Cryostats and Cryomodules

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A bit of History

- **Cryostat** (from *cryo* meaning cold and *stat* meaning stable)**:** ***"****a device used to maintain at cryogenic temperatures samples or devices mounted within the cryostat"*

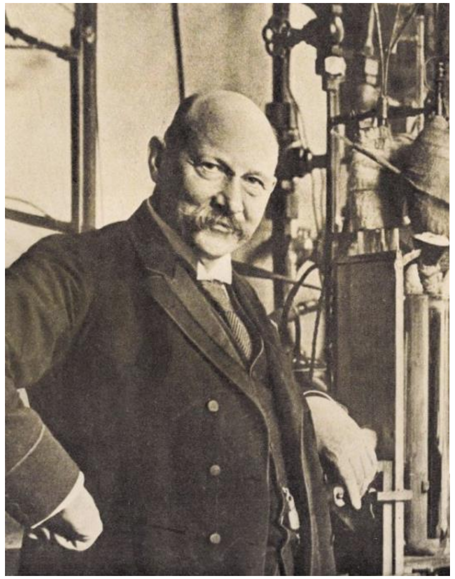
- Sir James Dewar invents the "dewar", 1892, London

- A dewar: the first "cryostat"
  - ✓ silvered, double-walled, glass vacuum flask to contain cryogenic liquids → glassblowing "*enabling technology*"
  - ✓ J.Dewar: 1st liquefaction of H_2 in 1897
  - ✓ …but did not manage liquefaction of He, and did not patent his invention…

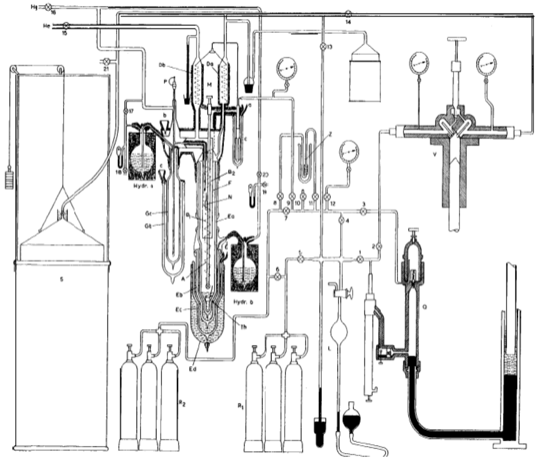
- Heike Kamerlingh Onnes : 1st liquefaction of He in 1908 and serendipitous discovery of superconductivity (Hg) in 1911 (Nobel Prize 1913)
- Founded the *"Leidse Instrumentmakersschool"* (still existing!: https://www.lis.nl/)

Sir James Dewar (1842-1923)

dewar

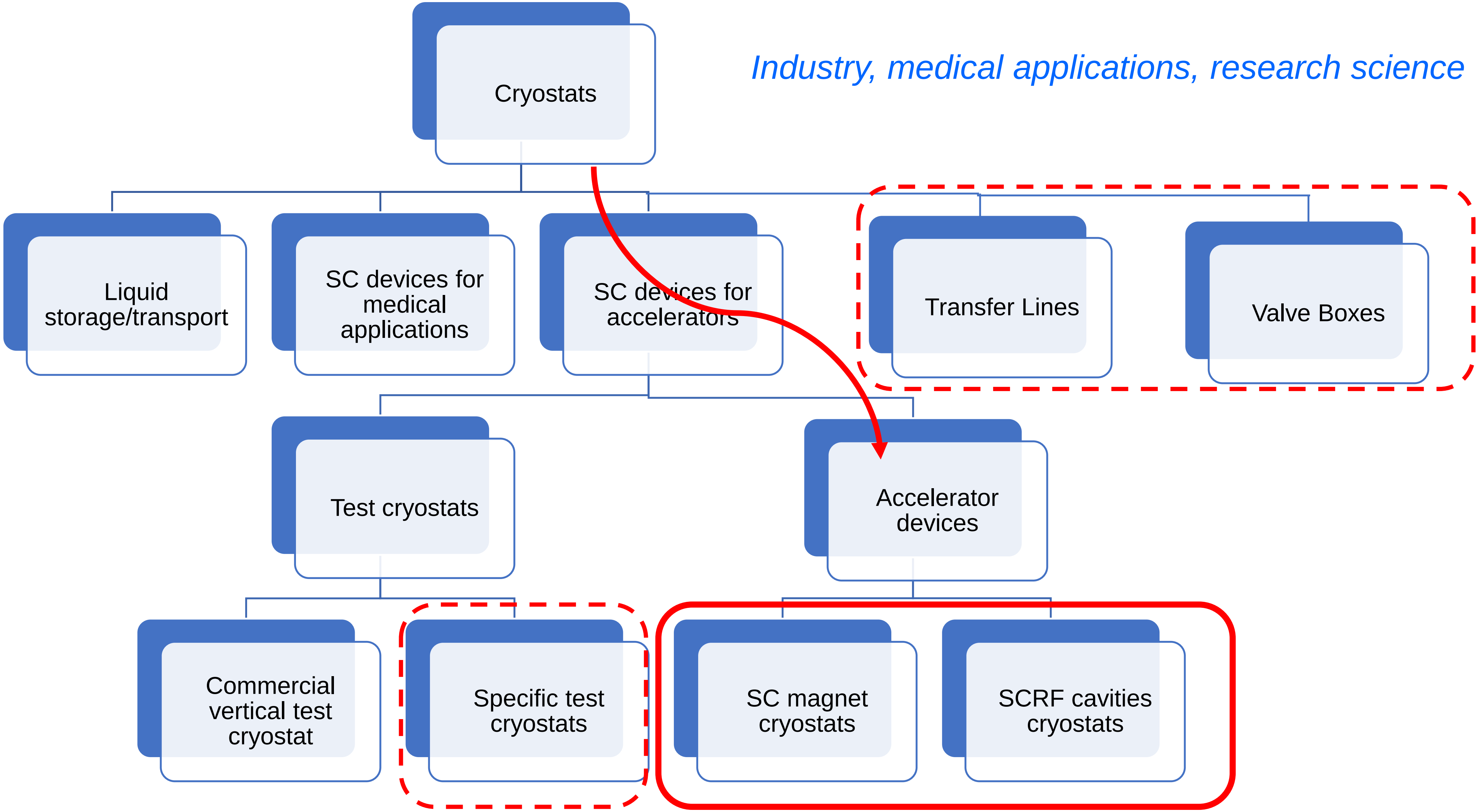


Kamerlingh Onnes (1853-1926)



Helium liquefaction stage with liquid hydrogen precooling

Cryostats by their application

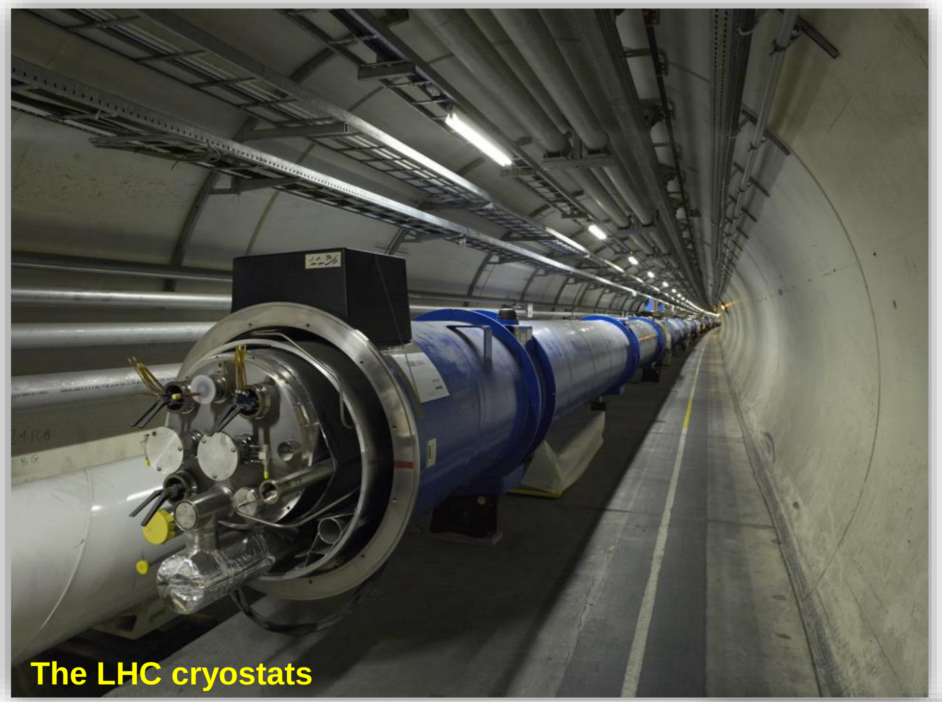


Industry, medical applications, research science

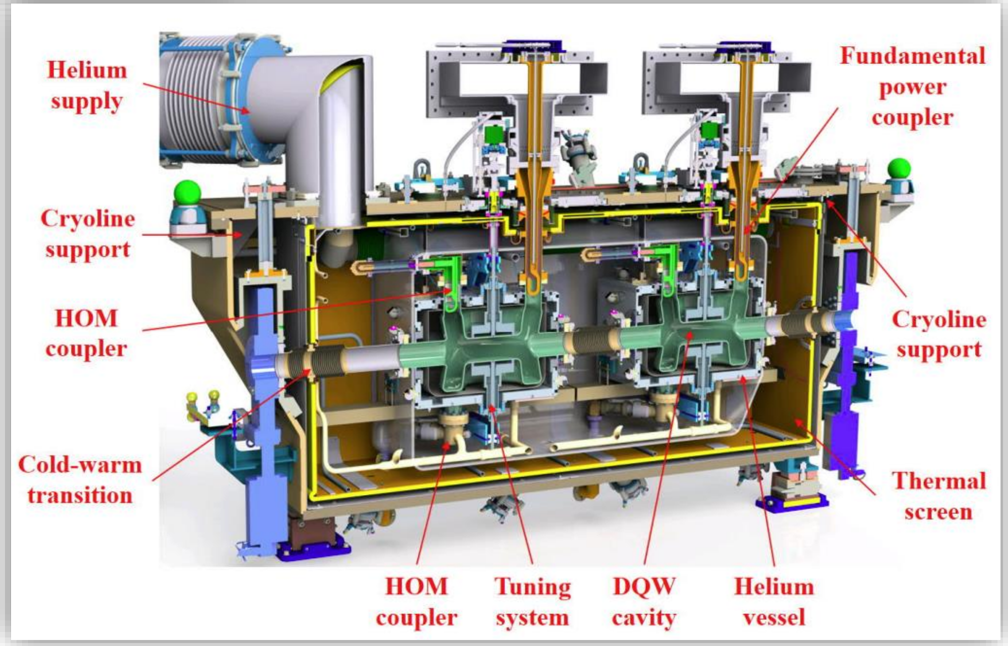
«Cryostats» «Cryomodules»

A few examples…

240l LHe storage


The LHC cryostats

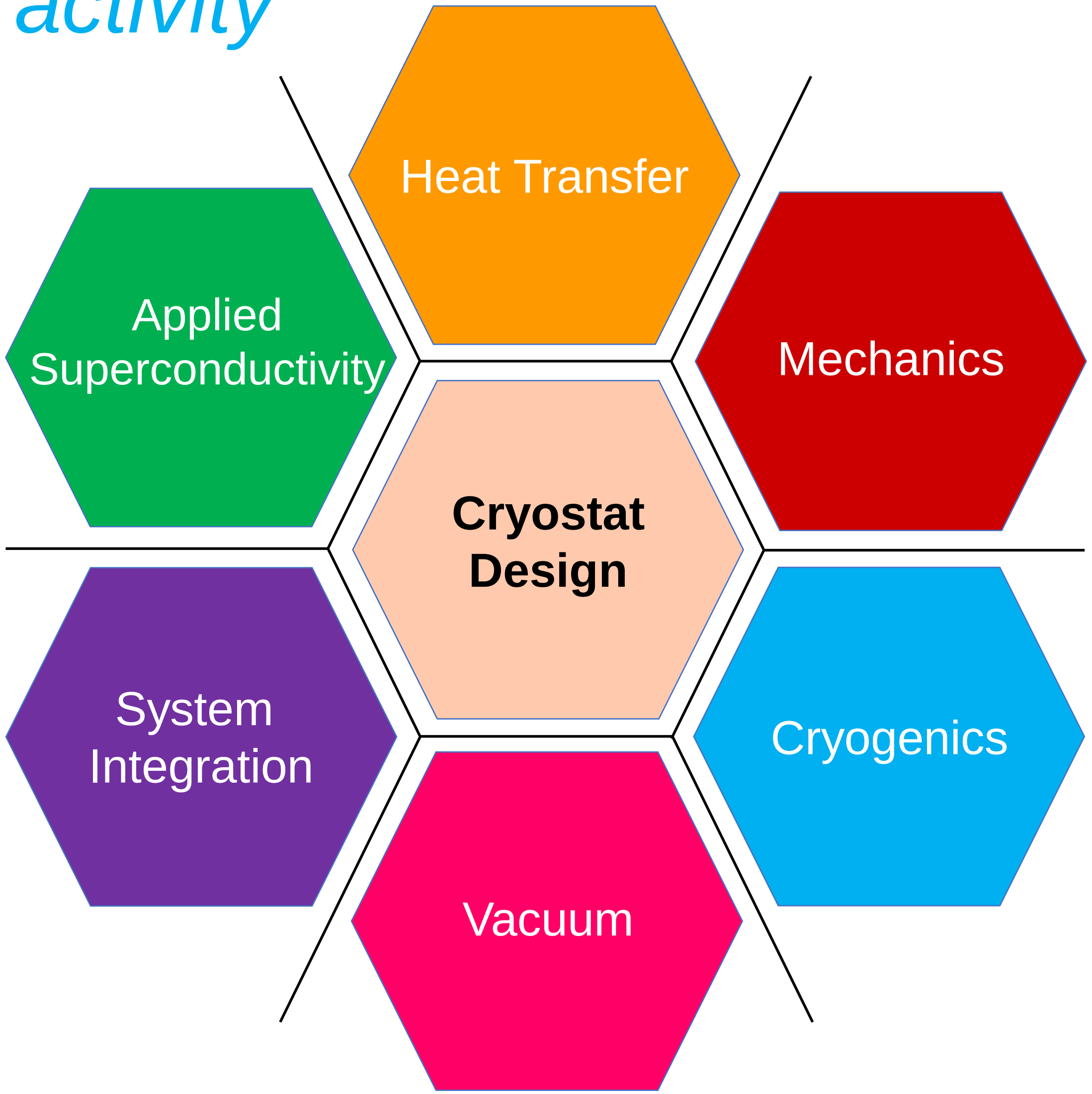

LHC He transfer line (before magnet installation)



HL LHC Crab Cryomodule

Cryostat Design for SC devices for accelerators:

A multidisciplinary activity



Heat Transfer

Applied Superconductivity

Mechanics

Cryostat Design

System Integration

Cryogenics

Vacuum

Content

- Cryostats for SC devices, functions and requirements

- Alignment and positioning of SC devices in cryostats/cryomodules

- Temperatures, pressures and Heat Loads

- Heat transfer mechanisms and thermal design:
  - ✓Radiation, shielding and MLI
  - ✓Solid conduction and feed throughs

- Materials and mechanical design considerations

- Notions of cryogenic safety *(bonus if I manage time)*

Functions of a SC device cryostat for accelerators

Main function: position a SC device and enable its operation.

Two technical requirements:

1. Mechanical housing of the device:
   - Support, accurately position and align SC devices in accelerators

2. Thermal efficiency:
   - Cooling to cryogenic T_{op} (steady state, CD/WU)
   - Good thermal insulation

Often conflicting → calls for trade off design solutions

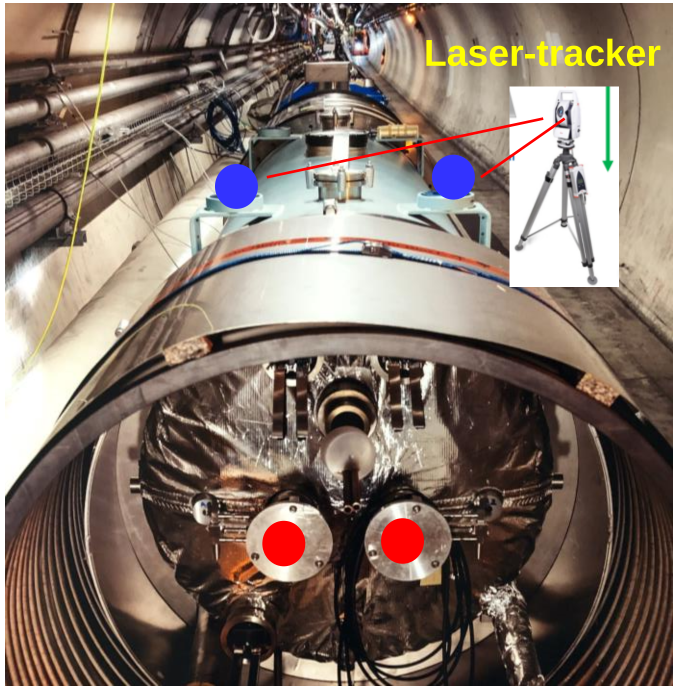
Many other complementary functions and requirements…:

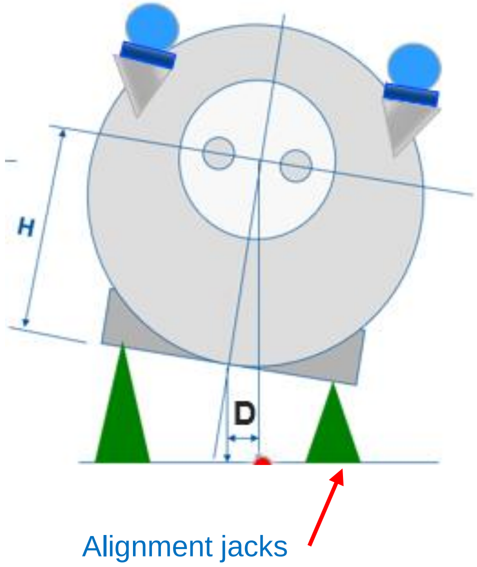
- Cryogenics operation and control → specific equipment (piping, ph.separators, valves, instrumentation etc.)
- SC device powering: → magnet current leads, cavity RF power couplers/HOMs, etc.
- Integration of instrumentation (beam, vacuum, cryo, control/diagnostics, etc.) → feed-throughs
- magnetic shielding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

Positioning of SC devices

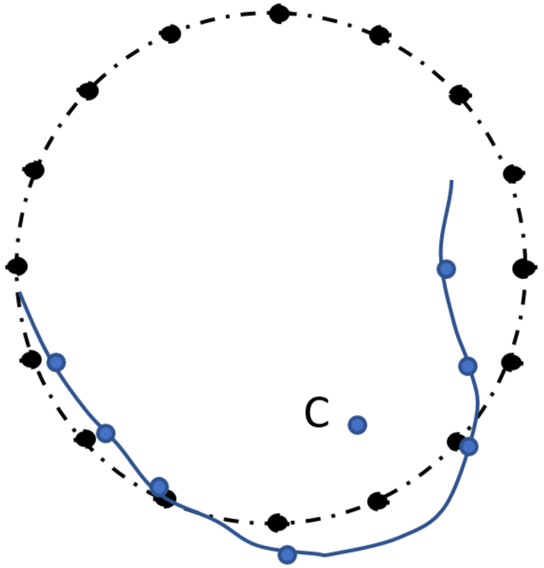
Positioning of a SC device in the accelerator

- *Accurate* & *reproducible* alignment of the SC device w.r.t. a tunnel geodesic network





- Survey team measures fiducials on the cryostat vessel (not directly the SC device inside the vessel!)
- Typically, alignment within a few tenths of mm w.r.t. nominal positions



Aligning elements in a ring

→ Survey consider cryostat and SC device are rigid bodies !

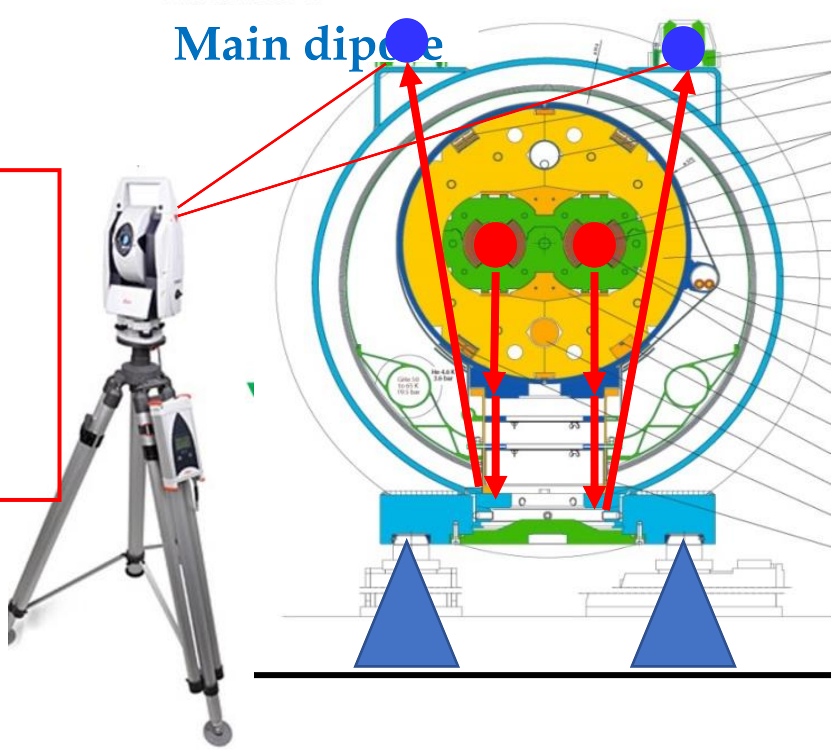
→ Alignment is done by adjusting external jacks

Reproducible positioning, a tough requirement !

Cryostats/SC device are not rigid bodies:

- SC devices are “weakly” supported inside the cryostat (thermal efficiency!)
- Cryostat vessels are (generally) “relatively” rigid, and not subject to “excessive” permanent deformation

→SC device supporting system: designed to guarantee “accurate & reproducible positioning of the SC device w.r.t. to cryostat fiducials”

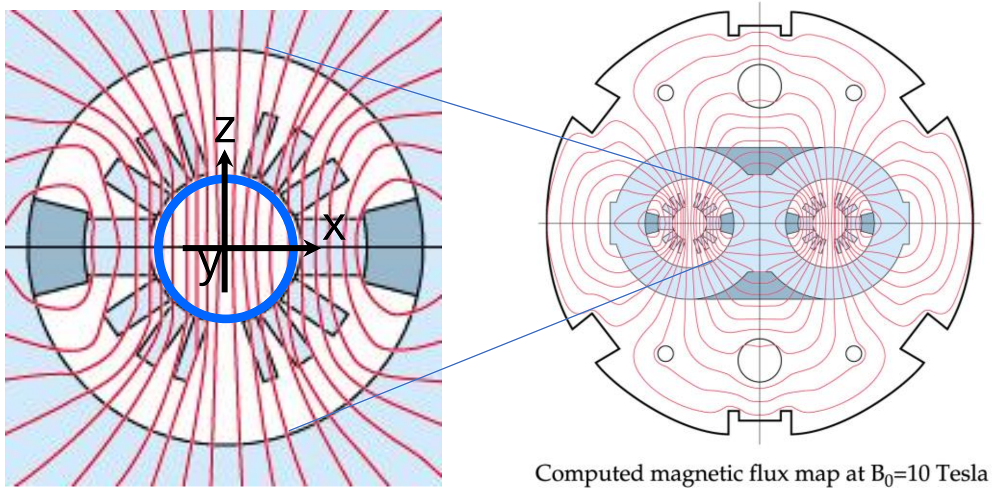


Note: internal monitoring excluded for cost reasons in large machines (LHC, XFEL, etc.)

Positioning of magnets in cryostats: how accurate/reproducible ?

- Dipole magnet positioning:
  - Transverse (x-z): tolerant (field has no horizontal axis). (LHC < 0.5 mm (rms))
  - Roll (about y): sensitive (gives a kick out of orbit plane). (LHC < 0.5 mrad (rms))

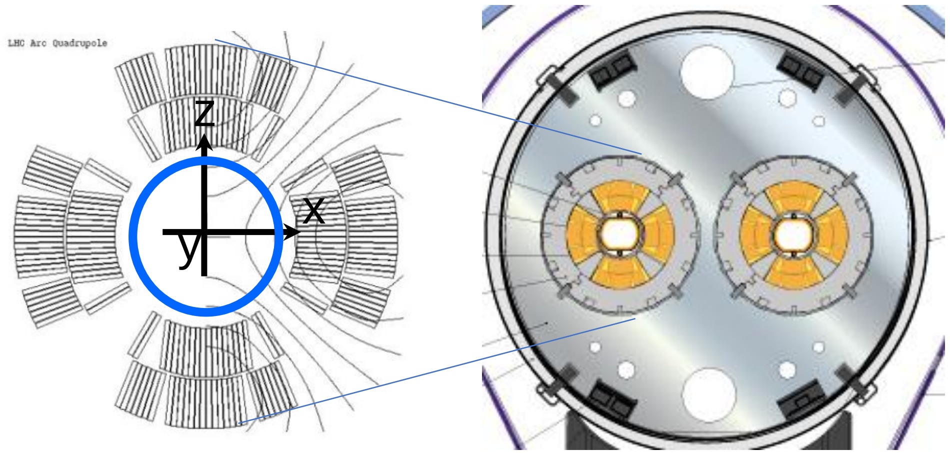
LHC dipole



Computed magnetic flux map at B_0=10 Tesla

- Quadrupole magnet positioning:
  - Transverse (x-z): sensitive (magnetic axis). (LHC < 0.25 mm (rms))
  - Roll (about y): tolerant (LHC < 1 mrad (rms))

LHC quadrupole



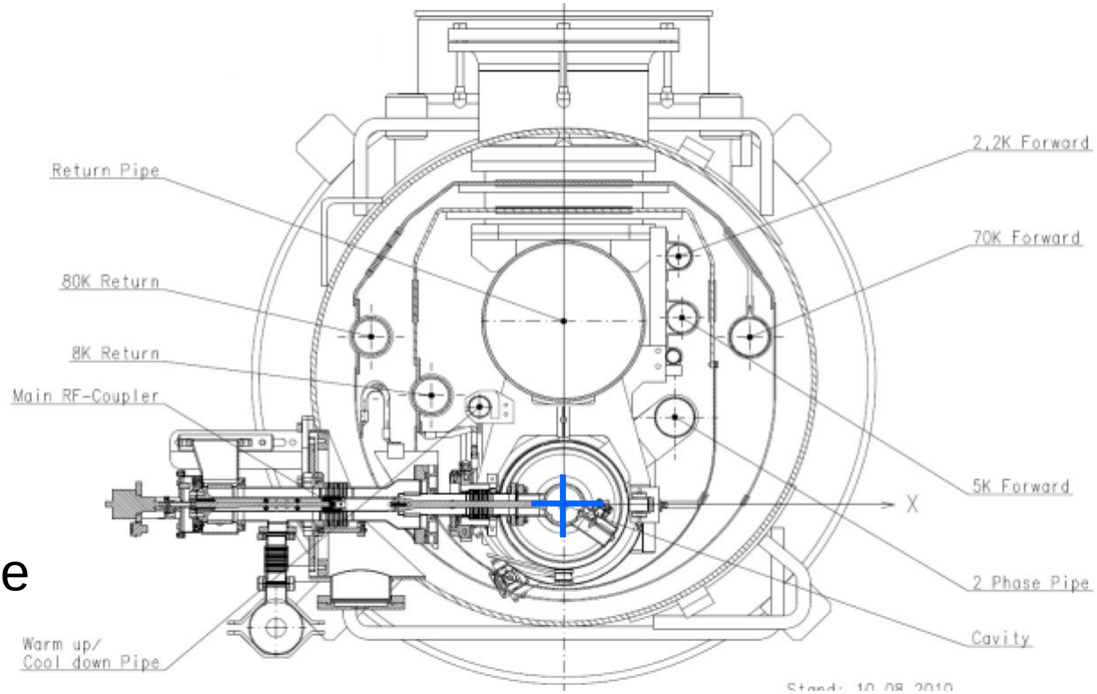
Reminder: 1 mrad ~ 1mm/m (small angles)

Positioning of cavities in cryomodules: how accurate/reproducible ?

- 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

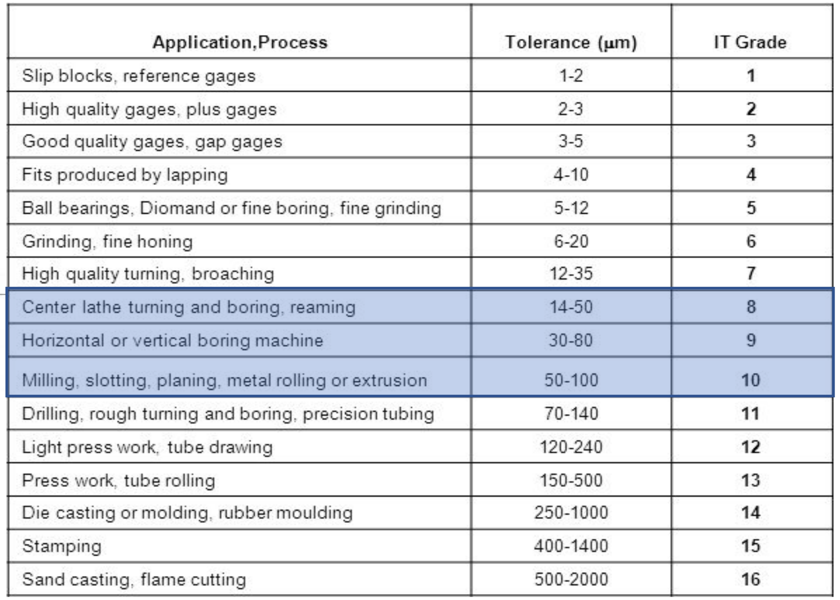
- Typical figures (r.m.s.):
  - ✓ EXFEL: cavities transverse ~ 1 mm, roll insensitive
  - ✓ HIE Isolde CM:
    - ➢ Cavities: transverse < ±0.45 mm
    - ➢ Solenoid: transverse < ±0.23 mm



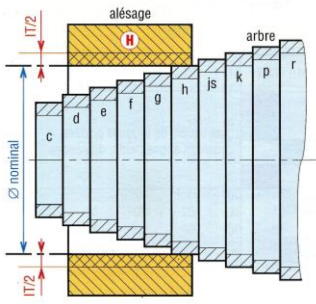

EXFEL, Desy, Hamburg

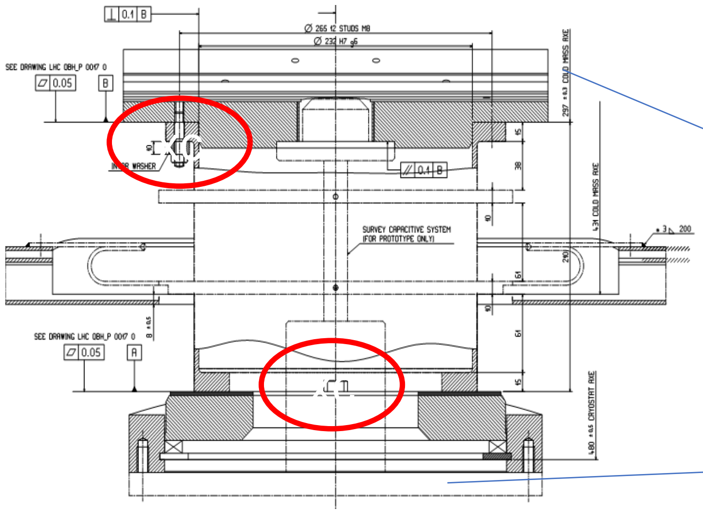
Mechanical tolerances for accuracy in cryostats parts/assembly

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



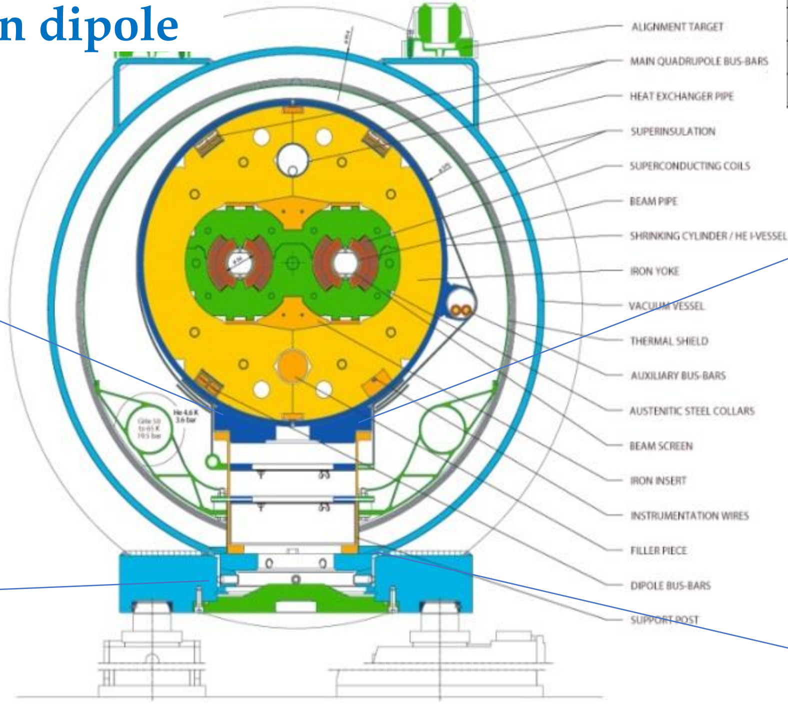
Application,Process	Tolerance (µm)	IT Grade
Slip blocks, reference gages	1-2	1
High quality gages, plus gages	2-3	2
Good quality gages, gap gages	3-5	3
Fits produced by lapping	4-10	4
Ball bearings, Diomand or fine boring, fine grinding	5-12	5
Grinding, fine honing	6-20	6
High quality turning, broaching	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

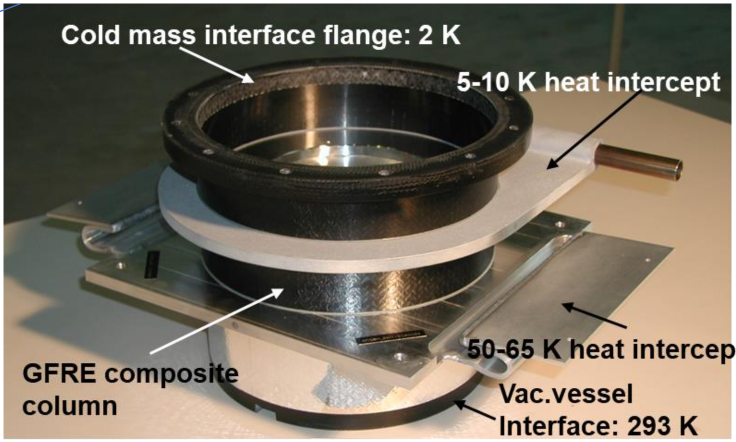




Central support post interfaced to vessel/coldmass (232 H7/g6 → play: 15-90 microns)

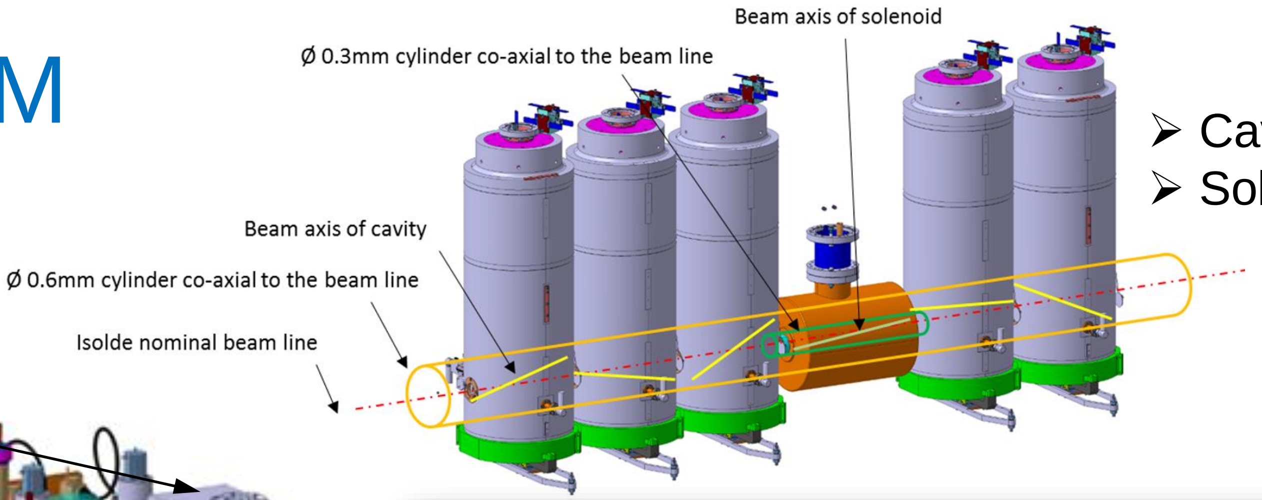
Main dipole

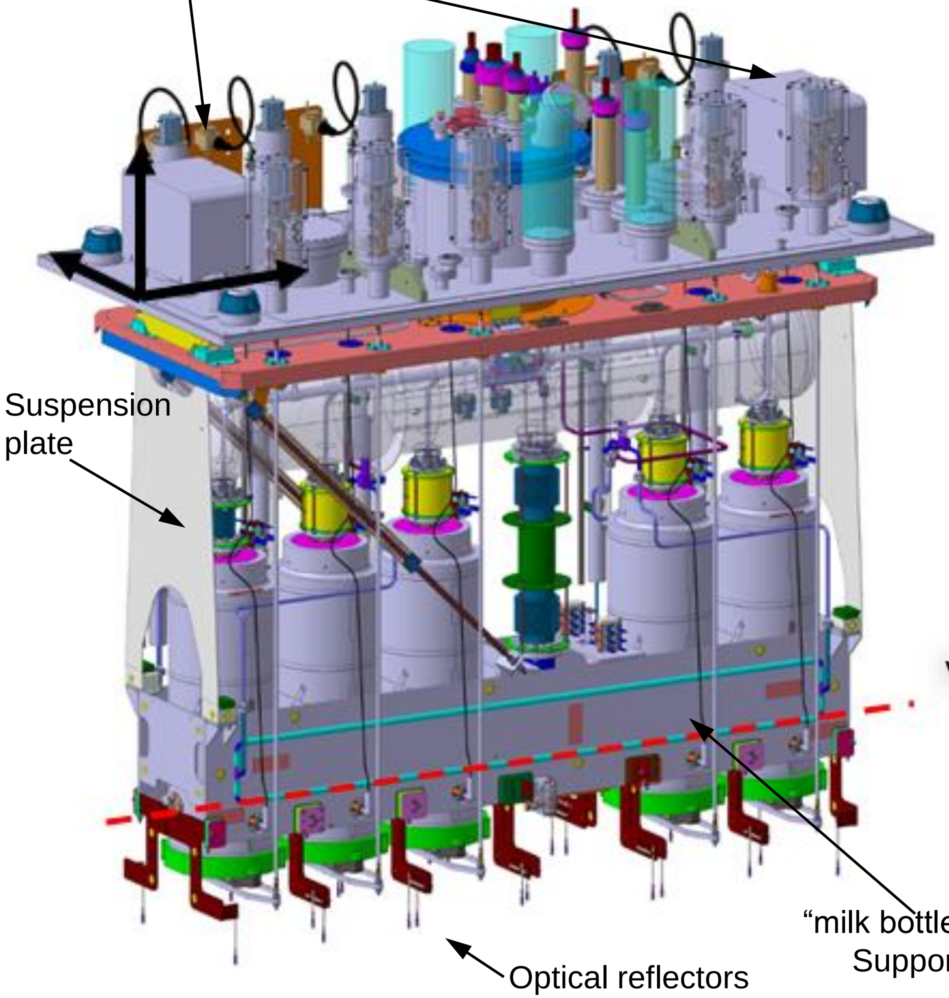


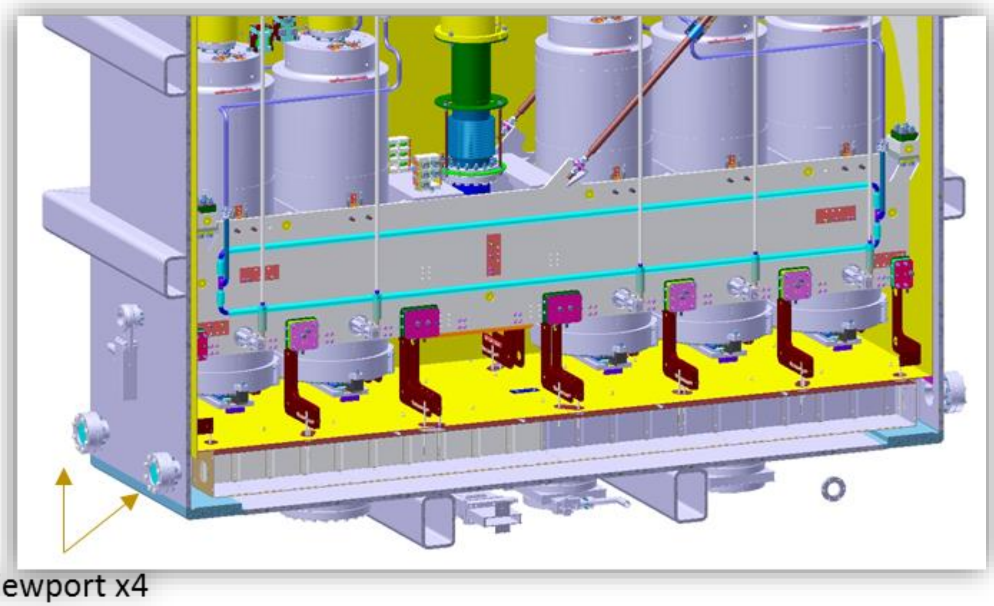


HIE Isolde CM

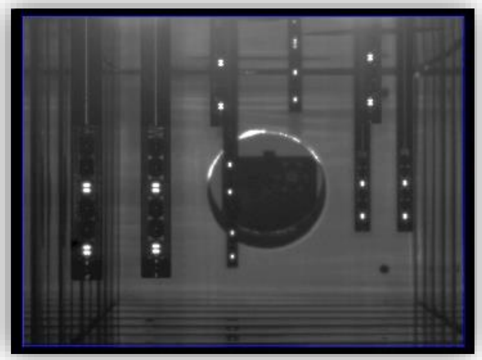
- ➢ Cavities: transverse < ±0.45 mm
- ➢ Solenoid: transverse < ±0.23 mm



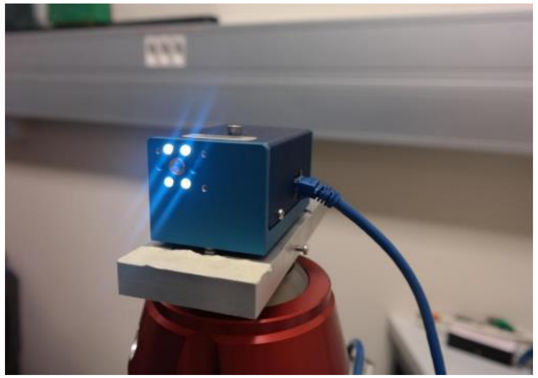




optical monitoring and adjustment of position



Targets viewed from viewports

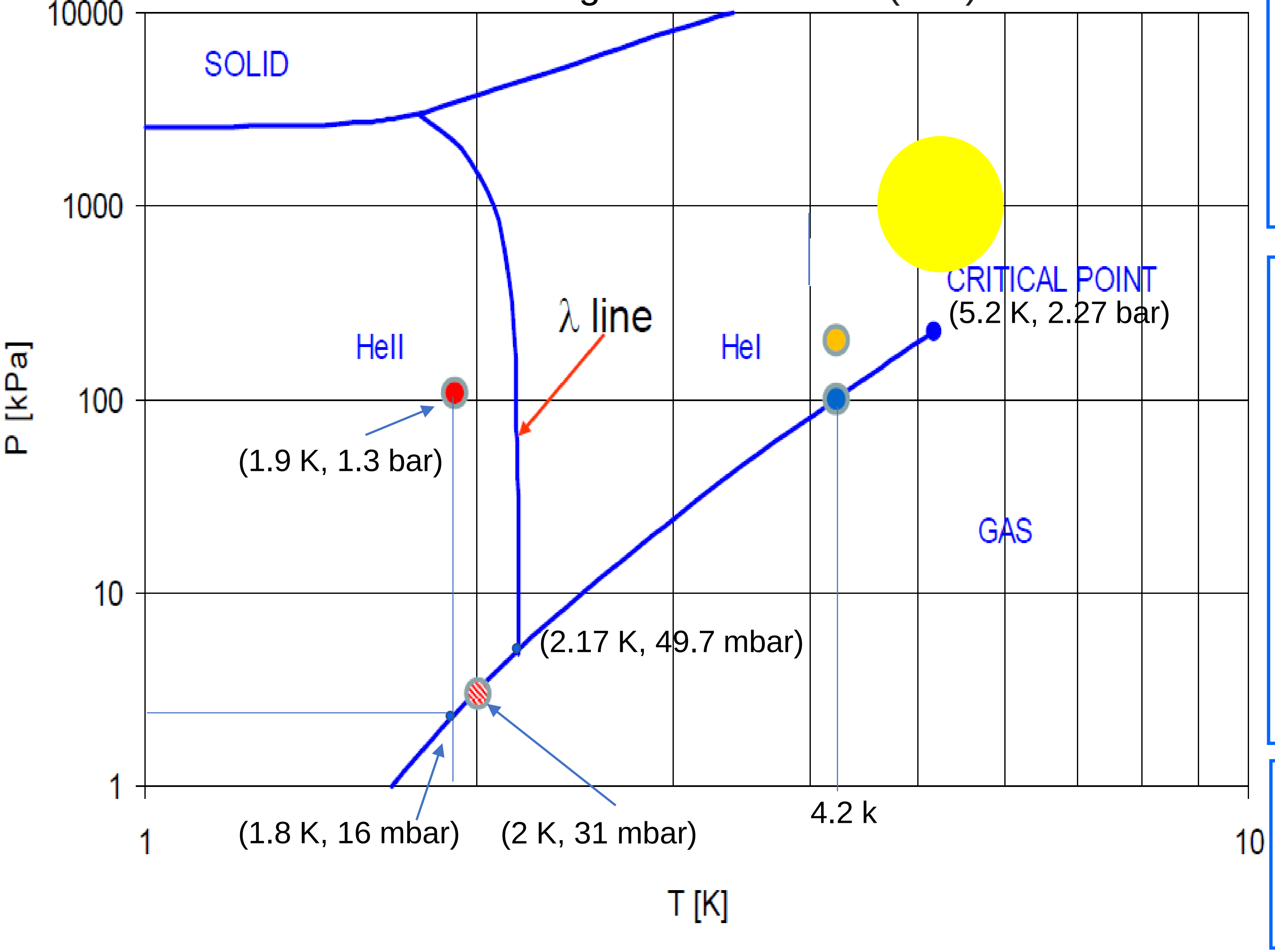


HBCM optical CCD cameras

Temperatures, pressures and Heat Loads

What temperature T_{op} (and pressure) ?

Phase diagram of helium-4 (^4He)



SC magnets:
superconductor NbTi: $T_{op} < T_c = 9$ K

- ● 1.9 K He II, Magnets (LHC, Tore Supra)
- ● 4.2 He I, Magnets (HERA, Tevatron)

P: > 1 bar (1.3-5 bar) for higher voltage breakdown (Paschen curve in He)

SRF cavities: depends on technology (Bulk or sputtered Nb), frequency:
$T_{op}\downarrow \rightarrow R_{BCS}\downarrow$ and $P_{refrig.}\uparrow \propto (T_{amb} / T_{op}-1)$
→ Opt. T_{op}: 2K - 4.2K

- ▨ Saturated He II (2K), CEBAF, SNS, EXFEL, ESS, PIP-II, ILC
- ● Pool boiling, He I (4.2K), HERA, LEP, LHC, KEKB

P: 31mbar / 1 bar (saturation line)

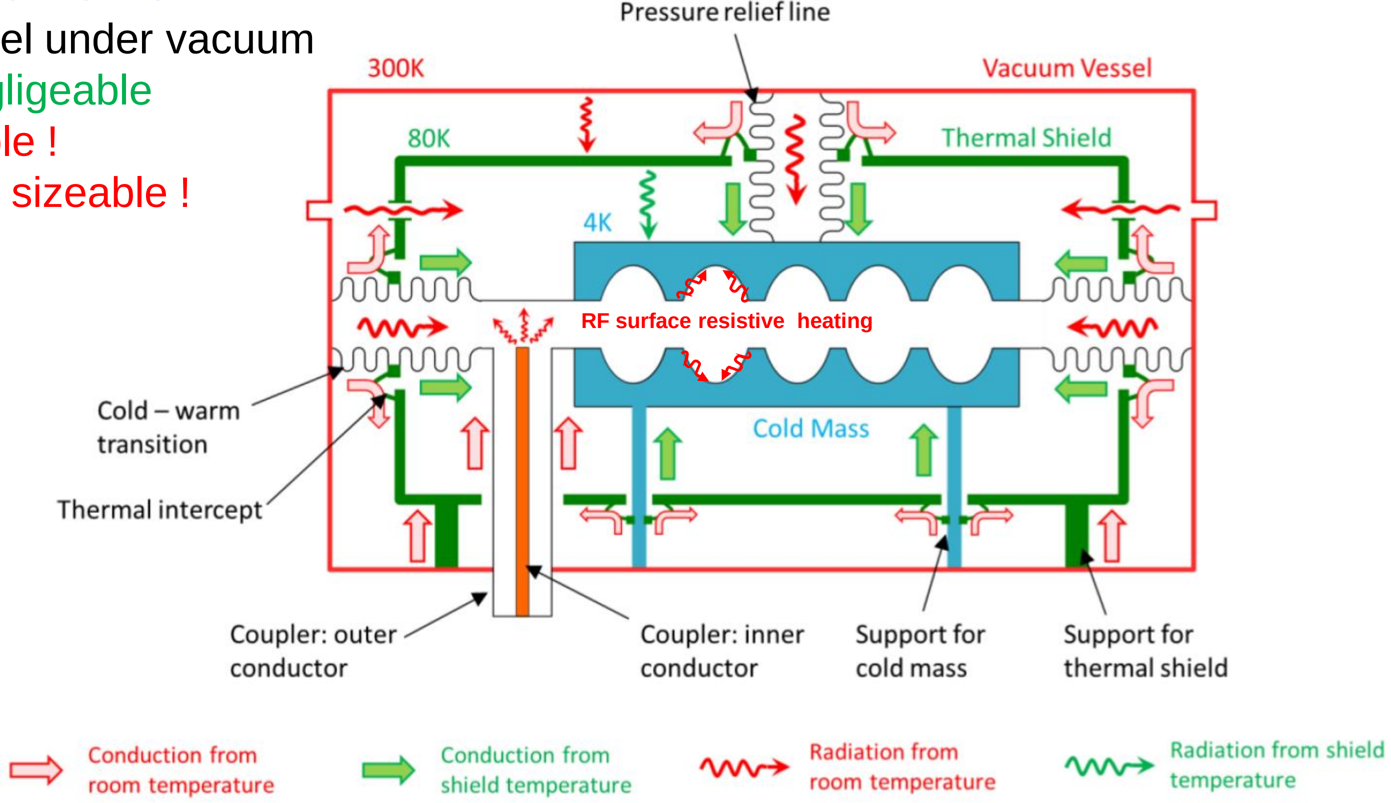
● **Thermal shields (~50 K), heat intercepts (5-50 K):**
Non-isothermal cooling (ΔT ~ 5-20 K)
→ supercritical helium

Heat Loads

- Static:
  - ✓ Very much cryostat related (supports, shielding, feedthroughs, etc.)
  - ✓ always present when machine is cold

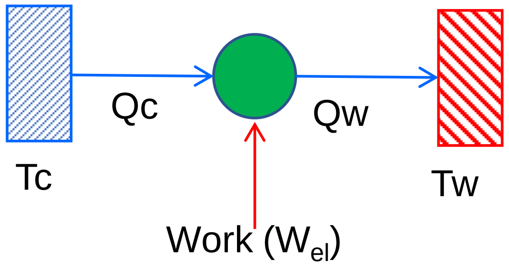
- Dynamic:
  - ✓ SC device operation (e.g. RF surface resistive heating)
  - ✓ Beam interaction (e.g. synchrotron radiation, HOM)
  - ✓ Can be dominant, but only present during machine operation (duty cycles)

- 3 heat transfer mechanisms:
  - ✓ Convection → vessel under vacuum (~10^{-6} mbar) → negligeable
  - ✓ Radiation → sizeable !
  - ✓ Solid conduction → sizeable !



What is the power need for refrigeration ?

- Extracts a heat load at Tc < RT and rejects it at Tw (normally ambient T=293 K)
- 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

$$Qc + Wel = Qw$$

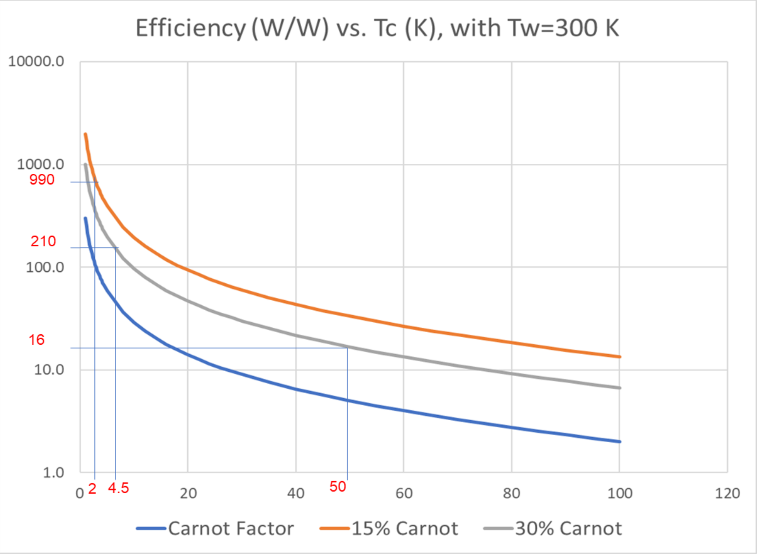
$$\frac{Qw}{Tw} \geq \frac{Qc}{Tc}$$

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

$$W_{el} \geq Qc\,\frac{Tw - Tc}{Tc} = \frac{Qc}{COP_{max}}$$

Fluid (at 1 bar)	T [K]	Carnot factor (1/COPmax or W_{el}/Qc) [W_{el}/W_{th}] (considering Tw=293K)
LN2	77	2.8
LH2	20.4	13.4
LHe	4.2	**68.4**
LHe	1.8	161.8

- Real machines (irreversibilities) : efficiency expressed in fraction (or %) of Carnot
- State-of-the-art figures for large cryo-plants (LHC-like, ~18 kW @ 4.2K):
  - ✓ COP @ 4.2 K : ~ 30% of Carnot (1 W_{th} costs **210 W_{el}**)
  - ✓ COP @ 2 K : ~ 15% of Carnot (1 W_{th} costs **990 W_{el}**)
  - ✓ COP @ 50 K : ~ 30% of Carnot (1 W_{th} costs 16 W_{el})


Efficiency (W/W) vs. Tc (K), with Tw=300 K

→ To minimize cryostat refrigeration costs: heat extraction at higher T levels:
- ✓ Heat intercepts on feedthrough (at least one)
- ✓ Actively cooled thermal shield

Cryostats/cryomodules and cryogenic operation

Cryoplant

T_{return}

T_{supply} Cryogen transfer line

T_{op}

SC device cryostat/cryomodule

Delivers:

- Helium mass flow ($\dot{m}$), T_{supply}, returns T_{return} > T_{supply}
- Cryogenic cooling power supply:

Needs:

- T_{op}, reached "conveniently" → transients
- Cryogenic cooling power received:

Cp: specific heat of cryogen

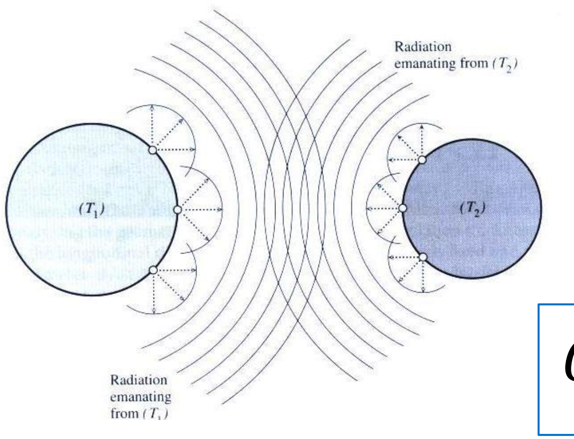
$$\boxed{Q = \dot{m}\, Cp\, (T_{return} - T_{supply}) \quad \geq \quad Q = \dot{m}\, h\, A\, (T_{op} - T_{supply})}$$

h: heat transfer coeff.
A: exchange area

→ Cryostat designed to <u>minimise Heat Loads</u> from environment ($T_{ambient}$)

→ Cryostat (and the SC device) designed to <u>ensure cooling heat exchange</u>

Thermal Radiation



Stefan-Boltzmann's law:

$$\boxed{Q = \varepsilon\, \sigma\, A\, T^4}$$

$$\sigma = 5.67\ 10^{-8}\ W\ m^{-2}\ K^{-4}$$

Stefan-Boltzmann's constant

$$\text{gray body}, \varepsilon < 1$$

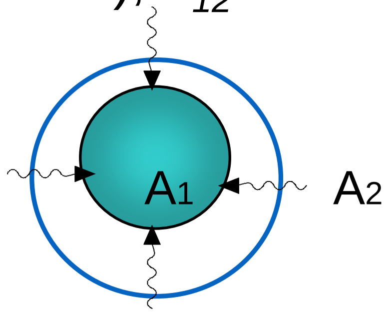
Power exchange between **gray bodies**:

$$\boxed{Q_{1-2} = E_{12}\, \sigma\, A_1\left({T_1}^4 - {T_2}^4\right) = E_{21}\, \sigma\, A_2\left({T_1}^4 - {T_2}^4\right)}$$

- E, effective emissivity, a function of view factors and emissivity ε_1 and ε_2 of the bodies
- A, T area and temperature of the bodies, ε emissivity

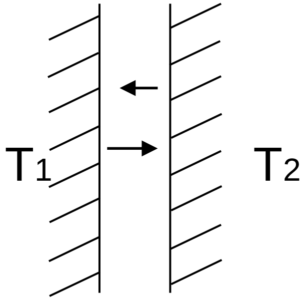
- For **2 enclosed cylinders** or **spheres** (not necessarily concentric!), *F*$_{12}$=1 :

$$\boxed{q_{1\_2} = \frac{\sigma A_1({T_1}^4 - {T_2}^4)}{\frac{1}{\varepsilon_1} + \frac{A_1}{A_2}\left(\frac{1}{\varepsilon_2} - 1\right)}}$$



- Radiation **between flat surfaces** (A1=A2=A), *F*$_{12}$=1 :

$$\boxed{q_{1-2} = \frac{\sigma A({T_1}^4 - {T_2}^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}}$$

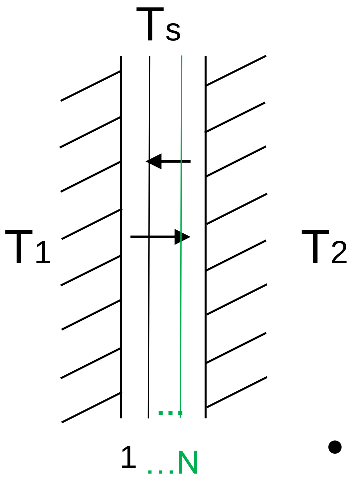


Radiation with an intermediate floating shield(s)

- With **1 intermediate floating shield** and **same ε :**

$$\boxed{q_{1-2} = \frac{\sigma\, A\, ({T_1}^4 - {T_2}^4)}{\boxed{2}(\frac{2}{\varepsilon} - 1)}}$$

$$T_s^{\,4} = \frac{{T_1}^4 + {T_2}^4}{2}$$



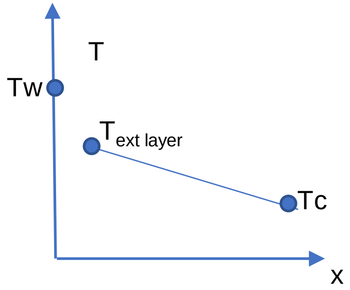
→ ½ of the power exchange without shield

- With **N intermediate floating shield** and **same ε** can be generatized**:**

$$\boxed{q_{1-2} = \frac{\sigma\, A\, ({T_1}^4 - {T_2}^4)}{\mathbf{(N+1)}(\frac{2}{\varepsilon} - 1)}}$$

→ 1/(N+1) of the power exchange without shield

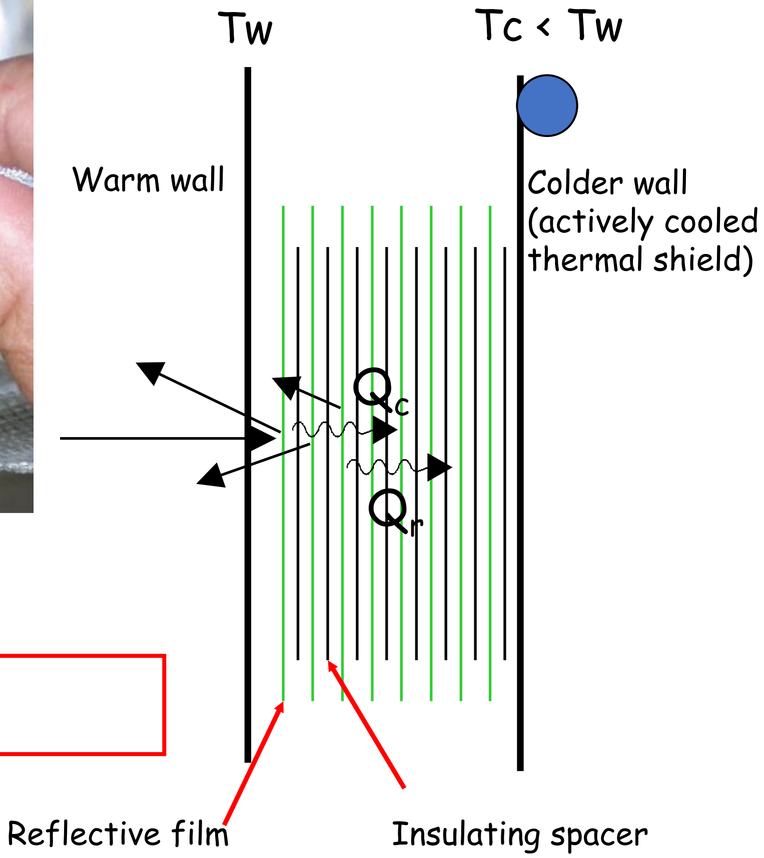
N shields → Multi Layer Insulation (MLI)



Insulating mechanism:

- Multi-layer to enhance radiation protection:
  - N+1 radiation shielding
- Low emissivity of aluminium layer
- Minimal thermal conduction between reflective layers → interposing of isolating layers (e.g polyester net):
- Enhanced performance at low T → use actively cooled shield:
  - Lower emissivity of reflective material layers at low T
  - Extract heat at higher thermal shield T → thermodynamic efficiency

Interleaved reflectors and spacers



→ *Actively cooled (50-80 K range) thermal shield with MLI* ***is a must*** *in all cryostats*

MLI performance

- Typical values (for a thermally well optimized large-scale application like LHC) :
  - 293 K to 50 K thermal shield with 30 MLI layers: → ~1 W/m^2
  - 50 K to 2 K magnet with 10 MLI layers: → ~ 50 mW/m^2

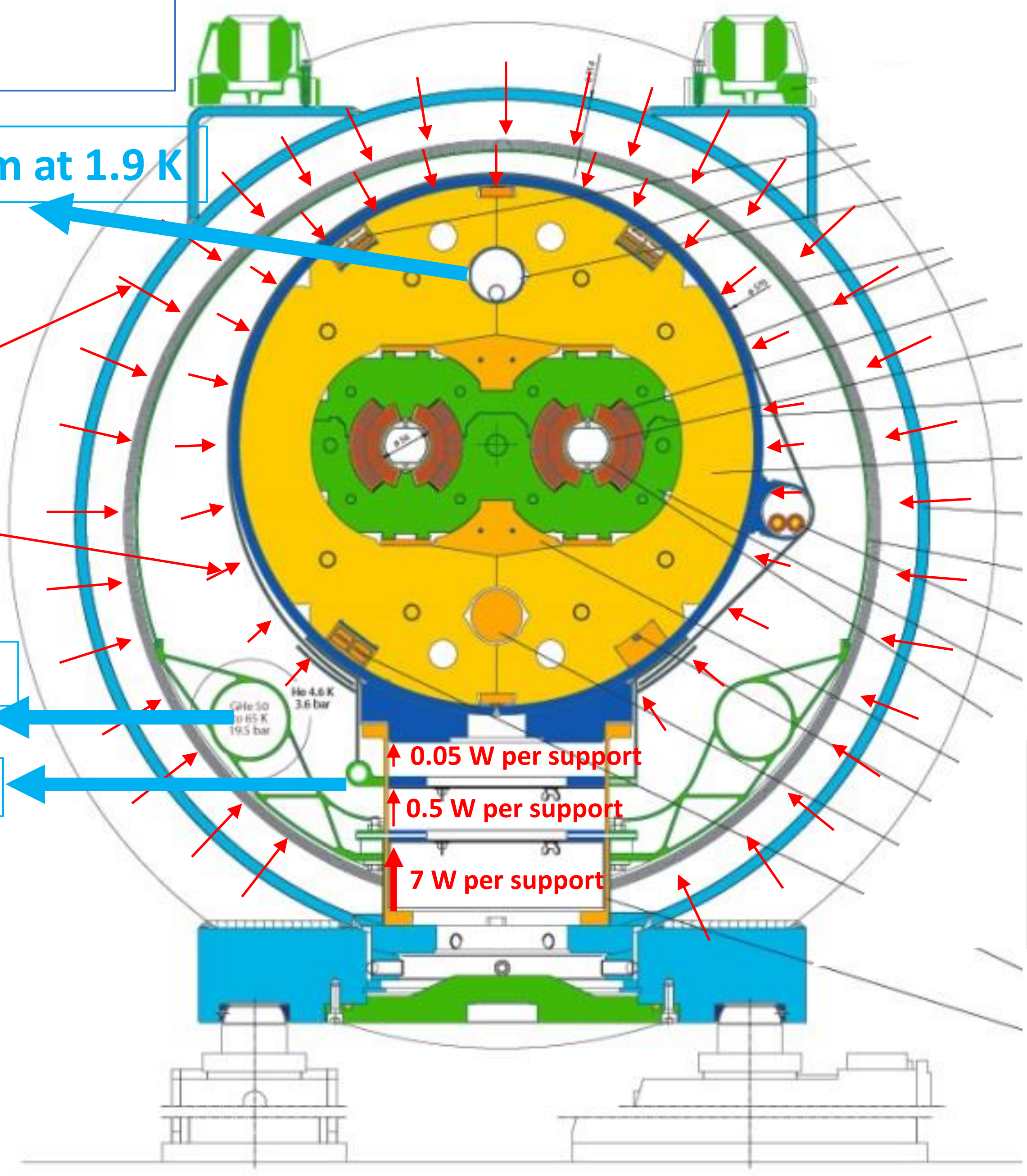

1 blanket on CM, 2 on thermal shield

LHC MLI Features:
1 blanket (10 reflective layers) on cold masses (1.9 K)
2 blankets (15 reflective layers each) on Thermal Shields (50-65 K)
Reflecting film: 6 µm thick polyethylene teraphthalate (PET) film coated with 400 Å minimum aluminium on each side
Spacer: polyester net of very low weight (< 5 g/m2)
Stitched Velcro™ fasteners for rapid mounting and quality closing


MLI on Cold-to-Warm transitions

Heat Loads in 1 m length

LHC magnet Cryostats



Heat exchange: 0.45 W/m at 1.9 K

Thermal radiation from vacuum vessel at room temperature (293 K) to thermal shield (50 K)

Thermal radiation from thermal shield (50 K) to magnet (1.9 K)

Heat extraction: 5 W/m at 50 K

Heat extraction: 0.15 W/m at 10 K

0.05 W per support

0.5 W per support

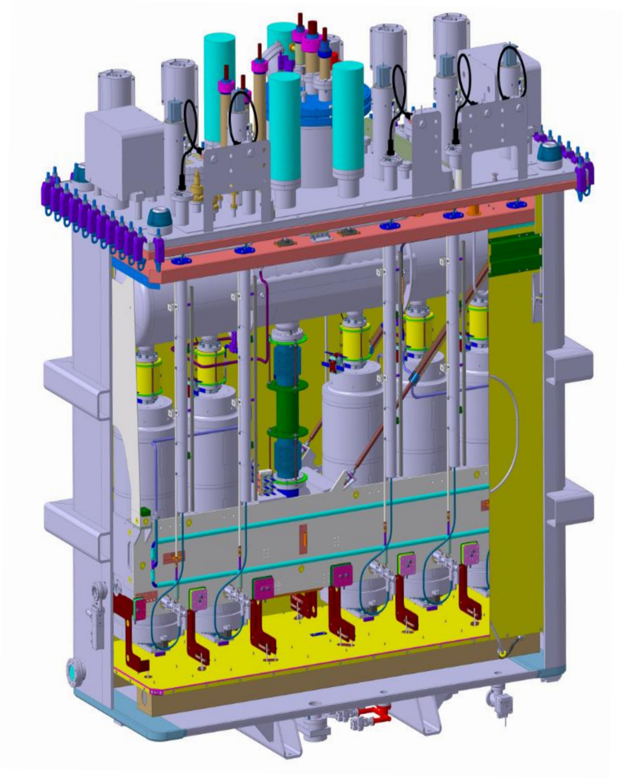
7 W per support

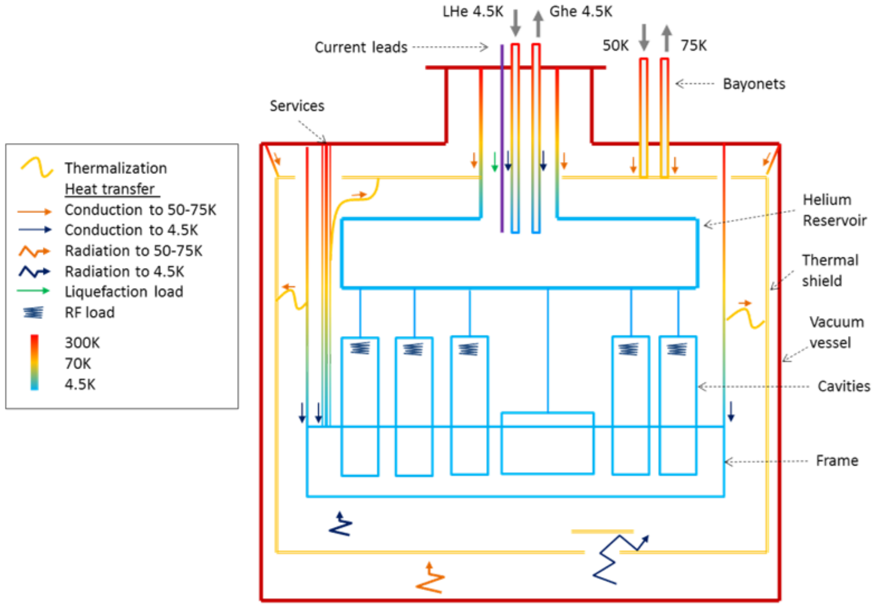
- Static Heat Loads:
  - ✓ 0.25 W/m at 1.9 K
  - ✓ 5 W/m at 50-65 K
- Dynamic Heat Loads (resistive heating + beam induced effects):
  - ✓ ~ 0.2 W/m at 1.9 K (magnet)
  - ✓ ~ 0.15 W/m at 4.6-20 K (beam-screen)

Refrigeration power (for 1 m cryostat)

	HL at 1.9 K	HL at 10K	HL at 65K
Heat Loads (Wth)	0.45	0.15	5
Carnot (COPmax)	0.0065	0.0353	0.2851
Carnot factor (1/COPmax)	153.21053	28.3	3.507692
% of Carnot	15	30	30
Real refrigeration power (Wel)	460	14	58
Total refrigeration power (Wel)	532		

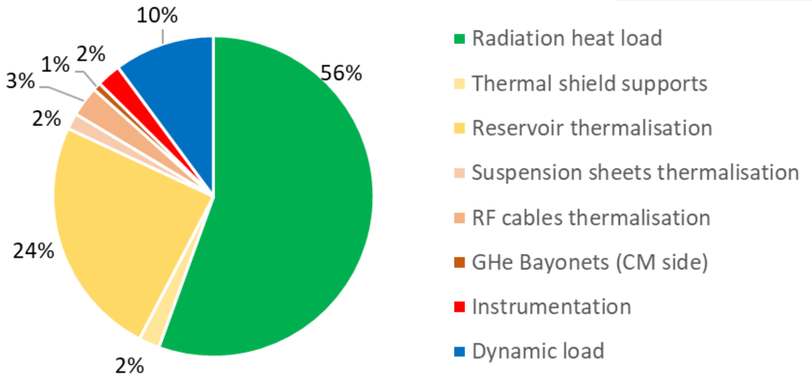
HIE Isolde Cryomodule: No MLI



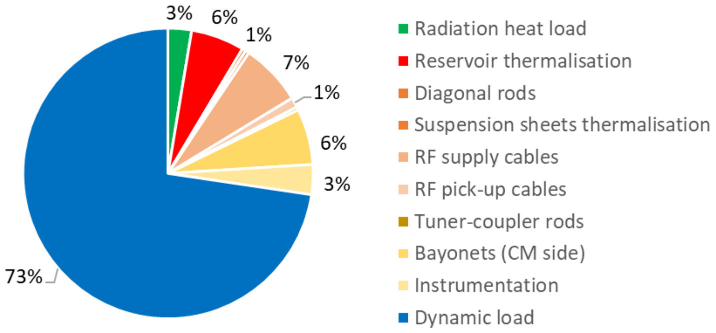


	Nominal [W]
To GHE circuit 50-75K	**362**
To LHE circuit 4.5K + liquefaction load 0.03 g/s	**70**

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



Static and dynamic heat load to the GHe circuit.



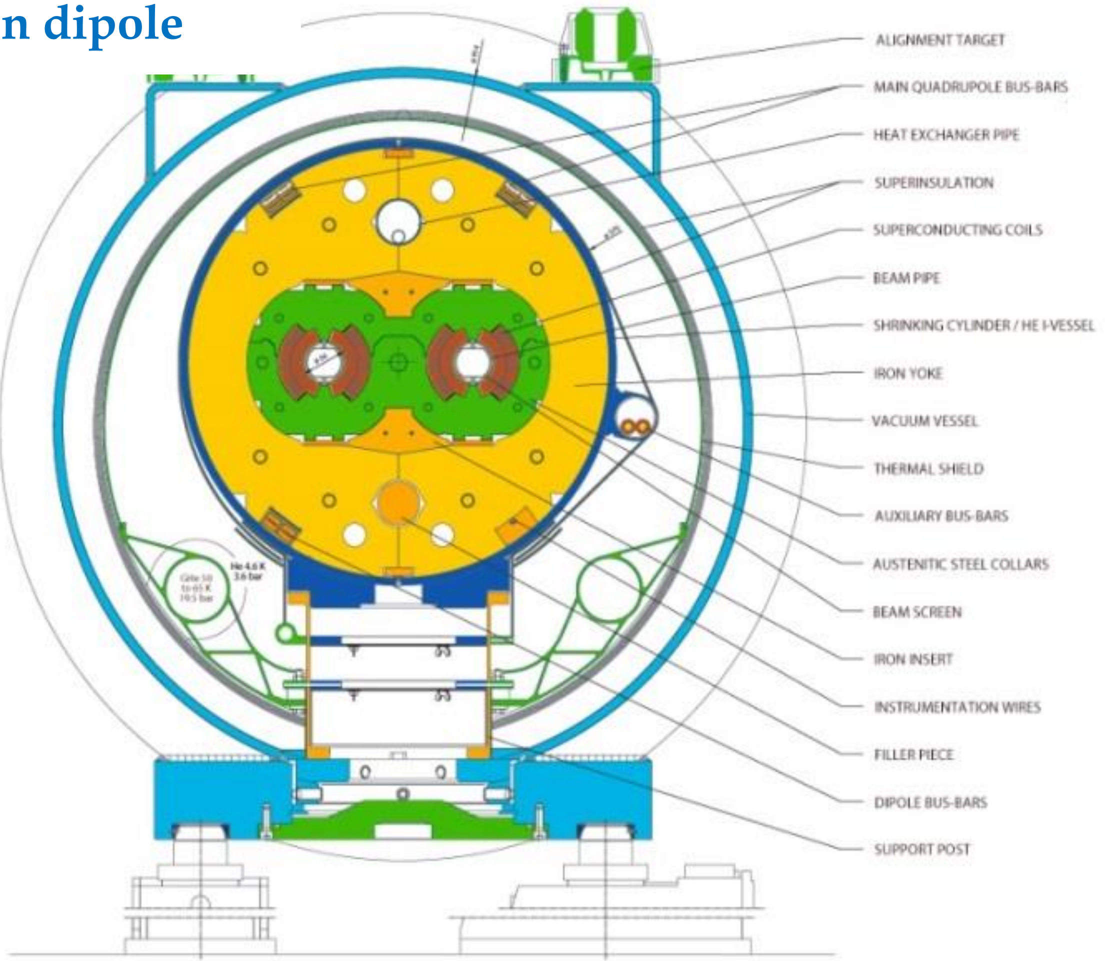
Static and dynamic heat load to the LHe circuit.

Materials and mechanical design considerations

Typical breakdown of a SC device cryostat/cryomodule

basic components

- Helium tank (for SC device, ph.separator, etc.):
  - ✓ austenitic st.steels (Fe-Cr-Ni): 304L(1.4307), 316L(1.4404), 316LN
  - ✓ titanium alloys (Grade 7, Grade-5 (Ti-6Al-4V)) in SRF
- Internal (cold) supporting system
  - ✓ Composites (e.g. GFRE, CFRP, ULTEM)
  - ✓ St.steel, titanium alloys (tie rods)
- Thermal shielding/MLI:
  - ✓ aluminum alloys (series 5xxx, 6xxx, 7xxx)
  - ✓ Copper (Cu OF, Cu OFE)
- Vacuum vessel:
  - ✓ Low carbon steels (e.g. DIN GS-21 Mn5)
  - ✓ st.steels (304L)
- Cryogenic piping and expansion joints (bellows):
  - ✓ st.steel (304L)
  - ✓ Cu (HX tubes)
- Current leads (for SC magnets)
  - ✓ Cu, HTS, st.steel, elect. insulating (Kapton), thermal insulating (G10),etc.
- RF Couplers/HOM (for SRF):
  - ✓ St.steel Cu plated, Nb, ceramics, etc.
- Magnetic shielding (for SRF, as needed)
  - ✓ μ-metal, Cryoperm®, etc.



Main dipole

Relevant mechanical failure mechanisms in cryostats

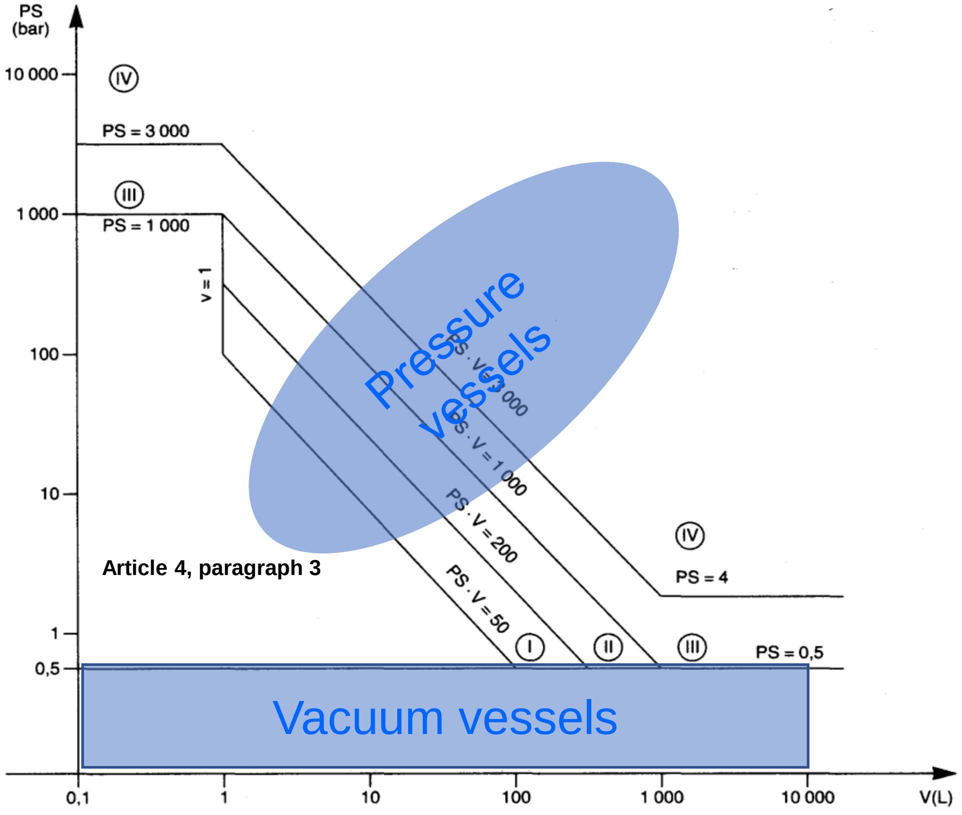
- Helium tanks:
  - ✓ Rupture (rare!) or permanent deformation due to excessive mechanical stress (pressure loads)
  - ✓ Helium leaks in welds or material micro-crack
- Cryogenic lines/expansion joints:
  - ✓ Buckling of expansions joints with or without rupture/leaks
  - ✓ Helium leaks in welds or material micro-crack
- Vacuum vessels:
  - ✓ Buckling under external pressure
  - ✓ Permanent deformations due to excessive stress concentrations
- Internal supporting systems:
  - ✓ Failure due to excessive mechanical stress
  - ✓ Failure due to thermo-mechanical stress
  - ✓ Buckling under compressive load
- Thermal shields:
  - ✓ Permanent deformation due to thermo-mechanical stress (CD/WU transients)
- Alignment jacks:
  - ✓ Break of floor/fixations due to excessive load

Useful material standards for cryostats

Plates and sheets	• EN 10028-1:2007+A1:2009 Flat products made of steels for pressure purposes - Part 1: General requirements • EN 10028-3:2009 Flat products made of steels for pressure purposes - Part 3: Weldable fine grain steels, normalized • EN 10028-7:2007 Flat products made of steels for pressure purposes - Part 7: Stainless steels
Tubes	• EN 10216-5:2004 Seamless steel tubes for pressure purposes - Technical delivery conditions - Part 5: Stainless steel tubes • EN 10217-7:2005 Welded steel tubes for pressure purposes - Technical delivery conditions - Part 7: Stainless steel tubes
Forged blanks	• EN 10222-1:1998 Steel forgings for pressure purposes - Part 1: General requirements for open die forgings • EN 10222-5:1999 Steel forgings for pressure purposes - Part 5: Martensitic, austenitic and austenitic-ferritic stainless steels
Castings	• EN 10213:2007 Steel castings for pressure purposes
Pipe fittings	• EN 10253-4:2008 Butt-welding pipe fittings - Part 4: Wrought austenitic and austenitic-ferritic (duplex) stainless steels with specific inspection requirement
Bars	• EN 10272:2007 Stainless steel bars for pressure purposes
Aluminium	• EN 12392:2000 Aluminium and aluminium alloys – Wrought products – Special requirements for products intended for the production of pressure equipment (choose materials included in the list given in EN 13445-8 section 5.6)

Pressure vessel codes regulations

- Pressure European Directive 2014/68/EC (PED) is a legal obligation in the EU since 2002
  - Applies to internal pressure **≥ 0.5 bar gauge**
  - Vessels must be designed, fabricated and tested according to the requirements defined
  - Establishes the conformity assessment procedure depending on the vessel category, which depends on the stored energy, expressed as Pressure x Volume in bar.l

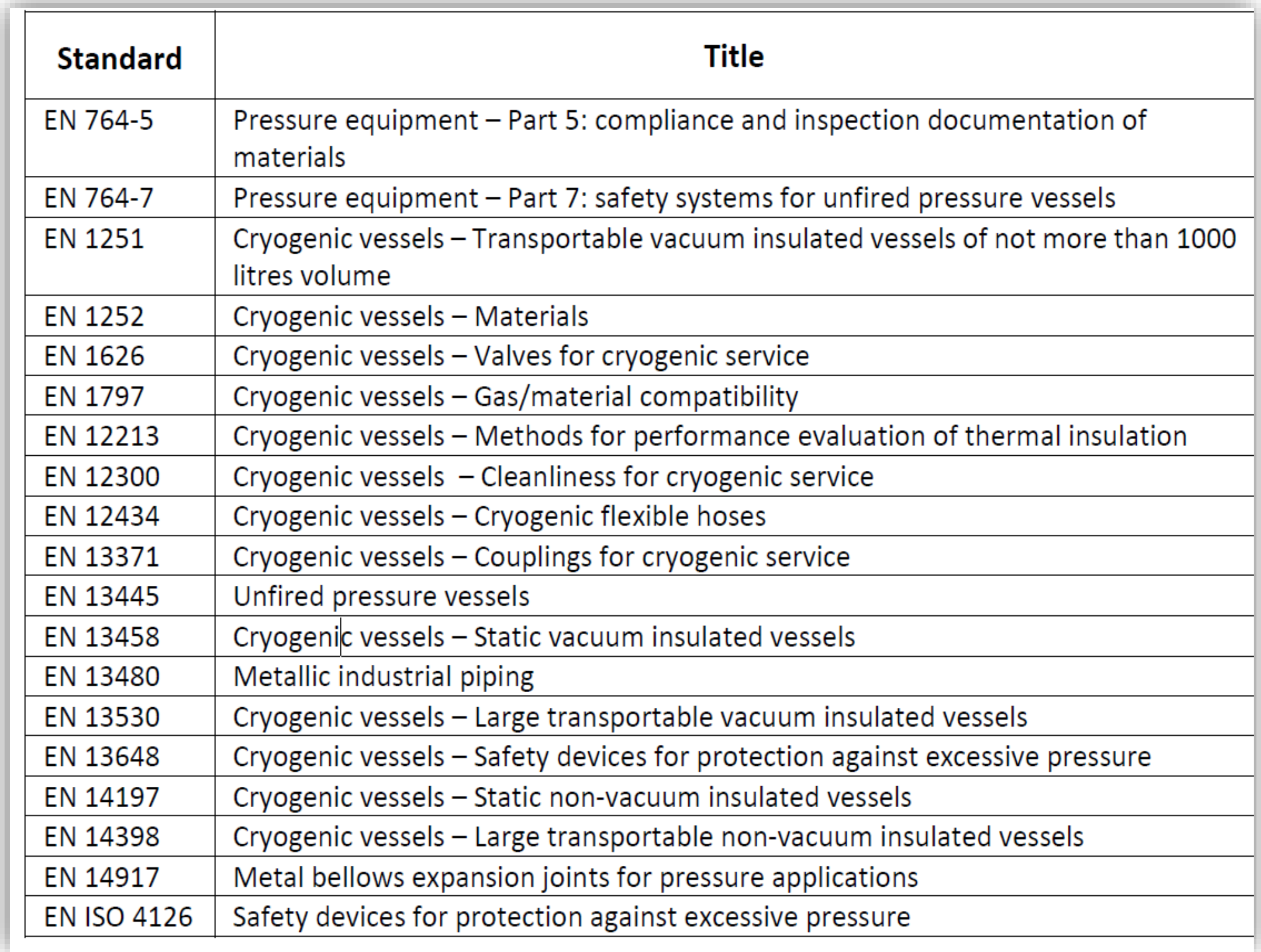


For vessels with non-dangerous gases (cryogenic liquids are treated as gas)

Category	Conf. assessment module	Comment
SEP	None	The equipment must be designed and manufactured in accordance with sound engineering practice. No CE marking and no involvement of notified body.
I	A	CE marking with no notified body involvement, self-certifying.
II	A1	The notified body will perform unexpected visits and monitor final assessment.
III	B1+F	The notified body is required to approve the design, examine and test the vessel.
IV	G	Even further involvement of the notified body.

Harmonised codes and standards

- Harmonised standards give presumption of conformity with the PED, within their scope. Useful codes for cryostat design and fabrication, including safety devices:



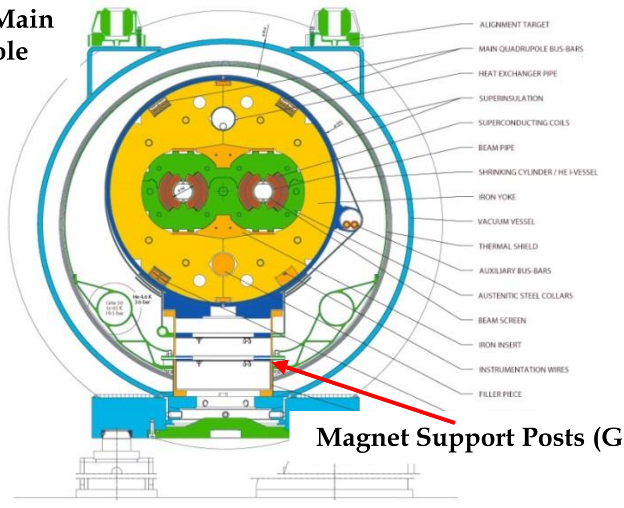
Standard	Title
EN 764-5	Pressure equipment – Part 5: compliance and inspection documentation of materials
EN 764-7	Pressure equipment – Part 7: safety systems for unfired pressure vessels
EN 1251	Cryogenic vessels – Transportable vacuum insulated vessels of not more than 1000 litres volume
EN 1252	Cryogenic vessels – Materials
EN 1626	Cryogenic vessels – Valves for cryogenic service
EN 1797	Cryogenic vessels – Gas/material compatibility
EN 12213	Cryogenic vessels – Methods for performance evaluation of thermal insulation
EN 12300	Cryogenic vessels – Cleanliness for cryogenic service
EN 12434	Cryogenic vessels – Cryogenic flexible hoses
EN 13371	Cryogenic vessels – Couplings for cryogenic service
EN 13445	Unfired pressure vessels
EN 13458	Cryogenic vessels – Static vacuum insulated vessels
EN 13480	Metallic industrial piping
EN 13530	Cryogenic vessels – Large transportable vacuum insulated vessels
EN 13648	Cryogenic vessels – Safety devices for protection against excessive pressure
EN 14197	Cryogenic vessels – Static non-vacuum insulated vessels
EN 14398	Cryogenic vessels – Large transportable non-vacuum insulated vessels
EN 14917	Metal bellows expansion joints for pressure applications
EN ISO 4126	Safety devices for protection against excessive pressure

Very useful
guidelines and design rules

Feedthroughs in cryostats and heat intercepts

Solid conduction paths:

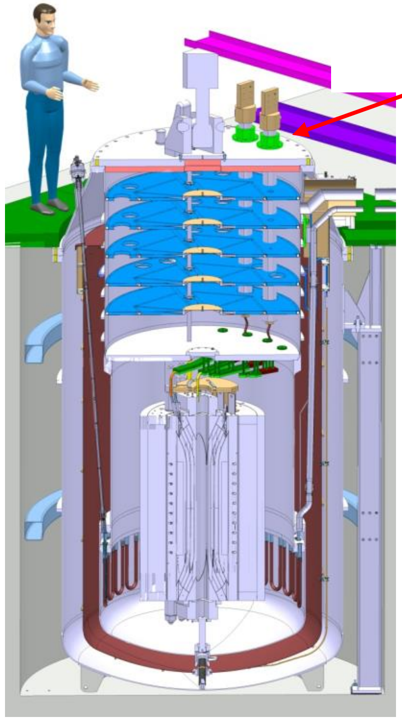
- Supporting systems
- Current leads
- RF main coupler
- Instrumentation feed-throughs
- Beam tubes Cold-to-Warm (CWT) transitions
- …



LHC Main dipole

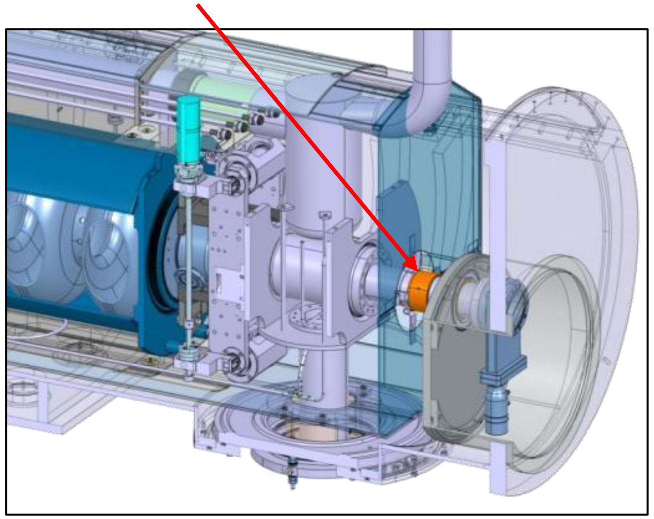
Magnet Support Posts (GFRE)

ERN AC/DI/MM — 06-2001



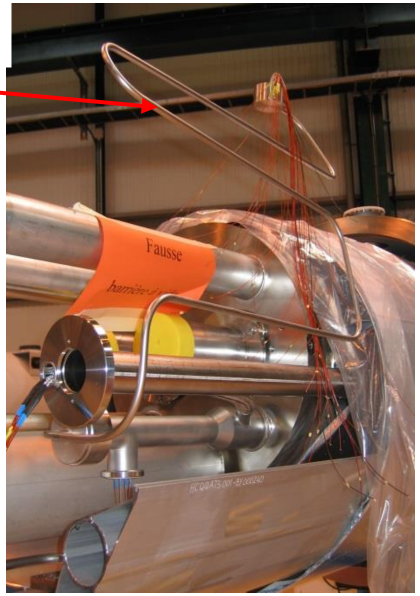
Current leads

Vertical cold magnet test cryostat



CWT SPL cryomodule

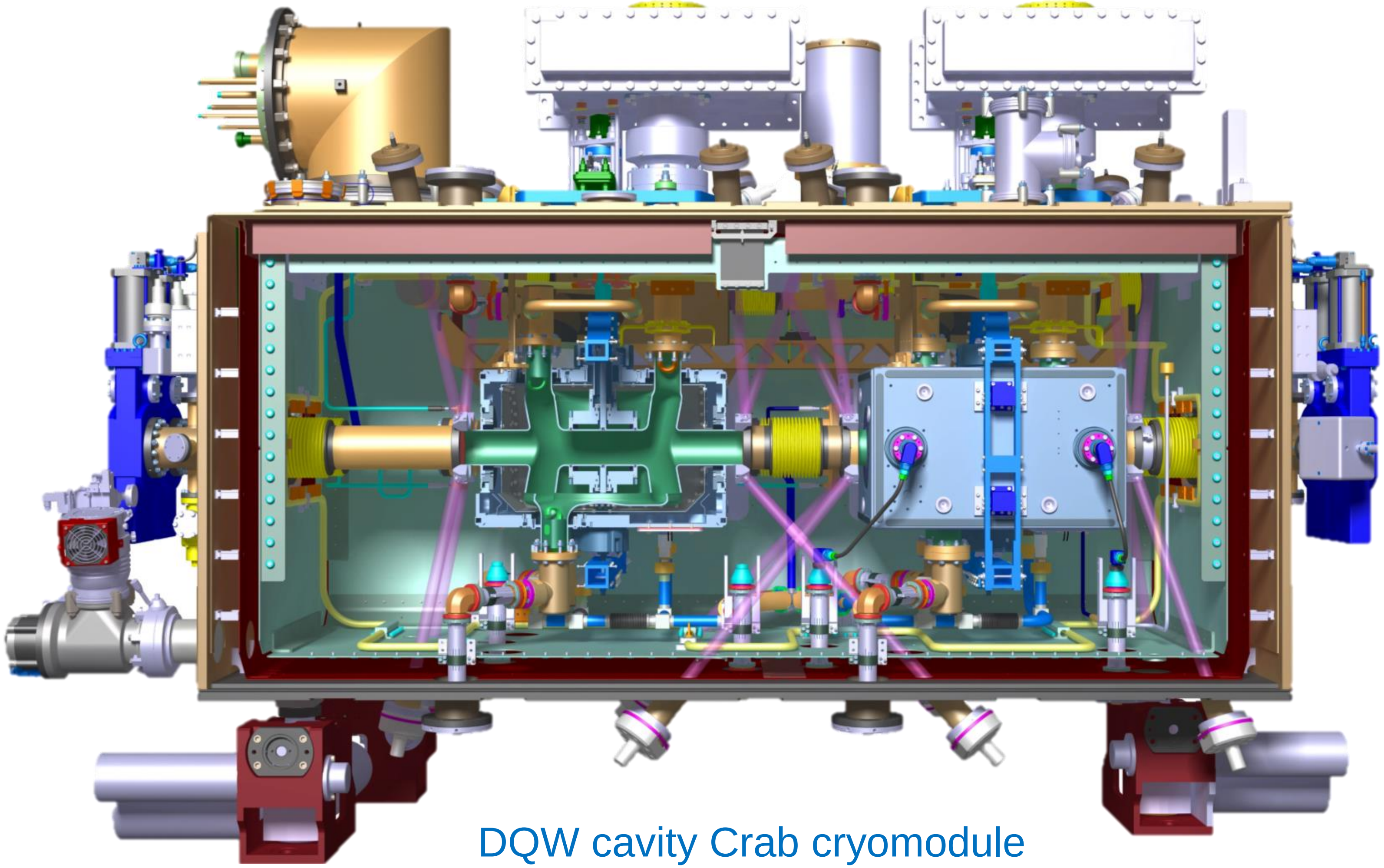
SPL cryomodule



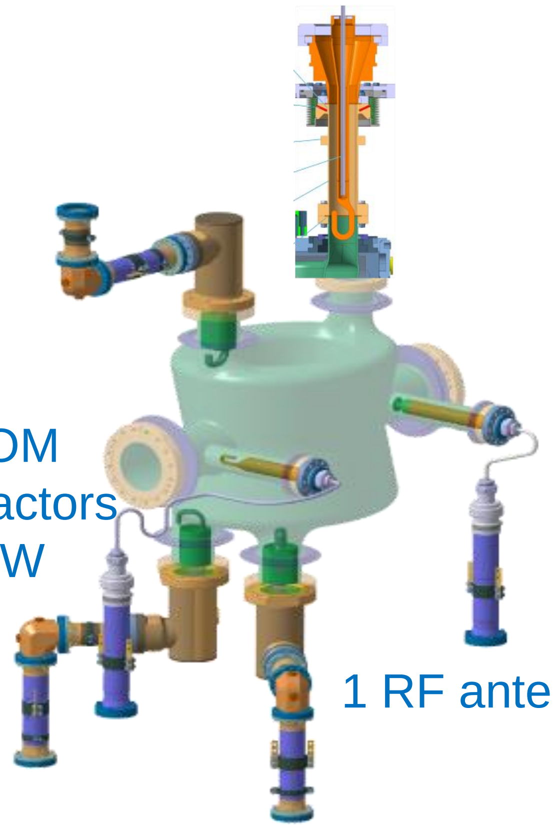
LHC instrumentation capillary at assembly

LHC Quadrupole cryostat

Crab cryomodule at CERN



DQW cavity Crab cryomodule



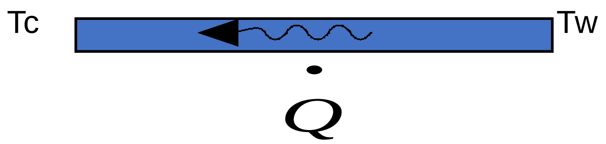
1 power coupler (40kW-CW)

4 HOM extractors ~1 kW

1 RF antenna)

DQW cavity with RF feeds

Thermal Conduction



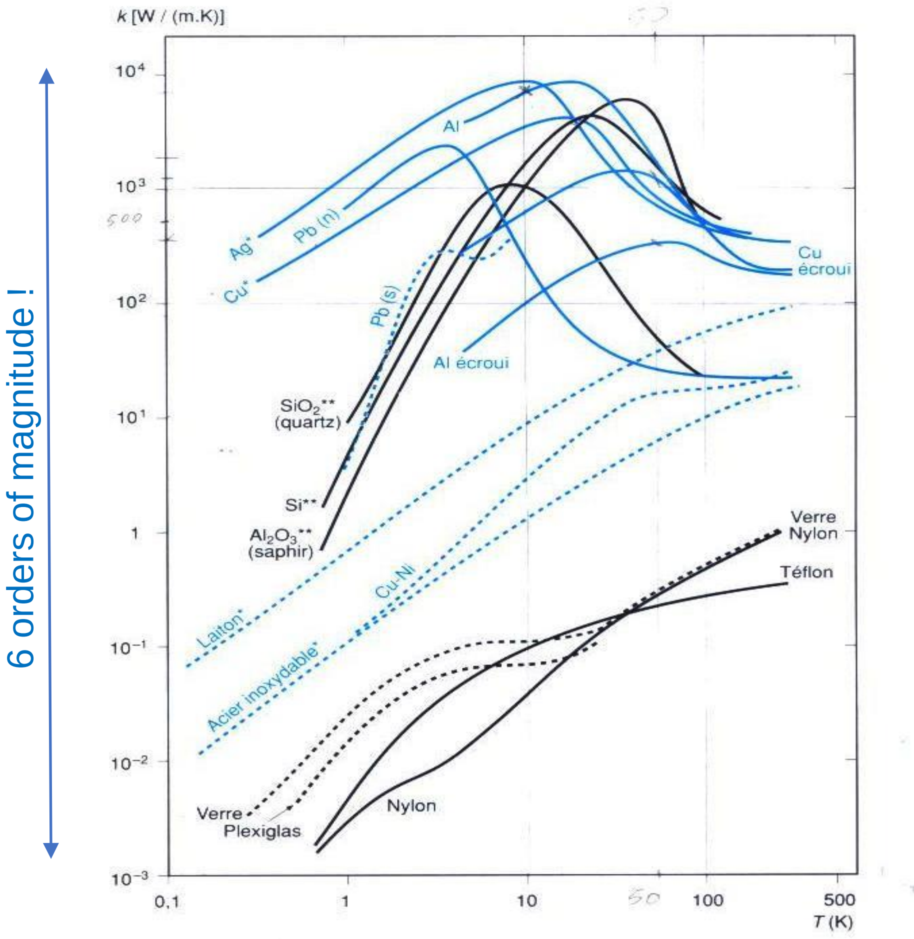
- ΔT in a body → heat transfer from the high T to the low T (Fourier Law):

$$\dot{Q} = -kA\, grad(T)$$

- For one-dimensional problems (ex. a bar or tube):

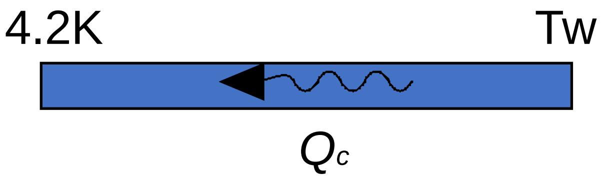
$$\dot{Q} = -kA\frac{dT}{dx}$$

- k is the thermal conductivity (W m^{-1} K^{-1}), normally a function of P,T, material structure, non-homogeneity, anisotropy (ex. Composite materials).
- k is strongly T-dependent and non-linear at low T
- "good conductors" vs. "poor conductors" → k range ~ 5-6 orders of magnitude



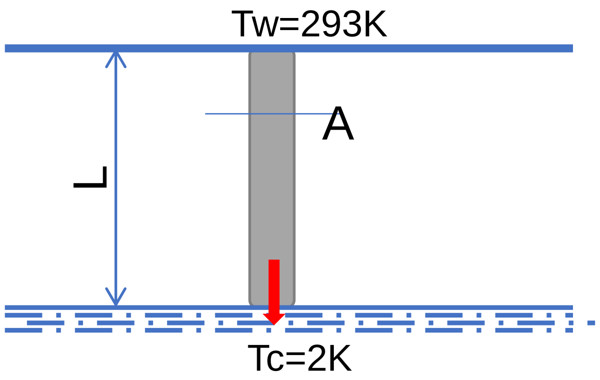
Thermal conductivity integrals (conductance) for some materials [W/m]

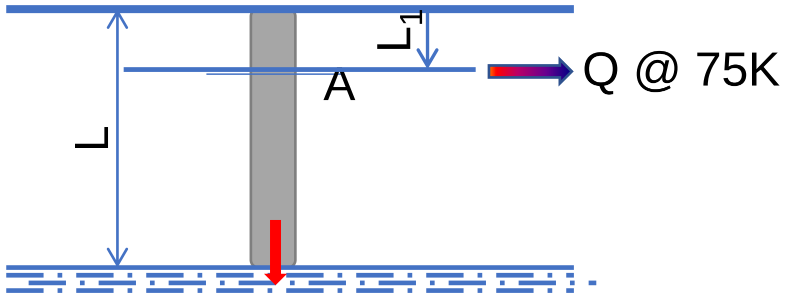
$$Qc = \frac{A}{L} \int_{4.2K}^{Tw} k(T)dT$$

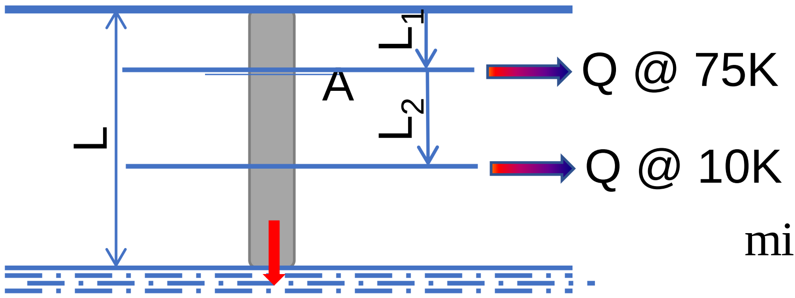


Highest T *(Lowest T =4.2 K)*	20 K	80 K	290 K
OFHC Copper	11000	60600	152000
DHP Copper	395	5890	46100
Aluminium 1100	2740	23300	72100
Aluminium 2024	160	2420	22900
Stainless steel AISI 304	16,3	349	3060
Typical Glass-fiber/Epoxy Composite G-10	2	18	153

Heat intercepts (heat sinking) at intermediate temperatures







- simple solid conduction

$$\dot{Q} = \frac{A}{L}\int_{Tc}^{Tw} k(T)\,dT$$

- 1 heat intercept at optimal distance

$$\min\{f(L_1) = C1 \cdot \frac{A}{L_1}\int_{Tw}^{80K} k(T)\,dT + C2 \cdot \frac{A}{L - L_1}\int_{80K}^{Tc} k(T)\,dT\}$$

$\rightarrow$ L_1

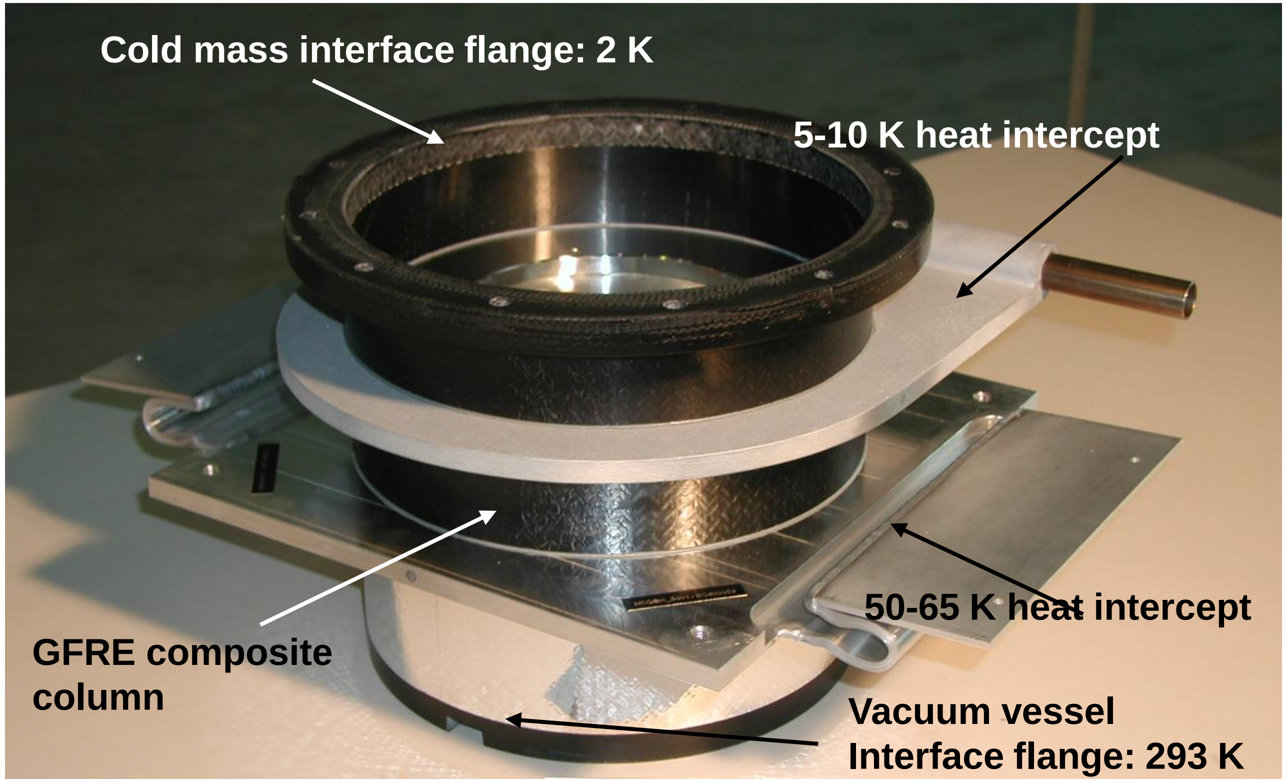
- 2 heat intercepts at optimal distance

$$\min\{f(L_1, L_2) = C1 \times \frac{A}{L_1}\int_{Tw}^{80K} k(T)\,dT + C2 \times \frac{A}{L_2 - L_1}\int_{80K}^{8K} k(T)\,dT + C3 \times \frac{A}{L - L_2}\int_{8K}^{Tc} k(T)\,dT\}$$

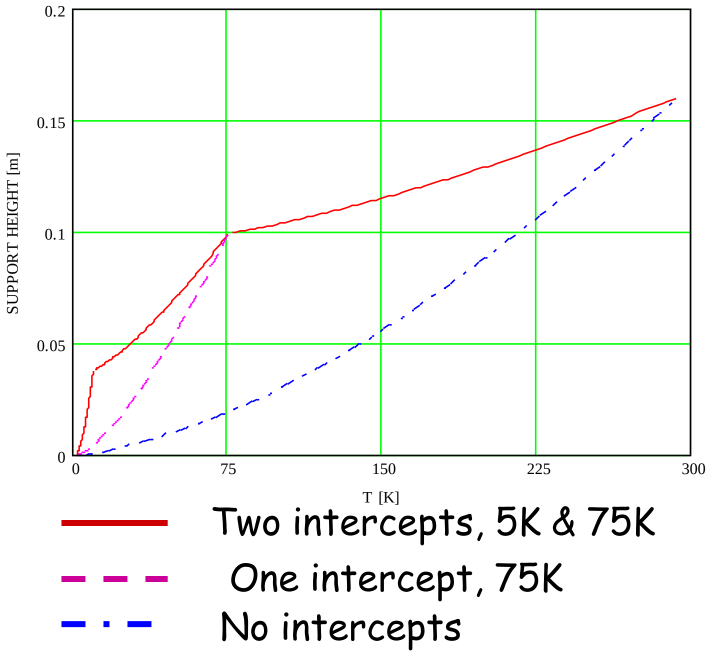
$\rightarrow$ L_1, L_2

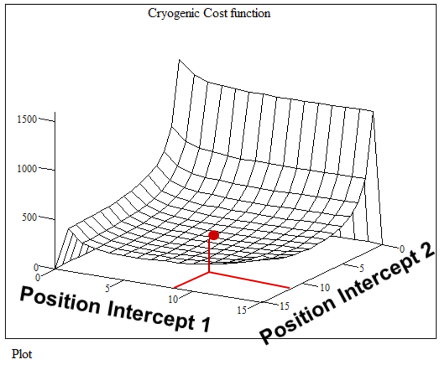
C1, C2, C3, COP at relevant T

LHC supports



- >10 tons vertical compression load
- **4-mm thickness**, glass-fiber epoxy
- Manufactured by **Resin Transfer Moulding (RTM):**
  - Suited to a large-scale industrial production (4’700 units)
  - High reproducibility in thermo-mechanical properties





Minimizing using efficiency factors:

C_1 = 16 w/w @ 75 K

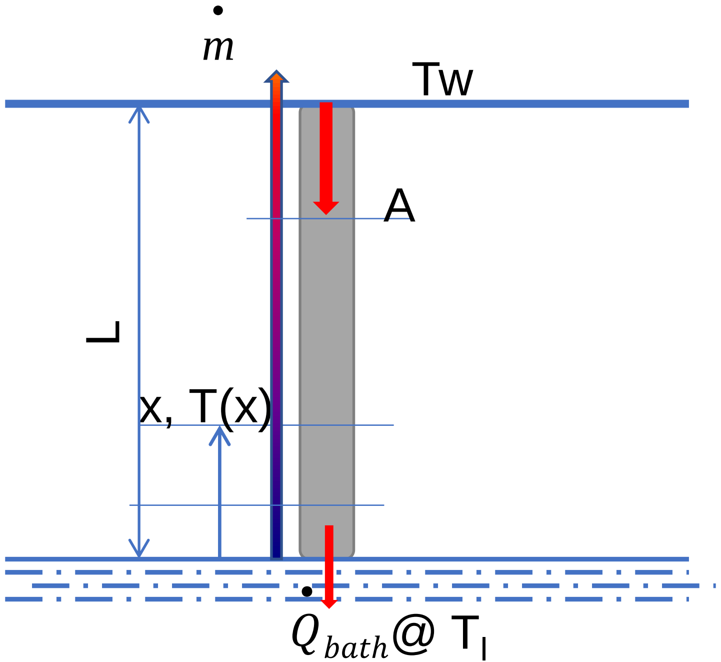
C_2 = 210 w/w @ 5 K

C_3 = 990 w/w @ 1.9 K

	$Q_{1.8K}$ [W]	Q_{5K} [W]	Q_{75K} [W]	$Q_{elec.}$ [W]
1	2.79	-	-	2790
2	0.541	-	6.44	638
3	0.047	0.42	7.1	252

Heat loads comparison for GFRE with & without heat intercepts

Vapour cooling in solid conduction



Large enthalpy in He vapours (1550 kJ/kg from 4.2K to 300K) → usable cooling capacity

- Vapor cooled wall
- Assuming perfect exchange ($T_{vapor} = T_{wall}$)

$$k(T)\cdot A\cdot\frac{dT}{dx}=\dot{Q}_{bath}+\dot{m}\cdot Cp\cdot(T-Tl)$$

- With $\dot{Q}_{bath}$ the residual heat to the bath
- If $\dot{Q}_{bath}$ is equivalent to the evaporation mass flow → self-sustained mode:

$$\rightarrow \dot{Q}bath=\dot{m}\cdot Lv \qquad Lv,\ \text{latent heat of evap.}$$

$$\boxed{\dot{Q}_{bath}=\frac{A}{L}\cdot\int_{T_l}^{Tw}\frac{k(T)}{\boxed{1+\frac{(T-Tl)\cdot Cp}{Lv}}}\cdot dT}$$

attenuation factor (w.r.t. solid conduction)

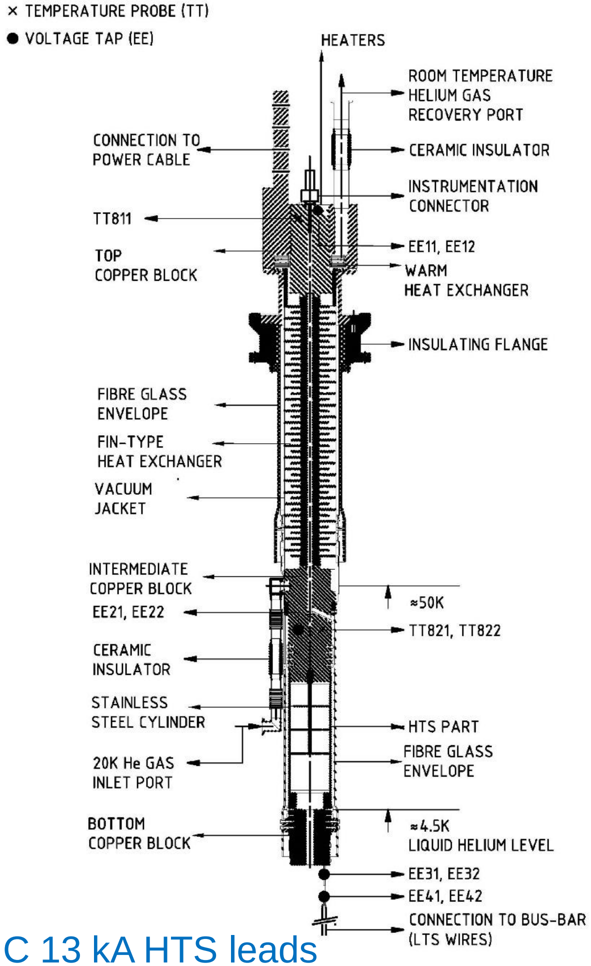
thermal conductivity integral (4K - 300 K)	Conduction $[W.cm^{-1}]$	Self-sustained vapour-cooling $[W.cm^{-1}]$	% Ratio
ETP copper	1620	128	8%
OFHC copper	1520	110	7%
Aluminium 1100	728	39.9	5%
Nickel 99% pure	213	8.65	4%
Constantan	51.6	1.94	4%
AISI 300 st. steel	30.6	0.92	3%

Ideal values

Real case depends on how good the heat exchange is

Application: Current leads and RF power couplers

- Vapour/forced flow cooled current leads (conventional or HTS)

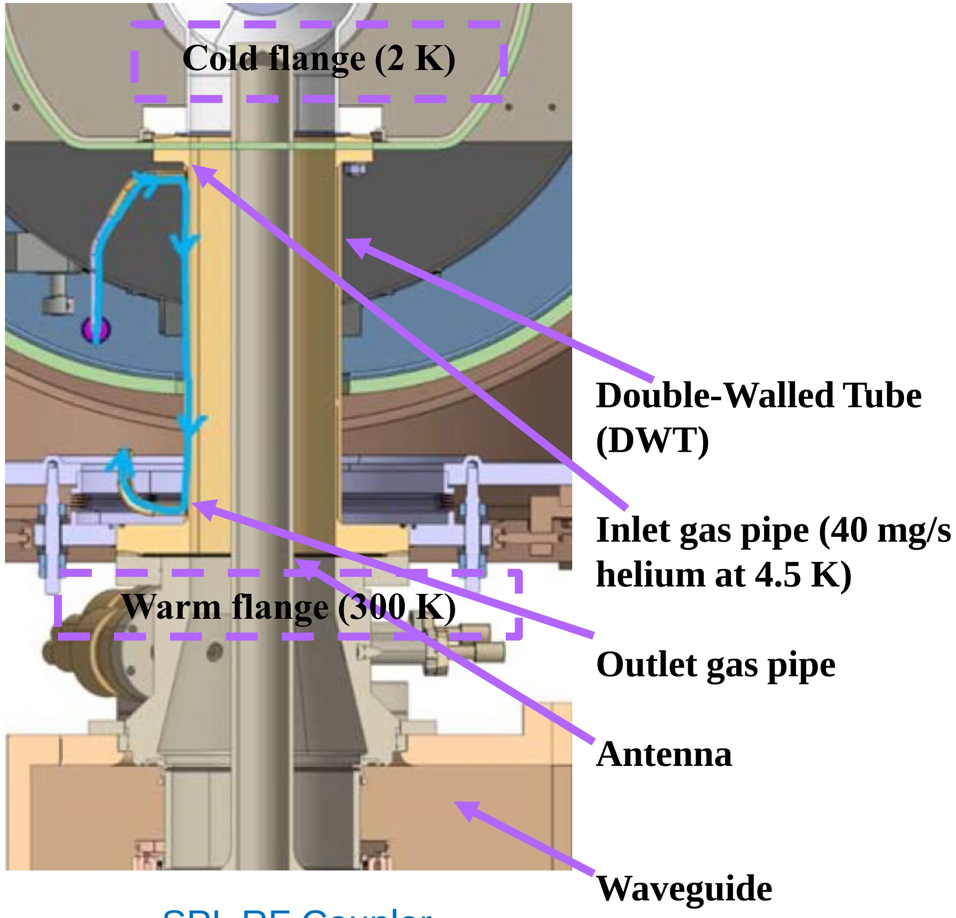


CERN `LHC 13 kA HTS leads

Effectiveness:

- Reduced static heat conduction
- Partial intercepting of I^2R resistive heating

- Vapour/forced flow cooled RF couplers external conductors



SPL RF Coupler

Effectiveness:

- Reduced static heat conduction
- Partial intercepting of RF resistive heating
- Regulation flexibility (stand by, RF power on)

Main take-aways from this talk

- SC device supporting systems to ensure accurate/reproducible positioning

- Thermal design:
  - ✓ Radiation → Actively cooled thermal shield with MLI
  - ✓ Feedthroughs → low conductivity materials + heat interception (vapour cooling for powering feedthroughs)

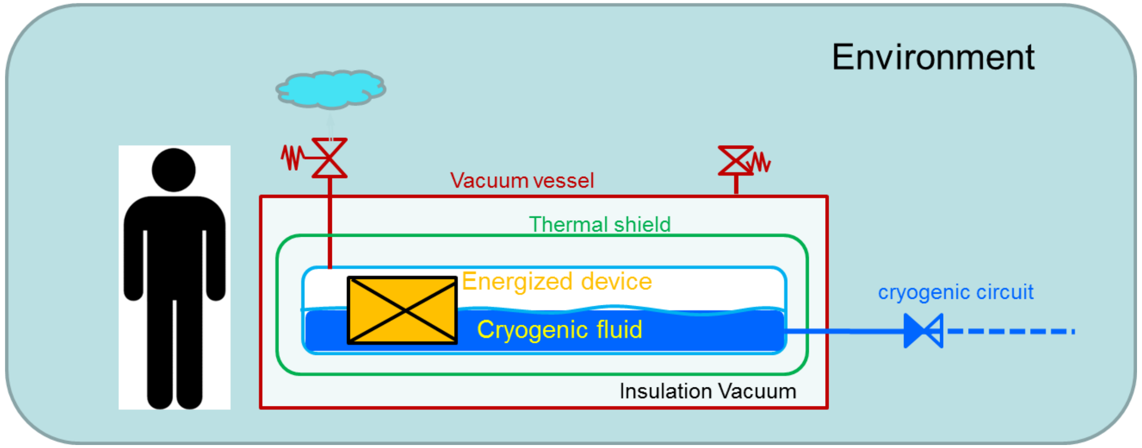
- Materials: mostly commercial grades (st.steels), also specific (Ti alloys), use standards

- Pressure vessels and legal liability (PED)

- Beware of cryogenic safety aspects

A few words on Cryogenic Safety

Cryostats and safety



- Cryostats include inventory of cryogenic fluids, *potentially* unstable stored energy, and sometimes large electro-magnetic stored energy in superconducting devices

- Managing safety in cryostat covers multiple aspects: safety of personnel and equipment
  - Risk assessment: cryostat as part of a cryogenic system in an environment
  - Safety hazard from relief of cryogens to the environment: ODH, burns, escape paths, safety training, use of personnel protection equipment, risk to adjacent equipment, etc.

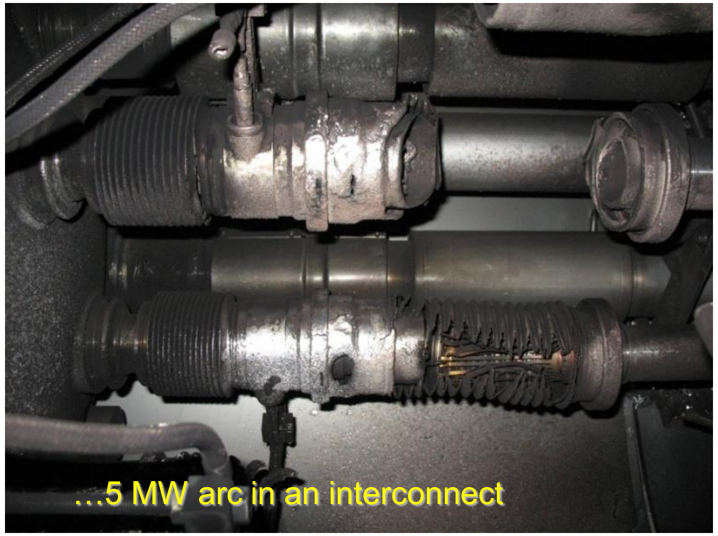
→ Understanding pressure hazards and making the correct choice of the pressure relief devices to protect from overpressure of the cryostat envelopes

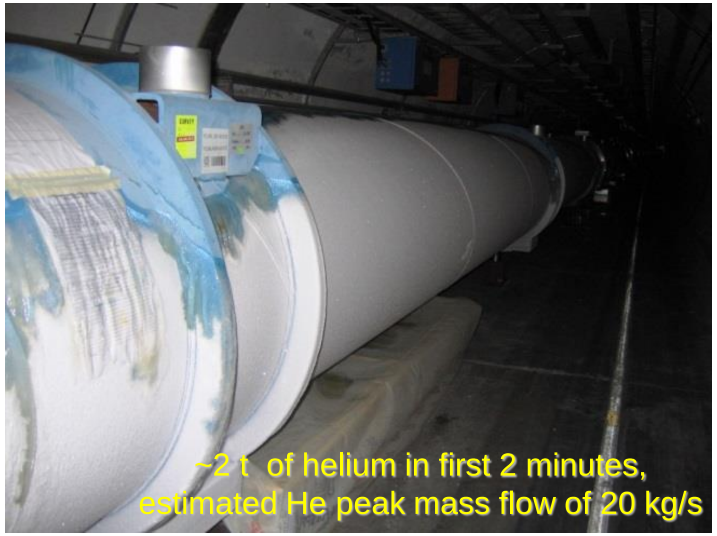
Example. 2005: LN2 dewar (70 l) overpressure blast at Ganil (France)

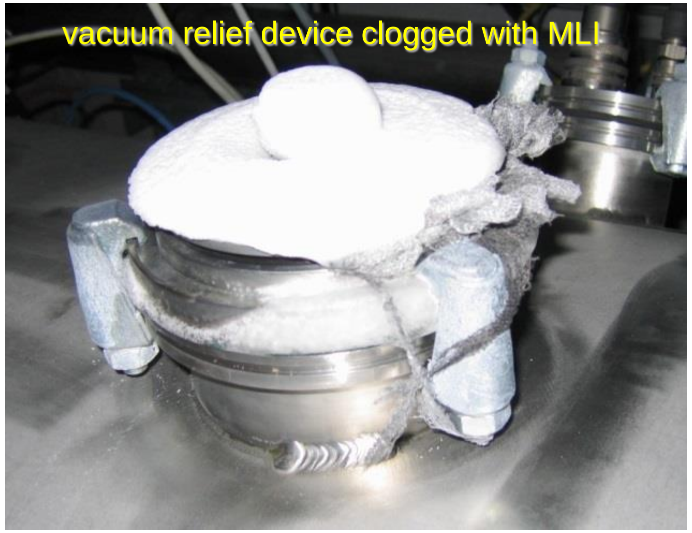
- September 21st 2005, 7:30 PM: explosion of a 70-liter LN2 dewar
- Cause: safety device directly implemented on the dewar (old equipment)
- Consequence: destruction of 200 m^2 of experimental rooms and offices, no casualties

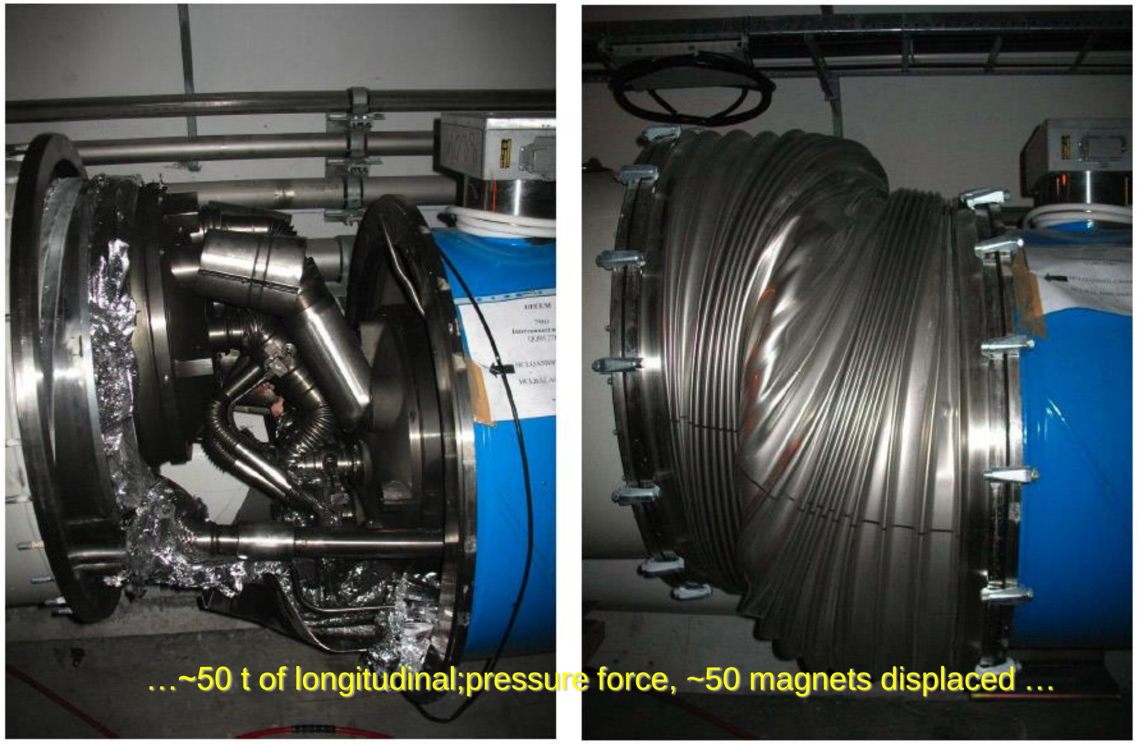
(courtesy N.Bazin, CEA-Saclay)

Example at CERN. LHC 19th sept. 2008


…5 MW arc in an interconnect


~2 t of helium in first 2 minutes,
estimated He peak mass flow of 20 kg/s


vacuum relief device clogged with MLI


…~50 t of longitudinal;pressure force, ~50 magnets displaced …

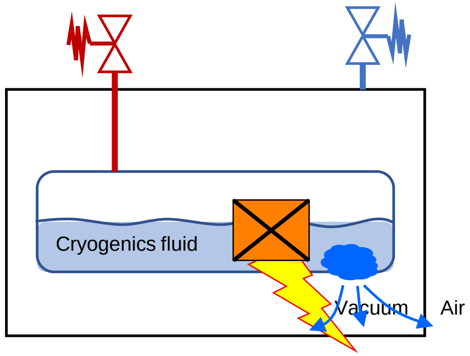

…uprooting of jacks

Report of the Task Force on the incident of 19 September 2008
at the LHC, CERN EDMS 992622

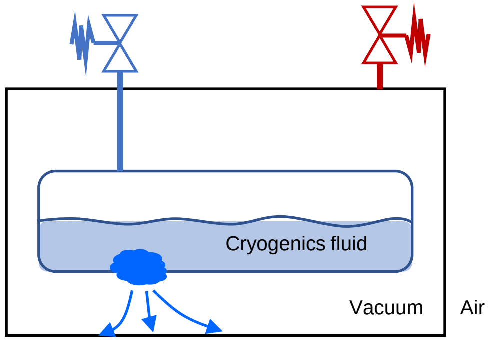
Pressure hazards in cryostats

- Potential pressure hazards:
  - Compressors connected to cryo lines
  - Heating of “trapped” volumes (typically in a circuit between valves) during warm-ups
  - Helium leak to insulation vacuum, with consequent increased conduction/convection heat loads to cryogenic liquid vessels
  - Cryo-condensed air leaks on cold surfaces and consequent pressure increase and increased conduct/convection heat loads during warm-ups
  - …
  - A) Heating/vaporization of cryogens from sudden release of stored energy in SC device (e.g. quench or arcing in a SC magnet circuit)
  - B) Accidental release of cryogenic fluid to higher T surfaces (thermal shield and vacuum vessel), and consequent pressure increase and increased of conduction/convection heat loads to cold surfaces
  - C) Accidental air venting of insulation vacuum with sudden condensation on cold surfaces, helium boil-off and pressure build-up

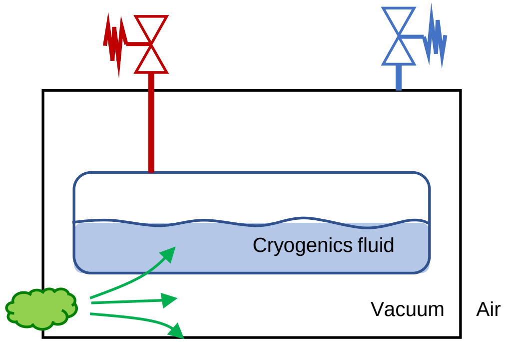
Usually the most critical



A) Quench (or el.arc)



B) Rupture of helium tank



C) Air venting

(Snowball effect A) + B) + C) → LHC event of Sept.2008)

EN 17527 Helium cryostats - Protection against excessive pressure

- Publication of EN 17527

BS EN 17527:2021

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 17527

December 2021

English Version

Helium cryostats - Protection against excessive pressure

DEUTSCHE NORM

Mai 2022

DIN EN 17527

DIN

Ersatz für
DIN SPEC 4683:2015-04

Gesamtumfang 126 Seiten

Publication date
May 2022

Scope includes:

- ✓ SC magnet cryostats
- ✓ SRF cavity cryomodules
- ✓ Ultra-low T refrigerator systems
- ✓ Coldboxes of helium refrigerators and liquefiers
- ✓ Helium distribution systems including valve boxes

Overall concept:

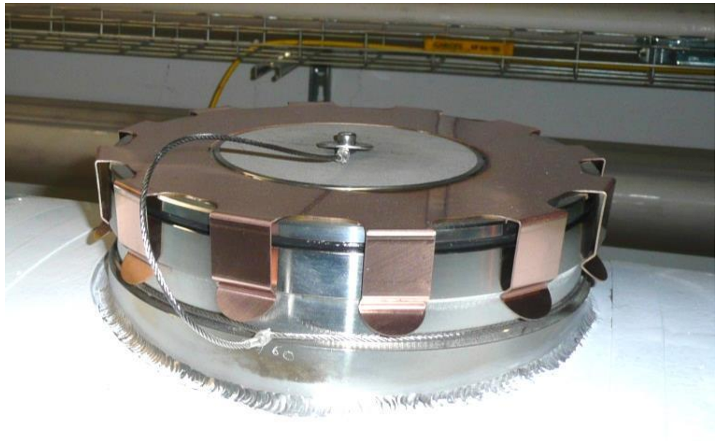
- ✓ Standardization of the approach
- ✓ Specification of procedures and minimum requirements
- ✓ Risk assessment, definition of scenarios
- ✓ Protection concepts (single-stage, multi-stage)
- ✓ Dimensioning rules of pressure relief devices (HEM Model)

Safety devices

1. Safety valves
2. Burst discs
3. Pressure relief plate

2.

1.



3.

<u>A few suppliers</u>

Herose, Rembe, Ramseyer, Leser…

Thank you for your attention

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Interested in learning more ? CERN Technical Training

Course on: ***Cryostat Engineering for Helium Superconducting Devices***

Format: 3.5 days

- Lectures (including tutorials) in classroom on **cryostat design, helium cryogenics (including LHeII)**
- Tutorials, case study in classroom (by groups of students)
- Visit of a CERN cryogenic installation

When: Oct./Nov. 2024 (dates still to be finalized)

Place: CERN training centre

Contact: technical.training@cern.ch

Note: open to external participants from laboratories (no. places limited)