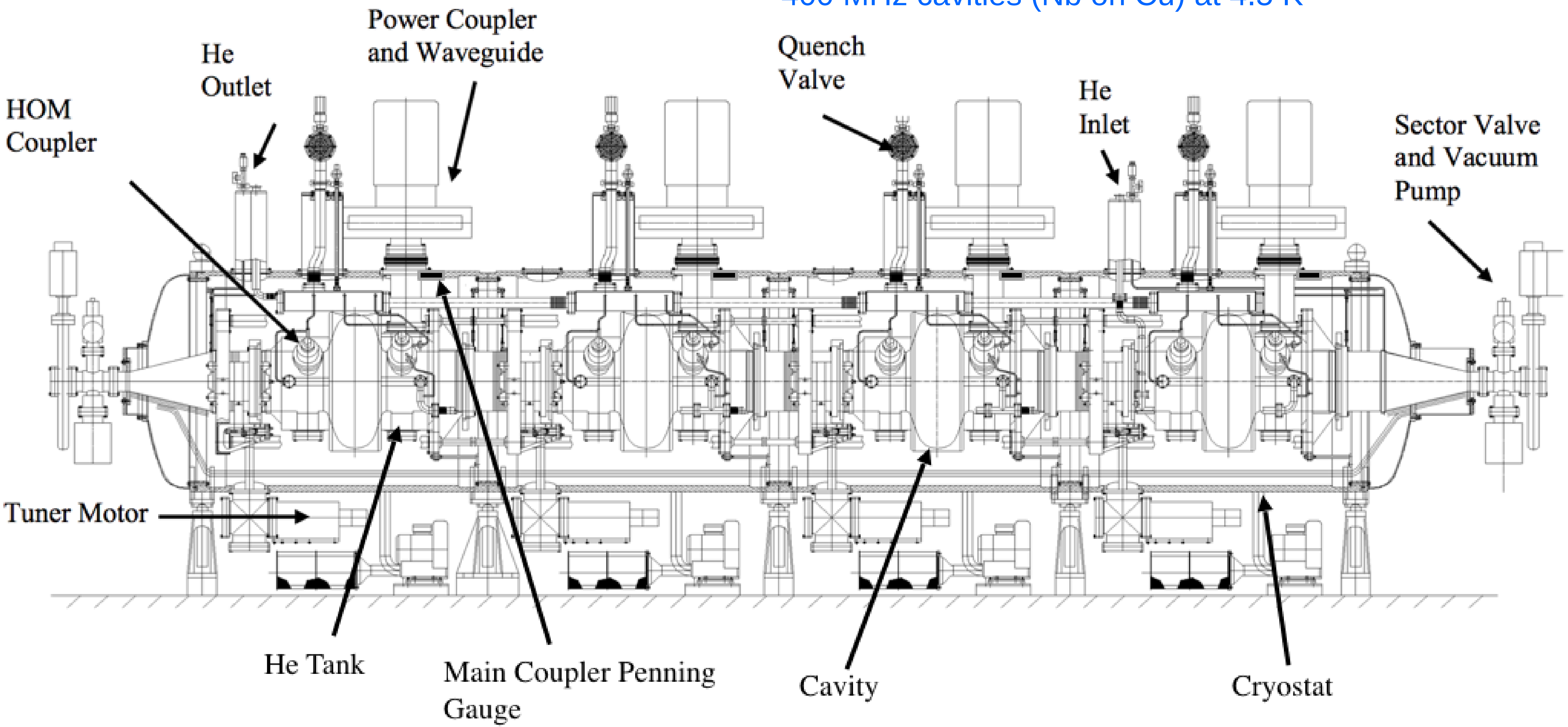
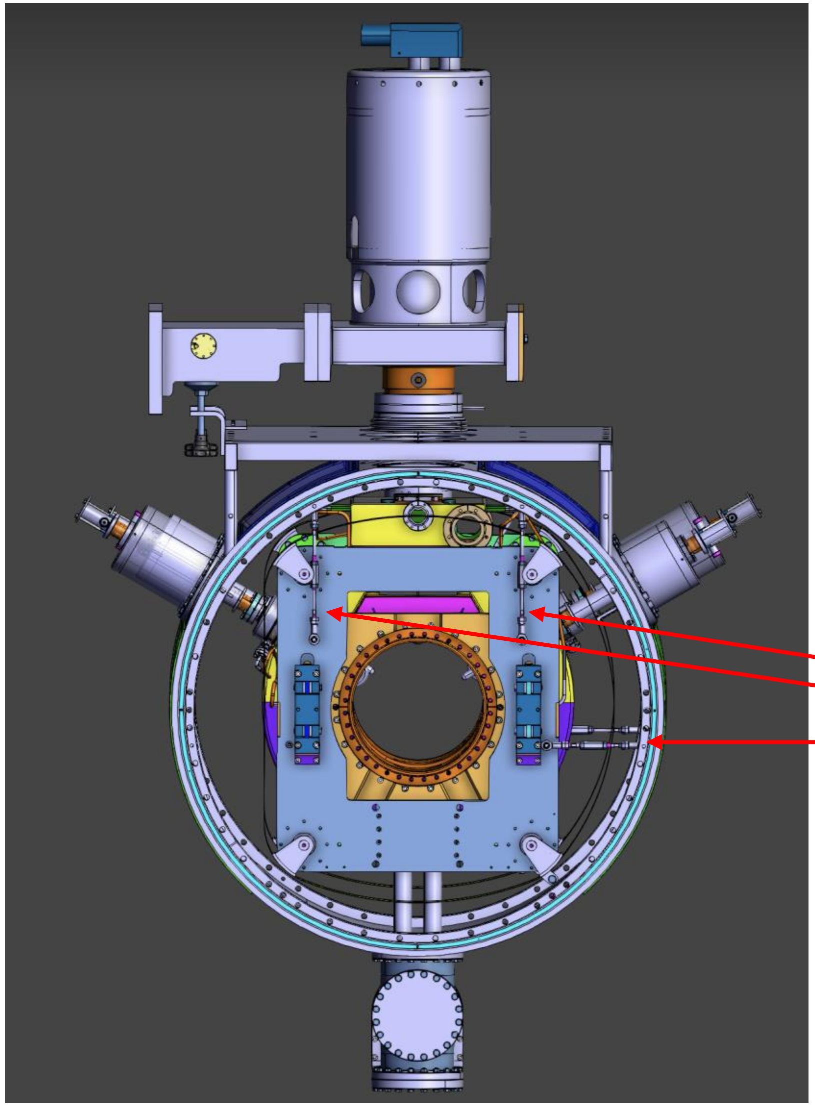
Appendix 1: Supporting systems

LHC Cryomodule

400 MHz cavities (Nb on Cu) at 4.5 K

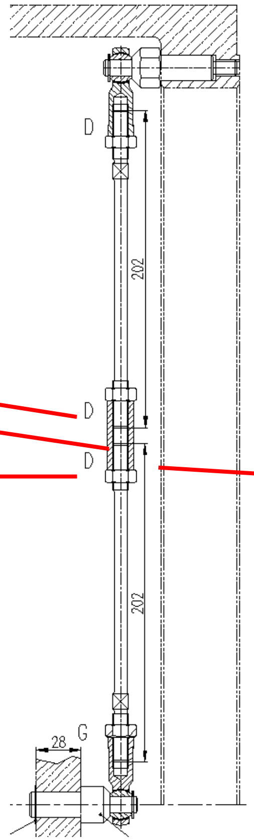


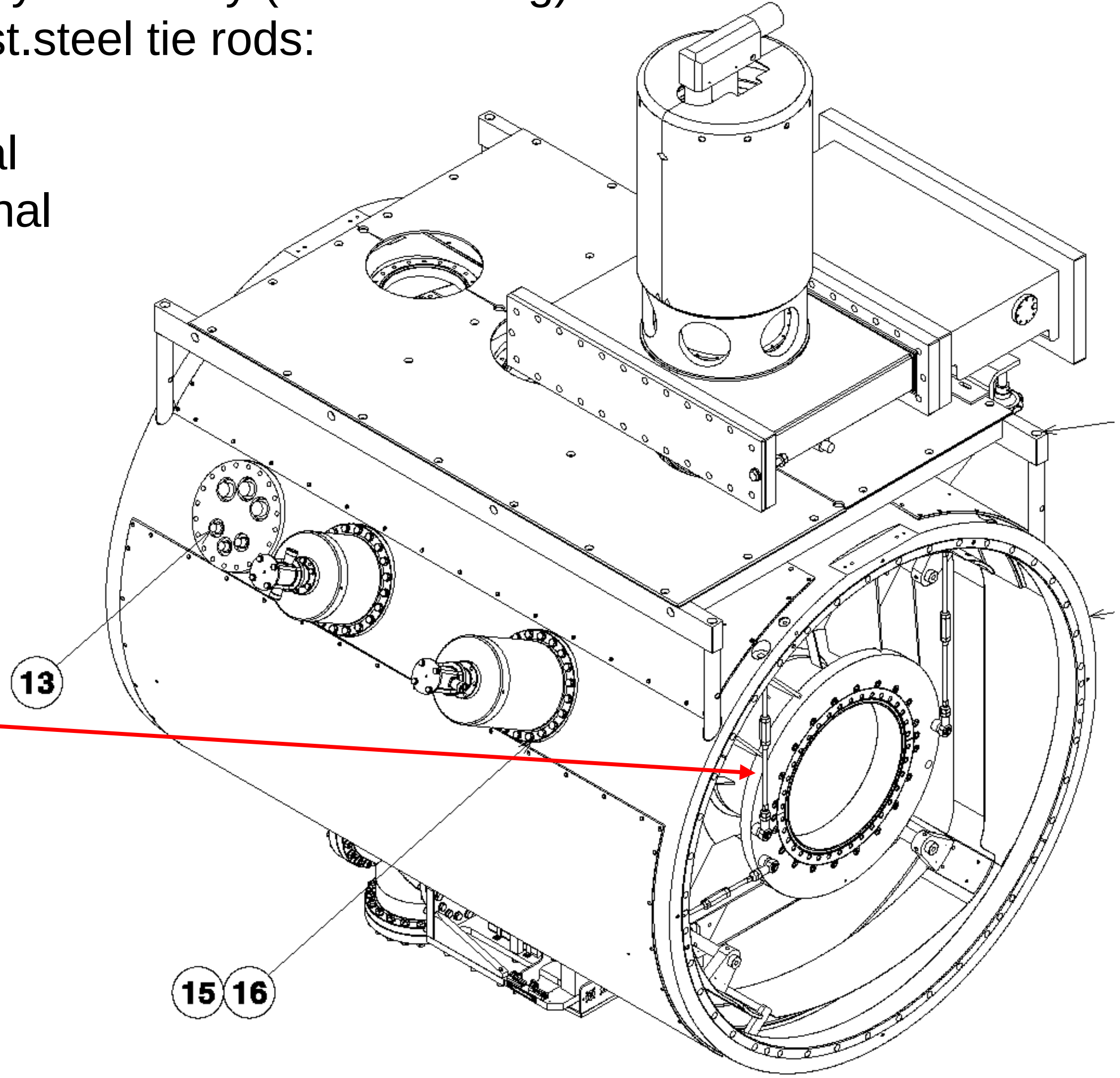
LHC Cryomodule Supporting System



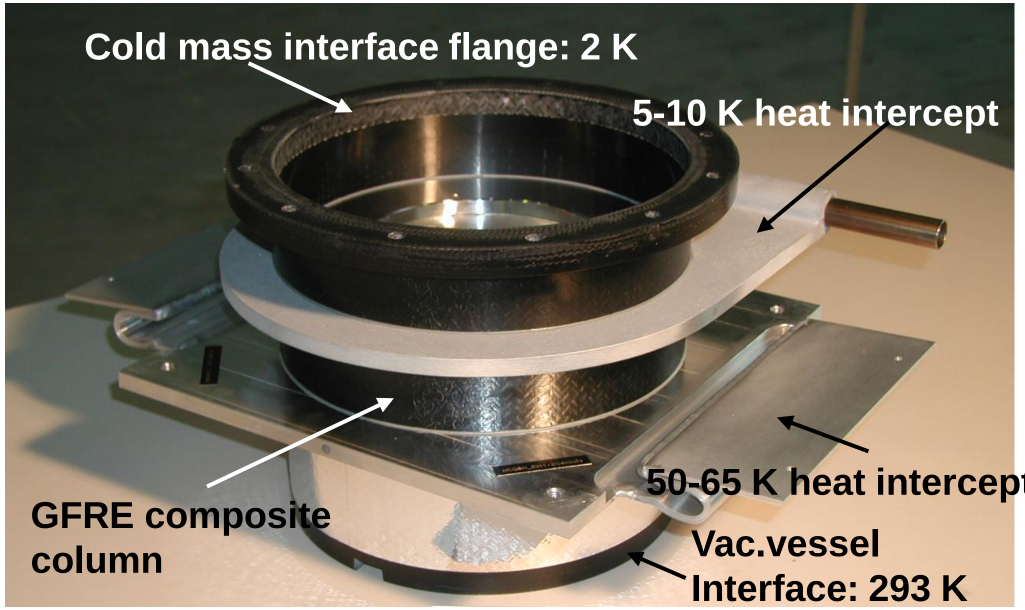
For each cavity assembly (about 500 kg):
7 adjustable st.steel tie rods:

- 4 vertical
- 2 horizontal
- 1 longitudinal



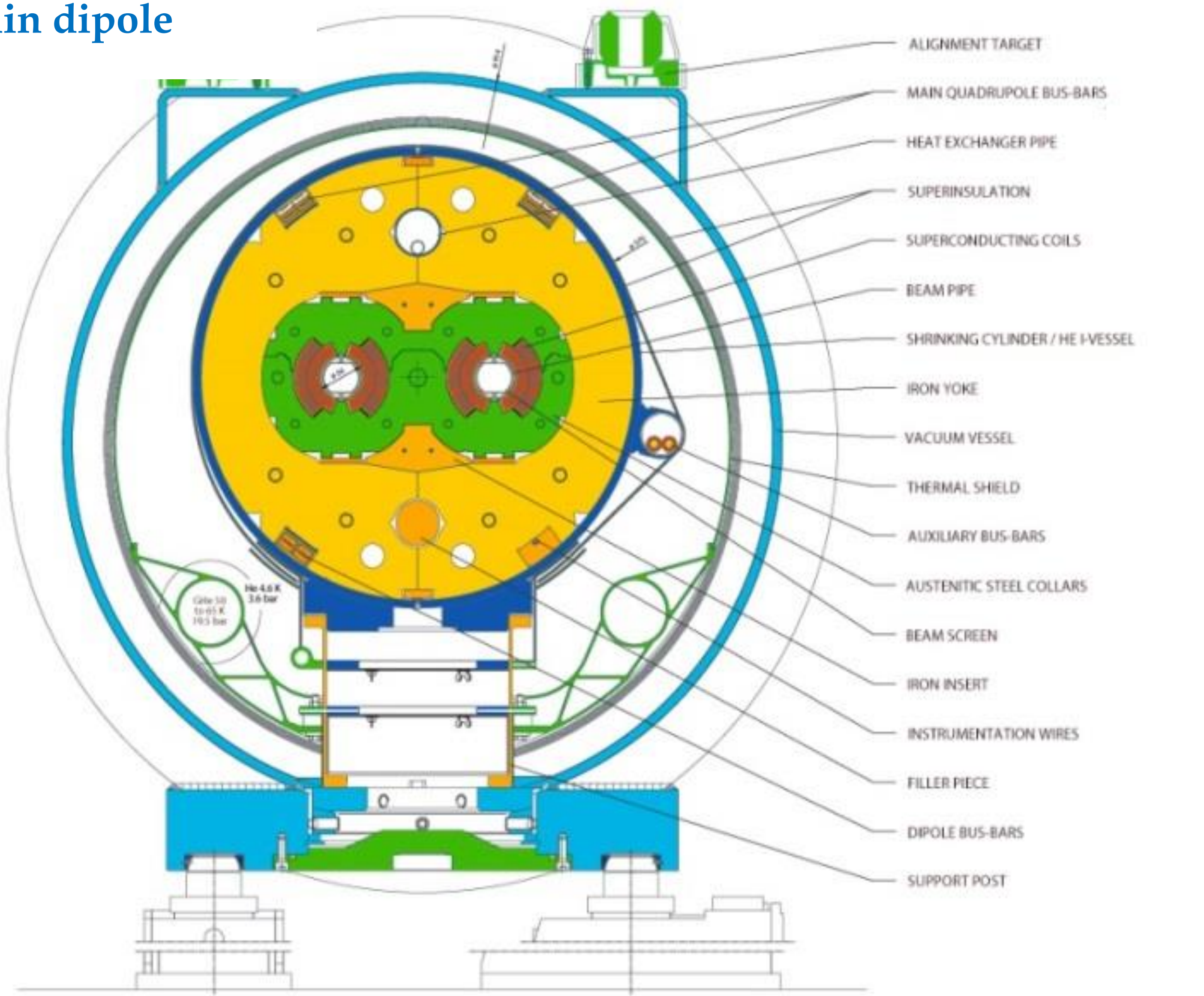


LHC magnet Cryostats



- **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

Main dipole



Lay-up, calculated safety factors, material properties

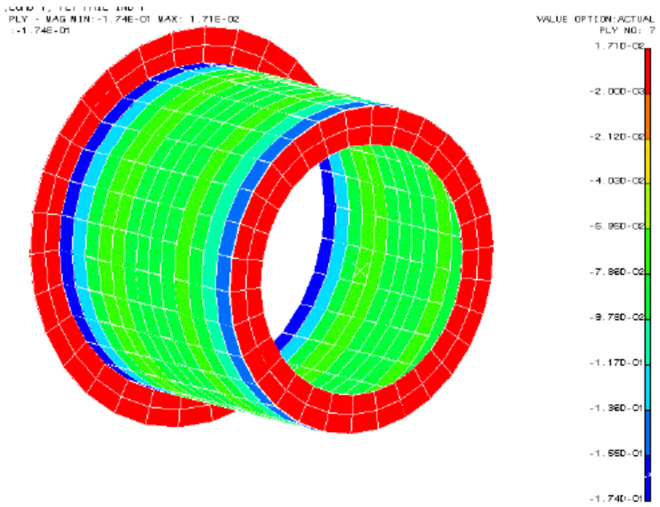
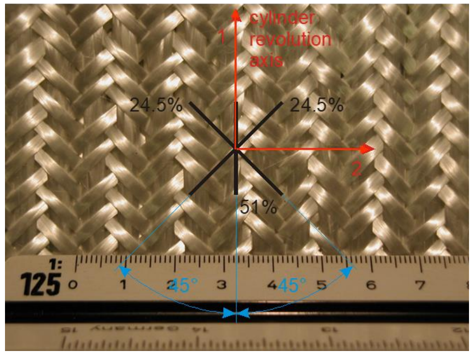
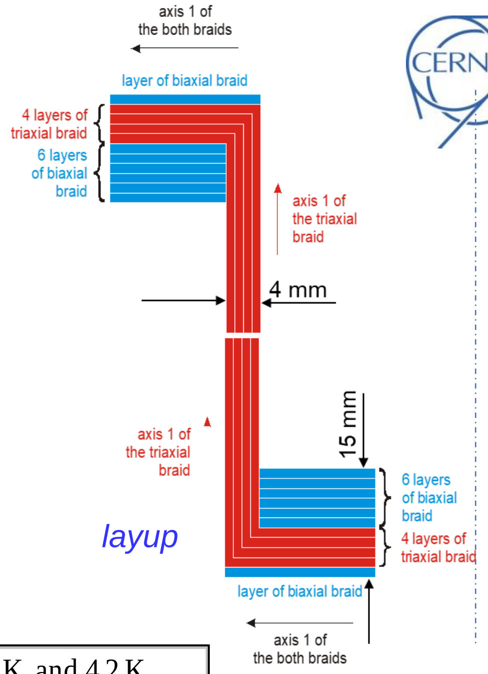


Figure 4.2.1.1 Ply Failure Index. LS 1.1-A

Compression load: 175kN (175% gravity load, transport limit)
Tsai-Wu ply failure: Safety Factor = **6**
E modulus: 24 GPa



Triaxial braid and % fiber volumes



layup

Tensile testing on 5 longitudinal samples, at 293 K, 77 K, and 4.2 K.

Test at 293K	Rm (MPa)	Test at 77K	Rm (MPa)	Test at 4.2K	Rm (MPa)
Average	**459.3**	**Average**	**570.4**	**Average**	**496.7**
Min.	436.6	Min.	535	Min.	441.2
Max.	485.1	Max.	586	Max.	519.5

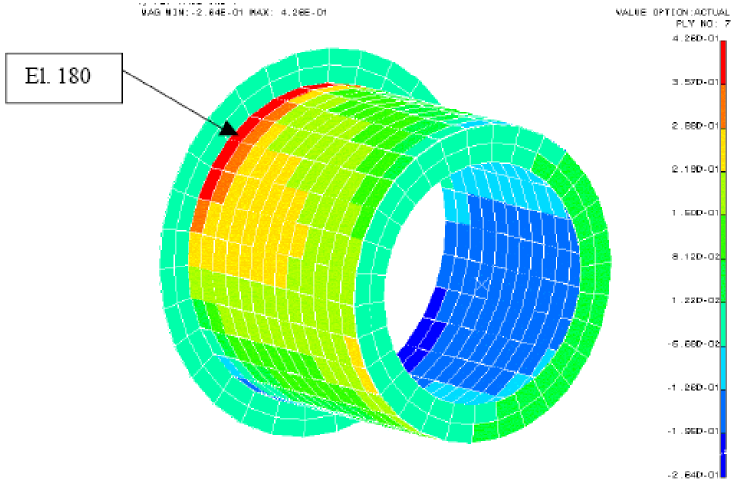
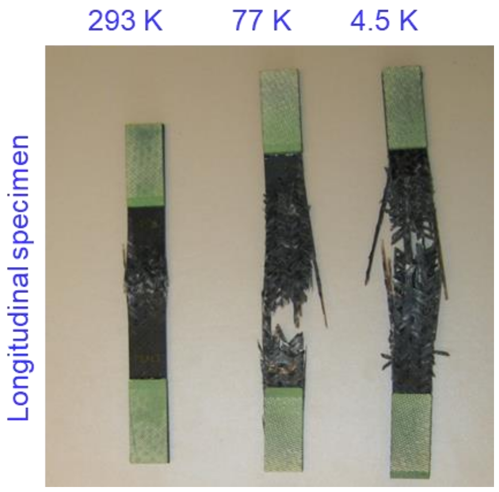


Figure 4.2.2.1 Ply Failure Index. LS 1.2.1-A

Bending cantilever 40 kN. (vacuum barrier load)

Tsai-Wu ply failure: Safety Factor = **2.7**



Resin Transfer Moulding

Cutting the fabrics to length

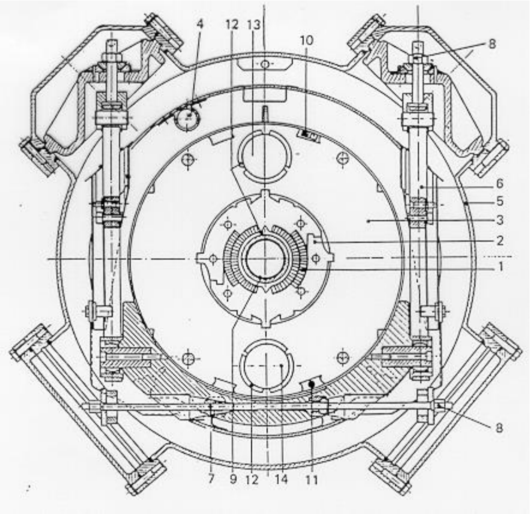
Lay-up stacking

Sealed closing of mould

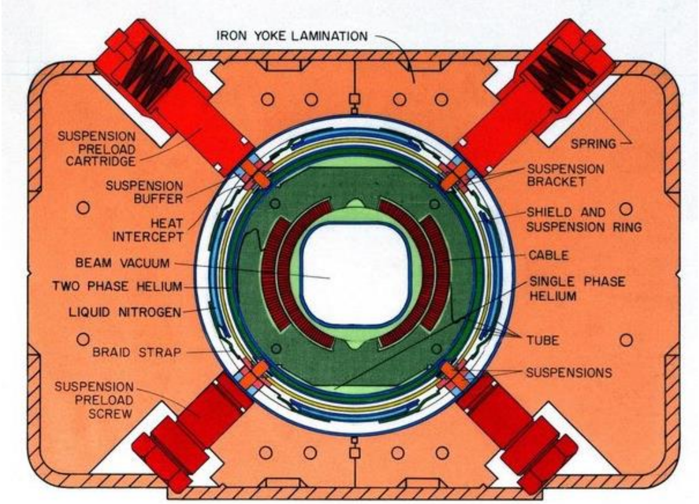
RTM processing
(complete manufacture cycle: 4 hrs)

Columns as de-moulded

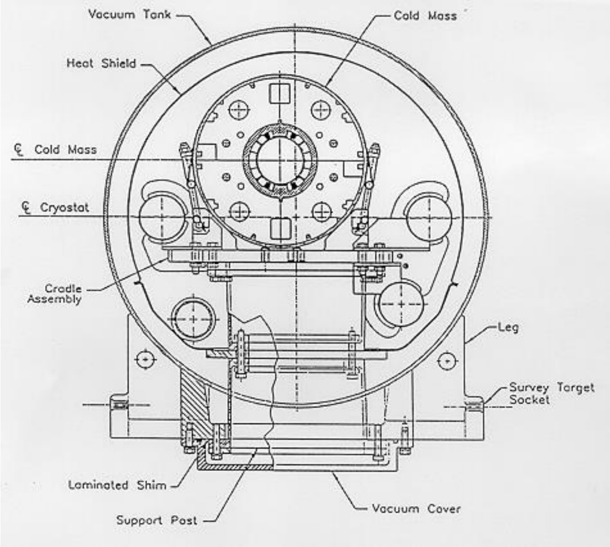
SC magnet supporting systems from other machines



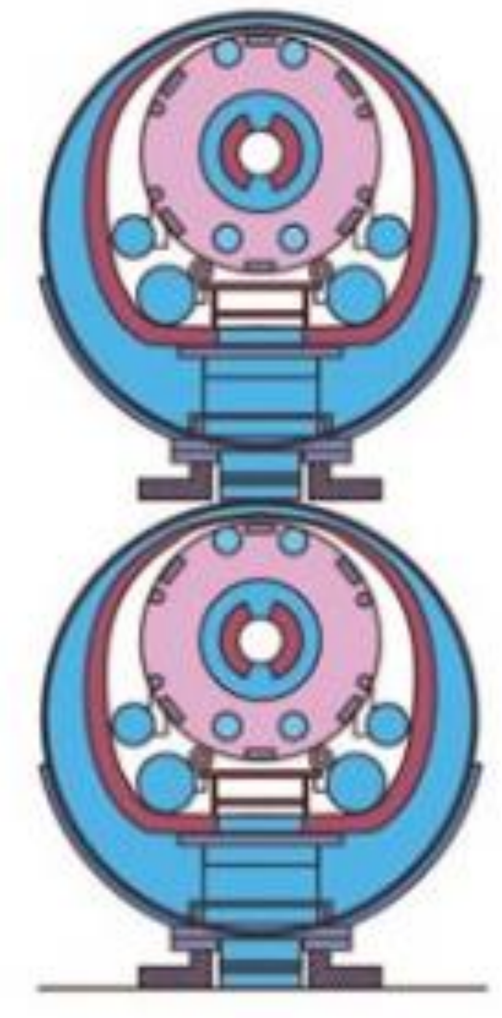
Hera dipole



Tevatron

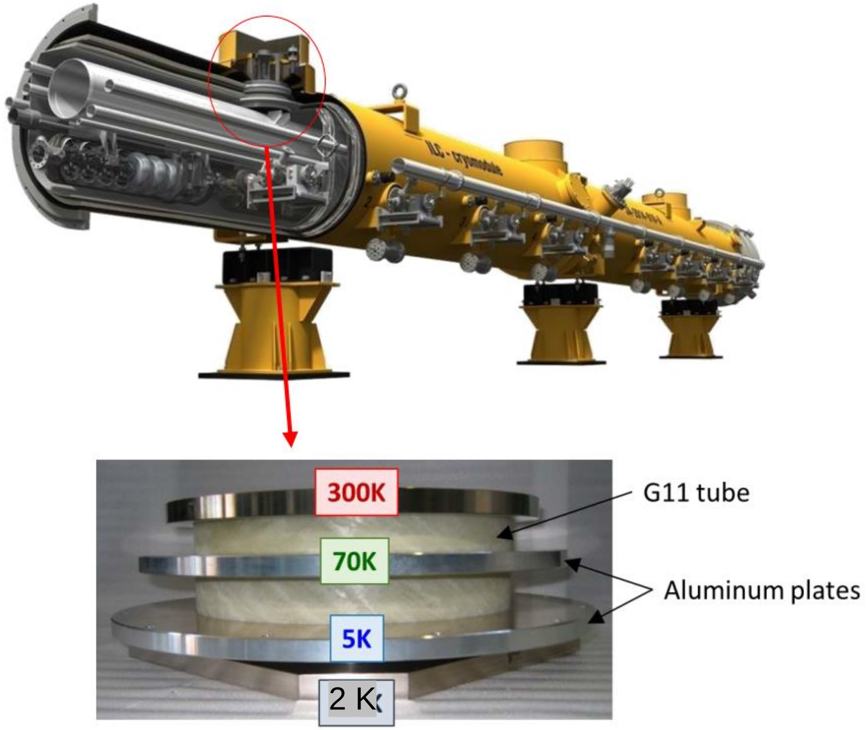


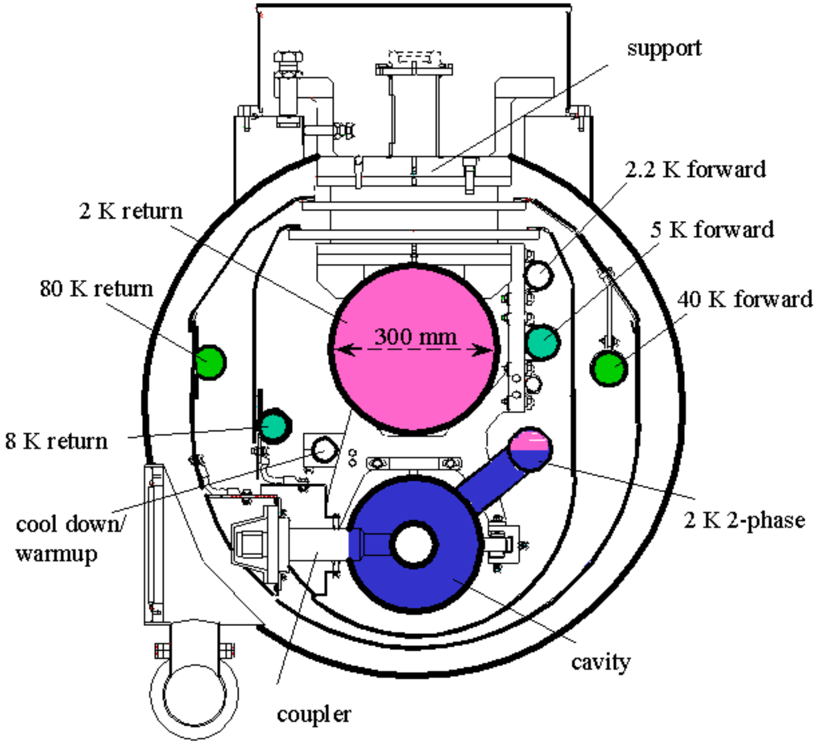
RHIC dipole

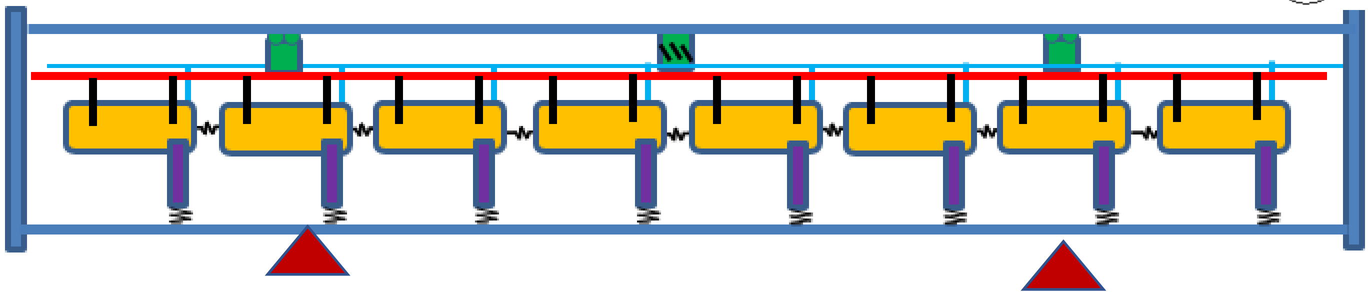


SCC

Supporting system of Tesla/TTF/ILC Cryomodule



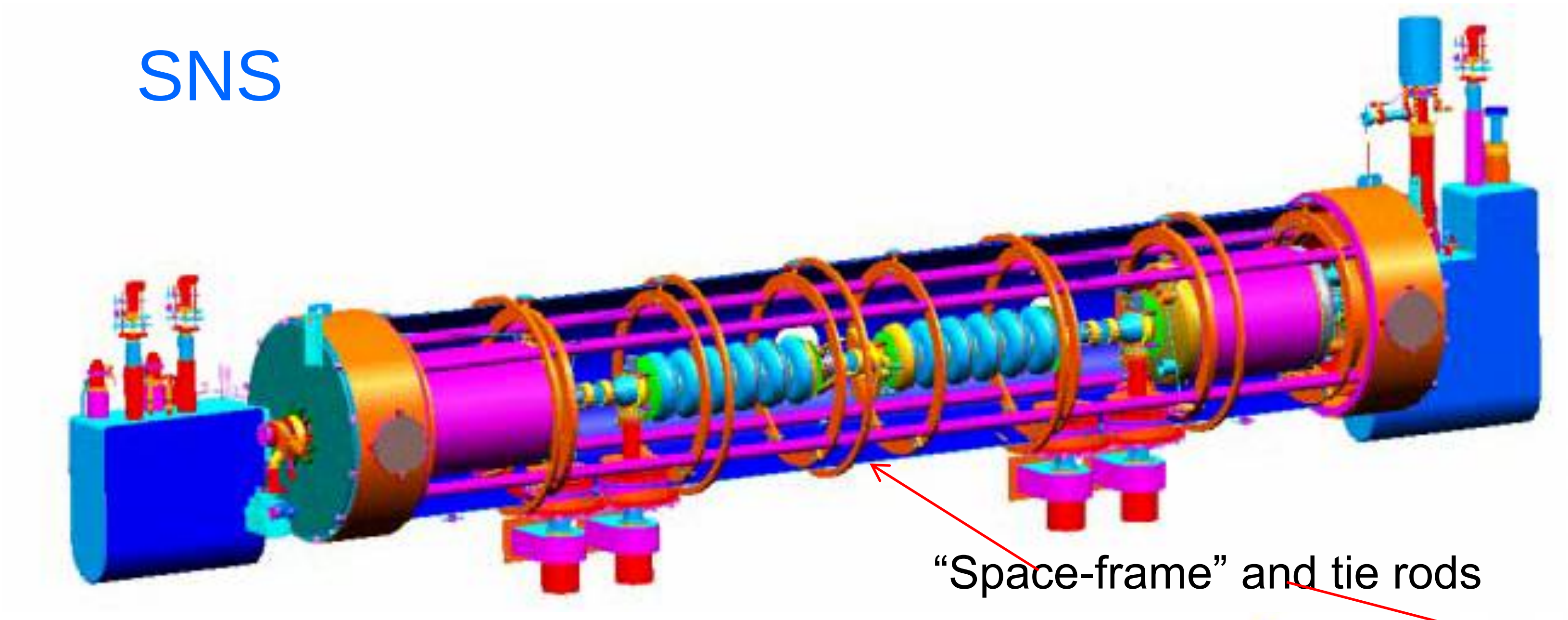




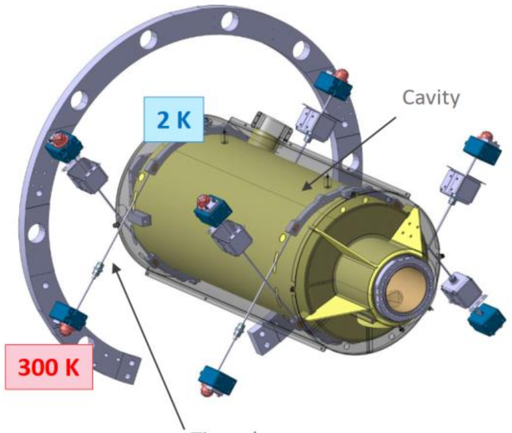
- RF coupler (with bellows)
- Invar longitudinal positioner
- DN 300 as back-bone
- Fixed support
- Sliding support
- External supports (jacks)

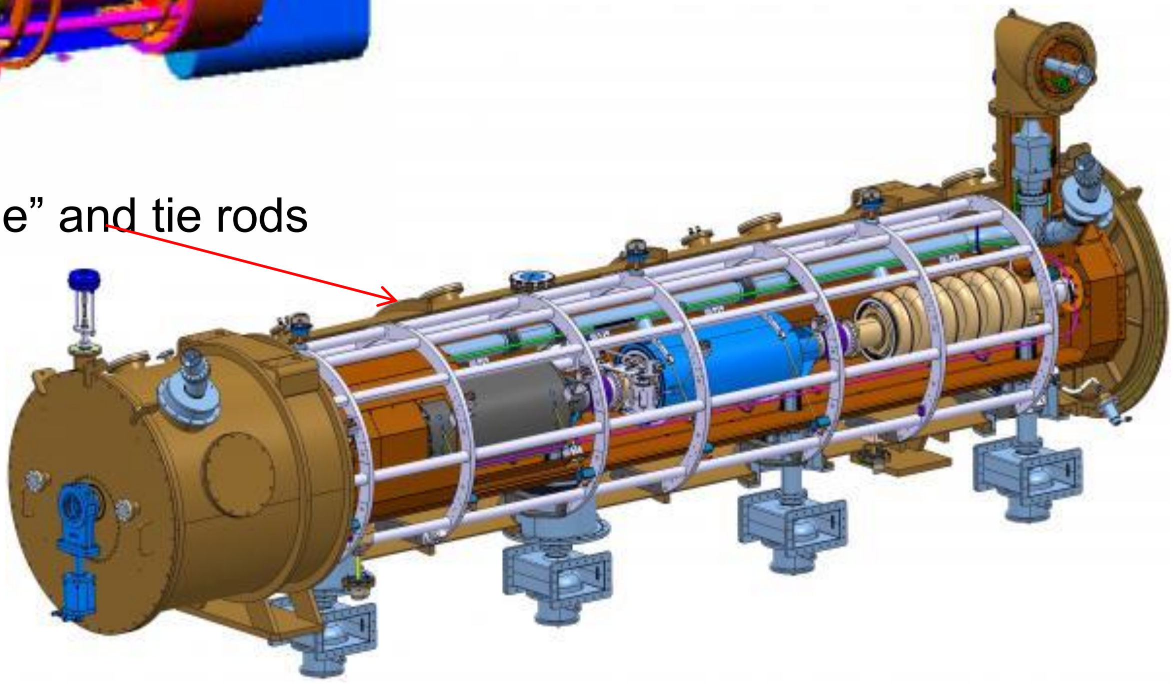
Supporting system of SNS and ESS high β Cryomodules

SNS



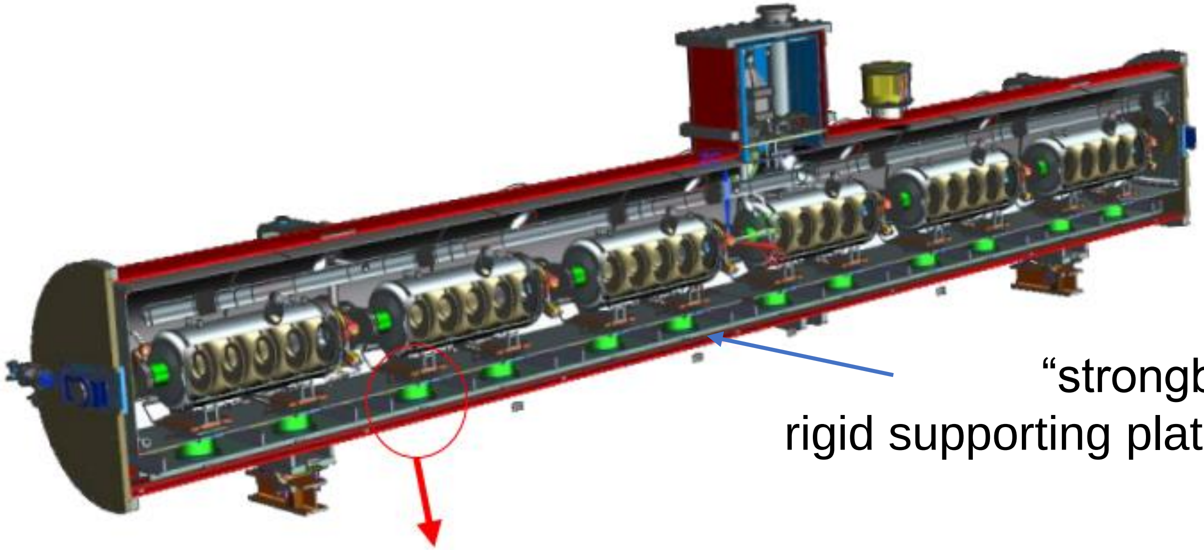
“Space-frame” and tie rods

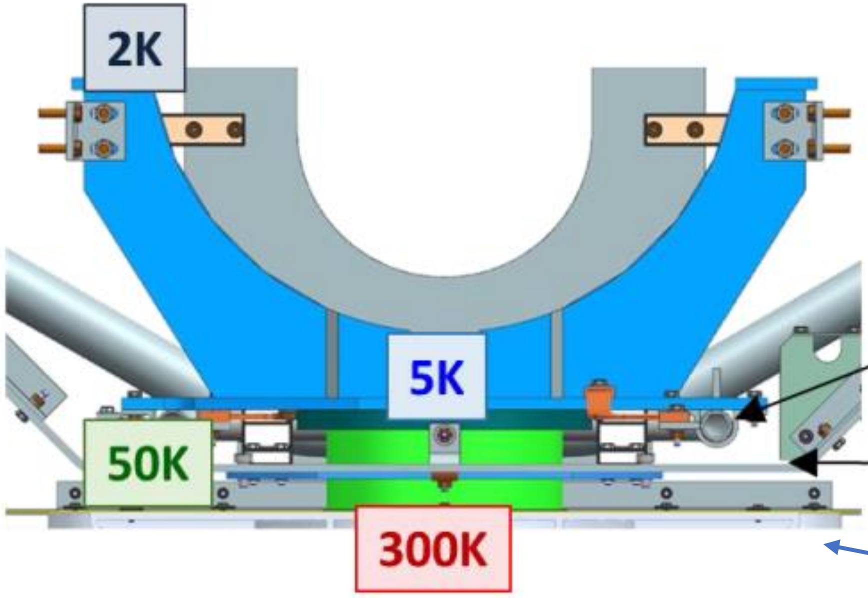




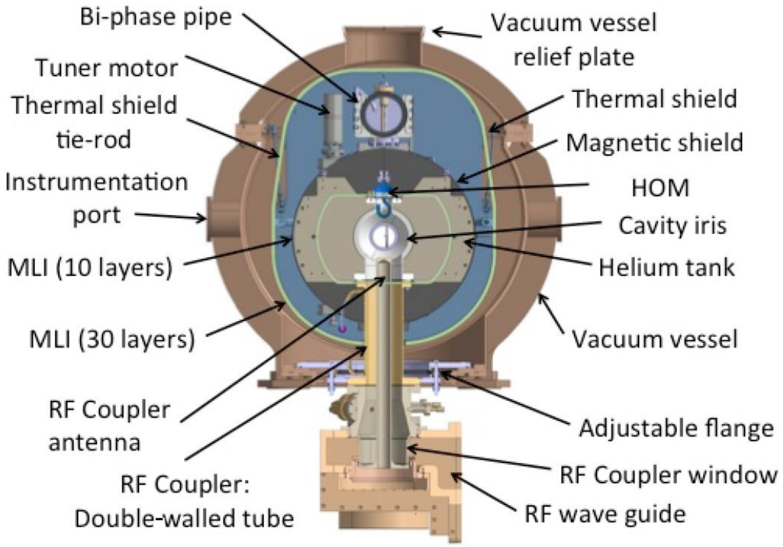
ESS

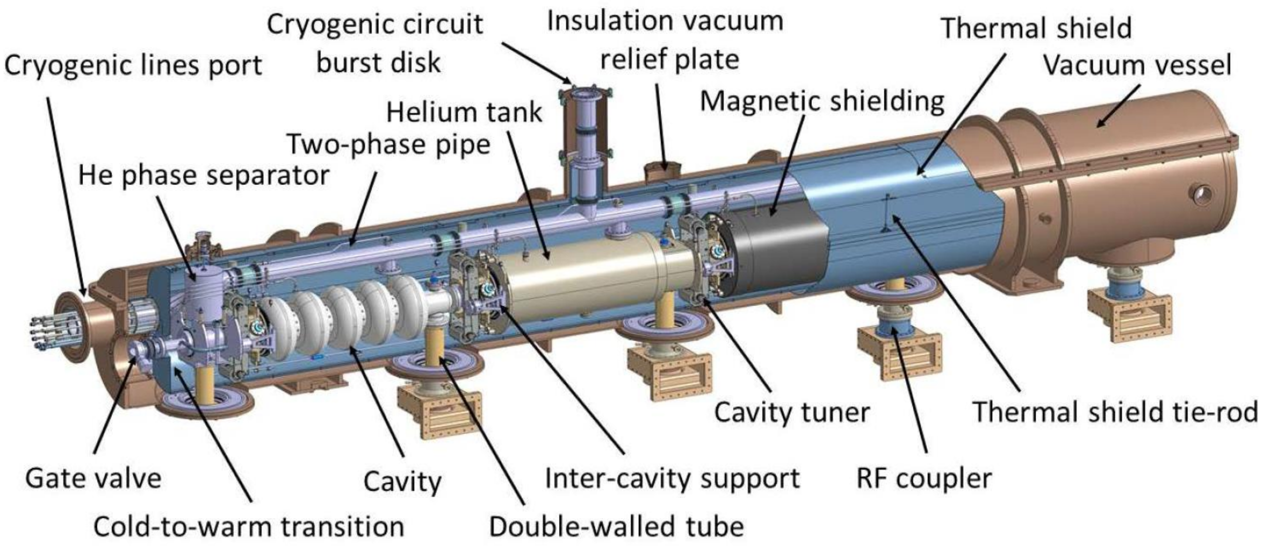
Supporting system of PIP II Cryomodule

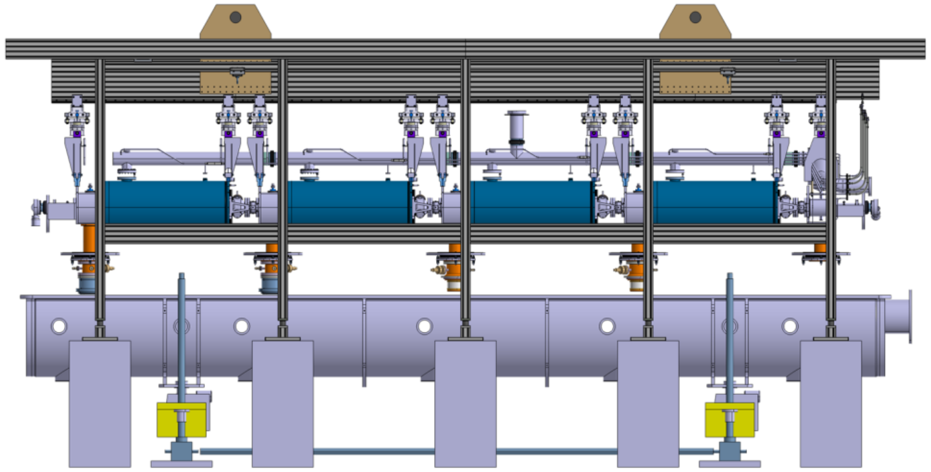




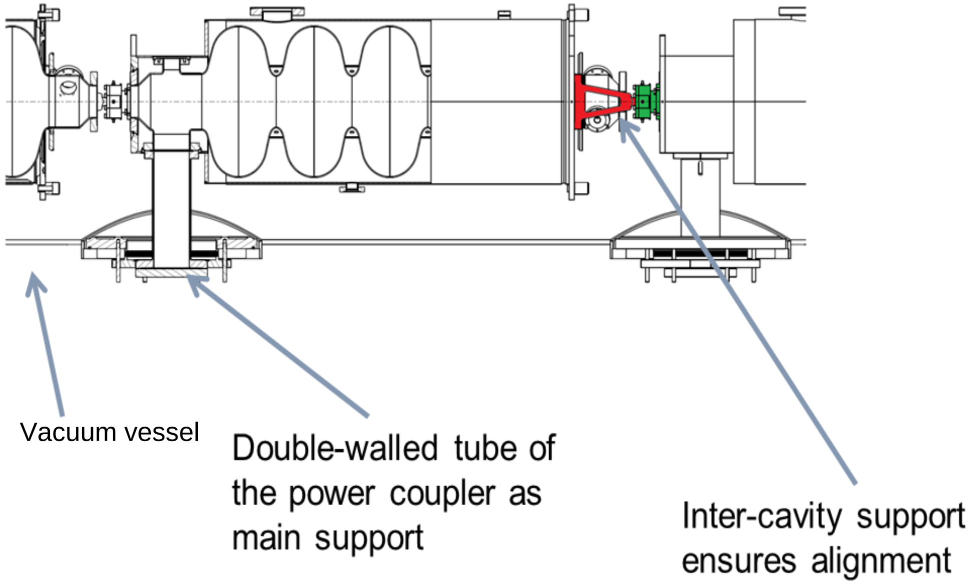
SPL cryomodule: RF Coupler as support







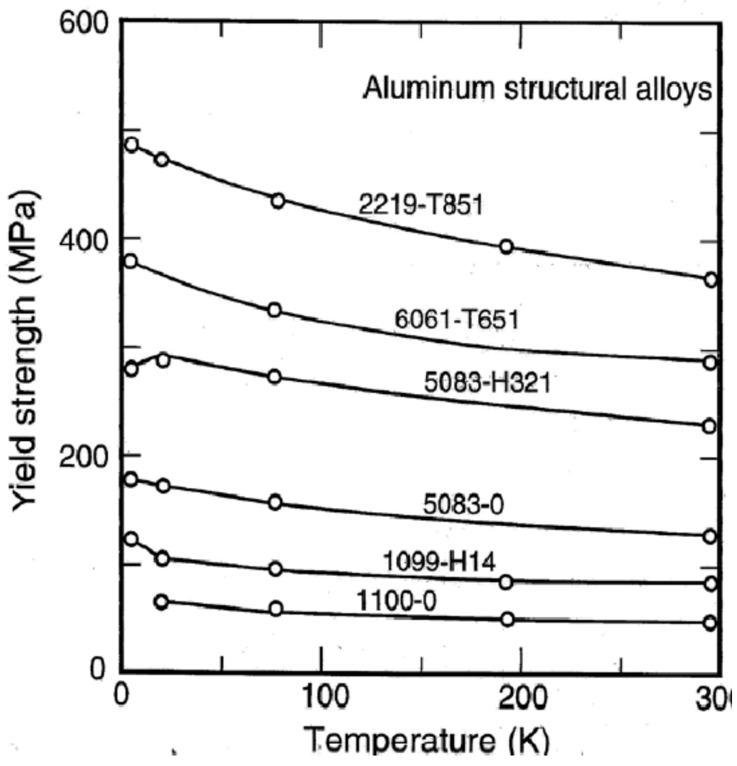
Vertical loading of cavities string

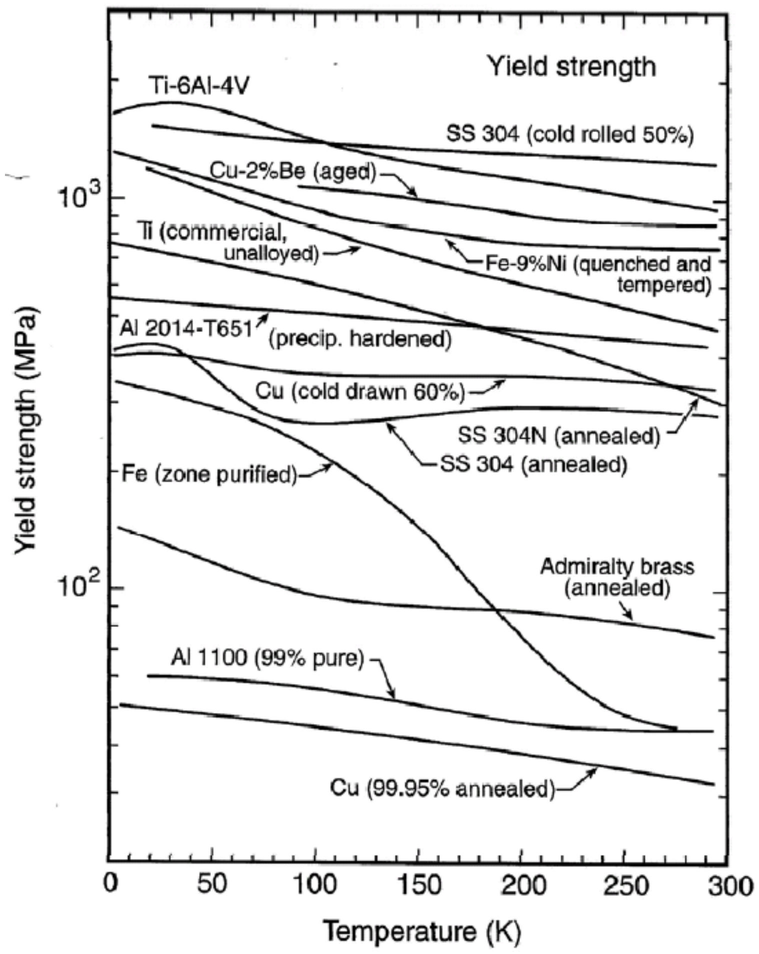


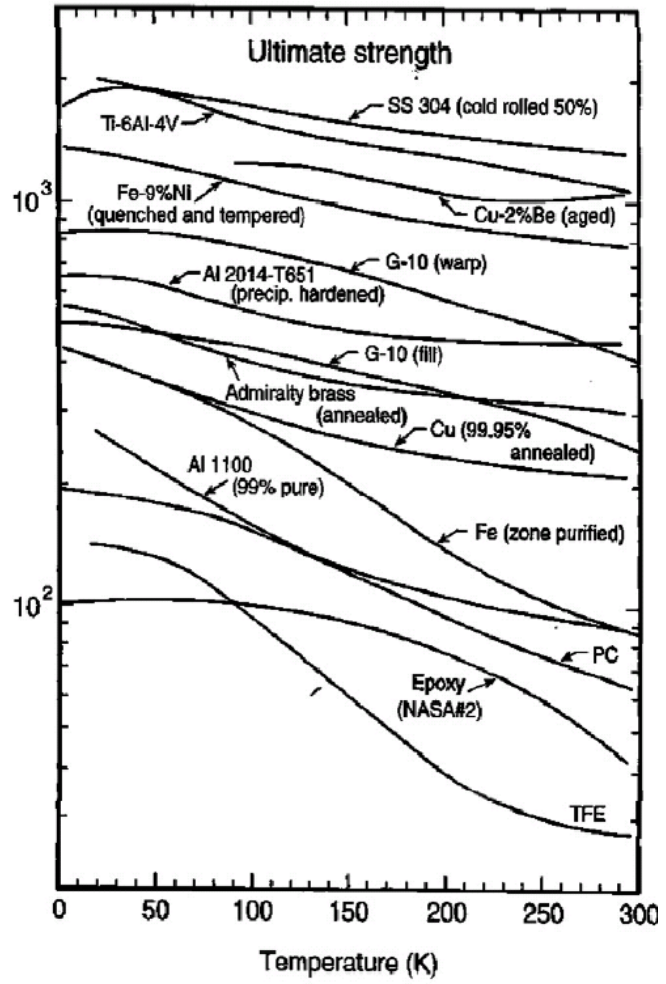
Appendix 2: material mechanical properties at low T

Mechanical Properties at cryogenic temperatures

- Yield, ultimate strength
  - ✓ Yield and ultimate strengths increase at low temperature





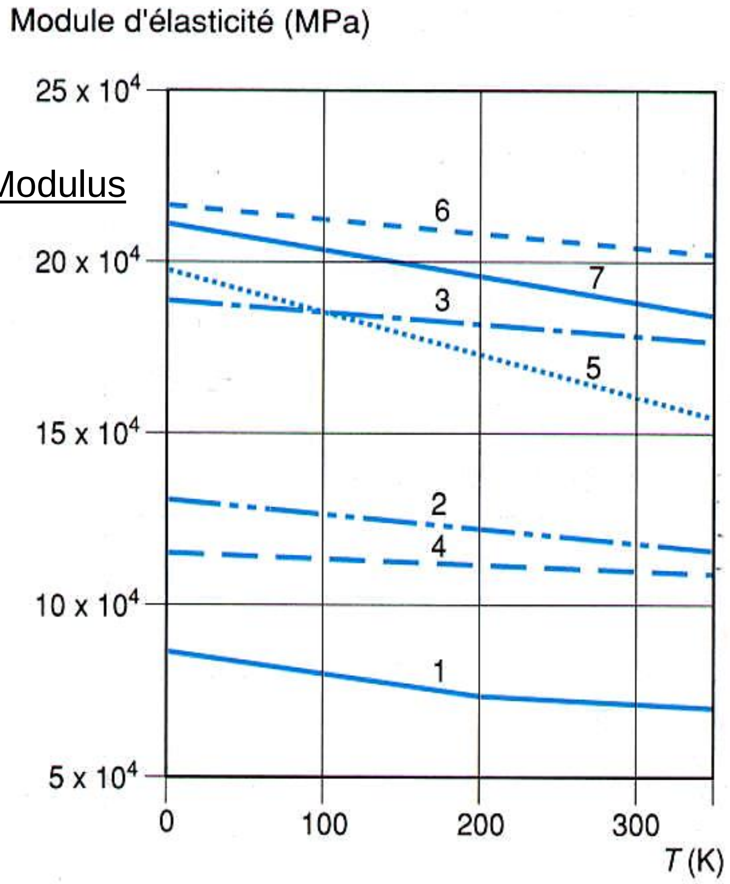


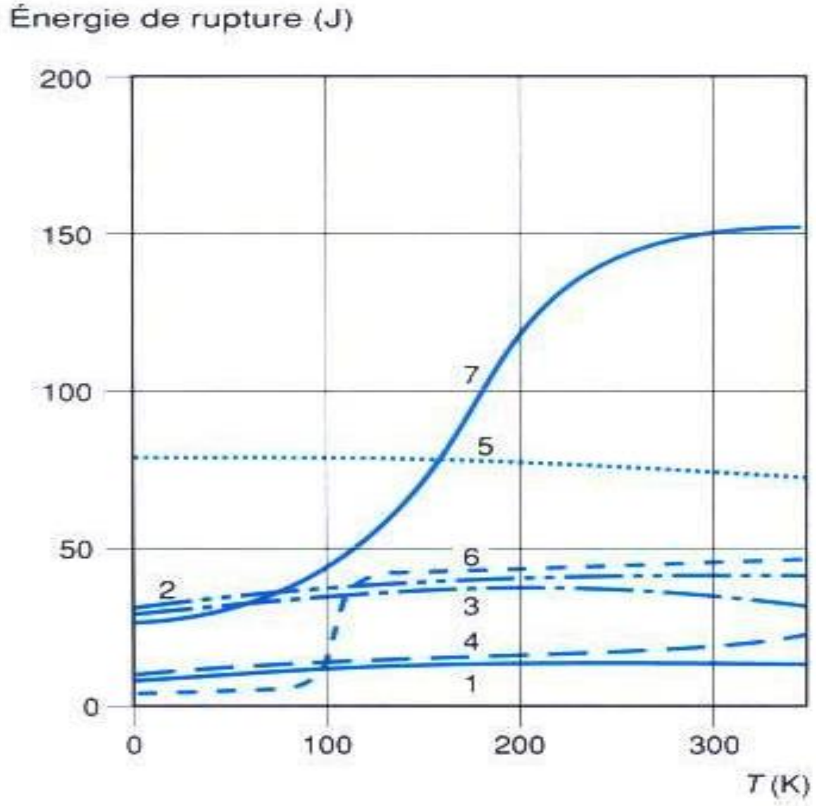
From: Ekin, J.W. Experimental Techniques for Low Temperature Measurements

Mechanical Properties at cryogenic temperatures (cont.d)

- Young modulus
- Fracture toughness

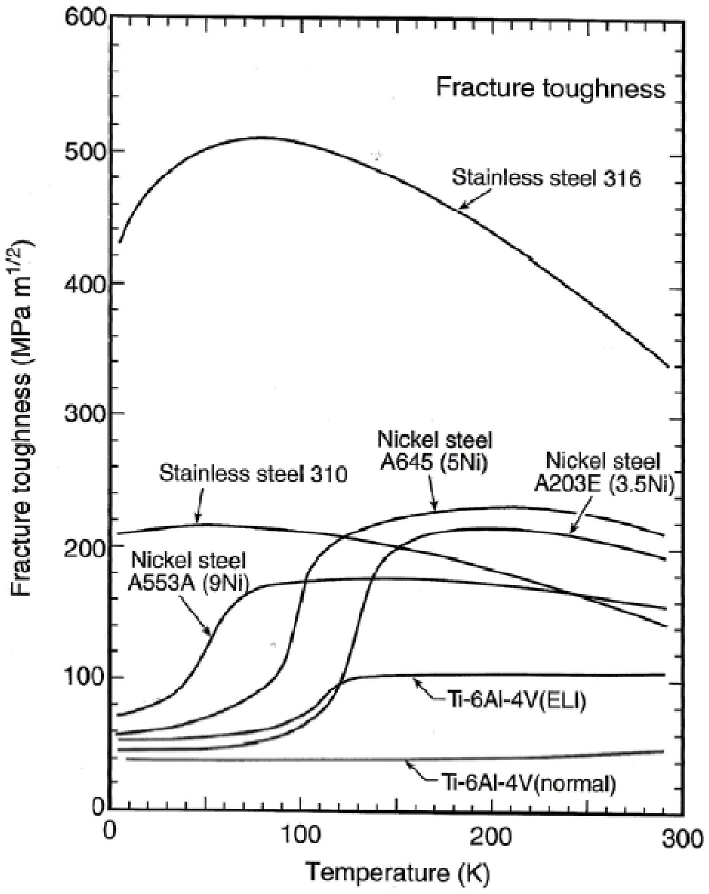
Young Modulus





1 : 2024 T4 aluminium
2 : copper-beryllium
3 : K monel
4 : Titanium
5 : SS 304
6 : Carbon Steal C 1020
7 : Steel 9% Ni

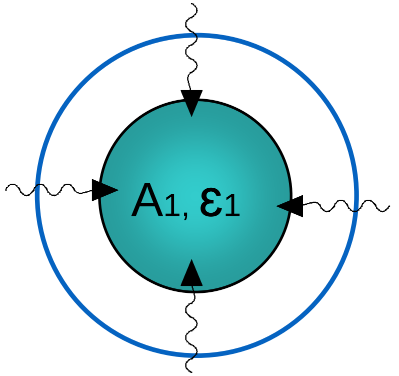
From: Technique de l'Ingénieur



From: Ekin, J. Experimental Techniques for Low Temperature Measurements

Appendix 3: Thermal radiation in cryostats: numerical application

Radiation in LHC-like cryostat (1/4)



- Thermal radiation HL for a 1-m cryostat unit length
- Vacuum vessel diameter: 1m ($A_2 = \pi \times 1 = 3.14\ m^2$)
- Cold mass diameter: 0.5 m ($A_1 = \pi \times 0.5 = 1.57\ m^2$)
- T_1 cold mass: 2 K
- T_2 vac.vessel: 293 K
- $\varepsilon_1 = 0.12$ (st.steel, mec.polished, 2 K)
- $\varepsilon_2 = 0.2$ (low carbon.steel, mec.polished, 293 K)

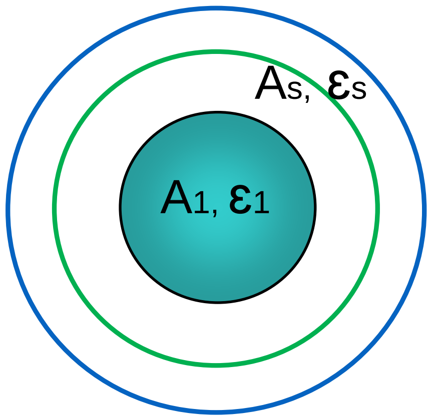
→ $q_{1\text{-}2} = 63.5\ W\ (41.6\ W/m^2)$

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

Radiation in LHC-like cryostat (2/4)

- Floating Al shield

$$q_{1-2} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 F_{1s}} + \frac{1-\varepsilon_{s,1}}{\varepsilon_{s,1} A_s} + \frac{1-\varepsilon_{s,2}}{\varepsilon_{s,2} A_s} + \frac{1}{A_s F_{s2}} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}}$$



Floating Al shield:

- Thermal shield diameter: 0.75 m (A_s= π x 0.75 = 2.35 m^2)
- F_{1s}= 1; F_{2s}= 1
- T_s = 80 K (first guess)
- $\varepsilon_{s,1} = \varepsilon_{s,2}$ = 0.1 (Aluminum, mec.polished, 80 K)

→ $q_{1-2} = q_{1-s} = q_{s-2}$ = 28.5 W

- Calculate Ts by *trial and error* to obtain power balance $q_{1-s} = q_{s-2}$

→ T_s = 260 K → increase $\varepsilon_{s,1} = \varepsilon_{s,2}$ (0.15?) and recalculate

→ $q_{1-2} = q_{1-s} = q_{s-2}$ = 35.4 W (to be compared to 63.5 W without shield)

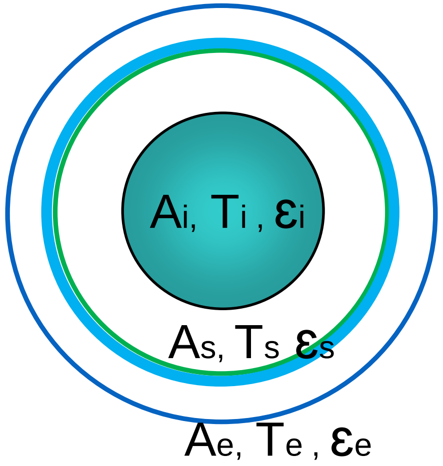
→ q_{1-s} = 35.4 W (22.5 W/m^2), q_{s-2} = 35.4 W (15 W/m^2)

→ 1 floating thermal shield reduces to almost ½ the radiation to the low T (close to flat plates approximation for this geometry)

Radiation in LHC-like cryostat (3/4)

- MLI with N reflectors, floating shields
- Radiation between shield and vac.vessel (flat plat approximation):

$$q_{s-e} = \frac{\sigma Aav(Ts^4 - Te^4)}{(N+1)(\frac{2}{\varepsilon_{av}} - 1)}$$



- N = 30
- T_s = 80 K (first guess)
- ε_e = 0.2 (low carbon.steel, mec.polished, 293 K)
- ε_s = 0.08 (Aluminium reflector, electrolytical deposition, 80 K)
- ε_{av} = ½ (ε_s+ ε_e) (average emissivity)
- A_{av} = ½ (A_s + A_e) (average area)

→ $q_{s\text{-}e}$ = 2.7 W (0.14 W/m^2) (with T_s = 80 K)

- Radiation between shield (80 K) and helium vessel (formula between enclosed cylinders):

→ $q_{i\text{-}s}$ = 0.23 W (0.012 W/m^2) (with T_s = 80 K)

- Calculate T_s by *trial and error* (and tune ε_s) to obtain power balance $q_{s\text{-}e}$ = $q_{i\text{-}s}$ (floating shield condition)

→ T_s = 143 K, → ε_s= 0.1

$q_{s\text{-}e}$ = $q_{i\text{-}s}$

→ $q_{s\text{-}e}$ = 2.6 W (1.65 W/m^2)

→ $q_{i\text{-}s}$ = 2.6 W (0.96 W/m^2)

→ MLI (30 layers) reduce the HL to the thermal shield (and cold surface) by a factor x25 wrt no shield

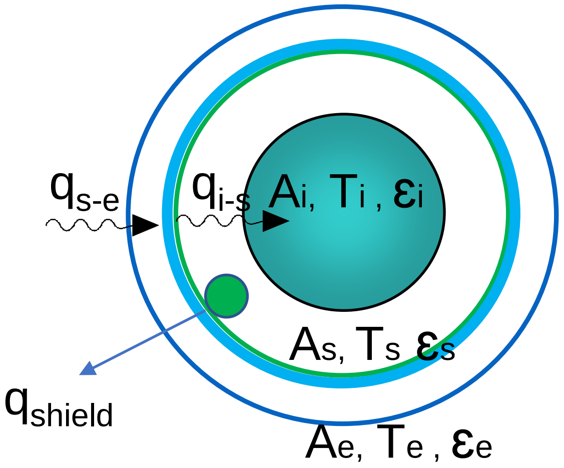
Radiation in LHC-like cryostat (4/4)

- MLI with N reflectors, actively cooled shield
- Radiation between shield and vac.vessel (flat plat approximation):

$$q_{s-e} = \frac{\sigma\, Aav\, (Ts^4 - Te^4)}{(N+1)(\frac{2}{\varepsilon_{av}} - 1)}$$

- N = 30
- T_s = 80 K (now an input)
- ε_s = 0.08 (Aluminium reflector, electrolytical deposition, 80 K)
- ε_{av} = ½ (ε_s+ ε_e) (average emissivity)
- A_{av} = ½ (A_s + A_e) (average area)

→ q_{s-e} = 2.78 W (1.0 W/m^2)



- Radiation between shield (80 K) and helium vessel (2 K) (formula between enclosed cylinders):

→ q_{i-s}* = 0.23 W (0.14 W/m^2) (x10 times less than with floating shield !)

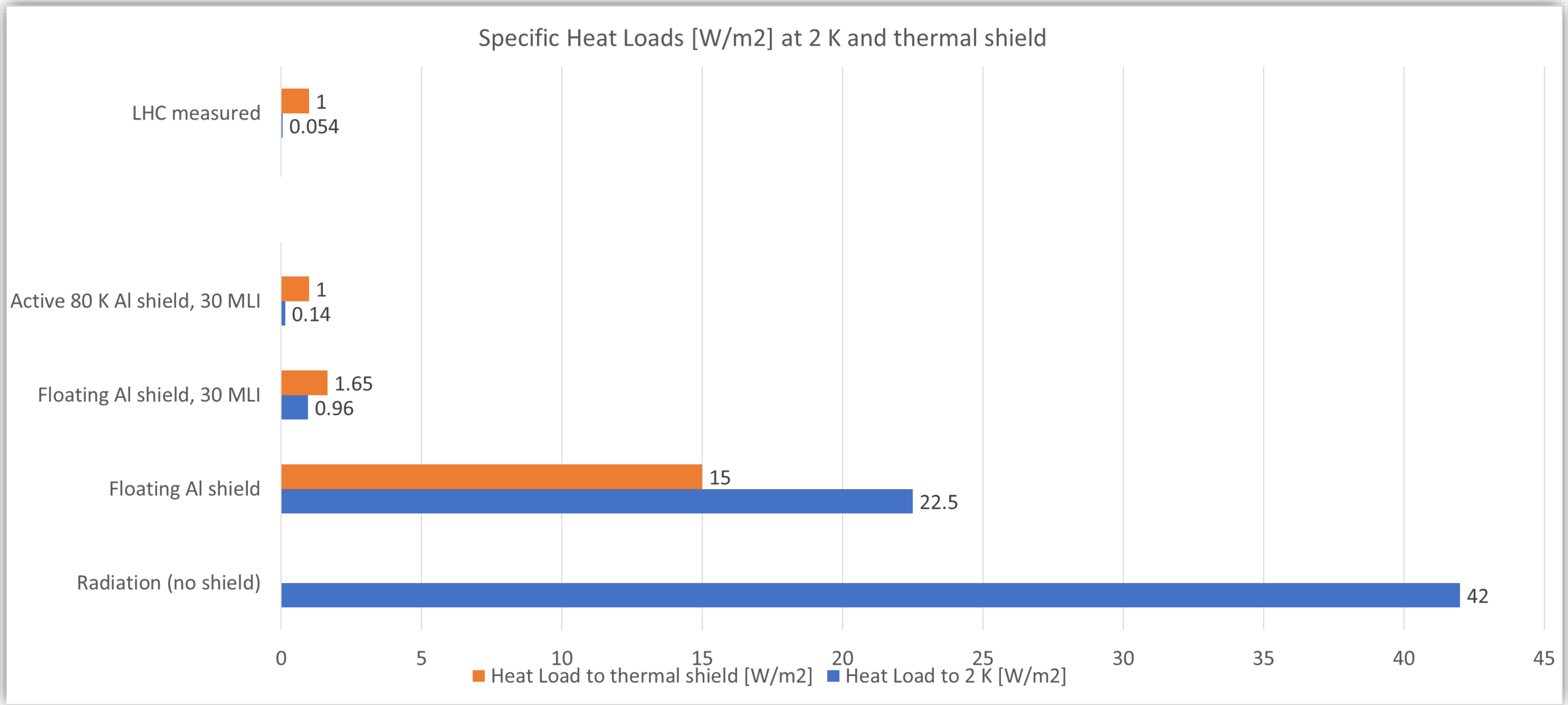
- Radiation heat extraction from thermal shield (not to be forgotten!):

→ q_{shield} = q_{s-e} - q_{i-s} = 2.55 W

→ Actively cooled shield with MLI dramatically reduces radiation to the low T: this is a standard practice in cryostats!

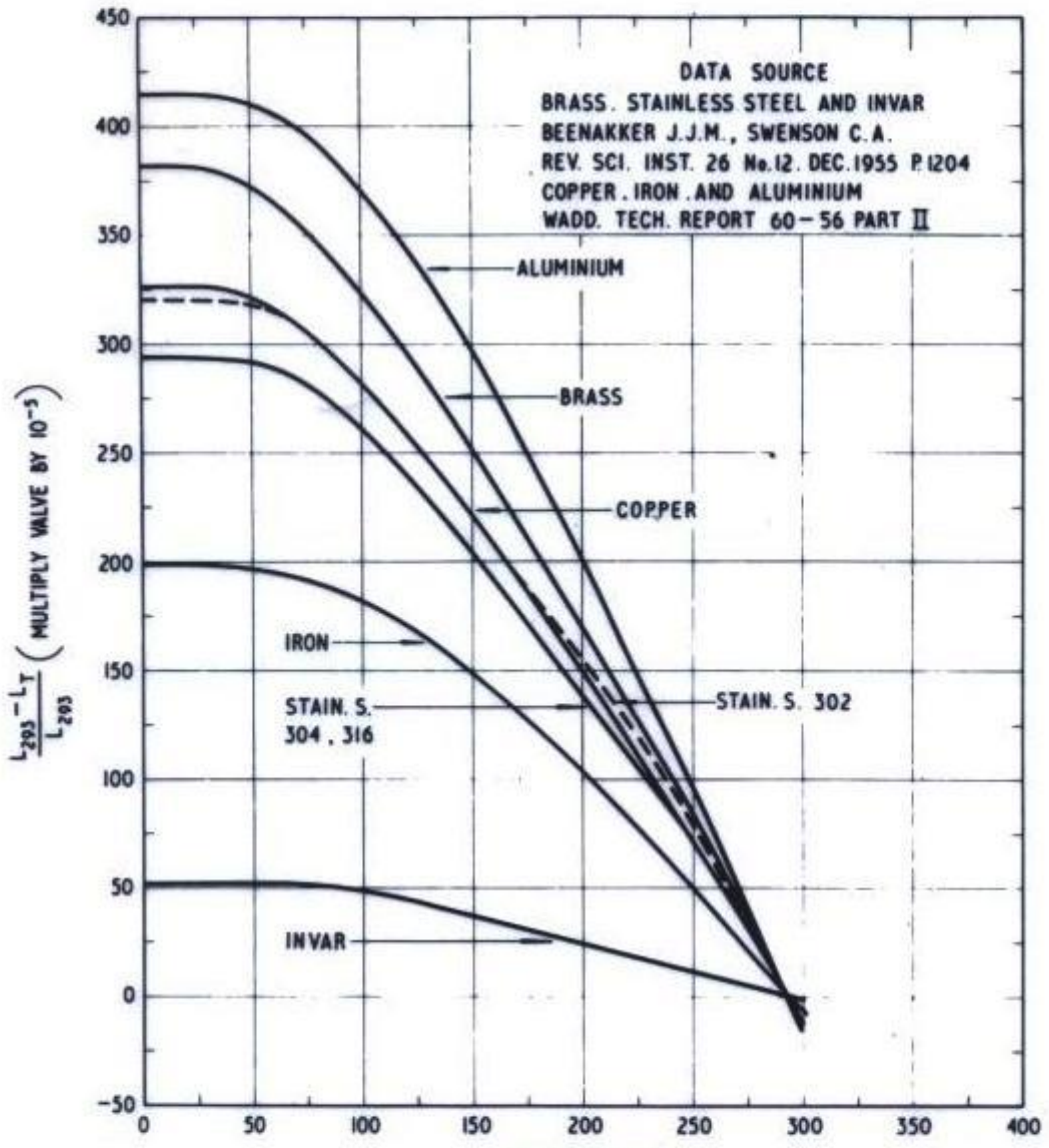
(*) can be further reduced to 0.18 W (0.11 W/m^2) with ε_i = 0.08 (for example 1 or more MLI layers on cold mass)

Summary of radiation

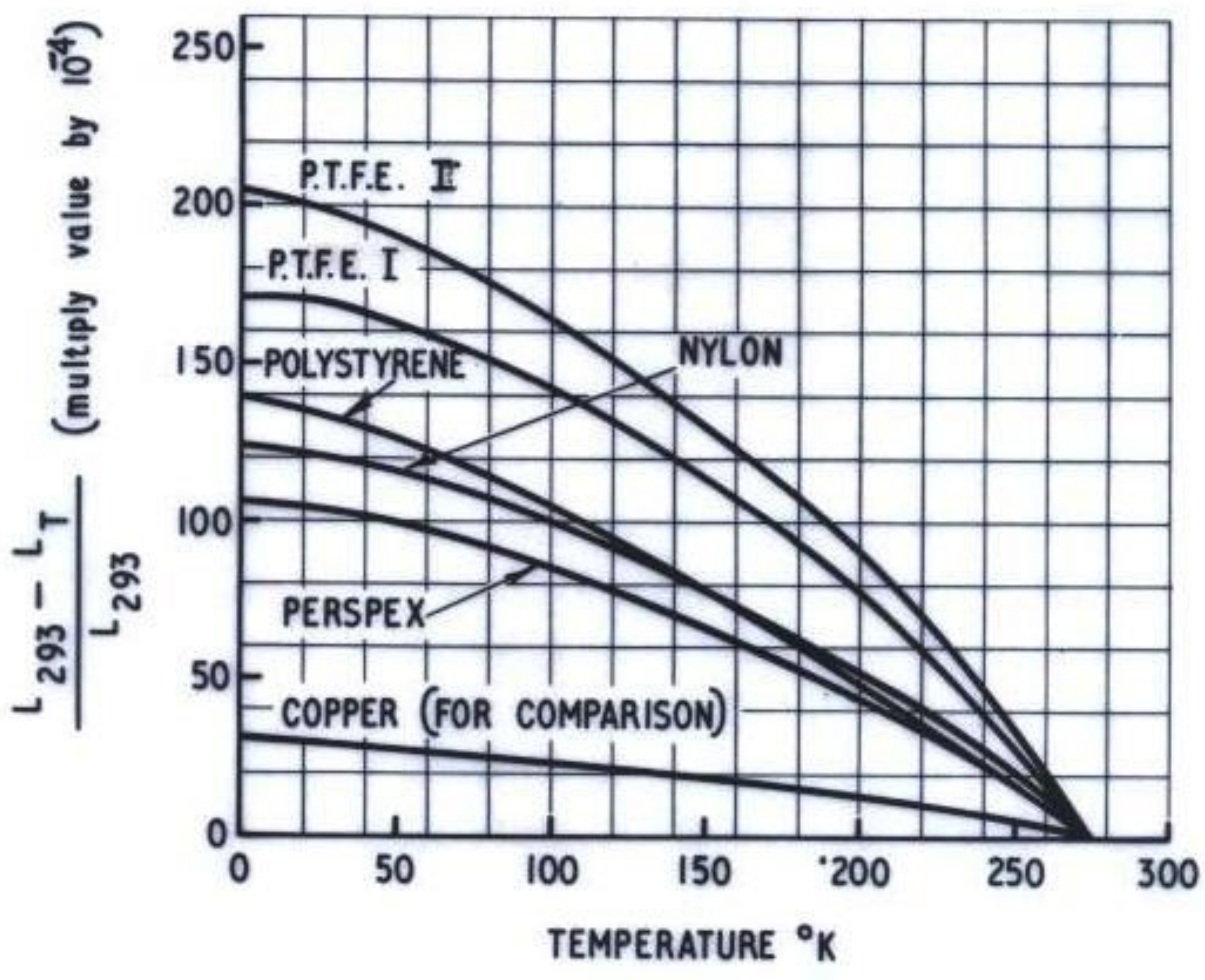


Appendix 4: Thermo-mechanical considerations

Thermal expansion of some materials



THERMAL EXPANSION OF METALS

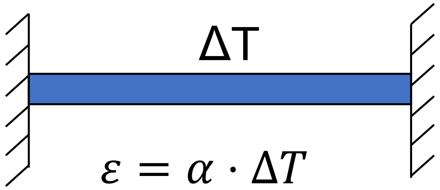


THERMAL EXPANSION OF PLASTICS

DATA SOURCE:- CRYOGENIC DATA BOOK UCRL-3421 P.88

Thermal stress in composite material assemblies: 3 cases

A) Restrained component



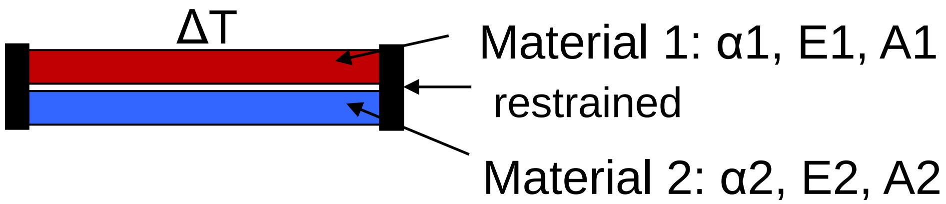
$$\varepsilon = \alpha \cdot \Delta T$$

$$\sigma = \alpha \cdot \Delta T \cdot E$$

α = thermal expansion coefficient [K^{-1}]

E = Young modulus

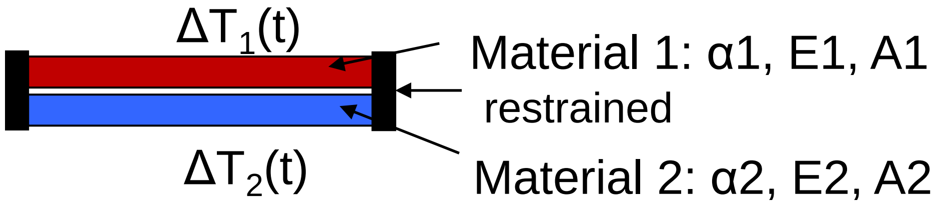
B) Assembly of different materials



$$\sigma 1 = \frac{E1\ E2\ A2}{E1\ A1 + E2\ A2}(\alpha 2 - \alpha 1) \cdot \Delta T \qquad \sigma 2 = \frac{E1\ E2\ A1}{E1\ A1 + E2\ A2}(\alpha 2 - \alpha 1) \cdot \Delta T$$

C) Different cooling $\Delta T_1(t) \neq \Delta T_2(t)$

(different material diffusivity or different cooling)



$$\sigma 1 = \frac{E1\ E2\ A2}{E1\ A1 + E2\ A2}(\alpha 2\ \Delta T2 - \alpha 1\ \Delta T1) \qquad \sigma 2 = \frac{E1\ E2\ A1}{E1\ A1 + E2\ A2}(\alpha 2\ \Delta T2 - \alpha 1\ \Delta T1)$$