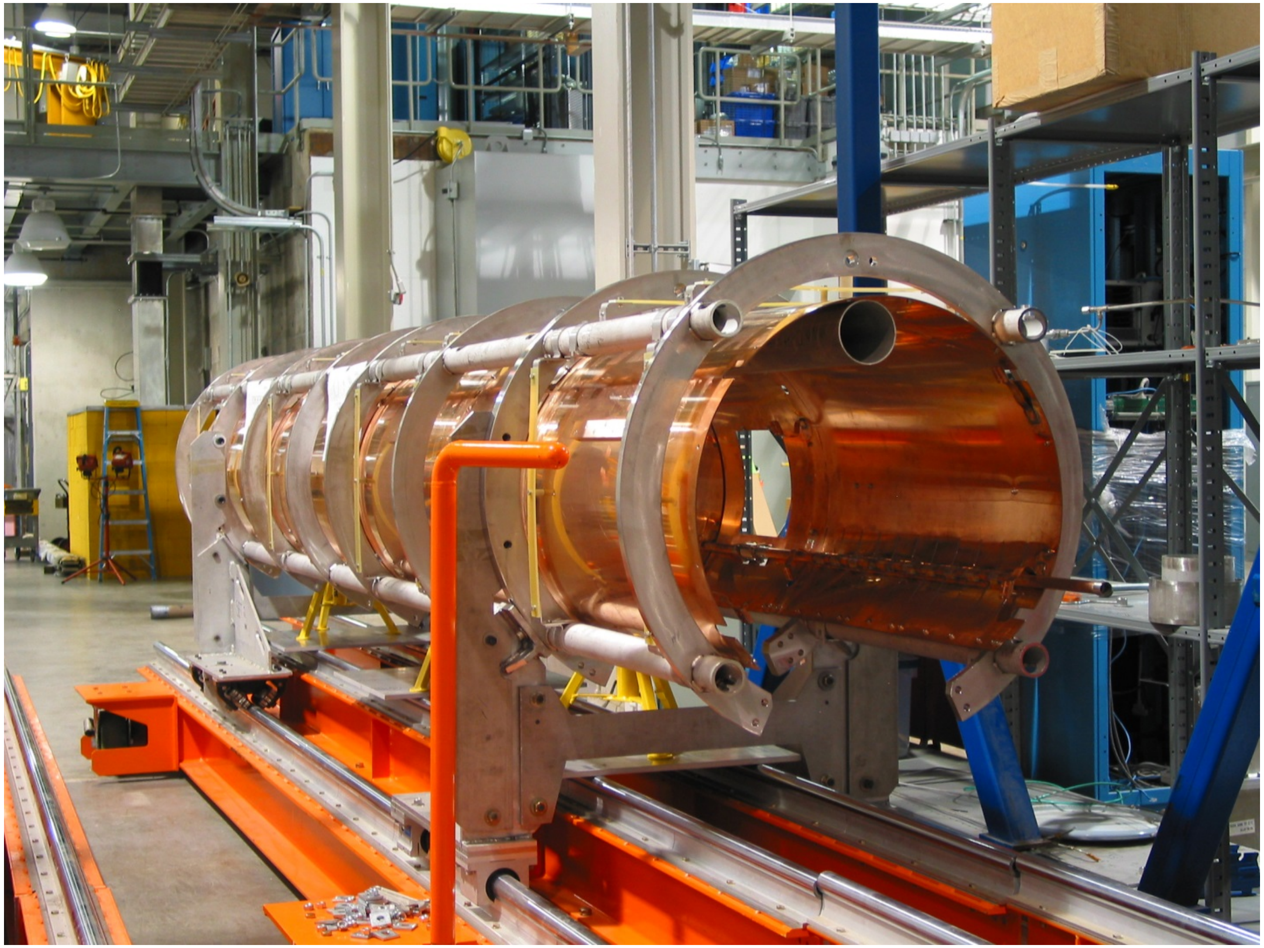
Thermal Shields and Insulation (cont'd)

ILC cryomodule thermal shields and MLI

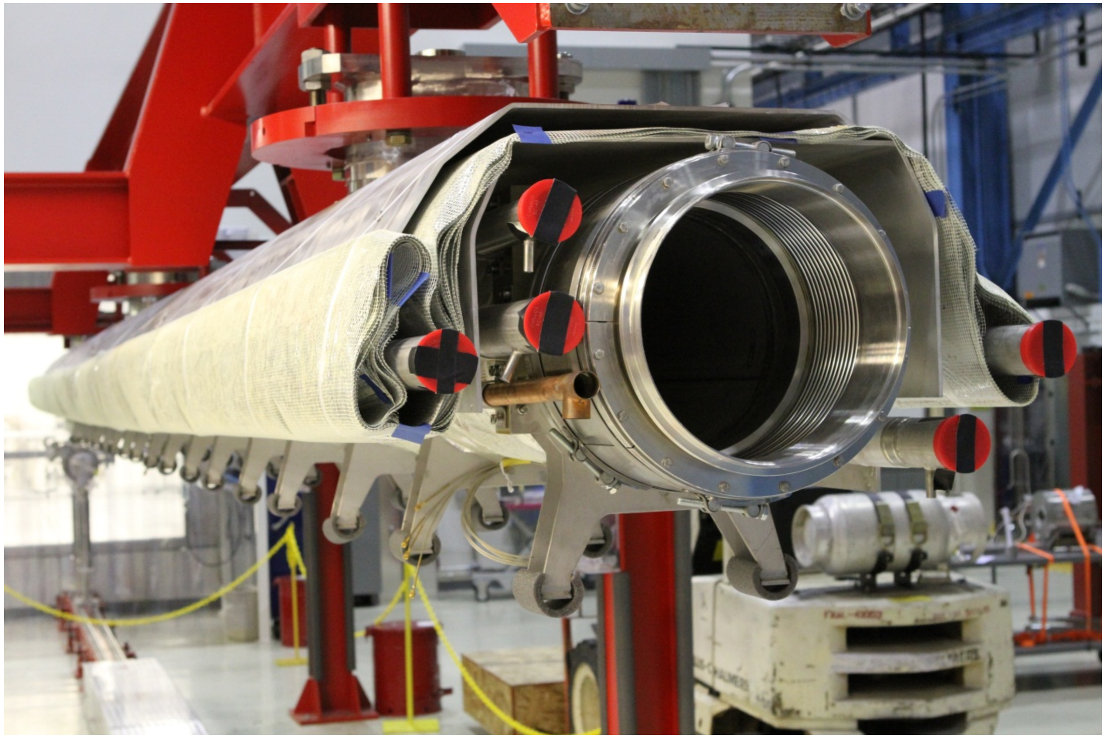


Thermal Shields and Insulation (cont'd)

Jefferson Lab upgrade thermal shield



Thermal Shields and Insulation (cont'd)



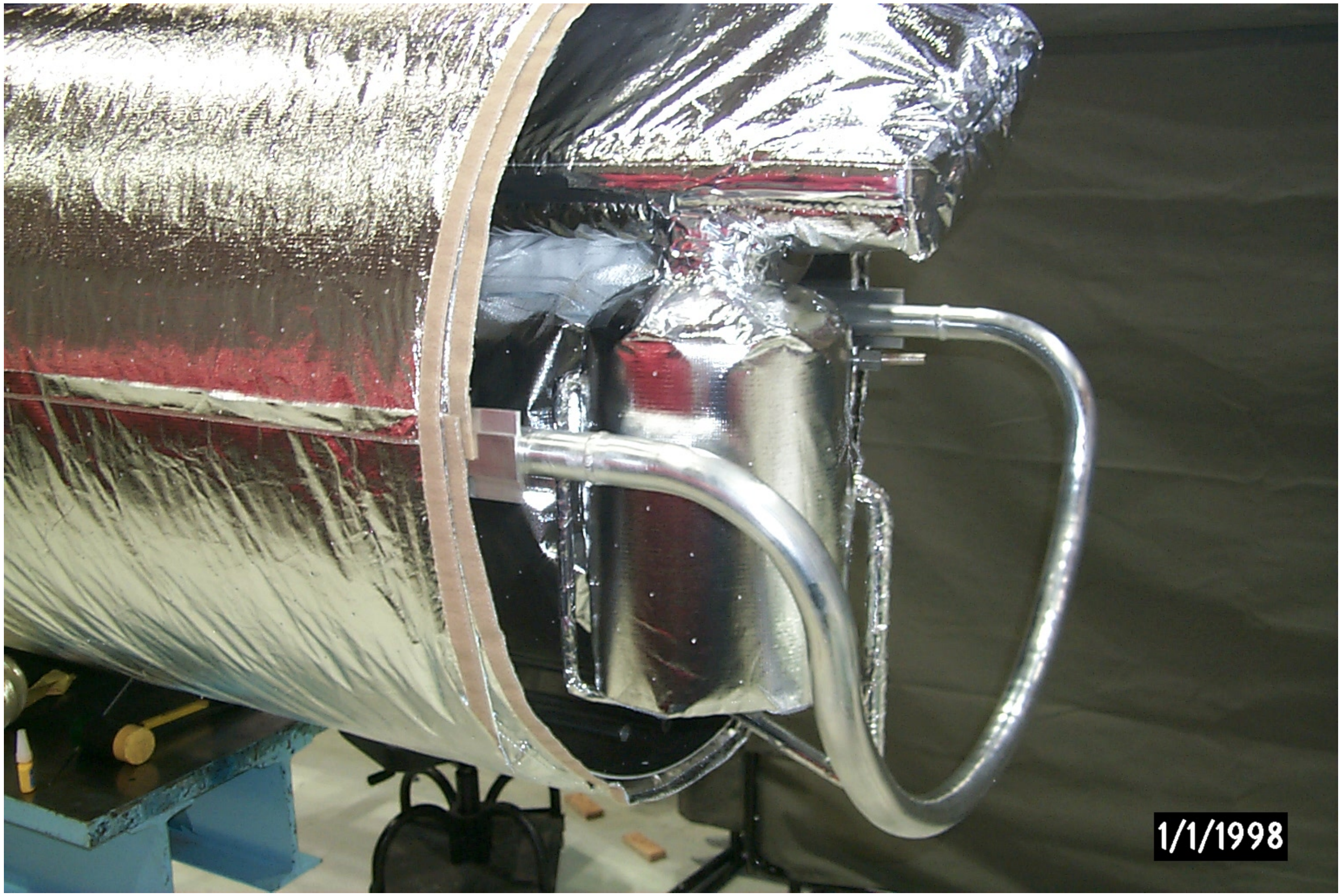
ILC cryomodule shields and MLI

Thermal shield bowing

Fermilab

Thermal Shields and Insulation (cont'd)

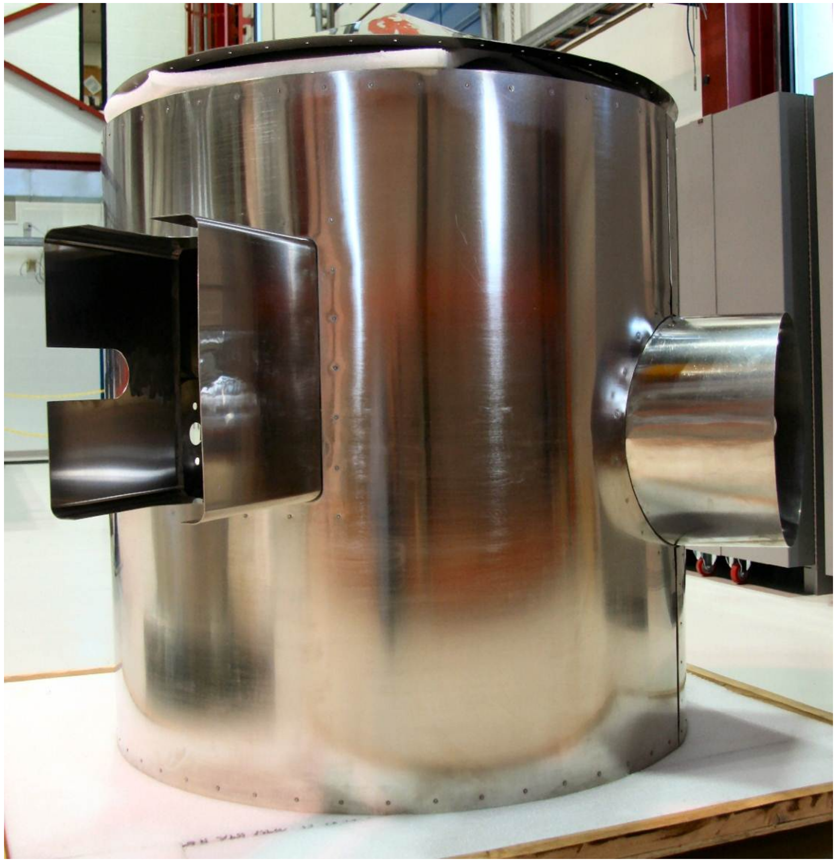
MLI blankets in an LHC IR quad



Magnetic Shielding

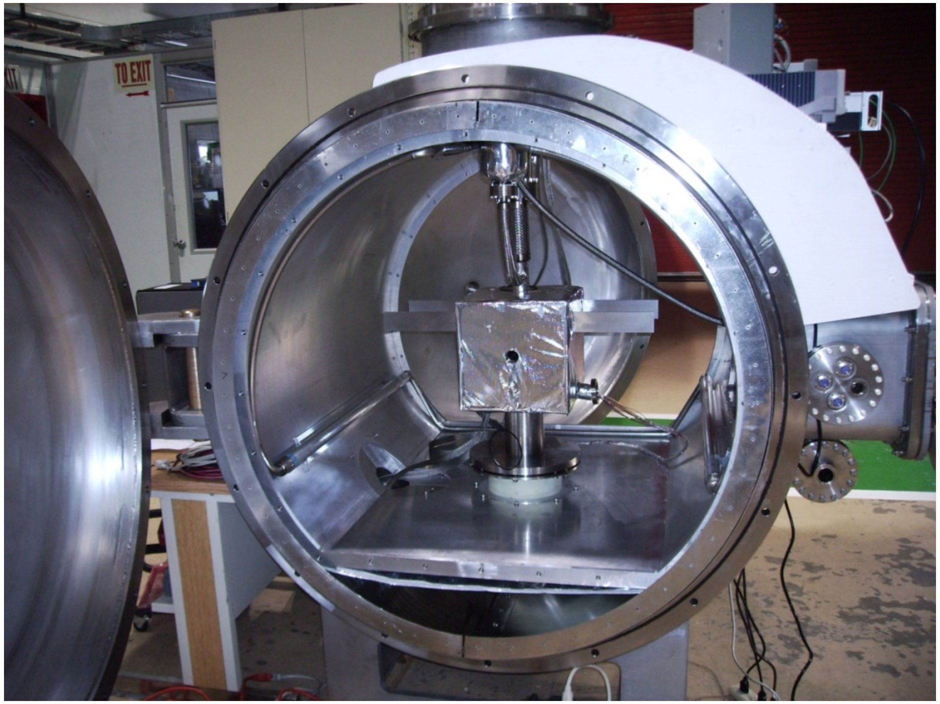
- When installed external to the main cryomodule components, provides protection from external magnetic fields, primarily the earth's field.
- When installed around cavities, focusing elements or both, provides protection from external and internally generated fields.
- Material is mu-metal (nickel-iron alloys) in various grades that exhibit high magnetic permeability compared to carbon steel. Low temperature materials are available, e.g. Cryoperm from Amuneal or Cryophy from Aperam.
- Necessary to maintain high cavity Q, especially in high-Q designs.
- Options are single or multiple shells, their location, and materials.
- Magnetic shielding inside the helium vessel is possible, but complicates helium and heat flow.

Magnetic Shielding (cont'd)



Room temperature global magnetic shield

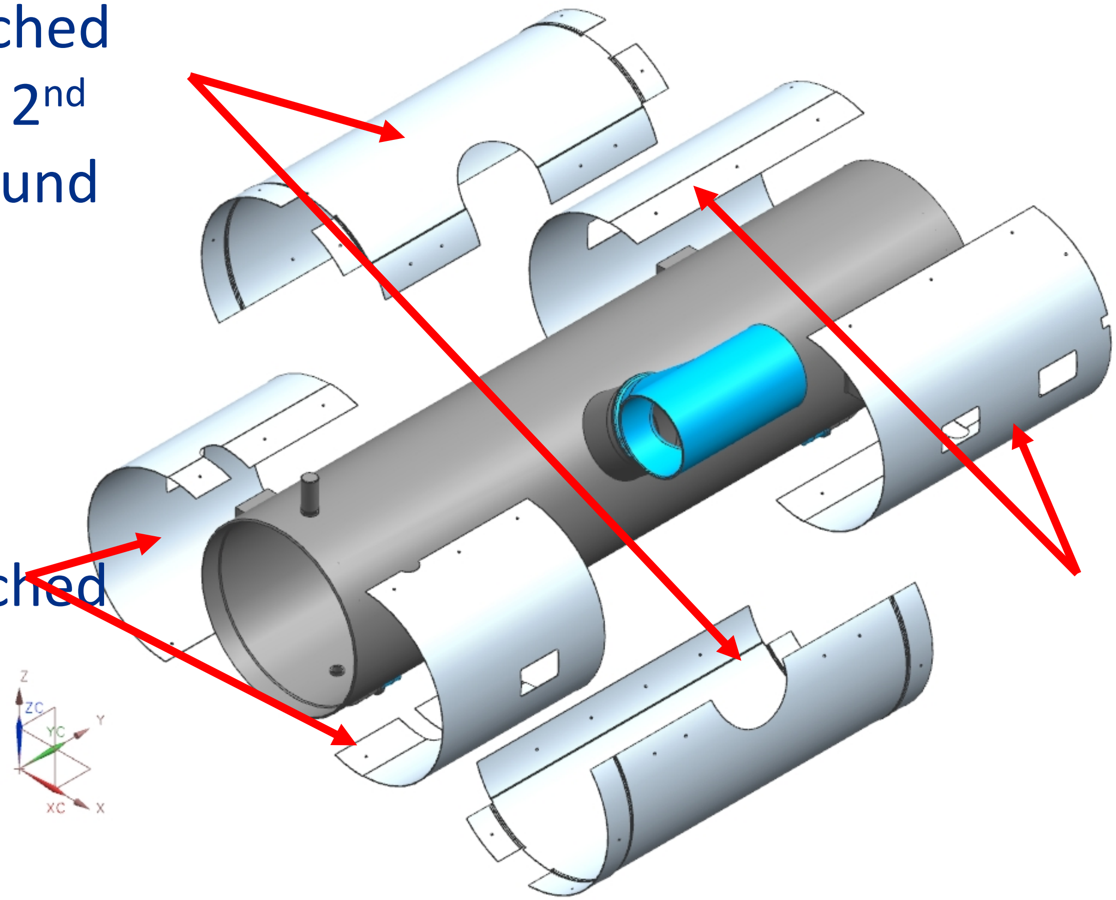
Cold internal magnetic shield



Magnetic Shielding (cont'd)

3rd Pair Attached Over 1st and 2nd Pair and Around "Chimney"

All Shield Parts 1mm Thick



1st Pair Attached

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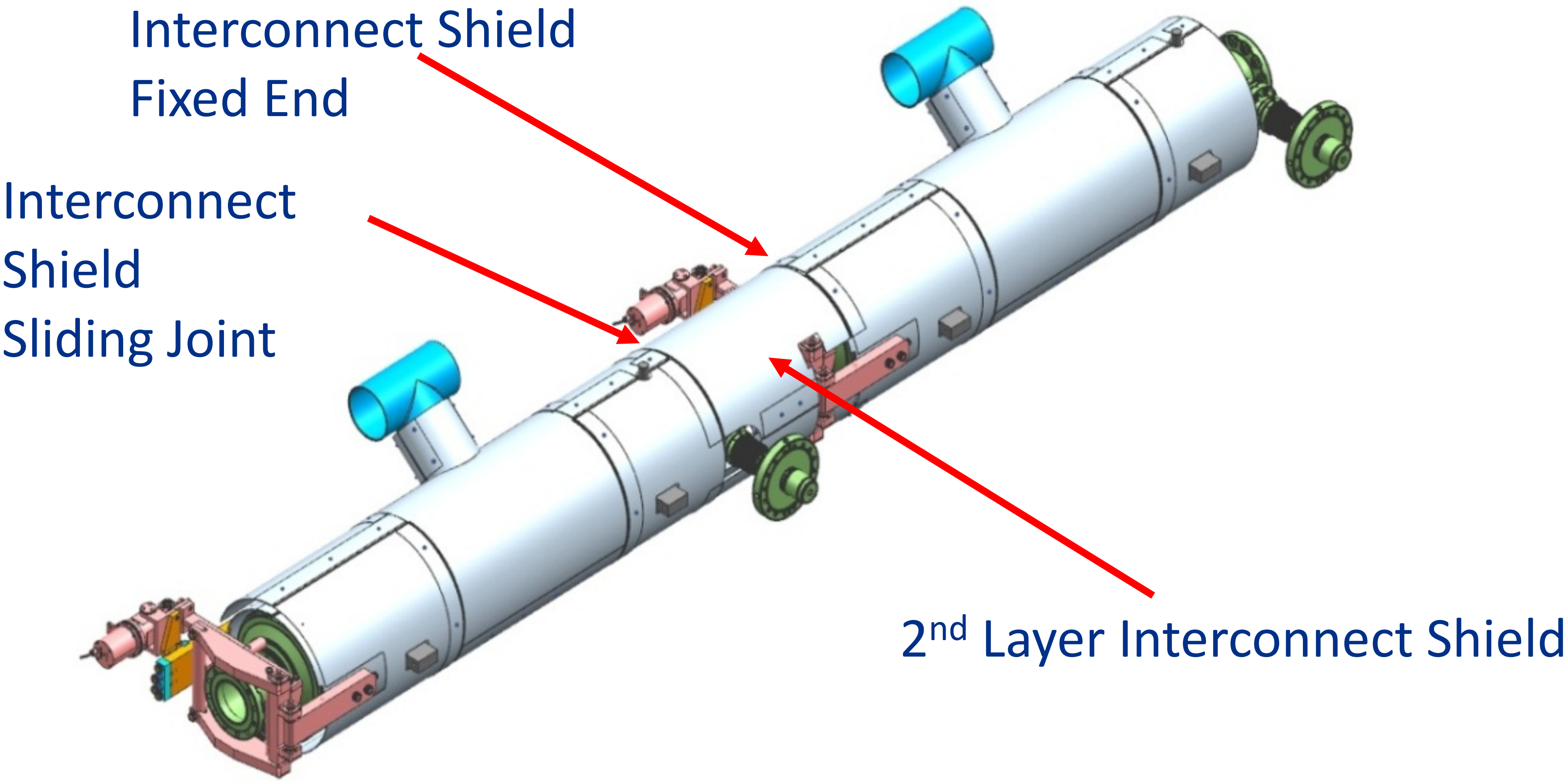
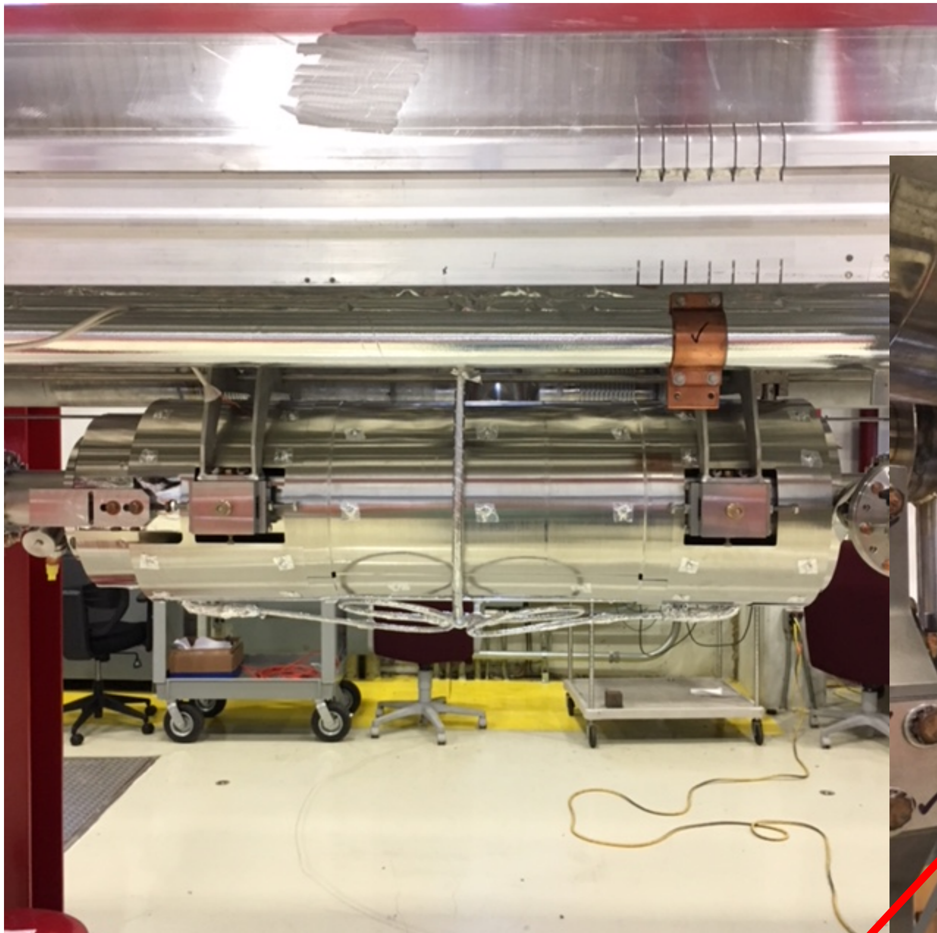
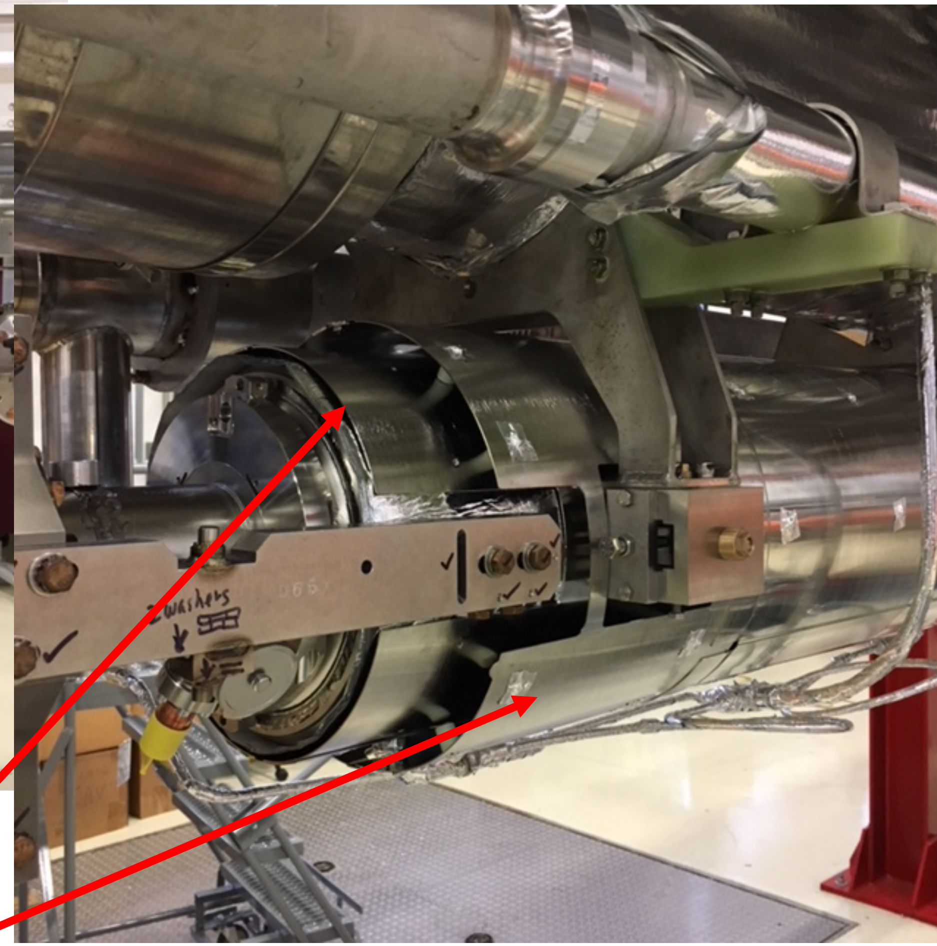
Magnetic Shielding (cont'd)



Magnetic Shielding (cont'd)

LCLS-II cavity magnetic shields





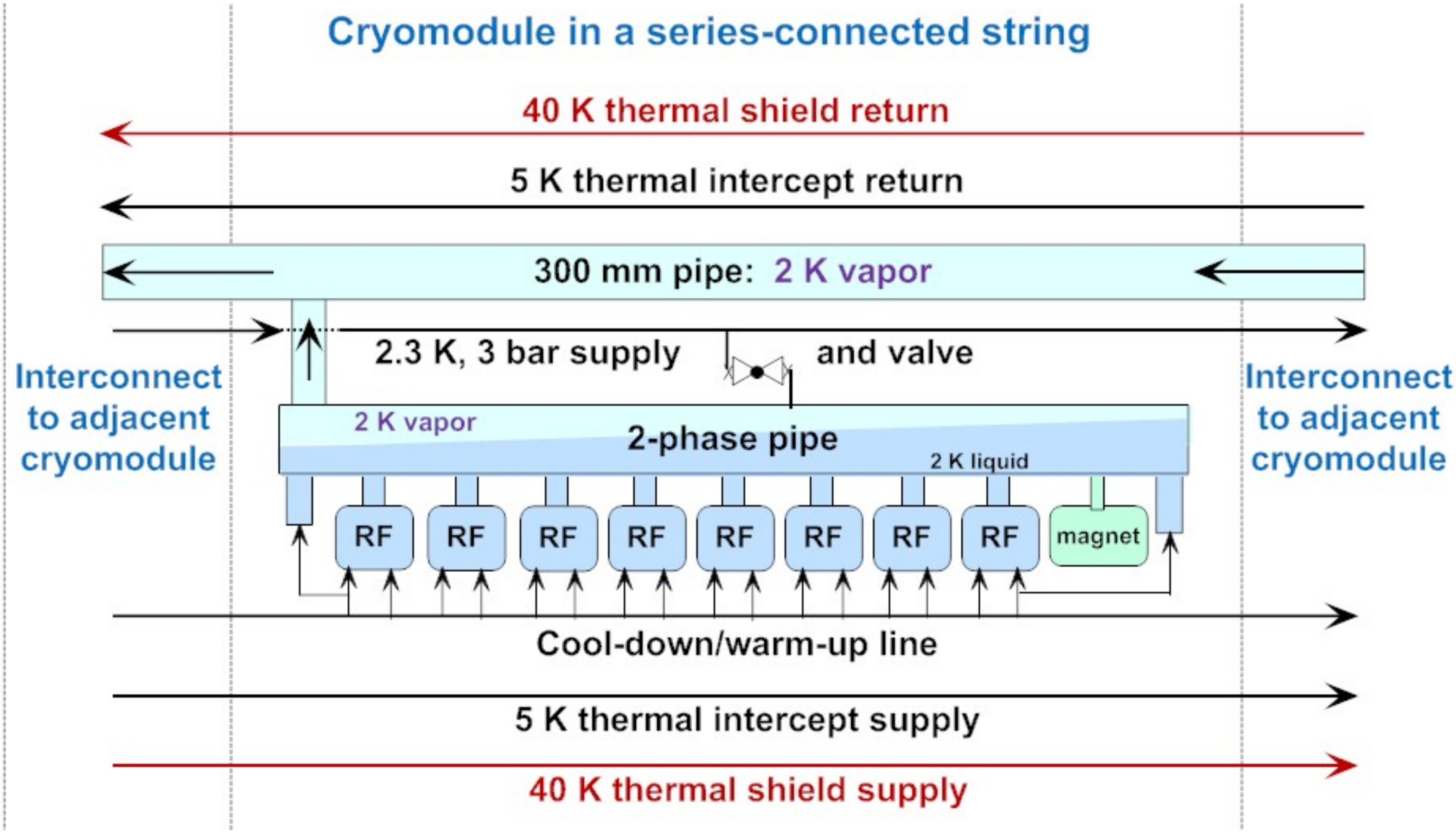
Inner layer

Outer layer

Cryogenic Piping

- Provides fluid flow for the thermal shield(s) and supplies cooling to the SRF devices and focusing elements.
- Acts as part of the cryogenic supply system, i.e. some pipes may just pass through the cryomodule with no internal connections, e.g. return lines.
- Materials are generally stainless steel, aluminum or copper. Aluminum and sometimes copper require bi-metallic transition joints to connect to interconnect piping and bellows.

Cryogenic Piping (cont'd)

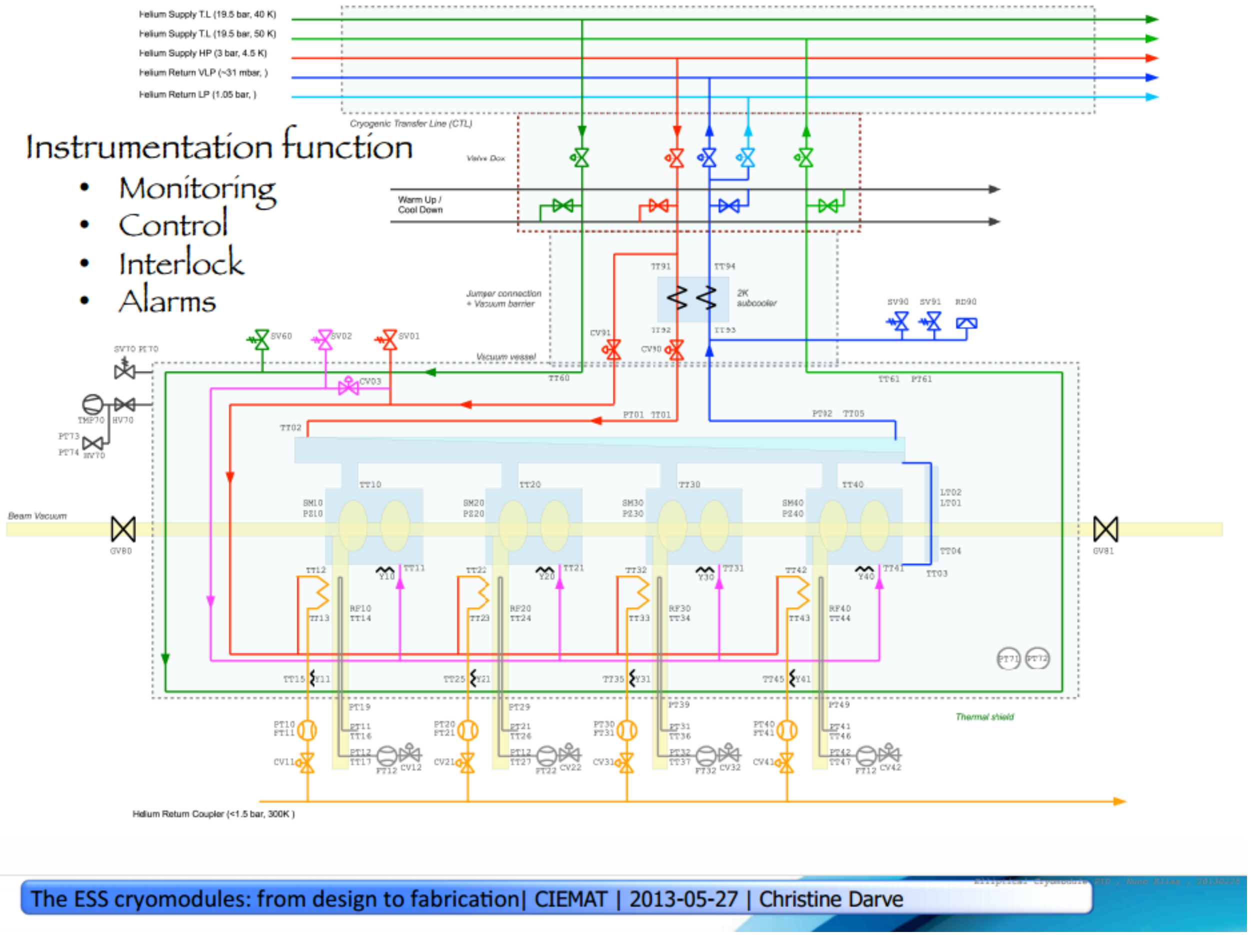


Cryomodule piping connections for course segmentation (e.g. XFEL, LCLS-II)

Cryogenic Piping (cont'd)

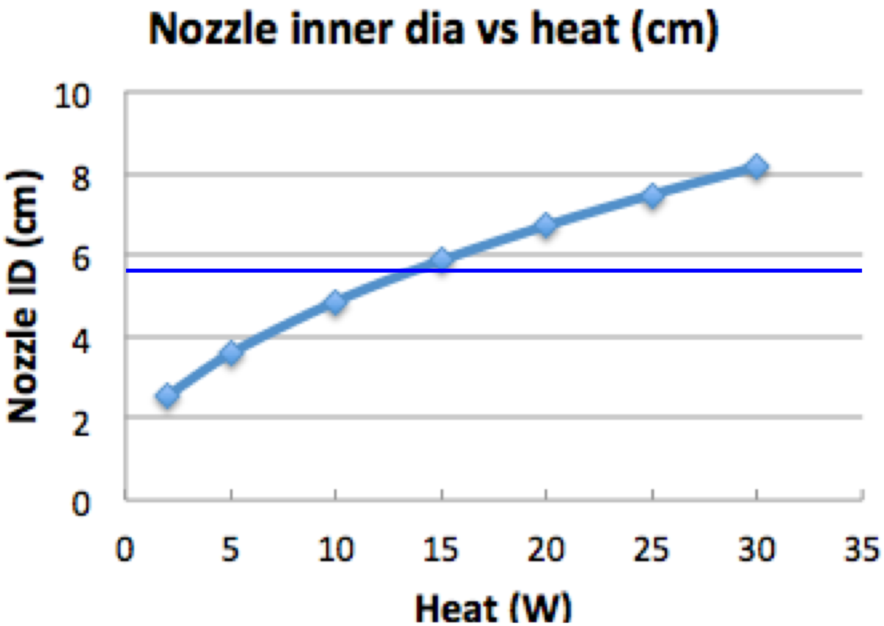
Instrumentation function

- Monitoring
- Control
- Interlock
- Alarms



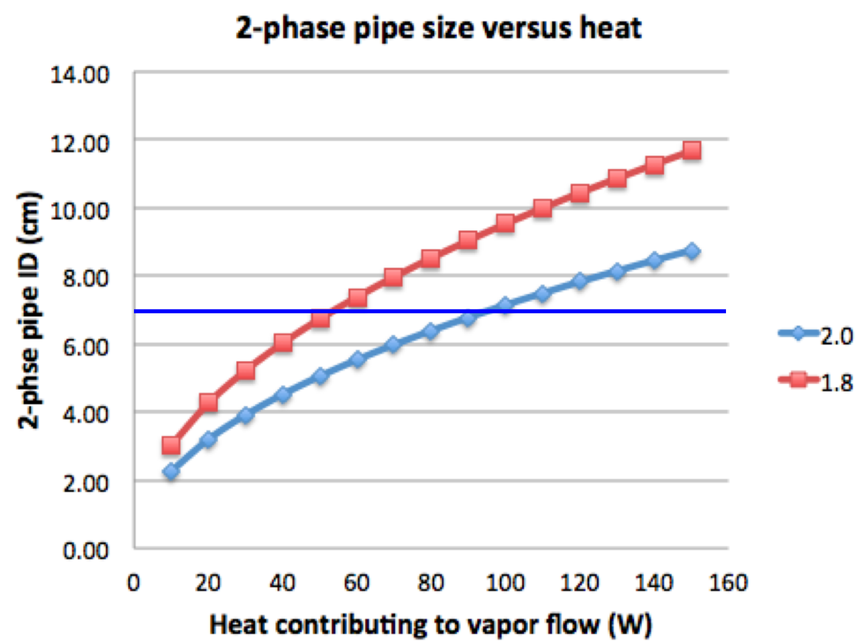
Cryomodule piping connections for fine segmentation (e.g. CEBAF, SNS, ESS)

Cryogenic Piping (cont'd)



Connection diameter vs. heat flux

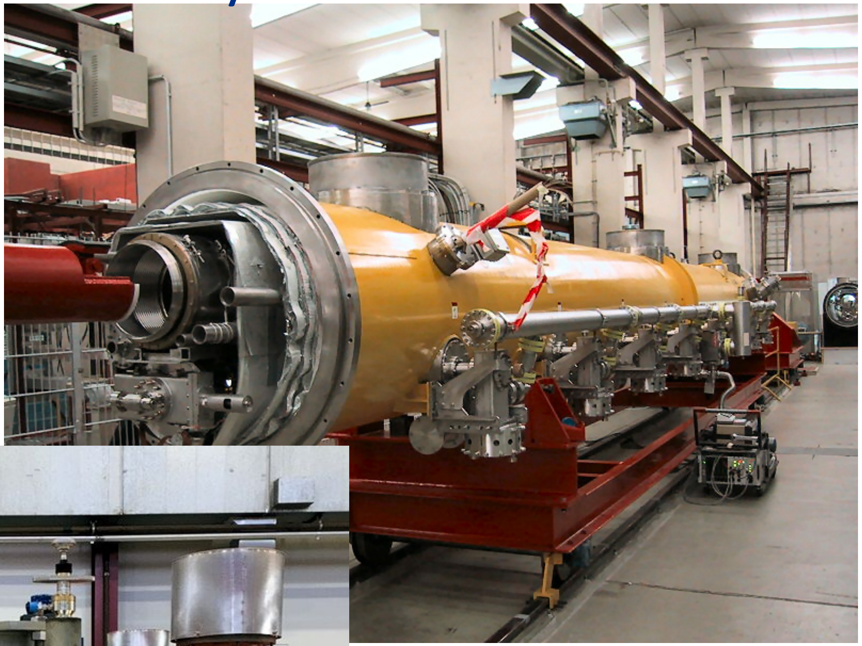
5 meter/sec speed limit for vapor over liquid sets 2-phase pipe size



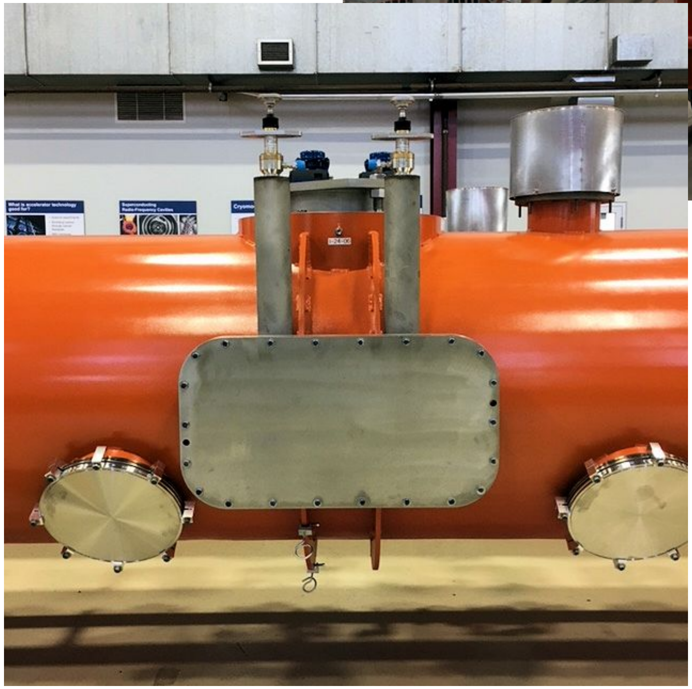
Fermilab

Cryogenic Piping (cont'd)

1.3 GHz elliptical cavity XFEL cryomodule at DESY



12 Gev upgrade cryomodule at JLab

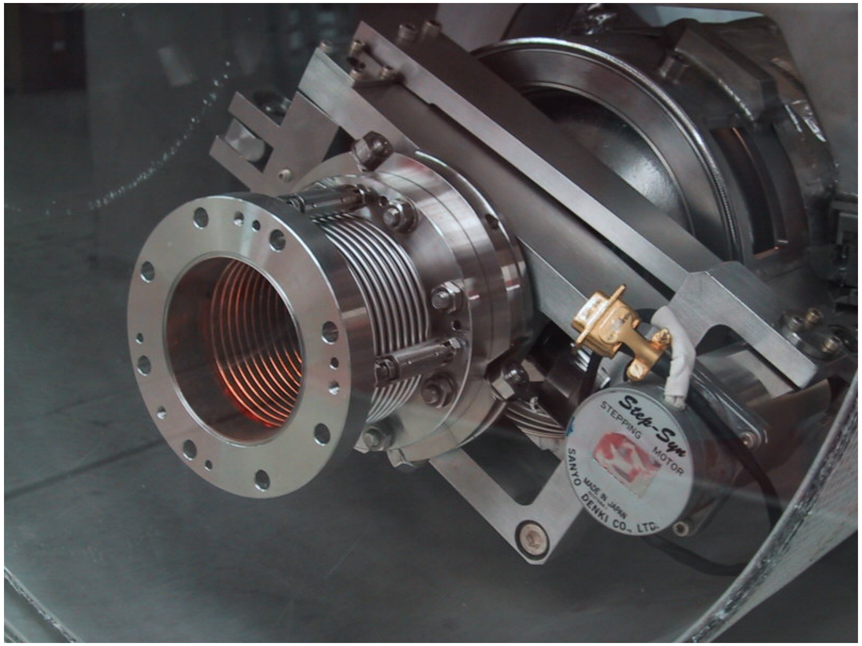


LCLS-II cryomodule at Fermilab

Tuners

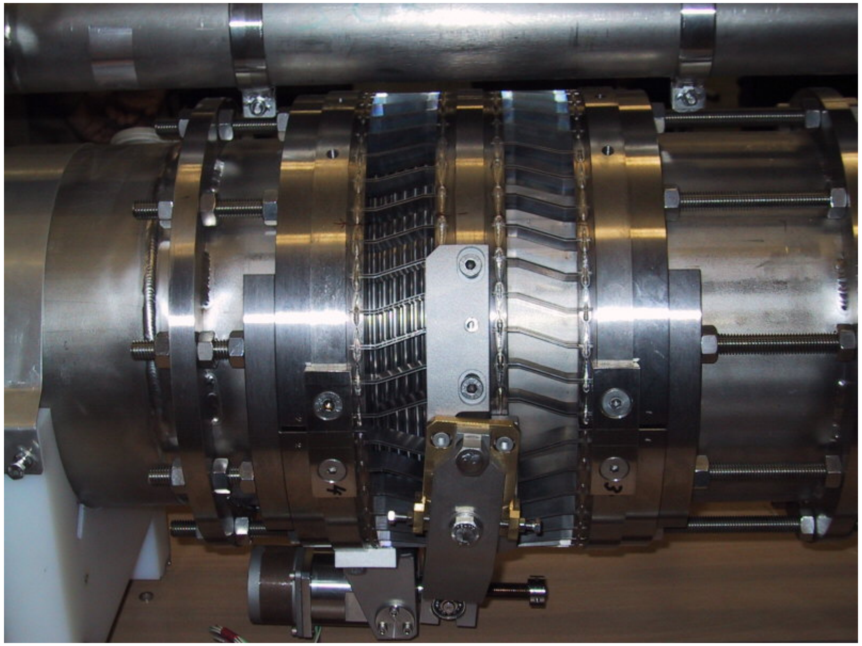
- Tuners are installed on each cavity to ensure cavities operate at the proper frequency.
- Slow tuners react to things like system pressure changes to tune individual cavity frequencies in real time.
- Fast tuners react to things like Lorentz forces, also to tune individual cavities, but much faster than the slow tuner.
- There are many types of tuner mechanisms, especially slow tuners – lever, blade, scissors, pneumatic, etc.
- Fast tuners are generally a piezo cartridge integrated into the slow tuner mechanism so they can act concurrently.

Tuners (cont'd)

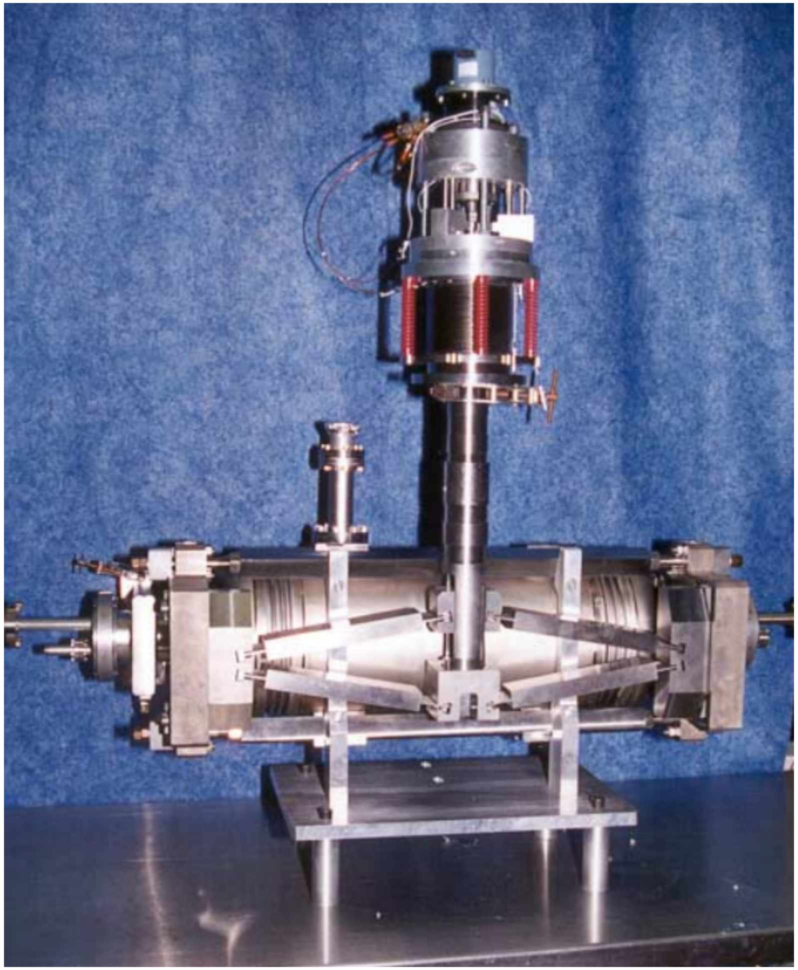


Lever tuner

Blade tuner

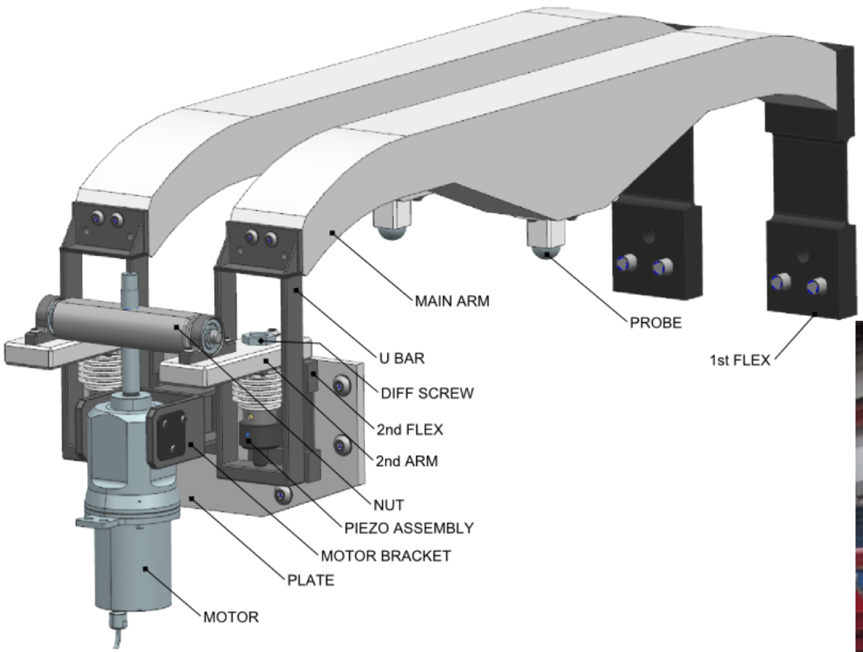


Tuners (cont'd)



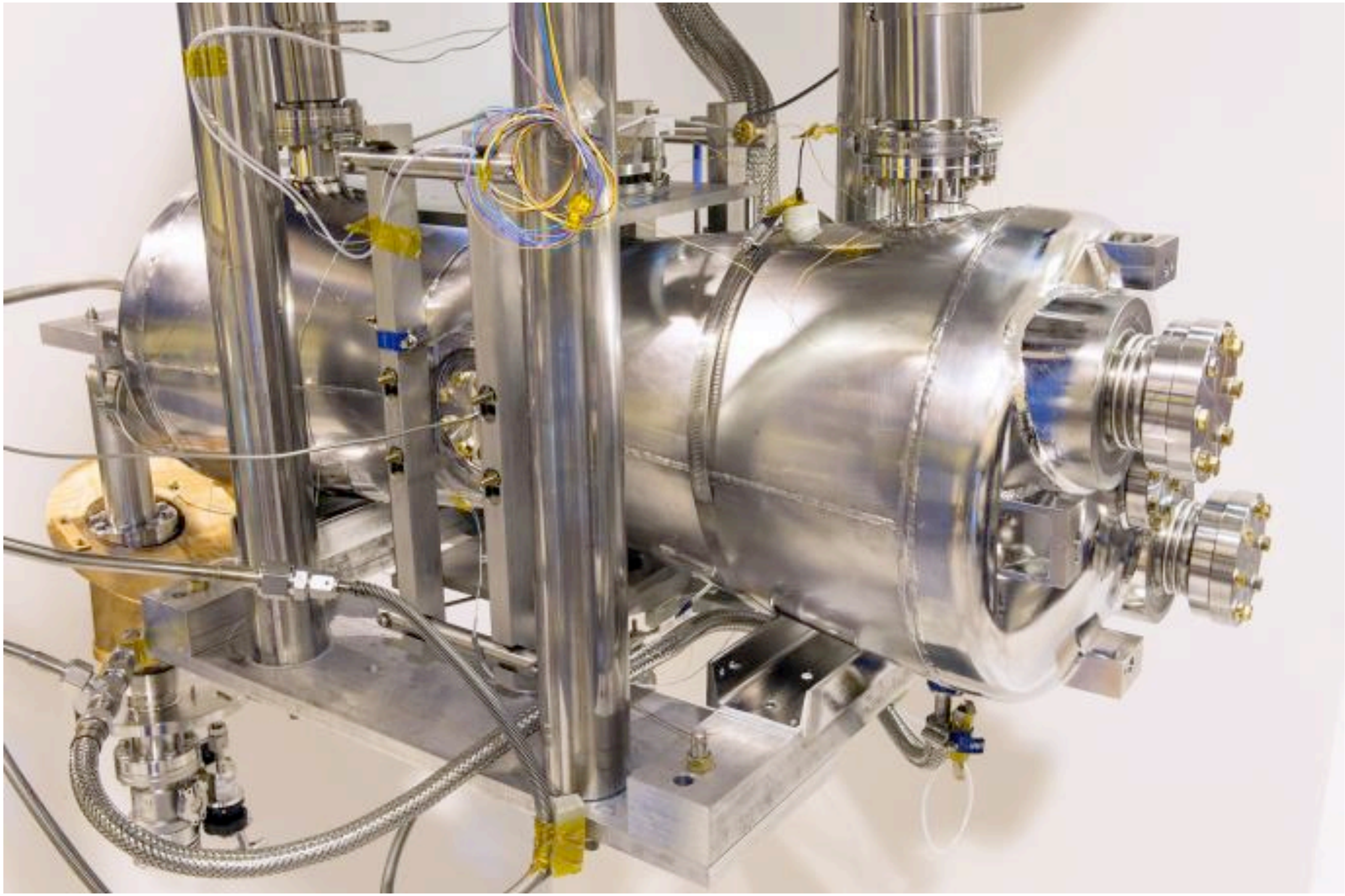
Scissors jack tuner

Tuners (cont'd)



Lever style tuner on a single spoke resonator

Tuners (cont'd)



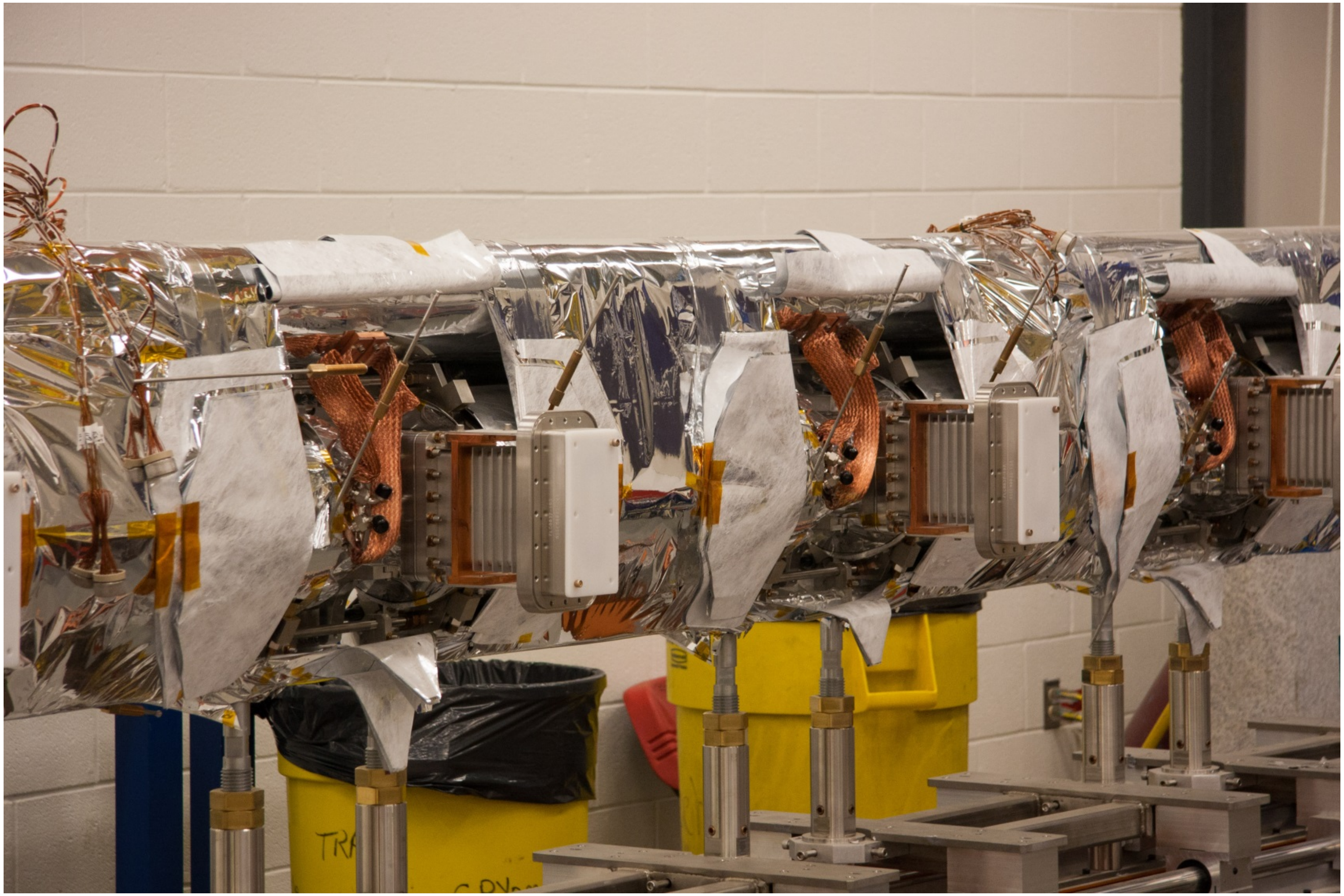
Pneumatic tuner on a HWR cavity at Argonne

Couplers

- Provide RF power to the cavities.
- Are generally either coaxial or waveguide.
- Usually have either one or two ceramic windows to isolate the cavity from the environment.
- Can be fixed or variable.
- Often require built-in flexibility to accommodate thermal contraction of the cavity, cavity supports or both.

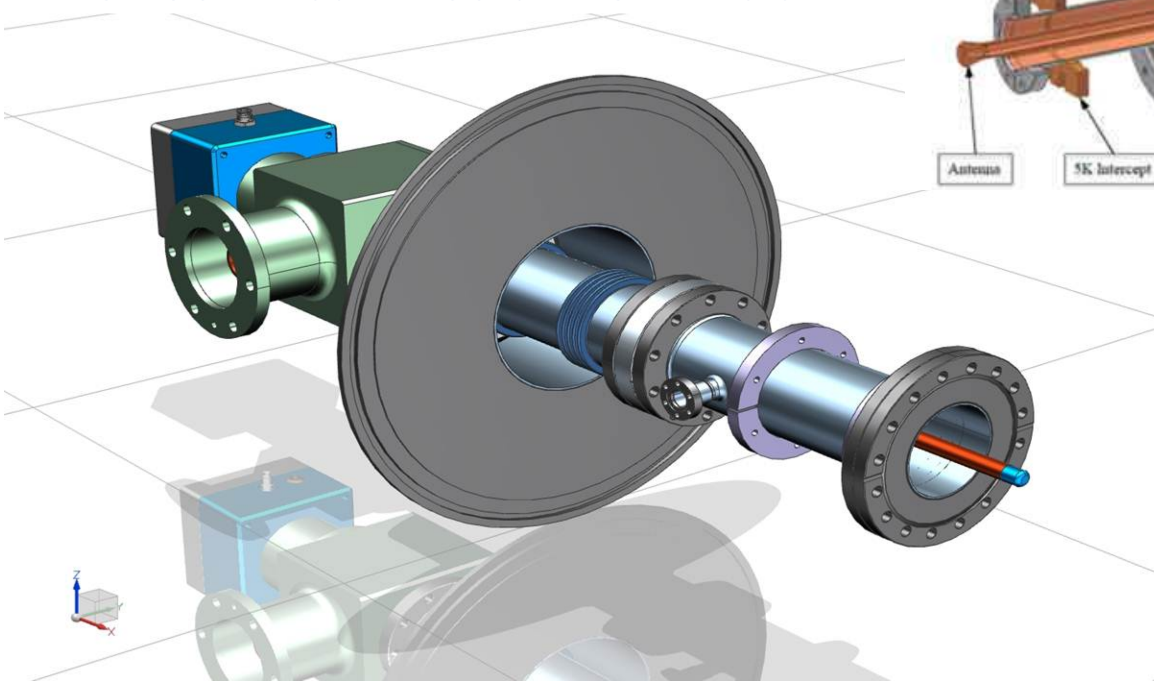
Couplers (cont'd)

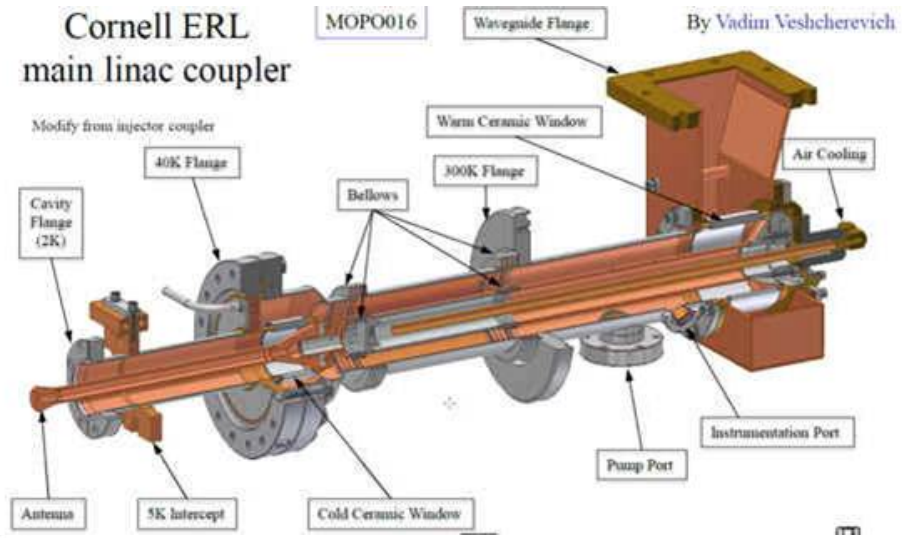
Couplers (cont'd)



Couplers (cont'd)

Single window coaxial coupler for SSR1 cavities at Fermilab

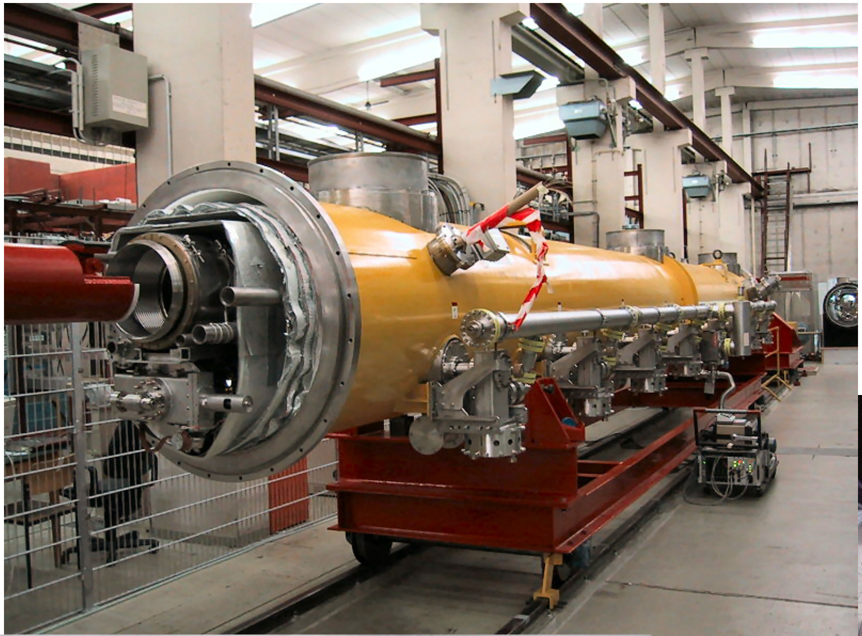


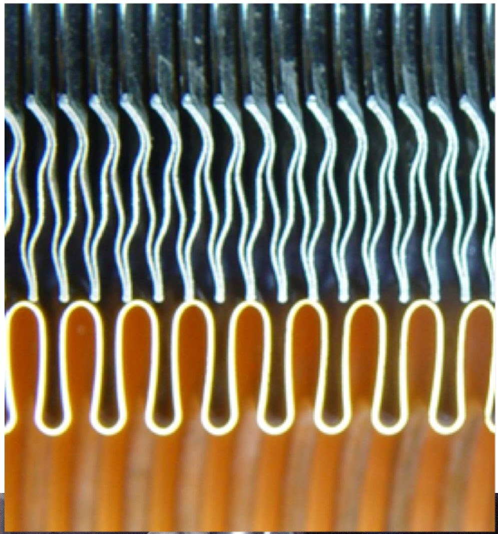


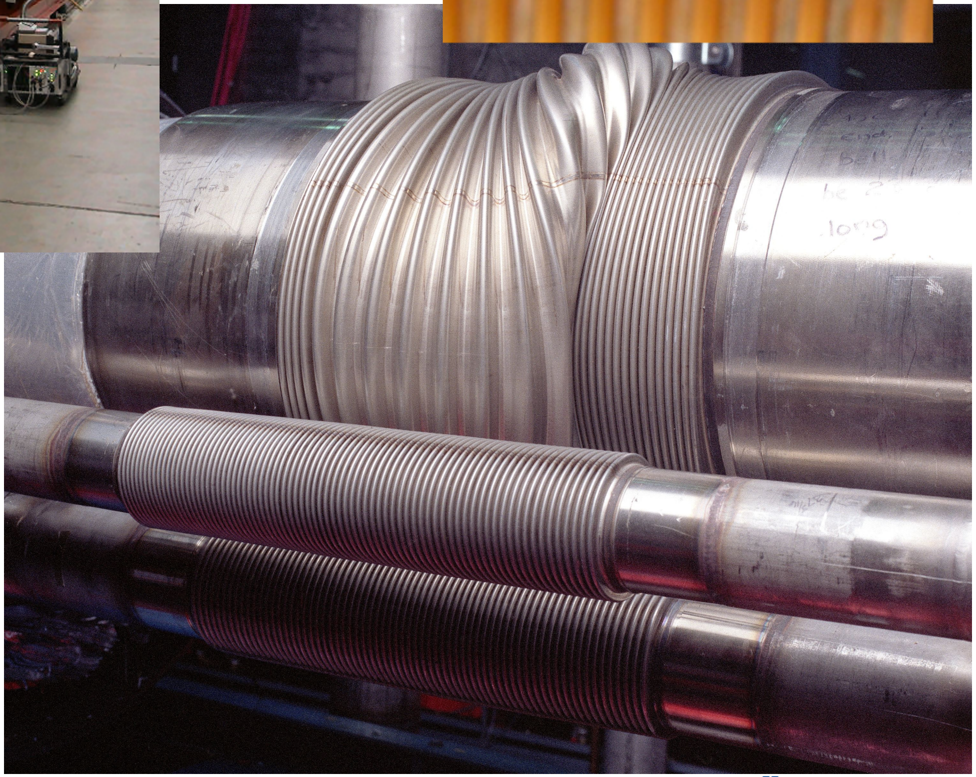
Bellows and Interconnects

- Bellows are used in many places and for many reasons in nearly all accelerator devices, but especially in superconducting magnets and RF cryomodules.
  - They accommodate thermal expansion and contraction during warm-up and cooldown.
  - They make up small differences in pipe locations at magnet or cryomodule interconnects.
  - They allow some adjusting capability in the overall cryostat or cryomodule position during alignment.
  - They allow some adjustment in things like RF input couplers and provide tuning capability for SRF cavities.
- There are basically two types of bellows commonly used – hydroformed and edge-welded.
- Design parameters are governed by the ASME Boiler and Pressure Vessel Code and the Expansion Joint Manufacturers Association (EJMA).

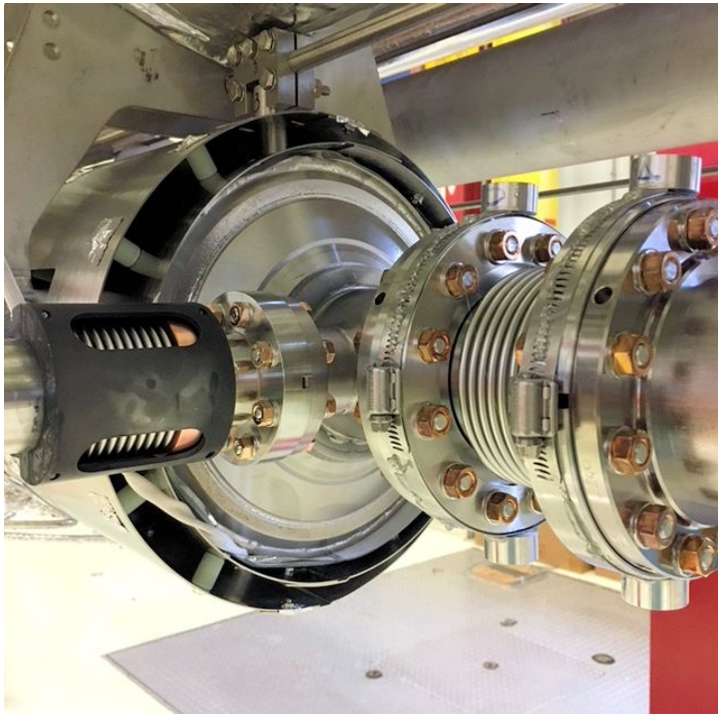
Bellows and Interconnects (cont'd)



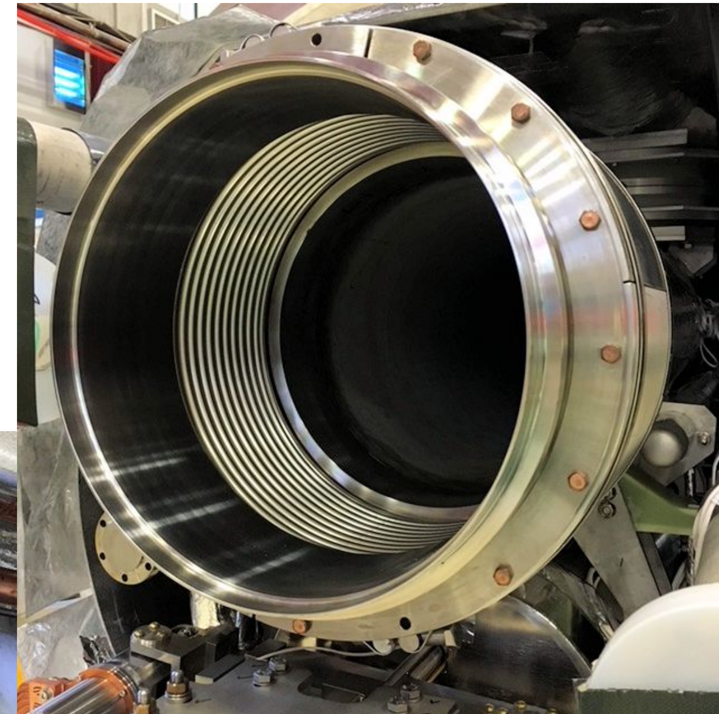


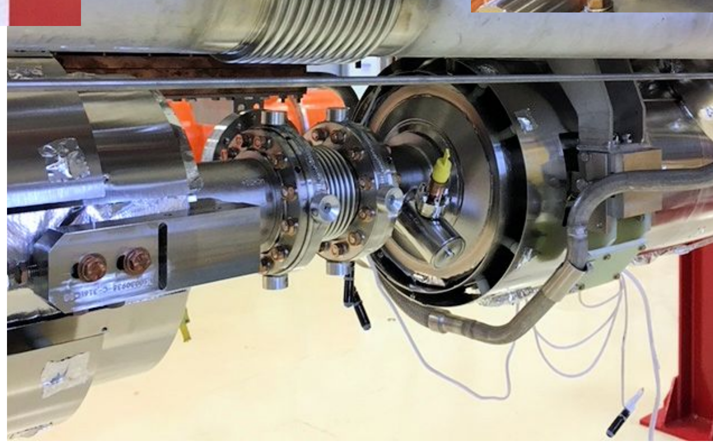


Bellows and Interconnects (cont'd)



Various LCLS-II cryomodule bellows





Alignment

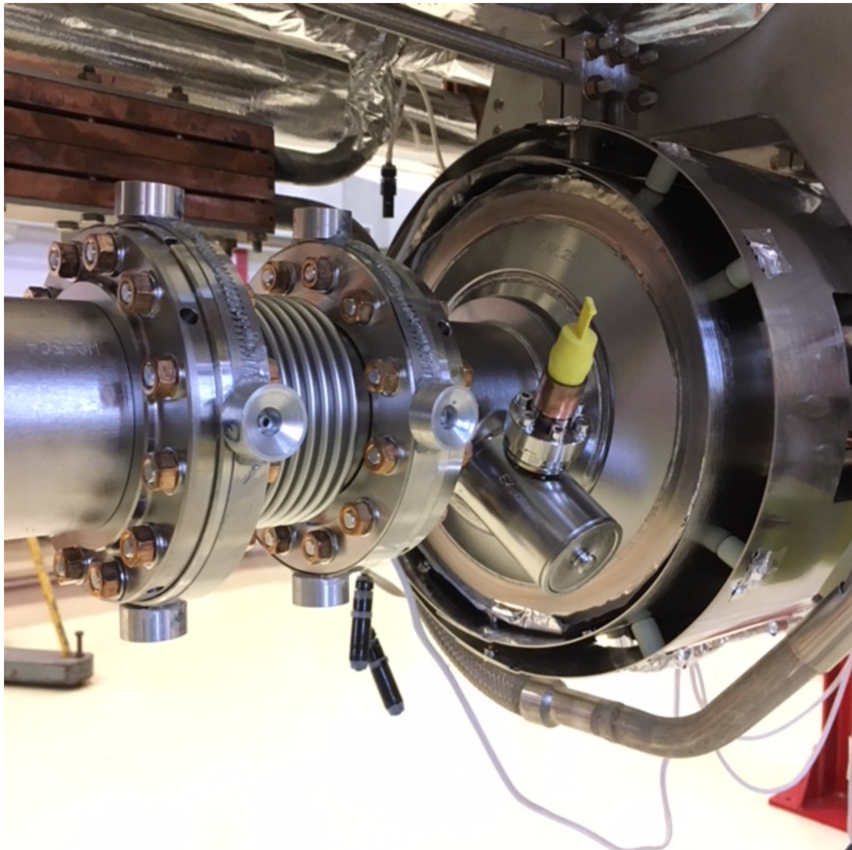
- Alignment is required of nearly all accelerator components. In the context of this subject, that means cavities, magnets, and complete cryomodules, to ensure their proper operation and connection to adjoining devices, minimal perturbations to the beam, proper focusing, etc.

Alignment (cont'd)

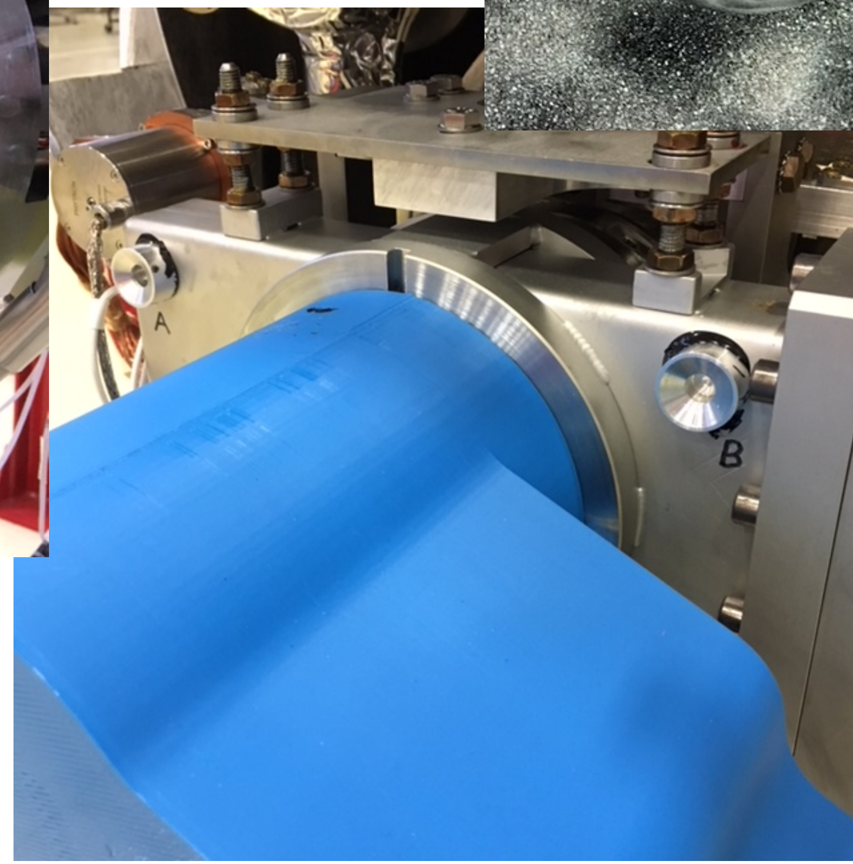
GENERAL REQUIREMENTS

General		
	Physical beam aperture, mm	118
	Overall length (flange-to-flange), m	9.56
	Overall width, m	≤1.6
	Beamline height from the floor, m	1.3
	Cryomodule height (from floor), m	≤2.00
	Ceiling height in the tunnel, m	3.20
	Max allowed heat load to 70 K, W	300
	Max allowed heat load to 5 K, W	25
	Max allowed heat load to 2 K, W	220
	Maximum number of lifetime thermal cycles	50
	Intermediate thermal shield temperature, K	45-80
	Thermal intercept temperatures, K	5 and 45-80
	Cryo system pressure stability at 2 K (RMS), mbar	≤0.1
	Environmental contribution to internal field	10 mG
	Transverse cavity alignment error, mm RMS	<0.5
	Angular cavity alignment error, mrad RMS	≤1
	Beam duration for operation in pulsed regime, ms	≤1
	Repetition rate for operation in pulsed regime, Hz	≤20

Alignment (cont'd)



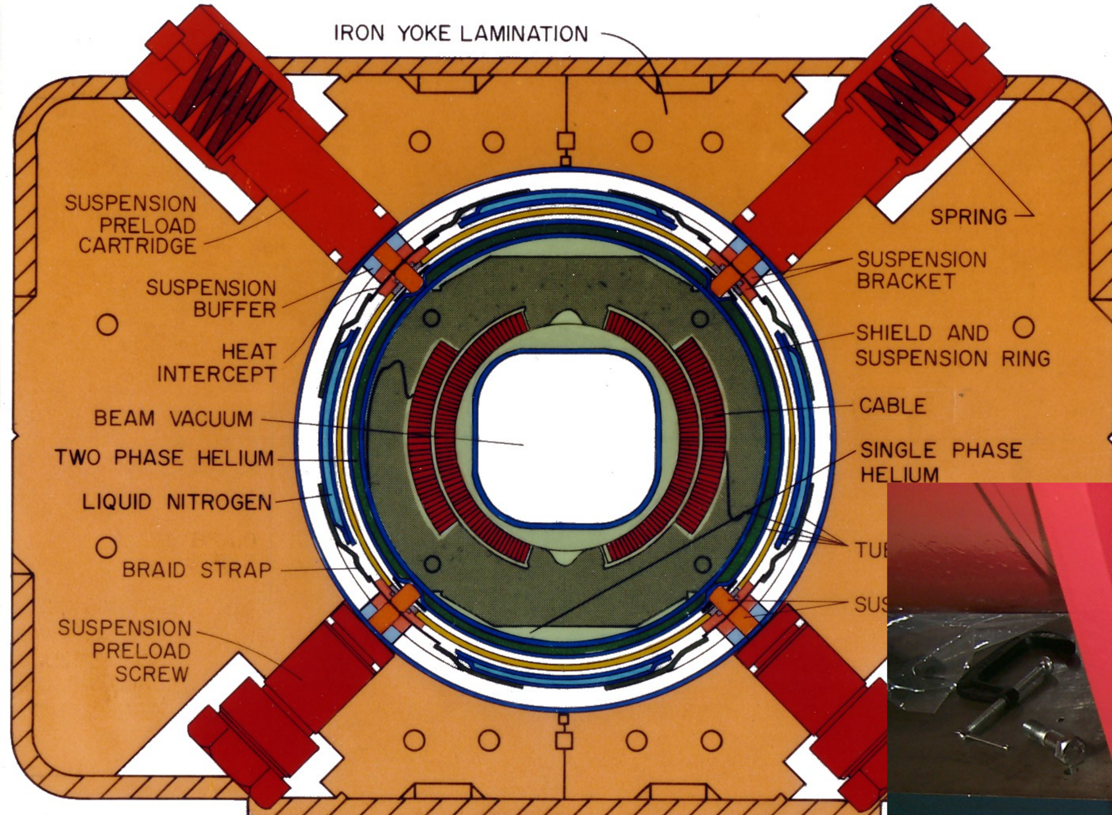
Alignment fiducials and holders



Alignment (cont'd)

Alignment fiducial

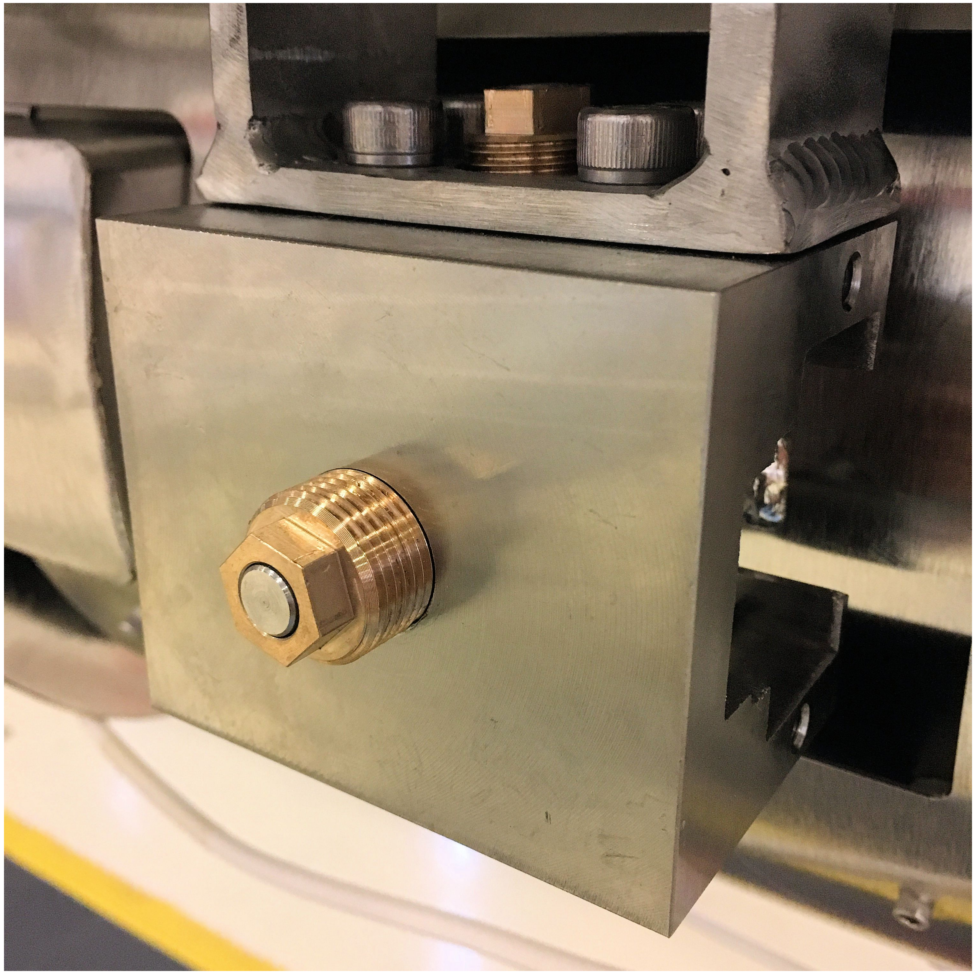
Alignment (cont'd)



Tevatron magnet alignment mechanism

LHC IRQ magnet alignment adjustment tooling

Alignment (cont'd)



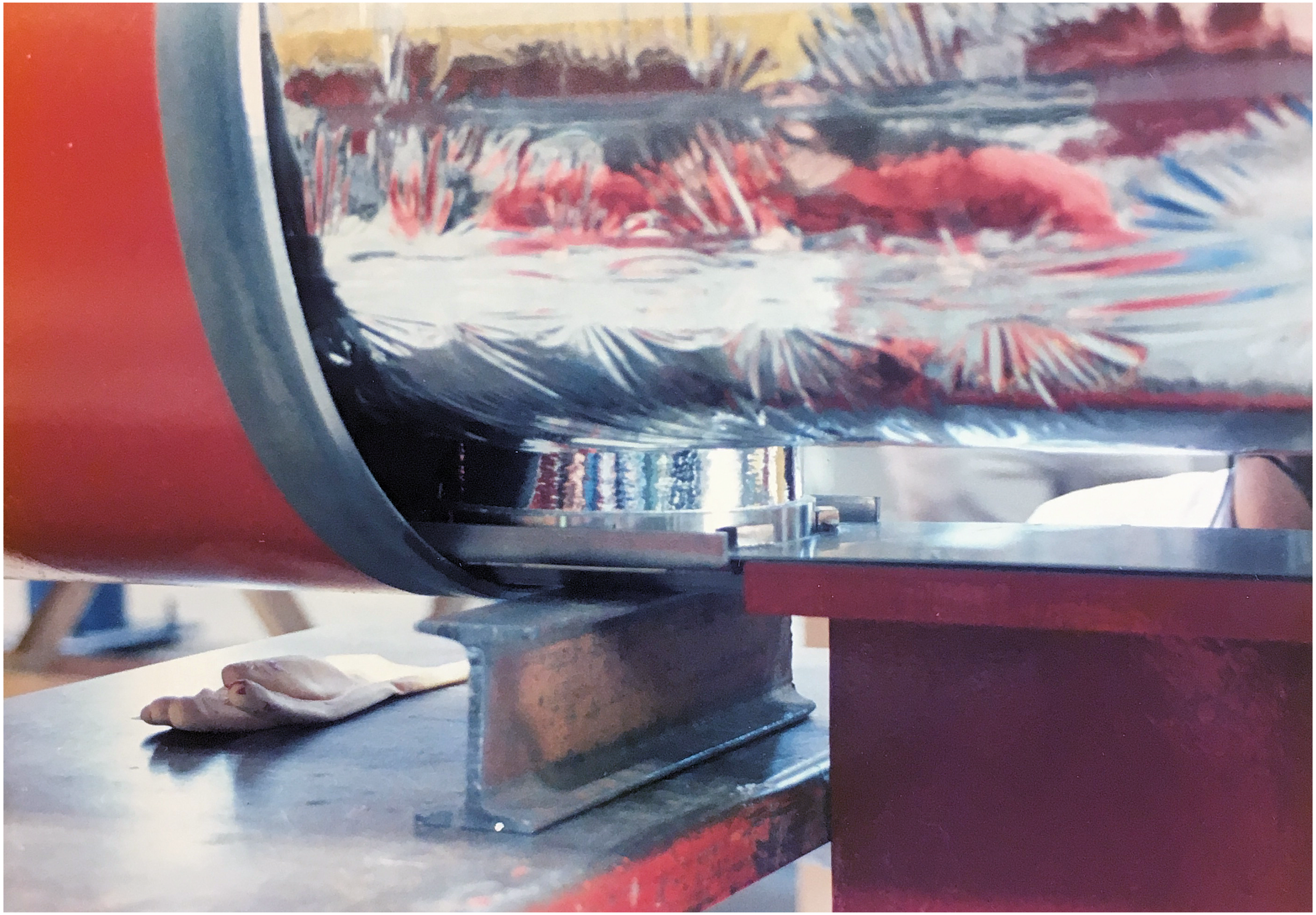
LCLS-II cavity string alignment adjustment block

Assembly Techniques

- There are many ways of doing the final assembly of the cold mass, consisting of the cavities, magnets, piping, shields, insulation, etc. into the vacuum vessel.
- The assembly techniques, tooling and other hardware depend on the configuration of the assembly, whether insertion is from the ends or the top, the weight, even the configuration of the assembly facility.

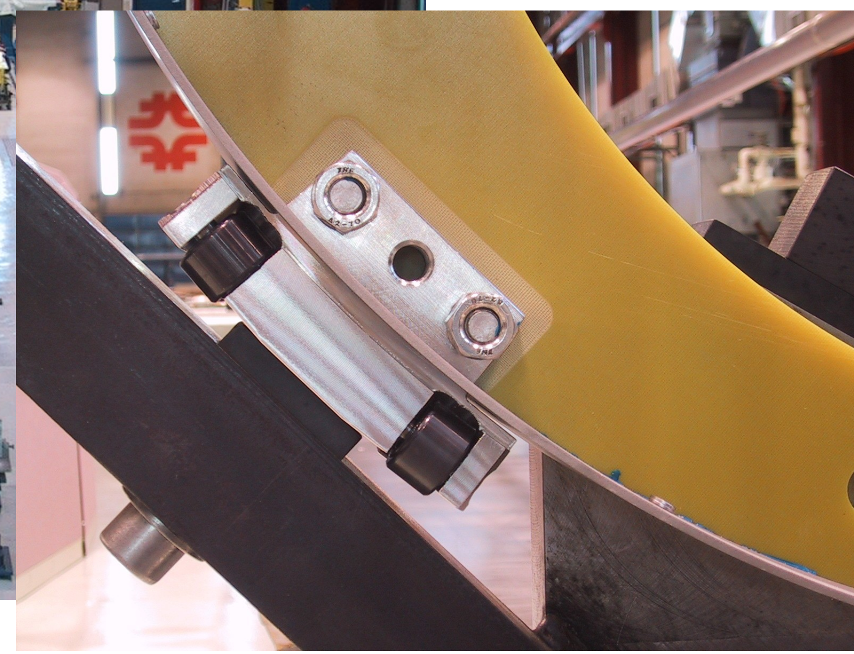
Assembly Techniques (cont'd)

Assembly Techniques (cont'd)



Assembly tooling for SSC dipole magnets

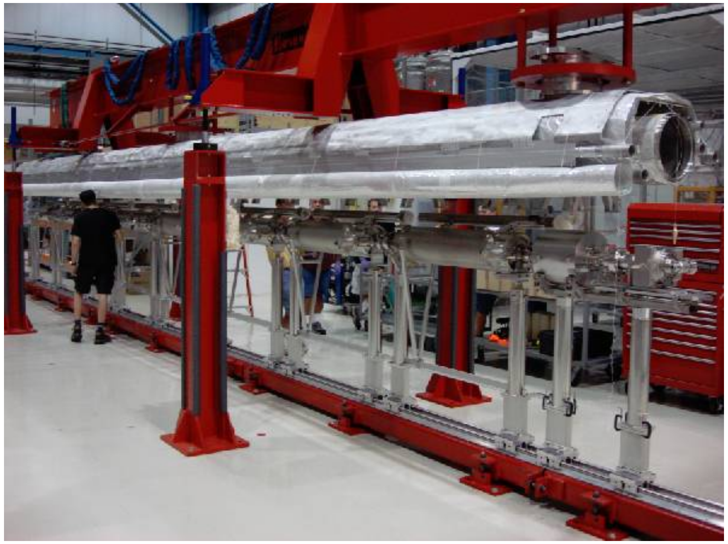
Assembly Techniques (cont'd)



Assembly tooling for LHC IRQ magnets

Assembly Techniques (cont'd)

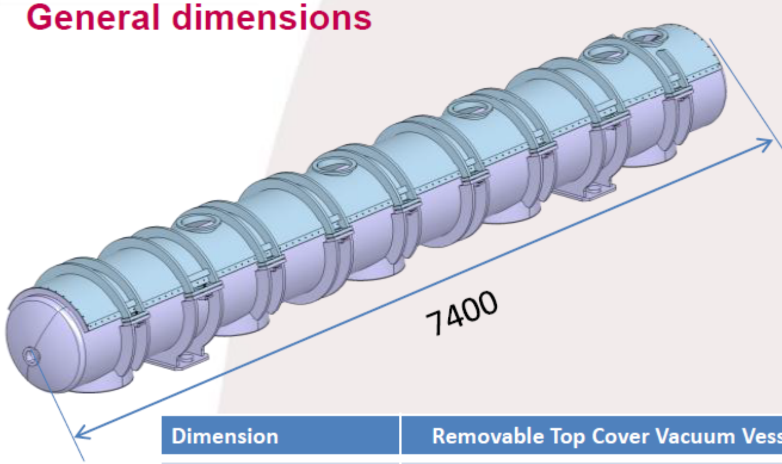
Assembly tooling for 1.3 GHz cavity cryomodules

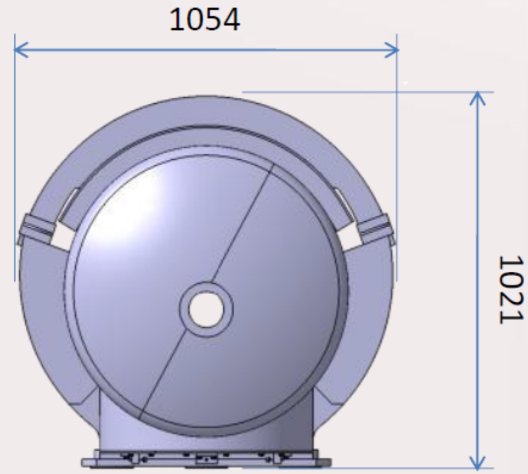


Assembly Techniques (cont'd)

REMOVABLE TOP COVER VACUUM VESSEL

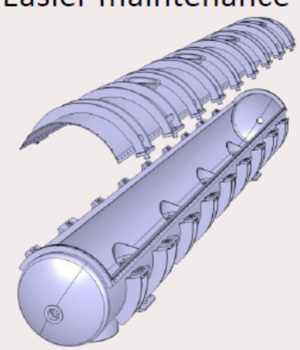
General dimensions





Dimension	Removable Top Cover Vacuum Vessel
Length (mm)	7400
Height (mm)	950
Thikness (mm)	10 (tube) and 6 (Top Cover)
Material	Steel and Stainless steel for flanges
Weight (ton)	2.4
Diametre (mm)	800/900
Number of openings	2 + 5 + 5 (2 beam flanges+ 5 coupler bearings ports + 5 access ports)
Number of Supports	2

Smaller diameter
⇒ Easier maintenance access



SPL cryomodule assembly concept

Transportation

MOPP021 Proceedings of LINAC2014, Geneva, Switzerland

XFEL CRYOMODULE TRANSPORT: FROM THE ASSEMBLY LABORATORY IN CEA-SACLAY (FRANCE) TO THE TEST-HALL IN DESY-HAMBURG (GERMANY)

S. Barbanotti[#], K. Jensch, W. Maschmann, O. Sawlanski, DESY, Hamburg, Germany

Abstract

The one hundred, 12 m long XFEL 1.3 GHz cryomodules are assembled at CEA Saclay (F) and have therefore to be transported, fully assembled, to the installation site in DESY Hamburg (D). Various studies and tests have been performed to assess and minimize the risk of damages during transport; a new transport frame and a specialised company are being used for the series transport. This paper resumes the studies performed, describes the final configuration adopted for the series transport and the results obtained for the first XFEL modules.

INTRODUCTION

XFEL TRANSPORT SYSTEM

The cryomodule is supported with a metallic frame consisting of two cages, one fixed to the truck and the other damped with helical coils in a compression-roll configuration connected to the cryomodule.

The supporting system includes two end-caps to lock the helium gas return pipe at the end position and to avoid transversal movement of the supporting posts.

The module is equipped with vacuum gauges to monitor the beam vacuum and 2 synchronised accelerometers to record the acceleration experienced by the module and evaluate the frame damping factor (one sensor on the fixed frame and one on the damped one).

Transportation

Fermilab

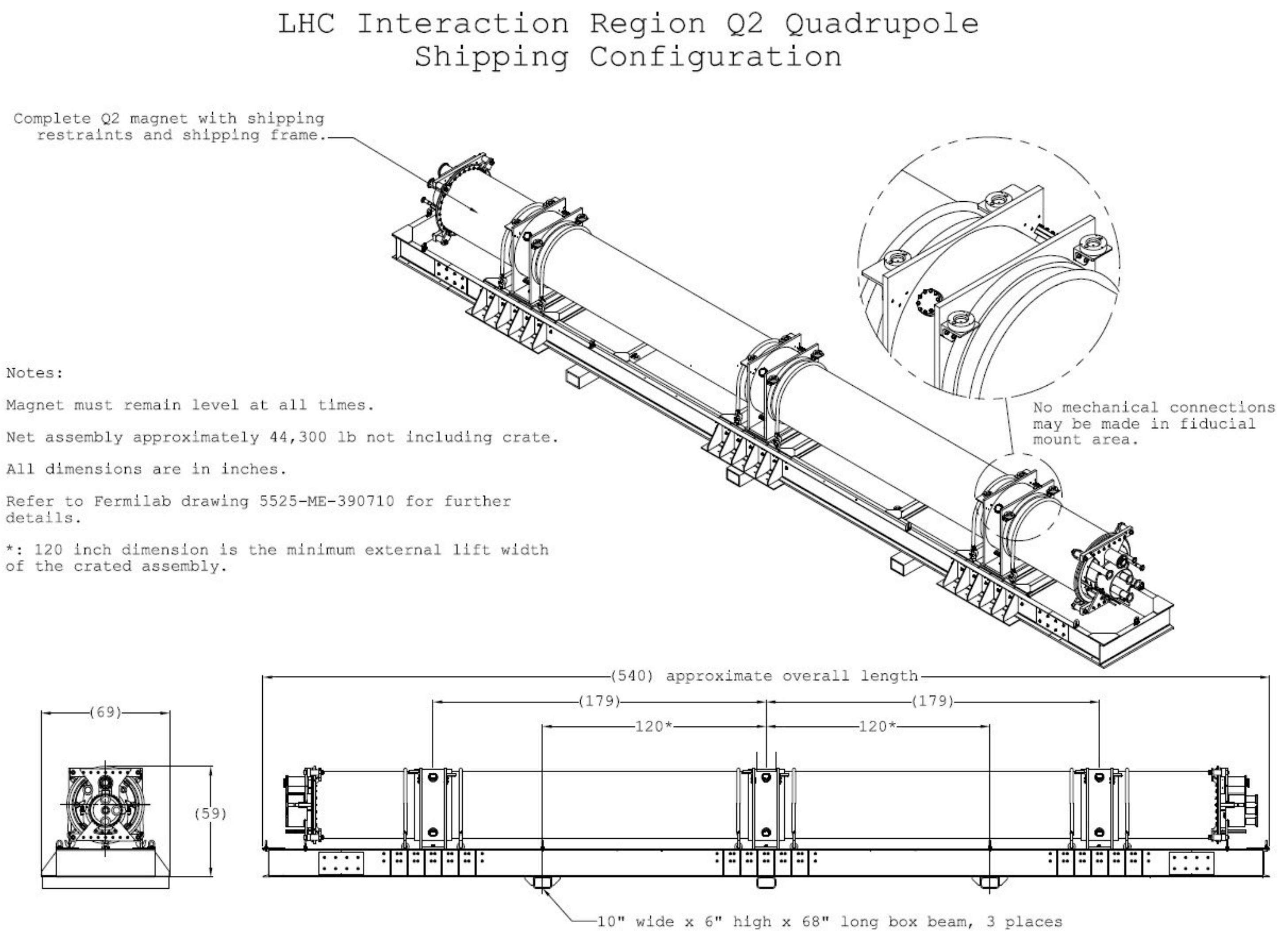
Fermi National Accelerator Laboratory
Technical Division
Engineering and Fabrication Department
P.O. Box 500
Batavia, IL 60510

LHC Interaction Region Quadrupole Crating and Shipping Specification

Fermilab Specification: 5520-ES-390718

Rev	Date	Description	Originated by	Approved by
None	December 13, 2003	Draft issue	T. Page	Thomas Nicol
A	February 3, 2004	General revision	T. Page	Thomas Nicol
B	July 29, 2005	General revision	T. Page	Thomas Nicol

Transportation

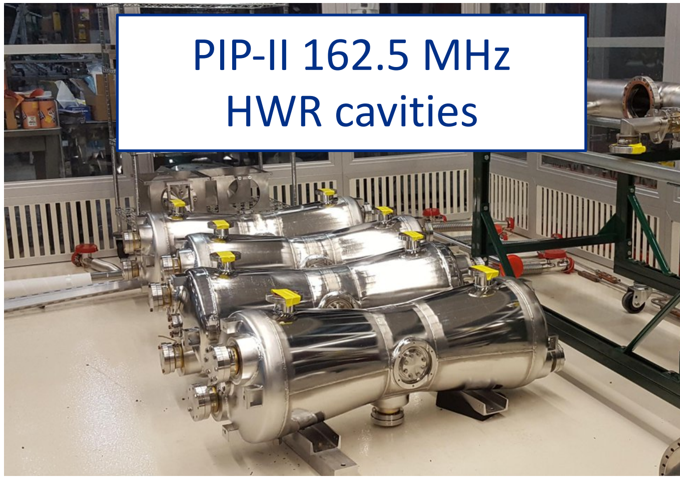


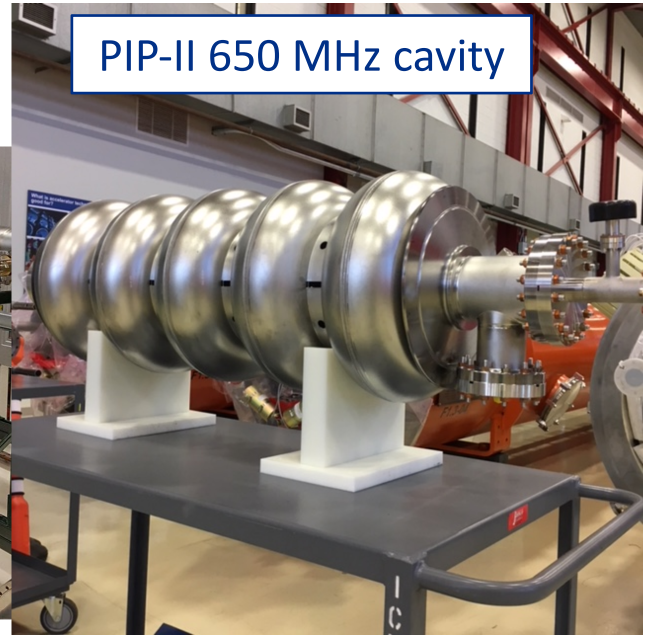
Transportation

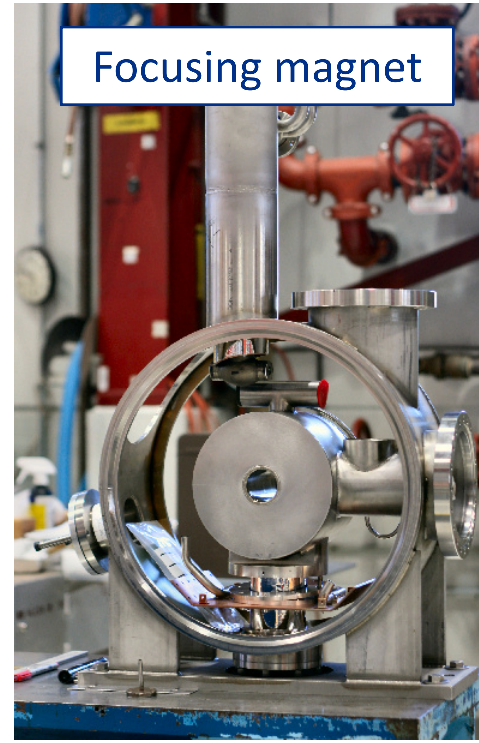
Transportation

Transportation

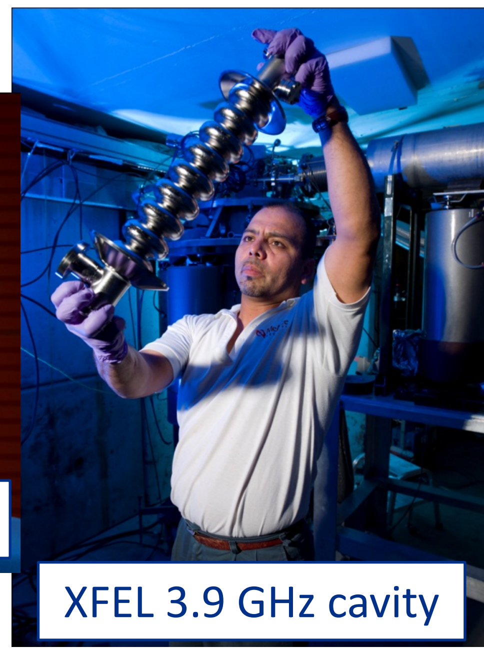
SRF Devices


PIP-II 162.5 MHz HWR cavities


PIP-II 650 MHz cavity


Focusing magnet


PIP-II 325 MHz spoke cavity


XFEL 3.9 GHz cavity


ILC 1.3 GHz cavity

Summary

Superconducting RF projects are in varying stages of design, manufacture, installation, and testing in laboratories around the world. In spite of their differences all share many common features. They remain challenging due to cleanliness requirements, high RF power, the need to reduce thermal losses, multi-pacting, mode extraction, tuning, alignment, and above all, cost. But, for now at least, they seem to be the dominant direction being taken in accelerator research, taking full advantage of the corporative spirit of an international community of scientists and engineers.

Thanks very much…

Fermilab