Helium Cryostats
for Superconducting Devices

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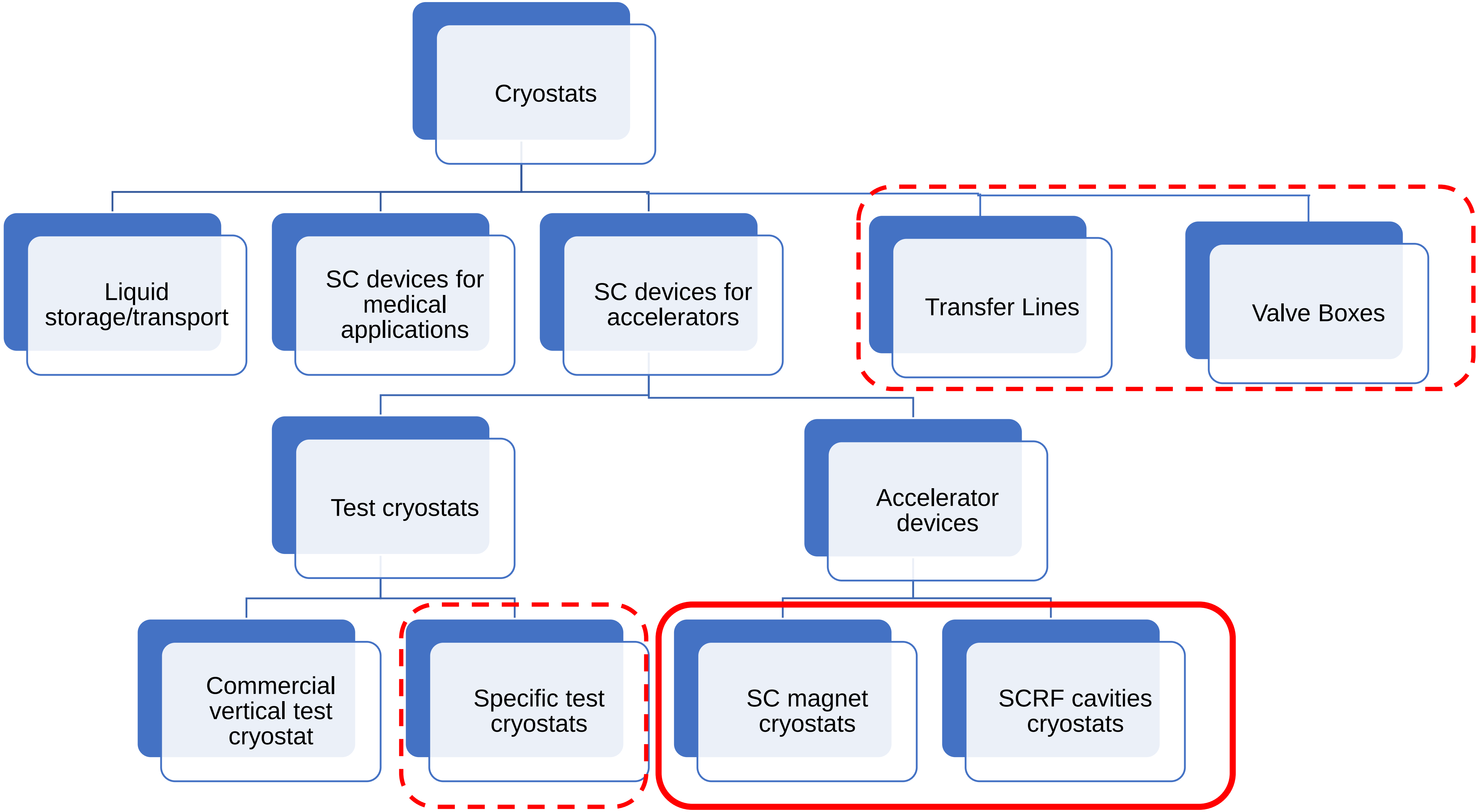
CERN – SY/RF Group

Technical Training: Cryostat Engineering for helium superconducting devices
CERN, 7-9 November 2022

Cryostats by their application



Cryostats

Liquid storage/transport

SC devices for medical applications

SC devices for accelerators

Transfer Lines

Valve Boxes

Test cryostats

Accelerator devices

Commercial vertical test cryostat

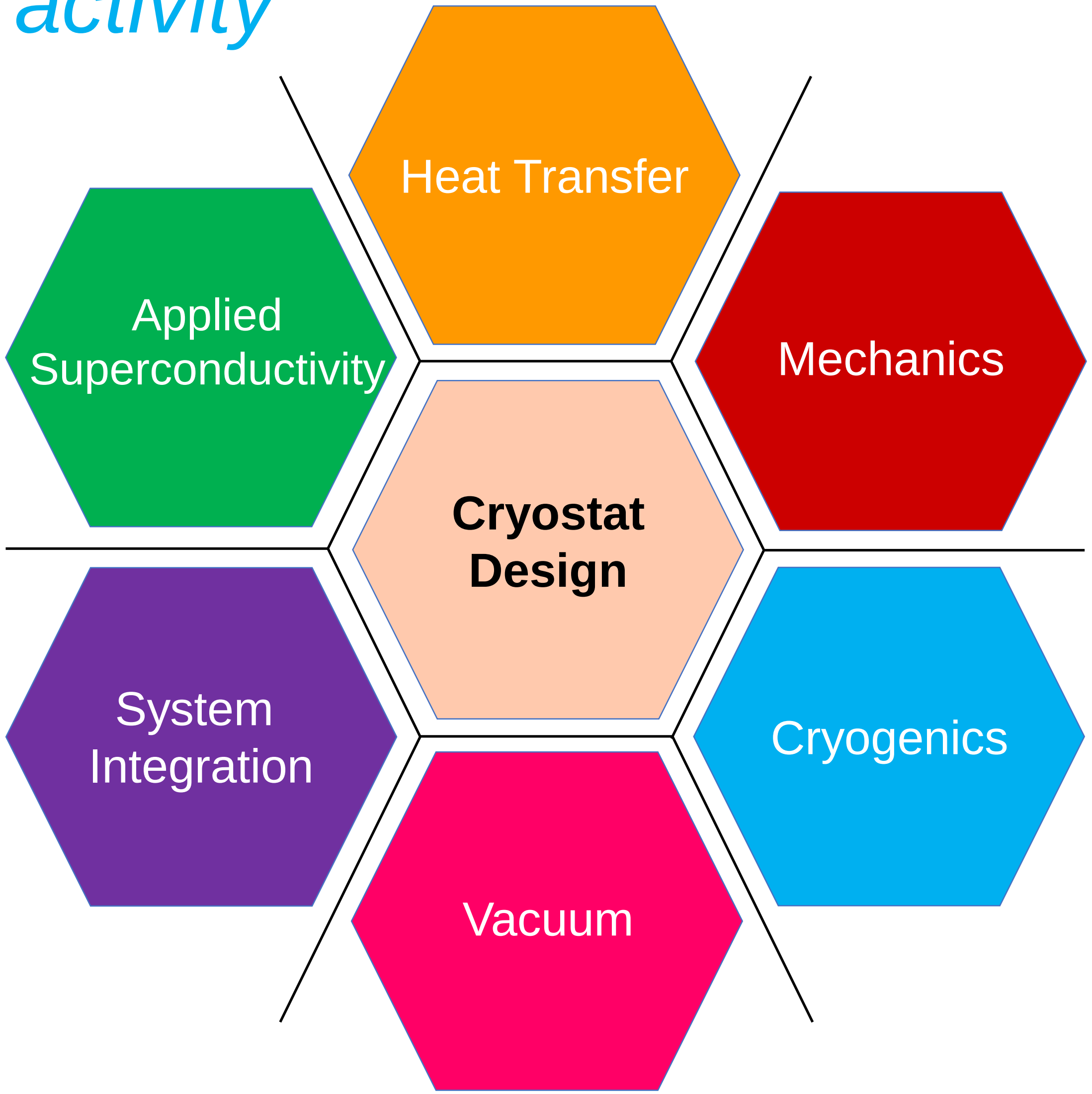
Specific test cryostats

SC magnet cryostats

SCRF cavities cryostats

Cryostat Design for SC devices for accelerators:

A multidisciplinary activity



Heat Transfer

Applied Superconductivity

Mechanics

Cryostat Design

System Integration

Cryogenics

Vacuum

Content

- Helium cryostats for SC devices, functions and requirements
- Examples of cryostats

1 h

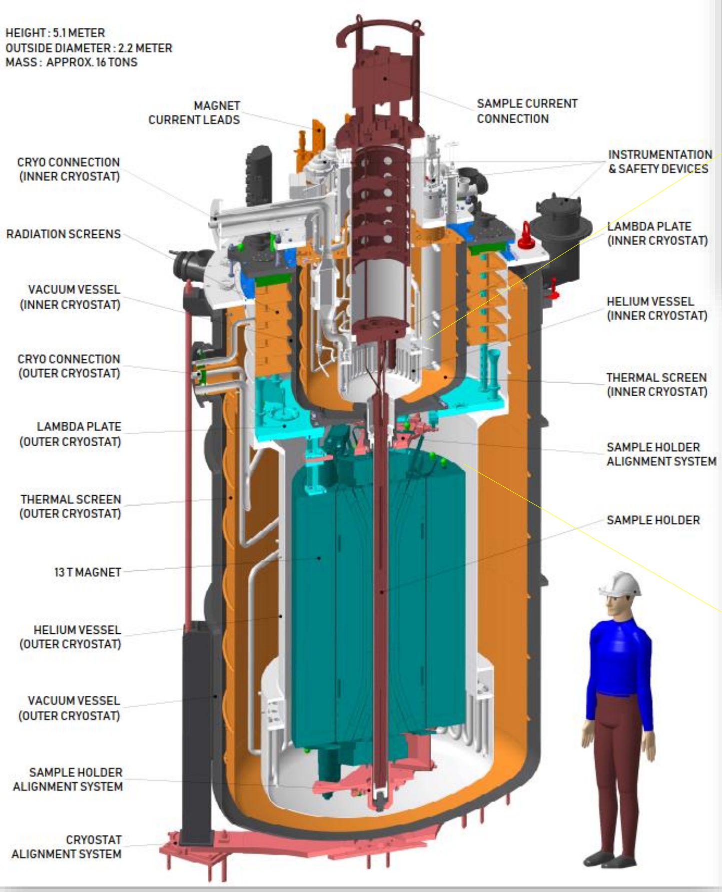
- Mechanical design and construction of cryostats:
  - Materials for cryostats and their properties
  - Pressure/vacuum vessels, codes, and norms
  - Supporting systems

1 h

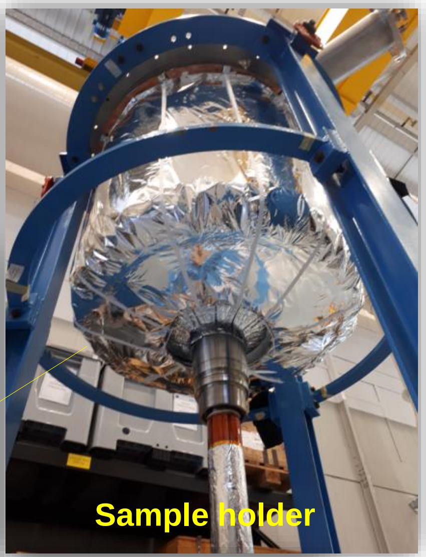
- Heat transfer mechanisms at cryogenic temperatures:
  - Thermal radiation and thermal design solutions (thermal shielding, MLI)
  - Thermal conduction and thermal design solutions (feedthroughs, heat intercepts)
- Notions of cryogenic safety
- Calculation tool: *Cryostat Toolbox v.1.1*

1 h

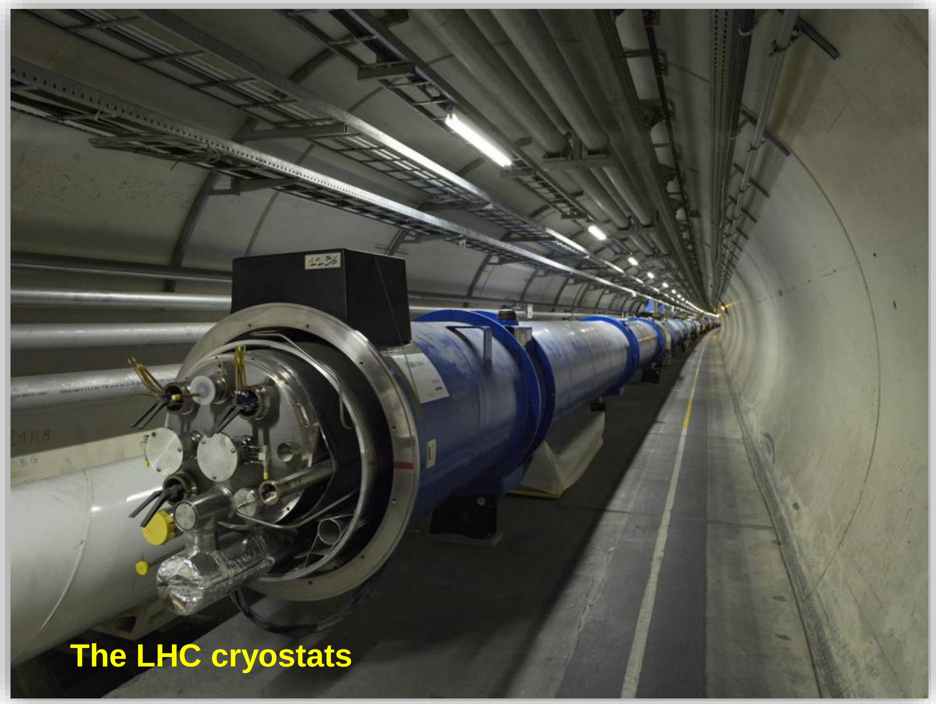
A few examples at CERN

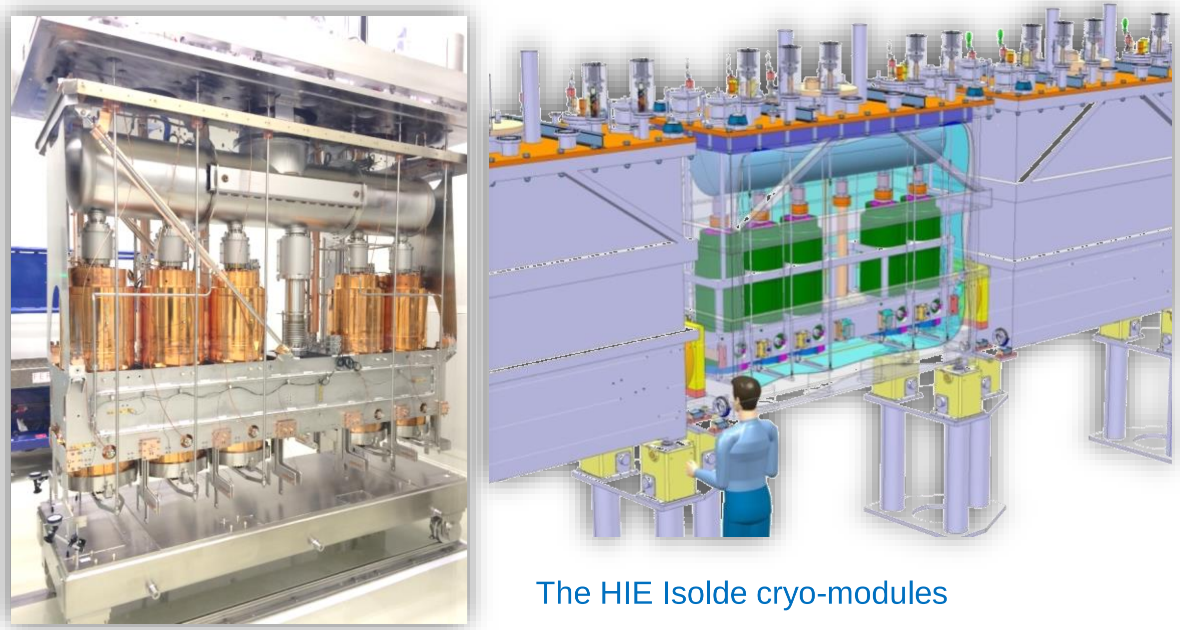


Fresca 2: test station for new SC cables

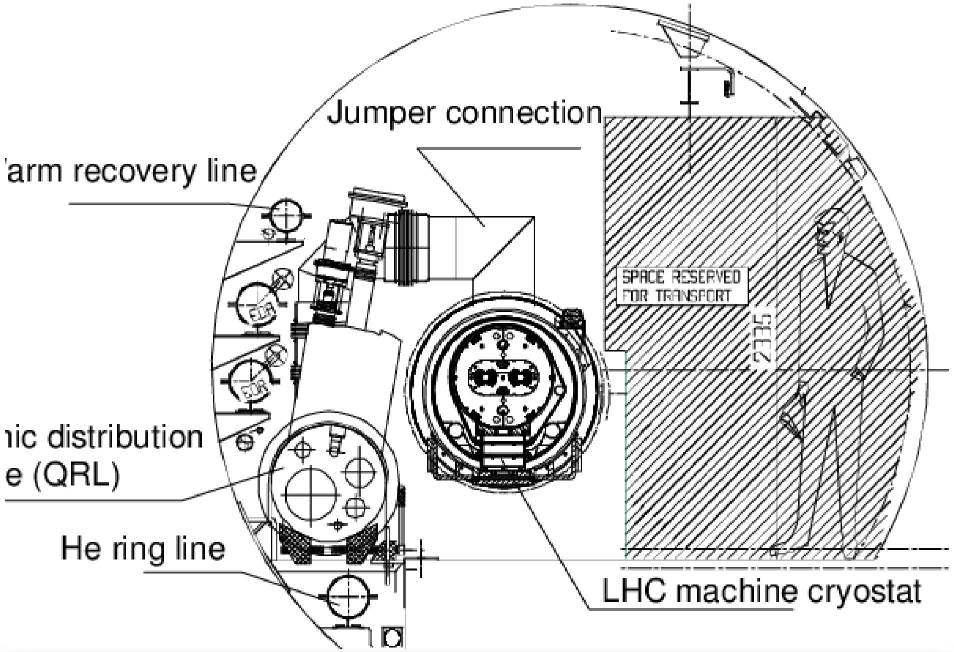

Sample holder

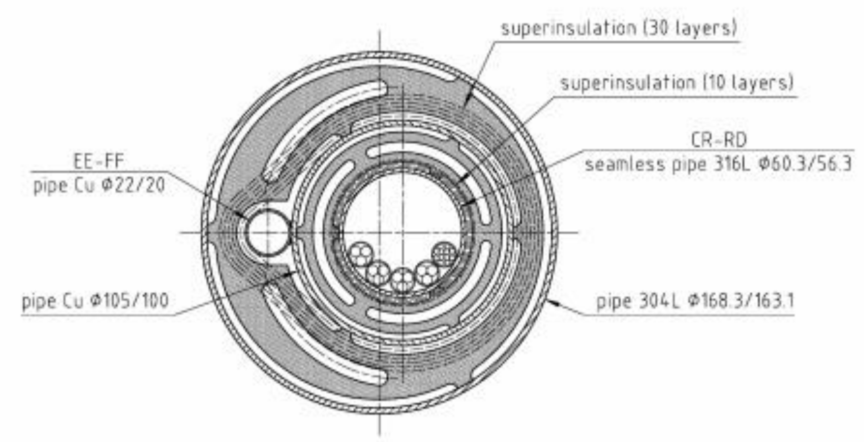

HFM 13 T dipole


The LHC cryostats


The HIE Isolde cryo-modules

A few examples at CERN transfer lines, valve boxes





LHC rigid transfer line for SC cables

HL LHC flexible line for SC cables

Functions of a SC device cryostat

Main function: house a SC device to enable it’s operation.

Two technical requirements:

1. Mechanical housing of the device:
   - Supporting, accurate positioning and alignment of SC devices in accelerators

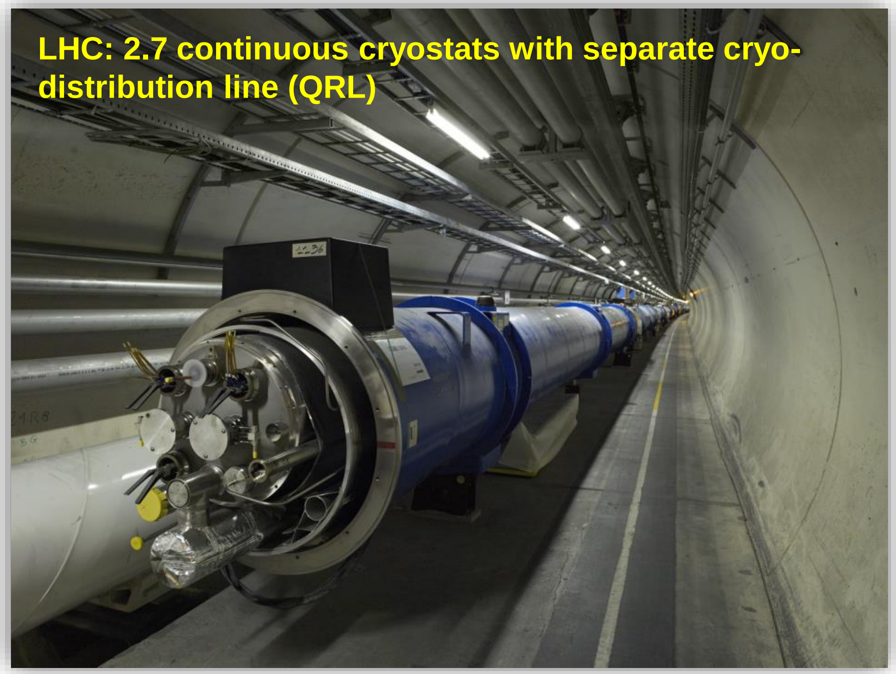
2. Thermal efficiency:
   - Cooling at cryogenic T (steady state, CD, WU)
   - Low T preservation → optimal thermal insulation

Often conflicting → calls for trade off design solutions

Many other complementary functions and requirements…:

- Cryogenics operation and control → specific equipment (piping, ph.separators, valves, instrumentation etc.)
- SC device powering: → magnet current leads, cavity RF power couplers/HOMs, etc.
- Integration of instrumentation (beam, vacuum, cryo, control/diagnostics, etc.) → feed-throughs
- magnetic shielding
- Maintainability (accessibility ports)
- Handling and transport features
- …

Accelerator architecture and cryostat layouts

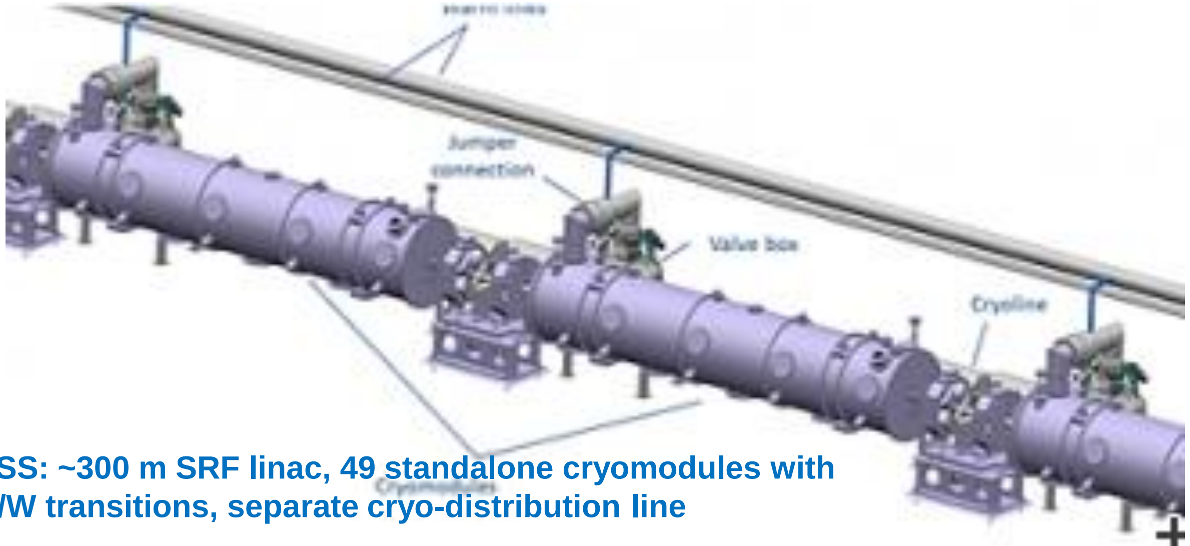


LHC: 2.7 continuous cryostats with separate cryo-distribution line (QRL)

Some key aspects:

- Continuity of SC magnets electrical circuits
- Thermal efficiency of continuous cryostats with integrated cryo-distribution
- C/W transitions: costs and heat loads
- RT equipment needs (e.g. beam instrumentation, beam sect. valves, non-SC magnets, etc.)
- Segmentation for maintainability (e.g. SRF CM can be replaced)
- Staged machine installation (e.g. SRF energy increase)

XFEL main linac: 96 CM, 1.7 km quasi-continuous cryostat with integrated cryo-distribution line.



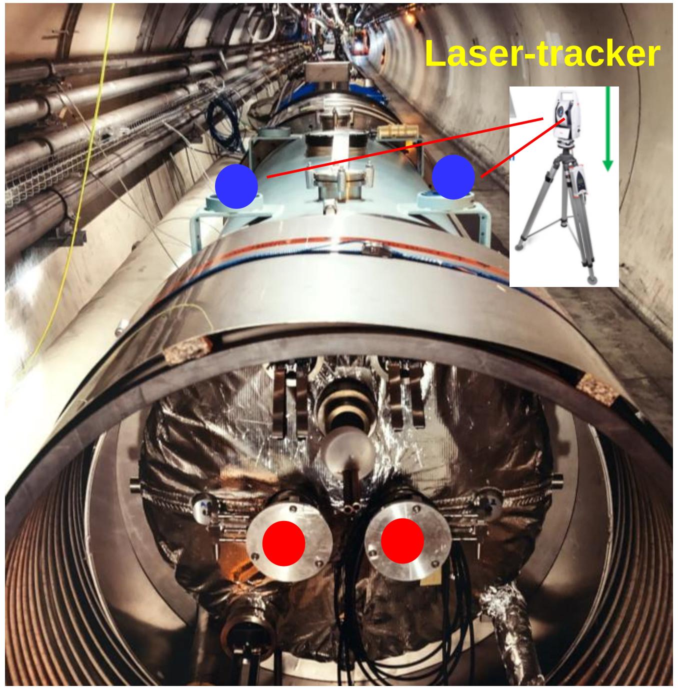
ESS: ~300 m SRF linac, 49 standalone cryomodules with C/W transitions, separate cryo-distribution line

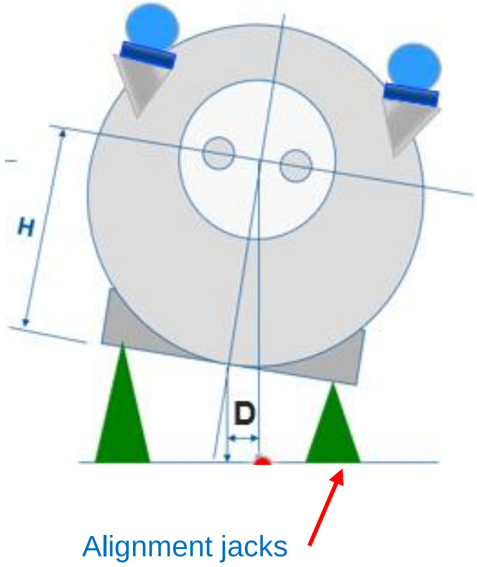
→ No general rule, but “long” machines opt for continuous cryostats to maximize:

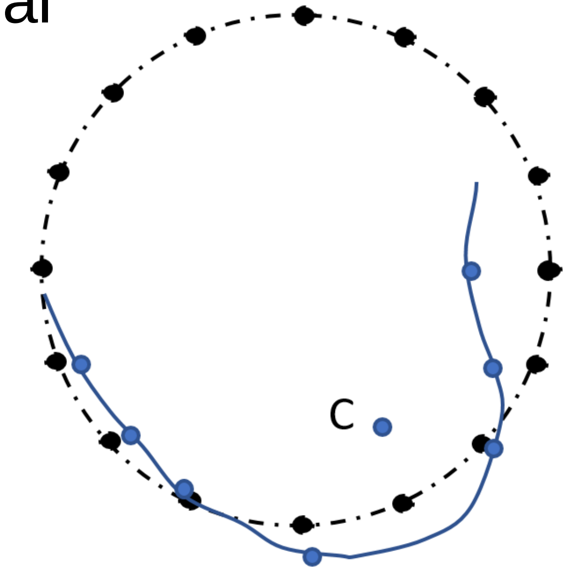
- Dipole magnetic length in circular machines (like LHC)
- Real estate accelerating gradient in linacs (XFEL, ILC)

Housing and alignment requirements in accelerators

- *Accurate* & *reproducible* alignment of the SC device w.r.t. a <u>machine reference network</u>
  - Survey measures fiducials on the cryostat vessel (not the device inside the vessel!)
  - Typically alignment within a few tenths of mm w.r.t. nominal







Aligning elements in a ring

→ Survey assumes that the cryostat and the inner SC device are rigid bodies !

→ Alignment is done by adjusting external jacks

Housing and alignment requirements in accelerators

With no internal measurment of the position of the SC device (costly for large machines)

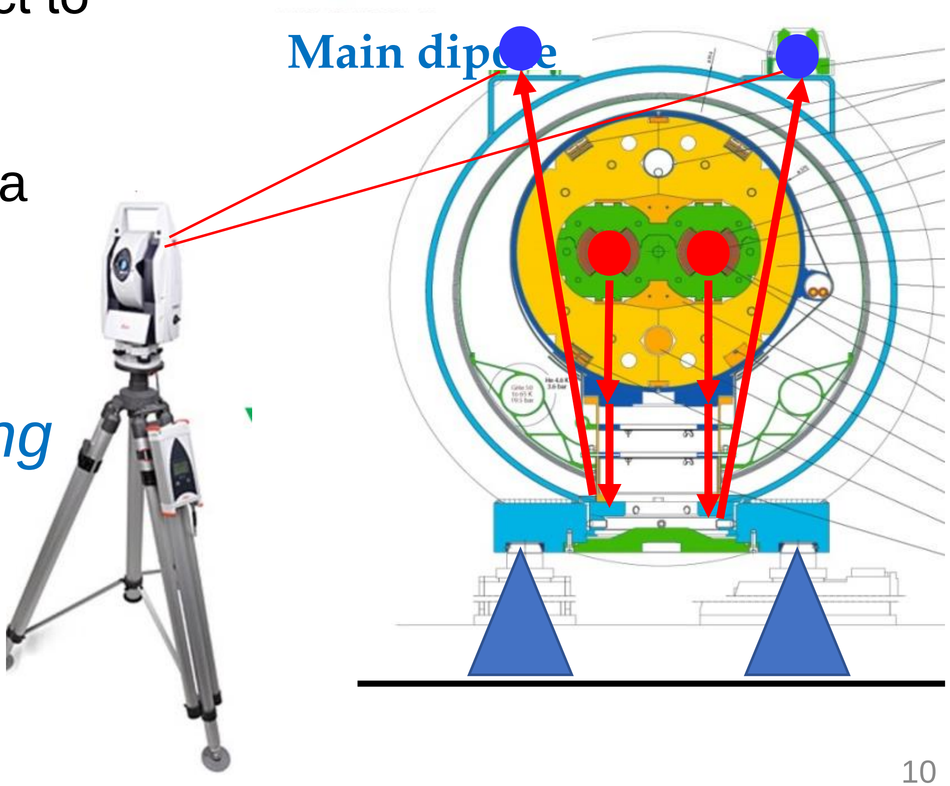
- Cryostats/SC device are not rigid bodies

- SC devices are "weakly" supported inside the cryostat (for thermal efficiency)

➢ Cryostat vessels are (generally) "relatively" rigid, and not subject to "excessive" permanent deformation

➢ SC device supporting system has to be designed to guarantee a known thermo-mechanical behaviour to ensure:

→ *Cryostat design: "Accurate & reproducible positioning of the SC device w.r.t. to cryostat fiducials"*



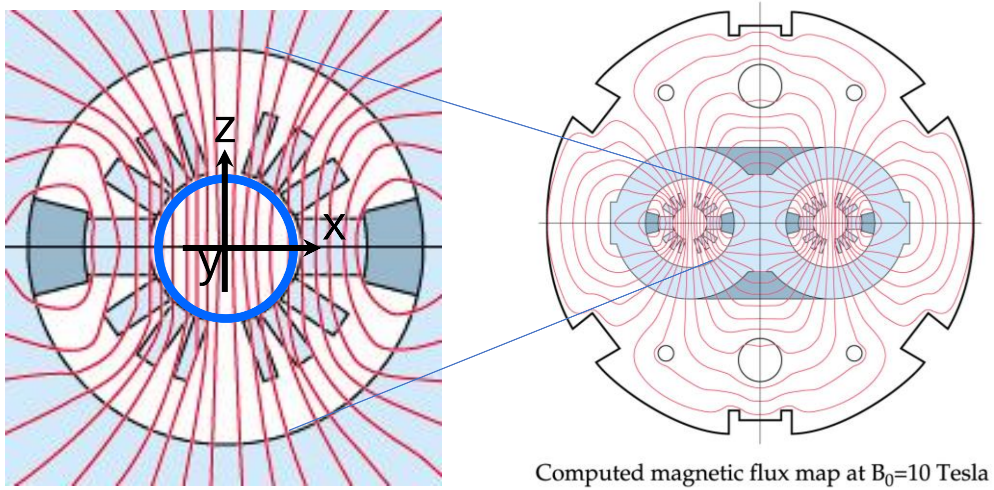
Positioning of SC magnets

✓Position of the beam tube axis

✓Measure magnetic field (main, multipoles) at warm and at cold (cold/warm correlation)

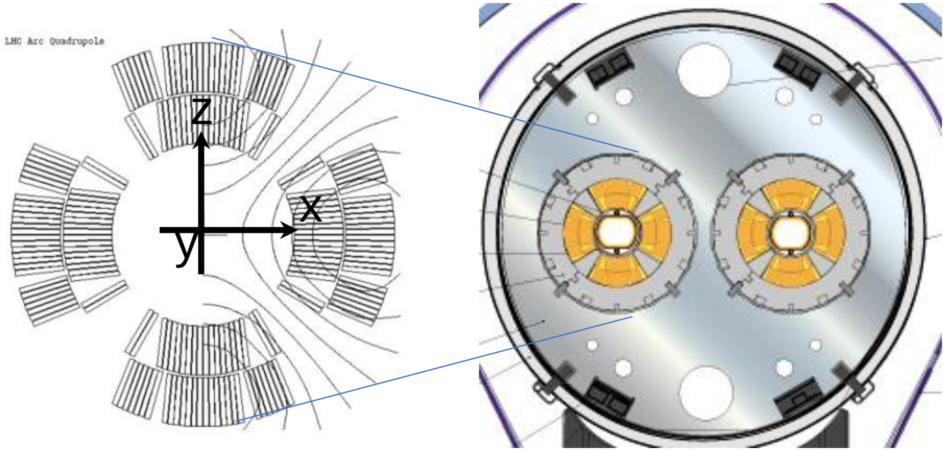
- Dipole magnet positioning accuracy:
  - x-z errors : more tolerant (field has no horizontal axis). (e.g. LHC < 0.48 mm radial (r.m.s.) after 1 year)
  - roll angle (about y) errors: sensitive (gives a kick out of orbit plane) (e.g. LHC < 0.7 mrad (r.m.s.) after 1 year)
- Quadrupole magnet positioning tolerances:
  - x-z errors : sensitive (magnetic axis). (e.g. LHC < 0.37 mm radial (rms) after 1 year)
  - roll angle (about z) errors: more tolerant (e.g. LHC < 1 mrad (rms) after 1 year)

LHC dipole



Computed magnetic flux map at B_0=10 Tesla

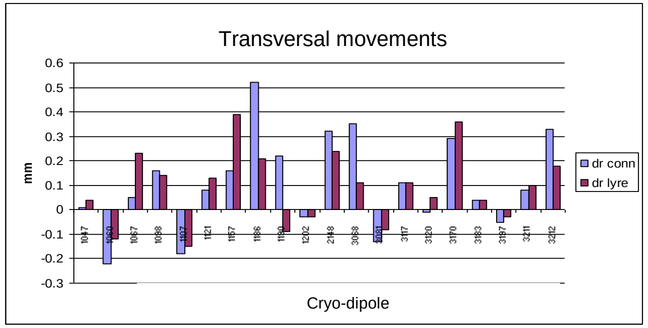
LHC quadrupole



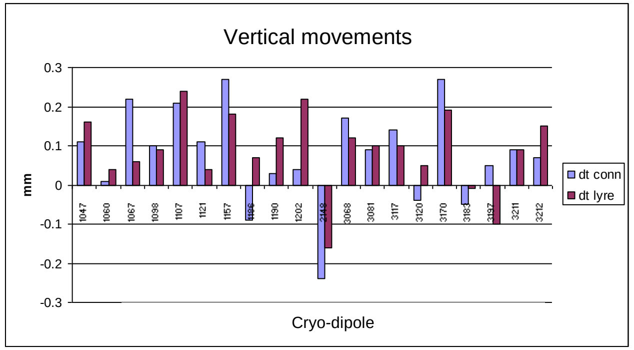
LHC geometrical stability: survey measurements

- Cold mass position stability w.r.t. fiducials measurements on 20 cryo-dipoles

After transport to the tunnel



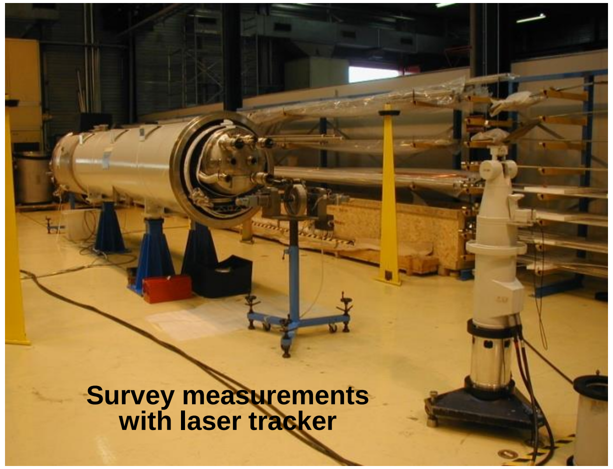
Mean: +0.1mm; r.m.s.: 0.17mm



Mean: +0.08mm; r.m.s.:0.11mm

- Quad CM positional stability and reproducibility at cold

Arc SSS (392 units)	Horizontal		Vertical	
	Mean [mm]	St.Dev. [mm]	Mean [mm]	St.Dev. [mm]
Positional reproducibility after 1 cool-down/warm-up cycle	-0.08	0.42	0.04	0.43
Cool-down movements	-0.17	0.22	-1.3	0.36



Survey measurements with laser tracker

ROCLA vehicle

Tunnel transportation

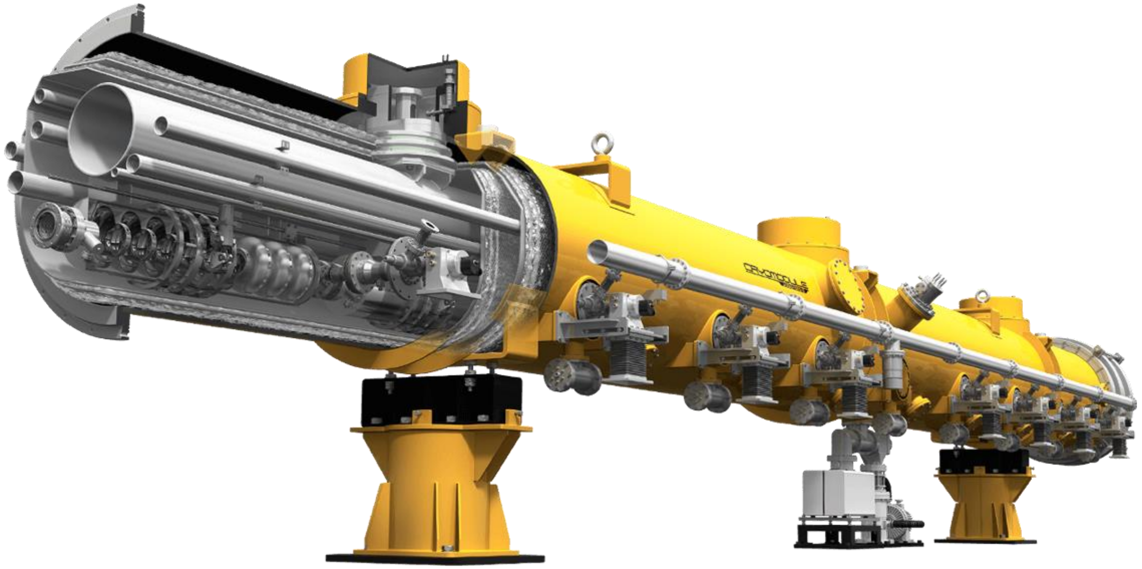
100 m descent to the tunnel

Positioning of SRF cavities

- In general, less stringent positioning tolerances. Also, cavities are smaller and lighter than magnets → less demanding support systems

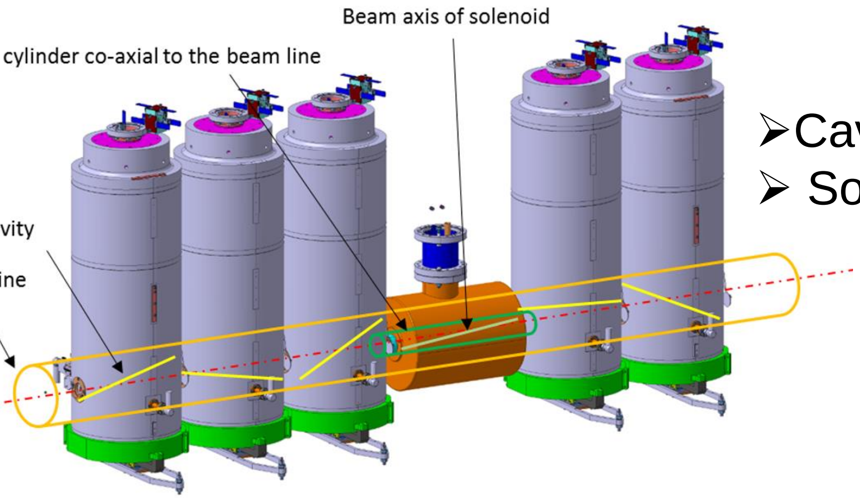
- Main effects of misalignment:
  - ✓ increased beam losses
  - ✓ beam emittance growth

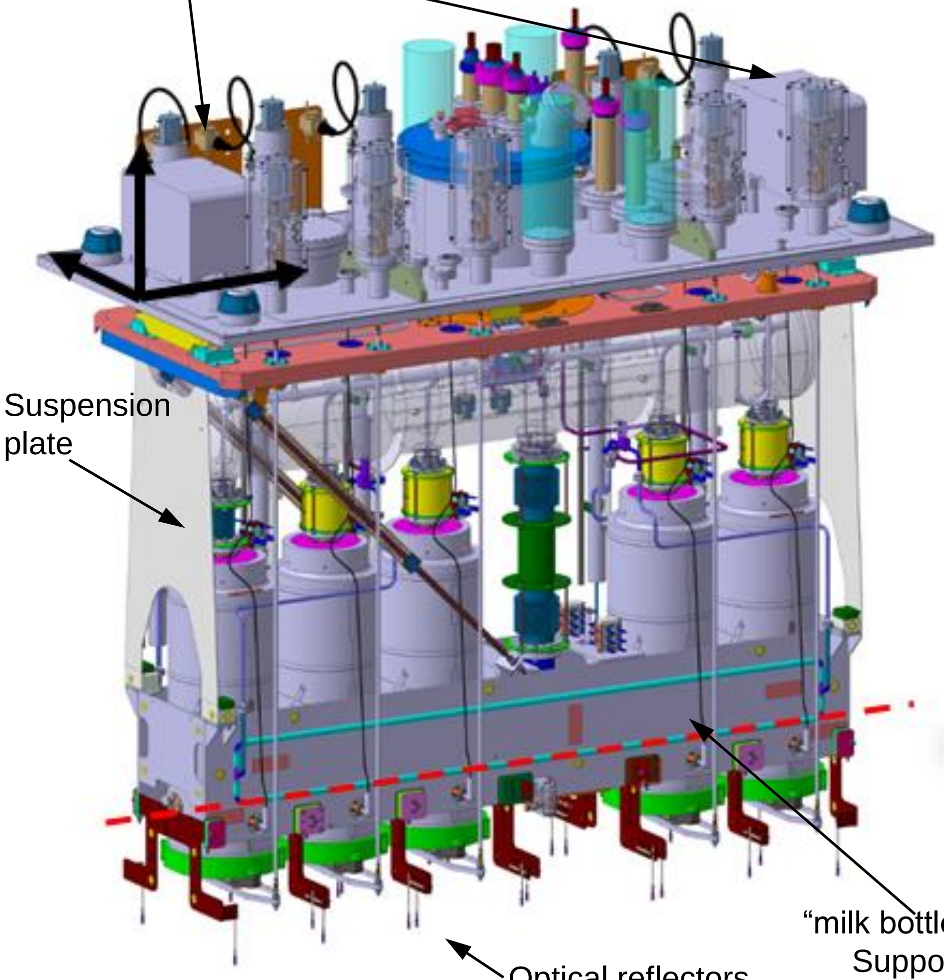
- Typical figures (r.m.s.):
  - ✓ ILC: radial ~0.3 mm, tilt ~0.3 mrad
  - ✓ HIE Isolde CM (next slide):
    - ➢ Cavities: transverse < ±0.45 mm
    - ➢ Solenoid: transverse < ±0.23 mm

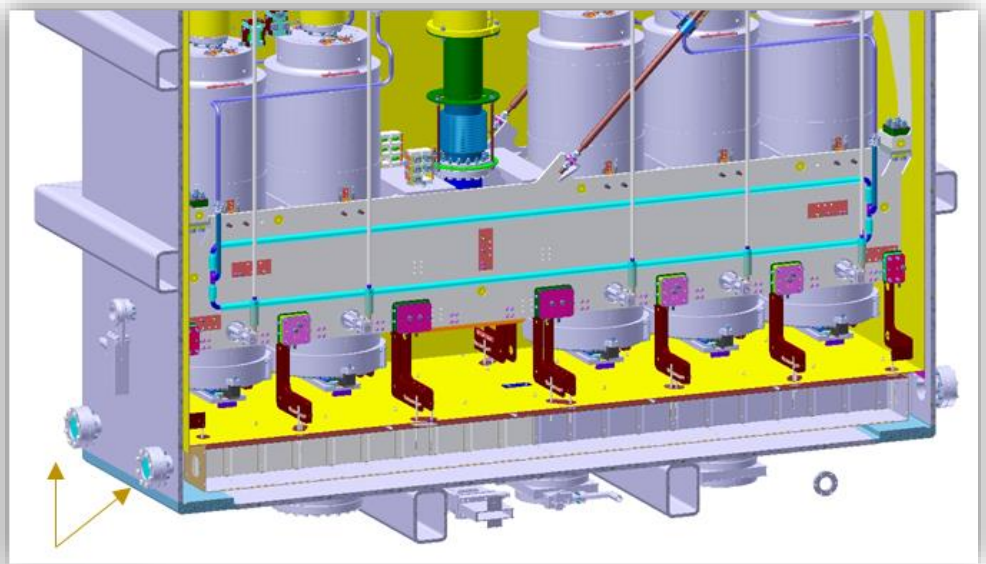


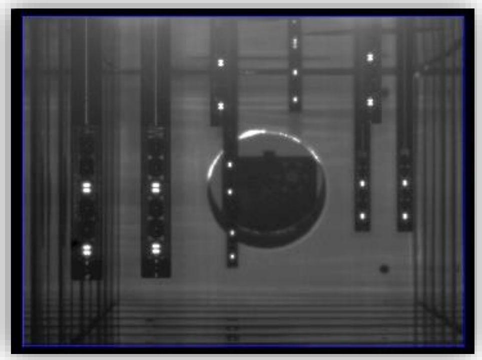
HIE Isolde CM

- Cavities: transverse < ±0.45 mm
- Solenoid: transverse < ±0.23 mm

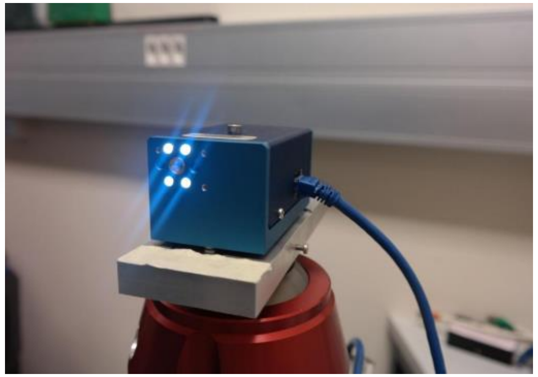








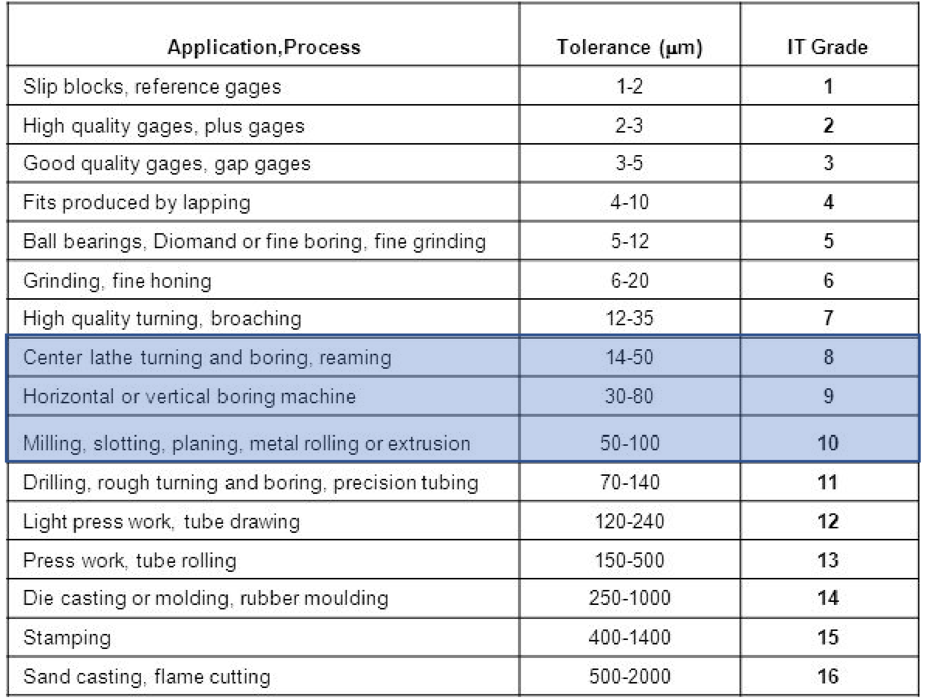
Targets viewed from viewports



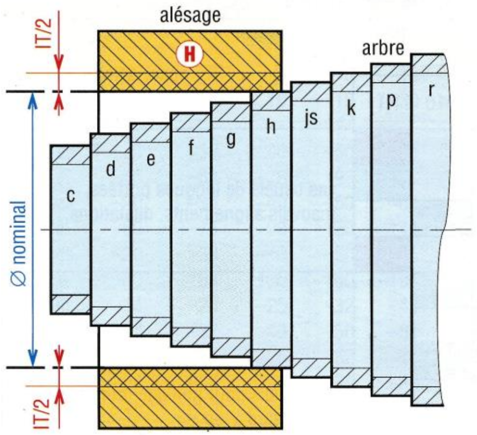
HBCM optical CCD cameras

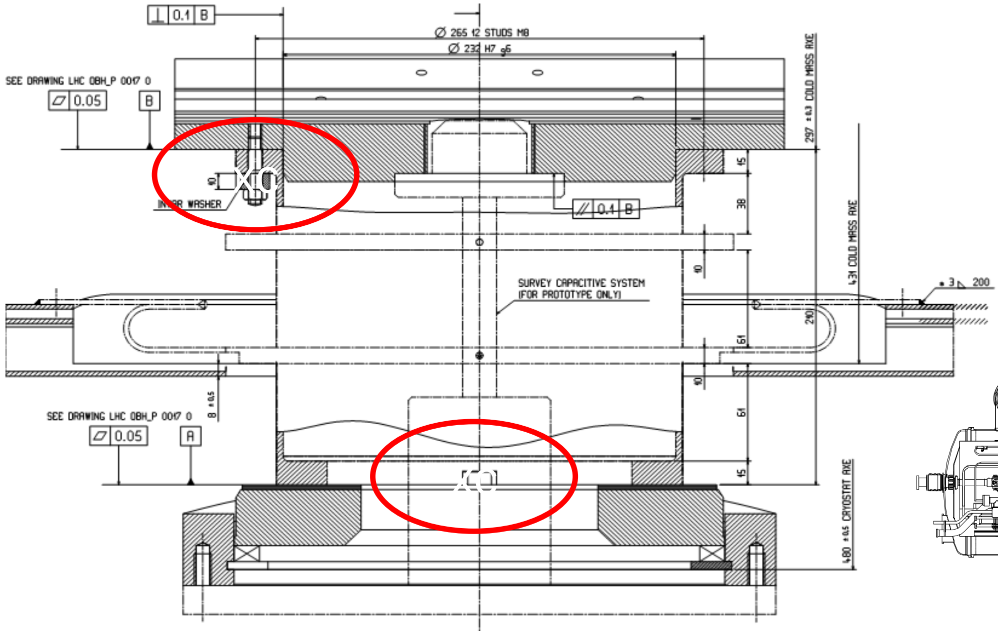
Mechanical accuracy in cryostats assembly

- Positioning accuracy is ensured by precision fitting at assembly
- Machining IT Grade range: 8-10
- Typical close fits: H7/g6



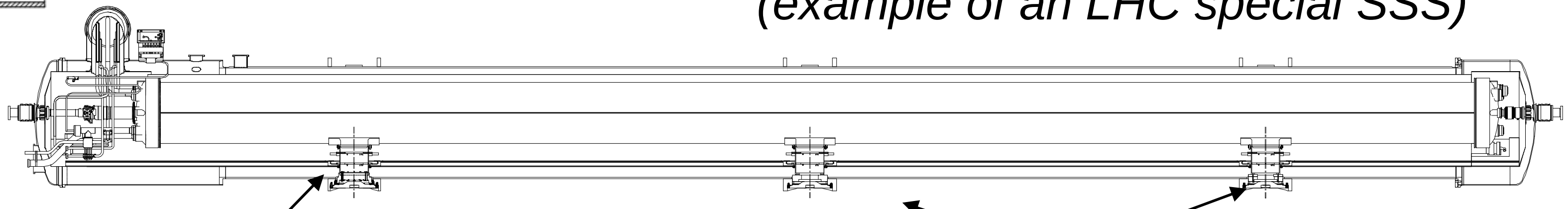
Application,Process	Tolerance (µm)	IT Grade
Slip blocks, reference gages	1-2	1
High quality gages, plus gages	2-3	2
Good quality gages, gap gages	3-5	3
Fits produced by lapping	4-10	4
Ball bearings, Diomand or fine boring, fine grinding	5-12	5
Grinding, fine honing	6-20	6
High quality turning, broaching	12-35	7
Center lathe turning and boring, reaming	14-50	8
Horizontal or vertical boring machine	30-80	9
Milling, slotting, planing, metal rolling or extrusion	50-100	10
Drilling, rough turning and boring, precision tubing	70-140	11
Light press work, tube drawing	120-240	12
Press work, tube rolling	150-500	13
Die casting or molding, rubber moulding	250-1000	14
Stamping	400-1400	15
Sand casting, flame cutting	500-2000	16





Central support post interfaced to vessel/coldmass
(232 H7/g6 → play: 15-90 microns)

(example of an LHC special SSS)



Fixed post

Sliding posts

Positioning *reproducibility* in cryostats assembly

Positioning reproducibility on:

1. Every cryo-assembly throughout lifetime (transport, thermal-cycles, etc.) → design concepts
2. Across total population of cryo-assemblies → quality & cost

Design concepts:

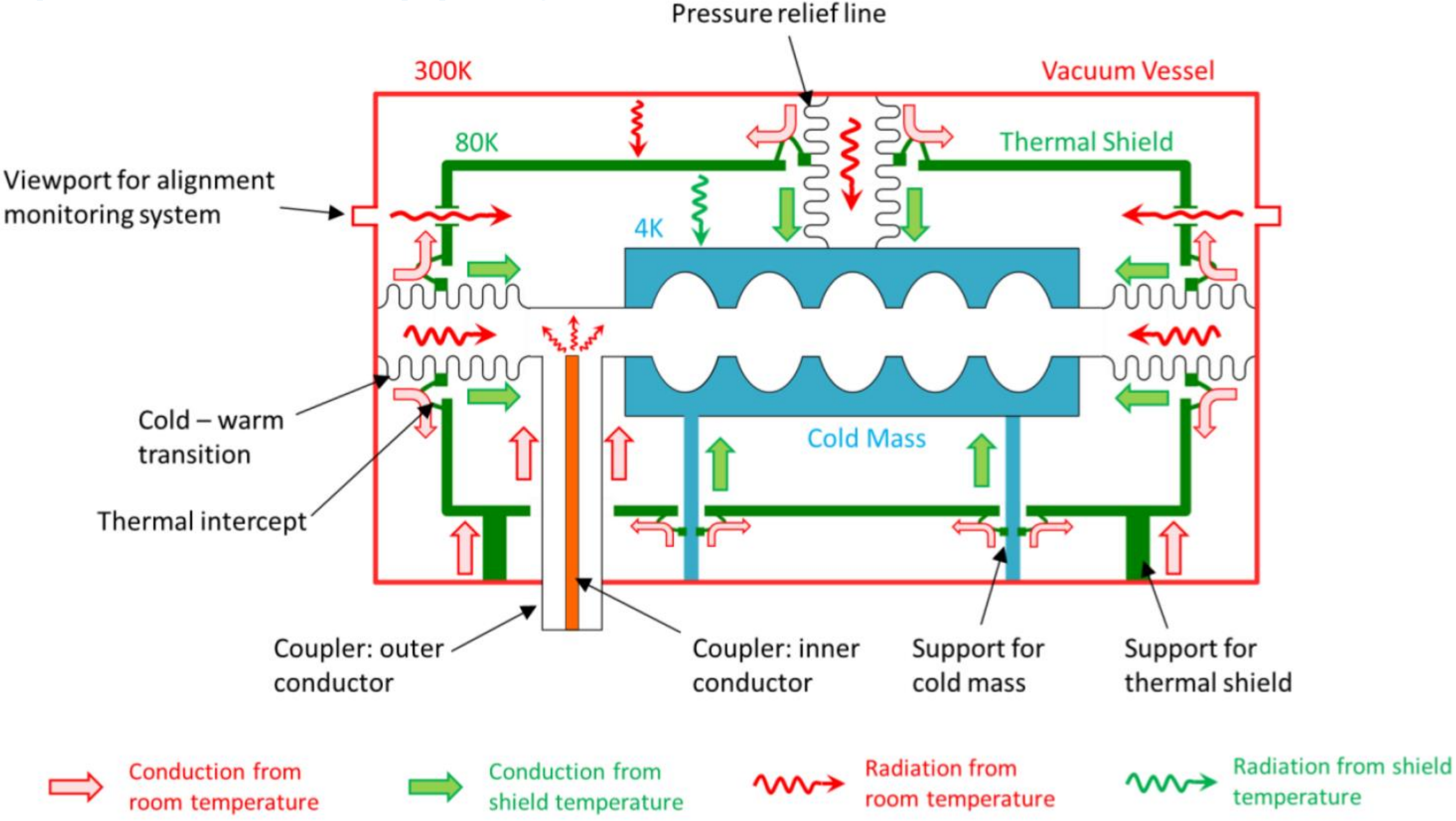
- Cryostat components in elastic domain (limited local plasticity)
- Stress relieving for dimensional stability (vacuum vessels after welding)
- Reproducibility to thermal cycles (limited plays & stick-slips, no micro-cracking etc.)
- No creep
- …

→ Prototyping and testing are mandatory !

Heat Loads and thermal design

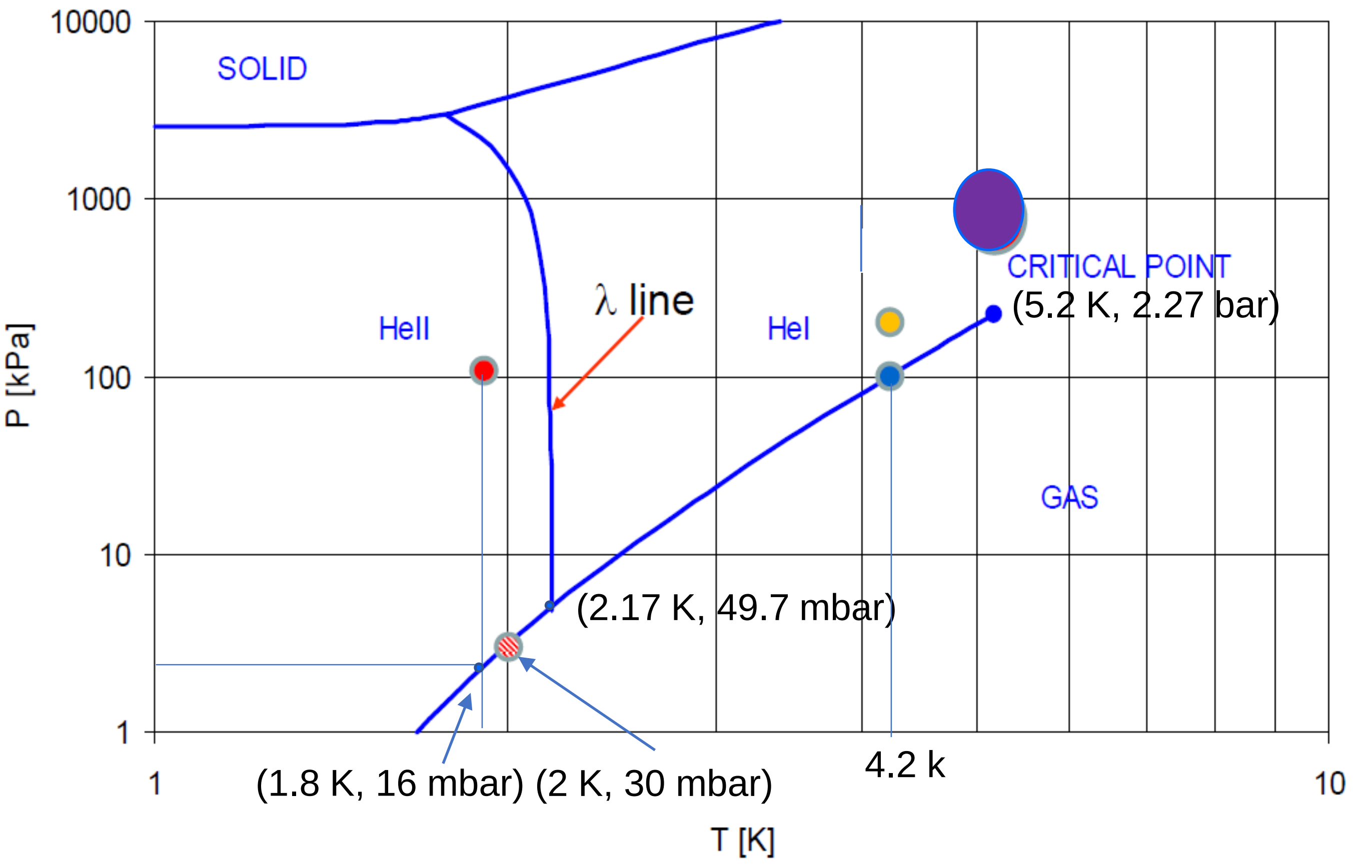
- Static Heat Loads
  - ➢ Very much cryostat related (supports, shielding, feedthroughs, etc.)
  - → always present when machine is cold
- Dynamic Heat Loads
  - ➢ inherent to SC device operation (e.g. resistive heating)
  - ➢ and beam interaction (e.g. synchrotron radiation, HOM)
  - → Dominant but only present during machine operation (duty cycles)
- Ensure operation T of the SC device (T_{op})
  - ➢ T_{op} depends on SC needs (normally below 25 K) → helium
  - ➢ helium phase diagram → choice of useful working points (p. T)
- Thermal design for thermodynamically efficient operation (i.e. minimal W_{el} of cryoplant):
  - ➢ Steady state helium heat transfer from the source (SC device, thermal shields, etc.) and transport to the cryoplant → ΔT budgets, heat and helium mass flows, pressures
  - ➢ CD/WU phases → thermo-mechanical transients of SC device, cryogenic cooling power → ΔT budgets, mass flows, pressures

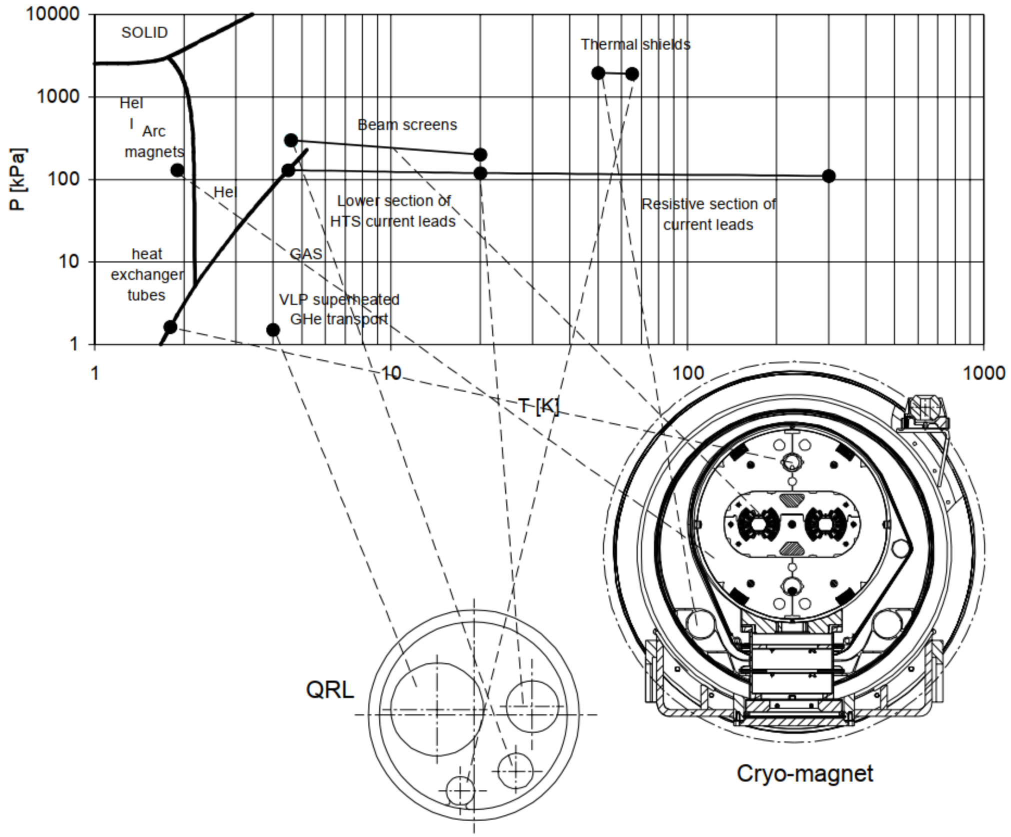
Temperature mapping and Heat Loads



Inspired by P. Duschene and JP. Thermeau

What temperature and pressure ?





🔴 Pressurized He II, Magnets (LHC, Tore Supra)
🟡 Pressurized He I, Magnets (HERA, Tevatron)

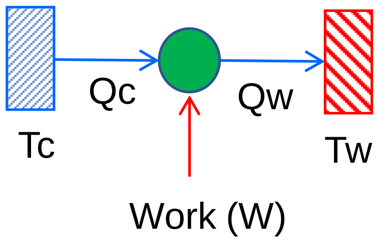
Higher press. to limit voltage breakdown (Paschen curve in He)

▨ Saturated He II, SRF (CEBAF, TTF, SNS, EXFEL, ESS, ILC)
🔵 Pool boiling, He I, SRF (HERA, LEP, LHC, KEKB)

🟣 Supercritical helium: cooling of thermal shielding

Refrigeration efficiency (Carnot principle)

- Extracts a heat load at Tc < RT and rejects it at Tw (normally RT)
- Carnot cycle: minimum mechanical work (i.e. Maximum Coefficient of Performance, COP_{max}), depends solely on Tw and Tc
- All real machines have a lower efficiency (non-reversible transformations), expressed in fraction of COP_{max}

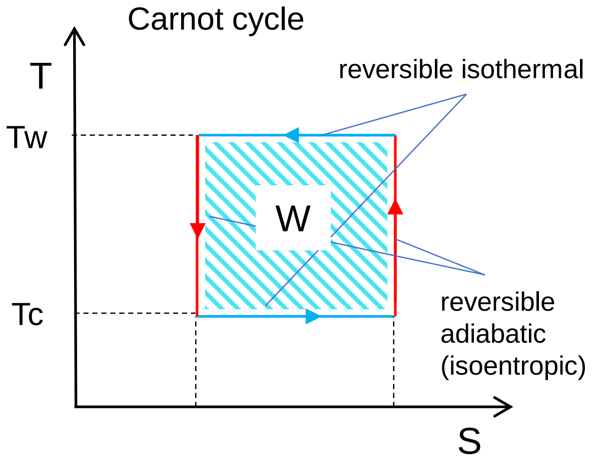


1st and 2nd laws of thermodynamics

$$\left[\begin{array}{l} Qc + W = Qw \\ \dfrac{Qw}{Tw} \geq \dfrac{Qc}{Tc} \end{array}\right.$$

$$\boxed{\rightarrow W \geq Qc \frac{Tw-Tc}{Tc} = \frac{Qc}{COP_{max}}}$$

$$\boxed{COP_{max}\,(\text{Carnot}) = \frac{Tc}{Tw-Tc}}$$



Efficiency of a real machine is expressed in *fraction (or %) of Carnot*:

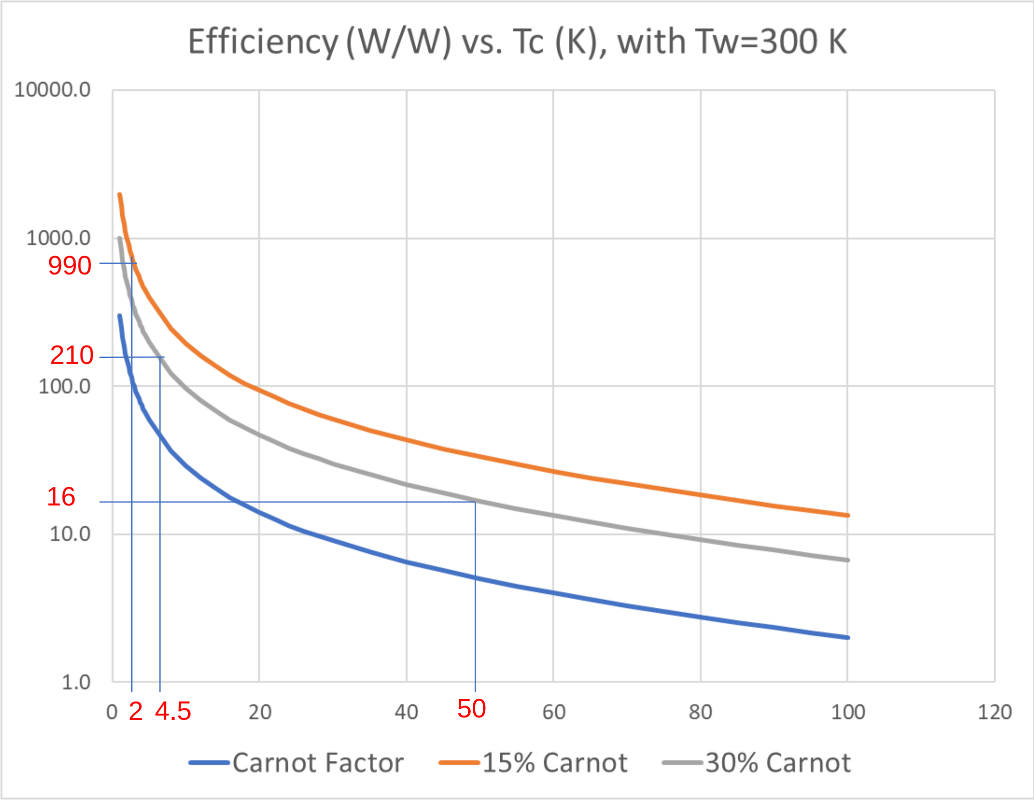
$$\boxed{W = \frac{1}{COP}\,Qc = \frac{1}{x\%\ COP_{max}}\,Qc}$$

Fluid	T [K]	Carnot factor (1/COPmax or W/Qc) [W/W] (considering Tw=293K)
LN2	77	2.8
LH2	20.4	13.4
LHe	4.2	68.4
LHe	1.8	161.8

Efficiency for large cryoplants

State-of-the-art figures for large cryo-plants (LHC-like, ~18 kW @ 4.5K):

- COP @ 2 K → ~ 15% of Carnot (990 W_{el}/W_{th})
- COP @ 4.5 K → ~ 30% of Carnot (210 W_{el}/W_{th})
- COP @ 50 K → ~ 30% of Carnot (16 W_{el}/W_{th})



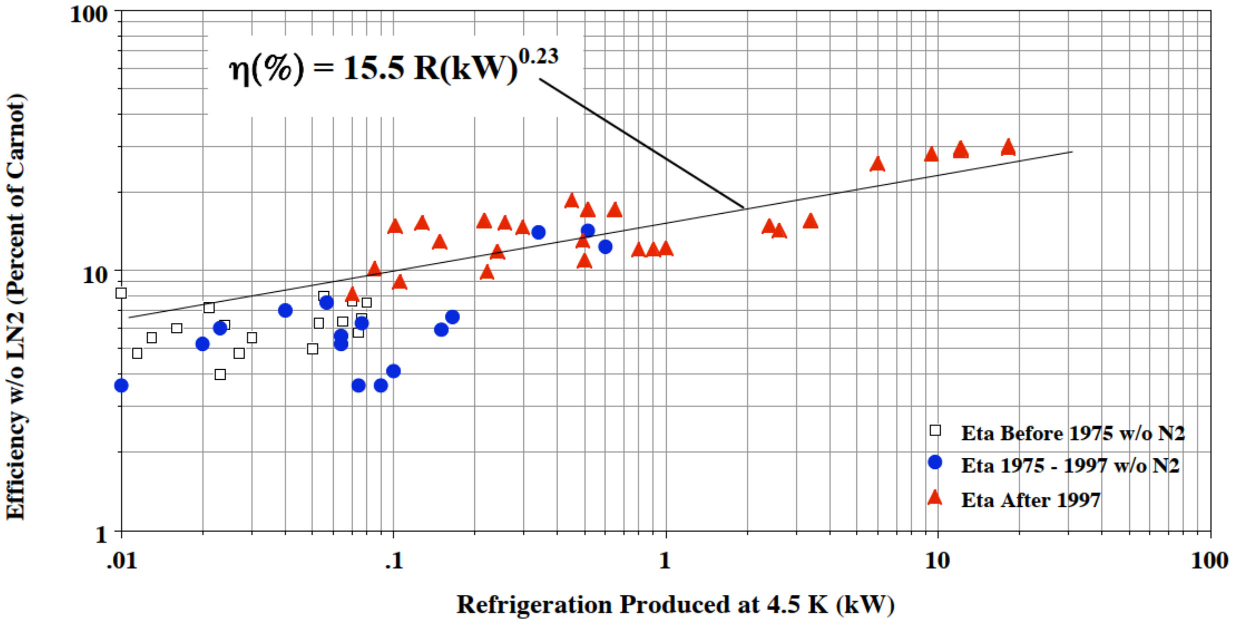


FIGURE 1. Helium Refrigerators Efficiency (percent of Carnot) as a Function of 4.5 K Refrigeration (kW). In all cases, there is no liquid nitrogen pre-cooling in the machines. The open squares are for machines made before 1975; closed circles are machines from 1975 to 1997, and closed triangles are for machines after 1997.

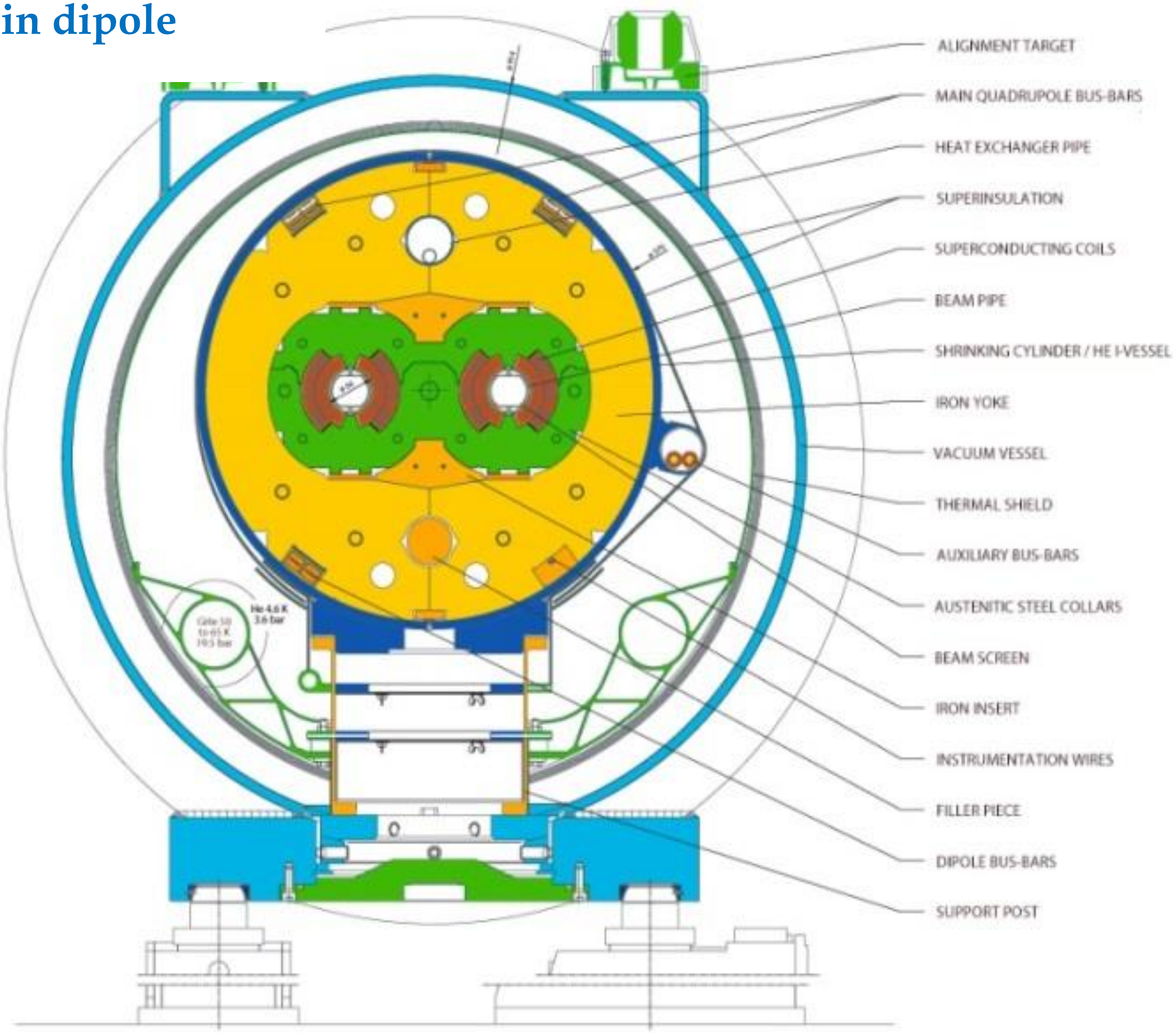
(Green, "The Cost of Helium Refrigerators and Coolers for Superconducting Devices as a Function of Cooling at 4 K", AIP Conference Proceedings 985, 872 (2008))

LHC magnet Cryostats

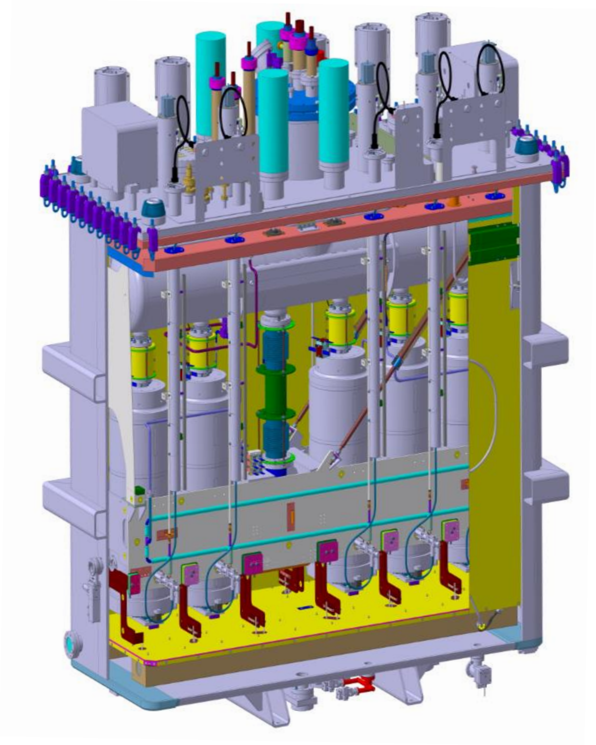
- Static Heat Loads:
  - ✓ 0.25 W/m at 1.9 K
  - ✓ 5 W/m at 50-65 K

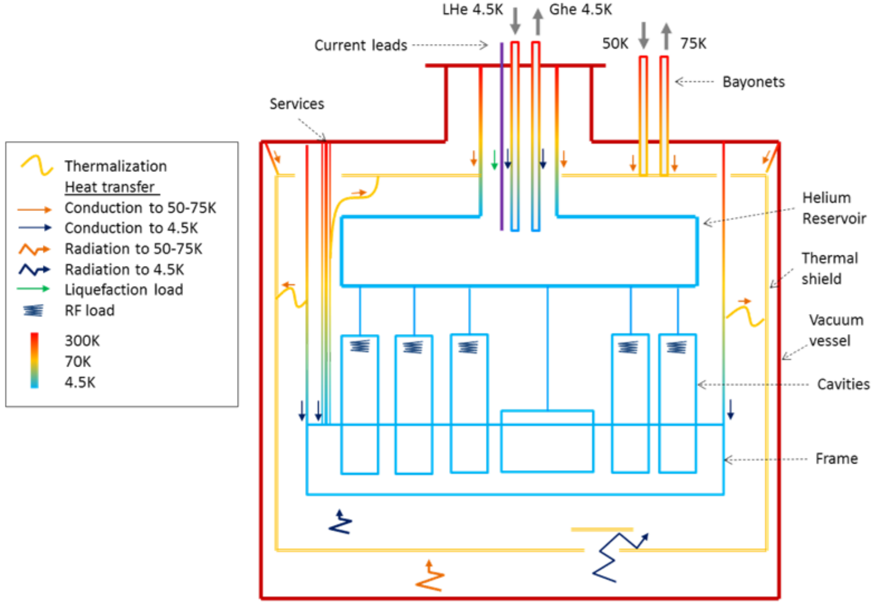
- Dynamic Heat Loads (resistive heating + beam induced effects):
  - ✓ ~ 0.2 W/m at 1.9 K

Main dipole



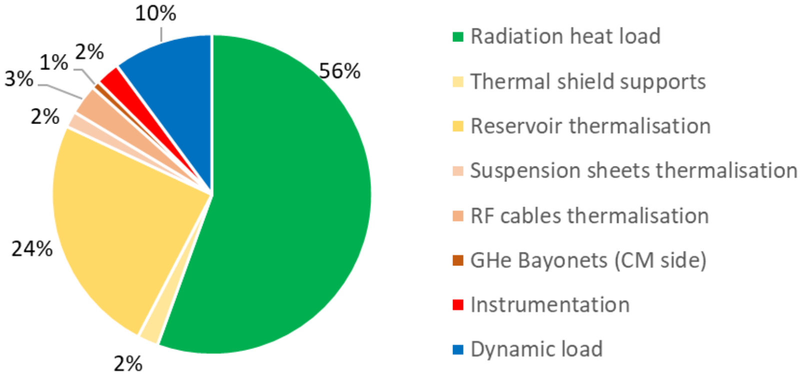
HIE Isolde Cryomodule: No MLI



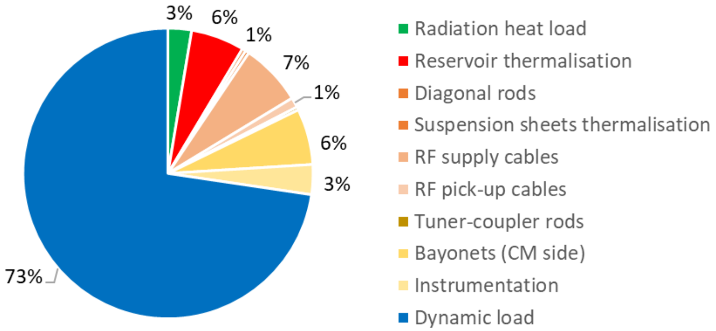


	Nominal [W]
To GHE circuit 50-75K	362
To LHE circuit 4.5K + liquefaction load 0.03 g/s	70

low-ε Ni plated (MLI-free)
Cu thermal shield



Static and dynamic heat load to the GHe circuit.



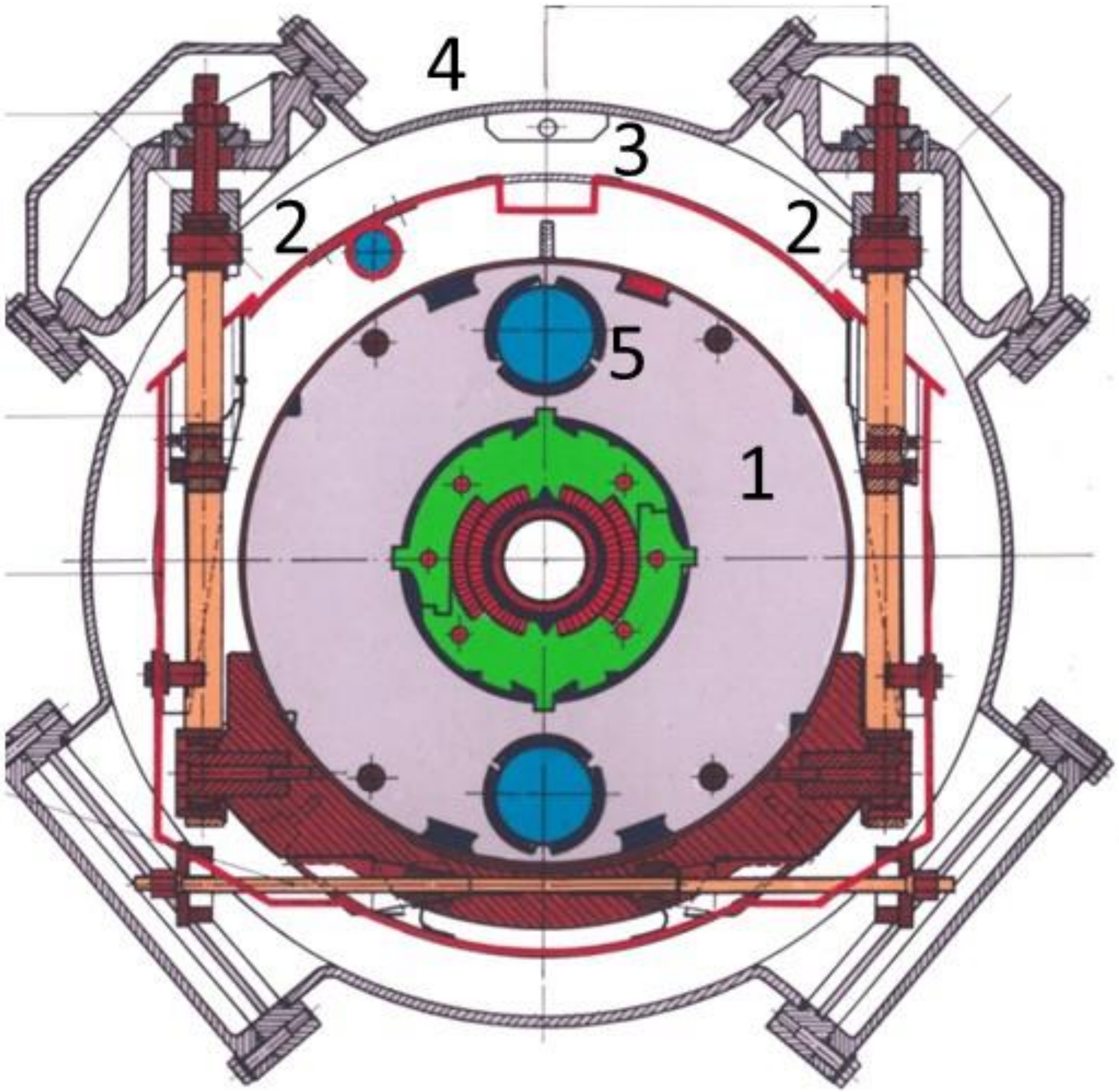
Static and dynamic heat load to the LHe circuit.

Hera Dipole

4.7 T, 75mm

9m

(4.5 K)



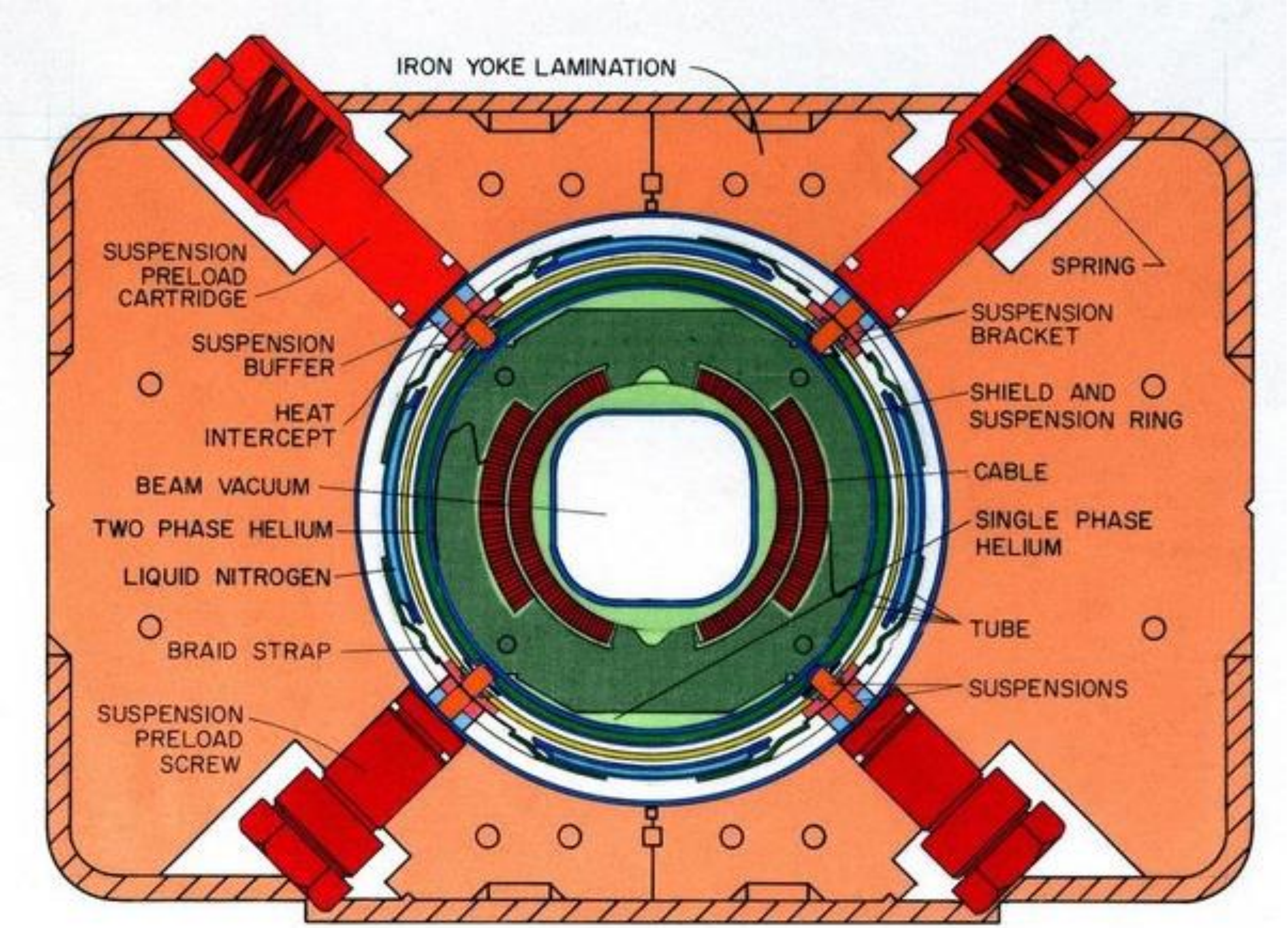
HERA dipole. 1 Helium vessel containing cold mass, 2 Suspension, 3 Radiation shield, 4 Vacuum vessel, 5 Helium pipes.

Tevatron Dipole

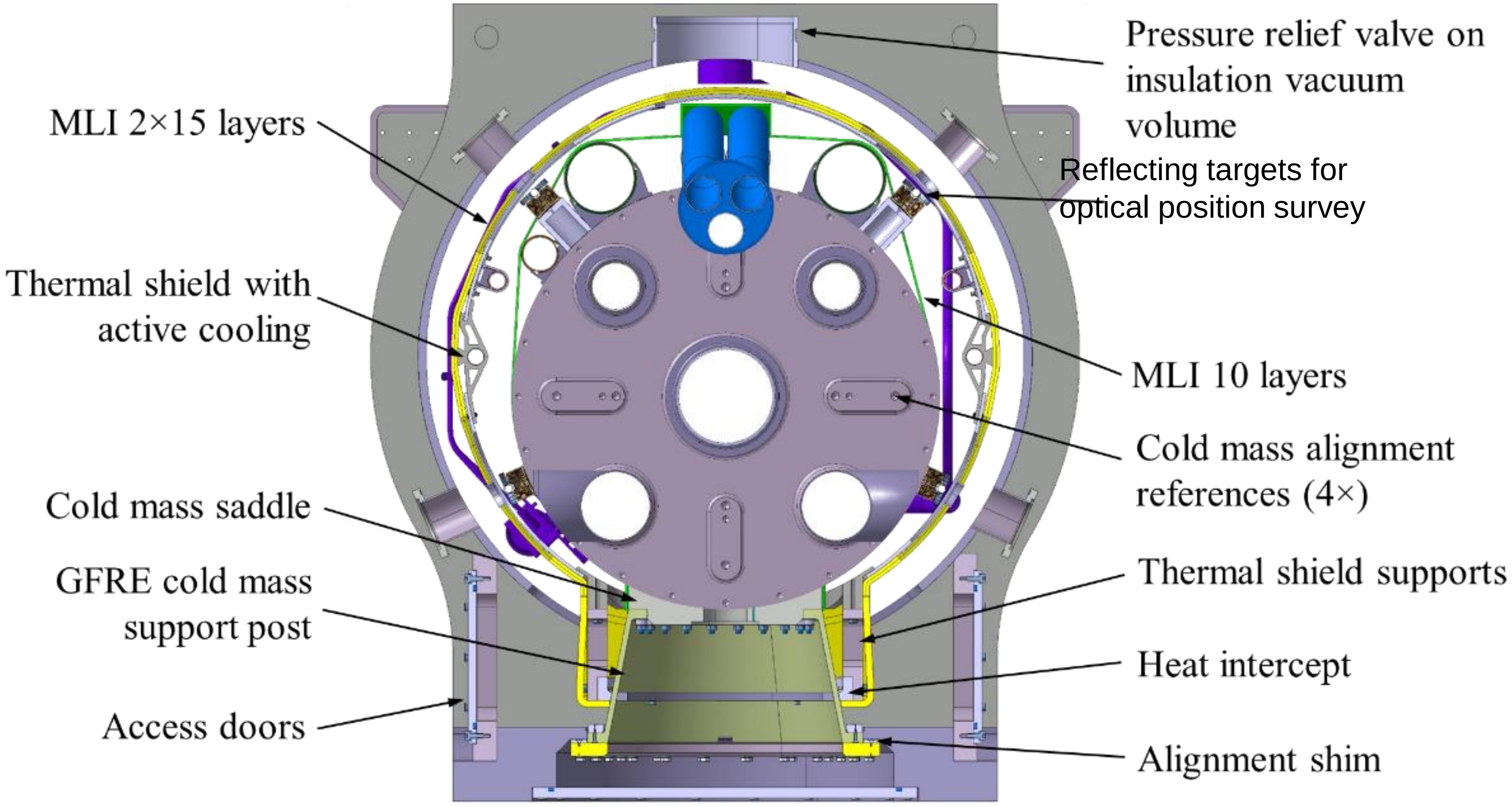
4.5 T, 76 mm

6m

(4.6 K)



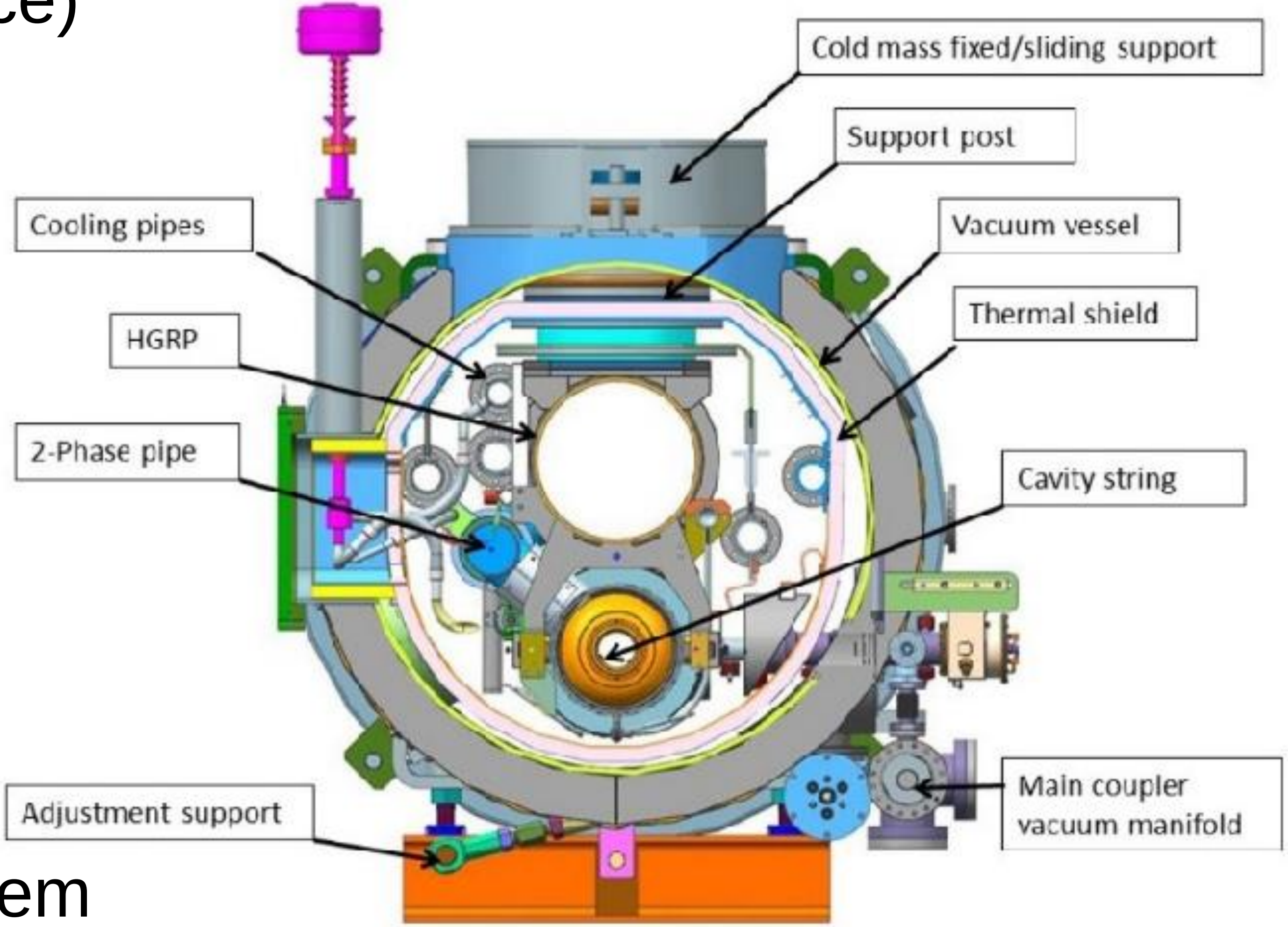
Hi Lumi LHC focusing quadrupole triplets



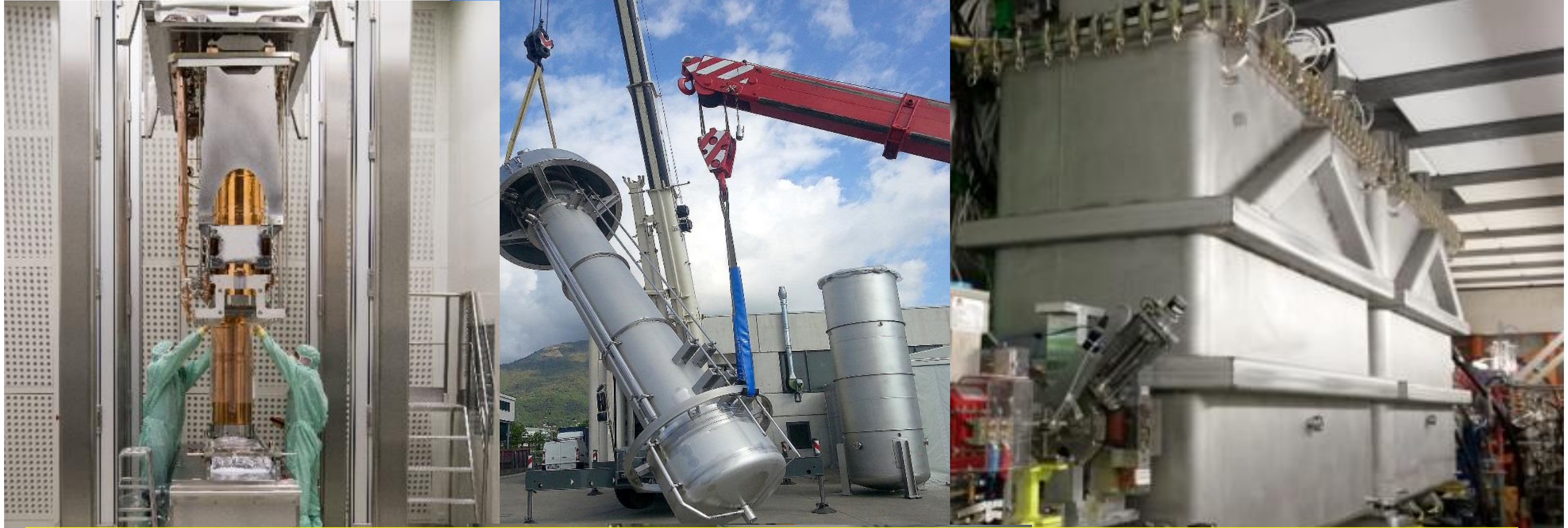
- NbTi SC magnets operated at 1.9 K (superfluid)
- Larger cold mass to be fitted within LHC dipole outer vacuum vessel diameter (tunnel limitations)
- Conical support posts for better mechanical stability
- Optical position survey and motorized external jacks (alignment in highly irradiated environment)

Typical breakdown of a SC device cryostat

- Helium tank (containing SC device)
- Internal (cold) supporting system
- Thermal shielding with MLI
- Vacuum vessel
- Cryogenic piping
- Instrumentation feedthroughs
- RF Couplers/HOM (for SRF)
- Current leads (for SC magnets)
- Magnetic shielding (for SRF, as needed)
- External supporting/aligning system



LCLS-II 1.3 GHz cryomodule (SLAC)



Thank you for your attention

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