# Helium Cryostats for Superconducting Devices

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# 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

# Mechanical design and construction of cryostats

# Materials in cryostats

- 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:
  - ✓ 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)
- RF Couplers/HOM (for SRF):
  - ✓ St.steel Cu plated, Nb, ceramics, etc.
- Current leads (for SC magnets)
  - ✓ Cu, HTS, st.steel, elect. insulating (Kapton), thermal insulating (G10),etc.
- Magnetic shielding (for SRF, as needed)
  - ✓ μ-metal, Cryoperm®, etc.

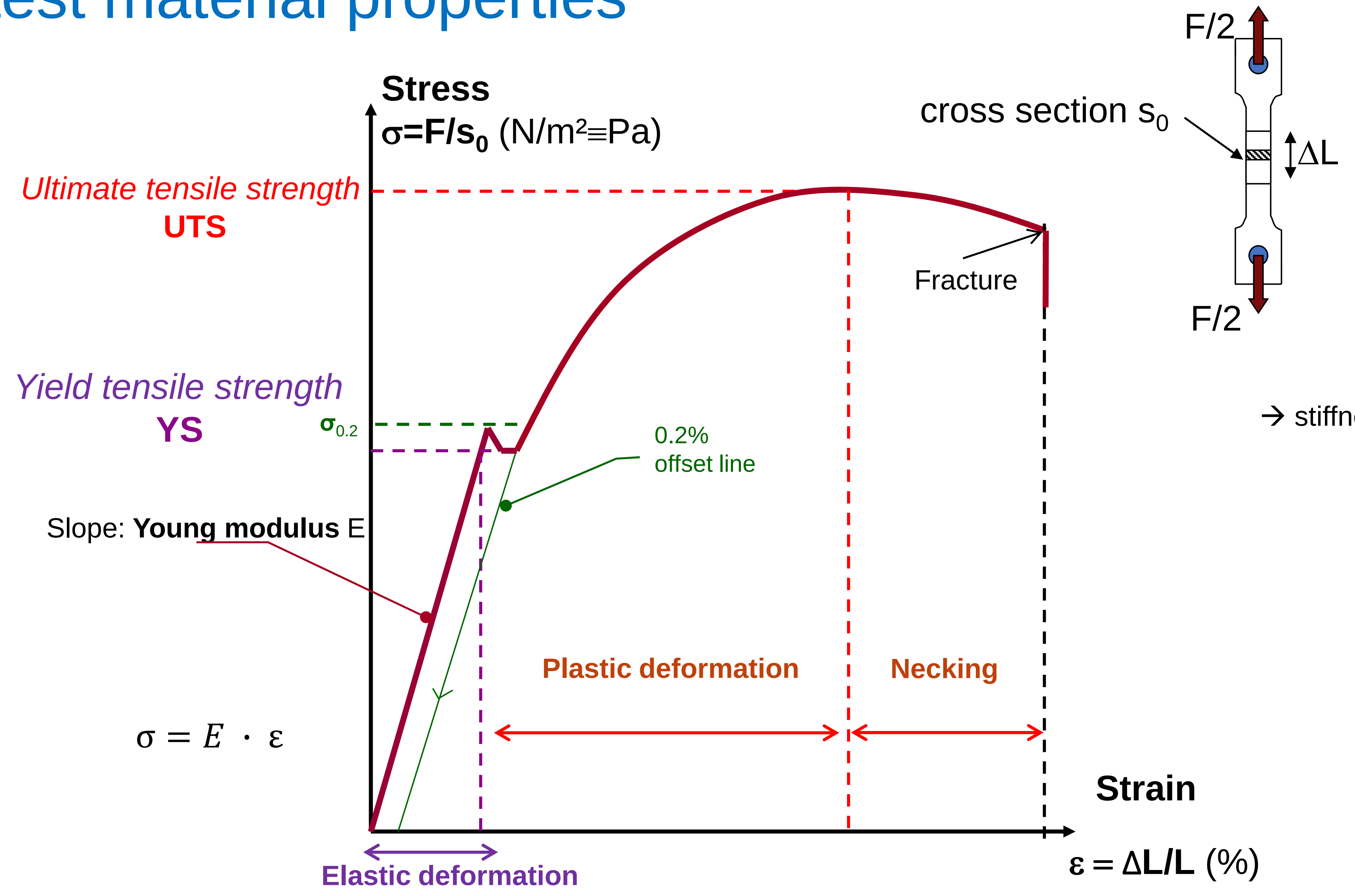
# Useful material standards for cryostats

| | |
|---|---|
| Plates and sheets | • EN 10028-1:2007+A1:2009 Flat products made of steels for pressure purposes - Part 1: General requirements<br>• EN 10028-3:2009 Flat products made of steels for pressure purposes - Part 3: Weldable fine grain steels, normalized<br>• 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<br>• 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<br>• 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) |

# 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

# Tensile test material properties

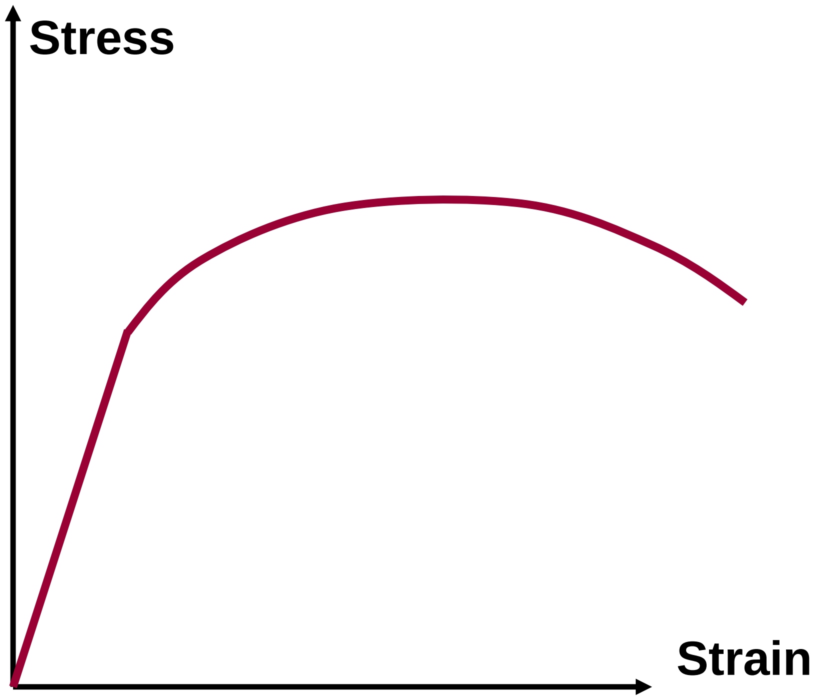



→ stiffness $k=EA/L$

# Ductile vs. brittle

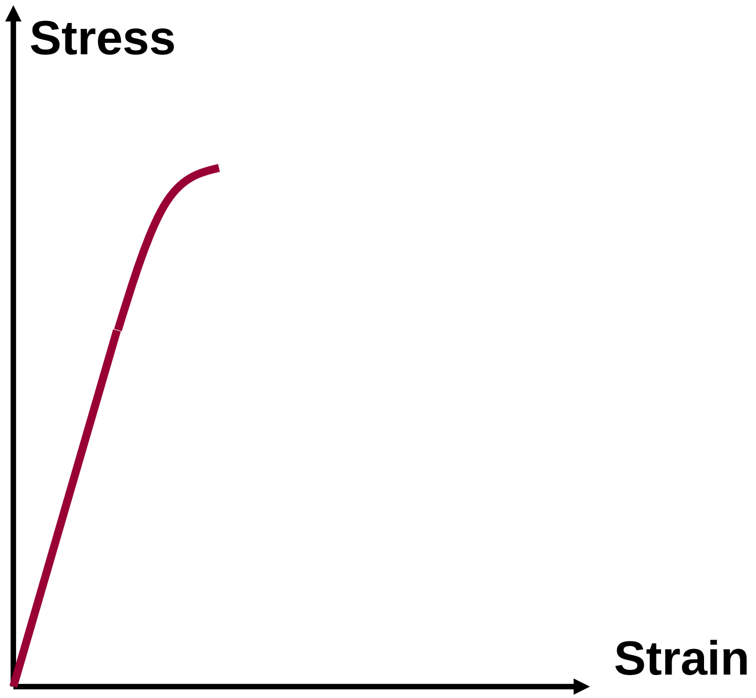
Ductile behaviour

(think about lead, gold...)

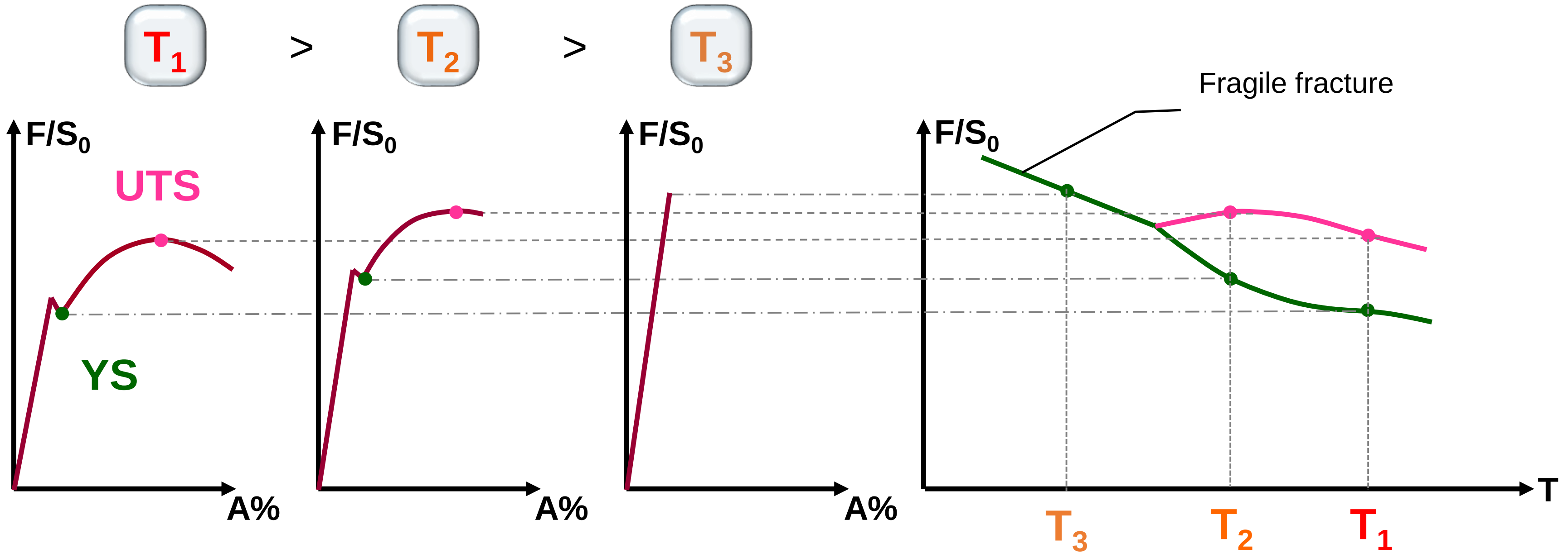



Brittle behaviour

(think about glass)



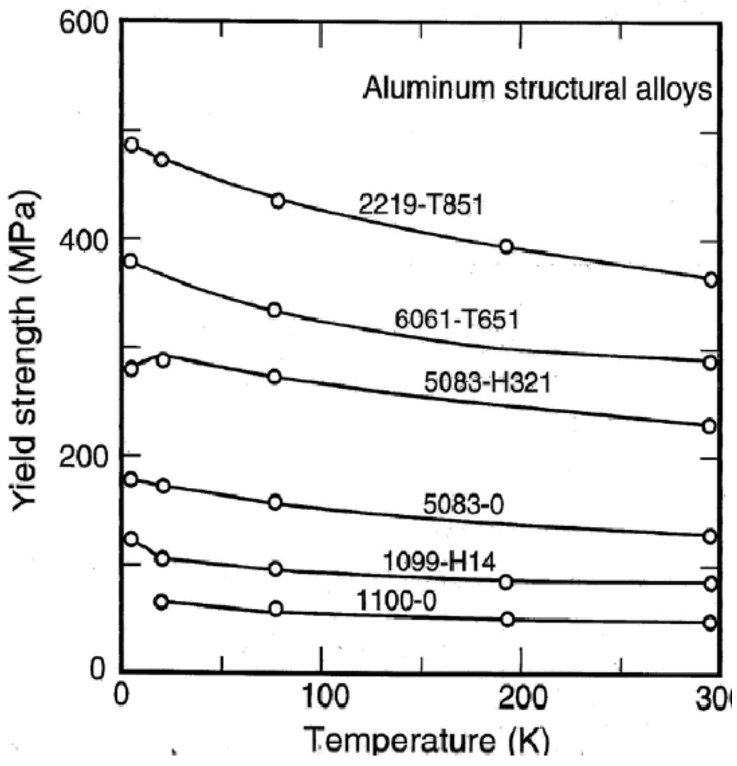
# Low temperature effect of tensile properties

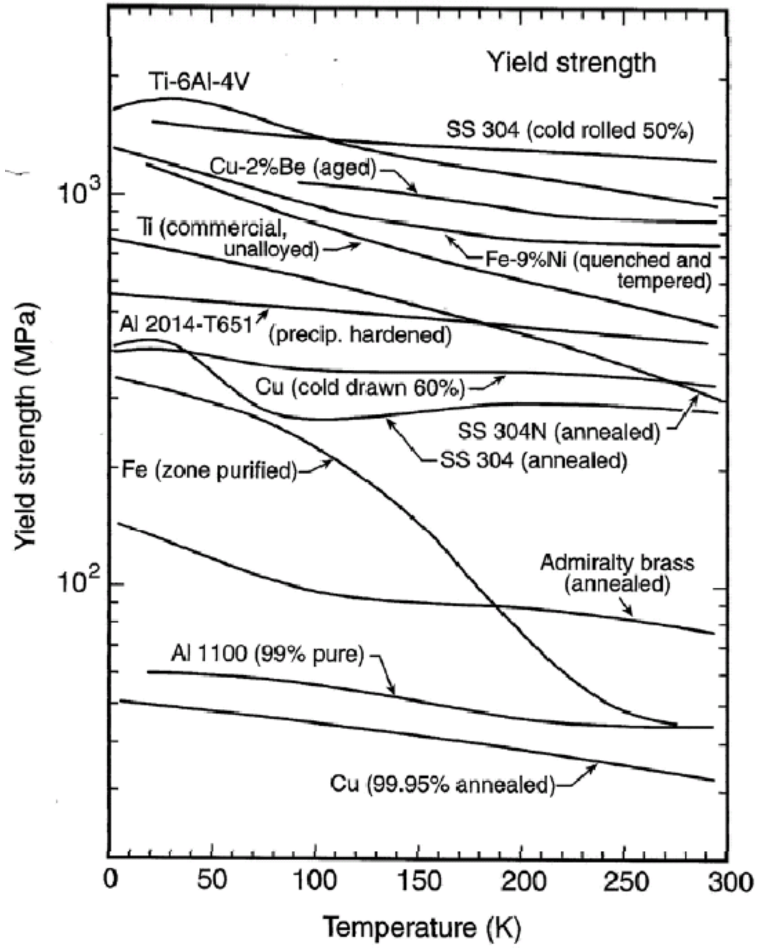


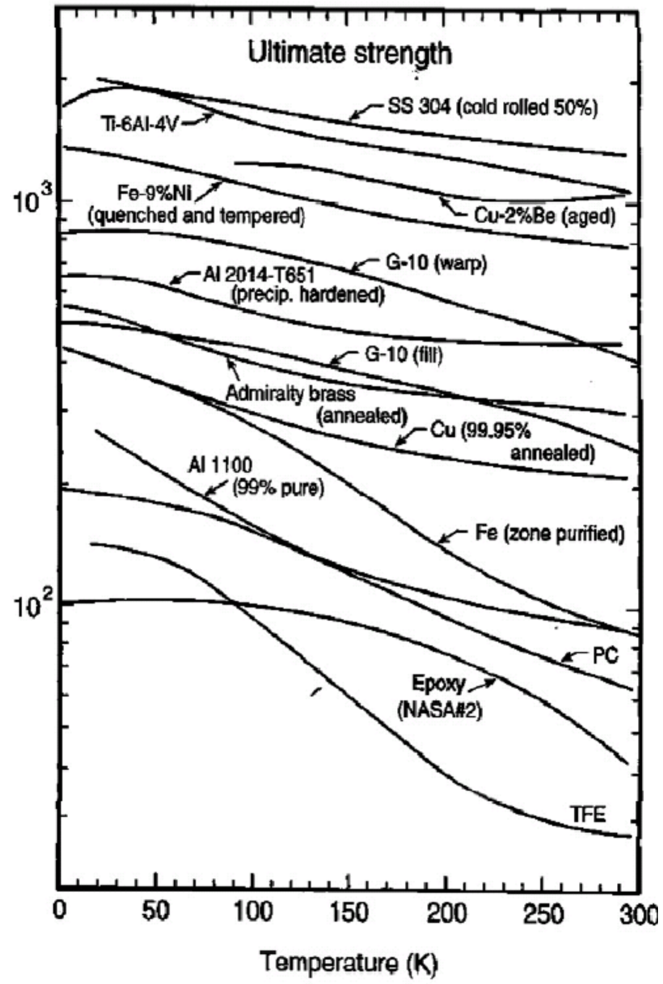

- Ductile materials tend to become brittle (fragile) at cryogenic temperatures
- Increase of the yield and ultimate strength
- Young modulus also (marginally) increases.

# Mechanical Properties at cryogenic temperatures

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



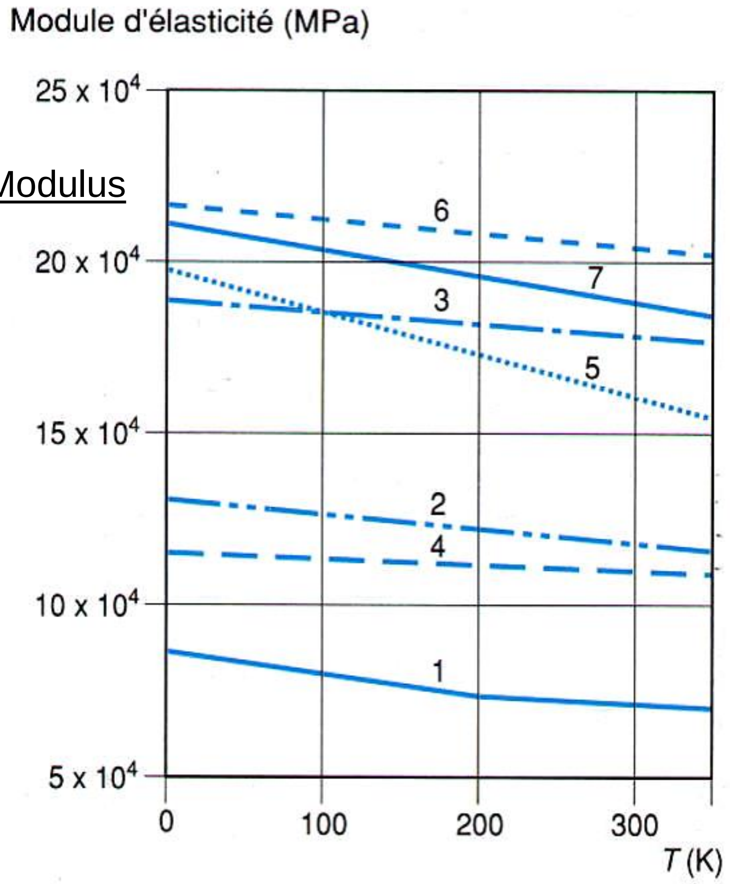



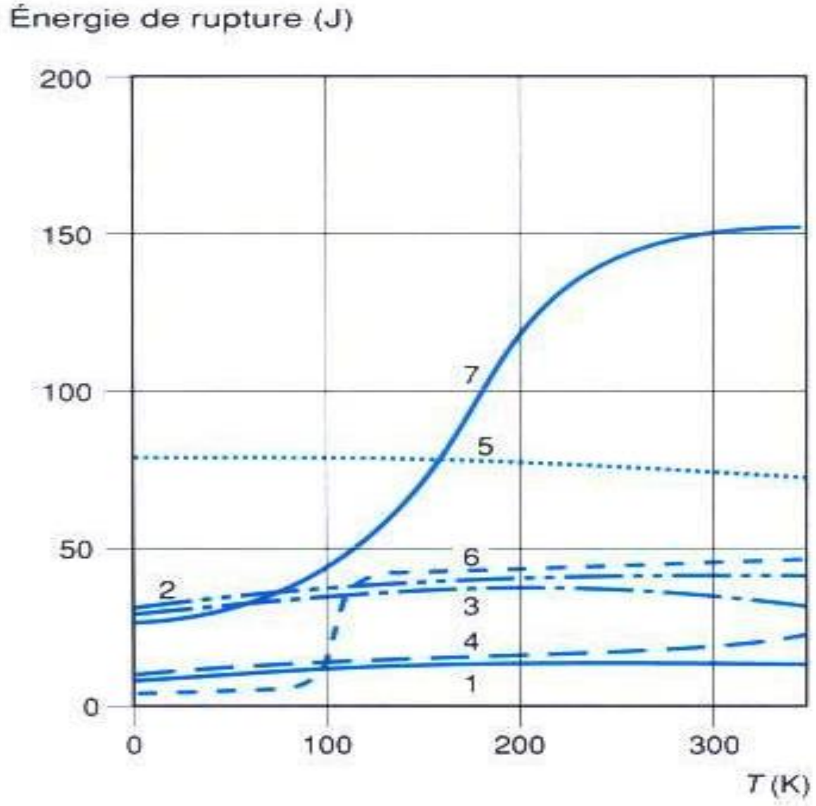

From: Ekin, J.W. Experimental Techniques for Low Temperature Measurements

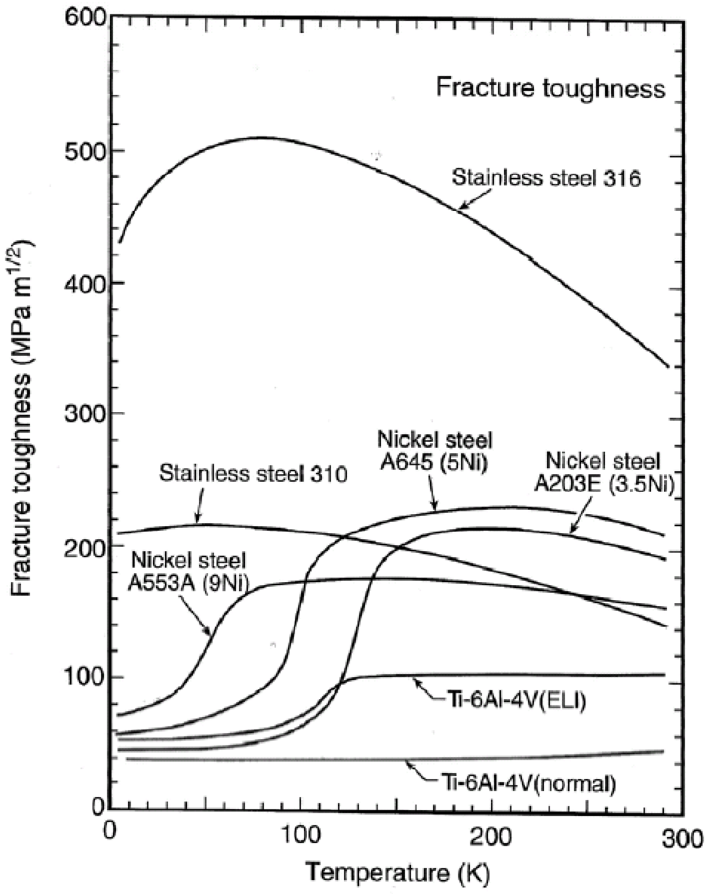
# Mechanical Properties at cryogenic temperatures (cont.d)

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

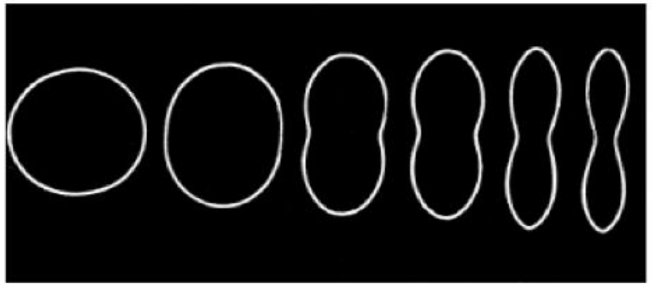
From: Technique de l'Ingénieur

# Thin shells under external pressure

Buckling:

- Non-linear phenomenon. Actual critical pressure depends on initial imperfections: Safety factor needed!
- Buckling critical pressure for a thin tube of infinite length

$$p_{cr} = \frac{E}{4(1-\nu^2)}\left(\frac{t}{r}\right)^3$$



- A conservative rule of thumb for stainless steel tubes under vacuum:

$$\frac{t}{r} \geq \sqrt[3]{\frac{0.1MPa \times 4 \times (1-0.3^2)}{200 \times 10^3 MPa}} = 0.012$$

- If we use a safety factor of 3:

$$\frac{t}{r} \geq 3.7\%$$

- Alternatively, we need to add reinforcements (e.g LHC vessels, t=12 mm)

Example:
- r = 500 mm
- t > 18.5 mm

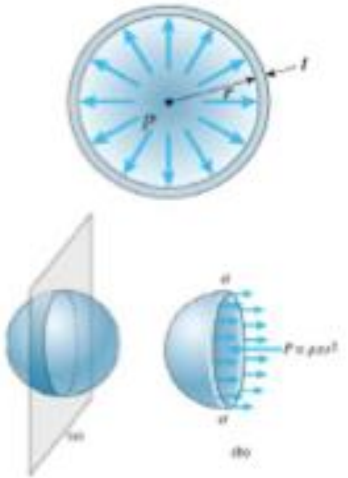
# Thin shells under internal pressure

For preliminary calculation

*For detailed calculation see EN 13458-2 Cryogenic vessels – static vacuum insulated vessels*

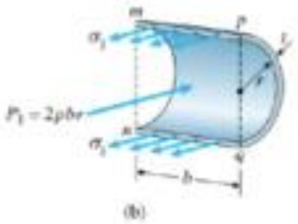
$valid\ for\ r \geq 10t$

**Sphere**



$$\sigma_1 = \sigma_2 = \frac{pr}{2t} \qquad \sigma_3 \cong 0$$

**Cylinder**



$$\sigma_1 = \frac{pr}{t} \qquad \sigma_2 = \frac{pr}{2t}$$

$$\sigma_3 \cong 0$$

Tresca yield criterion: $|\sigma_1 - \sigma_3| \leq \sigma_a$ Where $\sigma_a$ is the maximum allowable stress

$$\frac{pr}{2t} \leq \sigma_a$$

$$\frac{pr}{t} \leq \sigma_a$$

*Note why spherical vessels are often used in very high pressure applications!*

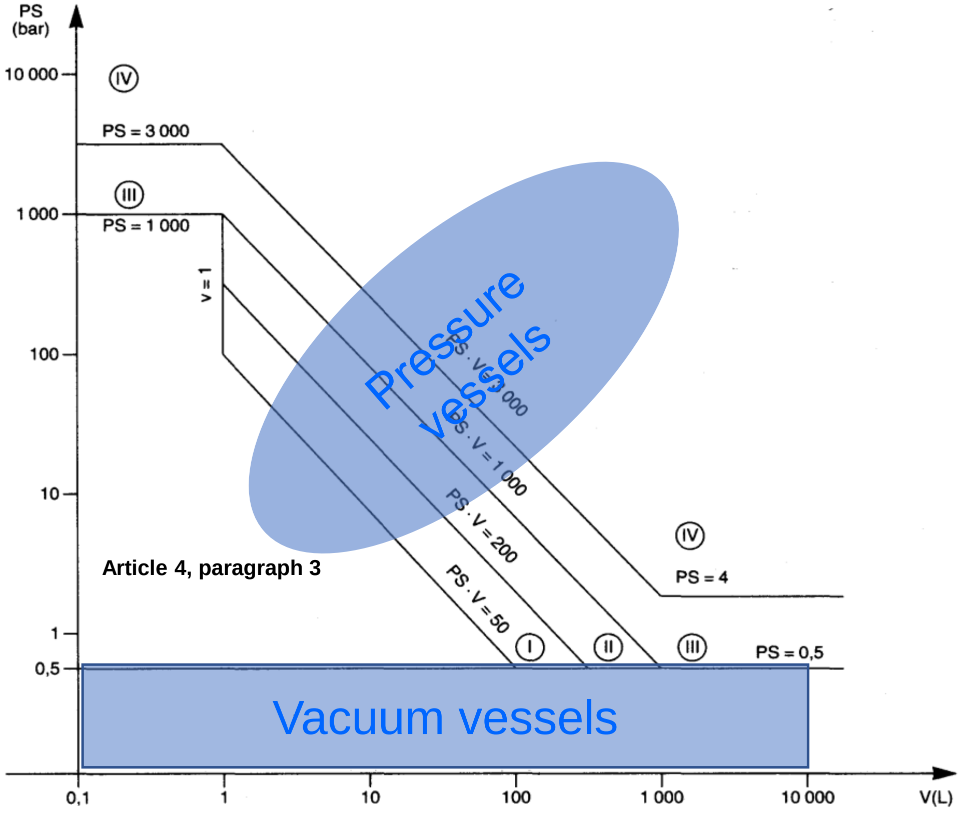
Example: cyl.helium tank

- r = 400 mm
- p = 4 barg (0.4 MPa)
- $\sigma_a$= 160 MPa (304L, $Rp_{0.2}$= 240 MPa, SF=1.5)
- t ≥ 1 mm

(Note: under vacuum (previous calculation) → t ≥ 15 mm !)

# 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

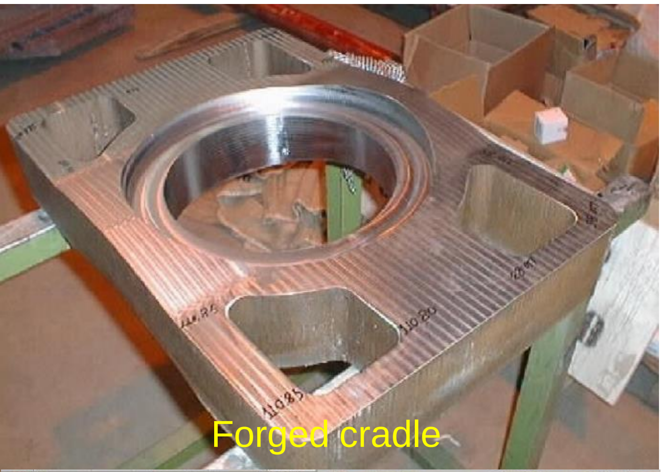
# LHC dipole Vacuum Vessels

**Main features:**

- Pipeline standard size: **36-inch OD (1013 mm)**, **12-mm thick**, low carbon steel (DIN GS-21 Mn5) tubes
- St. steel extremity flanges
- Material resilience: > 28 J/cm2 at -70ºC
- Forged cradles, welded rings reinforcements
- Dimensional stability:
  - Stress relieving
  - Final machining to achieve tolerances at interface

**Production:**

- 1250 units
- 2 firms
- 4 yrs of production



Forged cradle

Final lathe machining

Stress relieving

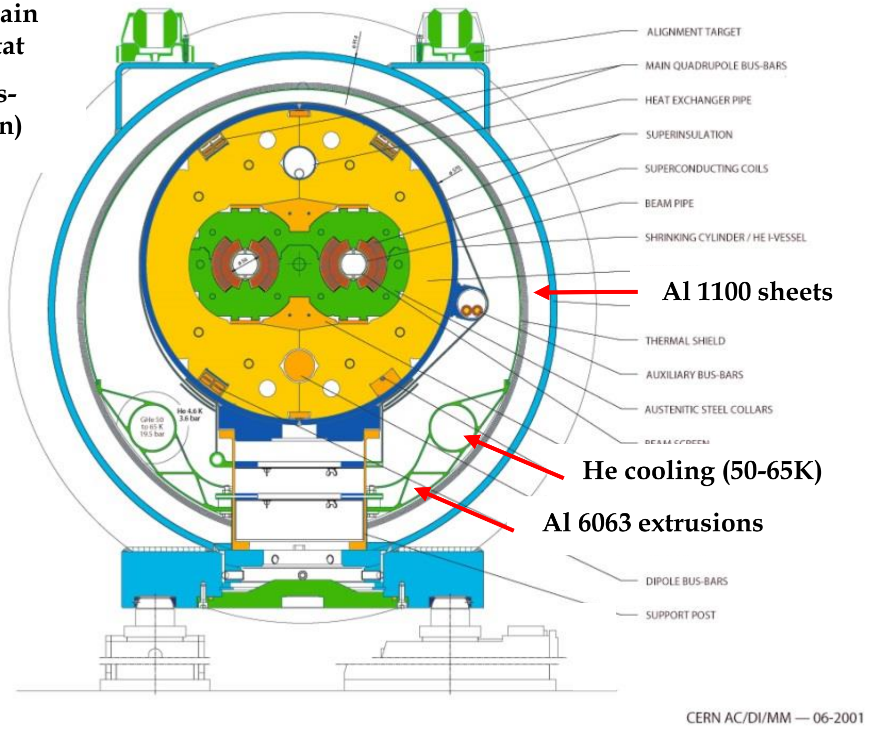
Out-doors storage at CERN

# LHC thermal shields

Aluminium alloy 6063 extrusions and 1100 top sheets

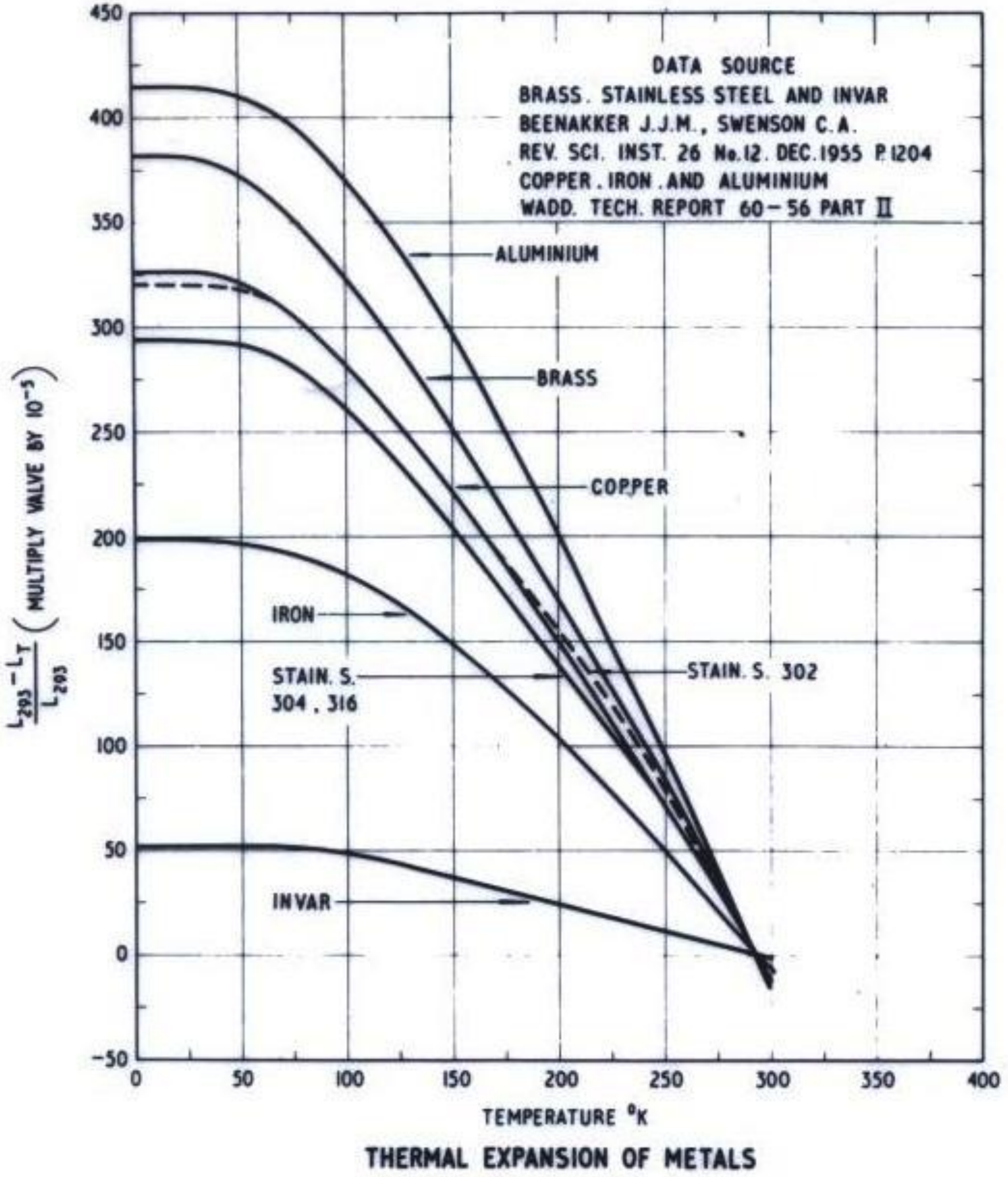
LHC Main Cryostat

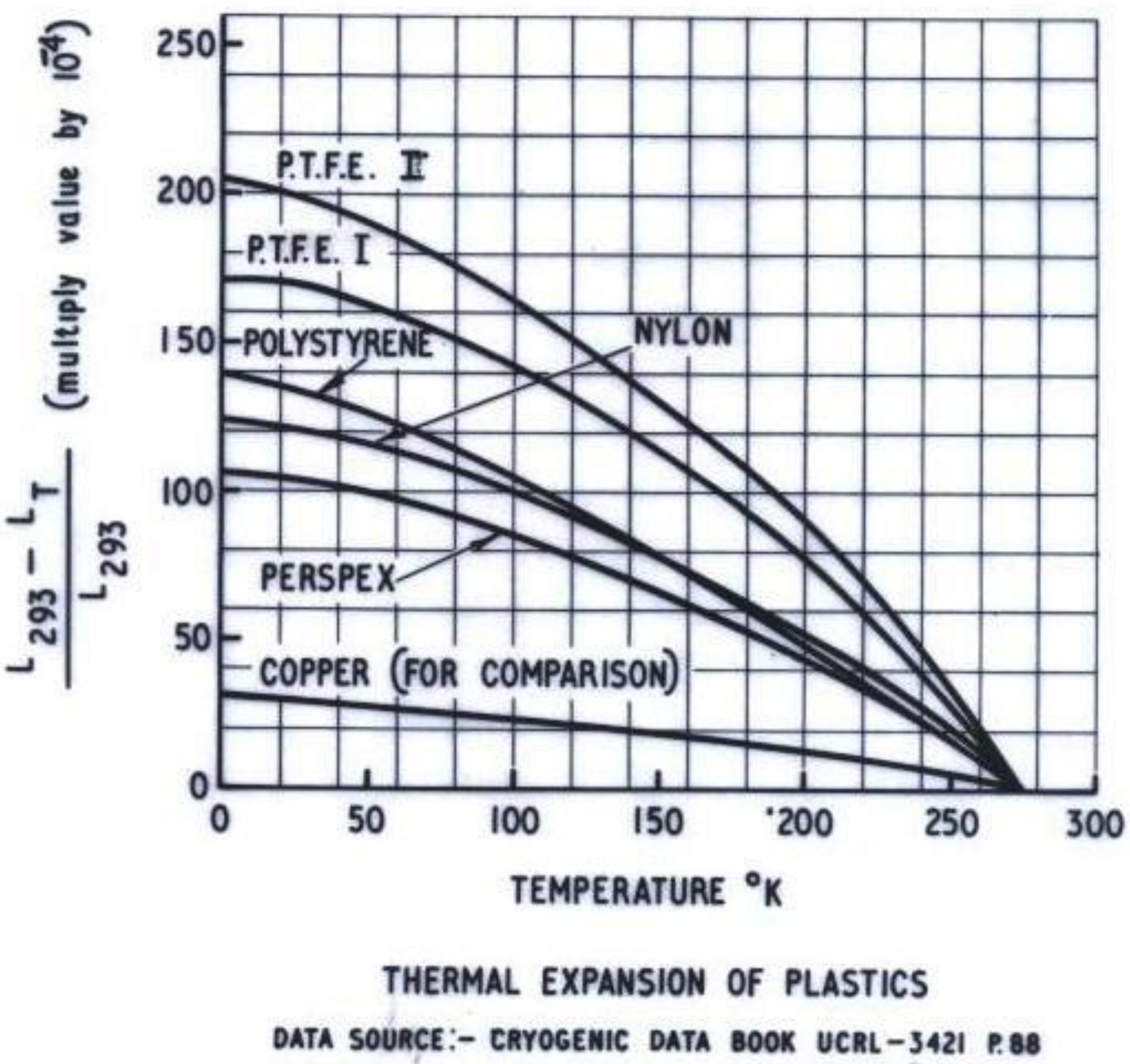
(Cross-Section)



# Thermo-mechanical considerations

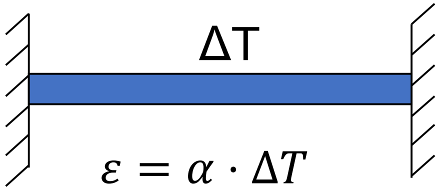
# Thermal expansion of some materials



# Thermal stress in composite material assemblies: 3 cases

## A) Restrained component

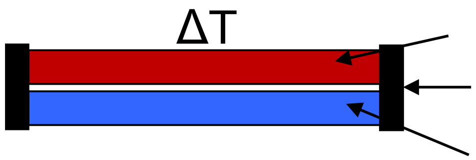



$$\varepsilon = \alpha \cdot \Delta T$$
$$\sigma = \alpha \cdot \Delta T \cdot E$$

$\alpha$ = thermal expansion coefficient [$K^{-1}$]

$E$ = Young modulus

## B) Assembly of different materials




Material 1: α1, E1, A1

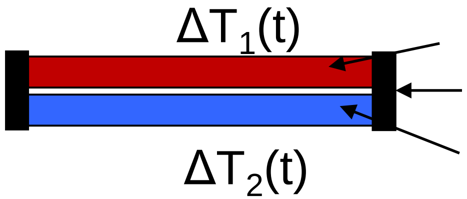
restrained

Material 2: α2, E2, A2

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

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

*(different material diffusivity or different cooling)*




Material 1: α1, E1, A1

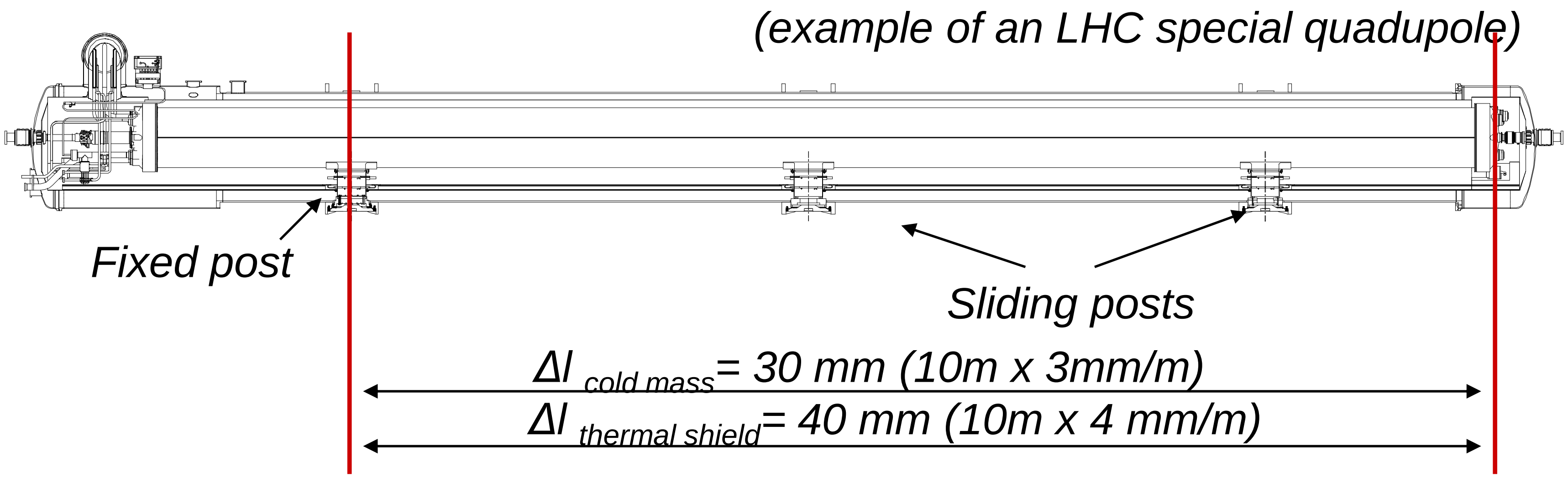
restrained

Material 2: α2, E2, A2

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

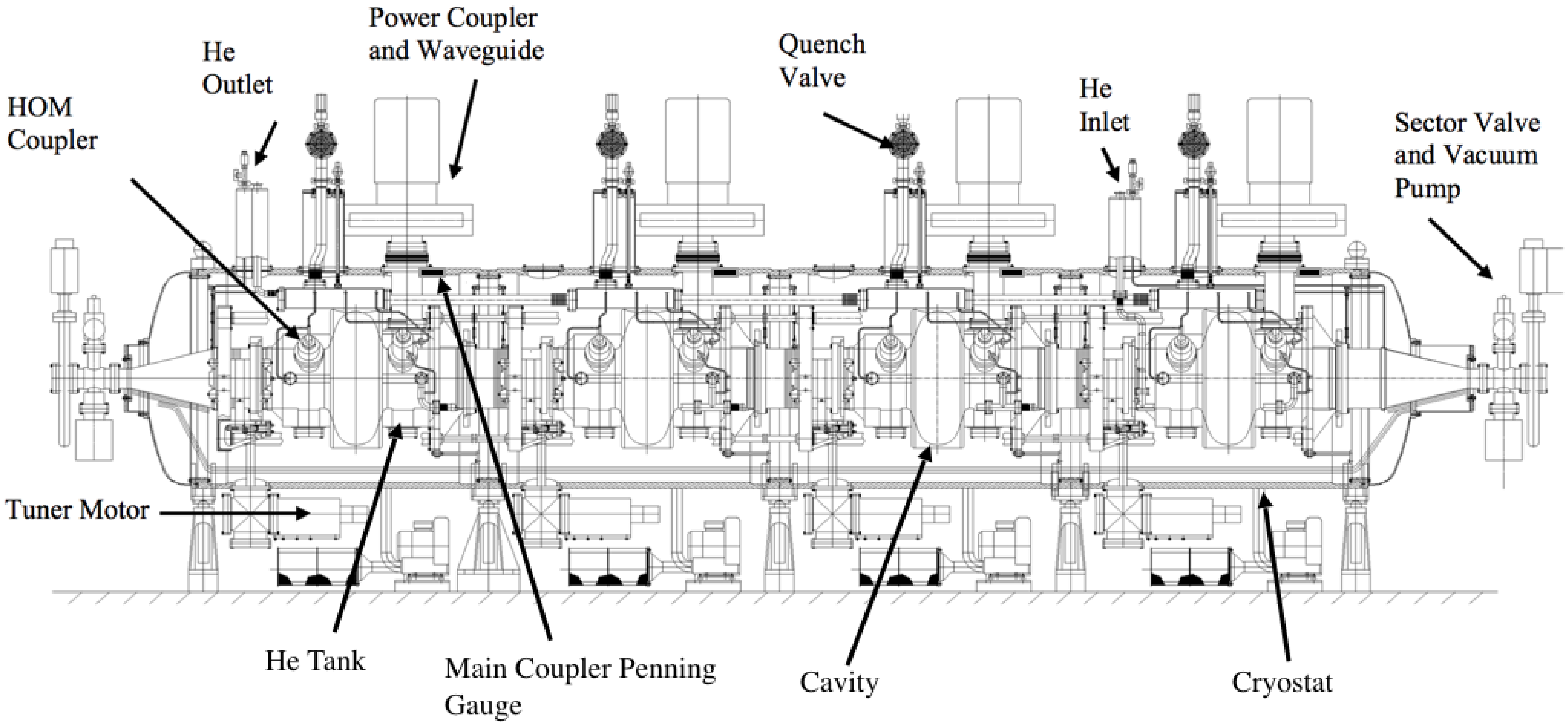
# LHC cryostats: longitudinal thermal contractions

- Cold mass, thermal shield, support posts and vacuum vessel must be free with each other to cope with longitudinal thermal contractions
- One fixed point per each component
- Leave plays to cope with all extreme T cases (ex. Cold mass cold, thermal shield warm)
- Guided sliding of cold mass onto vacuum vessel → slot/key
- Flexible thermalisation anchors



# Supporting systems

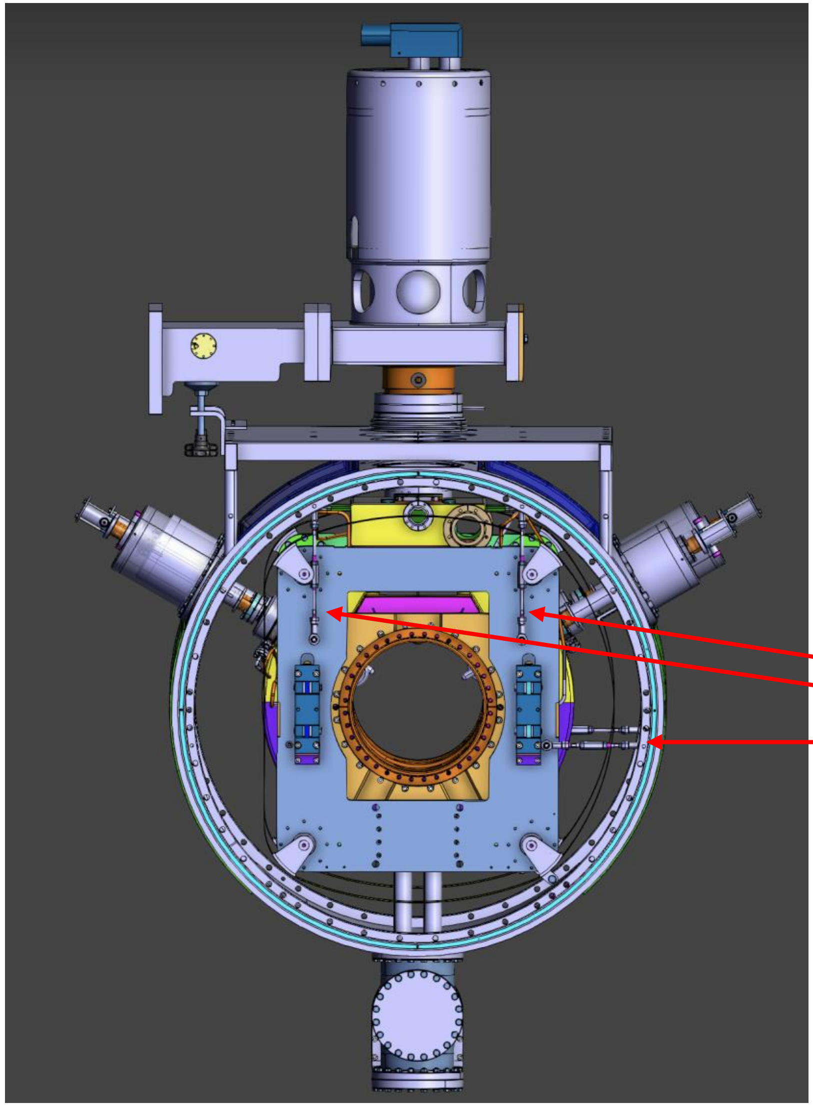
# LHC Cryomodule, 400 MHz cavities (Nb on Cu) at 4.5 K

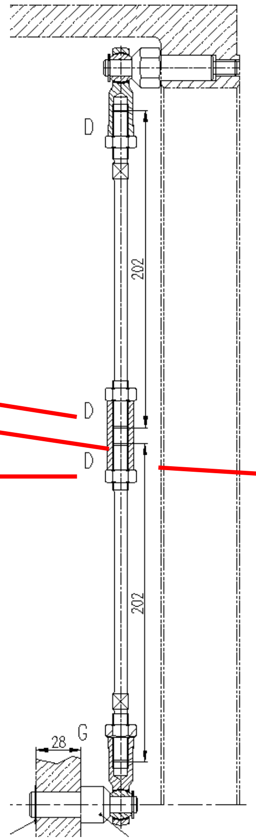


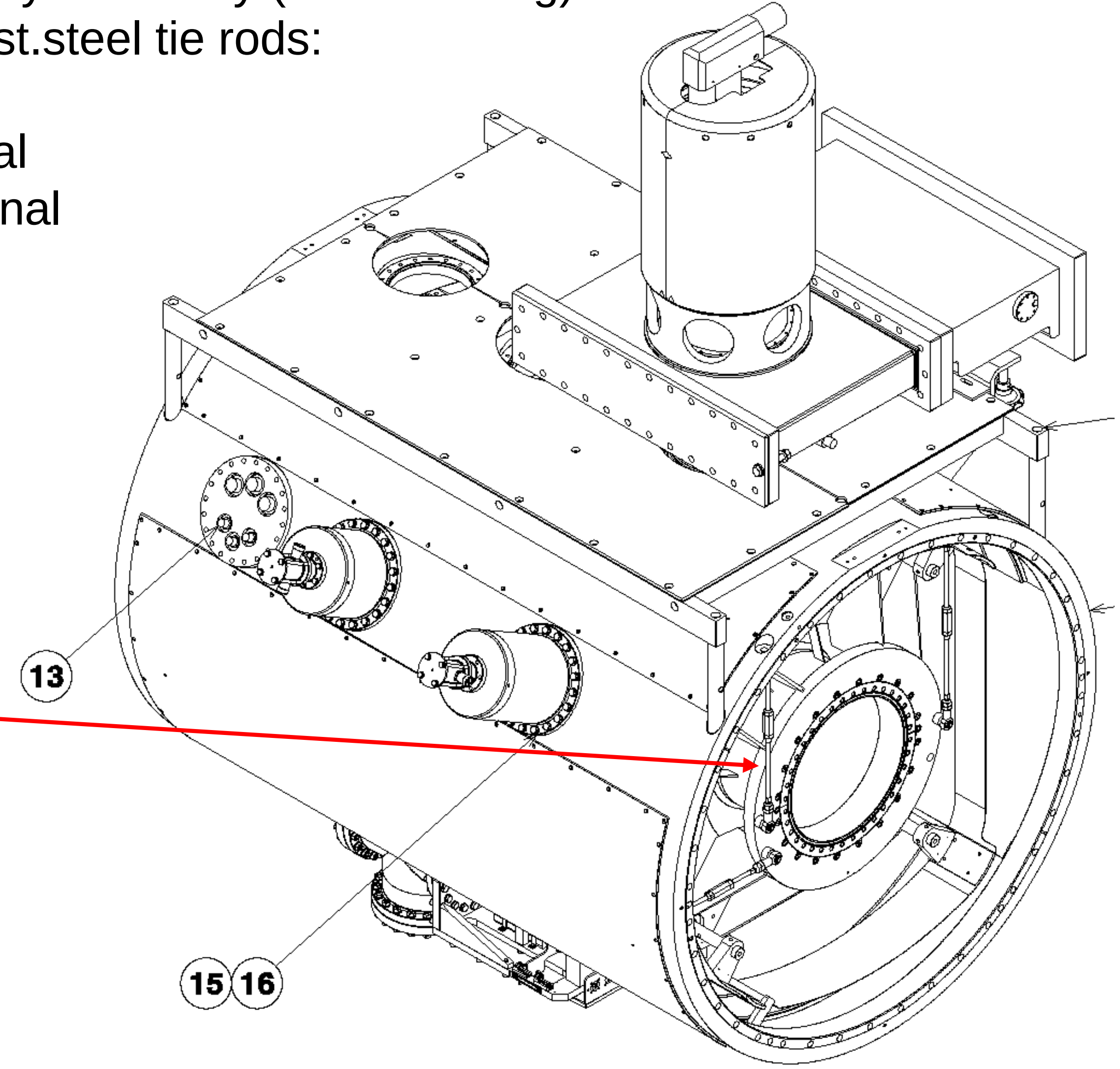
# LHC Cryomodule Supporting System

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

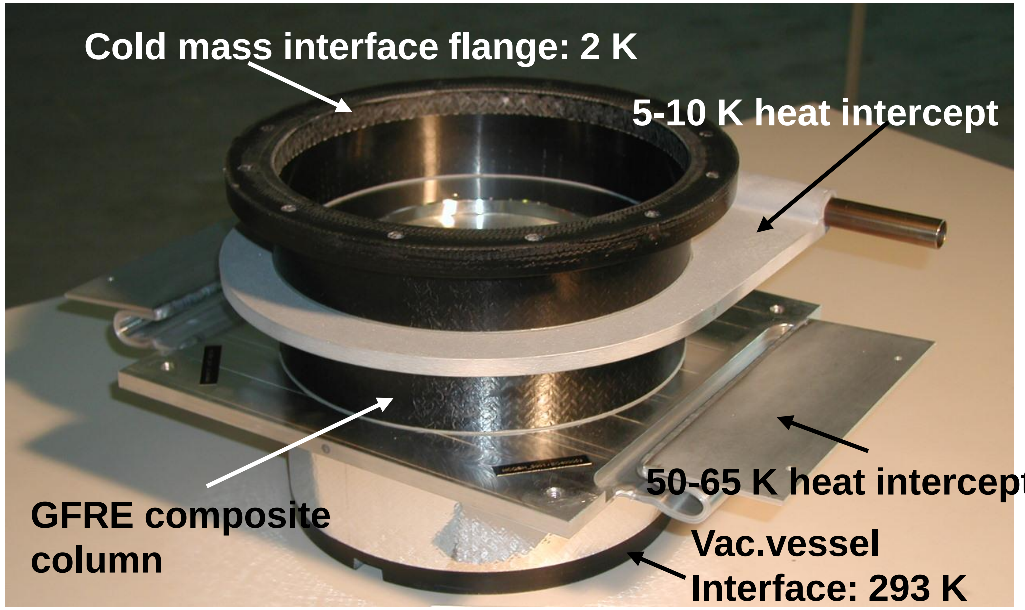
- 4 vertical
- 2 horizontal
- 1 longitudinal





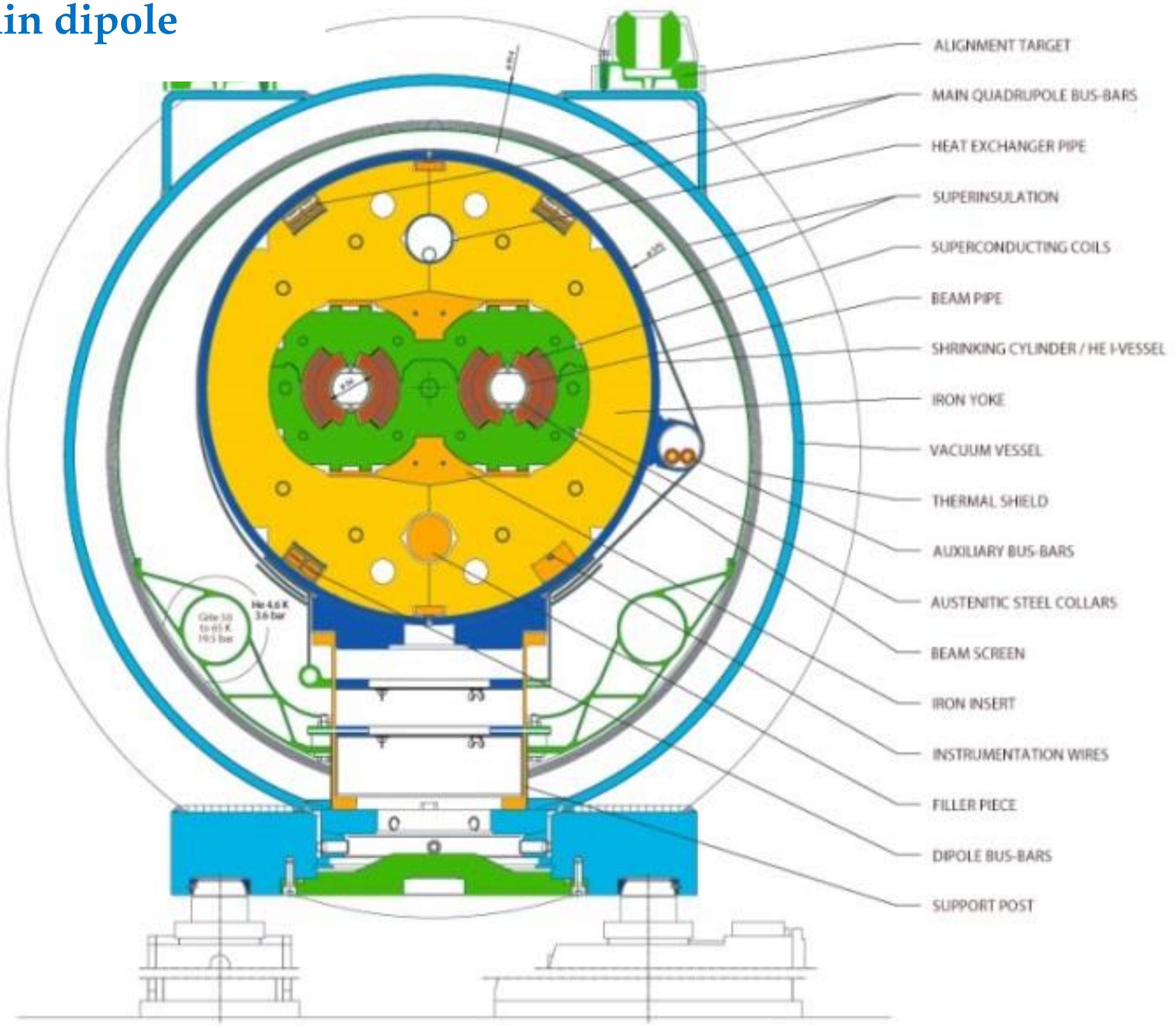



# LHC magnet Cryostats




- **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



# LHC Supporting system

The design is a trade-off between 2 conflicting requirements:

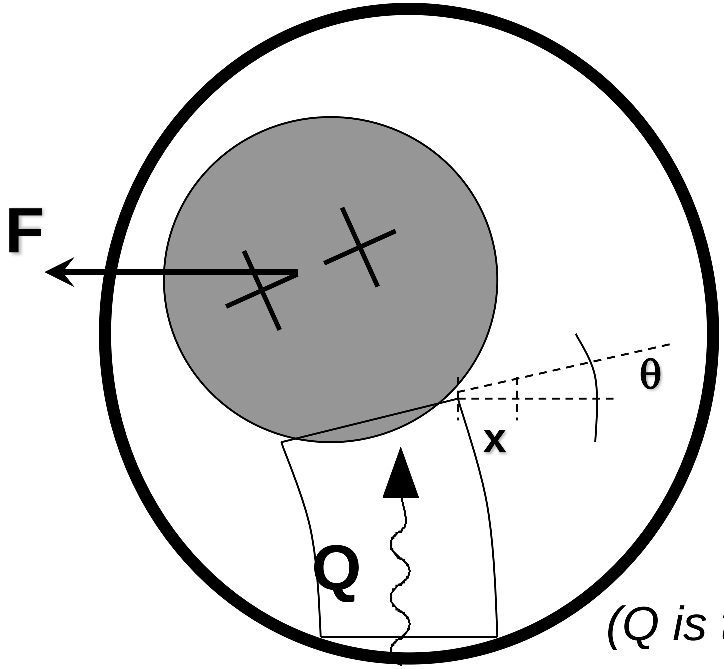
- High flexural stiffness (for mechanical stability) → thick and bulky structure
- Low heat in-leaks → thin and slender structure and low conductivity material

*(F is mainly the result of interconnect forces and gravity component)*

*F = 5 kN*

*x = 0.1 mm*

*θ = 1 mrad*




*(The acceptable x and θ are alignment requirements)*

*(Q is to be within budget)*

→ Flexural stiffness/conductivity as figure of merit in the choice of the material

# 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

# Lay-up, calculated safety factors, material properties

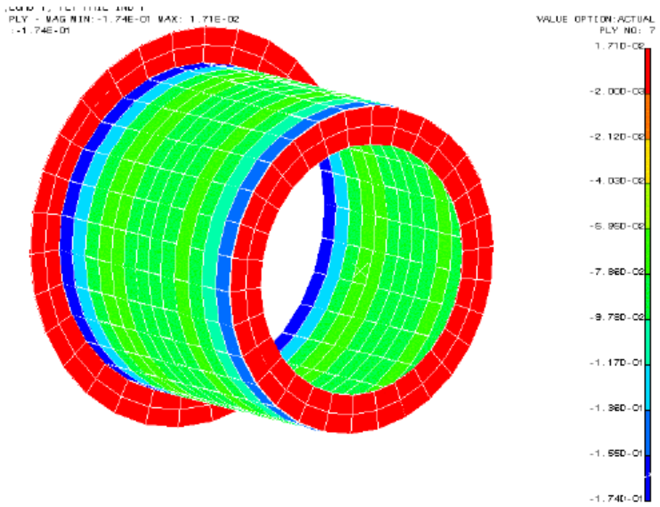
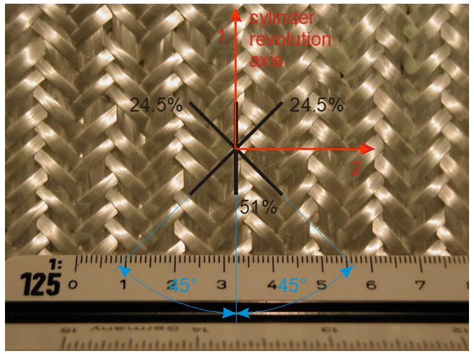
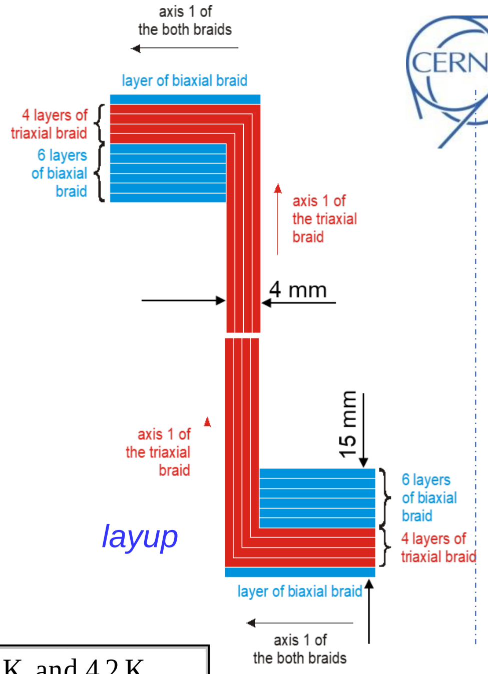


Figure 4.2.1.1 Ply Failure Index. LS 1.1-A

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 |

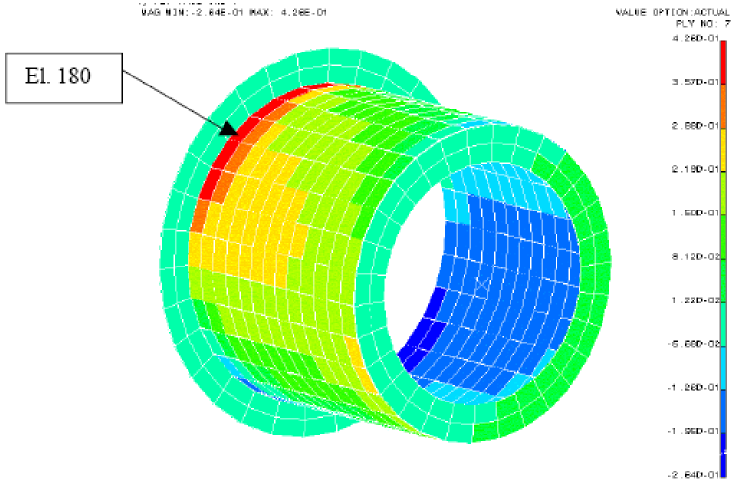
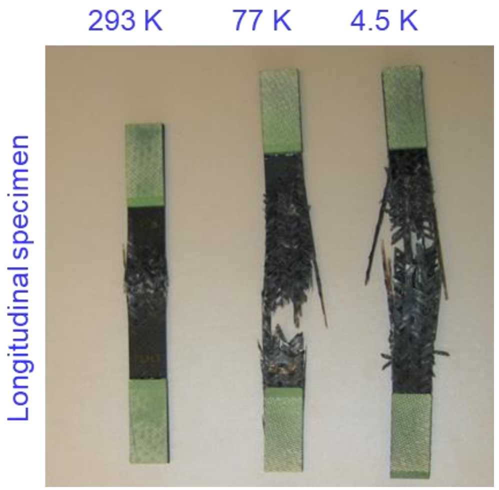


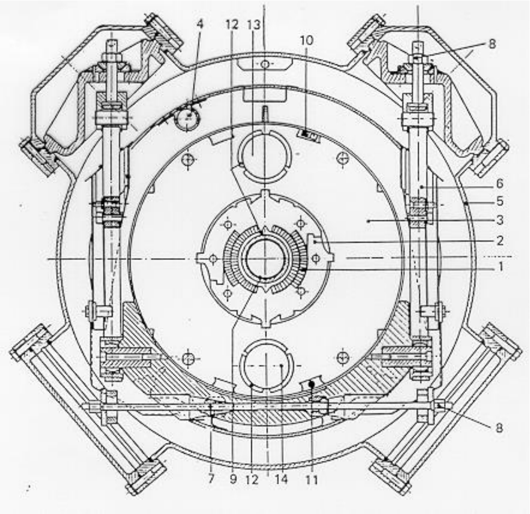

Figure 4.2.2.1 Ply Failure Index. LS 1.2.1-A

Bending cantilever 40 kN. (vacuum barrier load)

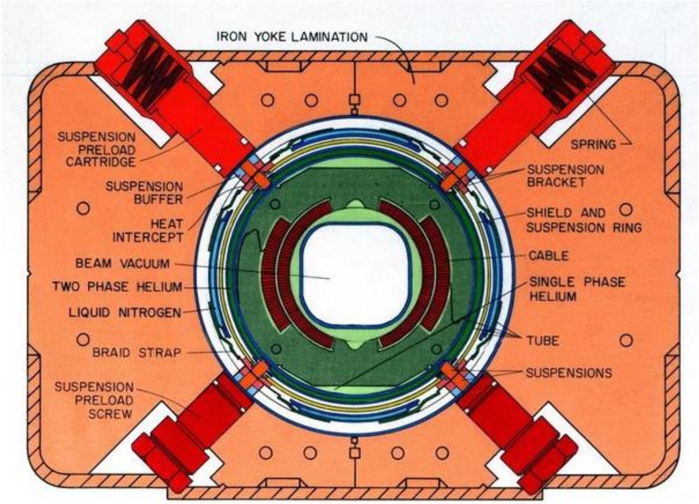
Tsai-Wu ply failure: Safety Factor = **2.7**



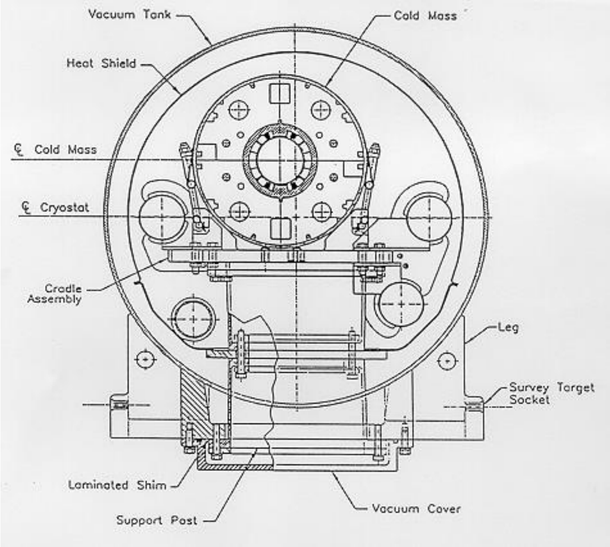
# SC magnet supporting systems from other machines



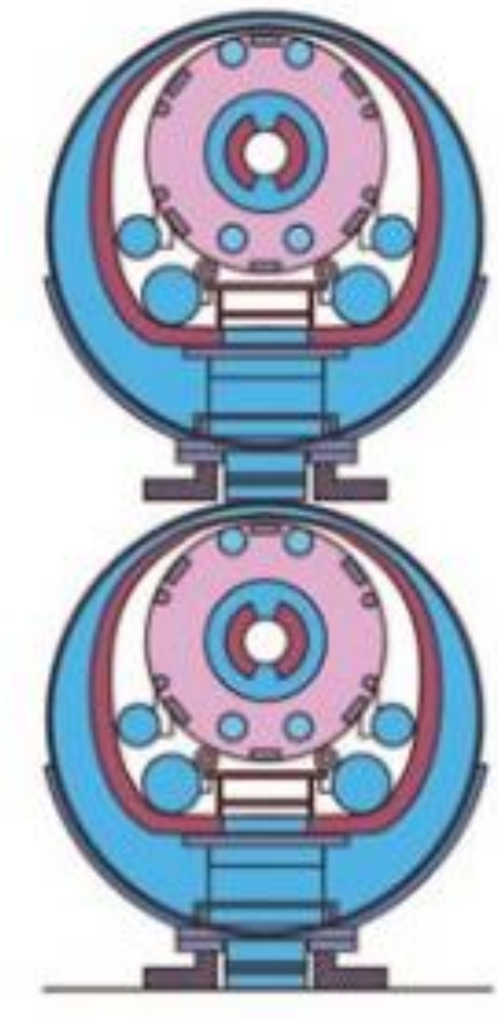

Hera dipole




Tevatron

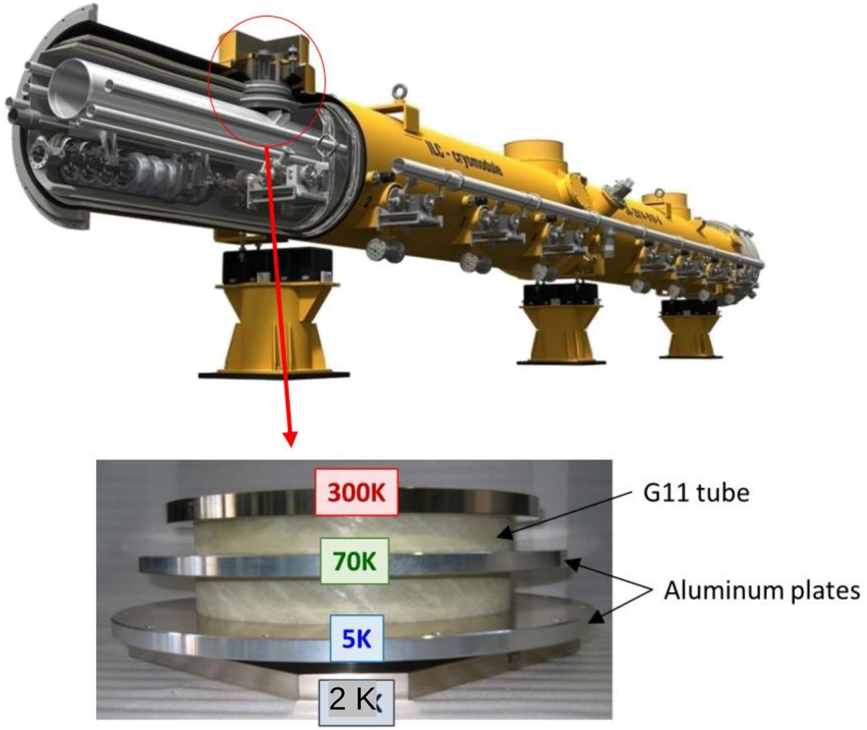


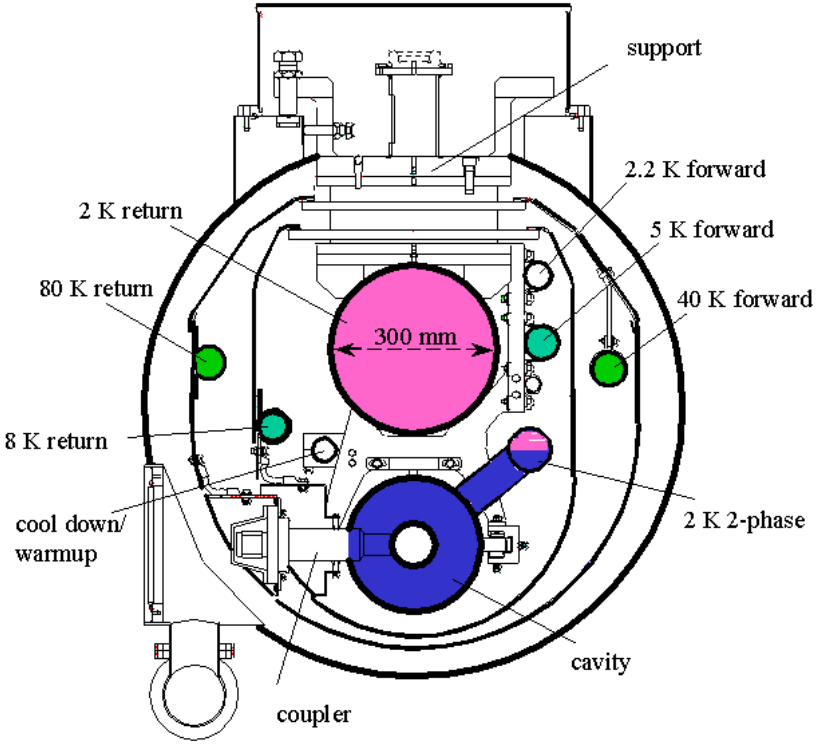

RHIC dipole

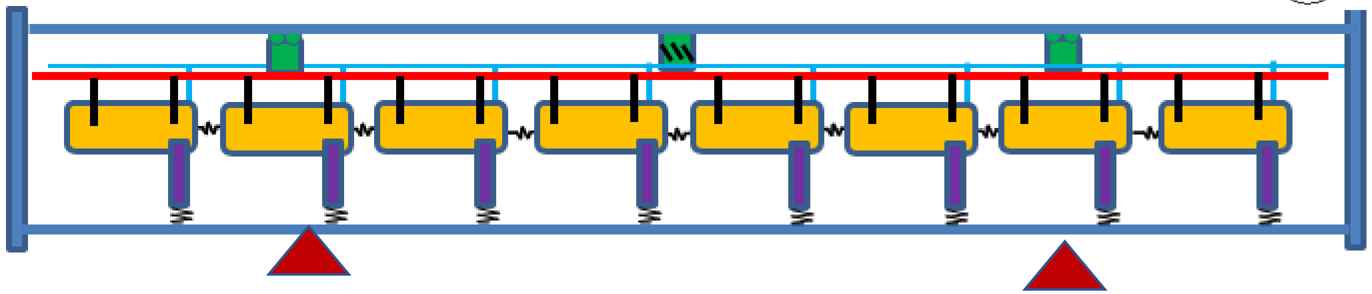


SCC

# Supporting system of Tesla/TTF/ILC Cryomodule



RF coupler (with bellows)

Invar longitudinal positioner

DN 300 as back-bone

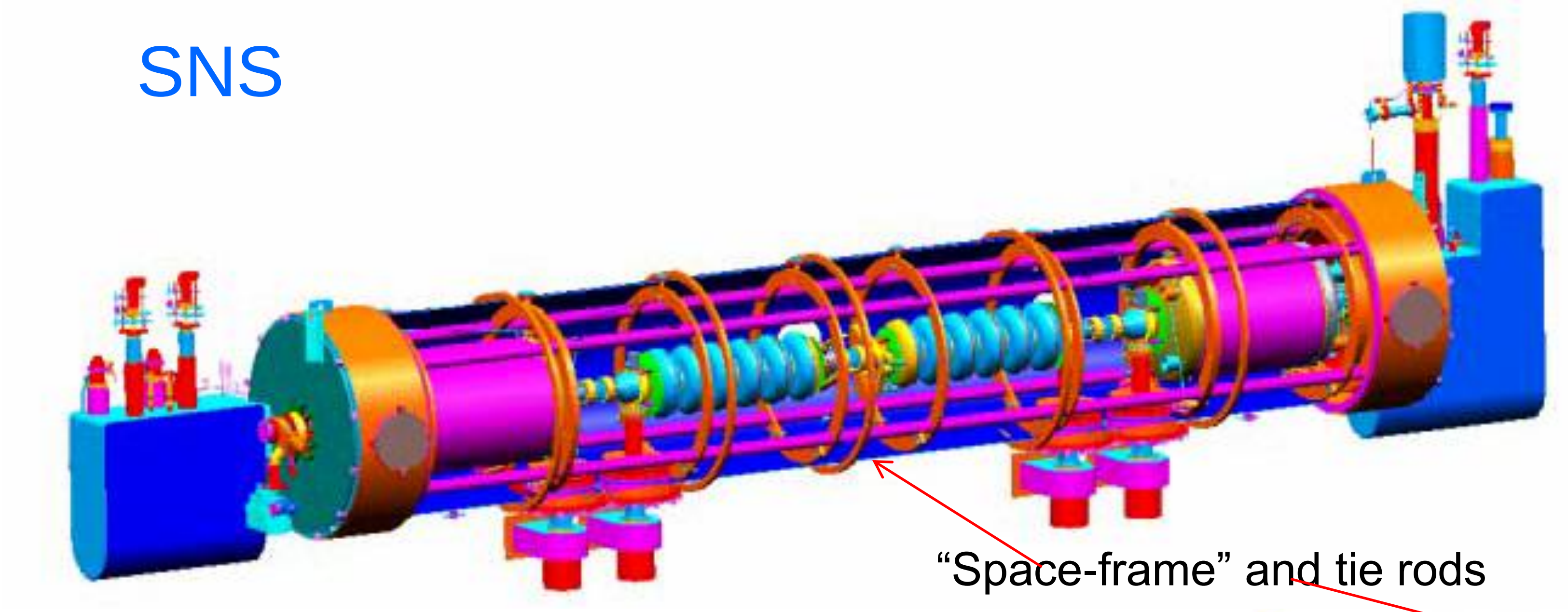
Fixed support

Sliding support

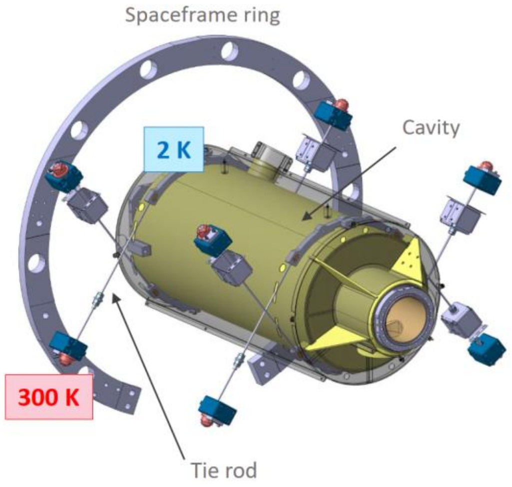
External supports (jacks)

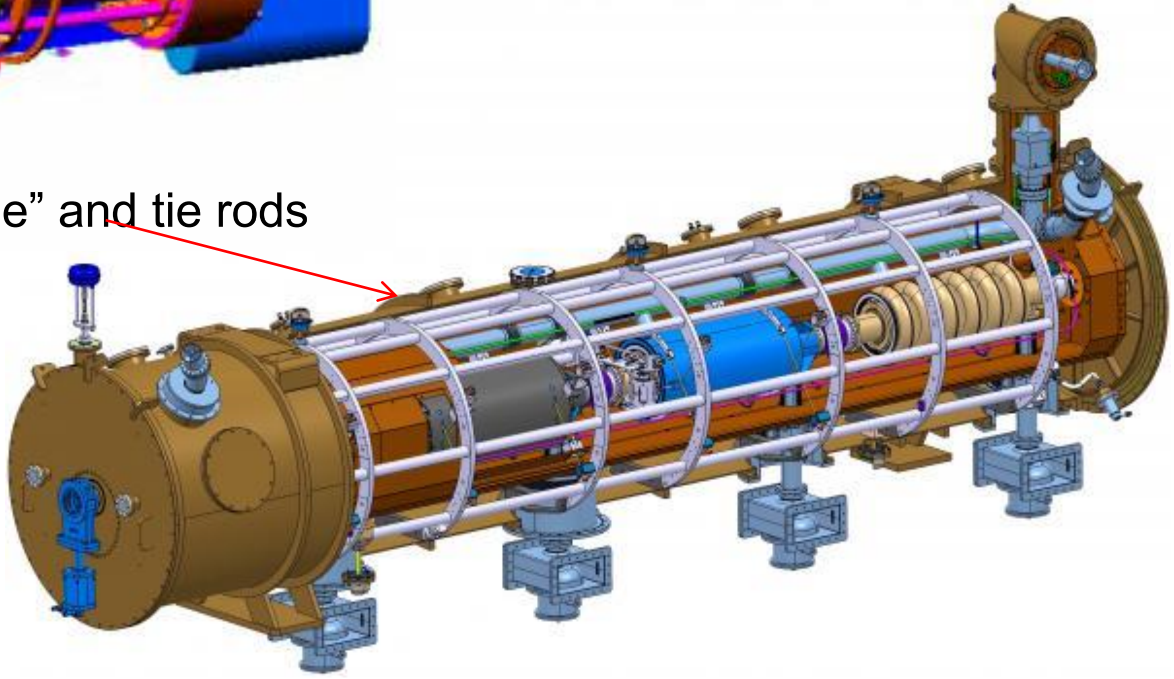
# Supporting system of SNS and ESS high β Cryomodules

SNS



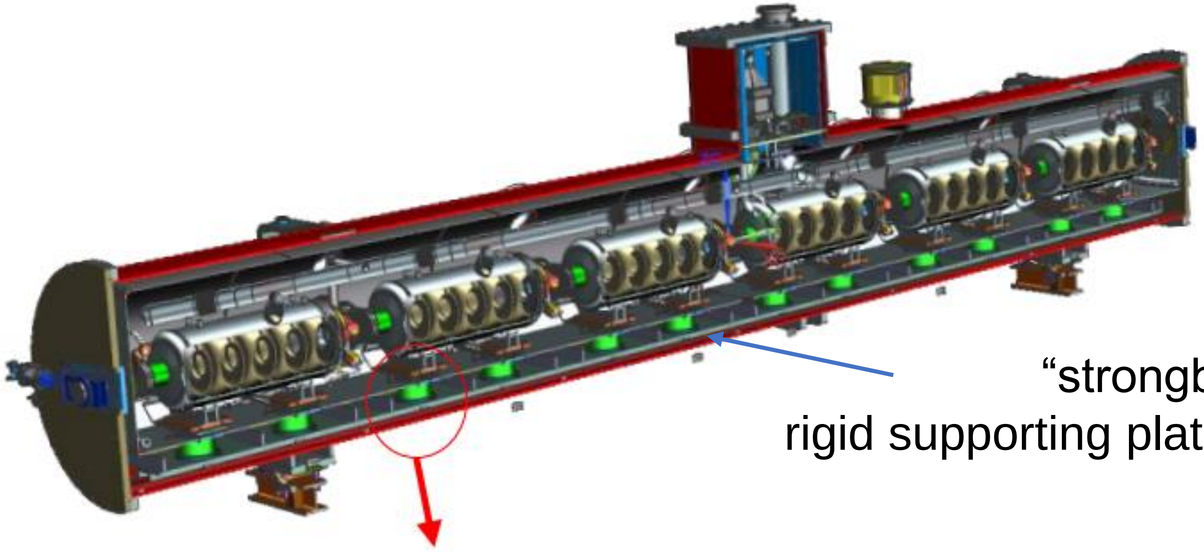
“Space-frame” and tie rods



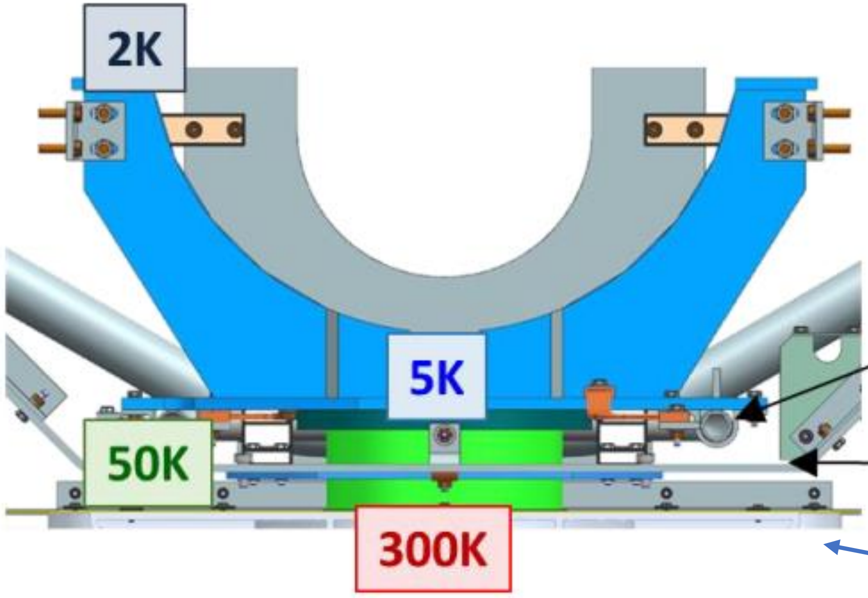



ESS

# Supporting system of PIP II Cryomodule



“strongback”:
rigid supporting plate in vacuum at RT

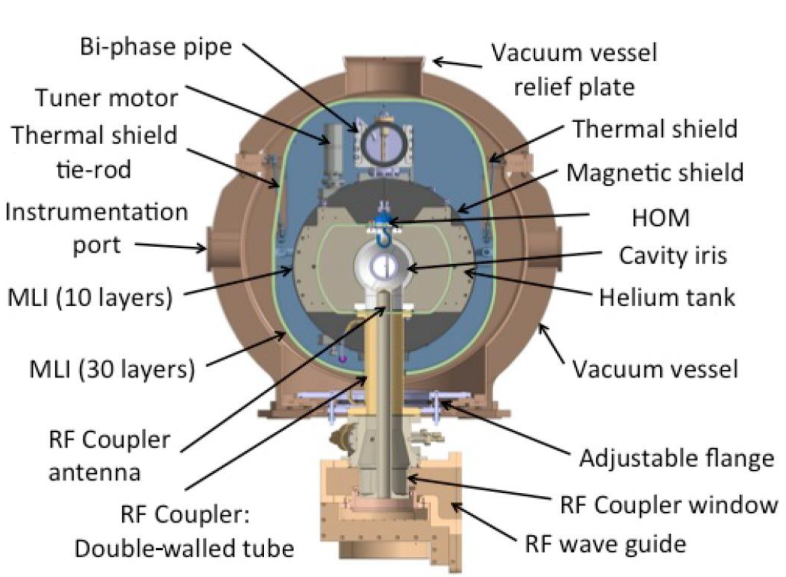


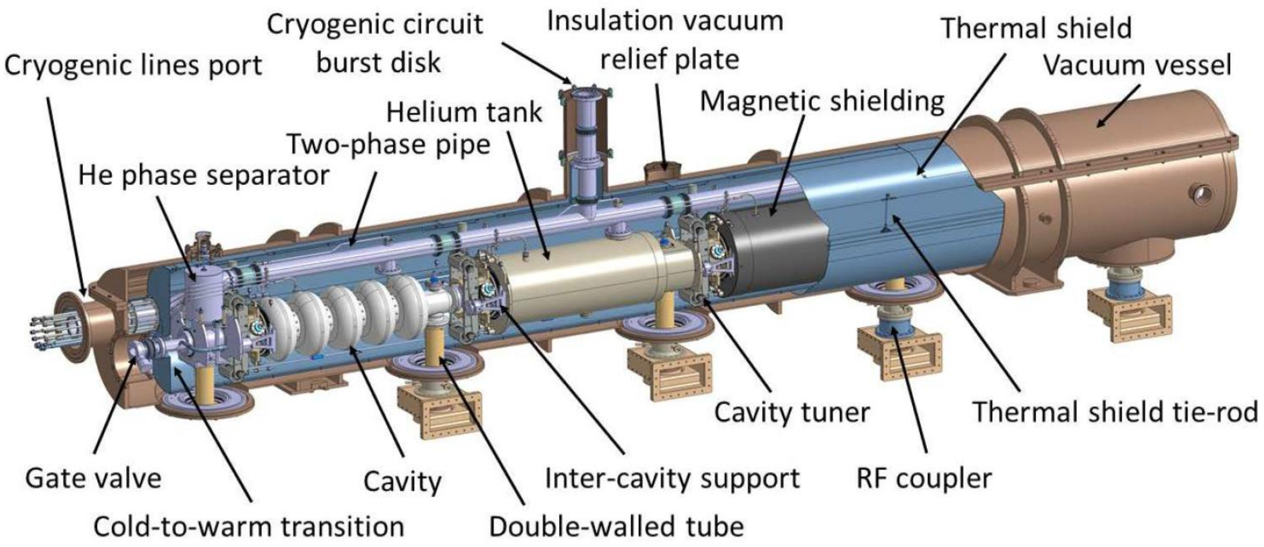

5K line

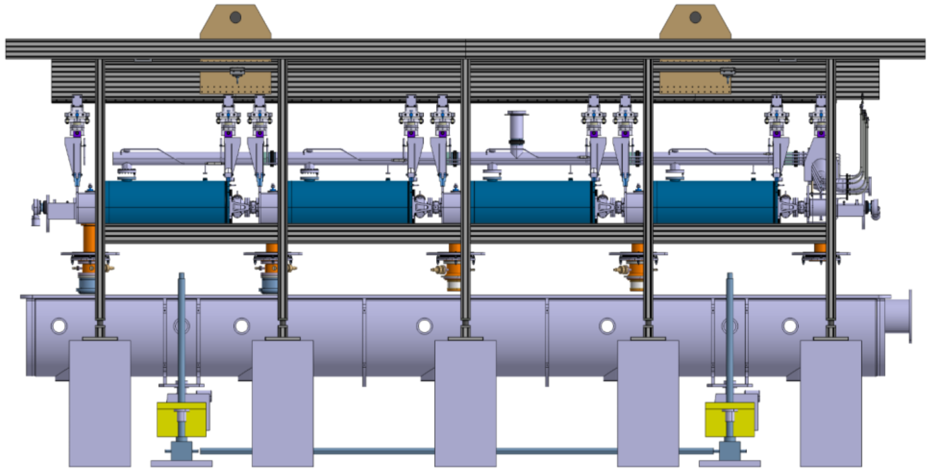
Thermal shield

strongback

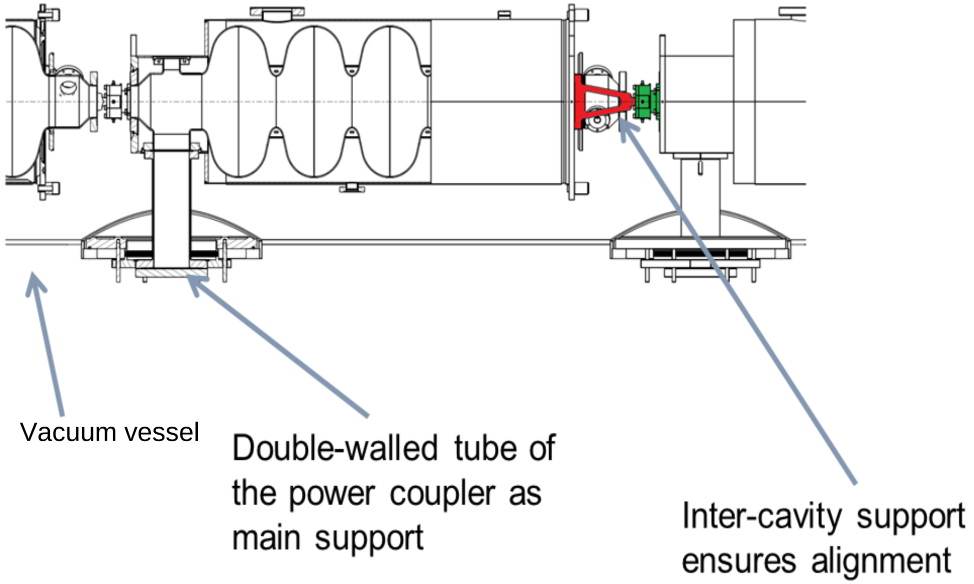
# SPL cryomodule: RF Coupler as support



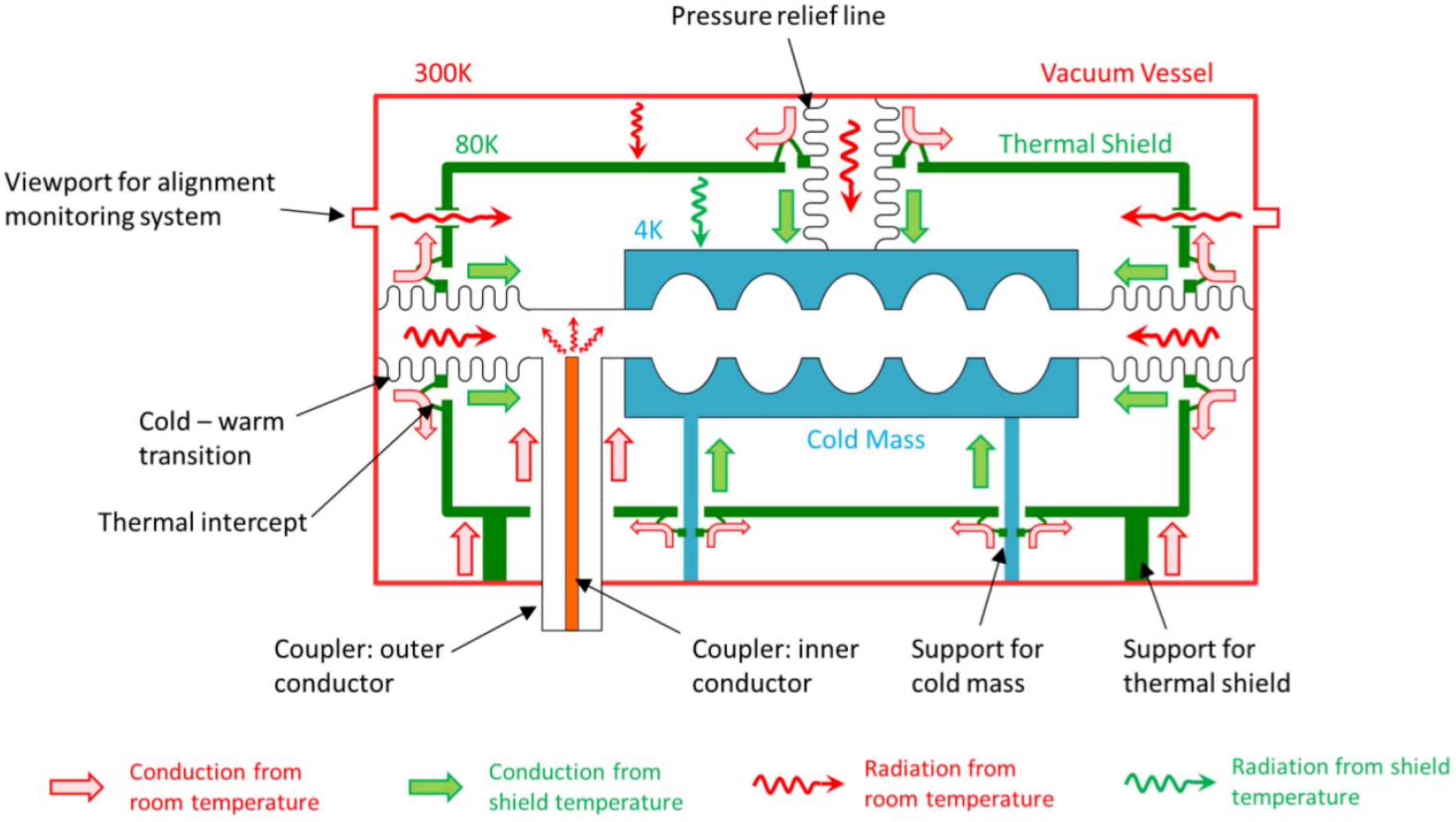
Vertical loading of cavities string



# Heat transfer mechanisms and thermal design

# Heat transfer mechanisms

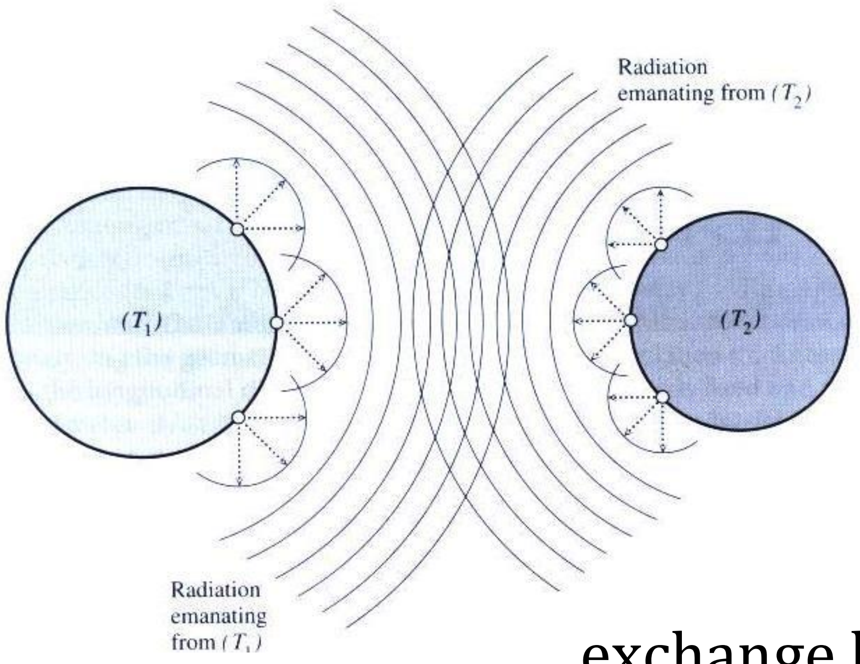
- Thermal radiation
- Thermal conduction
- Heat intercepts




*Inspired by P. Duschene and JP. Thermeau*

# Thermal Radiation

# Thermal Radiation




Stefan-Boltzmann's law

$Q = \sigma\, A\, T^4$ black body

$Q = \varepsilon\, \sigma\, A\, T^4$ gray body, $\varepsilon < 1$

$\sigma = 5.67\ 10^{-8}\ W\ m^{-2}\ K^{-4}$
Stefan-Boltzmann's constant

$A$, $T$ area and temperature of the body, $\varepsilon$ emissivity

exchange between **black bodies**

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

exchange between **gray bodies**

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

- F, geometrical view factors $F_{1-2}$ (<1) between $A_1$ and $A_2$ ($or\ F_{2-1}$ between $A_2$ and $A_1$), with $A_1 E_{12} = A_2 E_{21}$.
- E, effective emissivity, a function of view factors and emissivity $\varepsilon_1$ and $\varepsilon_2$ of the bodies

*Figures source:* "Heat Transfer", A.Bejan, John Wilney & Sons, Inc.

# Black body radiation

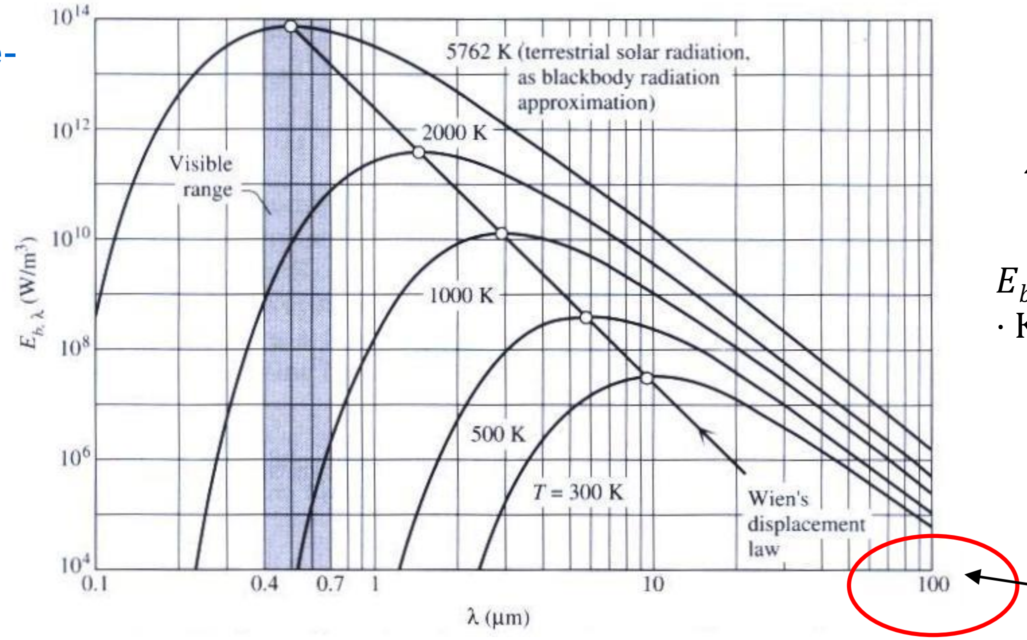
- Hemispherical monochromatic emissive power [W/m·m2] (energy per unit time, wave-length, and surface area)

$$E_{b,\lambda} = \frac{C_1 \lambda^{-5}}{e^{\left(\frac{C_2}{\lambda T}\right)} - 1}$$ Planck's law

$C_1 = 2\pi h c^2 = 3.742\ 10^{-16}\ W\ m^2$

$C_2 = \frac{h\ c}{k} = 1.439\ 10^{-2}\ K\ m$

hemispherical emissive power (monochromatic)




$$\lambda_{max} = \frac{2898}{T}\ (\mu m/K)$$

$$E_{b\lambda} \max(T) = 12.87 \cdot 10^{-6}\ W/m^3 \cdot K^5) \cdot T^5$$

In cryogenics: far infrared region (725 μm at 4 K)

- Total emissive power (integrating over λ):

$$Eb(T) = \int_0^{\infty} E_{b,\lambda} d\lambda = \sigma \cdot T^4 \quad (W/m^2)$$

$with:$

$$\sigma = \frac{2\pi^5 k^4}{15\ h^3\ c^2} = 5.67\ 10{-}8\ (W/m^2 \cdot K^4)\ \text{Stefan–Boltzmann's constant}$$

(k, Boltzmann constant, h, Planck constant, c, speed of light )

***In practice**: Blackbody emits ~ **420 W/m² at 293 K** , and only ~**2 W/m² at 77 K** (200 times less!)*

*Figures source:* "Heat Transfer", A.Bejan, John Wilney & Sons, Inc.

# Black and diffuse-gray model

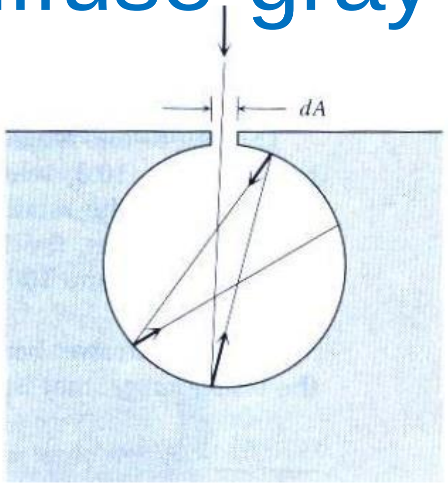
## Black model

$\alpha \rightarrow$ absorptivity
$\rho \rightarrow$ reflectivity
$\tau \rightarrow$ transmissivity

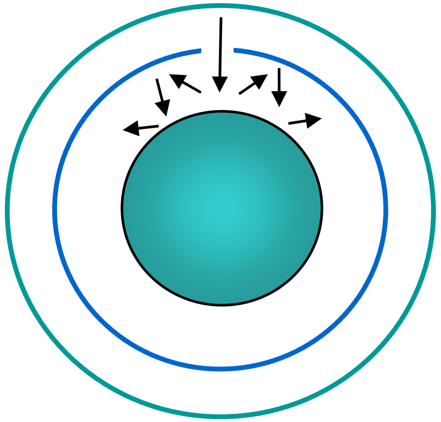
$$\alpha + \rho + \tau = 1$$

$$\alpha + \rho = 1 \quad (opaque, \tau = 0)$$

$$\alpha = 1 \quad (black, \rho = 0, \tau = 0)$$

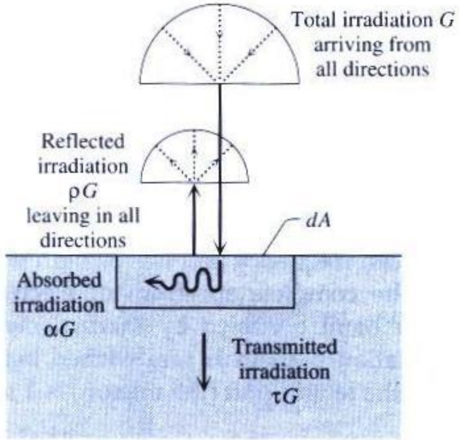


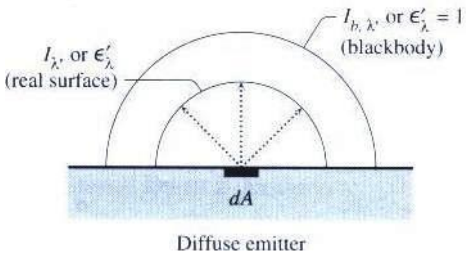

Black surface: $\alpha$ = 1

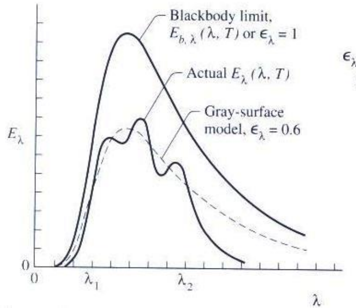


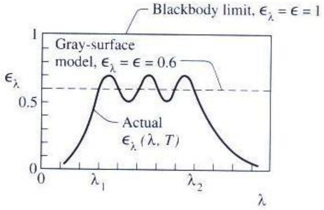
***Practical application*** *in cryostats: every gap in shields is a black surface*
(1 $cm^2$ gap exposed to 293 K, ε = 0.2 → ~10 mW)

## Diffuse-gray model



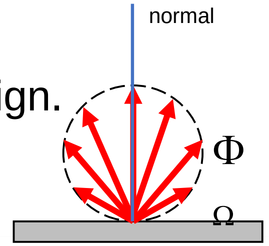

Diffuse-gray model (good approximation for real surfaces in engineering):

- Gray: $\varepsilon_\lambda(\lambda,T) \approx \varepsilon(T)$
- Diffuse emitter/absorber (not directional)
- Opaque (τ = 0)
- $\alpha(T) = \varepsilon(T)$

*Figures source:* "Heat Transfer", A.Bejan, John Wilney & Sons, Inc.

# Emissivity

- $\varepsilon$ depends on wave-length and direction (neglected in gray-diffuse model). In metals emissivity rises sharply and up to more than 40% above 50 deg. incidence from the surface normal
- Clean, well-polished metallic surfaces have smaller $\varepsilon$, non-metallic materials have higher $\varepsilon$
- Metals: $\varepsilon$ decreases with decreasing temperature, almost linearly at cryo temperatures
- Non-metals: $\varepsilon$ may decrease or increase with decreasing temperature (increases for organic materials)
- Engineering approach. Due to uncertainties on real $\varepsilon$ values, take conservatively high values for preliminary design. Measurement validation may be necessary




Directional distribution

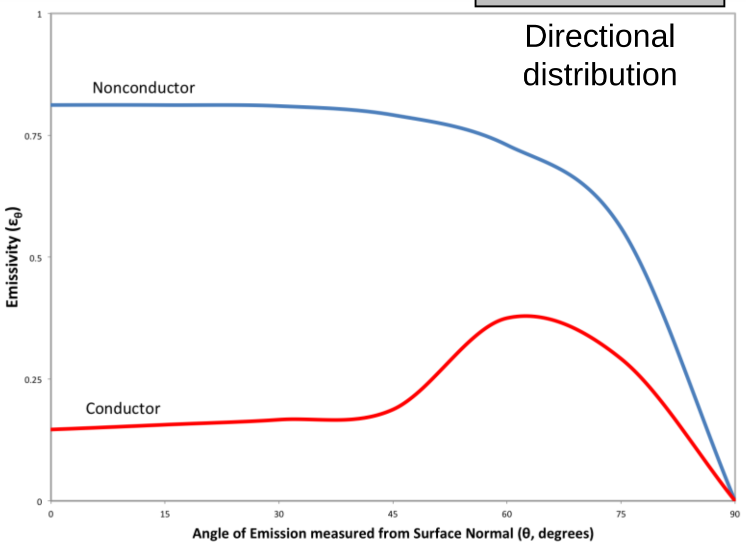
| Temperature [K] | 4 | 20 | 80 | 300 |
|---|---|---|---|---|
| Copper mechanically polished | 0.02 | | 0.06 | 0.1 |
| Copper black oxidized | | | | 0.8 |
| Gold | | | 0.01 | 0.02 |
| Silver | 0.005 | | 0.01 | 0.02 |
| Aluminium electropolished | 0.04 | | 0.08 | 0.15 |
| Aluminium mechanically polished | 0.06 | | 0.1 | 0.2 |
| Aluminium with 7μm oxide | | | | 0.75 |
| Magnesium | | | | 0.07 |
| Chromium | | | 0.08 | 0.08 |
| Nickel | | | 0.022 | 0.04 |
| Rhodium | | | 0.08 | |
| Lead | 0.012 | | 0.036 | 0.05 |
| Tin | 0.012 | | 0.013 | 0.05 |
| Zinc | | | 0.026 | 0.05 |
| Brass, polished | 0.018 | | 0.029 | 0.035 |
| St.steel 18-8 | 0.2 | | 0.12 | 0.2 |
| Glass | | | | 0.94 |
| Ice | | | | 0.96 |
| Oil paints any color | | | | 0.92-0.96 |
| Silver plate on copper | | 0.013 | 0.017 | |
| Aluminium film 400A on Mylar | | | 0.009 | 0.025 |
| Aluminium film 200A on Mylar | | | 0.015 | 0.035 |
| Nickel coating on copper | | 0.027 | 0.033 | |

*Ref. R.B.Scott, Cryogenic Engineering, (Van Nostrand, New York, 1959; Y.S.Touloukian, Thermophysical Properties of Matter, (Plenum Press, New York, 1995))*

*Tableau G. – Émissivité totale normale de quelques métaux.*

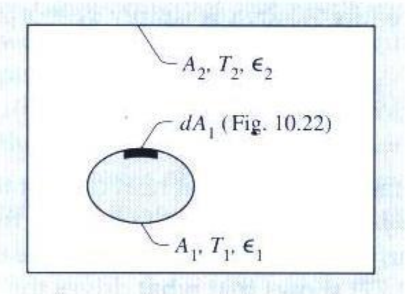
| Métal | $T$ (K) | $\varepsilon_n$ |
|---|---|---|
| Or | 300<br>80 | 0,02<br>0,01 |
| Argent | 300<br>80<br>4 | 0,02<br>0,01<br>0,005 |
| Aluminium commercial brut | 300<br>80<br>4 | 0,25<br>0,12<br>0,07 |
| Aluminium poli mécanique | 300<br>80<br>4 | 0,20<br>0,10<br>0,06 |
| Aluminium poli électrolytique | 300<br>80<br>4 | 0,15<br>0,08<br>0,04 |
| Chrome | 300 | 0,08 |
| Cuivre poli mécanique | 300<br>80<br>4 | 0,10<br>0,06<br>0,02 |
| Étain | 300<br>80<br>4 | 0,050<br>0,012<br>0,013 |
| Nickel | 300<br>80 | 0,05<br>0,02 |
| Laiton poli | 300<br>80<br>4 | 0,03<br>0,03<br>0,02 |
| Acier inoxydable 18-8 | 300<br>80<br>4 | 0,20<br>0,12<br>0,10 |

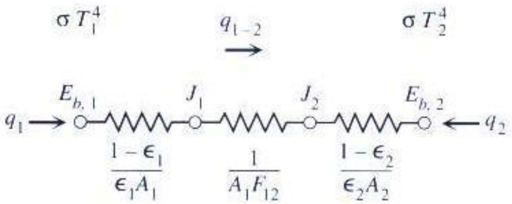
*Ref. Cryogenie, ses applications en supraconductivite.Techniques de l'ingenieur, Ed.1995*




*Ref. https://neutrium.net/heat-transfer/emissivity/*

# Radiation between 2 diffuse-gray enclosures



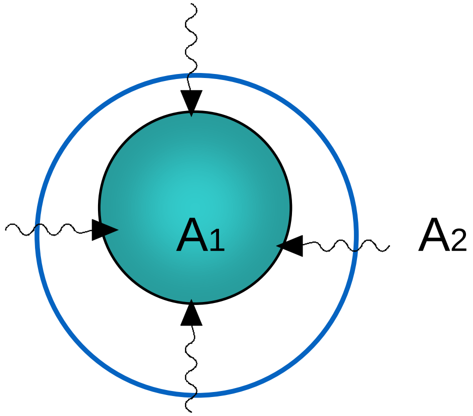




- Radiation balance between A1 and A2 surfaces:

$$q_{1-2} = \frac{\sigma (T_1^4 - T_2^4)}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 F_{12}} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}}$$

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

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




For cryostats, to **reduce heat load** to inner cold surface:

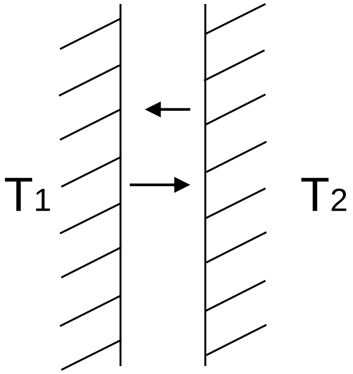
- **Limit size of $A_1$** (SC device vessel)
- **Reduce $A_2$** (vac.vessel as small as possible)
- **Small emissivities**: $\varepsilon_1$ reduced by low T; $\varepsilon_2$ at RT & moderated by $A_1/A_2$

*(see numerical application in Annex )*

*Figures source:* "Heat Transfer", A.Bejan, John Wilney & Sons, Inc.

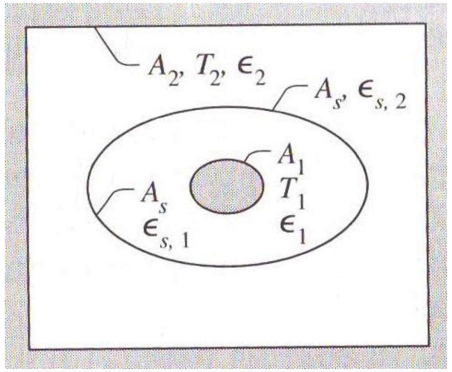
# Radiation between 2 diffuse-gray flat plates

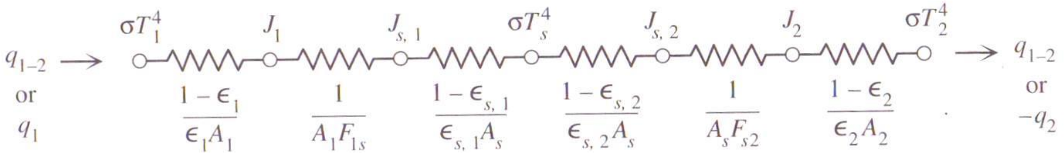
- Radiation balance between A1 and A2 (A1=A2=A), $F_{12}$=1 :




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

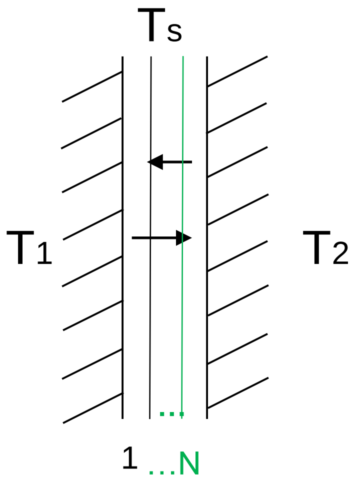
# Radiation with an intermediate floating shield




- Radiation balance between A1 and A2:

$$q_{1-2} = \frac{\sigma(T_1^4 - T_2^4)}{\underbrace{\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 F_{1s}} + \frac{1-\varepsilon_{s,1}}{\varepsilon_{s,1} A_s}}_{\text{A1 to S gap}} + \underbrace{\frac{1-\varepsilon_{s,2}}{\varepsilon_{s,2} A_s} + \frac{1}{A_s F_{s2}} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}}_{\text{S to A2 gap}}}$$




- For flat surfaces approximation, and same ε :

$$q_{1-s} = \frac{\sigma\, A\, (T_1^{\,4} - T_s^{\,4})}{(\frac{2}{\varepsilon} - 1)} = \frac{\sigma\, A\, (T_s^{\,4} - T_2^{\,4})}{(\frac{2}{\varepsilon} - 1)} = q_{s-2} \qquad \Rightarrow T_s^4 = \frac{T_1^{\,4} + T_2^{\,4}}{2}$$

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

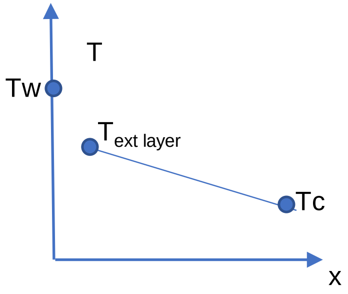
→ with 1 shield ½ of the rate without shield

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

→ with N shield 1/(N+1) of the rate without shield

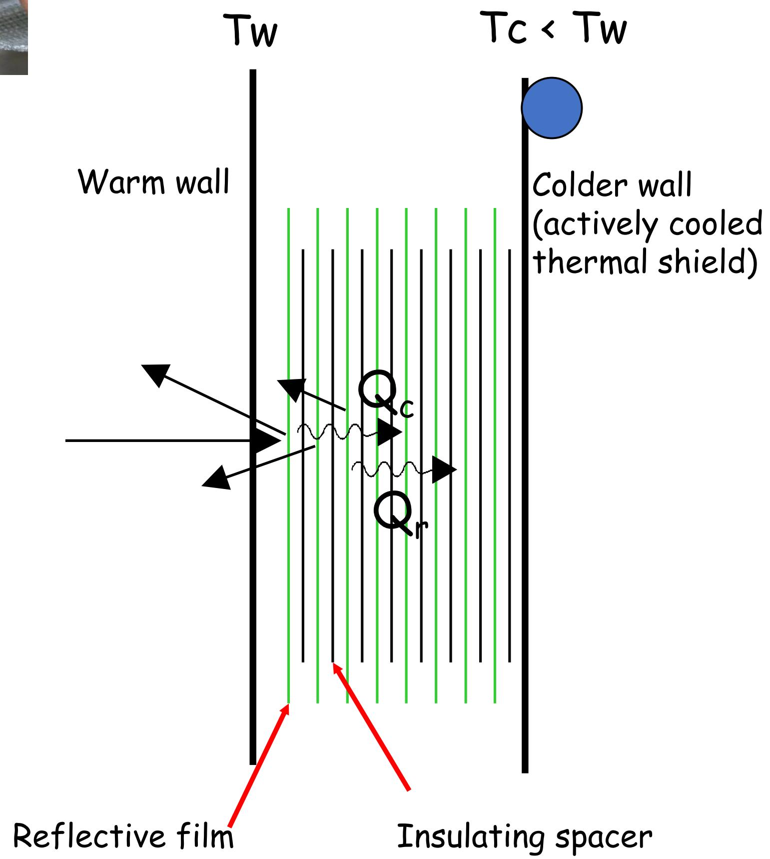
→ Can be generalized to N shields

# N shields → Multi Layer Insulation (MLI)


Working principles:

- Low emissivity of aluminium layer
- Multi-layer to enhance radiation protection:
  - N+1 radiation shielding
- 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
  - Reduce radiation from inner-most layers, cooled at T of shield
  - Extract heat at higher thermal shield T → thermodynamic efficiency

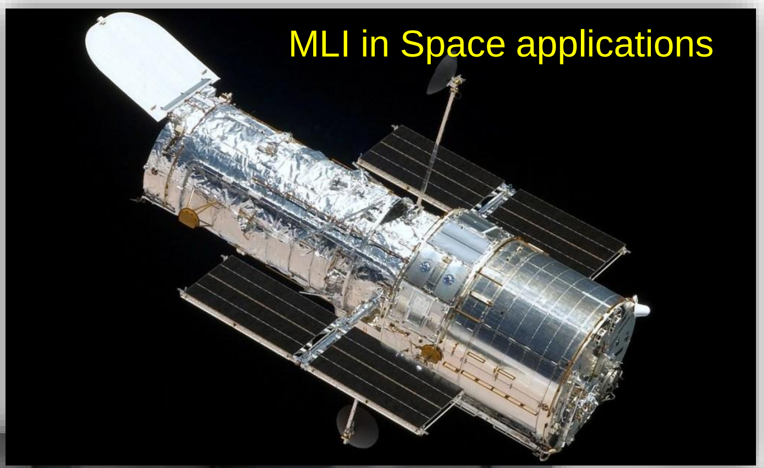


# MLI material

**LHC MLI:**

- **Reflecting film**: 6 µm thick polyethylene teraphthalate (PET) film coated with 400 Å minimum aluminium on each side (Physical Vapor Deposition process)
- **Spacer**: polyester net of very low weight (< 5 g/m2)
- 10 or 15 layer **pre-assembled blankets** (outermost layer reinforced with a polyester net)
- Blanket overall **thickness**: > 2 (3) mm for 10 (15) layers
- **Perforated layers** for outgassing: 0.05-0.15 % surface

Interleaved reflectors and spacers



MLI in Space applications


Decoration Al films

Velcro™ fasteners

Blanket manufacturing

MLI in residential construction

# LHC MLI blankets

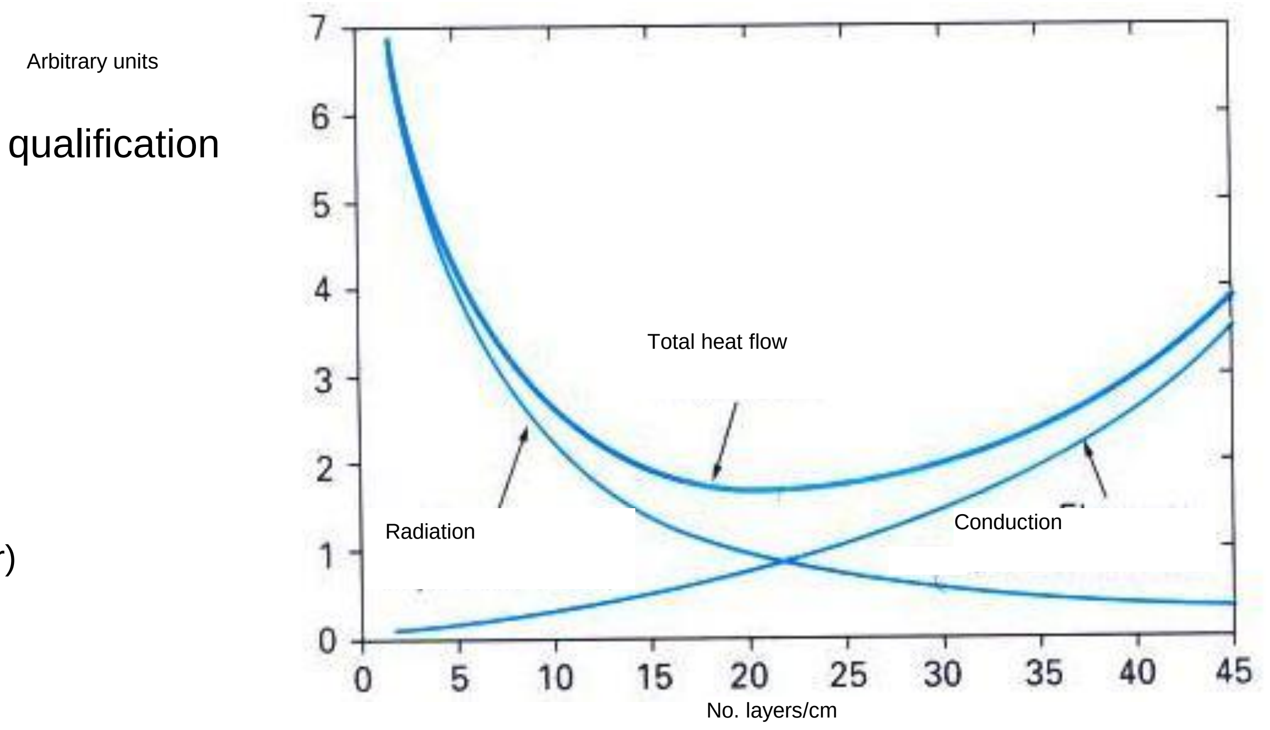
**Features:**
1 blanket (10 reflective layers) on cold masses (1.9 K)
2 blankets (15 reflective layers each) on Thermal Shields (50-65 K)
Reflective layer: double aluminized polyester film (2 $km^2$)
Spacer: polyester net
Stitched Velcro™ fasteners for rapid mounting and quality closing



Mock-ups for complex geometries


# MLI: How many reflective layers (N)?

- No straightforward answer ! Not just a matter of N !




- Complex system to model, with parameters needing experimental qualification

- Radiation vs. conduction
  - ✓ Radiation reduces as 1/N
  - ✓ Conduction proportional to packing density (N/mm)

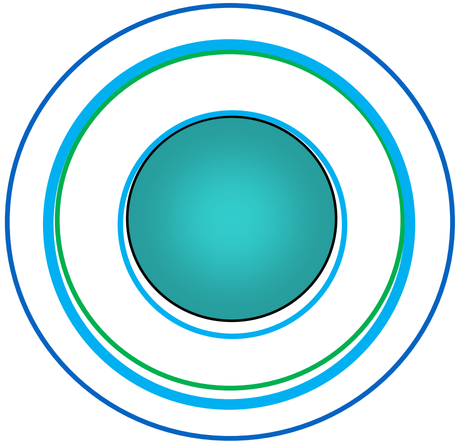
- Residual helium gas conduction
  - ✓ Negligeable at res. pressure $p < 10^{-4}$ Pa ($10^{-6}$ mbar)
  - ✓ Sizeable contribution at res. pressure $10^{-4}$ Pa $< p < 10^{-3}$ Pa ($10^{-5}$ mbar)
  - ✓ Dominates at res. pressure $p > 10^{-2}$ Pa ($10^{-4}$ mbar)

- Packing density should be limited → typically 20-25 N/cm
  - ➢ Avoid “compressed” blankets (do not put as much MLI as you can fit!)
  - ➢ Reserve space allocation for MLI blankets
  - ➢ Consider differential thermal contractions wrt support (Al shields, cold mass…): blankets must remain quite loose at cold

- Overall performance depends very much on:
  - ✓ Application design solutions
  - ✓ Craftsmanship quality

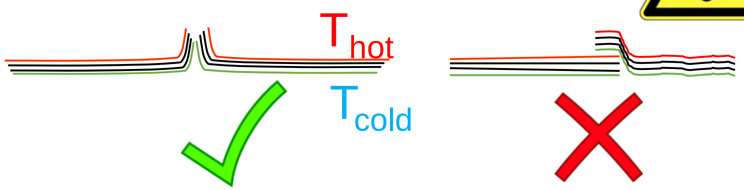
# MLI application: important tips

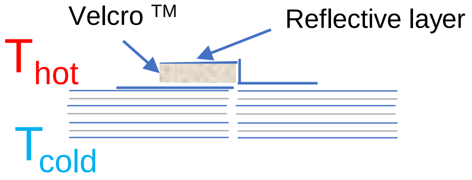
Handle MLI with gloves
(fingerprints are a black body!)

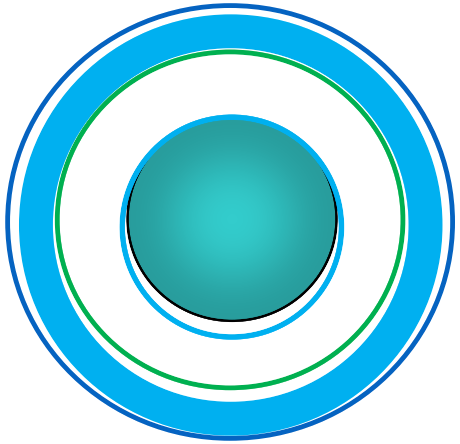


loose at RT
(MLI contracts more than metal support)

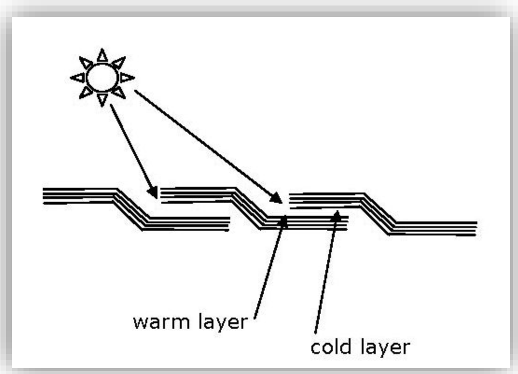
Thermal path warm to cold layers



Not tool much MLI
(risk of thermal shorts)




(images: courtesy of Meyer Tool & MFG.)

Some tapes are
resin coated = black body !
Check conductivity

# Performance measurements on MLI samples

- 300 K - 77 K, abundant literature *(see a few ref. [1], [2])*
- 77 K - 4 K, fewer results. CERN experimental work *(see a few ref.[3],[4],[5] )*
- Some values, in good vacuum (<$10^{-4}$ Pa) [3]:

$T_w$ = 300 K

| N | $T_c$ = 5 K-80 K |
|---|---|
| 10 | ~ 1.0 W/$m^2$ |
| 20 | ~ 0.5 W/$m^2$ |
| 30 | ~ 0.4 W/$m^2$ |

Virtually no Tc dependency, $T_w$ radiation dominates

(compare with 1 W/$m^2$ calculated in exercise)

$T_w$ = 80 K

| N | $T_c$ = 4.2 K |
|---|---|
| 1 or more | ~ 30-60 mW/$m^2$ |

Virtually no N dependency

(compare with 110-140 mW/$m^2$ calculated in exercise)


[1] T.Nast, Multilayer Insulation Systems, in Handbook of Cryogenic Engineering, ed. J.G.Weisend II, Taylor & Francis, Philadelphia (1998),

[2] M. G. Kaganer, Thermal Insulation in Cryogenic Engineering, Jerusalem, Israel Program for Scientific Translation, (1969),

[3] L.Mazzone et al., Measurements of Multi-Layer Insulation at high boundary temperature, using a simple non-Calorimetric method. Proceedings ICEC 19, 2002, Grenoble, France.

[4] Ph.Lebrun et al., Investigation and qualification of thermal insulation systems between 80 K and 4.2 K, Proceedings ICEC/ICMC, 1992, Kiev, Ukraine

[5] V.Venturi, Thermodynamic and technological optimization of complex insulation systems. PhD thesis, 2019, WUST University, Poland.

# Practical MLI performance values

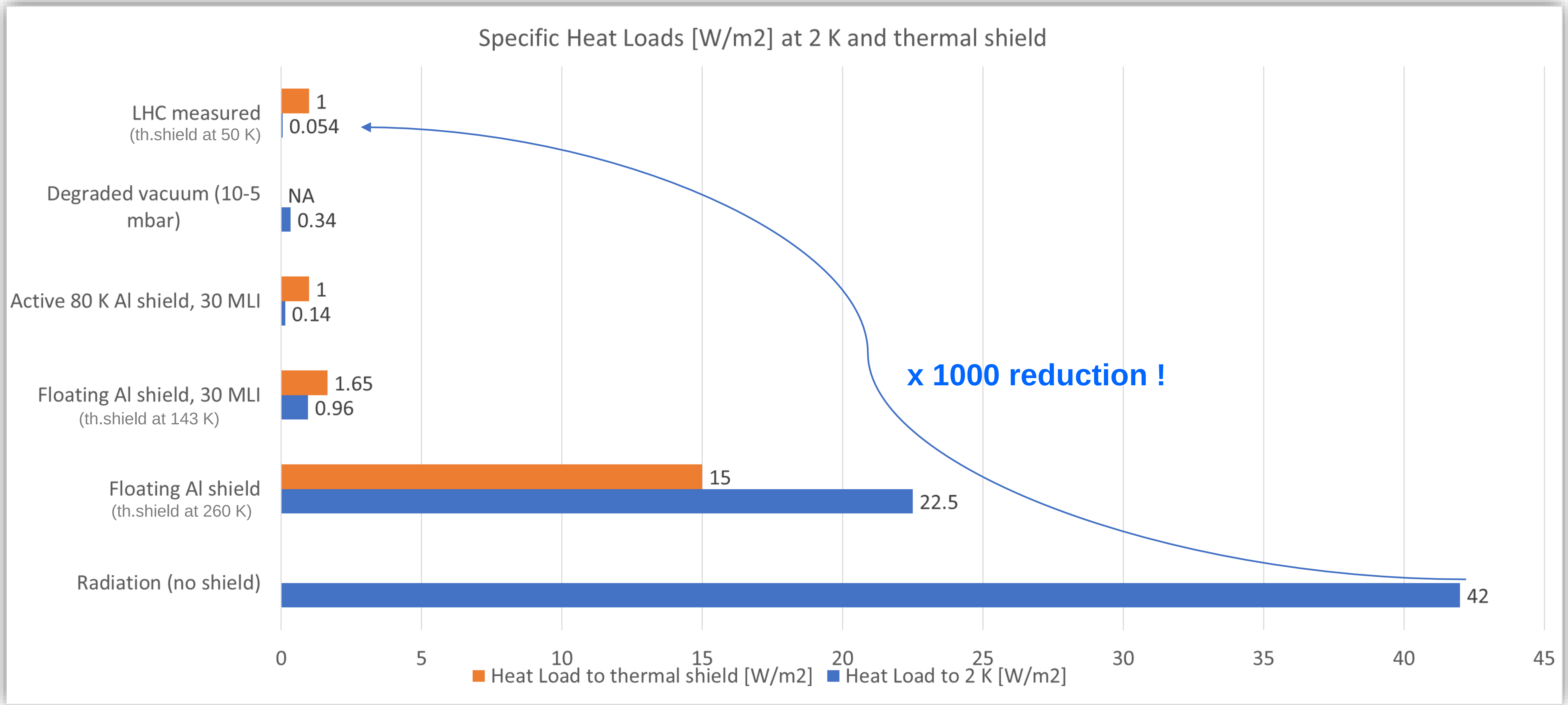
- MLI samples measured performance is considerably degraded in applications due to the engineered solutions and installation procedures:
  - pre-assembled blankets vs. rolled MLI
  - complex (non developable) geometries
  - junctions, stitches, Velcro™ fasteners, etc.
  - higher than ideal packing density (e.g. self-weight compaction)
  - thermal shorts between cold and warm layers (e.g. overlapped blanket closure)
  - quality of assembly (lab vs. industrial scale)

- Engineering values: what values should one use for HL first estimates?
  - Take generous margins. Rule of thumb → x 2 sample measurements

- LHC cryostat (+) (a thermally well optimized large-scale application), average measure on 2.7 km length sector :
  - 293 K to 50 K thermal shield with 30 MLI layers: → ~1 W/m²
  - 50 K to 2 K magnet with 10 MLI layers: → ~ 54 mW/m²

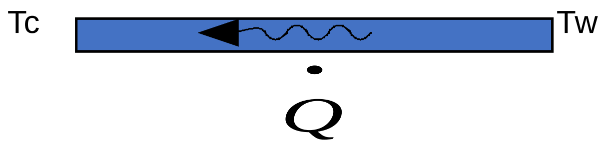
*(+) C. Maglioni, V. Parma: "Assessment of static heat loads in the LHC arc, from the commissioning of sector 7-8", LHC Project Note 409, 2008.*

# Summary of radiation HL exercises (for details see spare slides)



# Thermal Conduction

# Thermal Conduction




- When a T gradient exists in a body, there is a heat transfer from the high T region to the low T region (Fourier Law):

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

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

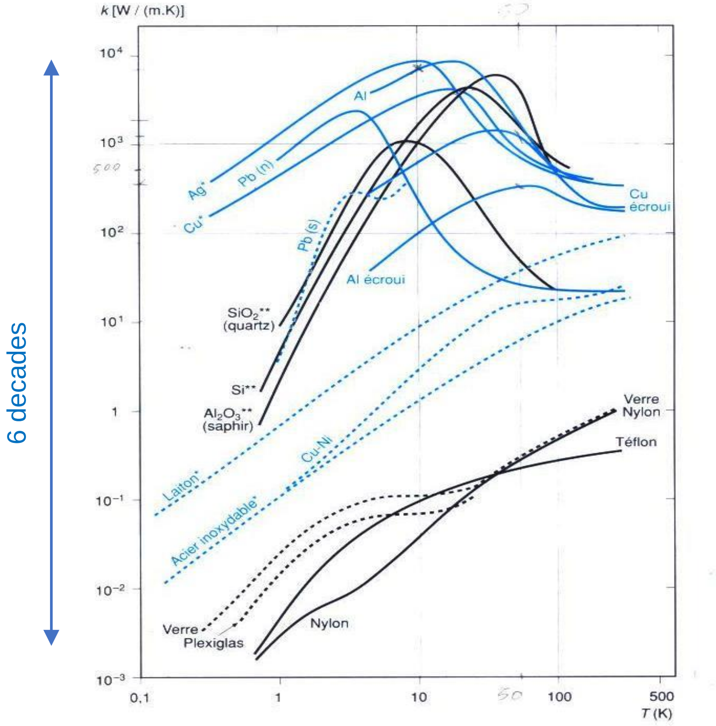
$$\dot{Q} = -kA\frac{dT}{dx}$$

- k is the thermal conductivity (W $m^{-1}$ $K^{-1}$), normally a function of P,T, material structure, non-homogeneity, anisotropy (ex. Composite materials).

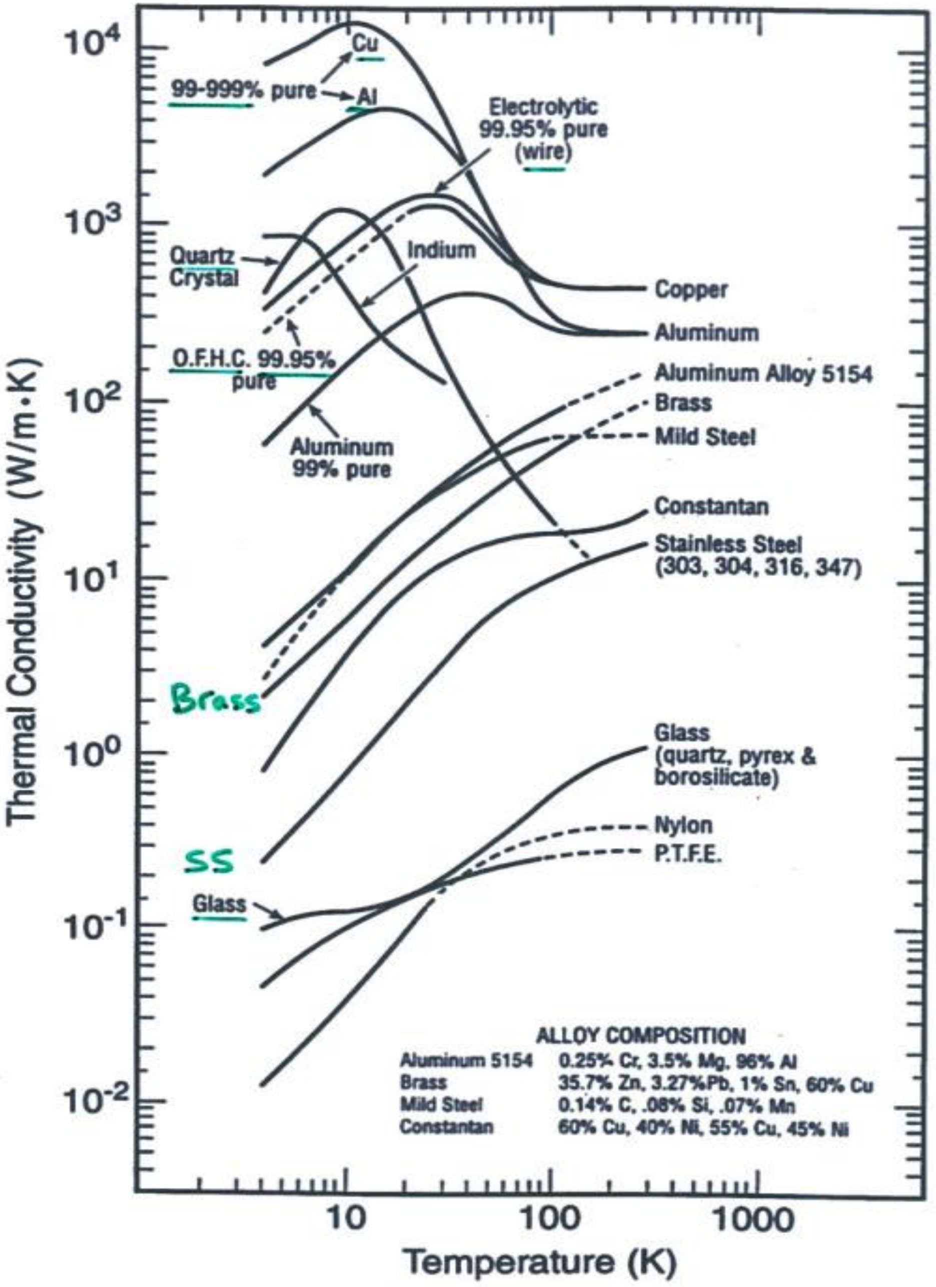
$$k = k(T, P, x, y, z)$$

- 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 of various materials




- Metals: mainly free electron contribution
- Resistivity from electron scatter with phonons (lattice vibrations) α $T^2$ and with impurities α 1/T
- Increasing effect of impurities in less pure metals and dominates in alloys
- Maximum of conductivity reduces and shifts towards higher T with increasing impurities
- Al and st.steel alloys: conductivity α T
- Non cristalline materials and insulators dominated by phonon contribution

# Thermal conductivity in epoxy-based composite materials

- Low conduction (little electron conduction), essentially phonon driven

- Anisotropic structure, (fibers/matrix) with constituents-specific thermal conductivity properties

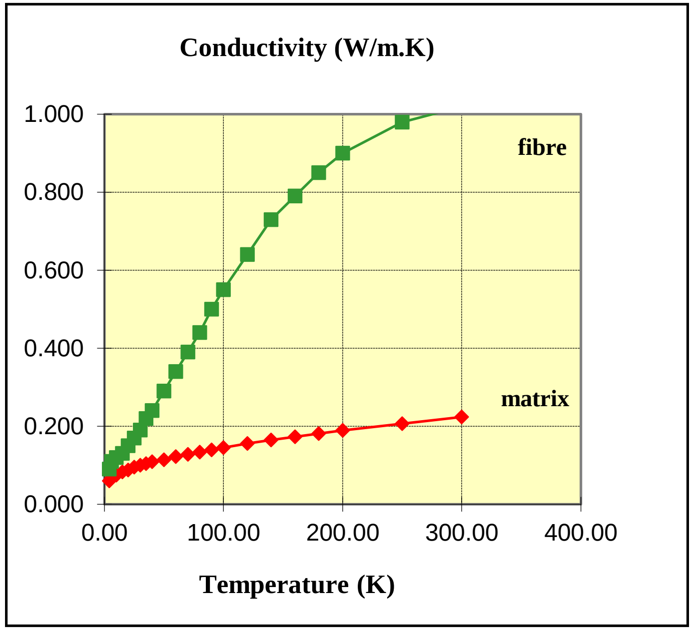
- Conductivity highly depends on:
  - Material (fiber) orientation
  - Ratio between fibre and matrix (Vf)

- Glass-fiber is the “conductive” fraction and also the “structural” constituent

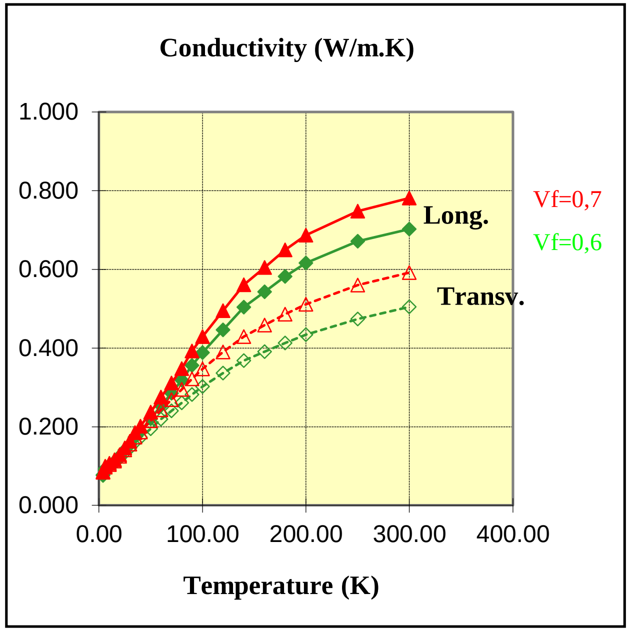
- Epoxy is the “isolating” fraction material and is the “less structural” constituent

- Vf typically around 40-70%

- Cryogenic grade G10-CR and G11 are widely used standard laminates in various forms (plates, tubes, rods). Properties data can be found in: https://trc.nist.gov/cryogenics/index.html

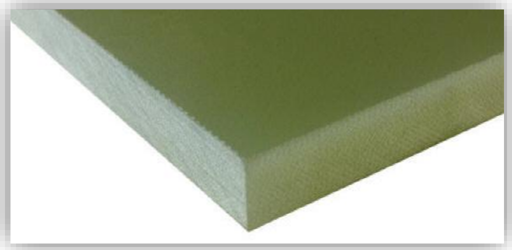



(Data from Schwartzberg F.H., Cryogenic Material Data Handbook, Martin Marietta Corrp, Denvers, Co, 1970)



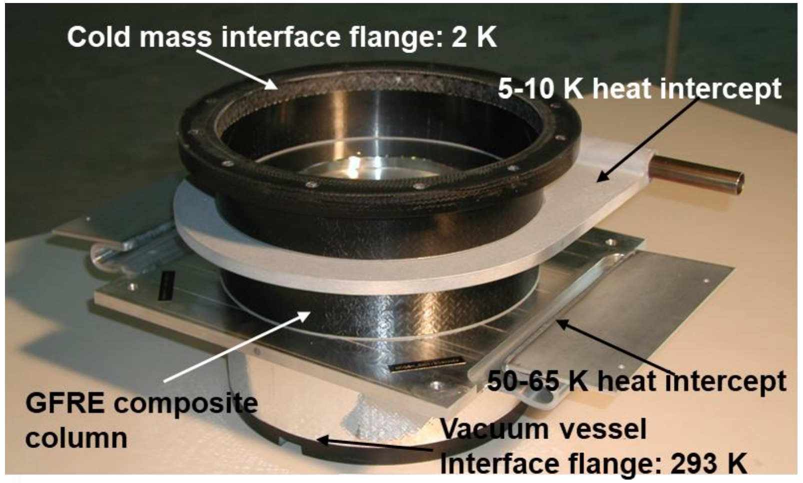

Longitudinal and transversal conductivity laminate studies for LHC supports, (based on data from Schwartzberg F.H.), collaboration CERN-ESIGEC (Univ.Savoie), 1997

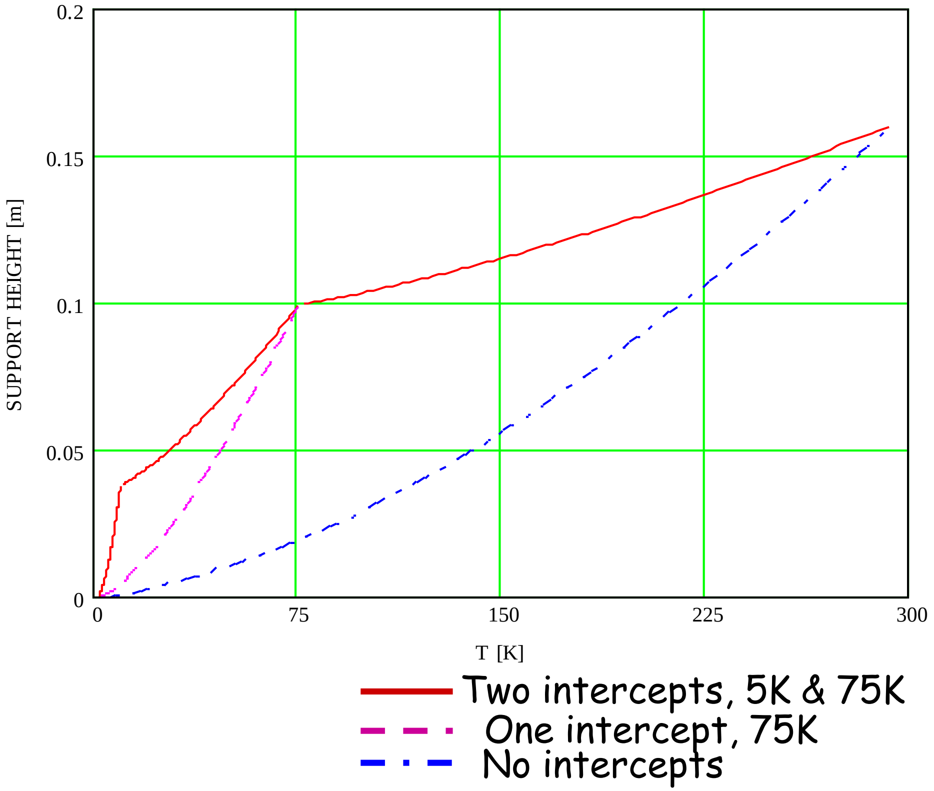
Glass-fiber dry fabric

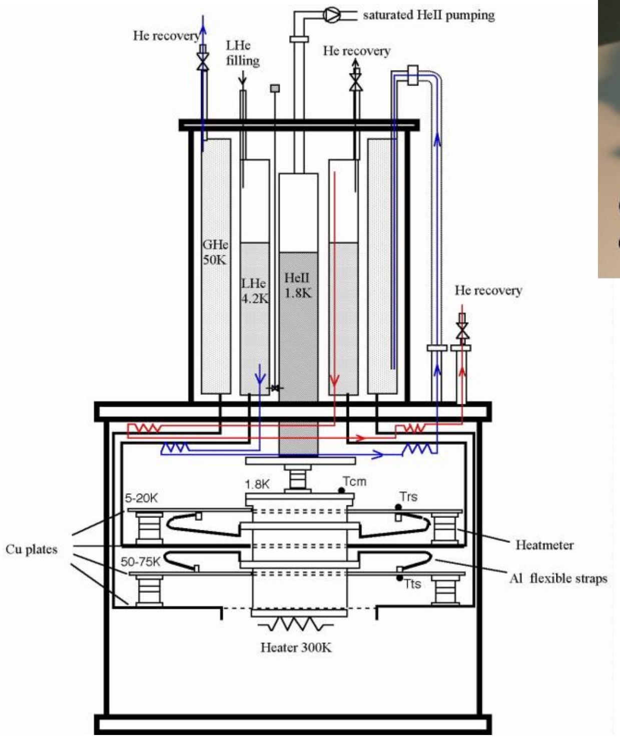


Standard G10-CR plate and rods

# LHC supports

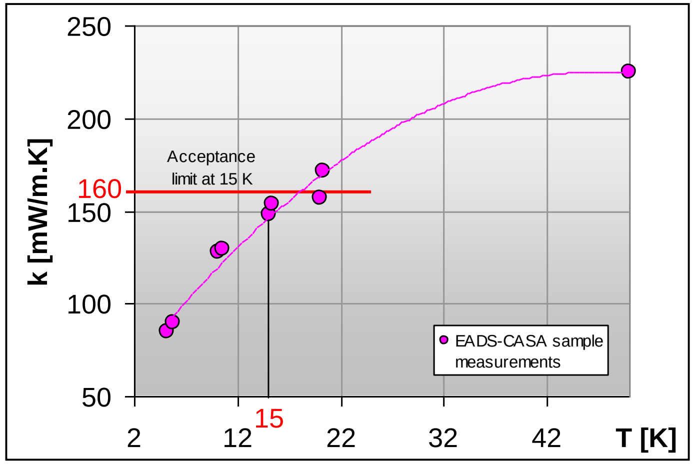



Support posts measurements

49 ± 10% mW @ 1.9K
450 ± 10% mW @ 4.5-10K
7.1 ± 5% W @ 50-65K

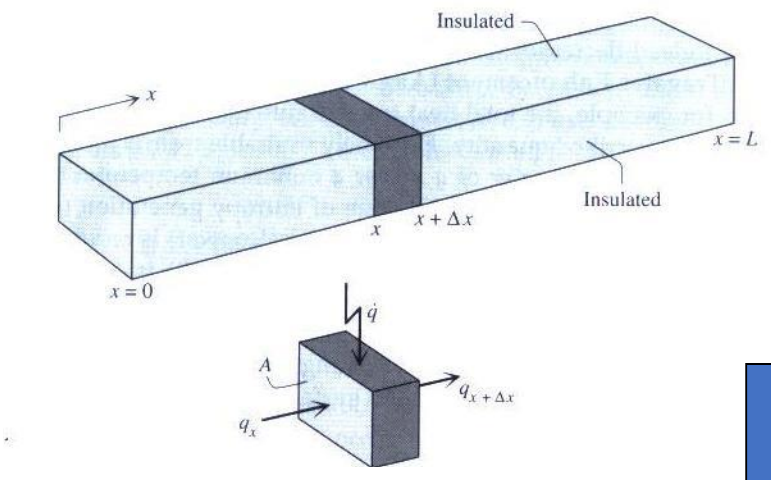



conductivity acceptance criteria at low T

| | $Q_{1.8K}$ [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**

# The conduction equation (unidirectional case)




$$q_x - q_{(x+\Delta x)} + \dot{q} = \frac{\partial U}{\partial t} \quad \text{(1st principle of thermodyn.)}$$

$$q_x = -kA\frac{\partial T}{\partial x} \quad \text{(Fourier law of heat conduction)}$$

$$q_{x+\Delta x} = q_x + \frac{\partial q_x}{\partial x}\cdot\Delta x \quad \text{(Taylor expansion)}$$

$$\frac{\partial U}{\partial t} = \rho c A \Delta x \frac{\partial T}{\partial t} \quad \text{(change of internal energy)}$$

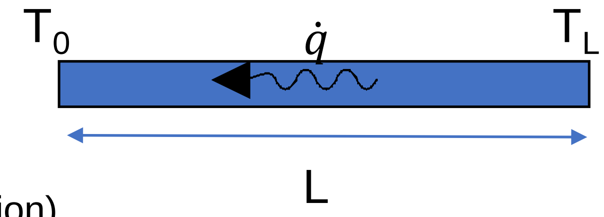
$$\frac{\partial}{\partial x}\left(k\cdot\frac{\partial T}{\partial x}\right) + \dot{q} = \rho c \cdot \frac{\partial T}{\partial t}$$

**Longitudinal conduction** — **Internal heat generation** — **Thermal inertia**

# No heat deposition and steady-state

$$\frac{\partial}{\partial x}\left(k \cdot \frac{\partial T}{\partial x}\right) = 0$$

with boundary conditions:
1) x=0, $T=T_0$
2) X=L, $T=T_L$

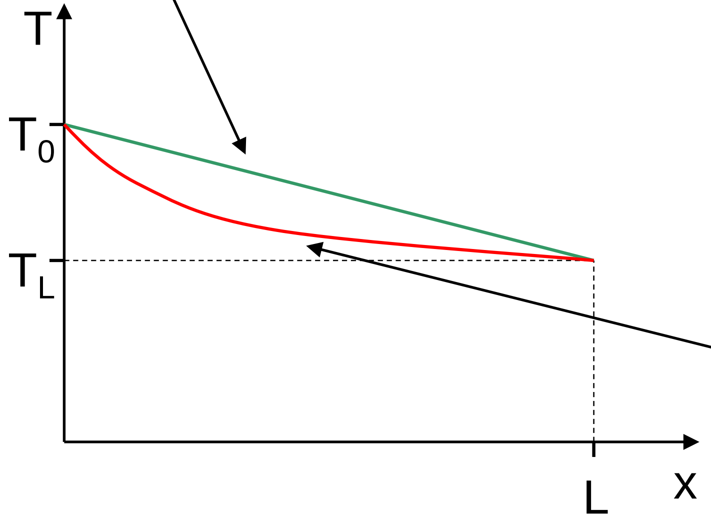



- **If *k* constant with *T*:**

$$\frac{\partial^2 T}{\partial x^2} = 0 \Rightarrow \boxed{T = T_0 + \frac{(T_L - T_0)}{L} x}$$

(Linear solution)

$$\boxed{\dot{q} = -kA\frac{\partial T}{\partial x} = -\frac{kA}{L}(T_L - T_0)}$$




- **If *k* = *k(T)*:**

$$\frac{\partial}{\partial x}\left(k(T) \cdot \frac{\partial T}{\partial x}\right) = 0 \qquad \dot{q} = -k(T)A\frac{\partial T}{\partial x}$$

$$\dot{q}\int_o^L dx = -A\int_{T_o}^{T_L} k(T)dT$$

$$\dot{q} = -\frac{A}{L}\int_{T_o}^{T_L} k(T)dT$$

Thermal conductivity Integral (**conductance**)

- For metal alloys (ex.steels) at low T:

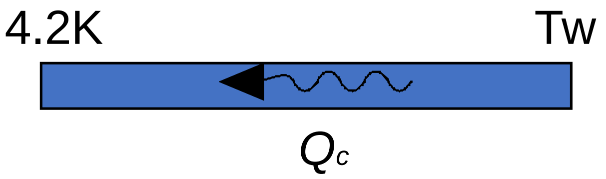
$$k \cong \frac{T}{a_i} \Rightarrow \boxed{\dot{q} = -\frac{A}{L}\cdot\frac{1}{2}\frac{\left(T_L^2 - T_0^2\right)}{a_i}}$$

(quadratic solution)

$$\boxed{T = \sqrt{T_o^2 + \frac{(T_L^2 - T_o^2)}{L}x}}$$

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

$$Q_c = \frac{A}{L} \cdot \int_{4.2K}^{Tw} \lambda(T)\,dT$$




| *Highest T* <br> *(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 |

# …more conductivity integrals

Tableau E. – Valeurs de l'intégrale $\int_{4,2}^{T} k(T)\,dT$ pour quelques matériaux.

| Matériau \ T (K) | 6 | 8 | 10 | 15 | 20 | 60 | 80 | 300 |
|---|---|---|---|---|---|---|---|---|
| **Conducteurs** (en W/cm) | | | | | | | | |
| Cuivre extra-pur | 166 | 382 | 636 | 1270 | 1790 | 2960 | 3090 | 4000 |
| Cuivre électroécroui | 8,0 | 19,1 | 33,2 | 80,2 | 140 | 587 | 707 | 1620 |
| Argent | 320 | 670 | 990 | 1610 | 1980 | 2570 | 2670 | 3570 |
| Aluminium extra-pur | 73 | 168 | 280 | 600 | 907 | 1740 | 1840 | 2390 |
| Aluminium du commerce | 1,38 | 3,42 | 6,07 | 15,2 | 27,6 | 170 | 232 | 728 |
| Or | 41 | 93 | 149 | 274 | 364 | 612 | 682 | 1370 |
| Laiton | 0,0531 | 0,129 | 0,229 | 0,594 | 1,12 | 10,4 | 17,7 | 172 |
| Plomb (normal) | 27,0 | 37,3 | 42,4 | 49,0 | 52,5 | 73,8 | 81,3 | 160 |
| Titane | 0,115 | 0,277 | 0,488 | 1,21 | 2,20 | 15,5 | 22,6 | 99,6 |
| Monel | 0,0235 | 0,0605 | 0,112 | 0,315 | 0,618 | 5,23 | 8,24 | 52,5 |
| Acier inoxydable | 0,0063 | 0,0159 | 0,0293 | 0,0816 | 0,163 | 1,98 | 3,49 | 30,6 |
| **Isolants** (en mW/cm) | | | | | | | | |
| Verre | 2,11 | 4,43 | 6,81 | 13,1 | 20,0 | 115 | 194 | 1990 |
| Téflon | 1,13 | 2,62 | 4,4 | 9,85 | 16,4 | 93,6 | 139 | 702 |
| Plexiglas | 1,18 | 2,38 | 3,59 | 6,69 | 10,1 | 68,3 | 110 | 630 |
| Nylon | 0,321 | 0,807 | 1,48 | 4,10 | 8,23 | 85,9 | 142 | 895 |

# Electrical network analogy

- The inverse of the *thermal conductance* → *thermal resistance:*

*For variable k, define an average value $k_{AV}$:*

$$k_{AV} = \frac{\int_{T_o}^{T_L} k(T)dT}{(T_L - T_0)} \quad \Rightarrow \quad R_t = \frac{L}{k_{AV} A}$$

$$\dot{q} = -\frac{A}{L}\int_{T_o}^{T_L} k(T)dT = \frac{T_0 - T_L}{R_t}$$

- Analogy with the electrical resistance (replace q with I, T with V):

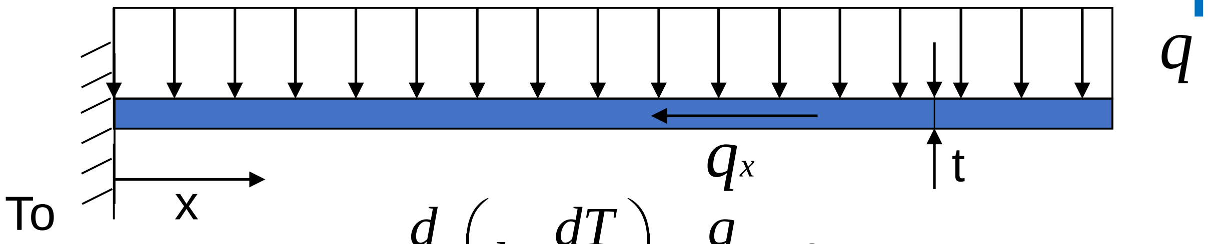
$$I = \frac{V_0 - V_L}{R}$$

- We can therefore model a complex thermal conductivity problem by elementary *thermal resistances* ***Ri***, and solve the network by using *Kirckhoff's laws*.

$$\sum_{i=1}^{n} \dot{q}_i = 0 \quad \textit{(at knots)}$$

$$\sum_{i=1}^{m} (T_i - T_{i-1}) = 0 \quad \textit{(in loops)}$$

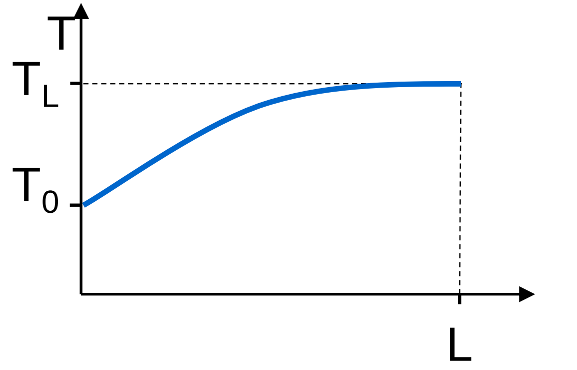
# Thermal conduction with uniform heat deposition




$$\frac{d}{dx}\left(k \cdot \frac{dT}{dx}\right) + \frac{q}{t} = 0$$

- Beam of length L, thickness t, width w (= 1m);
- beam *thermalized* on one side at To
- uniform heat deposition from one side, q (W/m$^2$)
- considering k constant with T
- Boundary conditions: a) for x= 0 T=To (heat sink); b) q=0 for x=L (isolated tip)
- Integrating and imposing the 2 boundary conditions:

$$T(x) = To - \frac{q}{2kt}x^2 + \frac{qL}{kt}x$$




$$\Delta T_{max} = T_L - To = \frac{qL^2}{2kt}$$

***practical interest:***

*calculate minimum thickness to limit $\Delta T_{max}$*

$$t = \frac{q \cdot L^2}{2 \cdot k \cdot \Delta T_{max}}$$

$$q_x(T) = -kwt\frac{dT}{dx} = qwx - qwL$$

x

# Thermal diffusivity

- Conduction equation (no heat generation)

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) = \rho\, c\, \frac{\partial T}{\partial t}$$

- For small variations of k with x:

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

$$\text{with } \alpha = \frac{k}{\rho\, c}$$

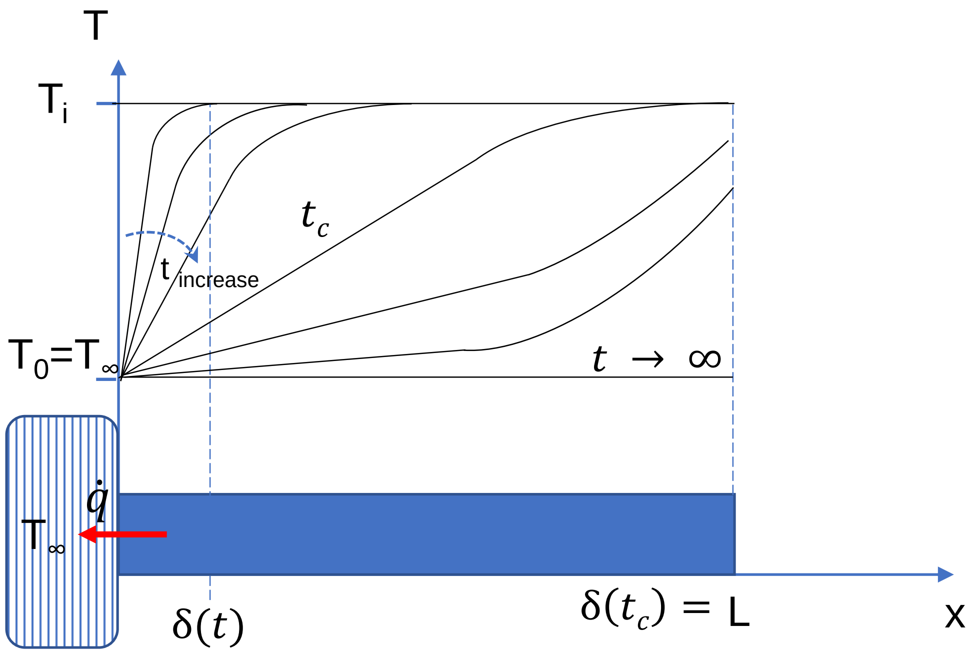
Thermal diffusivity [m²/s]

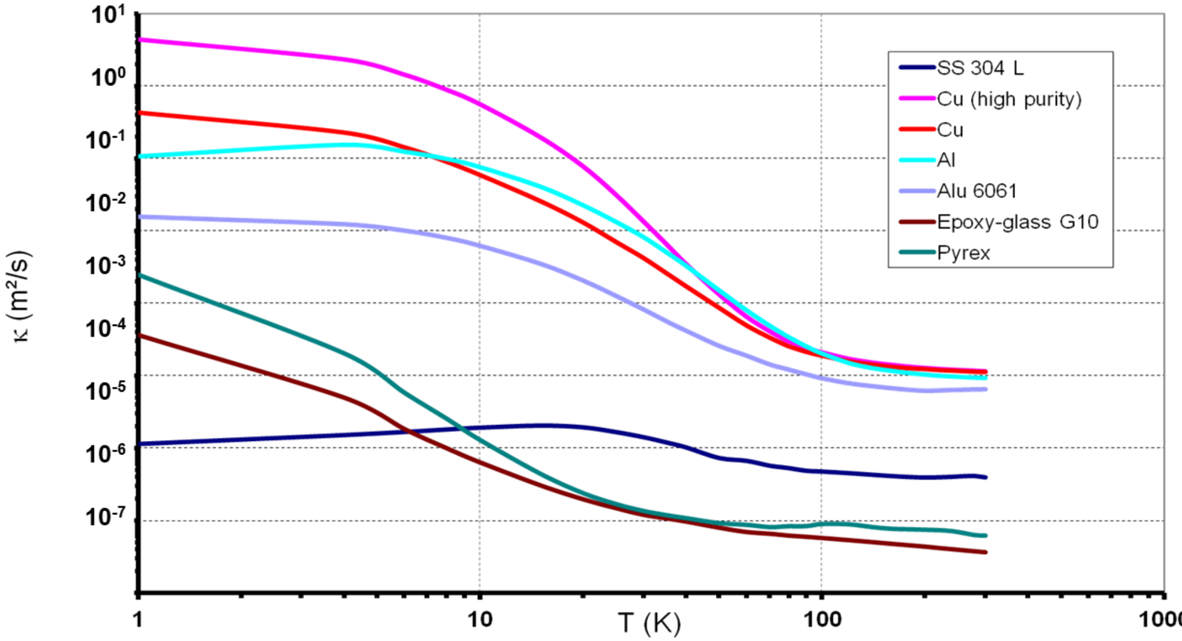
- Solid bar cooled at one tip
- T perturbation δ travels towards warm end:

$$\delta(t) \approx \sqrt{\alpha\, t}$$

- $t_c$, critical time for T perturb. to reach warm tip:

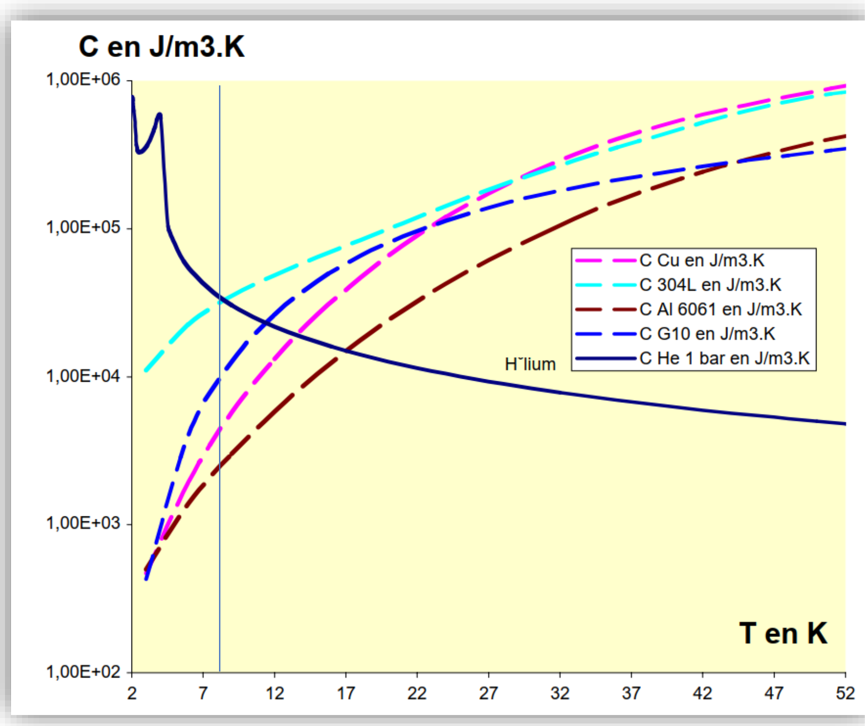
$$t_c \approx \frac{L^2}{\alpha}$$

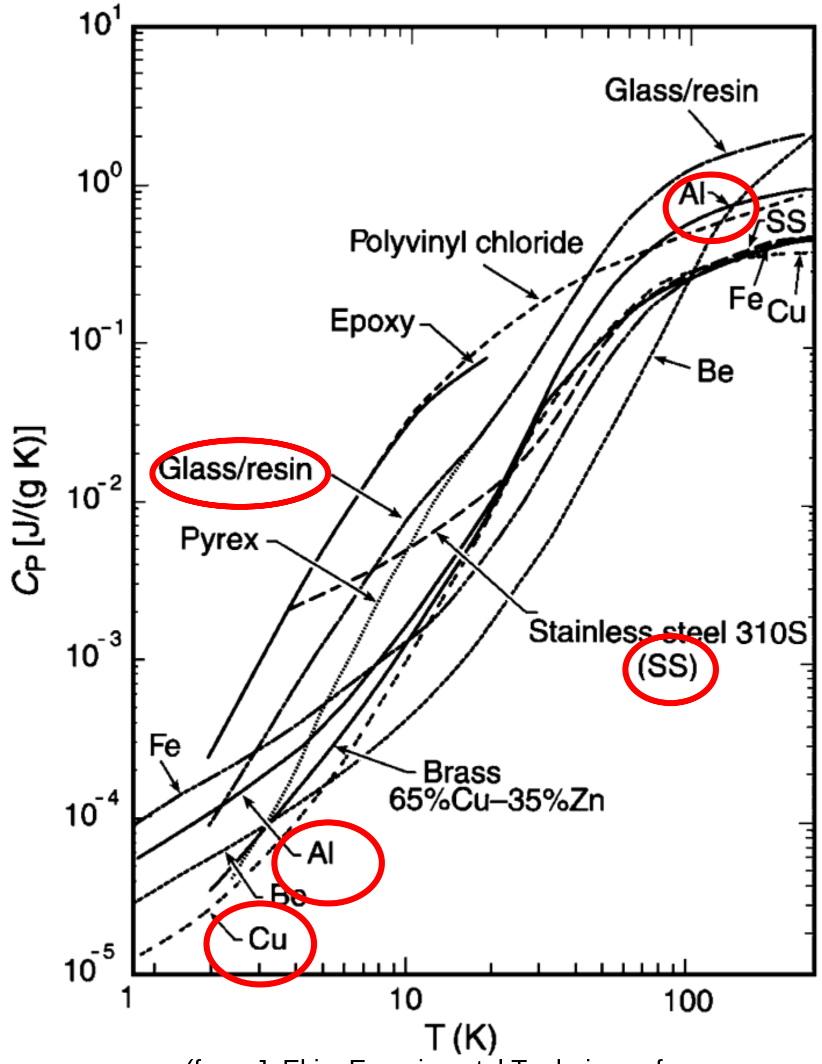


# Heat capacity

- Specific heats: $c_p = \left(\frac{\delta Q}{m\,dT}\right)_P = \left(\frac{1}{m}\frac{\partial H}{\partial T}\right)_P \qquad c_v = \left(\frac{\delta Q}{m\,dT}\right)_V = \left(\frac{1}{m}\frac{\partial U}{\partial T}\right)_V$
- For (incompressible) substances: $C_p(T) = C_v(T) = C(T)$
- Change of internal energy U (or enthalpy):
  - $\Delta U = Q = m \int_{T_1}^{T_2} c(T)\, dT$
- Cooling (or heating) power:
  - $P(T) = m\, c(T) \frac{dT}{dt}$
- Specific heats/unit vol. sometimes preferred
- Below 10 K enthalpy of helium overtakes all solids




(from J. Ekin, Experimental Techniques for Low-Temperature Measurements)

# Measuring Thermal Performance of Cryostats

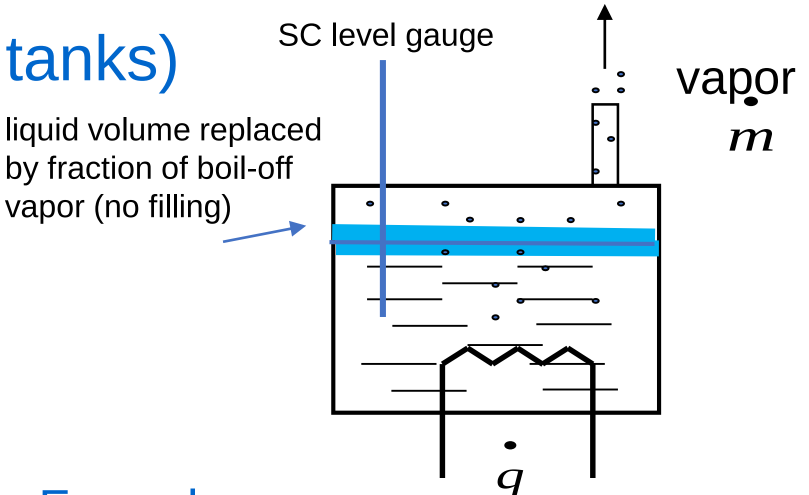
# Measure of Heat Loads to liquid helium tanks

## Isothermal cooling (2-phase helium tanks)

- He boil-off along saturation line
  - ✓ Latent Heat ($L_v$) of vaporisation
  - ✓ Isothermal cooling (T constant if P constant)
  - ✓ Measure p, and $\dot{m}$
  - ✓ Liquid/gas volumetric corrective factor

$$\dot{q} = \dot{m} \cdot Lv \cdot \left(\frac{v_g}{v_g - vl}\right)$$

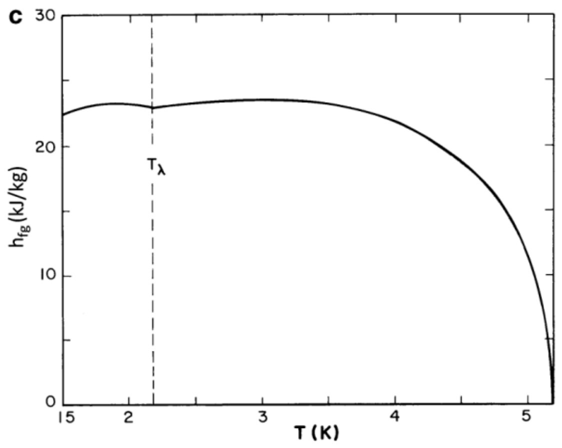
measure (→ $\dot{m}$) from diagrams (→ $Lv$, $v_g$, $vl$)



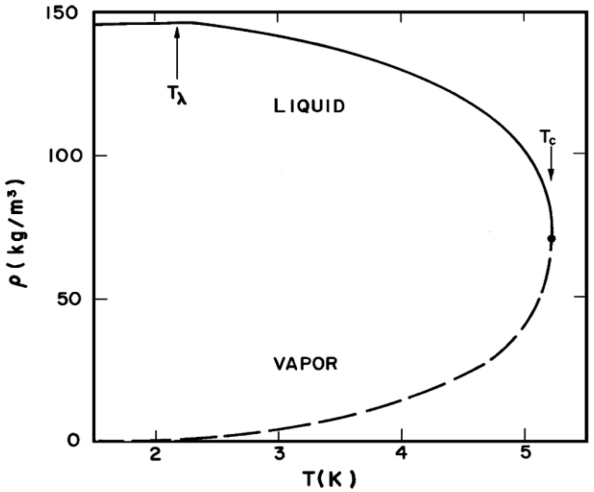

- Example:
  - ✓ Mass flow measurement: 7 g/s
  - ✓ P measured: 1.78 bar
  - ✓ (T on saturation line (phase diagram): 4.8 K)
  - ✓ $L_v$ = 14’116 (J/kg) (tables, or state equations)
  - ✓ $v_g$ = 3.0 10-2 (m3/kg); $v_l$ = 9.3 10-3 (m3/kg); (phase diagrams)

→ $\dot{q} = 7.0\ 10-3 \cdot 14116 \cdot \left(\frac{3.0\ 10-2}{3.0\ 10-2 - 9.3\ 10-3}\right)$ = 143 W

1.45 !




Latent heat of vaporization




Density of saturated liquid helium

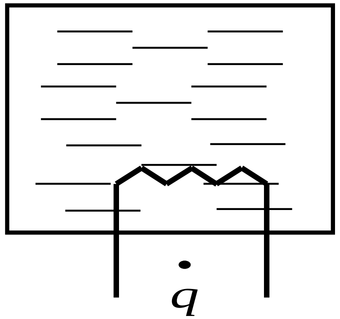
- He boil-off liquid level measurement:
  - Measure level l with SC level gauge
  - Boil-off mass flow measure through reservoir geometrical correlation between level and volume: f(l), and knowledge of density ρ and $L_v$

$$\dot{q} = f(\Delta l) \cdot \rho \cdot Lv$$

# Measure of Heat Loads to liquid helium tanks (cont.d)

## Non-isothermal cooling

- Calorimetry in superfluid helium (LHeII):
  - LHe II very high thermal conductivity → isothermal bath
  - Measure internal energy change (closed system) in time Δt
  - Needs precise measure of helium content
  - and sub-mK resolution measurement of T at T< 2.17 K

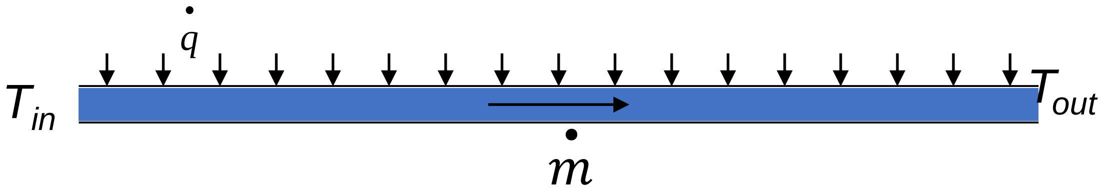



$$\dot{q} = \frac{\Delta U(t)}{\Delta t} = \frac{m \cdot \Delta u(t)}{\Delta t}$$

# Measure of Heat Loads to Thermal Shields

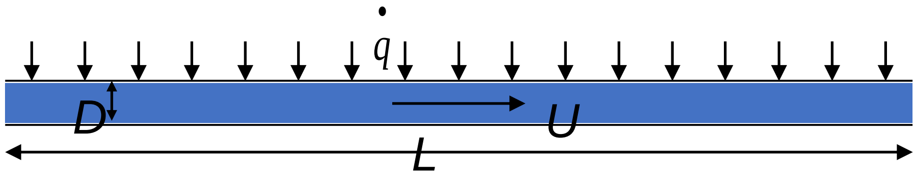
## Non-isothermal cooling

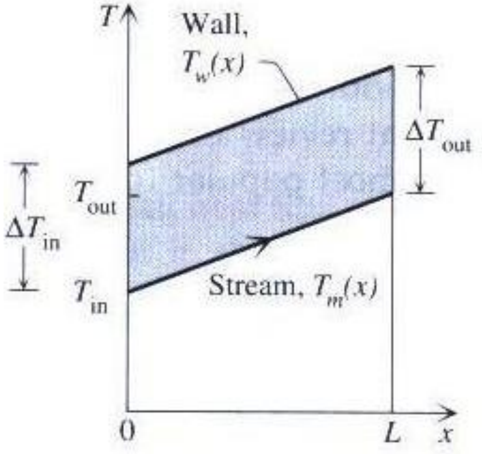
- Forced internal (conduit) convection of single-phase fluid:
  - Non-isothermal cooling: enthalpy change of fluid (here $c_p$ assumed constant)
  - Needs the measure of mass flow, and T at entry and exit of conduit




$$\dot{q} = \Delta H = \dot{m} \cdot cp \cdot (T_{out} - T_{in})$$

# Forced Convection heat transfer in conduits




- **Forced flow** of coolant fluid in **round tube** cooling lines
- Considering *hydro-dynamically* and *thermally* **fully developed flow**
- **Uniform** wall heat flux (linear T profiles)

$T_w = wall\ temperature$

$T_m = mean\ temperature$

- **Convection heat transfer** from wall to fluid:

$$\dot{q} = h \cdot D\pi L \cdot (T_w - T_m)$$

$\dot{m} = mass\ \ flow [kg/s]$

$T_{out} =\ fluid\ exit\ temperature$

$T_{in} =\ fluid\ entrance\ temperature$

- **Enthalpy balance** along the line L:

$$\dot{q} = \dot{m} \cdot c_p \cdot (T_{out} - T_{in})$$

- **Reynolds No.:**

$$\mathrm{Re}_D = \frac{UD}{\nu}$$

$\nu = \text{kinematic viscosity } (\mu/\rho)$

$Re_D > 2000$ → turbulent flow,
$Re_D < 2000$ → laminar flow

- **Nusselt No.:**

$$Nu_D = \frac{h \cdot D}{k}$$

$k = \text{therm. conductivity}$

✓ For **laminar flow**: constant

$$Nu_D = \frac{h \cdot D}{k} = 4.364$$

$$\frac{dT_m}{dx} = \frac{4}{D} \cdot \frac{\dot{q}}{\rho c_p U}$$

✓ For **turbulent flow**, $Nu_D = f(Re_D, Pr)$:
(Dittus and Boelter formula)

$$Nu_D = 0.023 \cdot \mathrm{Re}_D^{4/5}\, \mathrm{Pr}^{2/5}$$

*for heated fluid;*

$0.7 \le \mathrm{Pr} \le 120$

$2500 \le \mathrm{Re}_D \le 1.2410+5$

$Pr = \frac{\nu}{\alpha}$

$\alpha = thermal\ diffusivity$

# Frictional pressure drop in a tube

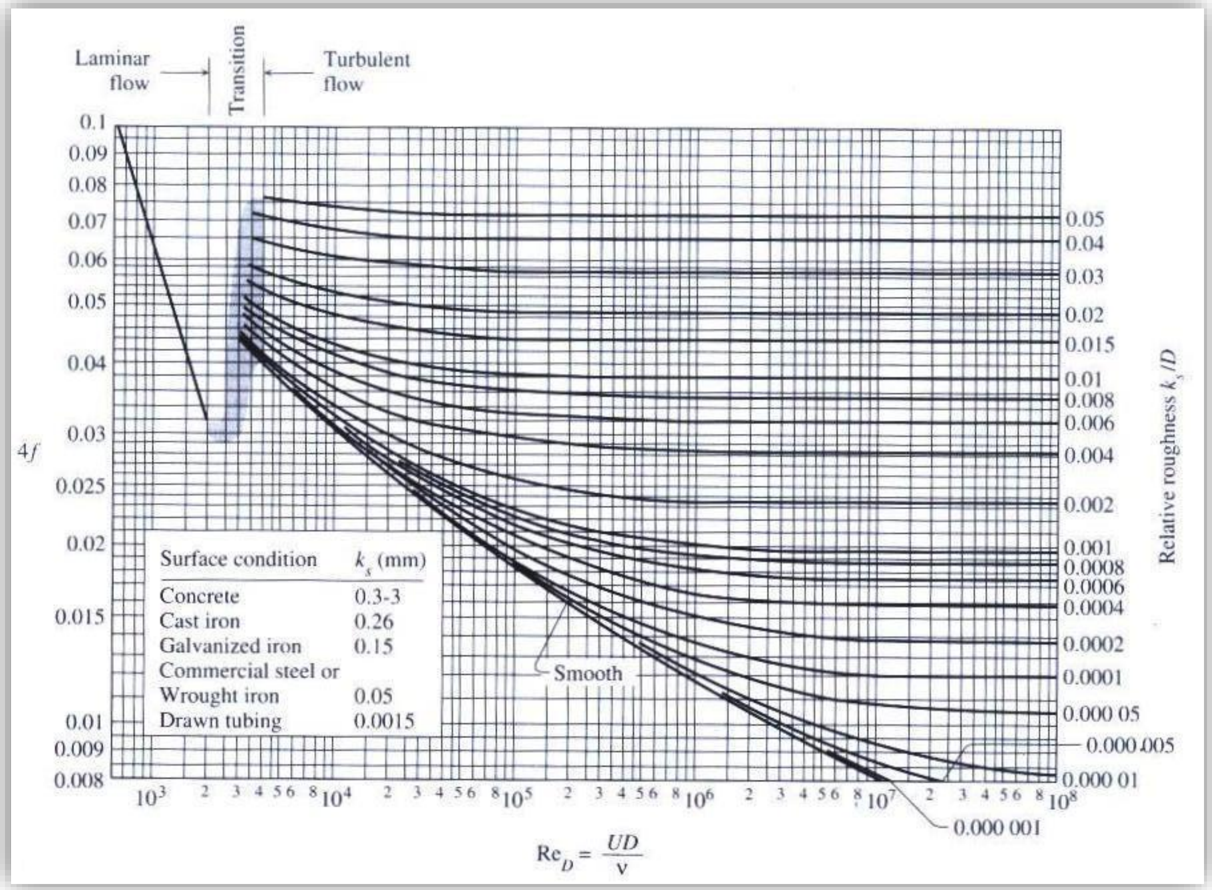
- **Pressure drop** along tube

$$\Delta P = f \frac{4L}{D} \frac{1}{2} \rho U^2$$

$f = Fanning\ friction\ factor$

$U = Mean\ velocity$

- Experimental plots or semi-empirical formulations (ex. Colebrook formulation)




*Ref.* "Heat Transfer", A.Bejan, John Wilney & Sons, Inc.

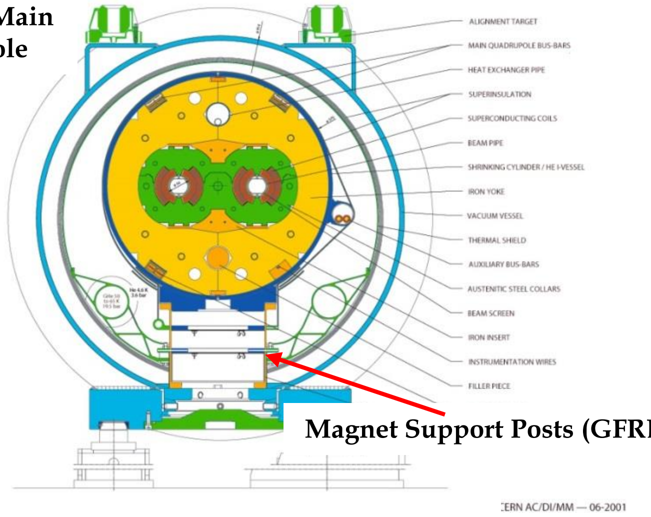
# Feedthroughs and heat intercepts

# Feedthroughs in cryostats

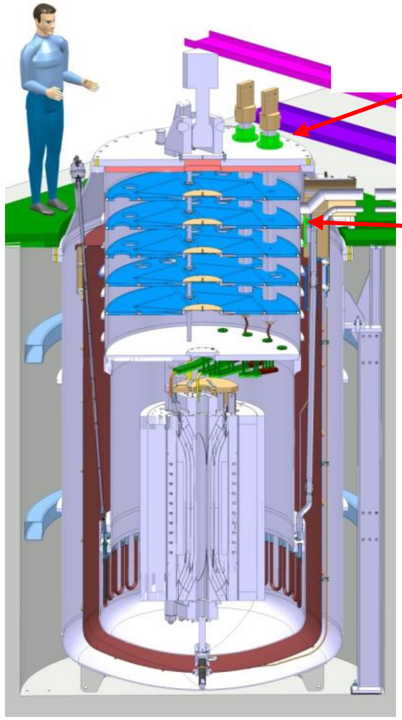
Solid conduction paths:

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

LHC Main dipole



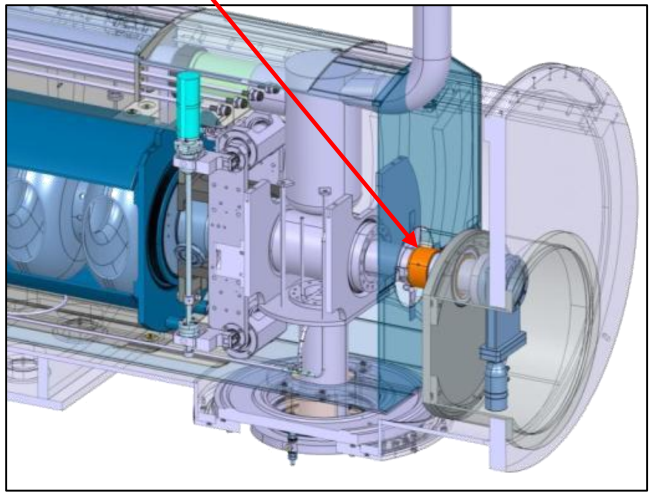

Magnet Support Posts (GFRE)



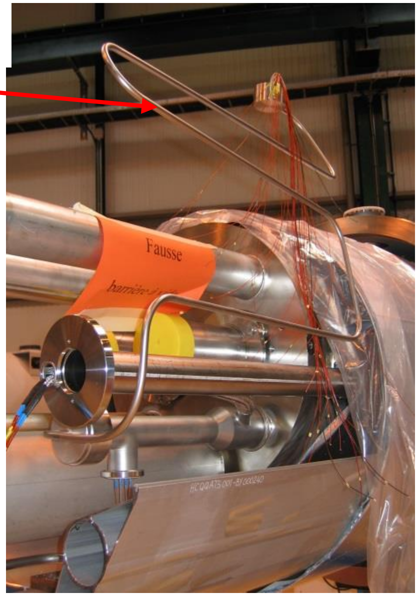
Current leads

Neck

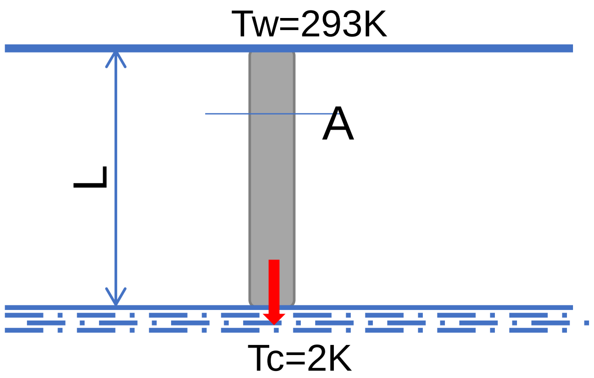
CWT SPL cryomodule



LHC instrumentation capillary at assembly

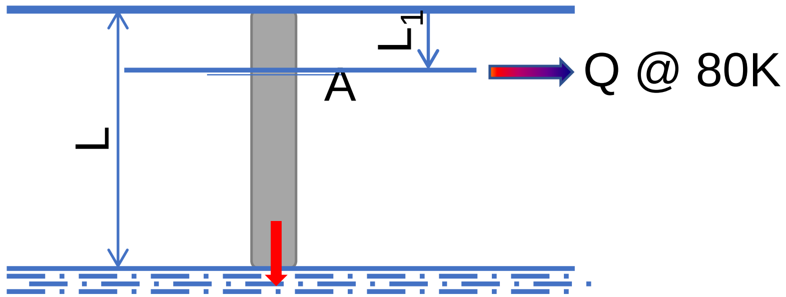


# Heat intercepts (heat sinking) at intermediate temperatures




- simple solid conduction

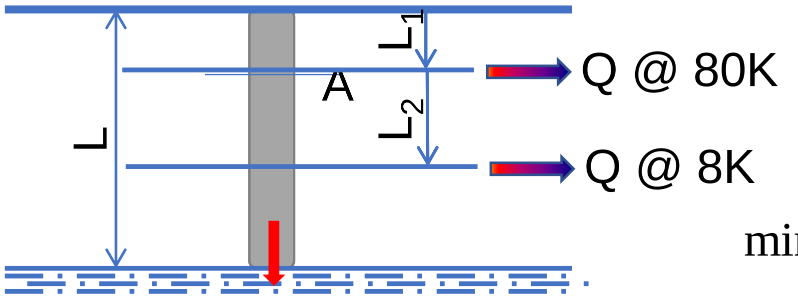
$$\dot{Q} = \frac{A}{L}\int_{Tc}^{Tw} k(T)dT$$




- 1 heat intercept at optimal distance

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

→ $L_1$

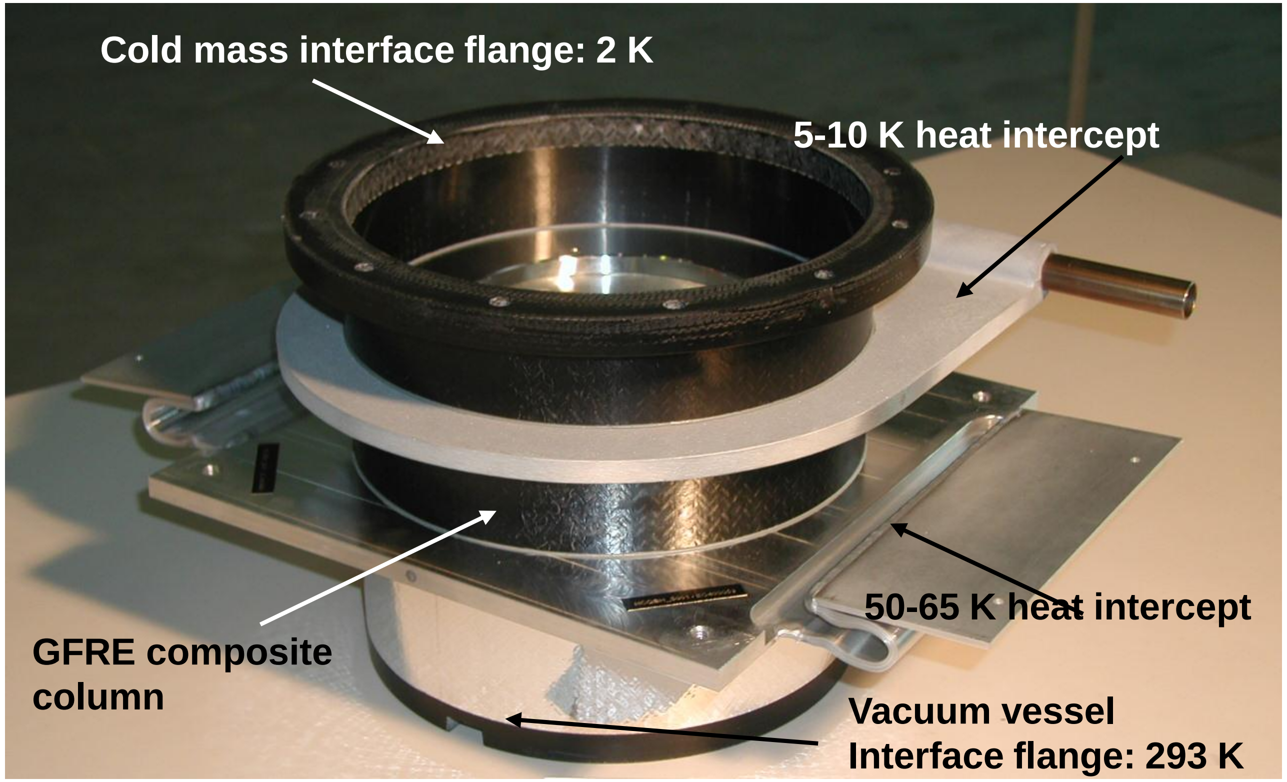



- 2 heat intercepts at optimal distance

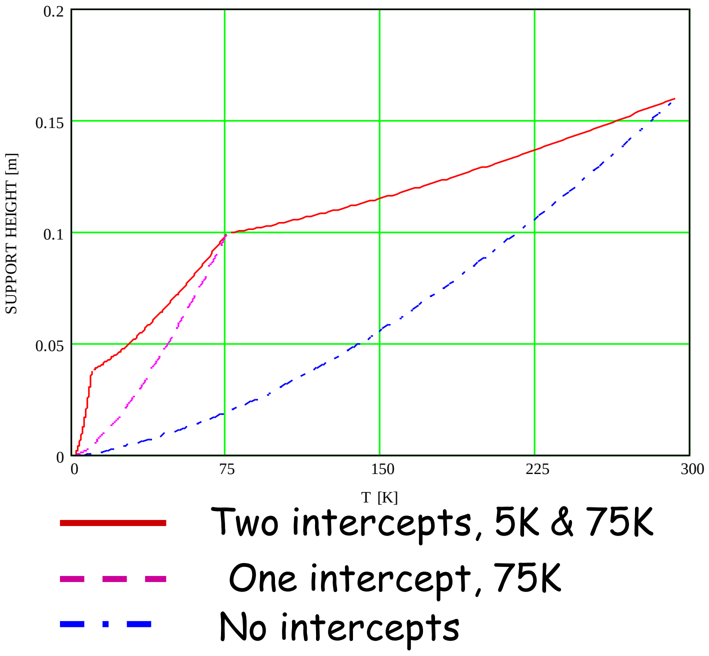
$$\min\{f(L_1, L_2) = C1\times\frac{A}{L_1}\int_{Tw}^{80K} k(T)dT + C2\times\frac{A}{L_2 - L_1}\int_{80K}^{8K} k(T)dT + C3\times\frac{A}{L - L_2}\int_{8K}^{Tc} k(T)dT\}$$

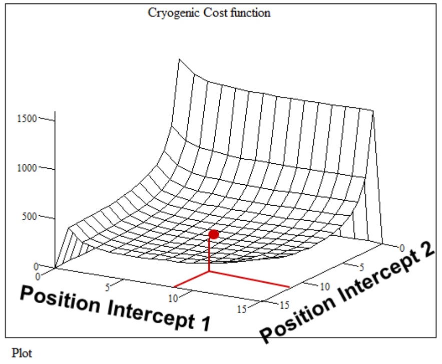
→ $L_1$, $L_2$

# LHC supports




- **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



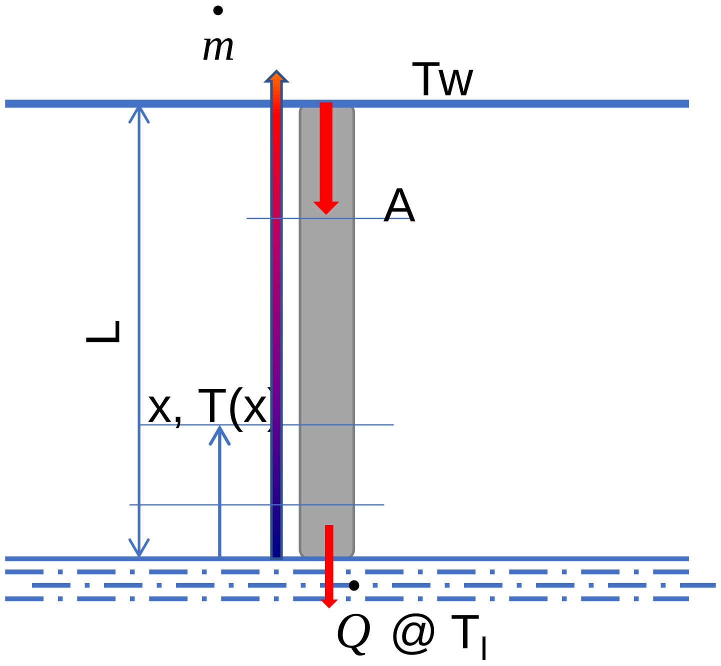




Minimizing using efficiency factors:
$C_1$ = 16 w/w @ 75 K
$C_2$ = 210 w/w @ 5 K
$C_3$ = 990 w/w @ 1.9 K

| | $Q_{1.8K}$ [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




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

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

- If $\dot{Q}$, which is the residual heat to the bath, is equivalent to the evaporation (i.e. self-sustained):

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

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

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

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

Reduced heat conduction in self-sustained helium cooling for selected technical materials

| | Thermal conductivity integral [W cm$^{-1}$] | Effective thermal conductivity integral [W cm$^{-1}$] |
|---|---|---|
| ETP copper | 1620 | 128 |
| OFHC copper | 1520 | 110 |
| Aluminium 1100 | 728 | 39.9 |
| AISI 300 st.steel | 30.6 | 0.92 |

(ref. G. Vandoni, Heat Transfer, CAS, Erice 2003)

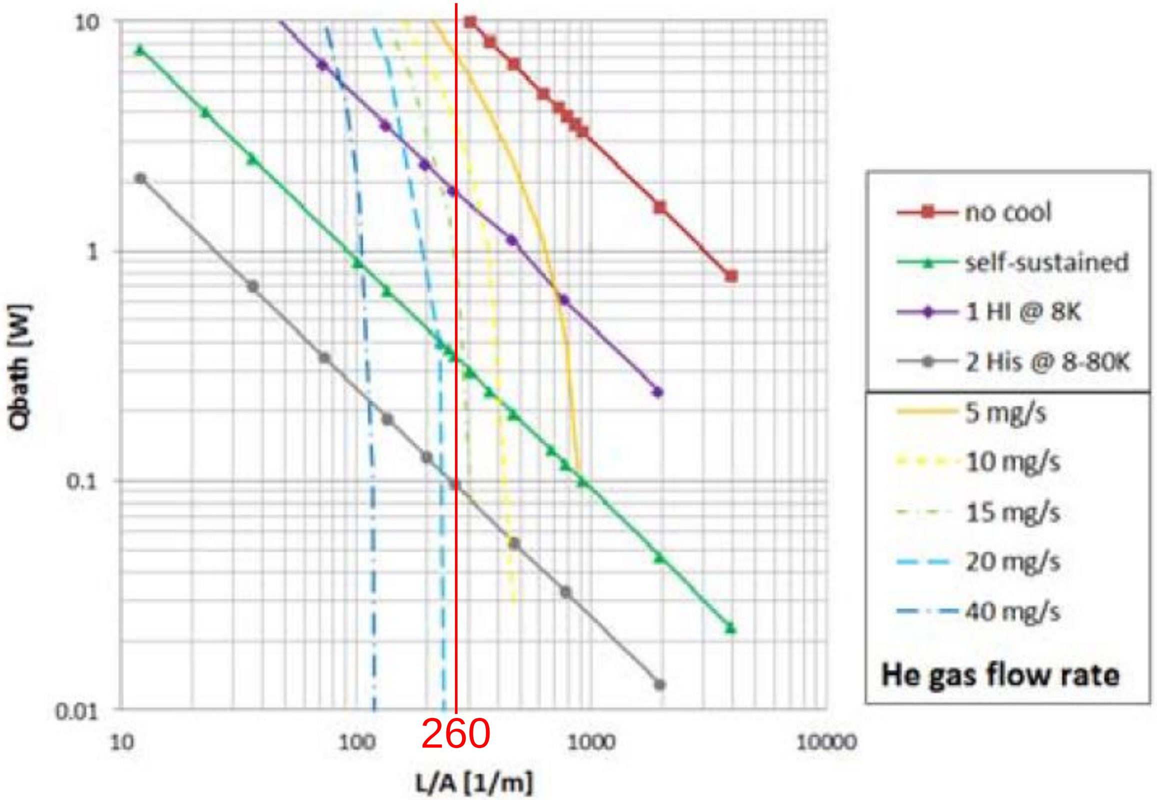
# SPL cryomodule: actively cooled RF main couplers

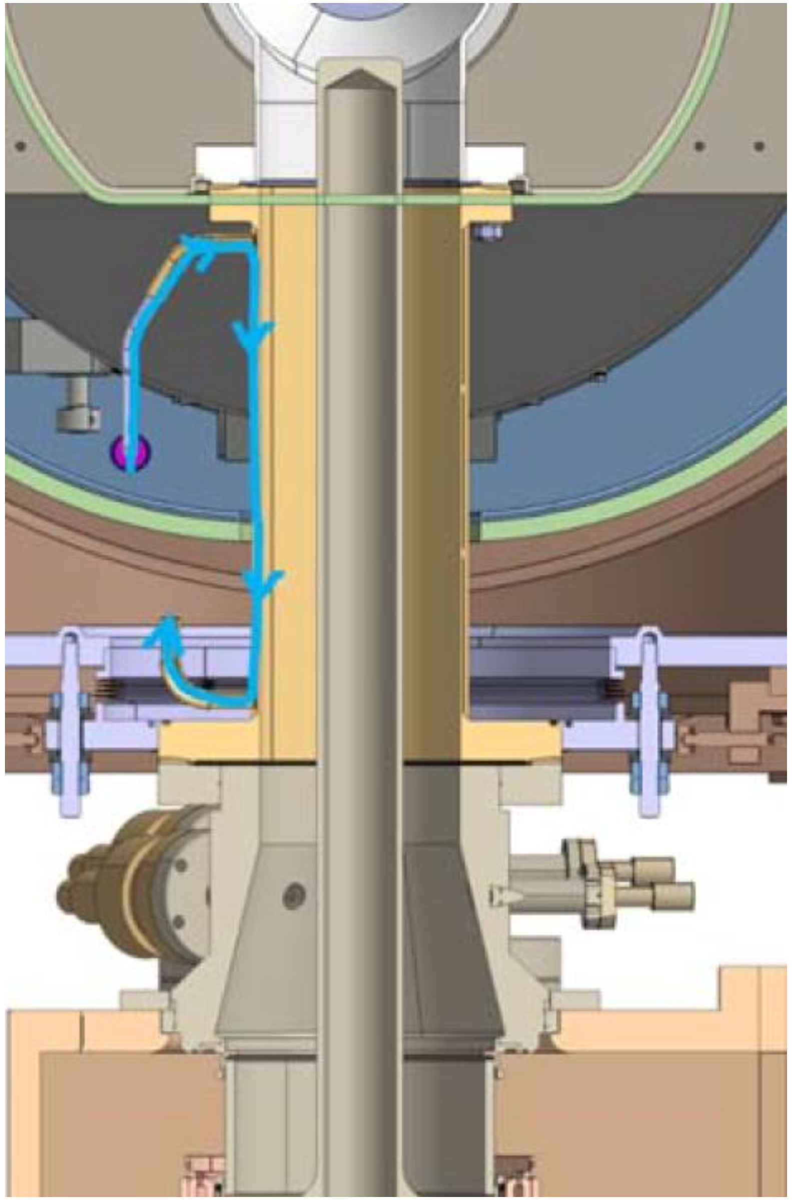
Vapor cooled RF coupler (double-walled tube). Effective cooling with gas regulation:

- Conduction heat loads (RF off)
- Conduction + RF EM resistive heating (RF on)

Double-walled tube:

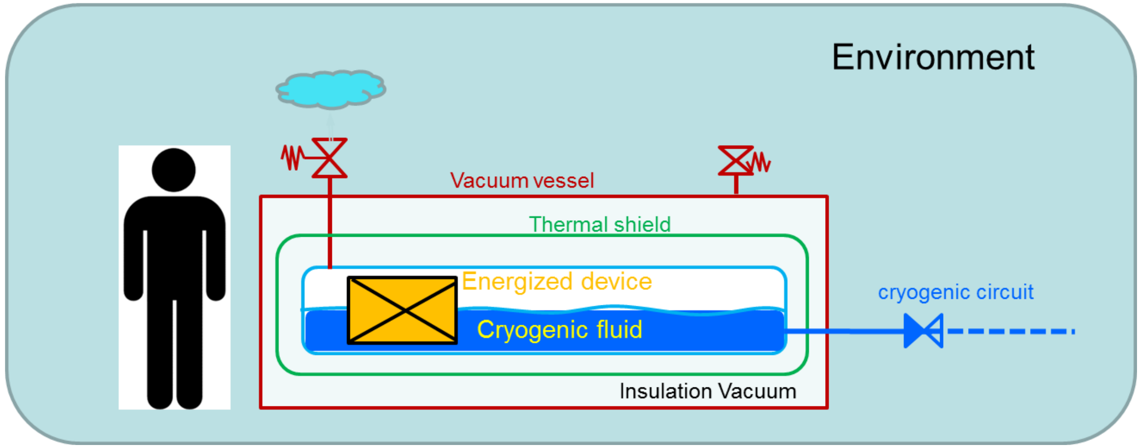
- ~Φ 100 mm
- Inner wall: st.steel, 1.5-mm thick
- External wall: st.steel, 2-mm thick



# Notions of 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.

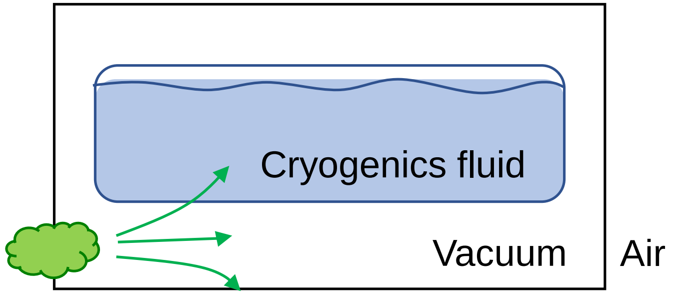
*→ Understanding pressure hazards and making the correct choice of the pressure relief devices to protect from overpressure of the cryostat envelopes*

# Liquid helium (and nitrogen) stored energies

| Property | Unit | $^4He$ | $N_2$ |
|---|---|---|---|
| $T_{boil.}$ (at 1'013 mbar) | [K] | 4.2 | 77.3 |
| Liquid density (at $T_{boil.}$) | [kg/m³] | 125 | 804 |
| Density ratio $\rho_{liquid}/\rho_{gas}$ (gas at boiling temperature and 1'013 mbar) | - | 7.4 | 175 |
| Gas/liquid volume ratio (gas at 273 K, 1'013 mbar) | - | 702 | 652 |
| Latent heat of evaporation (at $T_{boil.}$, and 1'013 mbar) | [kJ/kg] | 21 | 199 |
| Latent heat of evaporation per unit vol. (at $T_{boil.}$, 1'013 mbar) | [kJ/l] | 2.6 | 160 |
| Enthalpy change from $T_{boil.}$ to 300 K per unit vol. (at 1'013 mbar) | [kJ/l] | 194 | 189 |
| Total liquefaction energy in 1 liter of liquid | [kJ/l] | 196.6 | 349 |
| Expansion work (isobar at 1'013 mbar, reversible) for 1 liter of liquid | [kJ/l] | 71 | 66 |

**One LHC dipole:**

- Magnetic stored energy: ~7 MJ
- Helium content: 375 liters
- Total stored energy (in liquid): 74 MJ (x10 times stored magnetic energy!)
- Total magnet cold surface: ~4 $m^2$



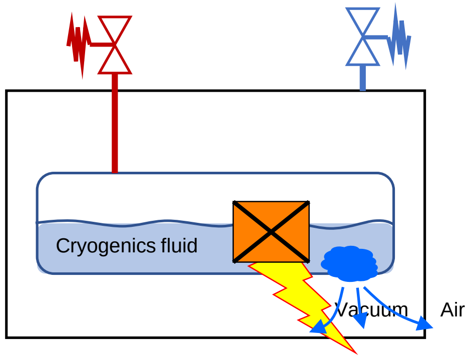

- Latent heat per unit volume: He x60 lower than $N_2$ → (*roughly*) venting a cryostat with ~6 liter air (~$N_2$) boils off He in 1 dipole
- Air condensation power on cold surface with MLI: 6 kW/$m^2$ (40 kW/$m^2$ on bare surface !)
- Vacuum insulation breach: peak power deposition: 24 kW → ~40 s to boil-off liquid, ~50 min. to deplete liquid stored energy,

→ **Large volumetric inventories** and energies **released in reduced time** ! → **pressure relief devices !**

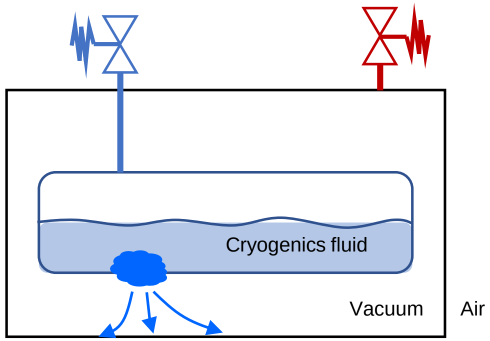
# Pressure hazards in cryostats

- 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

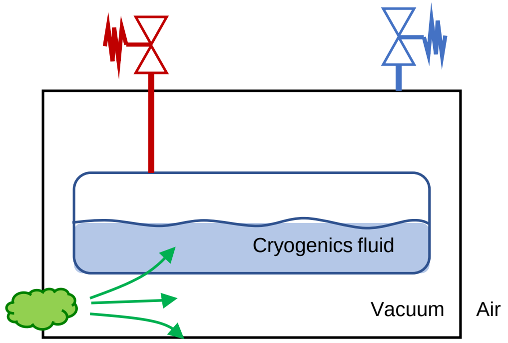
Usually the most critical



A) Quench (or el.arc)



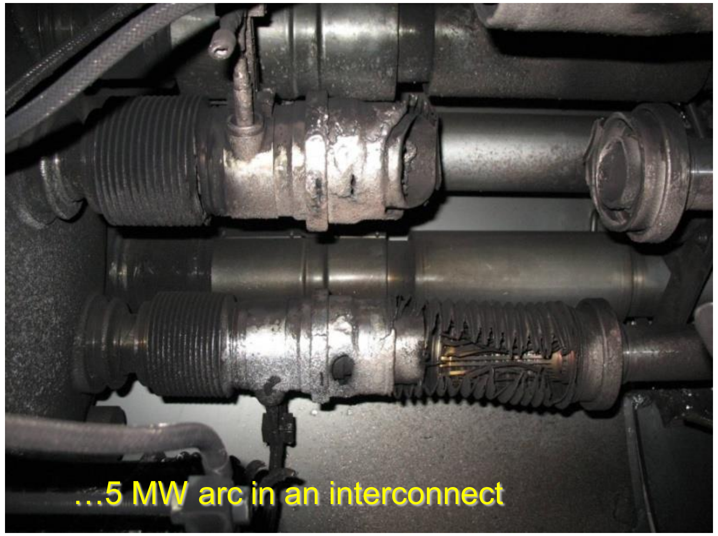
B) Rupture of helium tank

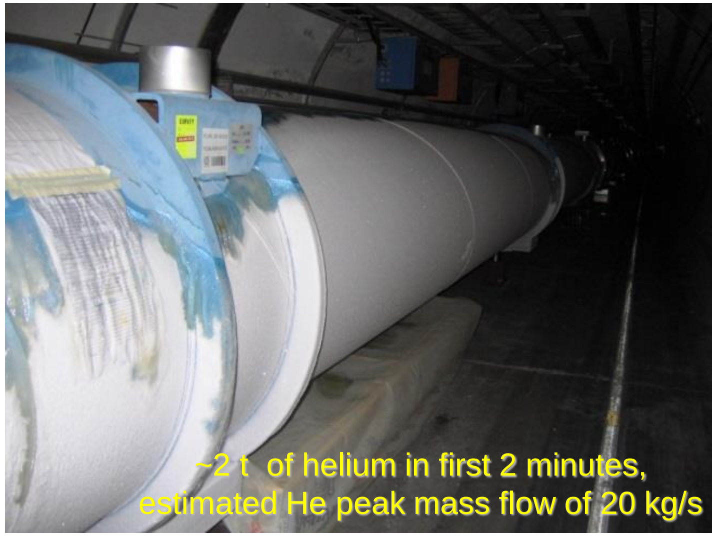


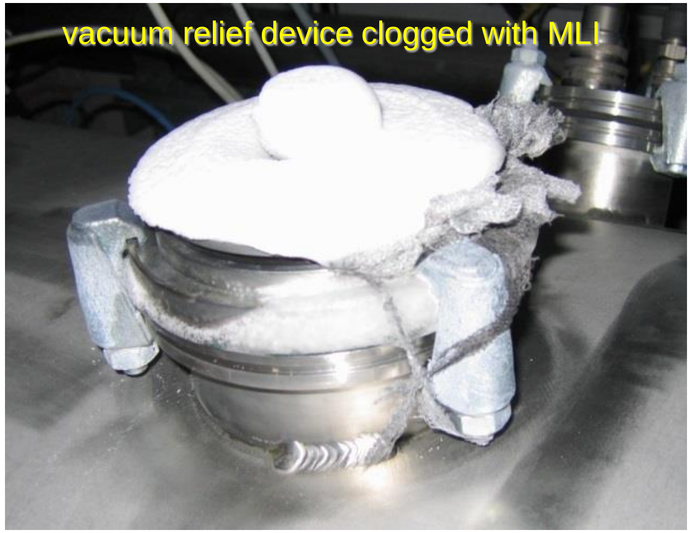
C) Air venting

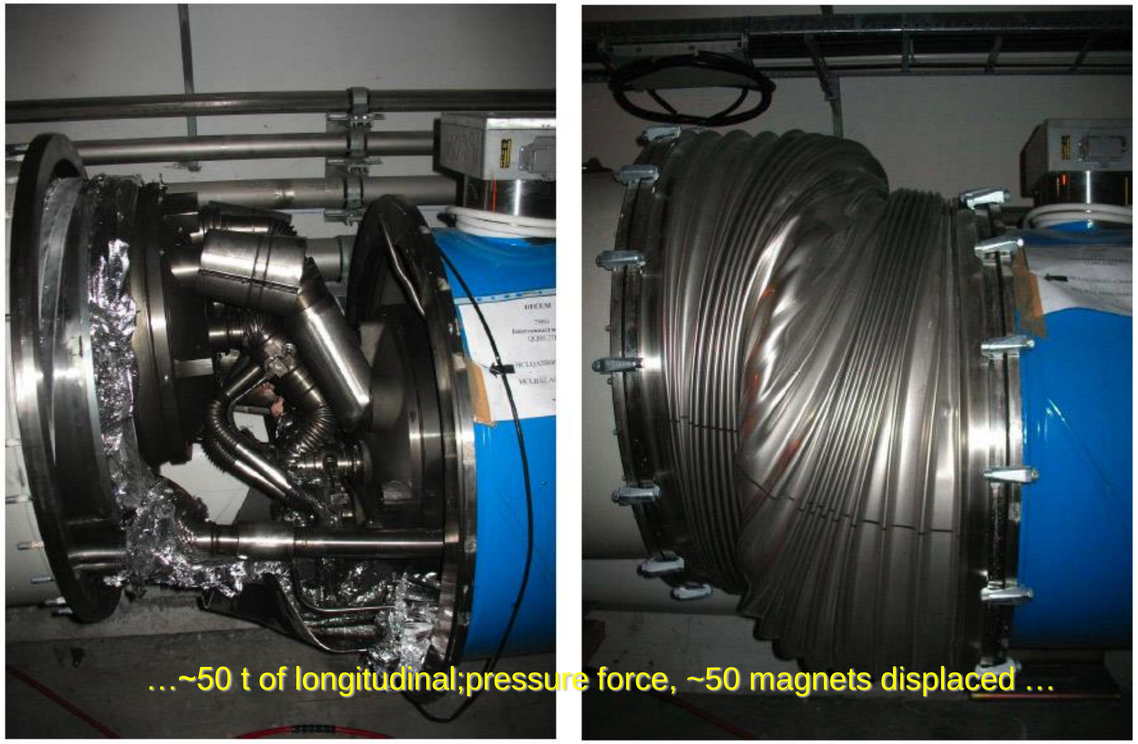
(Snowball effect A) + B) + C) → LHC event of Sept.2008)

# How things can go wrong…LHC 19th sept. 2008





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

# General approach for sizing of safety devices

## Risk analysis & mitigation:

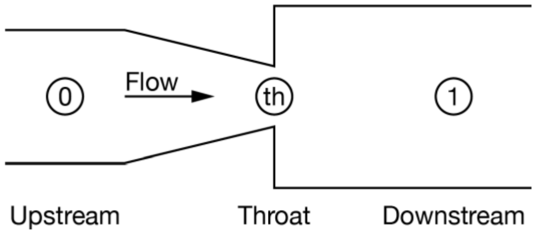
- Make a thorough risk analysis and evaluate risk hazards
- Identify mitigation measures (e.g. protections of exposed bellows and flanged connections)
- Identify severity of consequences and appreciate probability of the event
- Define the maximum credible incident(s) (MCIs) and design the safety relief system accordingly
- The safety relief system must be designed to keep pressure rise within the limits of the Maximum Allowable Working Pressure (MAWP)

## Design steps for the MCI:

- Estimate the heat flux to helium and its conversion to mass flow rates to be discharged
- Choose the type of safety device (burst disks, valves, plates) and size the safety device (orifice area and set pressure). Make use of standards and safety device manufacturers datasheet
- Check the sizing of piping (generally designed for normal operation) to the relief device and increase if necessary (pressure drop limited to a few % of total discharge Δp)

$$\dot{Q} \rightarrow \dot{M}$$

Heat flux (W) → Relieving mass flow rate (kg/s)




$$A_{th} = \frac{\dot{M}}{\rho_{th}\, vth}$$

$\rho_{th}\, v_{th}$, *density and velocity giving the* $\dot{m}$ *in the throat*

→ Methodology explained in a **new standard EN 17527 just issued** devoted to *Helium cryostats - Protection against excessive pressure*

# EN 17527 Helium cryostats - Protection against excessive pressure

- Publication of EN 17527


## 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:

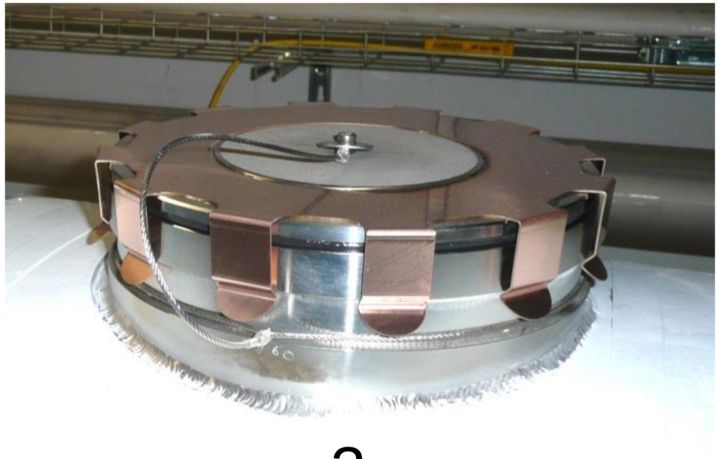
- ✓ Standardization of the approach
- ✓ Specification of procedures and minimum requirements
- ✓ Risk assessment, definition of scenarios
- ✓ Protection concepts (single-stage, multi-stage)
- ✓ Dimensioning rules of pressure relief devices (HEM Model)

# Safety devices

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

2.


1.



3.

<u>A few suppliers</u>
Herose, Rembe, Ramseyer, Leser…

# EN Standards for Safety Relief Devices

*EN 764-7:2002 Pressure equipment. Part 7: Safety systems for unfired pressure equipment*

*EN ISO 4126-1:2013 / Safety devices for protection against excessive pressure - Part 1: Safety valves (ISO 4126-1:2013) 12/08/2016*

*EN ISO 4126-2:2013 / Safety devices for protection against excessive pressure - Part 2: Bursting disc safety devices*

*EN ISO 4126-3:2006 / Safety devices for protection against excessive pressure - Part 3: Safety valves and bursting disc safety devices in combination (ISO 4126-3:2006) 12/08/2016*

*EN ISO 4126-4:2013 / Safety devices for protection against excessive pressure - Part 4: Pilot-operated safety valves (ISO 4126-4:2013) 12/08/2016*

*EN ISO 4126-5:2013 / Safety devices for protection against excessive pressure - Part 5: Controlled safety pressure relief systems (CSPRS) (ISO 4126-5:2013) 12/08/2016*

*EN ISO 4126-7:2013 / Safety devices for protection against excessive pressure - Part 7: Common data (ISO 4126-7:2013) 12/08/2016*

*EN 13648-1:2008 / Cryogenic vessels - Safety devices for protection against excessive pressure - Part 1: Safety valves for cryogenic service 12/08/2016*

*EN 13648-2:2002 / Cryogenic vessels - Safety devices for protection against excessive pressure - Part 2: Bursting disc safety devices for cryogenic service 12/08/2016*

*ISO 21013-3:2016 Cryogenic vessels -- Pressure-relief accessories for cryogenic service -- Part 3: Sizing and capacity determination*

*EN ISO 4126-6:2013 / Safety devices for protection against excessive pressure - Part 6: Application, selection and installation of bursting disc safety devices*

*EN ISO 4126-10:2013 / Safety devices for protection against excessive pressure - Part 10: Sizing of safety valves for gas/liquid two-phase flow*

*EN 13648-3:2002 Cryogenic vessels. Safety devices for protection against excessive pressure. Determination of required discharge. Capacity and sizing*

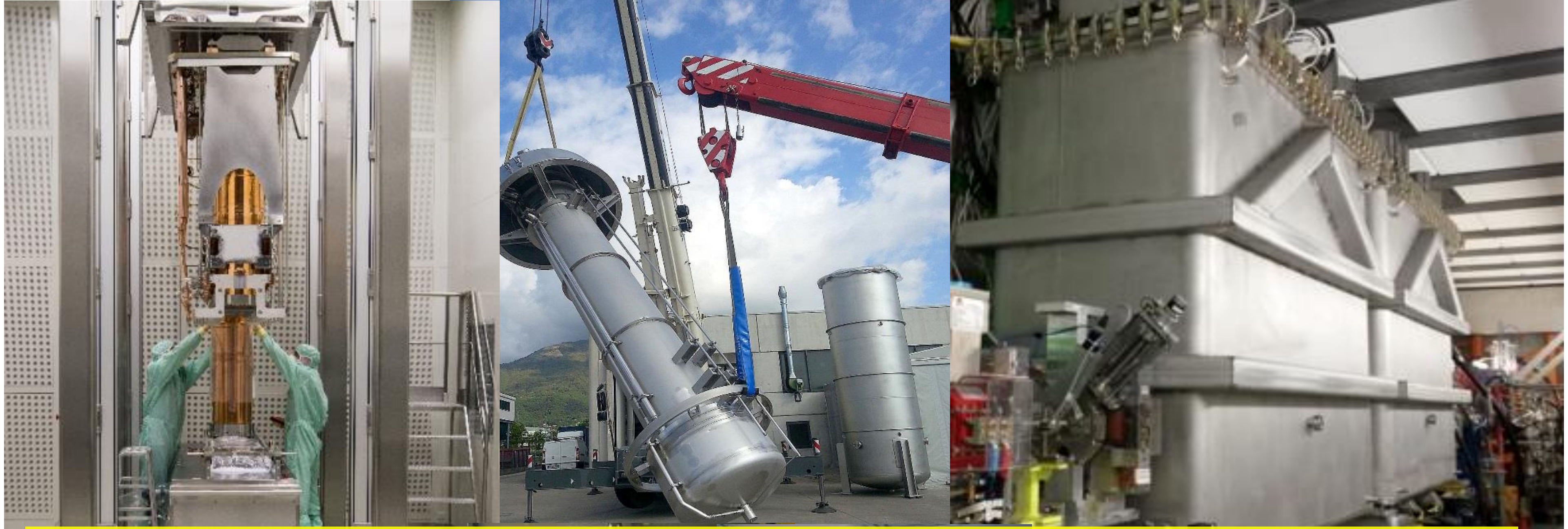
*ISO 21013-1:2008 Cryogenic vessels -- Pressure-relief accessories for cryogenic service -- Part 1: Reclosable pressure-relief valves*

*(ISO/AWI 21013-1 Cryogenic vessels -- Pressure-relief accessories for cryogenic service -- Part 1: Reclosable pressure-relief valves [Under development])*

*ISO 21013-2:2007 Cryogenic vessels -- Pressure-relief accessories for cryogenic service -- Part 2: Non-reclosable pressure-relief devices + ISO 21013-2:2007/Amd 1:2018*

*ISO 21013-4:2012 Cryogenic vessels -- Pilot operated pressure relief devices -- Part 4: Pressure-relief accessories for cryogenic service + ISO 21013-4:2012/Amd 1:2019*

*EN 17527 Helium cryostats - Protection against excessive pressure NEW (May 2022)*



# *Thank you for your attention*

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- J.Ekin, Experimental Techniques for Low-Temperature Measurements: Cryostat Design, Material Properties and Superconductor Critical-Current Testing
- CRYOCOMP® is a database code of the state and thermal properties for technical materials.
- NIST Cryogenic Materials database: http://www.cryogenics.nist.gov/MPropsMAY/material%20properties.htm

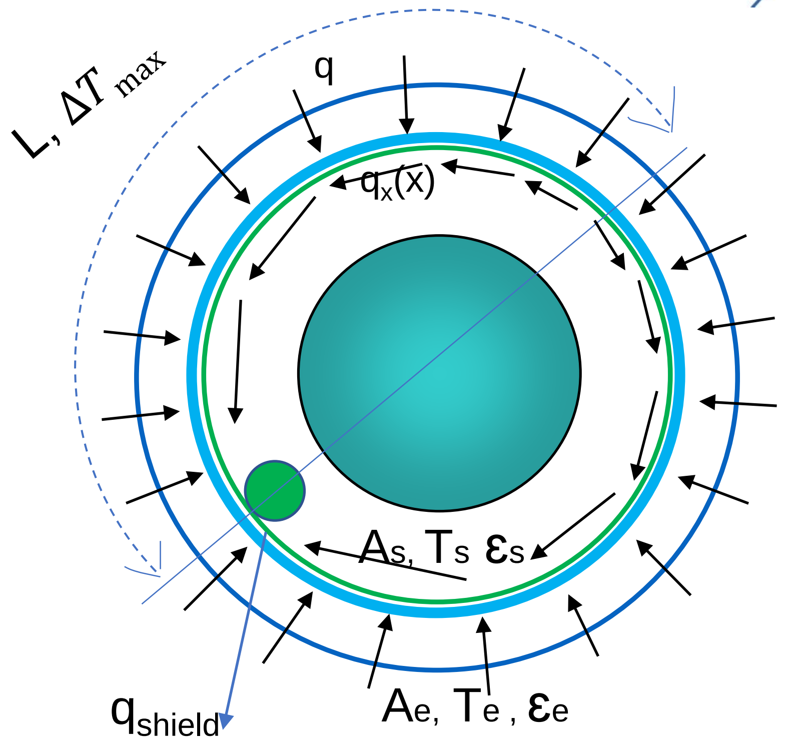
# Acknowledgments

The content of the training includes contributions from many colleagues from CERN and from external institutes. I wish to thanks them for their precious contributions.

# Annex:
# numerical calculations exercises

# **Exercise:** calculate a thermal shield thickness in an LHC-type cryostat

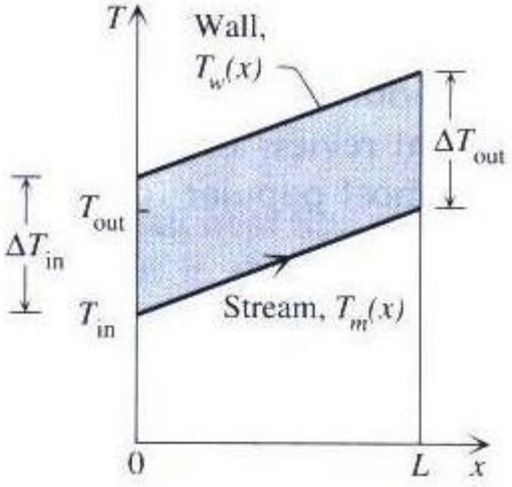
$$t = \frac{q \cdot L^2}{2 \cdot k \cdot \Delta T_{\max}}$$




- Symmetry: point opposite of cooling line is an isolated tip
- Take ½ shield: $L = \frac{1}{2}\frac{A_s}{1\,m}$ = ½ 2.35 m = 1.17 m
- Uniform heat deposition: $q = \frac{q_{\text{shield}}}{A_s} = \frac{2.55\,W}{2.35\,m^2} = 1.08\ \text{W/m}^2$
- Let's set the maximum $\Delta T_{\max} = 5\ \text{K}$
- Take k aluminium (Al6061) at ~80 K: 85 W/(K m)

→ t = 1.7 mm

# **Exercise:** calculate helium heat transfer in a thermal shield in an LHC-type cryostat

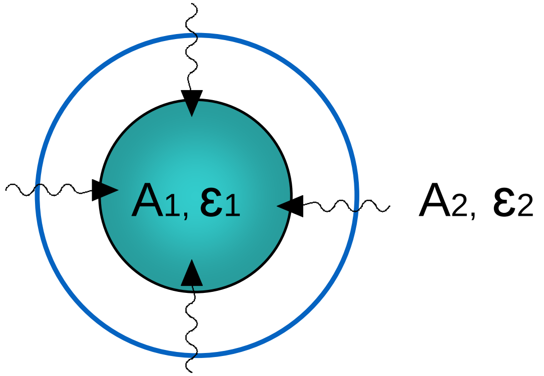



- Non-isothermal cooling along an L=3 km long thermal shielding line
- Cooling line: D=80 mm, roughness aluminium drawn tube (ε = 0.05 mm)
- $T_{in}$ = 60 K, $T_{out}$ < 75 K
- $p_{in}$ = 5 bar
- Calculate mass flow, heat exchange parameters, and pressure drop

- Assumptions: $T_m(x) = ½(T_{out}+T_{in})$ = const. ; $\Delta T_{in} = \Delta T_{out}$ (wall with uniform heat flux $\dot{q}$)
- Take $T_{out}$ = 75 K
- $T_m$ = ½ (75 K + 60 K) = 67.5 K
- $\dot{q} = q_{shield} \cdot L$ = 2.55 W/m · 3000 m = 7'650 W (see previous calculation of thermal shield heat load)
- From enthalpy balance (with $T_{in}$ = 60 K, $T_{out}$ = 75 K, and $C_p$(67.5 K) = 5300 J/kg/K) → $\dot{m} = \frac{\dot{q}}{C_p\,(Tout-Tin)}$ = 0.096 kg/s
- Calculate flow properties and thermal convection heat exchange (use *Cryostat Toolbox*):
  - Re = 1.9 10+5 , turbulent OK !
  - V = 5.4 m/s
  - Pr = 7.03
  - Nu = 345
  - h = 247 (W/m²/K)
  - $\Delta T_{in} = \Delta T_{out}$ = 0.04 K ($T_w \approx T_m$)
- Calculate pressure drop (use *Cryostat Toolbox*):
  - Δp = 380 mbar (~8%)

# Radiation calculation exercises for an LHC-like cryostat

# **Exercise:** Radiation in LHC-like cryostat




- Thermal radiation HL for a 1-m cryostat unit length
- Vacuum vessel diameter: 1m ($A_2$= π x 1= 3.14 $m^2$)
- Cold mass diameter: 0.5 m ($A_1$= π x 0.5 = 1.57 $m^2$)
- $T_1$ cold mass: 2 K
- $T_2$ vac.vessel: 293 K
- Ɛ1 = 0.12 (st.steel, mec.polished, 2 K)
- Ɛ2 = 0.2 (low carbon.steel, mec.polished, 293 K)

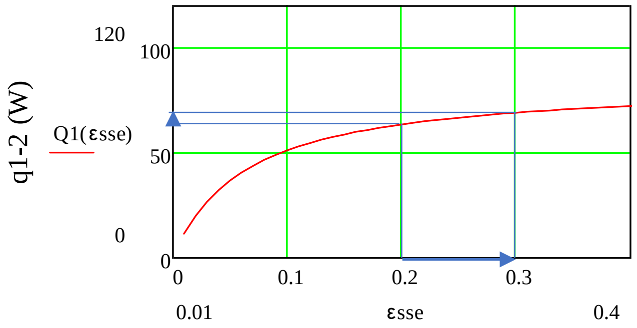
$$q_{1\_2} = \frac{\sigma A_1 (T_1^{\,4} - T_2^{\,4})}{\frac{1}{\varepsilon_1} + \frac{A_1}{A_2}\left(\frac{1}{\varepsilon_2} - 1\right)}$$

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

- Sensitivity wrt Ɛ uncertainties:
  - Ɛ1 = 0.18 (+50%), Ɛ2 = 0.20 → $q_{1\text{-}2}$ = 87 W (+37%)
  - Ɛ1 = 0.12, Ɛ2 = 0.30 (+50%) → $q_{1\text{-}2}$ = 69 W (+9%)
  - Ɛ1 = 0.18 (+50%), Ɛ2 = 0.30 (+50%) → $q_{1\text{-}2}$ = 98 W (+54%)
  - Note: assuming black bodies ($\varepsilon_1 = \varepsilon_2 = 1$) → $q_{1\text{-}2}$ = 656 W ! (x10!)

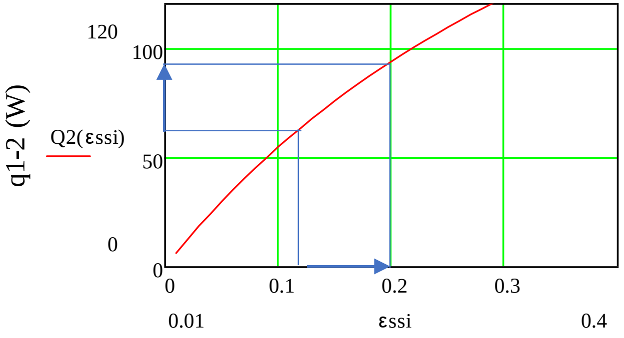
### → Influence of $\varepsilon_1$ is 4 times more important than $\varepsilon_2$

Sensitivity with Ɛ2



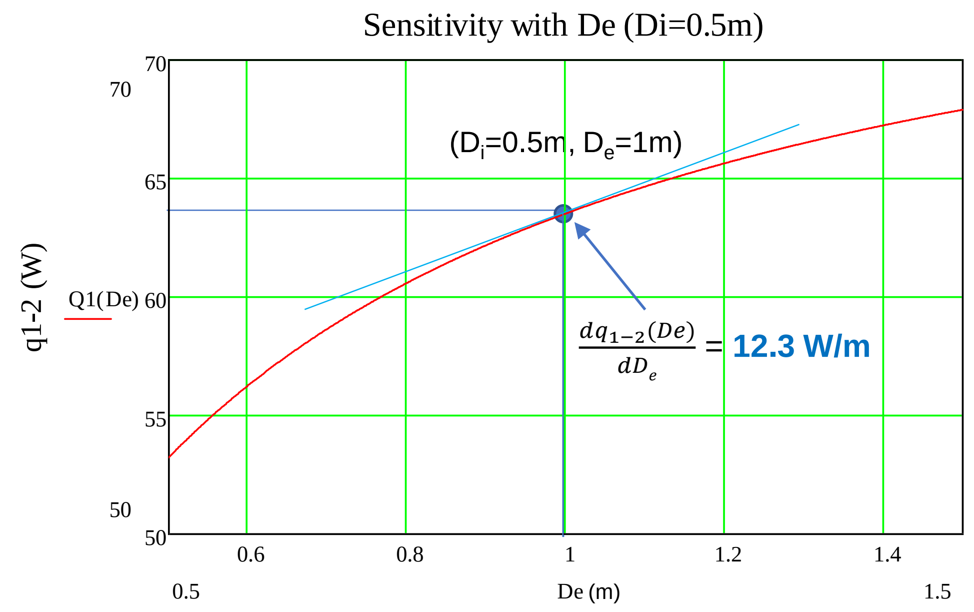

Ɛ2

Sensitivity with Ɛ1

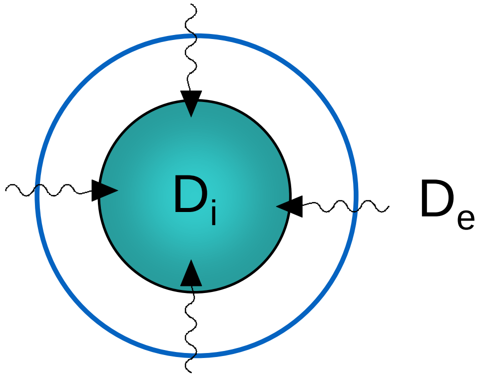



Ɛ1

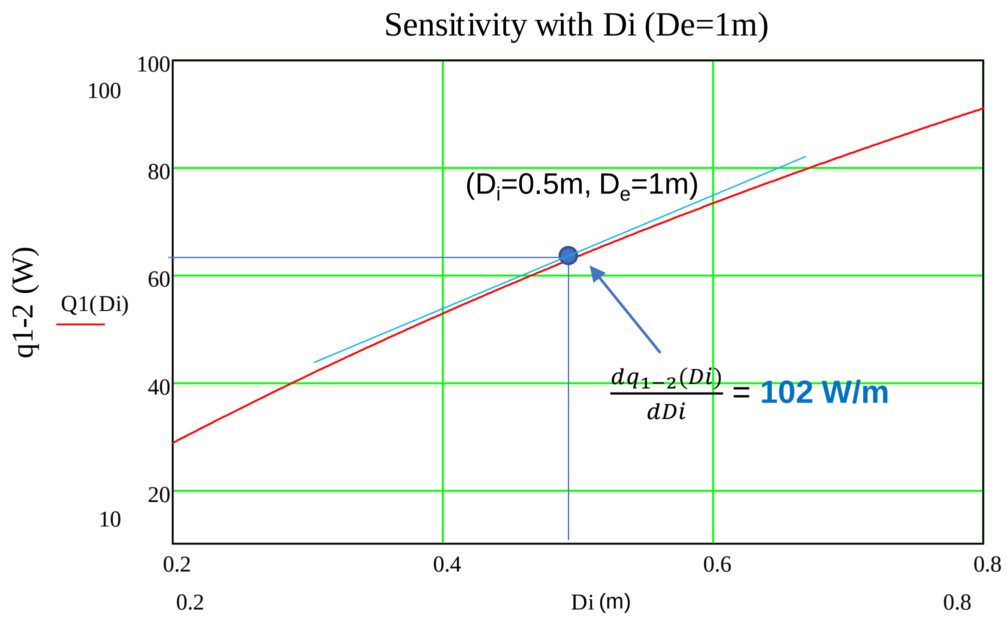
# **Exercise:** Radiation in LHC-like cryostat (cont.d)




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




- Sensitivity with vac.vessel diam. ($D_e$): ~12 W/m



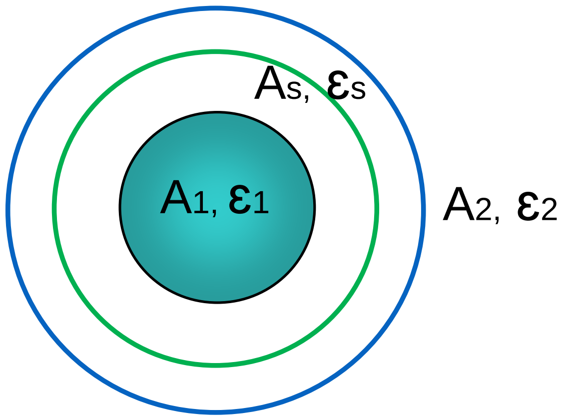

- Sensitivity with inner vessel diam. ($D_i$): ~ 100 W/m

→ $D_i$ x 8 times more sensitive than $D_e$ (for similar D ratios)

# **Exercise:** Radiation in LHC-like cryostat (cont.d)

- 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 ($A_s = \pi \times 0.75 = 2.35\ m^2$)
- $F_{1s} = 1$; $F_{2s} = 1$
- $T_s = 80$ 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)

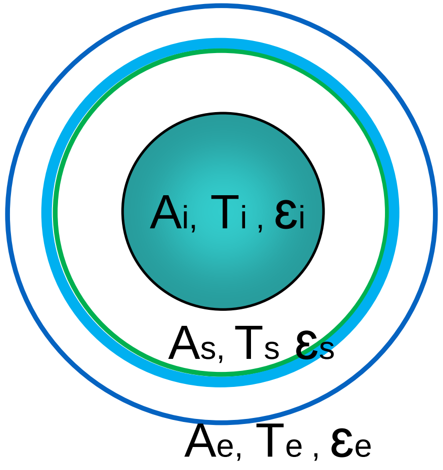
→ $q_{1-s} = 35.4$ W (22.5 W/m²), $q_{s-2} = 35.4$ W (15 W/m²)

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

# **Exercise:** Radiation in LHC-like cryostat (cont.d)

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

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




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

→ $q_{s-e}$ = 2.7 W (0.14 W/m²) (with $T_s$ = 80 K )

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

→ $q_{i-s}$ = 0.23 W (0.012 W/m²) (with $T_s$ = 80 K )

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

→ $T_s$ = 143 K, → $\varepsilon_s$= 0.1

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

→ $q_{s-e}$ = 2.6 W (1.65 W/m²)

→ $q_{i-s}$ = 2.6 W (0.96 W/m²)

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

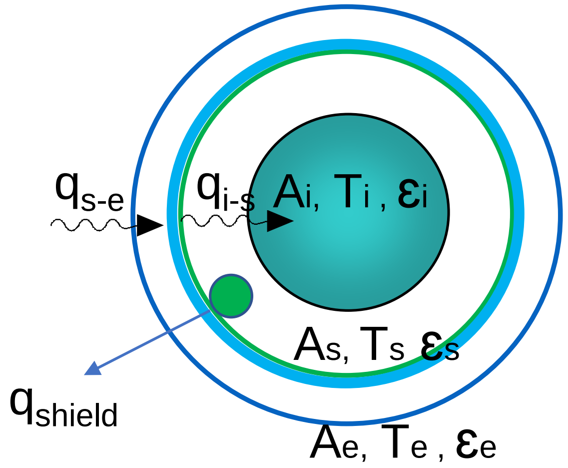
# **Exercise:** Radiation in LHC-like cryostat (cont.d)

- 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)
- $\varepsilon_s$ = 0.08 (Aluminium reflector, electrolytical deposition, 80 K)
- $\varepsilon_{av}$ = ½ ($\varepsilon_s$+ $\varepsilon_e$) (average emissivity)
- $A_{av}$ = ½ ($A_s$ + $A_e$) (average area)

→ $q_{s-e}$ = 2.78 W (1.0 W/m²)




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

→$q_{i-s}$* = 0.23 W (0.14 W/m²) (x10 times less than with floating shield !)

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

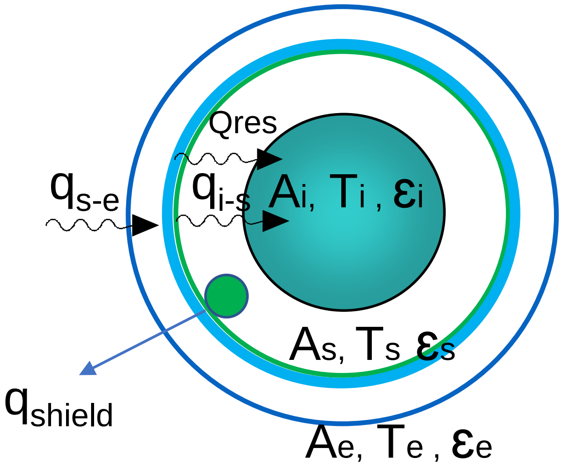
→ $q_{shield} = q_{s-e} - q_{i-s}$ = 2.55 W

→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/m² ) with $\varepsilon_i$ = 0.08 (for example 1 or more MLI layers on cold mass)

# **Exercise:** Residual gas conduction in LHC-like cryostat

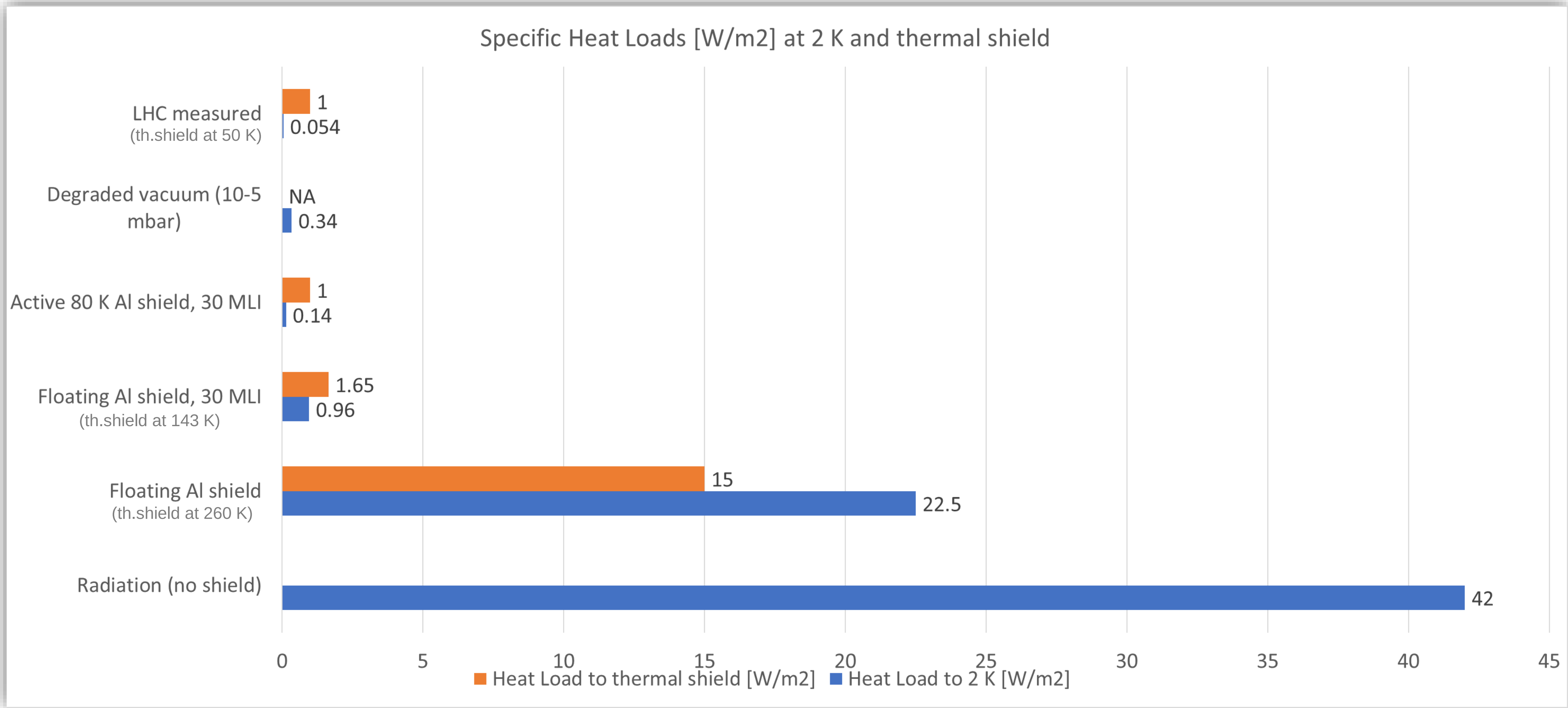
- Typical dimension (space between surfaces): d = 0.25 m
- **Good insulation vacuum:**
  - ✓ p = $10^{-6}$ mbar ($10^{-4}$ Pa) ("standard" good vacuum in cryostats)
- Calculate $\lambda_{molecule}$ (between shield and inner vessel):
  - ✓ $\lambda_{molecule}$ = 20 m (~ x100 d) → molecular regime
- Calculate residual gas conduction with Kennard's law:
  - ✓ $Q_{res}$ = 0.034 W (0.02 W/m$^2$)
- Negligeable additional contribution wrt previously computed radiation:
  - ✓ $q_{i\text{-}s}$ = 0.23 W (0.14 W/m$^2$)




- **Degraded insulation vacuum:**
  - ✓ p = $10^{-5}$ mbar ($10^{-3}$ Pa) (degraded vacuum from helium leak in cryostats)
- Calculate $\lambda_{molecule}$ (between shield and inner vessel):
  - ✓ $\lambda_{molecule}$ = 2 m (~ x10 d) → still molecular regime
- Calculate residual gas conduction with Kennard's law:
  - ✓ $Q_{res}$ = 0.34 W (0.22 W/m$^2$)

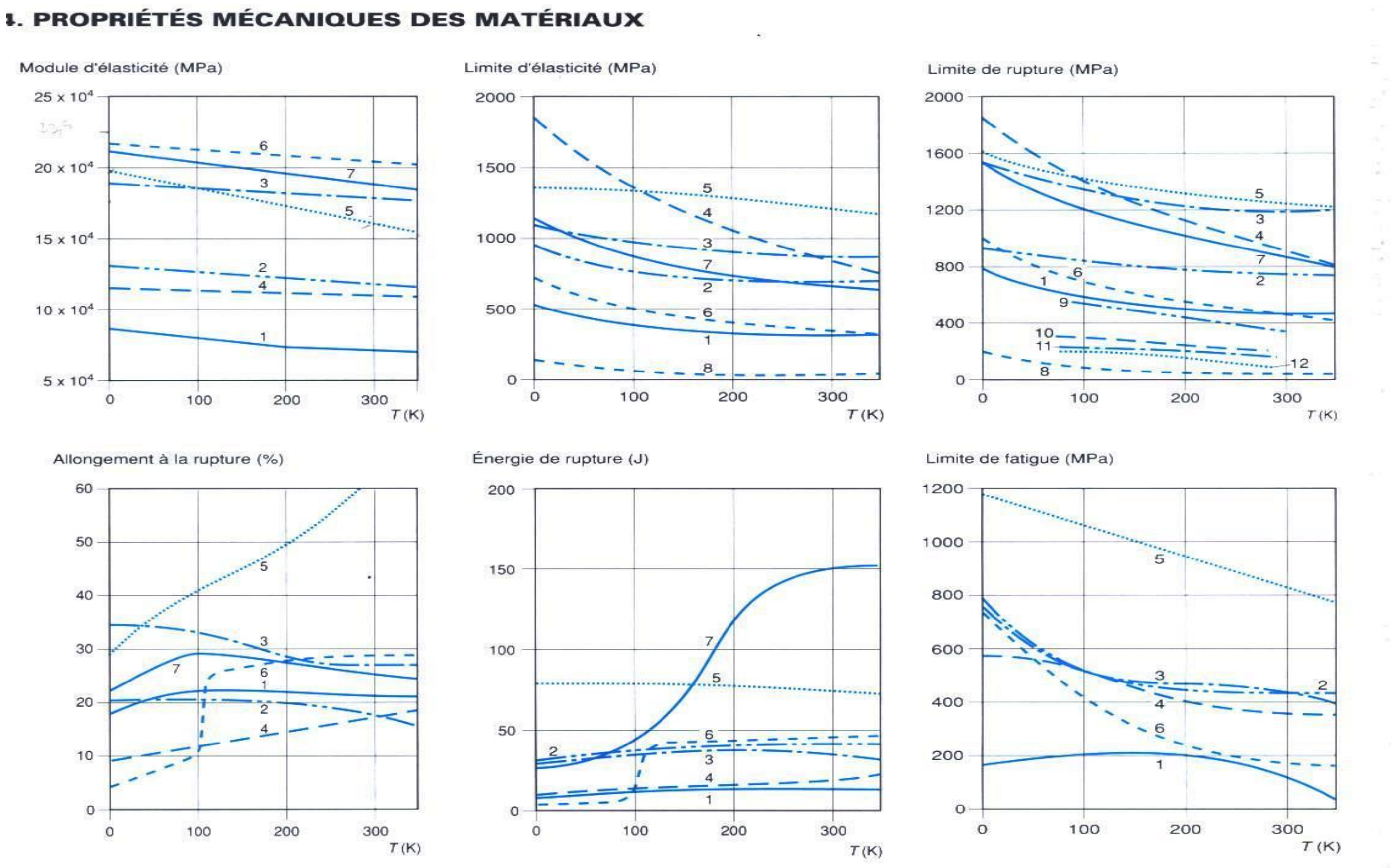
→ gas conduction contribution ($Q_{res}$ = 0.22 W/m$^2$) now higher than radiation ($q_{i\text{-}s}$ = 0.14 W/m$^2$). Total HL to cold surface: 0.34 W/m$^2$

# Summary of radiation HL exercises



# Spare slides

# Material mechanical properties at cryogenic temperatures




1 2024 T4 Aluminium
2 Cuivre - Béryllium
3 K Monel
4 Titane
5 Acier inoxydable 304
6 Acier au carbone C 1020
7 Acier 9% Ni
8 Téflon
9 Fibre de verre époxy
10 Kapton
11 Mylar
12 Nylon

**Fig. G. – Module d'élasticité, limite élastique, limite de rupture, allongement à la rupture, énergie de rupture mesurée au mouton de Charpy, limite de fatigue après 10⁶ cycles pour quelques matériaux [Baron].**

Source: Techniques de l'ingenieur

# Material mechanical properties at cryogenic temperatures

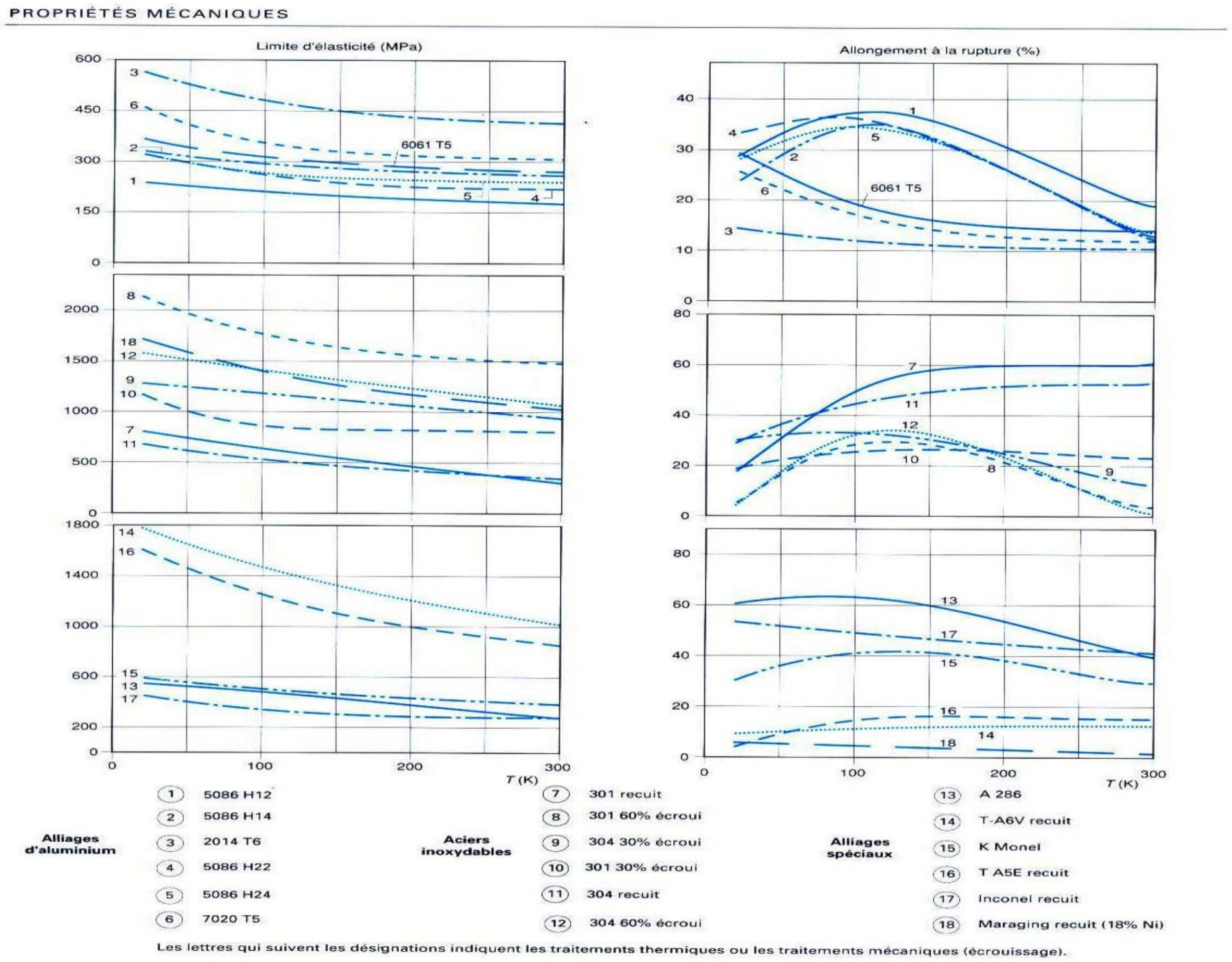
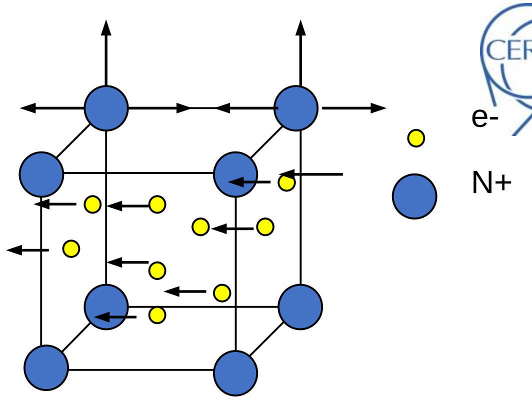



Fig. H. – Limite d'élasticité et allongement à la rupture d'alliages d'aluminium, d'alliages spéciaux et de diverses nuances d'aciers inoxydables.

Source: Techniques de l'ingenieur

# Thermal conductivity in solids (& metals)




- The conductivity is attributed to the movement of **conduction electrons** (“electron gas”), *k*e, and the effects of **phonon lattice vibrations**, *k*l :

$$k = k_e + k_l$$

- In metals, the electron contribution dominates :

$$k \approx k_e >> k_l$$

- The movement of conduction electrons is impeded by **scatter**: **interactions with phonons**, and **interactions with impurities/imperfections**. We can introduce ***thermal resistivities:***

$$\frac{1}{k_e} = \frac{1}{k_p} + \frac{1}{k_i} \qquad \frac{1}{k_p} = a_p T^2 \quad \frac{1}{k_i} = \frac{a_i}{T}$$

and $a_p, a_i$ constants

- Therefore for **metals**, the resistivity can be expressed as:

$$k = \frac{1}{a_p T^2 + \frac{a_i}{T}}$$

- And has a **maximum**, which shifts at higher T with increasing impurity (see coppers ) and vanishes for highly impure alloys (see steels), as impurity scatter dominates, and for which at T < RT:

$$k_{max} = \frac{3}{2^{2/3}} a_p^{1/3} a_i^{2/3} \text{ at } T = \left(\frac{a_i}{2a_p}\right)^{1/3}$$

$$k \cong \frac{T}{a_i}$$

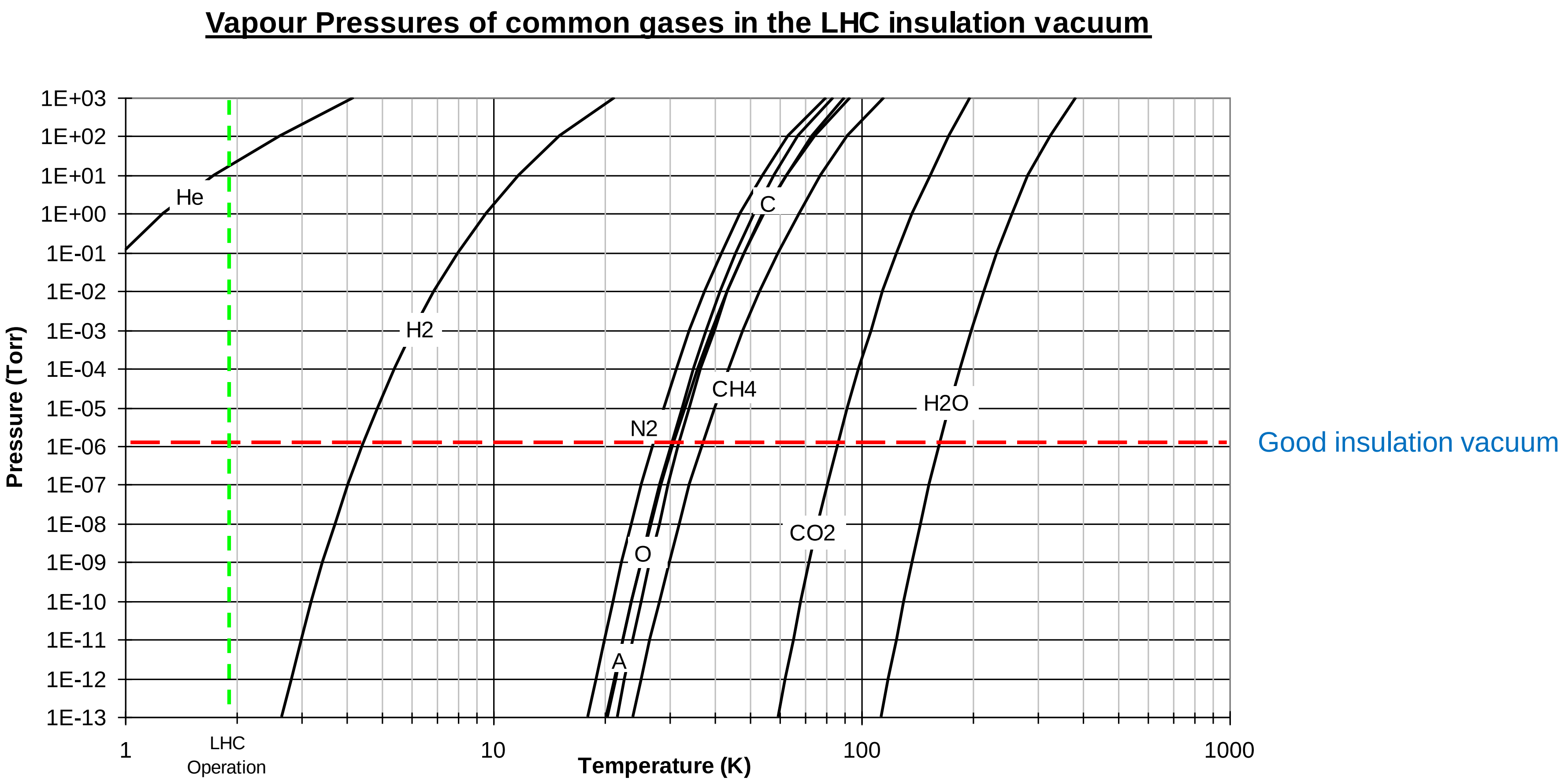
- For **metals**, analogy between electron thermal and electrical diffusion → ***Wiedemann-Franz law*** :
  - Good agreement at T<< RT >> T
  - Better agreement from T<< to T>> with increasing impurities

$$k = \frac{L_o}{\rho_e} T$$

Lorentz constant

$$L_o = 2.45 \cdot 10^{-8} \left(\frac{V}{K}\right)^2 \text{ (Constant for metals)}$$

# Vacuum in cryostats



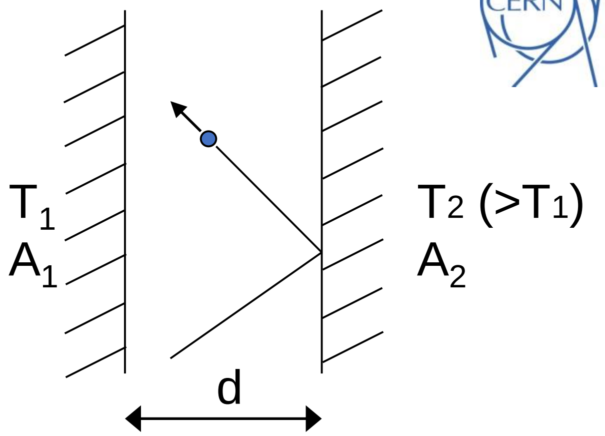

- 2-4.5 K surfaces have high pumping speed & capacity.
- Gas species have very low vapour pressure except helium.
- Without helium leaks, equilibrium pressures ≤ $10^{-6}$ mbar are obtained

# He gas conduction

$\lambda_{\text{molecule}}$ = mean free path

$$\lambda_{\text{molecule}} = \frac{\eta}{p}\sqrt{\frac{\pi R T}{2 M}}$$

$\eta$ = gas viscosity in $[Pa.s]$
p = pressure in, $[Pa]$
T = temperature, K
R = gas constant [J.K$^{-1}$.mol$^{-1}$]
M = molar mass [kg/mol]




- **Viscous regime ($\lambda_{\text{molecule}}$ << d):**
  - At “high” gas pressure: classical conduction (Fourier law-like)
  - independent of pressure
  - (*natural convection* should be added !)

$$Q_c = A_1 \cdot k \cdot \frac{(T_2 - T_1)}{d}$$

with $k = \frac{1}{3}\rho\sqrt{\frac{8RT}{\pi M}}\lambda C_v$

$\rho$ = gas *density* in $[kg/m^3]$
R = *ideal gas constant*
$\lambda$ = *mean free path* $[m]$
$C_v$ = *specific heat at constant pressure* [J.kg$^{-1}$K$^{-1}$.]

- **Molecular regime ($\lambda_{\text{molecule}}$ >> d):**
  - At “low” gas pressure
  - Kennard’s law
  - Conduction is proportional to p
  - A1 is the surface receiving the flow
  - α(T) → *accommodation coefficient* depending on gas species, T1, T2 and surface geometry *(applicable for flat parallel surfaces, coaxial cylinders and spheres)*

$$Q_{res} = A_1 \cdot \alpha \cdot \left(\frac{\gamma+1}{\gamma-1}\right) \cdot \left(\frac{R}{8\pi}\right)^{1/2} \cdot \frac{p}{\sqrt{M T}} \cdot (T_2 - T_1)$$

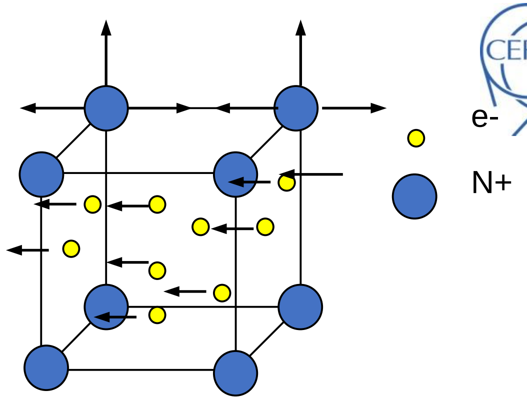
$$with\ \gamma = C_p/C_v$$

$$\alpha = \frac{\alpha_1 \alpha_2}{\alpha_2 + \alpha_1(1-\alpha_2)\frac{A_1}{A_2}}$$

Accommodation coefficient $\alpha_i$

| Temp. [K] | Helium |
|---|---|
| 300 | 0.3 |
| 80 | 0.4 |
| 20 | 0.6 |
| 4 | 1 |

# Thermal conductivity in solids (& metals)

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- And has a **maximum**, which shifts at higher T with increasing impurity (see coppers ) and vanishes for highly impure alloys (see steels), as impurity scatter dominates, and for which at T < RT:

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$$k = \frac{L_o}{\rho_e} T$$

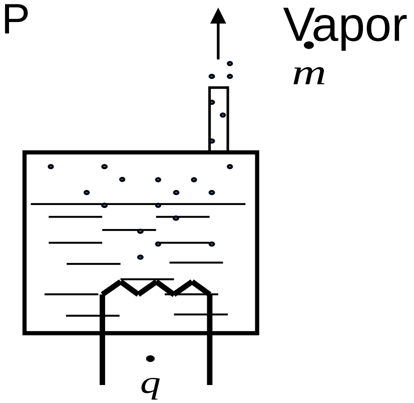
Lorentz constant

$$L_o = 2.45 \cdot 10^{-8} \left(V/K\right)^2 \text{ (Constant for metals)}$$

# 2 main mechanisms of interest for cryostats

- Vaporisation in pool boiling (2-phase)
  - Latent Heat (Lv) of vaporisation
  - Isothermal cooling (T constant if P constant)

$$\dot{q} = \dot{m} \cdot Lv$$

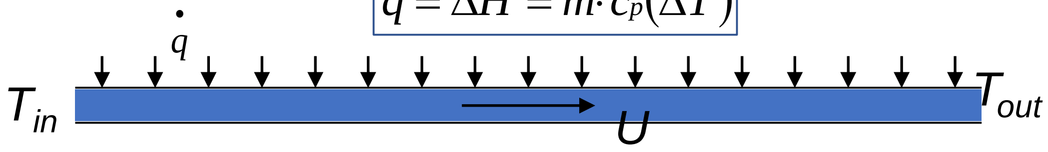



Vaporisation under 1 W heat load

| Cryogen | Latent Heat (at 1tm) [kJ/kg] | [mg/s] | [l/h] (liquid) | [l/min] (gas NTP) |
|---|---|---|---|---|
| Helium | 21 | 48 | 1.38 | 16.4 |
| Nitrogen | 199 | 5 | 0.02 | 0.24 |

- Forced internal (tube) convection of single-phase fluid:
  - Non-isothermal cooling: enthalpy change of fluid ($c_p$ assumed constant)
  - Depends on *thermo-hydraulics* of the flow (see next slide)
  - Used in cooling of thermal shields (supercritical He)

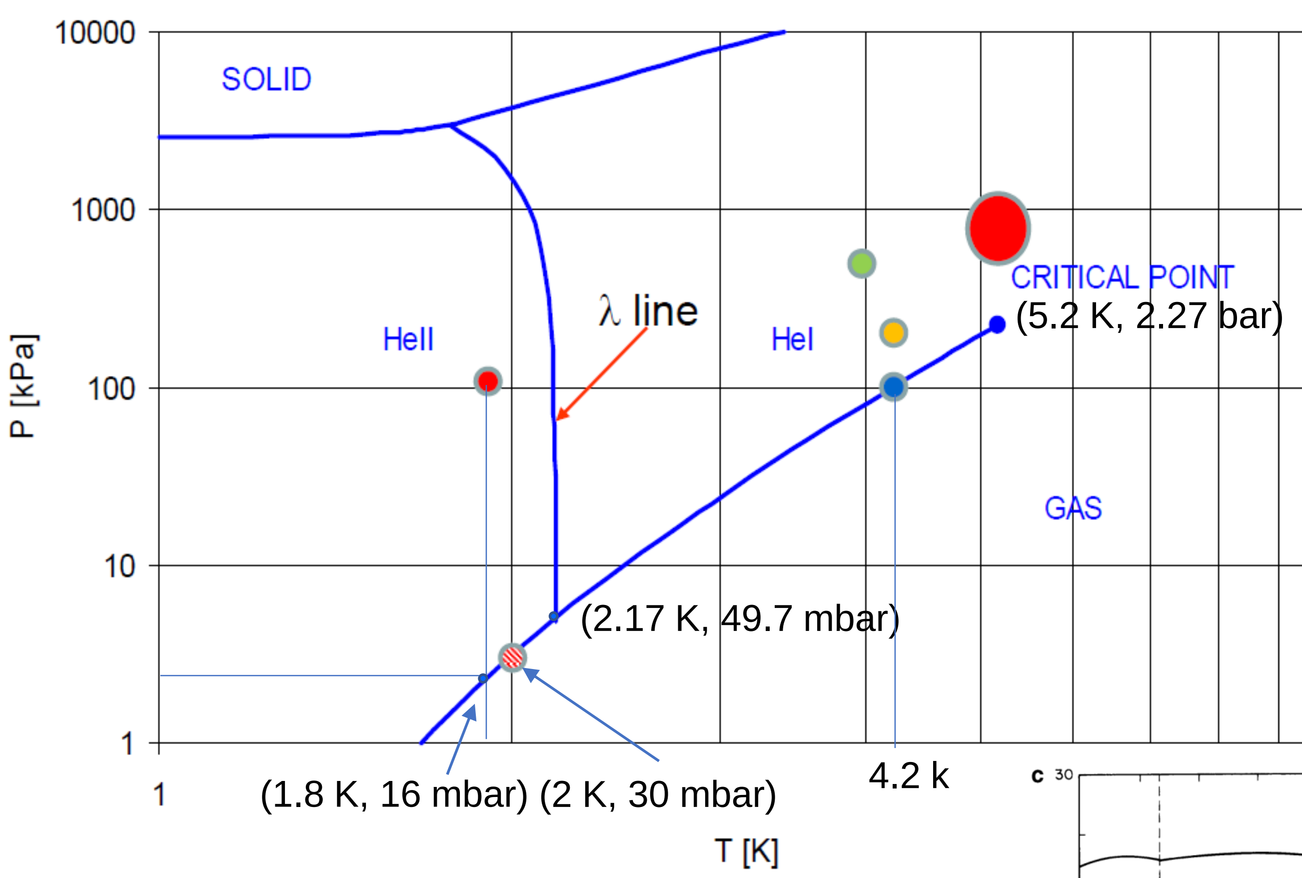
$$\dot{q} = \Delta H = \dot{m} \cdot c_p (\Delta T)$$



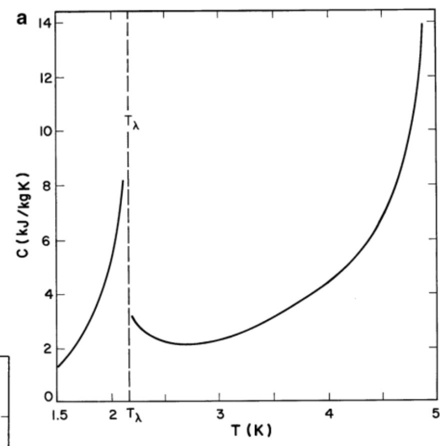

*For more cooling mechanisms see dedicated lectures*

# Helium as a coolant for SC devices

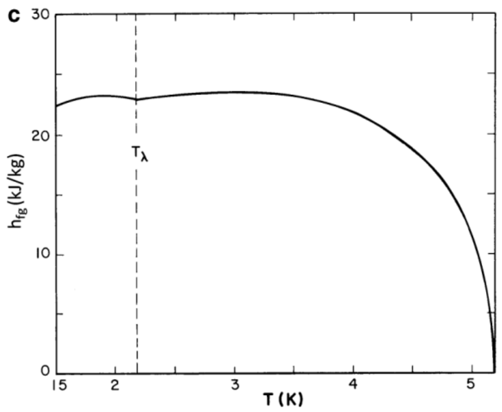
| Property | Units | $^4He$ | $N_2$ |
|---|---|---|---|
| Boiling T (at 1 atm) | K | 4.2 | 77.3 |
| Critical temperature | K | 5.2 | 126.1 |
| Critical pressure | $10^5$ Pa | 2.23 | 33.1 |
| Latent Heat of evaporation (at 1 atm) | kJ/kg | 21 | 199 |
| Enthalpy between T boiling and 300K | kJ/kg | 1550 | 233 |
| Liquid density (boiling at 1 atm) | kg/m3 | 125 | 810 |
| Saturated vapor density (at 1 atm) | kg/m3 | 17 | 4.5 |
| Gas density (at 1 atm 273.15K) | kg/m3 | 0.18 | 1.25 |
| Liquid viscosity (at boiling T) | μPa.s | 20 | 17 |



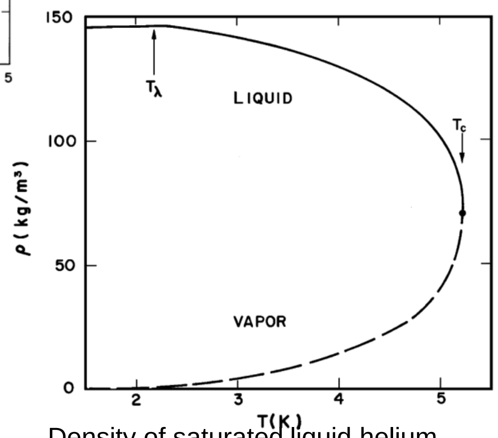

- Pressurized He II, Magnets: LHC, Tore Supra
- Pressurized He I, Magnets, HERA, Tevatron
- Saturated He II, SRF: CEBAF, TTF, SNS, EXFEL, ESS, ILC
- Pool boiling He I, SRF: HERA, LEP, KEKB
- Supercritical helium: cooling of thermal shielding



Specific heat of saturated liquid



Latent heat of vaporization

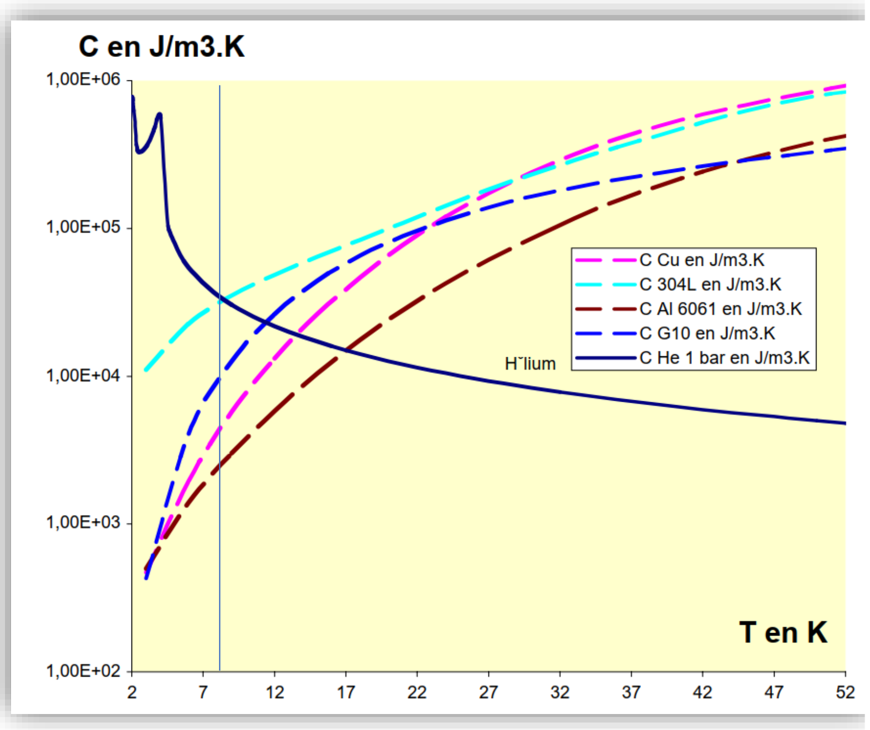


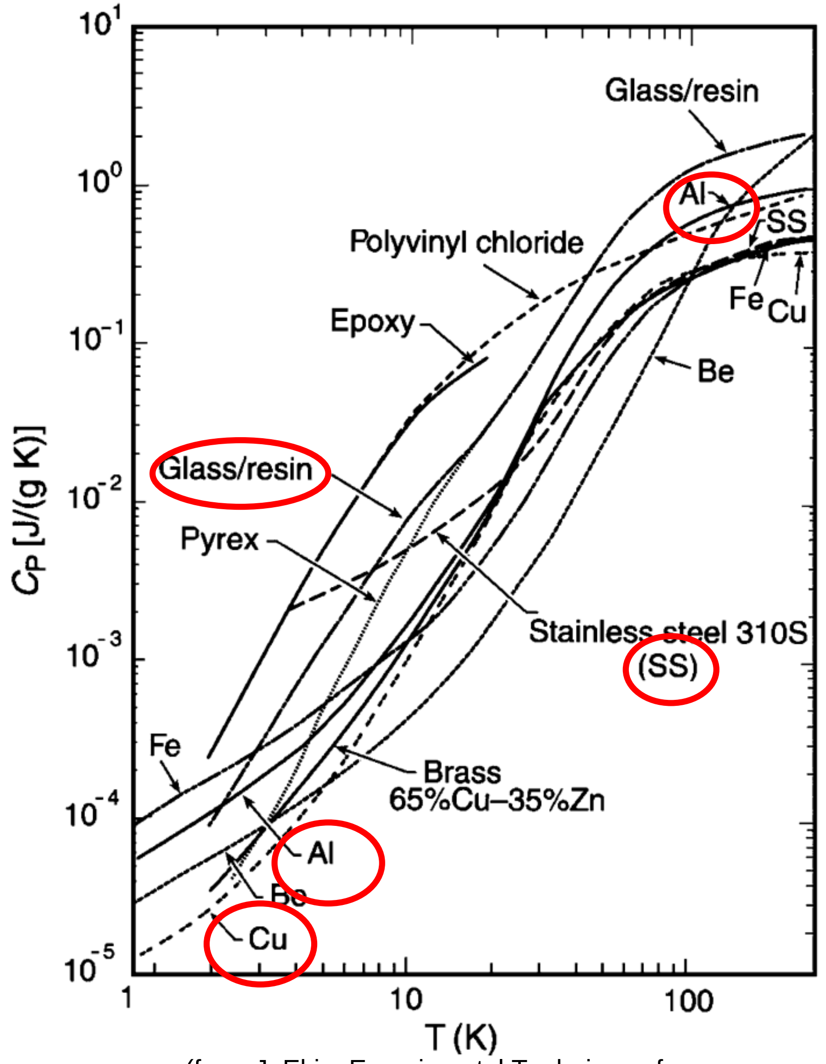
Density of saturated liquid helium

*(ref. S. Van Sciver, Helium Cryogenics)*

# Heat capacity

- Specific heats: $c_p = \left(\frac{\delta Q}{m\,dT}\right)_P = \left(\frac{1}{m}\frac{\partial H}{\partial T}\right)_P$ $c_v = \left(\frac{\delta Q}{m\,dT}\right)_V = \left(\frac{1}{m}\frac{\partial U}{\partial T}\right)_V$
- For (incompressible) substances: $C_p(T) = C_v(T) = C(T)$
- Change of internal energy U (or enthalpy):
  - $\Delta U = Q = m \int_{T_1}^{T_2} c(T)\, dT$
- Cooling (or heating) power:
  - $P(T) = m\, c(T) \frac{dT}{dt}$
- Specific heats/unit vol. sometimes preferred
- Below 10 K enthalpy of helium overtakes all solids




(from J. Ekin, Experimental Techniques for Low-Temperature Measurements)

# Design stresses for some materials

- Design stresses for plates less than 12 mm thick applicable to membrane stress (safety factor 1.5 included) according to EN 13445-3
- For stainless steels:

$$f = \frac{R_{p1.0}}{1.5} \qquad f_{test} = \frac{R_{p1.0}}{1.05}$$

| Material | $R_{p1.0}$ (MPa) | f (MPa) | $f_{test}$ (MPa) |
|---|---|---|---|
| 1.4306 (304L) | 240 | 160 | 228 |
| 1.4435/1.4404 (316L) | 260 | 173 | 247 |
| 1.4406/1.4429 (316LN) | 320 | 213 | 304 |
| AW 5083-O/H111 | | 83 | |

- For aluminium-magnesium alloys:

$$f = \min\left(\frac{R_{p0.2}}{1.5}, \frac{R_m}{2.4}\right) \qquad f_{test} = \frac{R_{p0.2}}{1.05}$$

| Material | $R_{p1.0}$ /$R_m$ (MPa) | f (MPa) | $f_{test}$ (MPa) |
|---|---|---|---|
| AW 5083-O/H111 | 125/270 | 83 | 119 |

# Best practices

- Using a coherent set of standards throughout the lifecycle of the cryostat is the simplest and safest approach. As an example when using only EN harmonised standards:
  - Error margins of pressure relief devices are taken into account in the design rules
  - The design rules are only applicable if the material has enough ductility
  - Materials certified for pressure vessels have measured minimum fracture toughness
  - Safety factors included in buckling formulae take into account shape imperfections up to the allowable tolerances layed out in the  manufacturing section of the standards
  - The extent of welding inspection must be compatible with the joint coefficient used in thickness calculations
  - Coherence of test pressure and testing procedure with the design rules

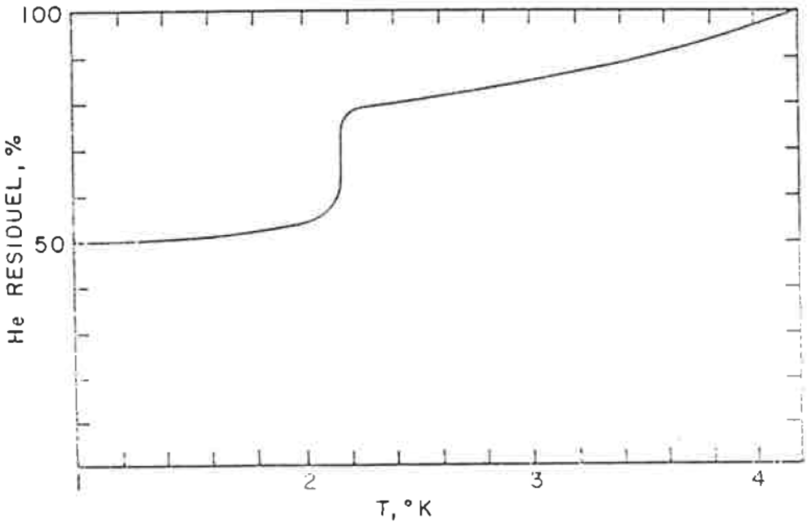
# Liquid helium pumping

- Pressure reduction by pumping above helium liquid at 4.2 K, with latent heat L(T) and specific heat c(T):

$$L(T)\,dm = m\,c(T)\,dT$$

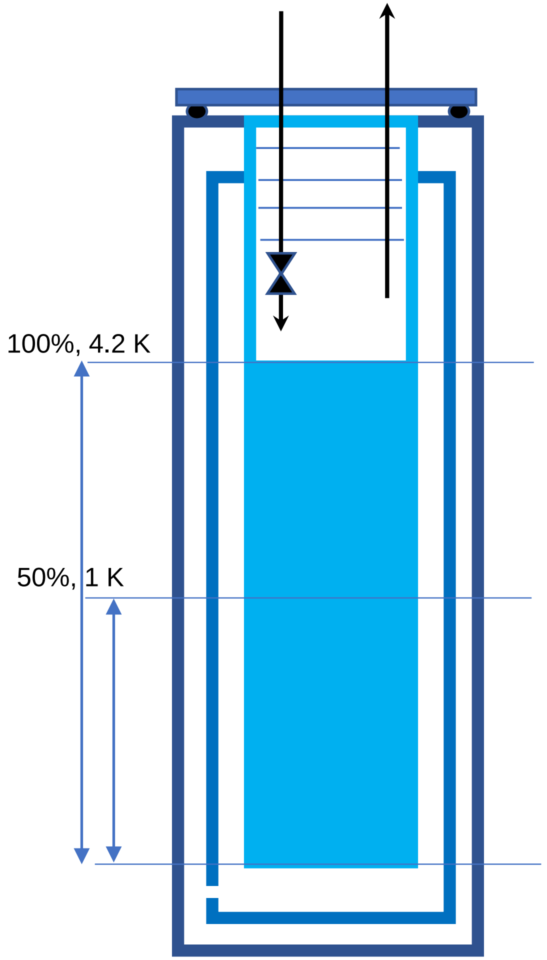
- Neglecting external heat loads and vessel heat capacity
- Integrating over T and m, with $m_0$ initial helium mass:

$$log\,\frac{m}{m_0} = \int_{4.2\ K}^{T} \frac{c(T)}{L(T)}\,dT$$




IG. 6-1. — Quantité d'hélium restant après refroidissement de 4,2 °K à la température T (6).

(ref. R.R.Conte, Elements de Crogenie)



# LHC dipole cryostat assembly

Assembly bench

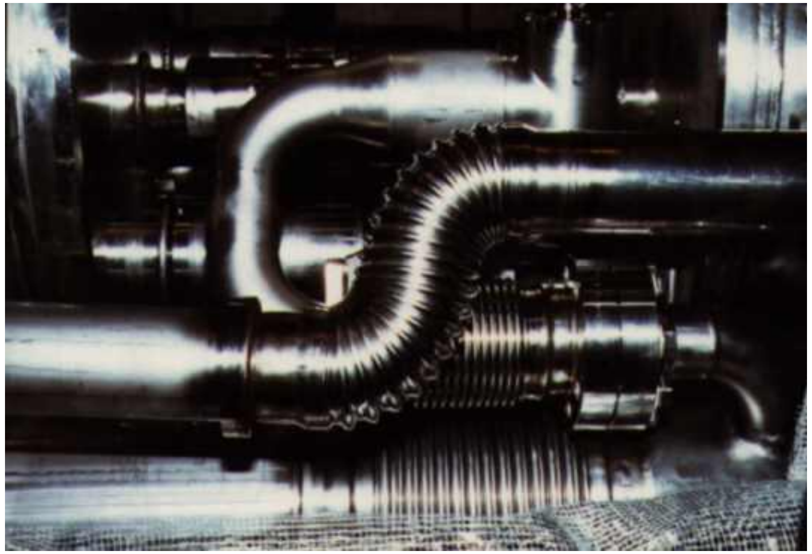
Towing through, sliding on vacuum vessel

# Expansion joints (bellows) for cryogenic lines

- Compensation of longitudinal thermal contractions
- Compensation of transversal and angular offsets (not twist!)

  →Extensive use in cryo-magnet interconnections
- Beware of bellows stability issues in pressurised lines:
  - Stiff guiding
  - Limit transversal and angular off-sets

*RHIC, BNL*



*LHC String 1, CERN*