Cryostat Design

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Content

1st hour

- Introduction to cryostats
- Cryostat requirements
- Heat transfer for cryostats:
  - Solid conduction
  - Residual gas conduction
  - Radiation, MLI protection, thermal shielding
- Cryogenics
- Heat intercepts

2nd hour

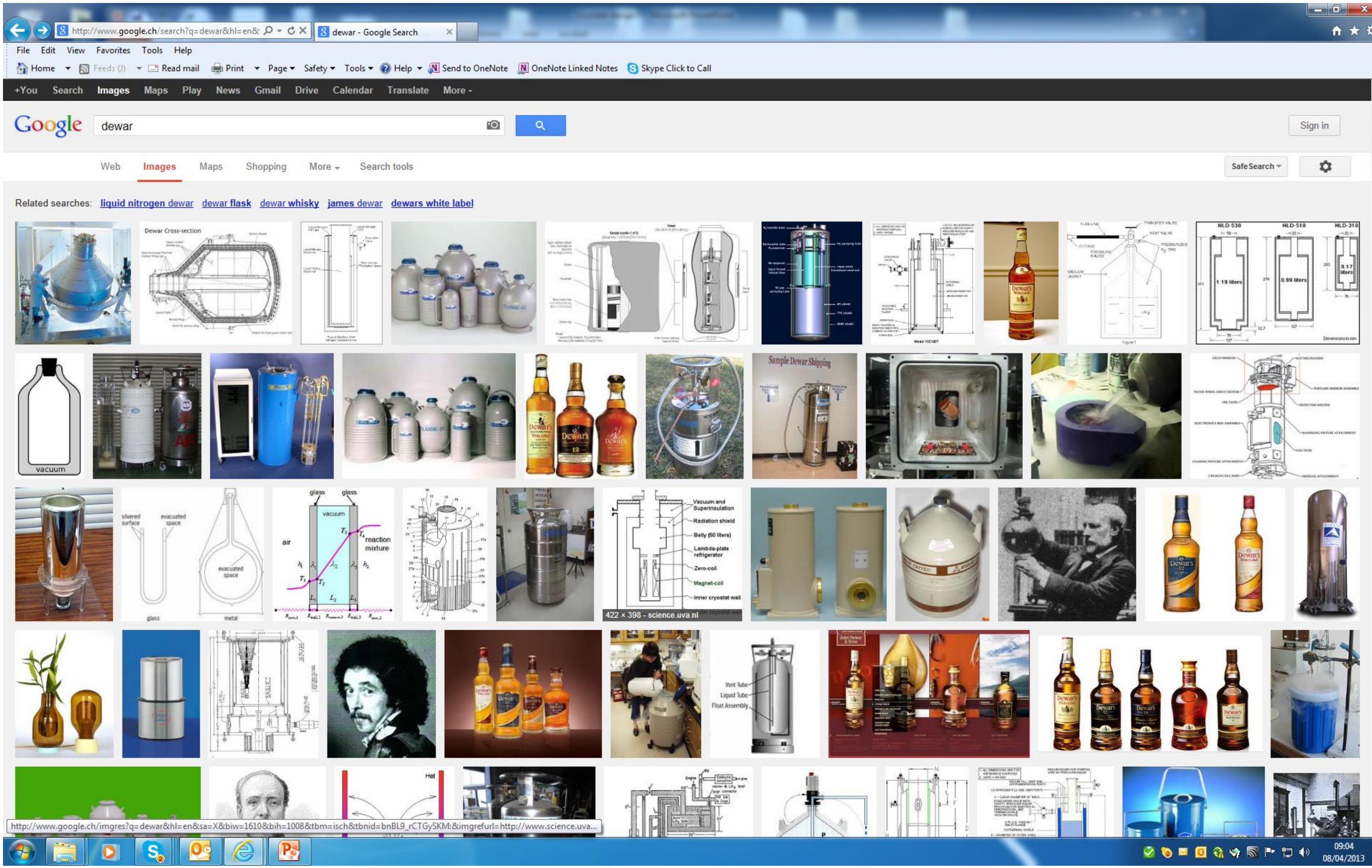
- Insulation vacuum and construction issues
- Mechanical considerations and construction codes
- Supporting systems
- Over-pressure safety issues

A bit of History

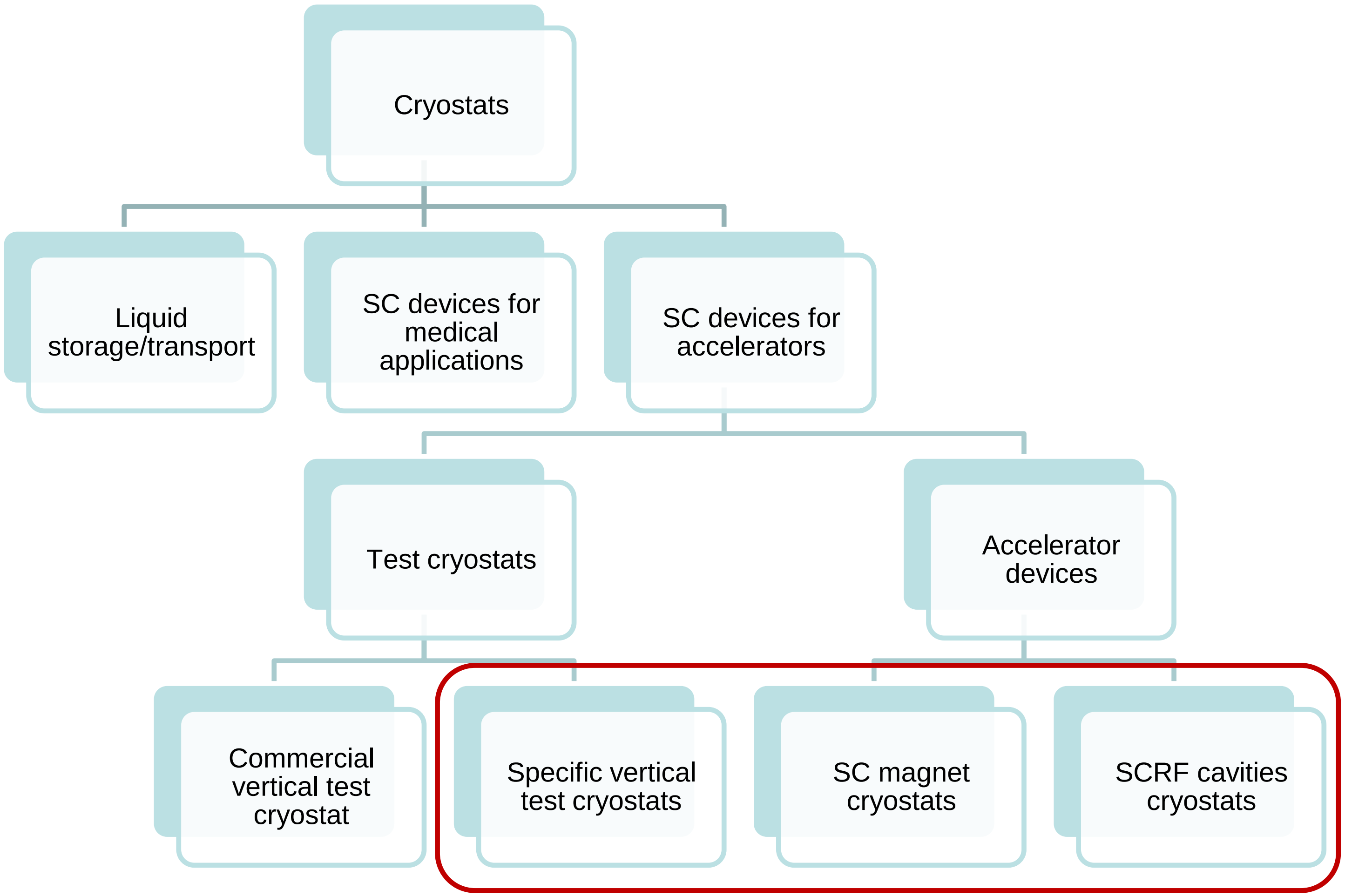
- **Cryostat** (from *cryo* meaning cold and *stat* meaning stable)**:** ***"****a device used to maintain at cryogenic temperatures samples or devices mounted within the cryostat"*
- Dewar invents the "dewar", 1892, London
- A dewar: the first performing cryostat
  - silvered, double-walled, glass vacuum vessel to contain cryogenic liquids
  - J.Dewar: 1st liquefaction of H_2 in 1897
  - …but did not manage liquefaction of He, achieved by H.Kamerlingh Onnes in 1908
- Glassblowers: the *"enabling technology"* of the epoque:
  - J.Dewar did not patent his invention…
  - H.K.Onnes created the "Leidse Instrumentmakersschool" (still existing!), and *industrialized* cryostats

Sir James Dewar (1842-1923)

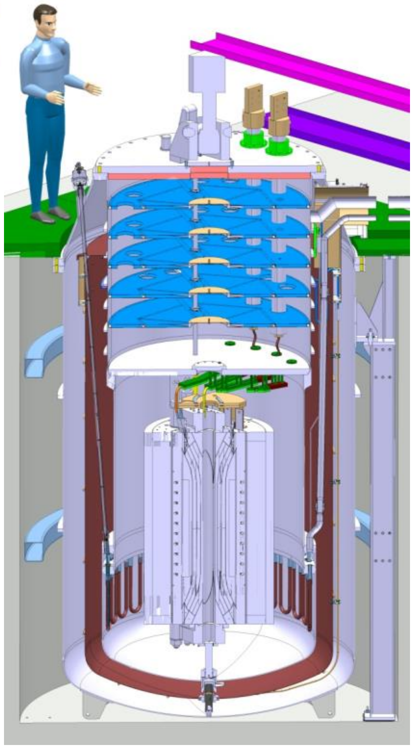
Dewars on “Google images”



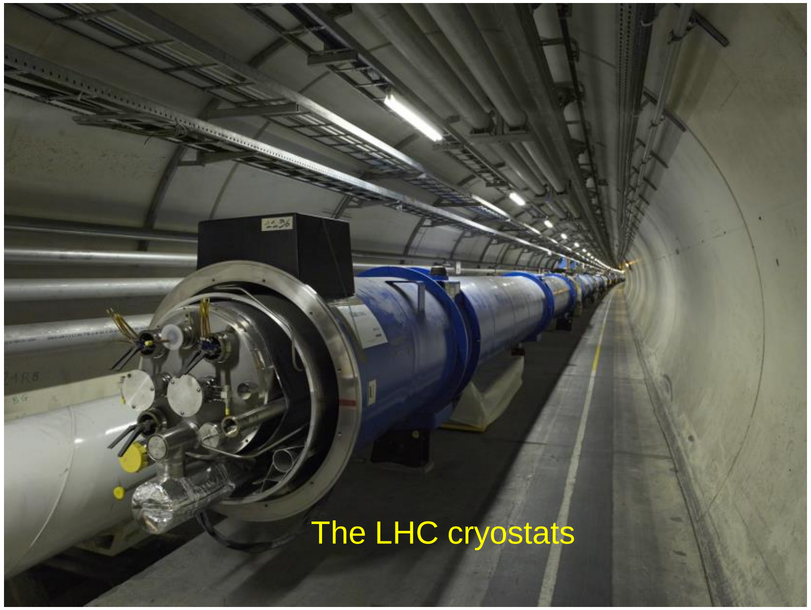
Applications

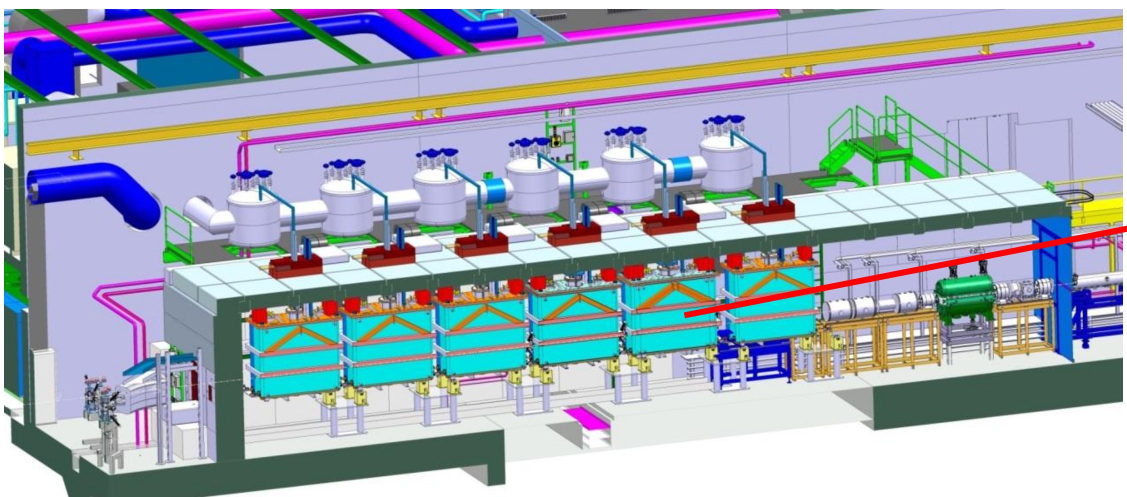


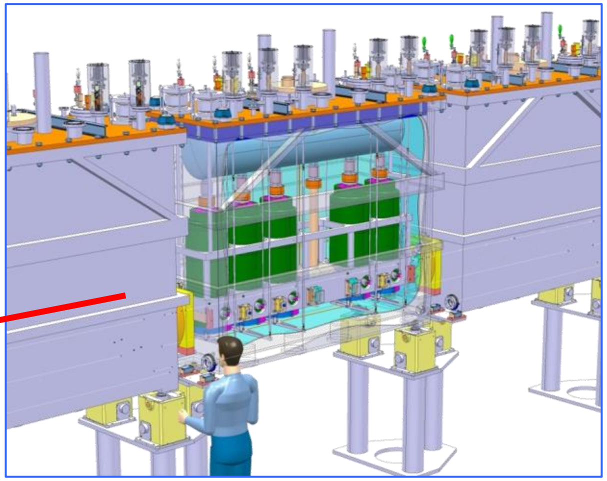
A few examples at CERN



The High Field Magnet test cryostat

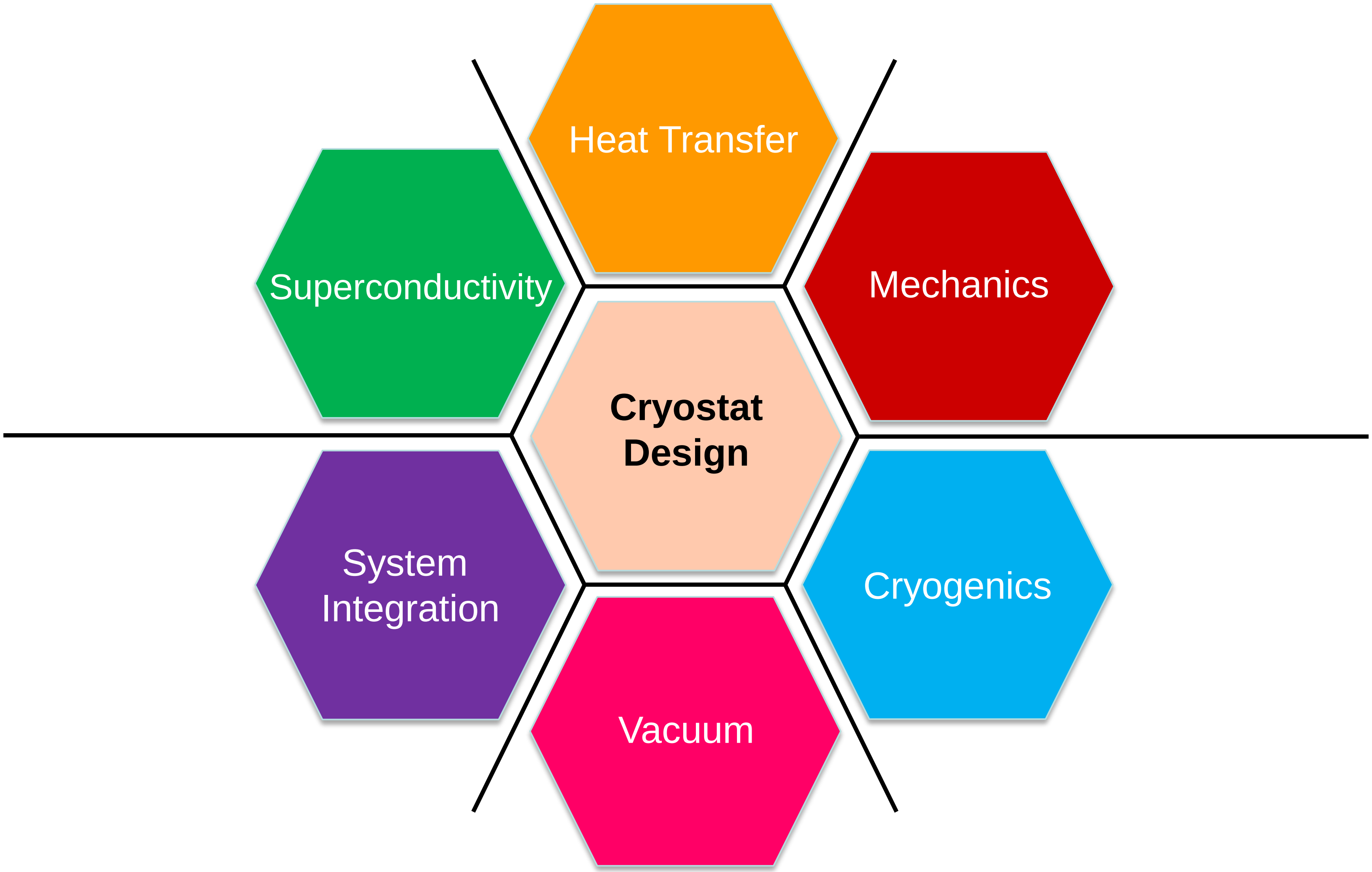






The HIE Isolde cryo-modules

Cryostats for SC devices for accelerators:
A multidisciplinary activity



Cryostat requirements

Functions

Two main functions:

- Mechanical housing of cryogenic devices (supporting systems):
  - Supporting of (sometimes heavy) SC devices
  - Accurate & reproducible positioning (almost always)
  - Precise alignment capabilities (SC devices in accelerators)
- Thermal efficiency of the cryostat (heat loads *as low as possible*):
  - Cooling capability (SC device, thermal shields and heat intercepts)
  - Insulation vacuum (SC devices “hidden” in vessels)
  - Thermal radiation shielding (screens, MLI)
  - Low heat conduction (low thermal conductivity materials)

Often conflicting, → calls for trade off design solutions

Many other complementary functions…:

- Integration of cryogenic equipment (ph.separators, valves, etc.)
- Cryogenic cooling piping and interfaces to cryoplant
- Integration of Beam instrumentation (e.g.BPMs, BLMs,etc.)
- Instrumentation wires feed-throughs (control/diagnostics)
- magnetic shielding from/to environment (e.g. SCRF cavites, magnets)
- Maintainability (access ports)
- Handling and transport features
- …

Mechanical Housing
example of LHC

LHC Main Cryostat

(Cross-Section)

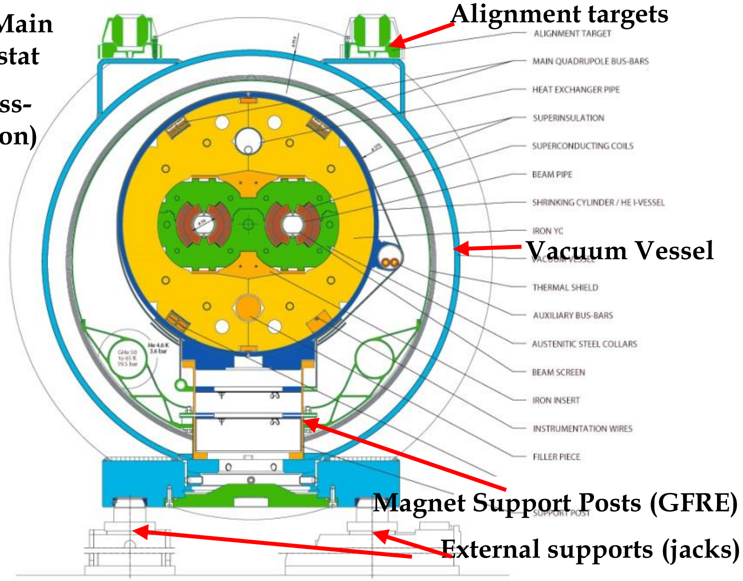
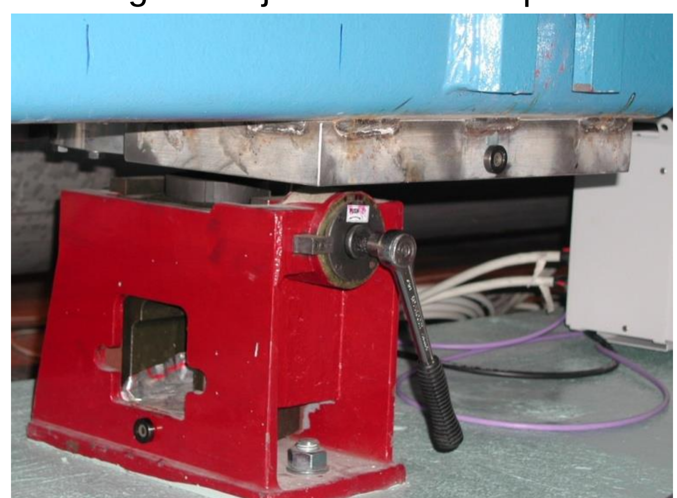


Table of main requirements for the support systems for dipole and quadrupoles

Requirement	Dipole	Quadrupole
Weight	300 kN	65 kN
Magnet positioning accuracy: *(after assembly)*		
x (radial)	± 1 mm	± 0.5 mm
y (longitudinal)	± 2 mm	± 1 mm
z (vertical)	± 1 mm	± 0.5 mm
Positioning reproducibility-stability: *(in operation, during lifetime)*		
x (radial)	< ± 0.3 mm (3σ)	< ± 0.3 mm (3σ)
y (longitudinal)	< ± 1 mm (3σ)	< ± 1 mm (3σ)
z (vertical)	< ± 0.3 mm (3σ)	< ± 0.3 mm (3σ)
θ y (radial tilt)	< ± 0.3 mrad (3σ)	< ± 0.3 mrad (3σ)
External supporting system		
Adjustable range required in X-Y directions		±10 mm
Adjustable range required in Z direction		±20 mm
Setting resolution :		
x (radial)		0.05 mm
y (longitudinal)		0.05 mm
z (vertical)		0.15 mm

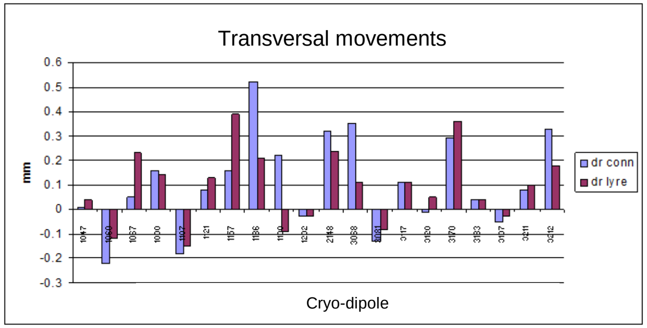
Low heat in-leaks support posts

Alignment jacks under a dipole

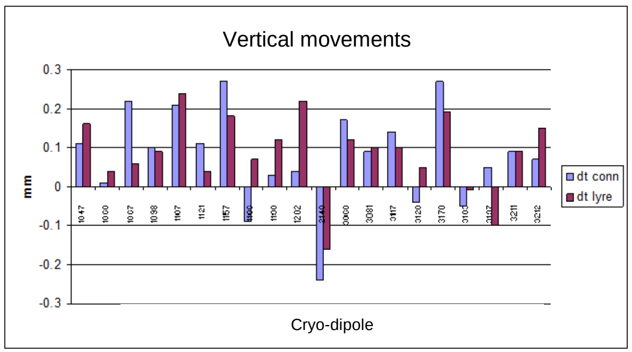


Geometrical Stability: survey measurements

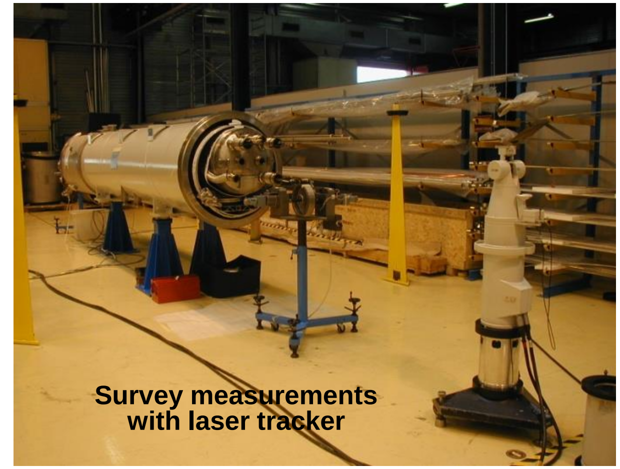
Cold mass stability w.r.t. fiducials measurements on 20 cryo-dipoles
After transport to the tunnel



Mean: +0.1mm; St.dev.: 0.17mm



Mean: +0.08mm; St.dev.: 0.11mm



- Quad CM positional stability and reproducibility at cold

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

Thermal efficiency

Cooling of SC device:

- Ensure operating T: cryo scheme, fluid distribution and heat transfer. Strongly coupled to cryoplant and cryo distribution system

Heat loads management:

- External heat in-leaks
  - Radiation
  - Residual gas conduction
  - Solid conduction
- Internal heat sources:
  - Joule heating (SC magnet splices)
  - BCS residual resistance (RF cavities)
- Beam-induced heat:
  - Synchrotron radiation
  - Beam image currents
  - Photoelectrons (e-cloud)

static

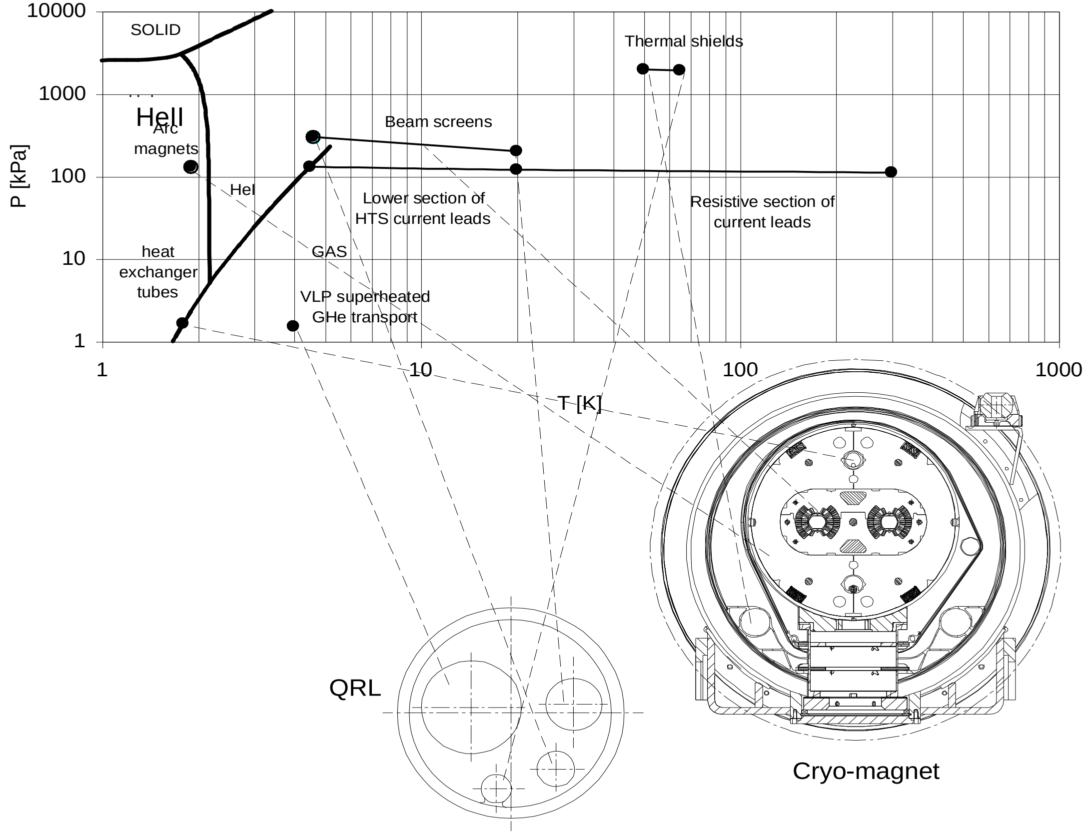
dynamic

Mitigation measures:

- 70 K shielding, MLI
- Vacuum < 10^{-4} Pa
- Low conductivity materials (non metallic), heat intercepts
- Special brazing (resistance < a few nΩ)
- Q enhancement, pulsed operation
- 5-20 K beam screens
- Cu plated beam screens
- 5-20 beam screens

Thermal efficiency

example of LHC



LHC budgeted distributed steady-state heat loads [W/m]

Temperature	50-75 K	4.6-20 K	1.9 K LHe	4 K VLP
Static heat inleaks*	7.7	0.23	0.21	0.11
Resistive heating	0.02	0.005	0.10	0
Beam-induced nominal**	0	1.58	0.09	0
Total nominal	7.7	1.82	0.40	0.11

* no contingency

** Breakdown	nominal
Synchrotron radiation	0.33
Image current	0.36
Beam-gas Scattering	0.05
Photoelectron	0.89

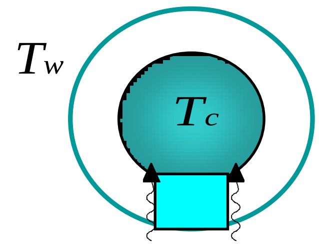
Heat Transfer for cryostats

Heat transfer: General

$T_w > T_c$

- Solid conduction:

$$Q_c = \frac{S}{L} \cdot \int_{Tc}^{Tw} \lambda(T)\,dT$$

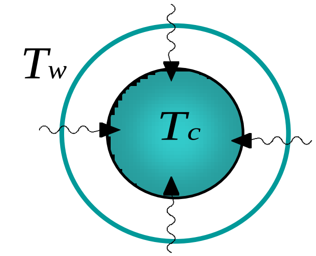


- Thermal radiation:

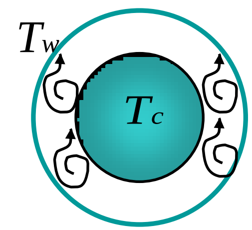
(with and without MLI)

$$Q_r = \sigma \cdot E \cdot S_i \cdot \left(T_w^4 - T_c^4\right)$$

Between cylinders: $E = \dfrac{\varepsilon_i \cdot \varepsilon_e}{\varepsilon_e + (1-\varepsilon_e) \cdot \dfrac{S_i}{S_e}}$

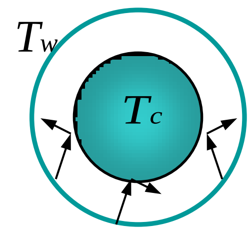


- *Viscous gas conduction* and *natural convection*: *(Negligible with good insulation vacuum, < 10^{-4} Pa)*



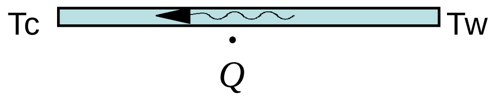
- Gas conduction: *molecular regime*

$$Q_{res} = A_1 \cdot \alpha(T) \cdot \Omega \cdot P \cdot (T_2 - T_1)$$



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):

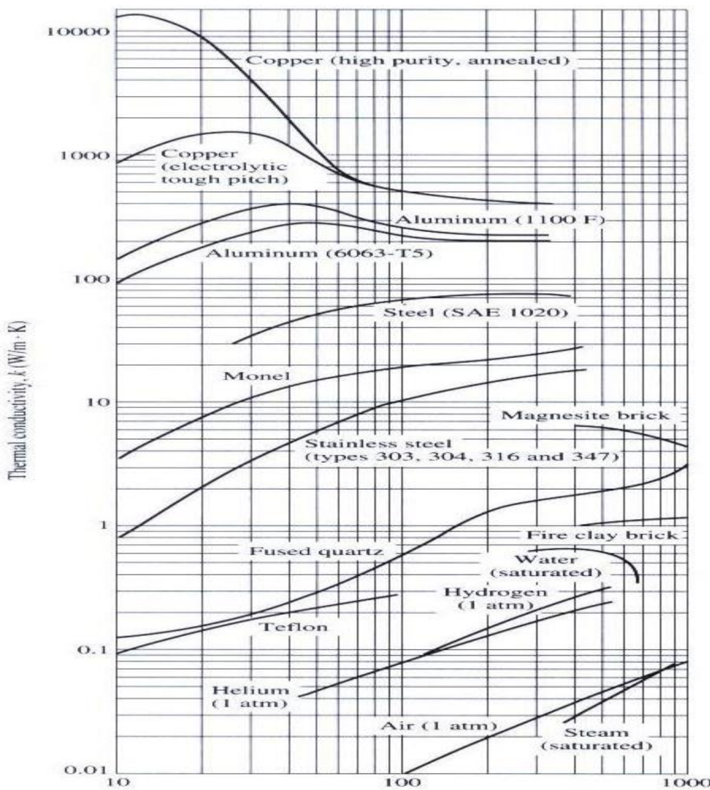
$$\dot{Q} = -kA\frac{dT}{dx}$$

- k is the thermal conductivity (W/mK^{-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 orders of magnitude

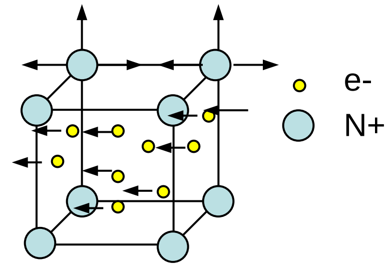


Note: sometimes conductivity denoted by λ.

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:***

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

and a_p, a_i constants

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

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

- And has a **maximum** conductivity:

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

Therefore, for **metals**:

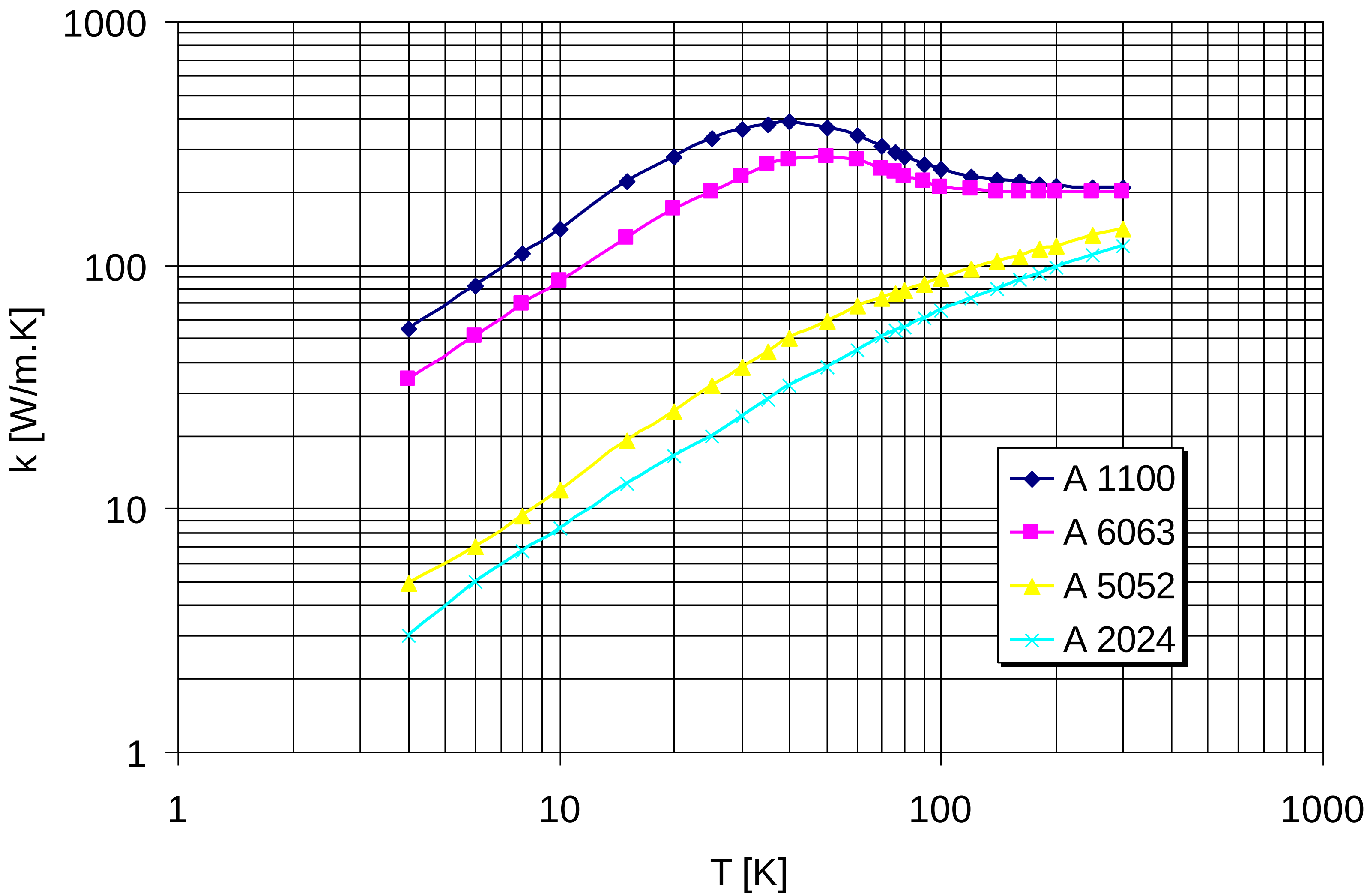
- *Kmax* shifts at higher T with increasing impurity (see coppers and aluminiums)
- The maximum vanishes for highly impure alloys (see steels) and in these cases impurity scattering dominates phonon scattering, thus at T < RT:

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

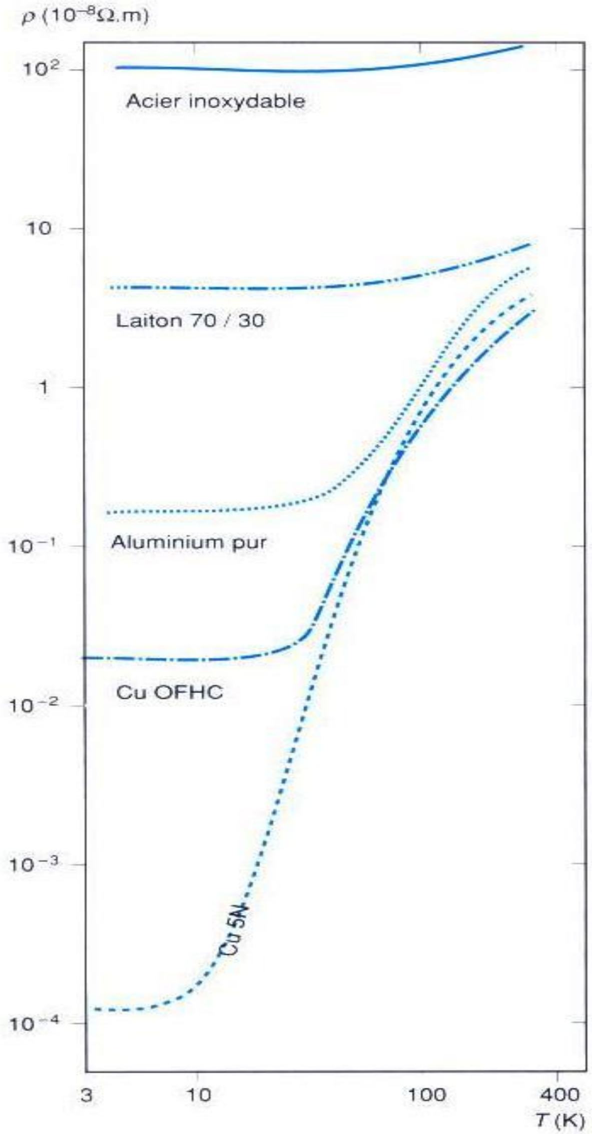
- For **metals**, from electron conduction theory and analogy with electrical diffusion → ***Wiedemann-Franz law*** :
  - Good agreement at T<< and T>> RT
  - Better agreement from T<< to T>> with increasing impurities
  - Electrical resistivity (ρ_e) easier to measure than thermal conductivity

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

Thermal conductivity for Aluminium alloys



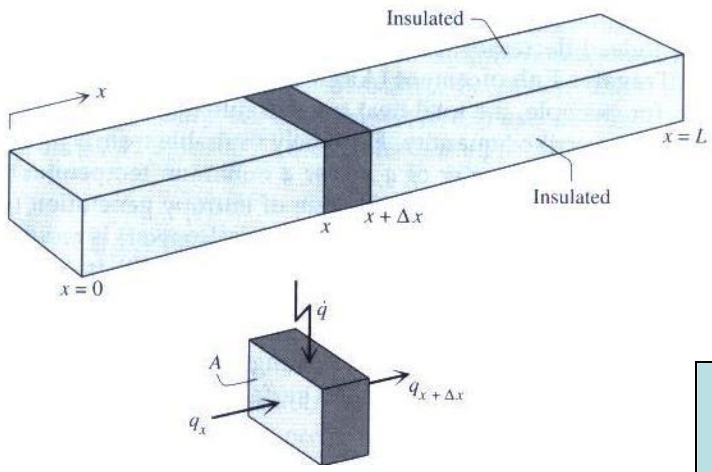
Electrical resistivity for some metals



OFHC Oxygen Free High Conductivity

Fig. 8. – Résistivité électrique des métaux.

The conduction equation (unidirectional case)



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

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

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

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

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

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

Or, if k ~ const.with T and introducing *α* thermal diffusivity:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\dot{q}}{k} = \frac{1}{\alpha}\cdot\frac{\partial T}{\partial t} \quad \text{with}\ \alpha = \frac{k}{\rho c}$$

α allows evaluating the characteristic propagation time τ of a thermal

No local heat deposition and steady-state

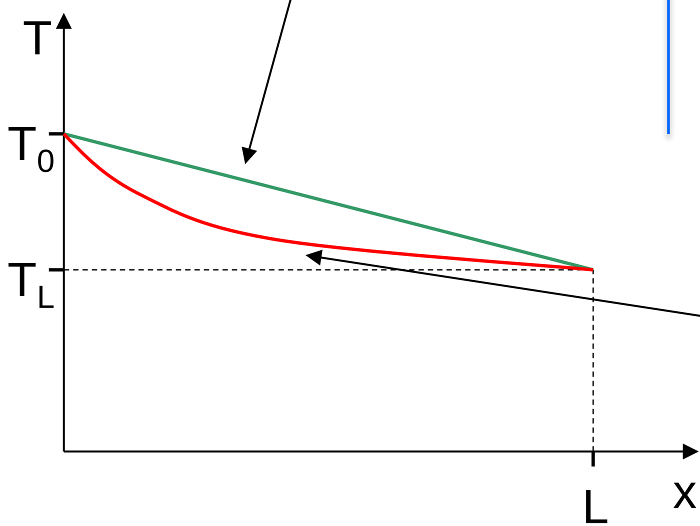
$$\frac{\partial}{\partial x}\left(k \cdot \frac{\partial T}{\partial x}\right) = 0$$

- **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)*:**

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

$$\dot{q}\int_o^L dx = -A\int_{T_0}^{T_L} k(T)dT$$

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

Thermal conductivity Integral (**conductance**)

- For impure metals (ex.steels) at low T:

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

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

(quadratic solution)

Electrical network analogy

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

a) For constant k:

$$R = \frac{L}{kA} \qquad \dot{q} = -\frac{kA}{L}(T_L - T_o) = \frac{T_0 - T_L}{R}$$

b) For variable k, define an average value k_{AV}:

$$k_{AV} = \frac{\int_{To}^{TL} k(T)dT}{(T_L - T_0)} \quad \Rightarrow \quad R_t = \frac{L}{k_{AV}A} \qquad \dot{q} = -\frac{A}{L}\int_{To}^{TL} k(T)dT = \frac{T_0 - T_L}{R_t}$$

- In both cases we can recognize an 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*.

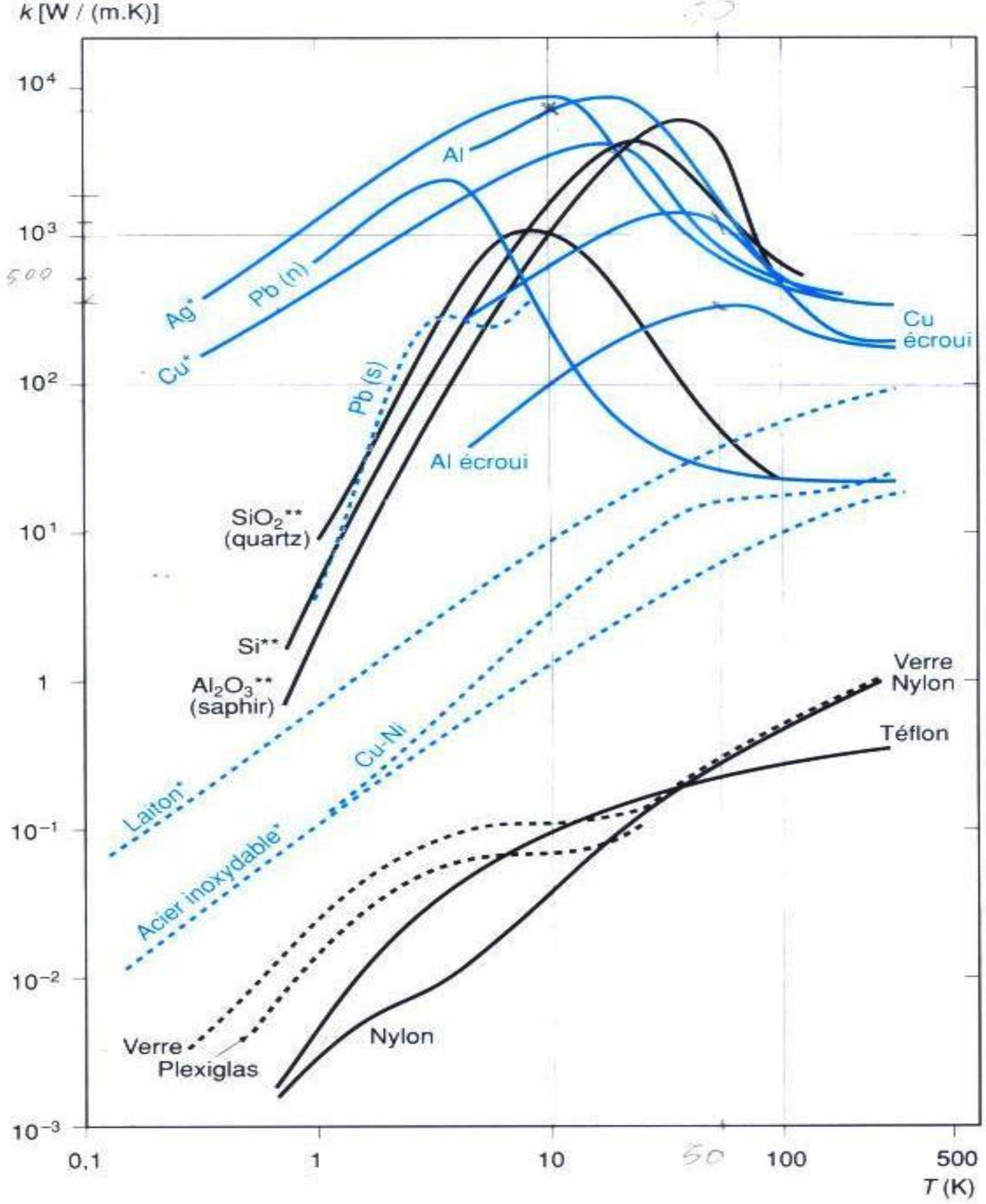
$$\sum_{i=1}^{n} \dot{q}_i = 0 \quad (at\, knots)$$

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

Thermal conductivity data for selected materials

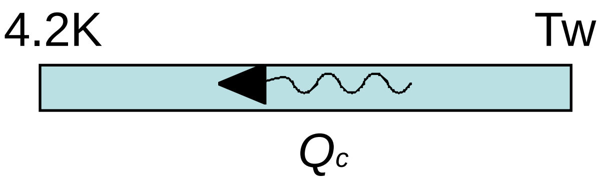
Thermal conductivity of various materials

Spans over about 5 orders of magnitude



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

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



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

…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

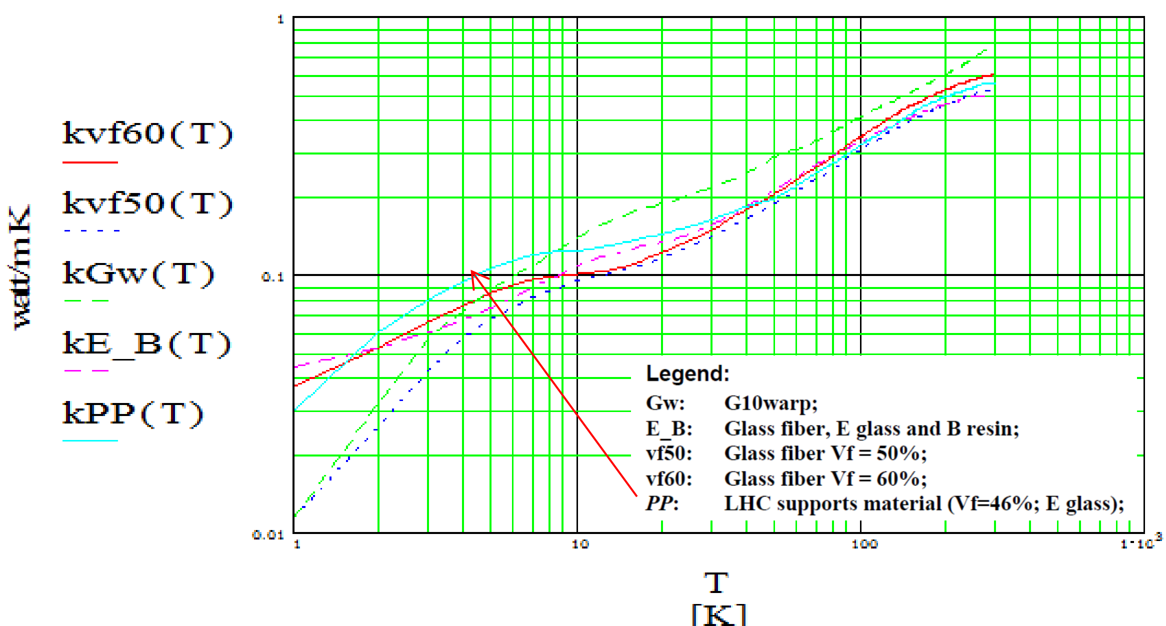
Thermal conductivity in composite materials

- Generally non-conductors (little electron conduction), essentially phonon driven
- Anisotropic structure, (fibers/matrix) with constituents-specific thermal conductivity properties
- Generally homogeneous at macroscopic scale, but non-homogeneous at microscopic level (interface effects)
- Conductivity highly depends on:
  - Material (fiber) orientation
  - Ratio between fibre and matrix (Vf)

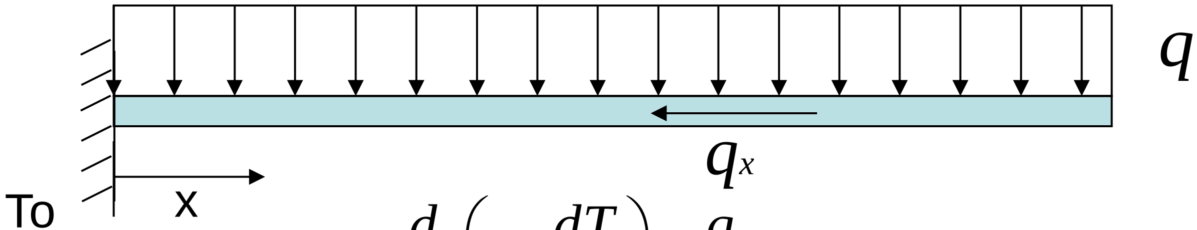
For Glass-fiber/epoxy matrix composites (of wide interest in cryostat applications):
- Glass is the "conductive" material and also the "structural" constituent
- Epoxy is the "isolating" material and also the "less structural" constituent

→ Vf typically around 40-60%
→ Conductivity calculation difficult, opt for experimental measurements

Conductivity measurement of candidate GFRE materials for LHC supports



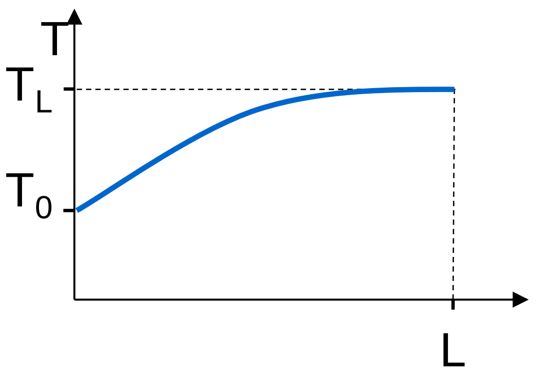
Thermal conduction with uniform heat deposition



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

- Beam of length L, thickness t, width w;
- beam *thermalized* on one side at To
- uniform heat deposition from one side, q (W/m2)
- 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:

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



$$DT_{max} = T_L - To = \frac{q \cdot L^2}{2 \cdot k \cdot t}$$

practical interest:
calculate thickness of a thermal shield

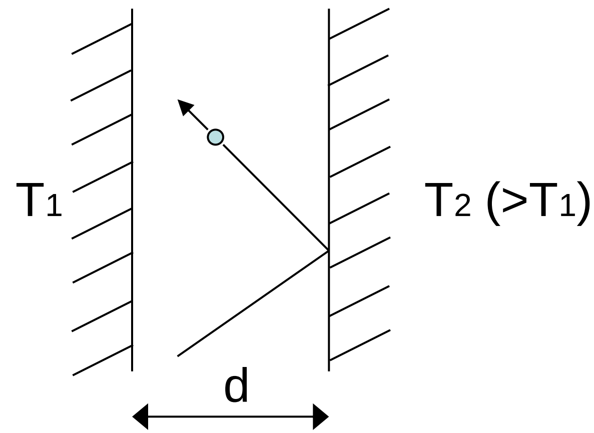
$$t = \frac{q \cdot L^2}{2 \cdot k \cdot \Delta T_{max}}$$

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

Residual Gas Conduction

λmolecule << d → Viscous regime

λmolecule >> d → Molecular regime



λmolecule = mean free path

- **Viscous regime:**
  - At High gas pressure
  - *Classical conduction* (q = - A k(T) dT/dx) with k independent of pressure
  - but *natural convection* must be included

- **Molecular regime:**
  - At low gas pressure
  - Kennard's law
  - Conduction is proportional to P
  - Ω depends on gas species (*for helium Ω = 2.13 W/m2.Pa.K*)
  - α(T) → *accommodation coefficient* depending on gas species, T1, T2 and surface geometry *(applicable for flat parallel surfaces, coaxial cylinders and spheres)*

$$\lambda_{molecule} = 8.6 \cdot 10^3 \frac{\eta}{P}\sqrt{\frac{T}{M}}$$

η = gas viscosity in poises

P = pressure in micometers of mercury, μHg

T = temperature, K

M = molecular weight, g/mole

$$Q_{res} = A_1 \cdot \alpha(T) \cdot \Omega \cdot P \cdot (T_2 - T_1)$$

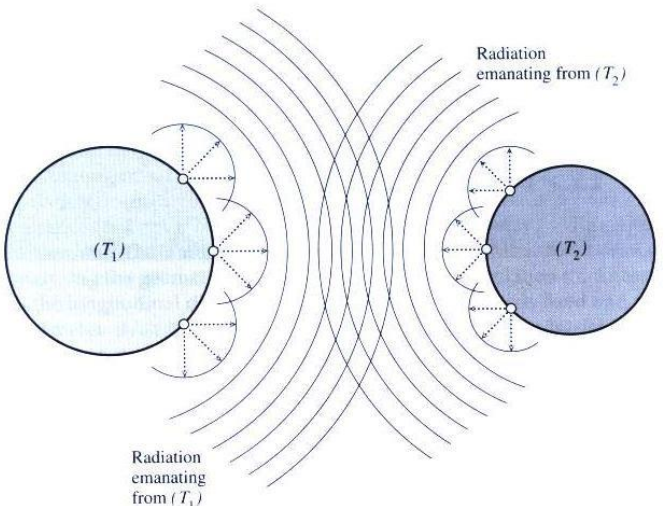
$$\alpha = \frac{\alpha_1 \alpha_2}{\alpha_2 + \alpha_1(1-\alpha_2)\frac{A_1}{A_2}}$$

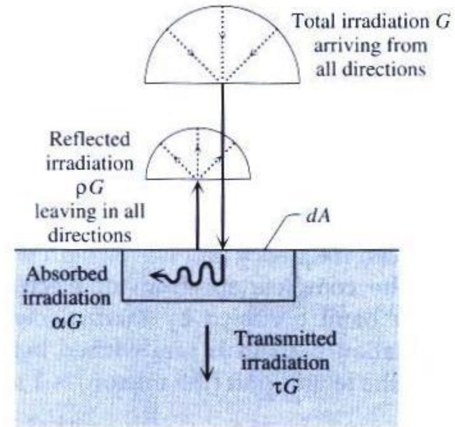
Accommodation coefficient α_i

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

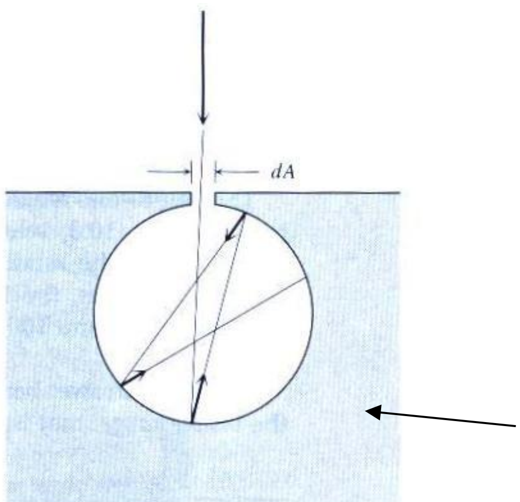
Thermal Radiation

Thermal Radiation





$$\alpha = absorptivity$$
$$\rho = reflectivity$$
$$\tau = transmissivity$$
$$\alpha + \rho + \tau = 1$$



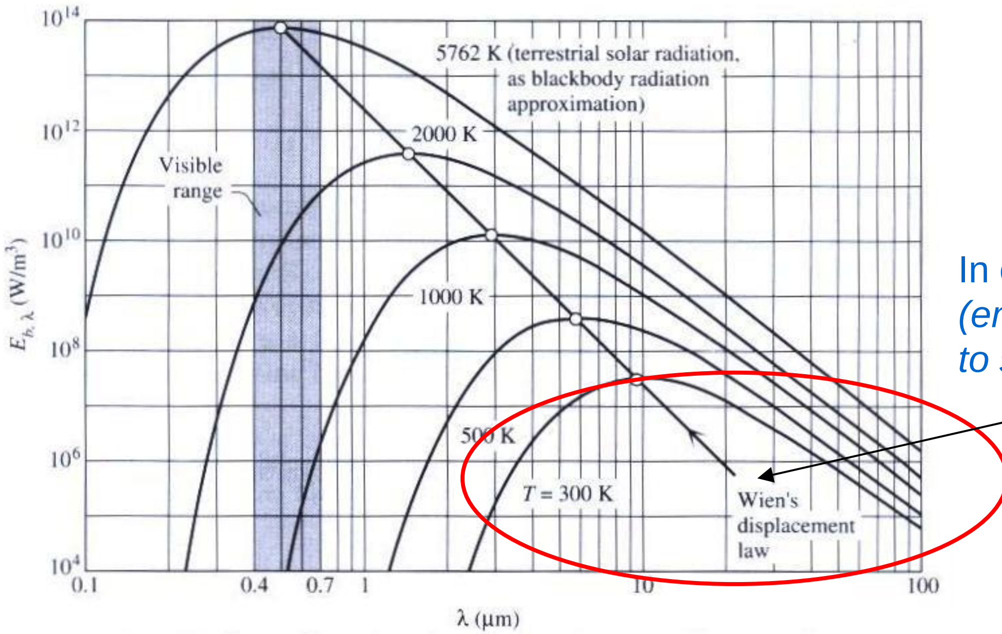
Black surface: $\alpha = 1$

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

***Practical interest** for cryostats shielding:*
every gap acts as a black surface (example: 1 cm² gap exposed to a 293 K surface (e.g. vac.vessel with ε = 0.2) receives ~10 mW

Black body radiation

- Emissive power (monochromatic)



In cryogenics: far infrared region:
(emissivity not necessarily related to surface appearance)

$$\lambda T = 2.898 \cdot 10-3\,(m \cdot K)$$

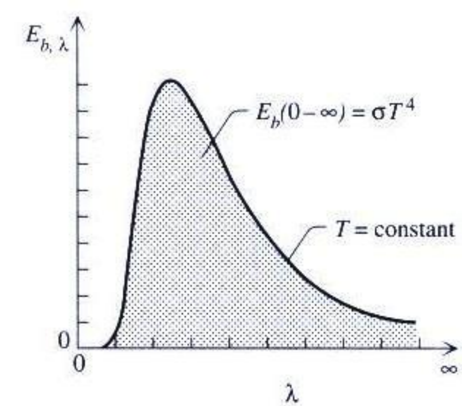
$$E_{b,\lambda,\max} = (12.87 \cdot 10-6\ \mathrm{W/m^3 \cdot K^5}) \cdot T^5$$

- Total emissive power (integrating over λ):

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

with:

$$\sigma = \frac{2\pi hc^2}{\left(\frac{hc}{k}\right)^4} \cdot \frac{\pi^4}{15} = 5.6710\text{-}8\left(\mathrm{W/m^2} \cdot K^4\right) \text{Stefan-Boltzmann's constant}$$



***In practice**: a blackbody at 293 K emits ~ 420 W/m²:*

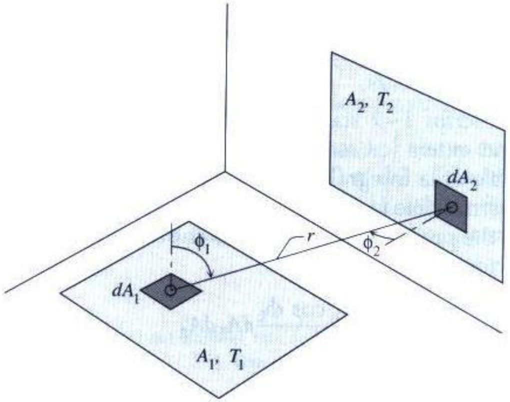
Radiation heat exchange between black bodies

- Radiation from A1 to A2:

$$q_{1\to 2} = \sigma T_1^4 A_1 F_{12}$$

with:

$$F_{12} = \frac{\text{radiation leaving } A_1 \text{ and intercepted by } A_2}{\text{Total radiation leaving } A_1} \quad \text{(Geometric view factor)}$$



- Radiation from A2 to A1:

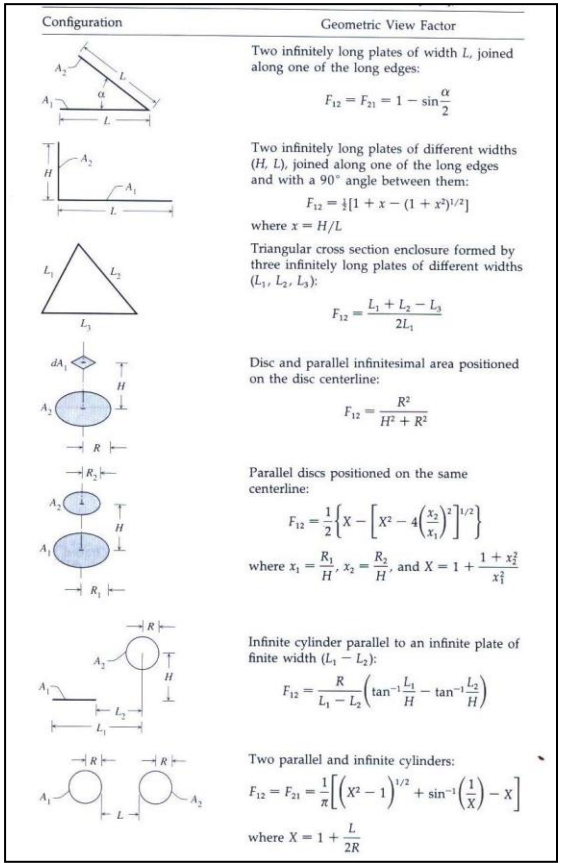
$$q_{2\to 1} = \sigma T_2^4 A_2 F_{21}$$

- Radiation balance between A1 and A2:

$$\boxed{q_{1-2} = \sigma (T_1^4 - T_2^4) A_1 F_{12}}$$

Note:

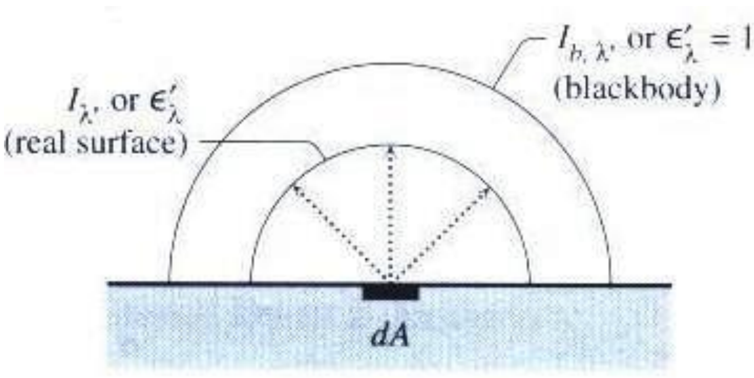
$$A_1 F_{12} = A_2 F_{21}$$



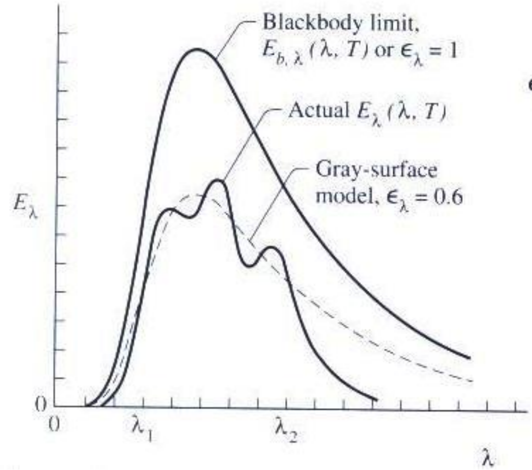
Configuration	Geometric View Factor
	Two infinitely long plates of width L, joined along one of the long edges: $F_{12} = F_{21} = 1 - \sin\frac{\alpha}{2}$
	Two infinitely long plates of different widths (H, L), joined along one of the long edges and with a 90° angle between them: $F_{12} = \frac{1}{2}[1 + x - (1 + x^2)^{1/2}]$ where $x = H/L$
	Triangular cross section enclosure formed by three infinitely long plates of different widths (L_1, L_2, L_3): $F_{12} = \frac{L_1 + L_2 - L_3}{2L_1}$
	Disc and parallel infinitesimal area positioned on the disc centerline: $F_{12} = \frac{R^2}{H^2 + R^2}$
	Parallel discs positioned on the same centerline: $F_{12} = \frac{1}{2}\left\{X - \left[X^2 - 4\left(\frac{x_2}{x_1}\right)^2\right]^{1/2}\right\}$ where $x_1 = \frac{R_1}{H}$, $x_2 = \frac{R_2}{H}$, and $X = 1 + \frac{1 + x_2^2}{x_1^2}$
	Infinite cylinder parallel to an infinite plate of finite width ($L_1 - L_2$): $F_{12} = \frac{R}{L_1 - L_2}\left(\tan^{-1}\frac{L_1}{H} - \tan^{-1}\frac{L_2}{H}\right)$
	Two parallel and infinite cylinders: $F_{12} = F_{21} = \frac{1}{\pi}\left[\left(X^2 - 1\right)^{1/2} + \sin^{-1}\left(\frac{1}{X}\right) - X\right]$ where $X = 1 + \frac{L}{2R}$

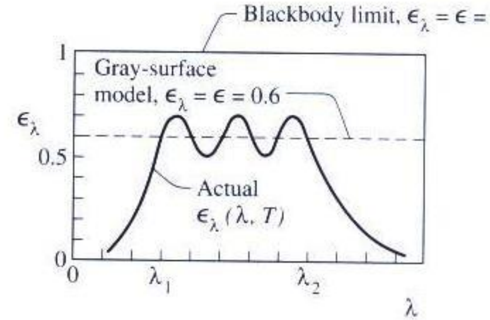
Non-black surfaces: the diffuse-gray model (real surfaces)

- Diffuse-gray emitter (good approximation for real surfaces)



Diffuse emitter





- Total hemispheric *emissivity*:

$$\varepsilon(T) = \frac{E(T)}{E_b(T)} \leq 1$$

(**Note**: @ cryo temp. ε is strongly T dependent)

- Similar considerations can be made for *adsorptivity* and *reflectivity*

- The ***Diffuse-gray*** *model*:
  - Gray
  - A diffuse emitter, absorber and reflector
  - Opaque (no transmittivity)

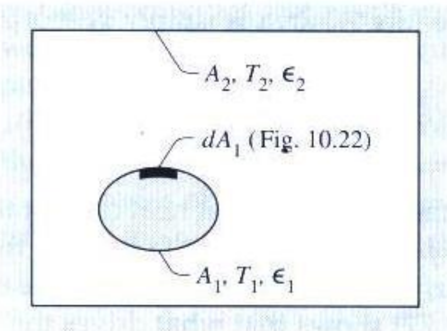
Emissivity of various materials as a function of T

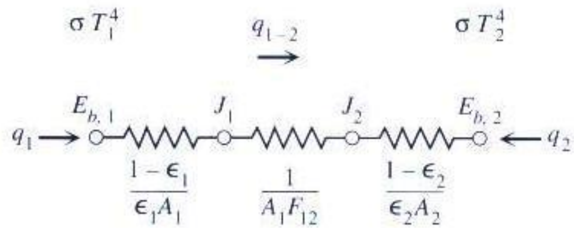
Temperature [K]	4	20	80	300
Copper mechanically polished	0.02		0.06	0.1
Copper black oxidized				0.8
Gold			0.01	0.02
Silver	0.005		0.01	0.02
Aluminium electropolished	0.04		0.08	0.15
Aluminium mechanically polished	0.06		0.1	0.2
Aluminium with 7μm oxide				0.75
Magnesium				0.07
Chromium			0.08	0.08
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	0.1		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	

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

- Strong T dependence (quasi proportional to T)
- Emissivity reduces with T
- At cryogenic temperatures low emissivity in the far infrared is not necessarily related to surface brilliance

Radiation between 2 diffuse-gray enclosures



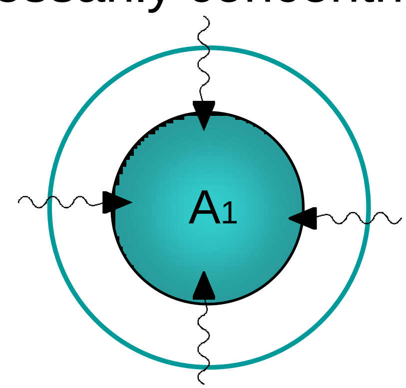


- Radiation balance between A1 and A2:

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

- For **2 enclosed cylinders** or **spheres** (not necessarily concentric!):

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

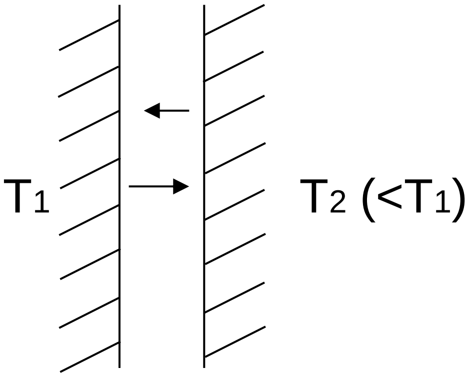


Hints to reduce heat load in a cryostat:

- Reduce A_2 (vac.vessel as small as possible)
- Small emissivities: ε_1 reduced by low T; ε_2 at RT & moderated by A_1/A_2

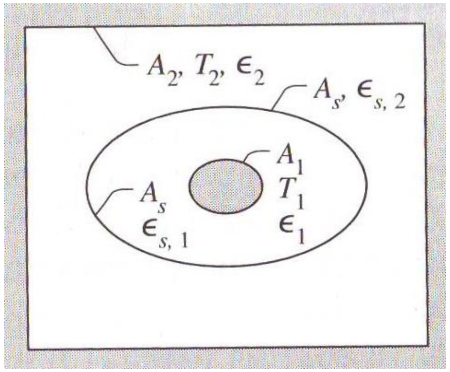
Radiation between 2 diffuse-gray flat plates

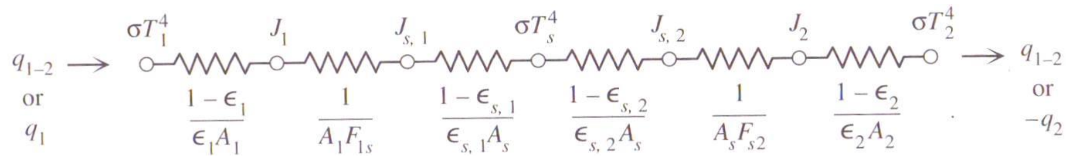
- Radiation balance between A1 and A2 (A1=A2=A):



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

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, it becomes :

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

→ ½ of the rate without shield (see previous slide)

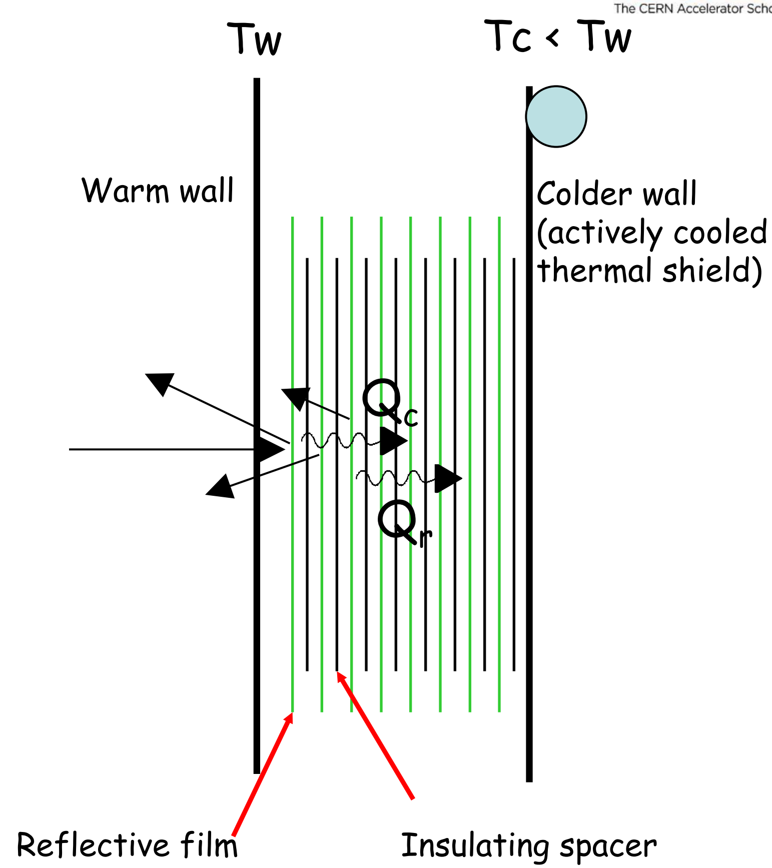
Hint: to reduce heat loads in a cryostat:

- Add one (or more) intermediate shields

Multi Layer Insulation (MLI)

MLI principle

- Low emissivity of aluminium layer
- Multi-layer to enhance radiation protection:
  - multi reflection of radiation…
- Minimal thermal conductivity between reflective layers: interposing of isolating layers
  - Reduced inter-layer thermal conduction heat loads
- Enhanced performance @ low T → use actively cooled shield
  - Lower emissivity of reflective material layers @ low T
  - Reduce radiation from inner-most layers, cooled at T of shield
  - Extract heat @ thermal shield T → more efficient heat extraction

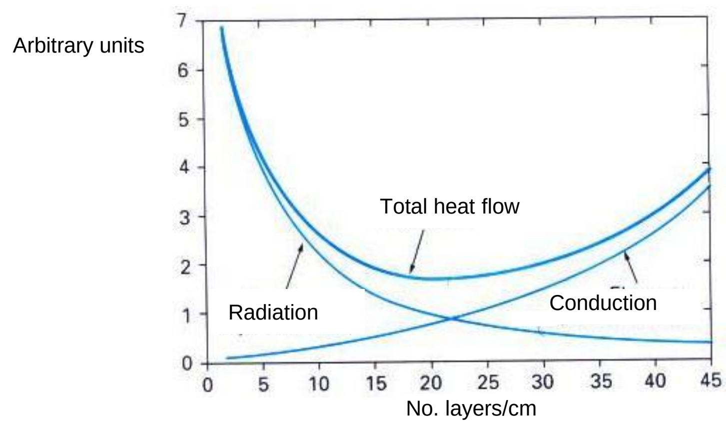


MLI:

How many reflective layers (N)?

Radiation vs. conduction, two conflicting phenomena

- Radiation reduces as 1/N
- Conduction is proportional to packing density (N/mm)



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

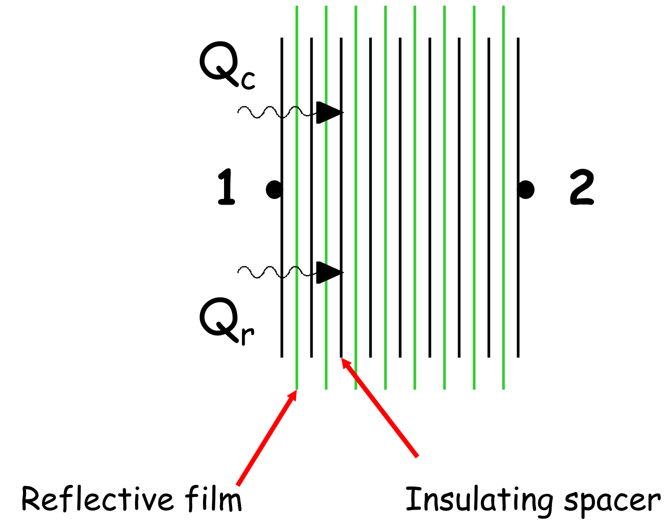
Multi Layer Insulation (MLI): a simplified calculation model

- A simplified model:
  - Radiation reduction
  - Solid conduction

$$Q_{MLI} = \left[\frac{\beta}{N+1} \cdot \left(T_1^{\ 4} - T_2^{\ 4} \right) \right] + \frac{\alpha}{N+1} \cdot \frac{T_1 + T_2}{2} \cdot (T_1 - T_2)$$

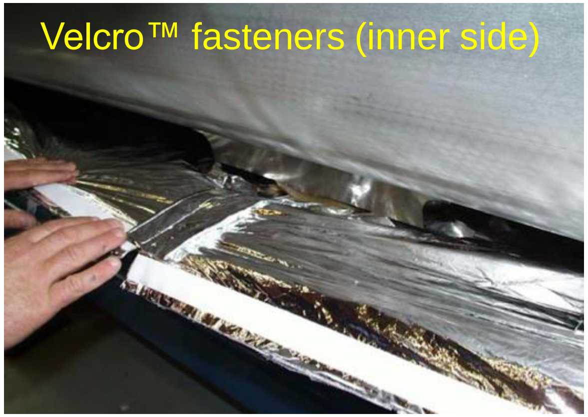
N = No. of reflective layers

α, β = average thermal conductivity and emissivity constants of the MLI system (obtained experimentally. For LHC cryostats: α=1.401 10^{-4}, β=3.741 10^{-9})



Considering the complexity of the phenomena Involved, an experimental characterisation of MLI performance, in particular for large machines, **must be made.** However, abundant literature data available.

LHC Multi Layer Insulation (MLI)



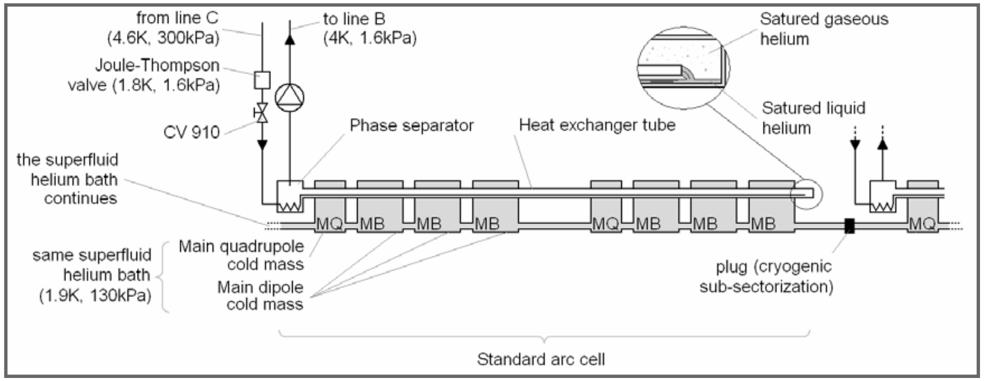
Features:

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

Measured thermal performance on LHC

LHeII calorimetric measurements of 1.9 K static heat loads in LHC

Static HL natural warm-up of cryogenic subsector after stop in cooling



Schematic of a standard arc cell, a common superfluid helium bath of 106 m cooled by a unique heat exchanger tube.

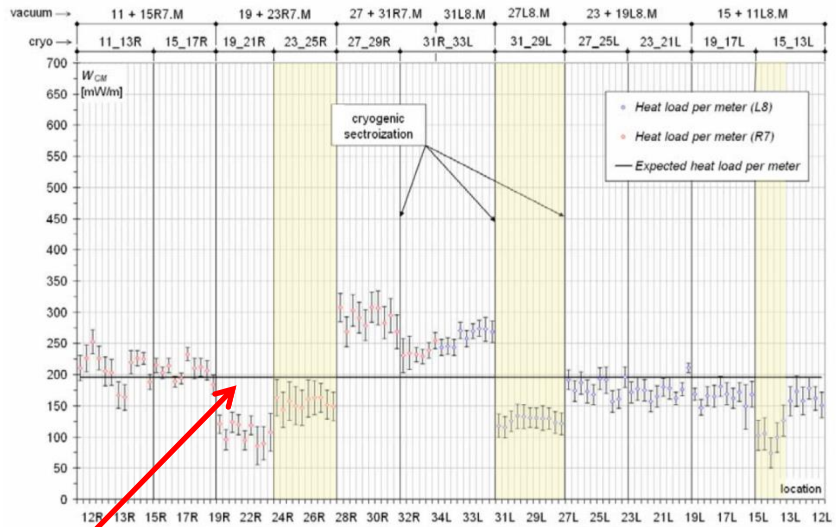
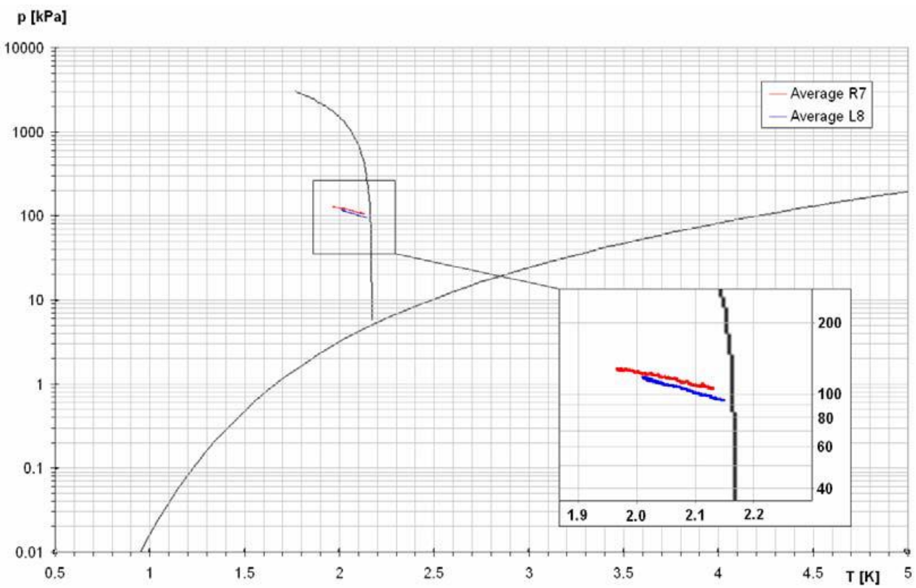


Figure 7 – Cold mass static heat loads in sector 7-8

$$W_{CM} = \frac{\Delta U_{CM}}{\Delta t \cdot L_{CM}}$$

ΔU_{CM} Change of internal energy

L_{CM} Length of string of magnets



Transformation in p-T helium phase diagram during warm up

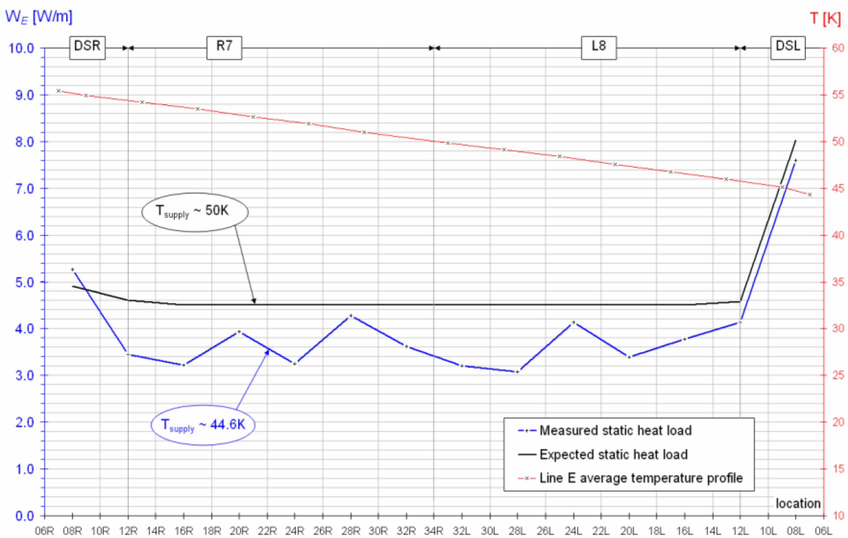
- Average heat load to cold mass (10 MLI layers) ~ 0.2 W/m
- Rescaled on cold mass surface and subtracting solid conduction contributions (lab tests on components) :

10 layers MLI between 50K and 1.9 K → *~ 0.054 W/m²*

→ Practical figure: *50 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.

Non-isothermal cooling of LHC thermal shield (2’700 m)



Thermal shield static heat load profile along sector 7-8

$$W_E = \frac{\Delta H_{avg}}{L_{TT}} = \frac{(\dot{m}_E \cdot \Delta h)_{avg}}{L_{TT}} \quad \text{[W/m]}$$

$\dot{m}_E$ Helium flow (measured)

Δh Specific enthalpy change
(T measurements and He properties)

L^{TT} Distance between T sensors

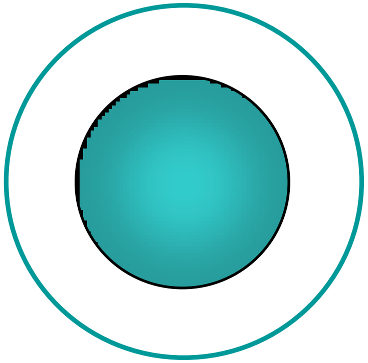
- Average heat load @ 50K of ~ 4 W/m
- Thermal shielding with MLI (30 layers)
- Rescaled on cold mass surface and subtracting solid conduction contributions (lab tests on components):

30 layers MLI between 300K and 50 K → ~ *1 W/m²*

→ Practical figure: *1 W/m²*

Numerical application on the LHC Cryostat

Application to an LHC-like cryostat

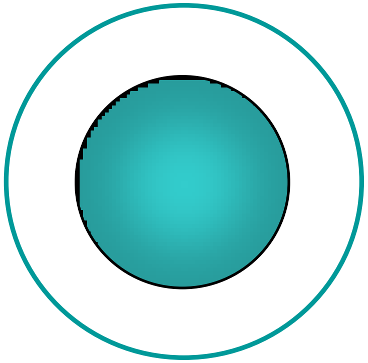


- heat loads HL will be calculated for a 1-m cryostat unit length
- Vacuum vessel diameter: 1m (A_{VV}= π x 1= 3.14 m^2)
- Cold mass diameter: 0.6 m (A_{CM}= π x 0.6 = 1.88 m^2)
- T cold mass: 2 K
- T vac.vessel: 293 K
- Budgets: HL_{CM} ~ 0.2 W/m; HL_{TS} ~ 5 W/m

$$Q = \frac{\sigma A_{CM} (T_{VV}^4 - T_{CM}^4)}{\frac{1}{\varepsilon_{CM}} + \frac{A_{CM}}{A_{VV}} \left(\frac{1}{\varepsilon_{VV}} - 1 \right)}$$

a) Bare cold mass

- Emissivity cold mass: ε_{CM} = 0.12
- Emissivity vac.vessel: ε_{VV} = 0.2

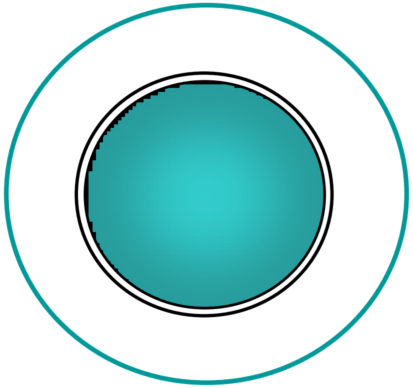


HL_{CM} = 63 W

Budget for LHC is ~0.2 W → HL too high

b) Cold mass wrapped with 1 layer of Al foil

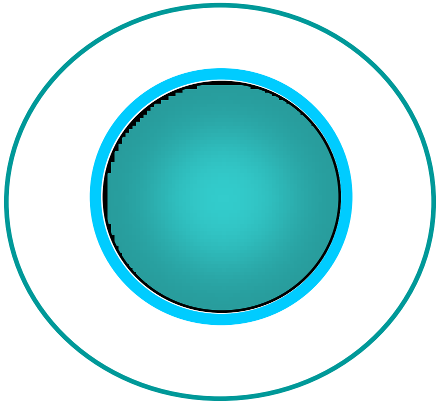
- Emissivity of Al foil (at 2 K): $\varepsilon_{CM} = 0.06$



$HL_{CM} = 40$ W → HL still too high

c) Cold mass wrapped with 30 layers of MLI

- HL from 290 K with 30 MLI layers *(calculated with MLI formula):* 1.2 W/m^2

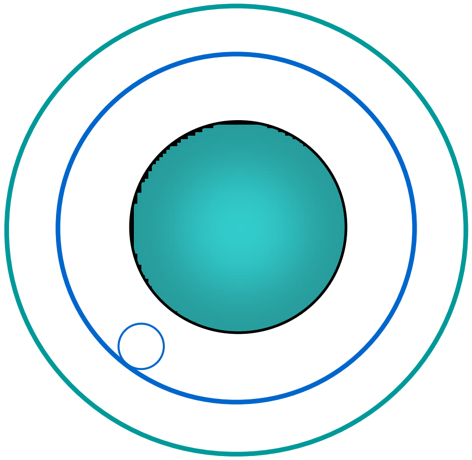


HL_{CM} = 1.2x1.88= 2.3 W

→ HL still 1 order of magnitude too high

d) Addition of thermal shield actively cooled

- Thermal shield diameter: 0.8 m (A_{TH}= = π x 0.8 = 2.51 m^2)
- Thermal shield at intermediate T → 80 K
- Emissivity of Al (at 80 K): ε_{TS} = 0.1

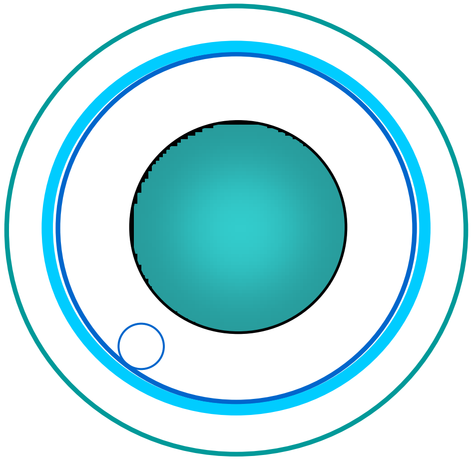


HL_{CM} = 0.26 W → Close to budget

HL_{TS} = 79 W → too high (Budget for LHC is 5 W)

e) Wrapping of MLI around thermal shield

- HL from 290 K with 30 MLI layers 1.2 W/m^2

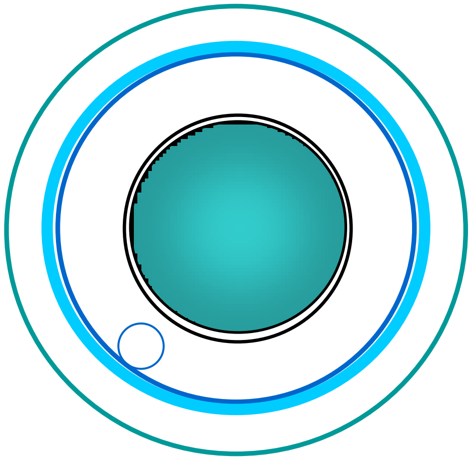


HL_{CM} = 0.26 W → Close to budget

HL_{TS} = 1.2x2.51= 3.01 W →Within budget for LHC (5 W)

f) Adding 1 Al foil around cold mass

- Emissivity of Al foil (at 2 K): ε_{CM} = 0.06



HL_{CM} = 0.18 W → within budget (0.2 W)

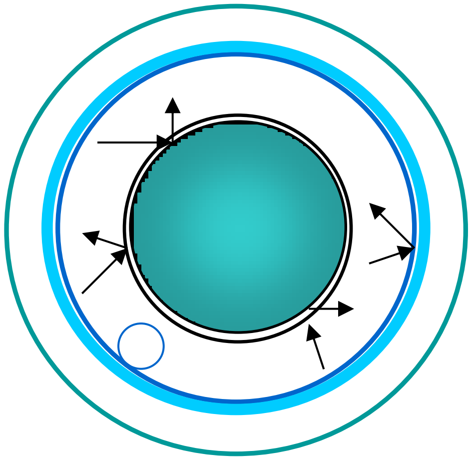
HL_{TS} = 3.01 W → Within budget (5 W)

g) What in case of bad vacuum (He leaks)?

→ Residual gas molecular conduction:

$$Q_{res} = A_1 \cdot \alpha(T) \cdot \Omega \cdot P \cdot (T_2 - T_1)$$

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



- From table, for He at 2 K: α_{CM}=1, for He at 80K α_{TH}=0.4 → α = 0.47
- for He, Ω = 2.13 W/m².Pa.K

- For 1 Al foil on cold mass, in case of degraded vacuum: $Q = Q_{rad} + Q_{res}$

- For P = 10^{-3} Pa (10^{-5} mbar):

(still quite good vacuum) $Q_{res} = \underline{0.15W}$ $Q = Q_{rad} + Q_{res} = 0.18 + 0.15 = \underline{0.33W}$

Exceeds budget

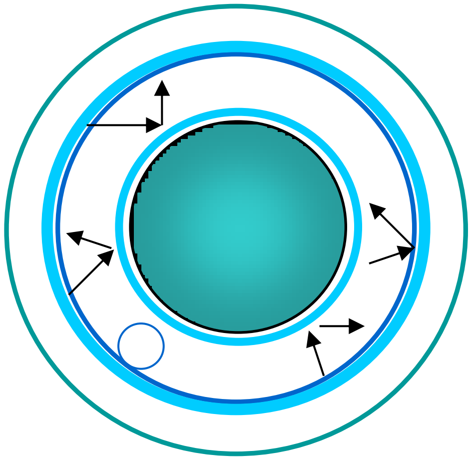
- For P = 10^{-1} Pa (10^{-3} mbar):

(degraded vacuum) $Q_{res} = \underline{\underline{15W}}$

2 orders or magnitude higher than budget!!

h) Add MLI around the cold mass

- 10 MLI layers on cold mass
- Using measured data
  - In good vacuum (<10^{-3}Pa): 50 mW/m^2



$$HL_{CM} = 1.88 \times 0.05 = 0.09\ W$$

$$(HL_{TS} = 3.59\ W)$$

HL even lower

  - Under degraded vacuum (~10^{-1} Pa): ~2W/m^2

$$HL_{CM} = 1.88 \times 2 = 3.8\ W$$

MLI cuts residual conduction by 4 !!

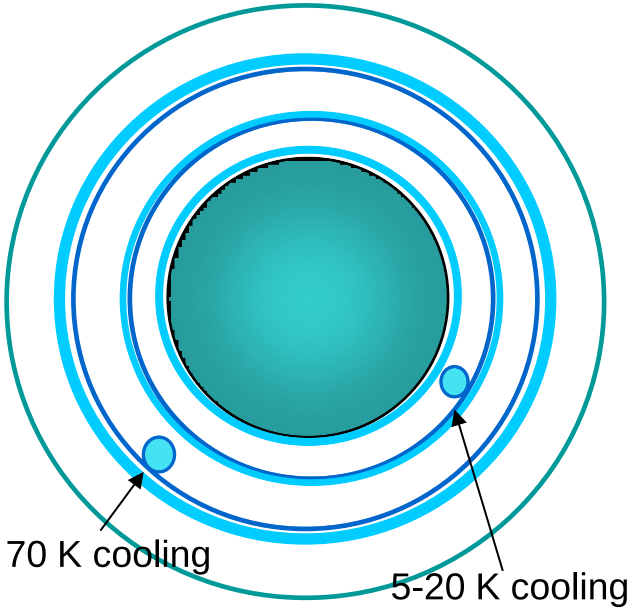
Important note: MLI on helium vessels also necessary to reduce by about 7 condensation heat fluxes in case of accidental cryostat venting with air (bare surface: q ~4 W/cm^2 ; 10 layers of MLI: q ~0.6 W/cm^2)

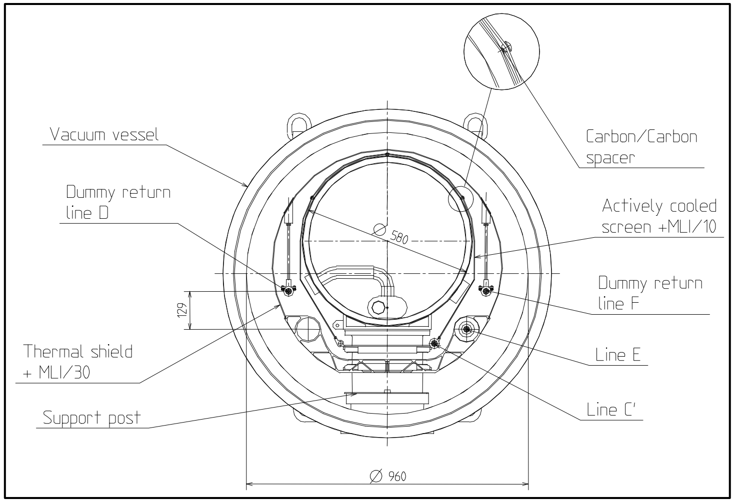
Summarizing

Case	2K heat loads	80 K heat loads
a) Bare Cold mass	63 W	N.A.
b) Cold mass with 1 Al foil	40 W	N.A.
c) Cold mass with 30 MLI layers	2.3 W	N.A.
d) 1 thermal shield at 80K, no MLI	0.26 W	79 W
e) 30 MLI layers on thermal shield	0.26 W	3.01 W
f) As e) + 1 Al foil on cold mass	0.18 W	3.01 W
g) As f) but degraded vacuum	up to 15 W (10^{-1} Pa)	> 3.01 W
h) +10 MLI layers on cold mass	0.09 W in good vac. 3.5 W in deg.vac.	3.59 W > 3.59

What about a second actively cooled shield?

- Experimental program for LHC cryostat in the late nineties (Cryostat Thermal Model, CTM)
- A 20 K active cooled screen with 10 MLI layers
- An estimated saving of up to ~0.15 W/m at 1.9 K
- but the an equivalent increase at the 5-20 K level (~5 times less costly)
- Overall electrical power saving: ~ 100 Wel/m
- Additional hardware (line, MLI, supports,etc) → higher capital cost
- Additional assembly complexity
- Breakeven only after ~10 years of operation
- For LHC we decided to keep 1 active shield at 70K





The Cryostat Thermal Model

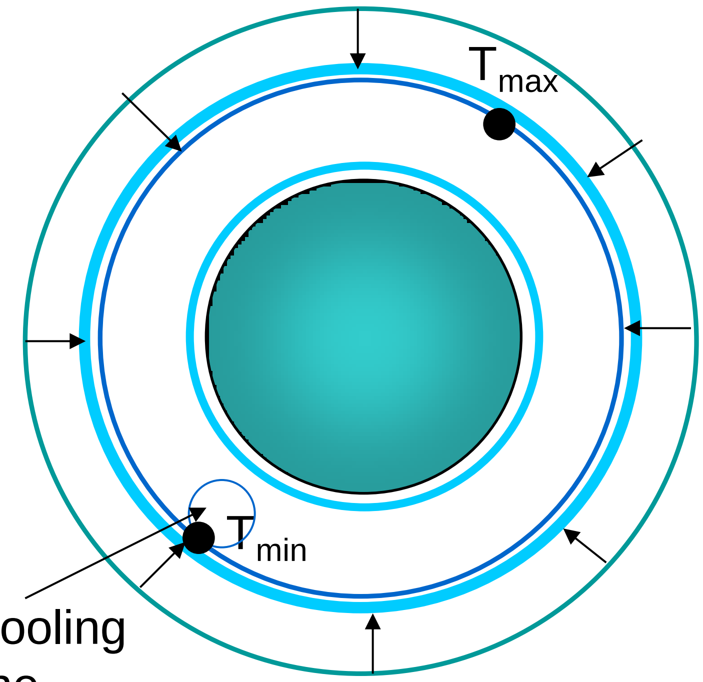
Thermal shield: what thickness ?

- Aluminium shield, in Al 5052
- Actively cooled by 1 cryo line at 80K

→ Average conductivity: $k = 80\ \mathrm{W\ K^{-1} m^{-1}}$

- Uniform heat deposition:

HL_{TS}= 3.59 W → q = 3.59/(0.8x1x π) = 1.43 W/m²



Calculate thickness with the requirement:

- Azimuthally quasi iso-thermal shield:
  - $\Delta T_{max} = T_{max} - T_{min} \approx 5\ K$

Remembering the formula yielding ΔT_{max}:

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

Replacing L by ½ circumference of diameter D (Tmax opposite to cryo line):

$$\boxed{\Delta T_{max} = \frac{q \cdot D^2 \cdot \pi^2}{8 \cdot k \cdot t}} \quad \Rightarrow \quad t = \frac{q \cdot D^2 \cdot \pi^2}{8 \cdot k \cdot \Delta T_{max}} = 2.8\ \mathrm{mm}$$

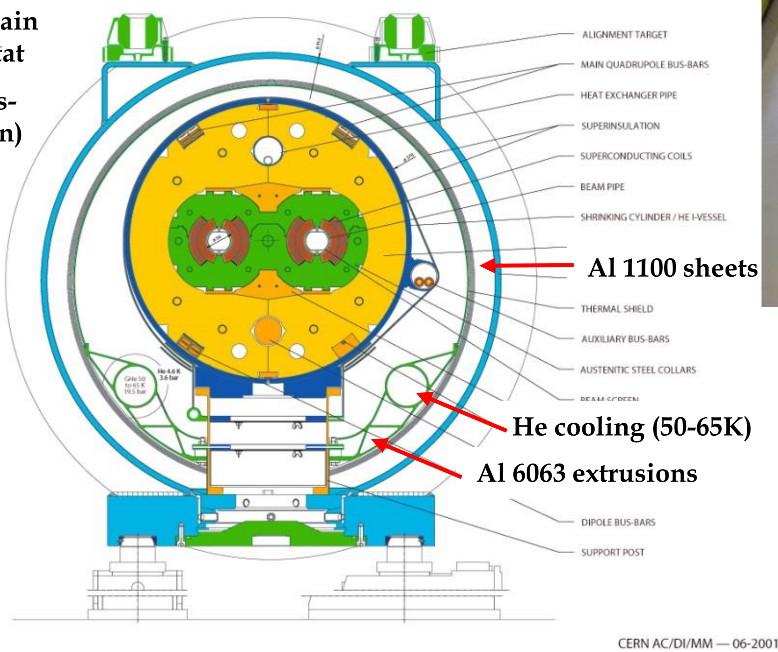
(for LHC, 2.5mm thick Al 1100 equivalent)

LHC thermal shields

Aluminium alloy 6063 extrusions and 1100 top sheets

LHC Main Cryostat

(Cross-Section)

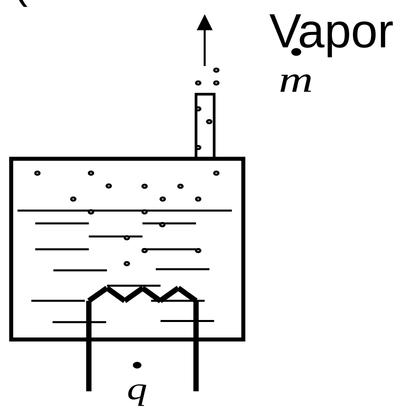


Heat transfer to cryogenic fluids

2 main mechanisms of interest for cryostats

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

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

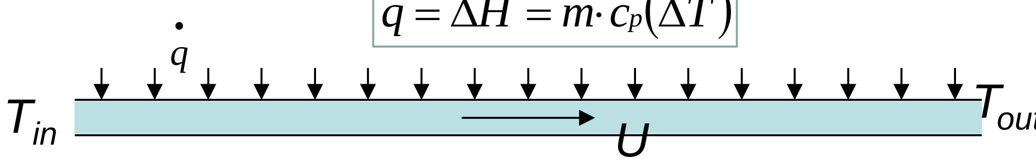


Vaporisation under 1 W heat load

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

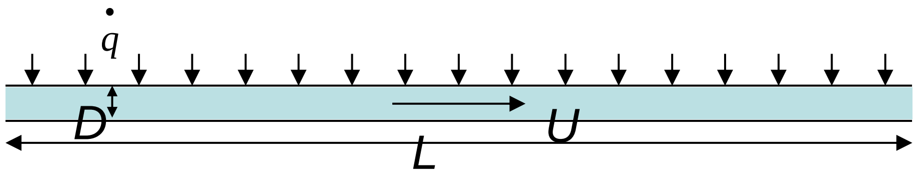
- Forced internal (tube) convection of single-phase fluid:
  – Non-isothermal cooling: enthalpy change of fluid
  – Depends from *thermo-hydraulics* of the flow (see next slide)
  – Used in cooling of thermal shields (supercritical He)

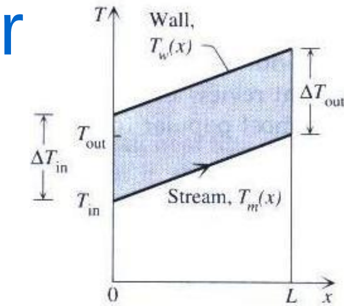
$$\dot{q} = \Delta H = \dot{m} \cdot c_p (\Delta T)$$



For more cooling mechanisms see dedicated lectures

Forced Convection Heat Transfer





- **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)

Case of a Thermal Shield

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

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

$T_w = wall\ temperature$

$T_m = mean\ temperature$

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

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

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

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

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

- **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.:**

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

$k = therm.\ conductivity$

- For **laminar flow**:

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

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

- For **turbulent flow**, $Nu_D = f(Re_D, Pr)$:

for heated fluid;

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

$2500 \le \mathrm{Re}_D \le 1.24\ 10+5$

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

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

$\alpha = thermal\ diffusivity$

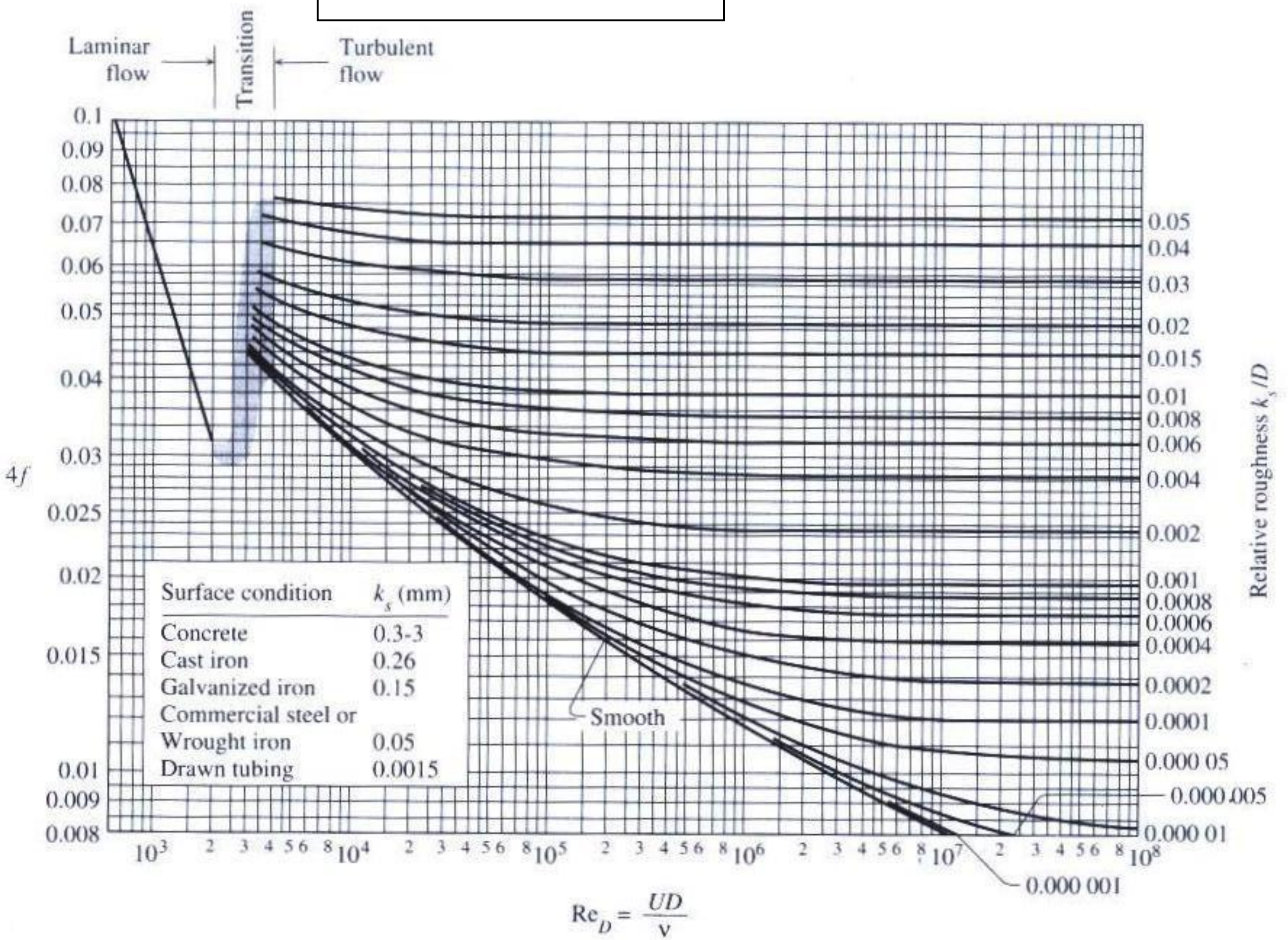
Frictional pressure drop in a tube

- **Pressure drop** along tube

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

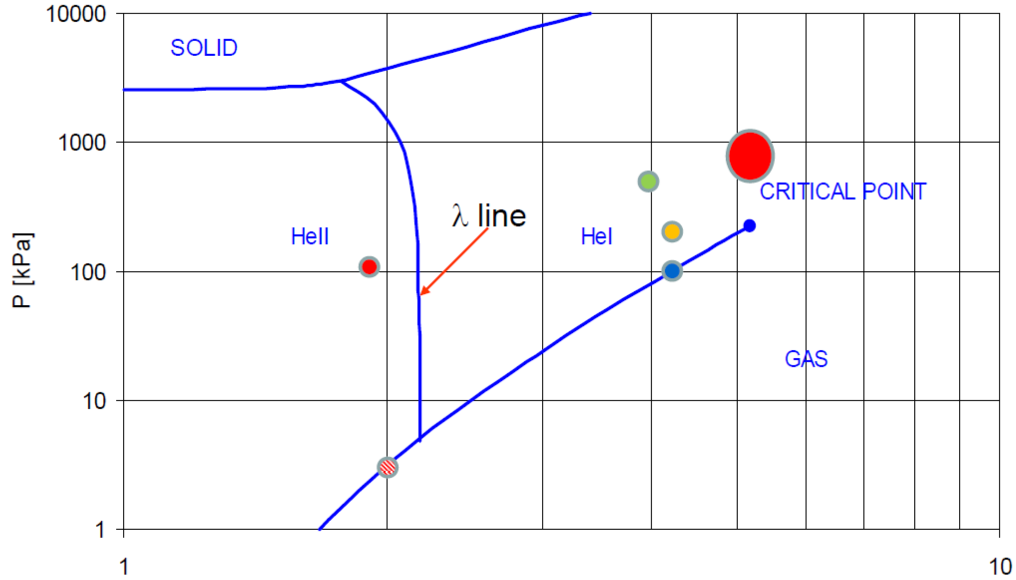
f = Fanning friction factor

U = Mean velocity



Cryogenics considerations

Helium as a coolant

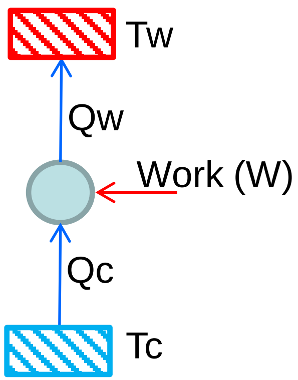


- Pressurized He II, Magnets: LHC, Tore Supra
- Pressurized He I, Magnets, HERA, Tevatron
- Saturated He II, SRF: CEBAF, TTF, SNS, EXFEL, ESS, ILC
- Pool boiling He I, SRF: HERA, LEP, KEKB
- Supercritical helium: cooling of thermal shielding

Property	Units	^{4}He	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

Refrigeration efficiency (Carnot principle)

- A refrigerator extracts a heat flow at a temperature below ambient and rejects it at a higher temperature (normally ambient)
- The Carnot cycle defines the minimum mechanical work/power (i.e. Maximum Coefficient of Performance, COP) which depends only on Tw and Tc
- All real machines have a lower efficiency (irreversibilities), expressed in fraction of COP

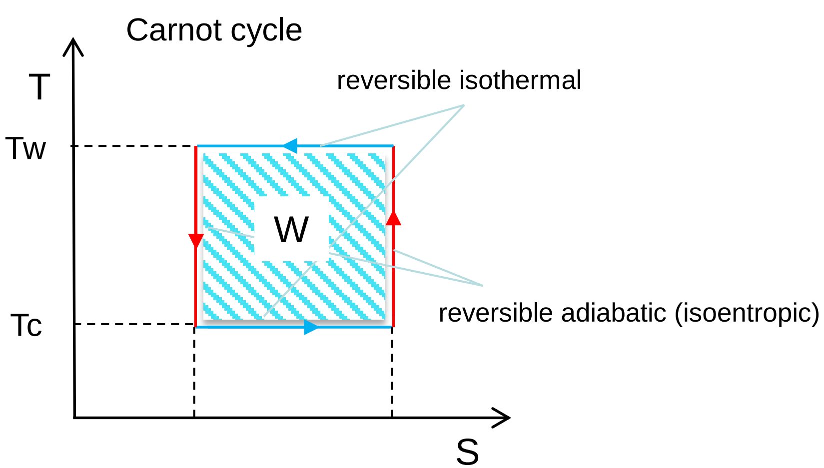


$$COPmax = \frac{Tc}{Tw - Tc}$$

$$\dot{Q}w + \dot{Q}c + W = 0 \qquad \text{(1st law)}$$

$$\frac{\dot{Q}w}{Tw} + \frac{\dot{Q}c}{Tc} \leq 0 \qquad \text{(2nd law)}$$

$$\text{Power Input:} \quad W \geq \dot{Q}c \cdot \frac{Tw - Tc}{Tc} = \frac{\dot{Q}c}{COPmax}$$

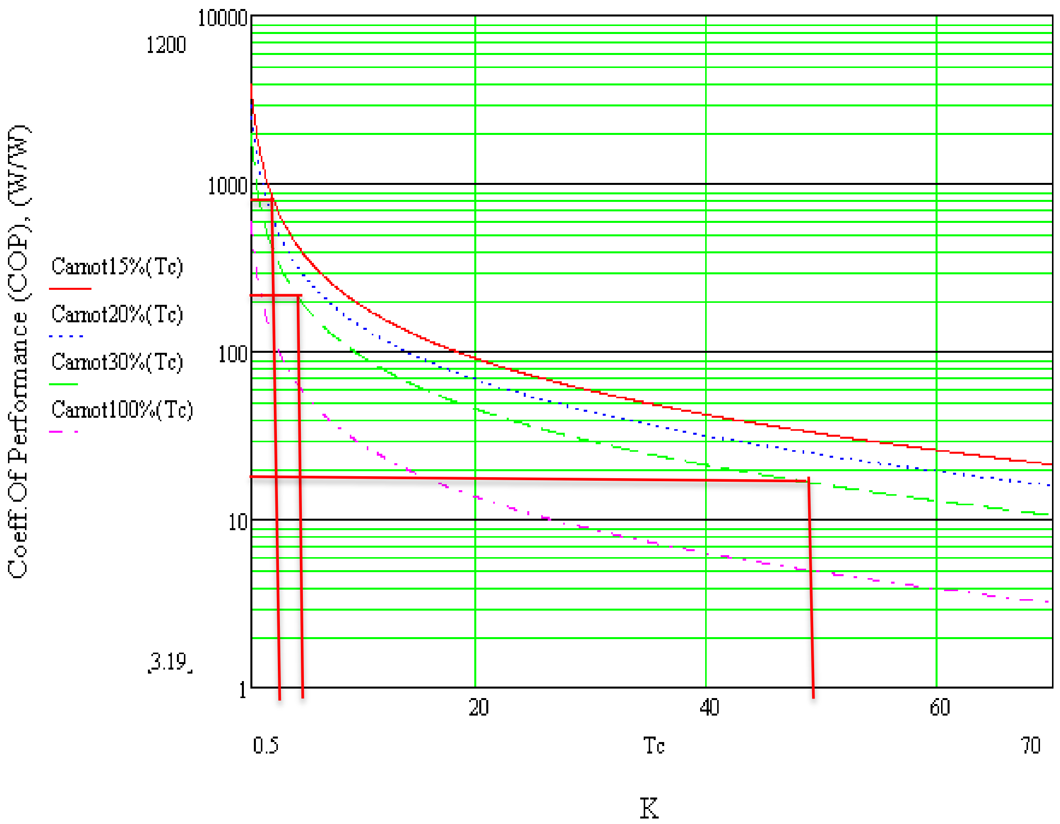


Fluid	T [K]	Carnot factor (W/Qc) [W/W] (considering Tw=293K)
LN2	77	2.8
LH2	20.4	13.4
LHe	4.2	68.4
LHe	1.8	161.8

Efficiency for large cryoplants

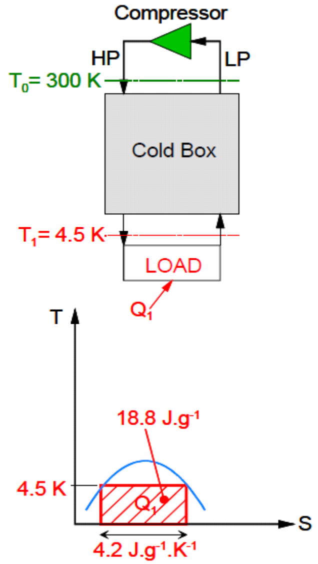
State-of-the-art figures for large cryo-plants (LHC-like, ~18 kW @ 4.5K):

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

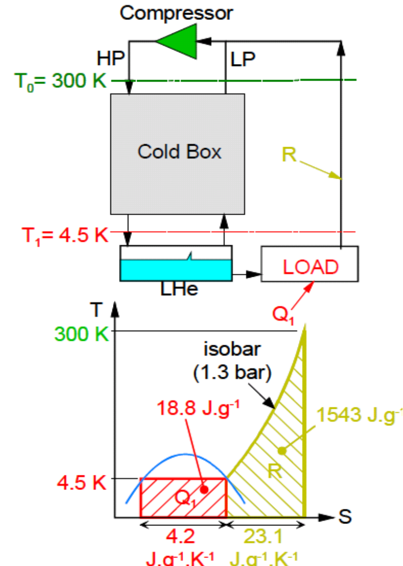


He Liquefaction: conversion to 4.5K isothermal capacity

- Refrigeration: recondensing cold vapours
  - Limited use of cryogenic power at boil-off (latent heat of evaporation)
  - Simpler cryoplant



He refrigeration



He Liquefaction

- Liquefaction: precooling + recondensing cold vapours
  - Availability of cold vapours enthalpy up to RT
  - Added complexity

$$W = T_0\,[Q_c/T_c - Q_c] = T_0\,\Delta S_c - Q_c$$

(combining 1st & 2nd principle of thermodynamics, and introducing entropy)

$$W_{liq} = \underbrace{T_0\,\Delta s_{cond} - Q_{cond}}_{W_{condensation}} + \underbrace{T_0\,\Delta S_{precool} - Q_{precool}}_{W_{Pre\text{-}cooling}} = T_0\,\Delta S_{cond} - \Delta H_{cond} + T_0\,\Delta S_{precool} - \Delta H_{precool}$$

For T_0 = 300 K, and S, H tables → W_{liq} = 6,600 W per 1 g/s of He liquef.

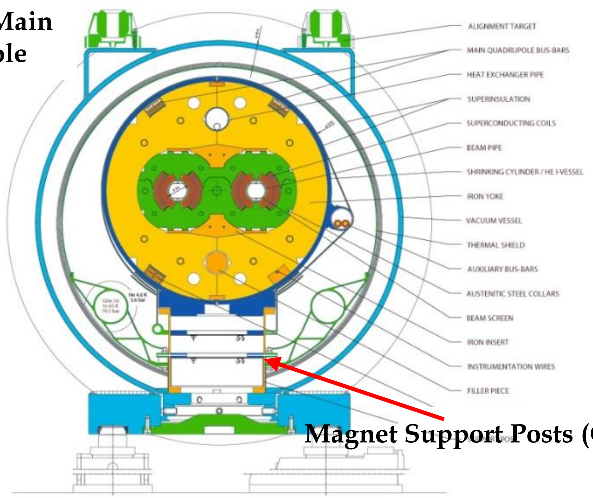
Take 66 W_{el}/W_{th} as minimum specific refrigeration work @ 4.5 K (Carnot):

*→ **1 g/s** of liquefied He (6,600 W) is equivalent to **~100 W_{th} @ 4.5 K***

Thermally efficiency solid conduction: heat intercepts, helium vapour cooling

Solid conduction in cryostats

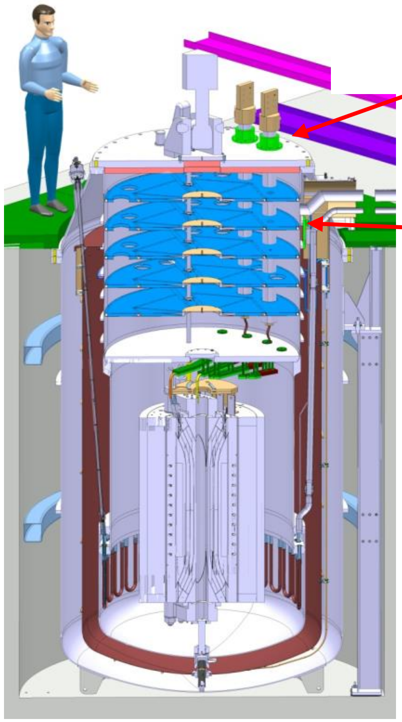
LHC Main dipole



Magnet Support Posts (GFRE)

Solid conduction paths:

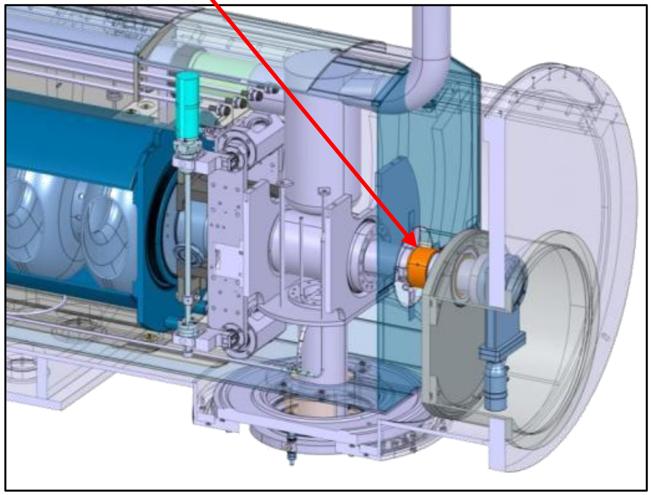
- Supporting systems
- Current leads
- RF main coupler
- Beam tubes Cold-to-Warm (CWT) transitions
- Instrumentation feed-throughs
- Necks (vertical cryostats)



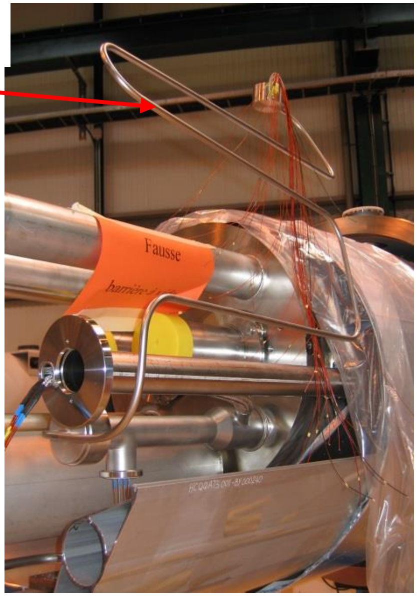
Current leads

Neck

CWT SPL cryomodule



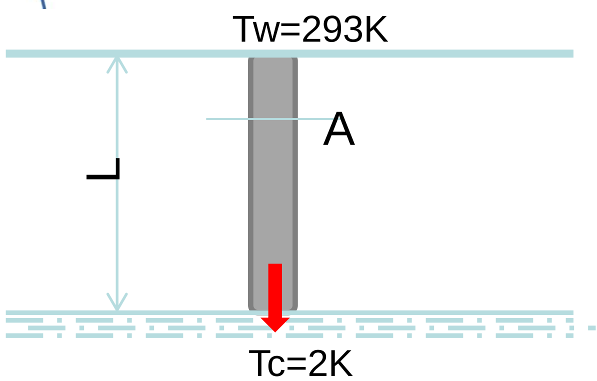
LHC instrumentation capillary at assembly



Solid conduction and heat intercepts

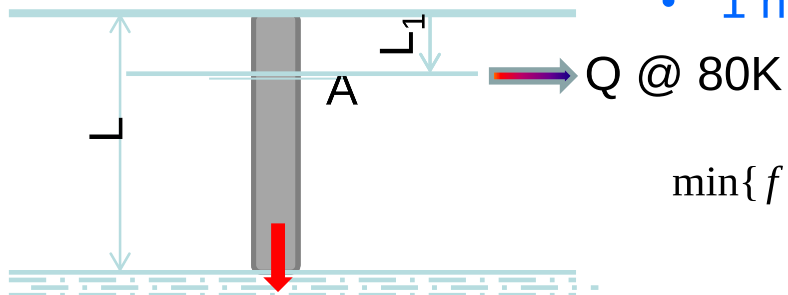
$$\dot{Q} = k(T) \cdot A \cdot \frac{dT}{dx}$$

- simple solid conduction



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

- 1 heat intercept at optimal distance

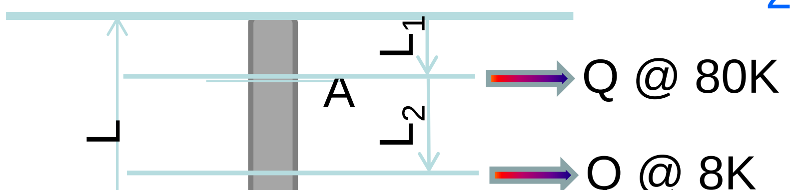


Minimizing using cost factors:
C_1 = 16 w/w
C_2 = 210 w/w
C_3 = 990 w/w

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

→ L_1

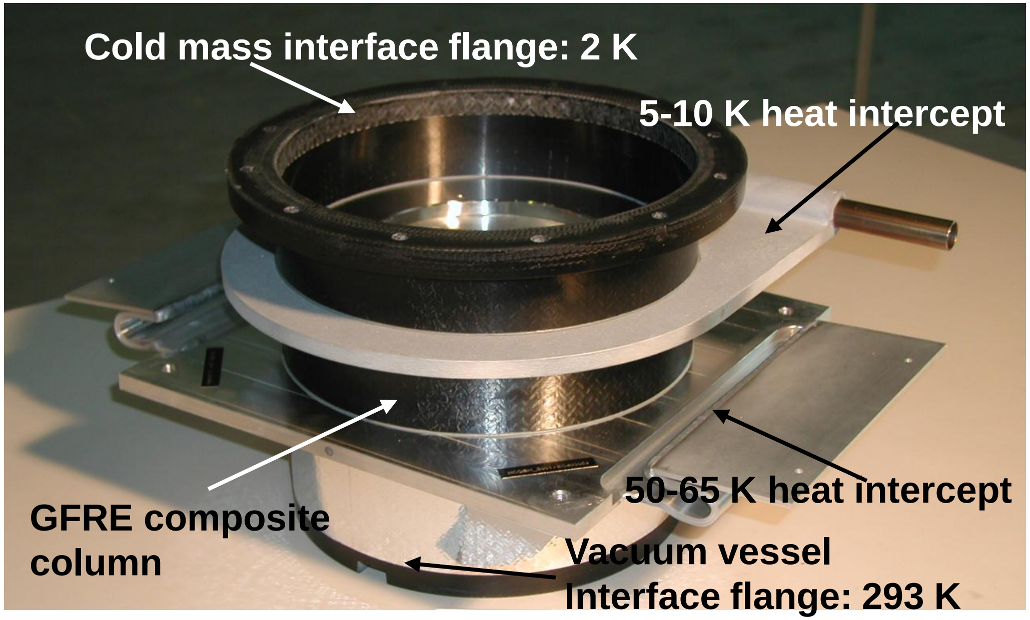
- 2 heat intercepts at optimal distance

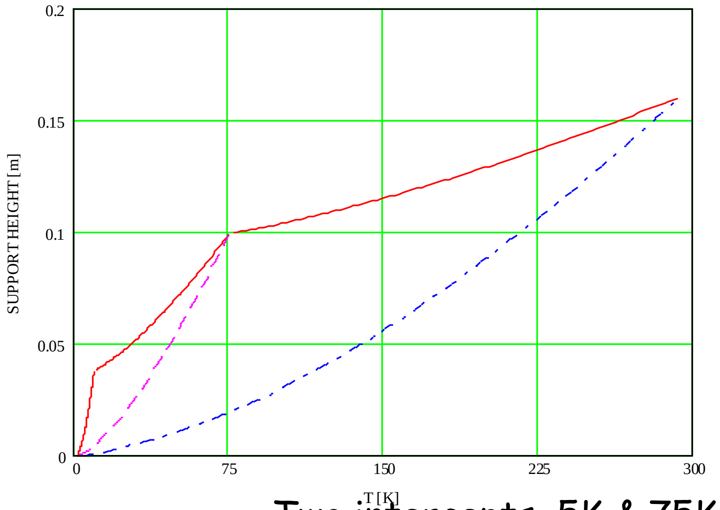


$$\min\{f(L_1, L_2) = C1 \times \frac{A}{L_1} \int_{Tw}^{80K} k(T)\,dT + C2 \times \frac{A}{L_2 - L_1} \int_{80K}^{8K} k(T)\,dT + C3 \times \frac{A}{L - L_2} \int_{8K}^{Tc} k(T)\,dT\}$$

→ L_1, L_2

LHC supports



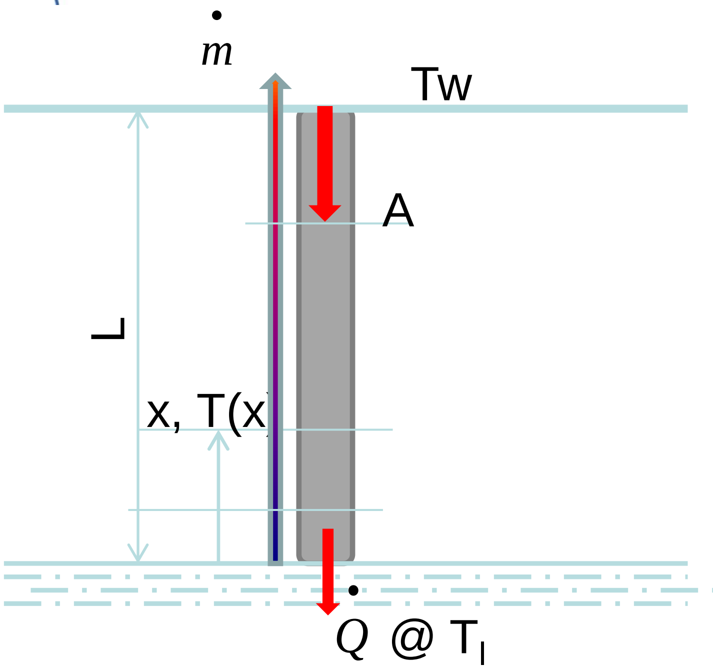


- **4-mm thickness**, single-part composite column (integrating interface flanges)
- Manufactured by **Resin Transfer Moulding (RTM):**
  - Suited to a large-scale industrial production (4’700 units)
  - High reproducibility in thermo-mechanical properties

	$Q_{1.8K}$ [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



- Vapour cooled wall
- Assuming perfect exchange (T gas = T wall)

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

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

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

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

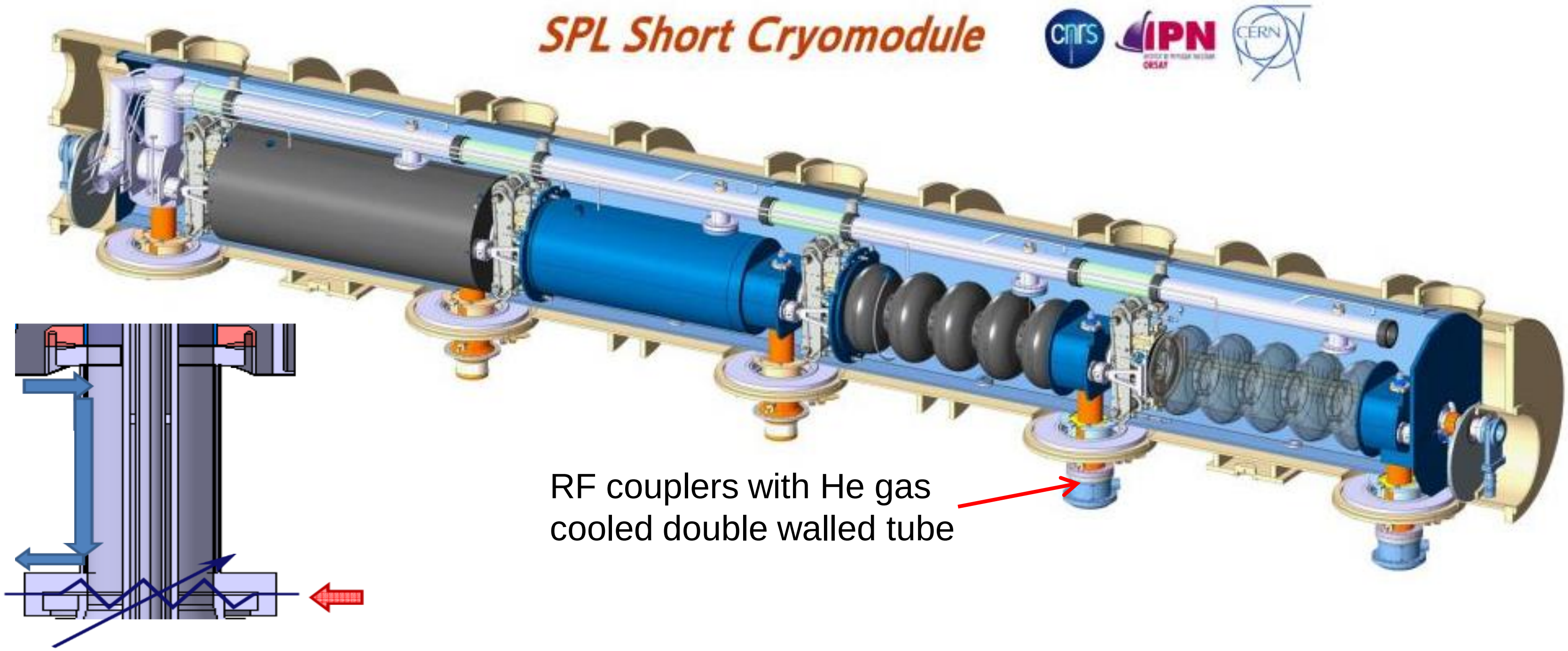
attenuation factor (w.r.t. solid conduction)

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

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

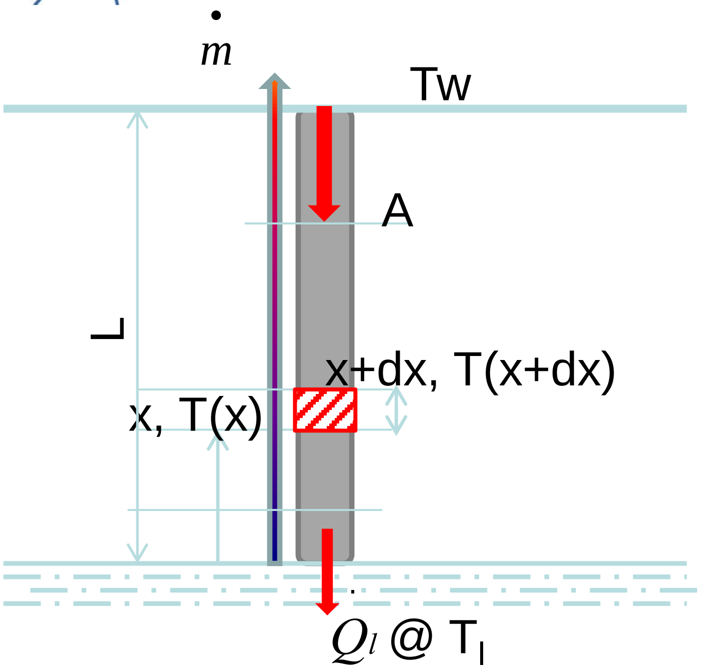
Vapour cooled RF coupler for SPL



Case	Q @ 2K [W]	Wel [W]	Q @ 8K [W]	Wel [W]	Q @ 80K [W]	Wel [W]	vapours rate g/s	Q equiv. @ 4.5K [W] (1g/s=100W)	Wel [W]	Total Wel [W]
A) No intercept	11.629	11512.71								11,513
B) 1 optimised and perfect intercept @ 80K	1.816	1797.84			39.513	632.208				2,430
C) 2 optimised and perfect intercepts @ 80K & 8K	0.129	127.71	2.64	580.8	26.816	429.056				1,138
D) 4.5K self-sustained vapour cooling	0.031	30.69					0.019	1.9	407	438
E) Real case, He vapour cooling, 4.5K-300K	0.1	99					0.04	4	880	1,039
F) Real case, He vapour cooling, 4.5K-300K, RF power on	**0.5**	**495**					**0.04**	**4**	**880**	**1,435**
G) Real case, No He vapour cooling, RF power on	**22**	**21780**					**0**	**0**	**0**	**21,780**

When RF is on, a distributed vapour cooling is essential to contain distributed RF heating (local heat intercepting can hardly provide efficient cooling)

Vapour cooling of current leads



$$\frac{d}{dx}\left(k(T)\cdot A\cdot\frac{dT}{dx}\right) - f\cdot\dot{m}\cdot Cp(T)\cdot\frac{dT}{dx} + \rho(T)\cdot\frac{I^2}{A} = 0$$

conduction — cooling (*efficiency 0 < f < 1*) — resistance heating

With:

I, current in the lead

Cp(T), specific heat

f = 0 → no cooling

f = 1 → perfect heat exchange (T(x) lead=T(x) vapour)

For current lead material following the Wiedmann-Franz law (most metals and allows, Cu for example):

$$\rho(T)\cdot k(T) = L_o\cdot T$$

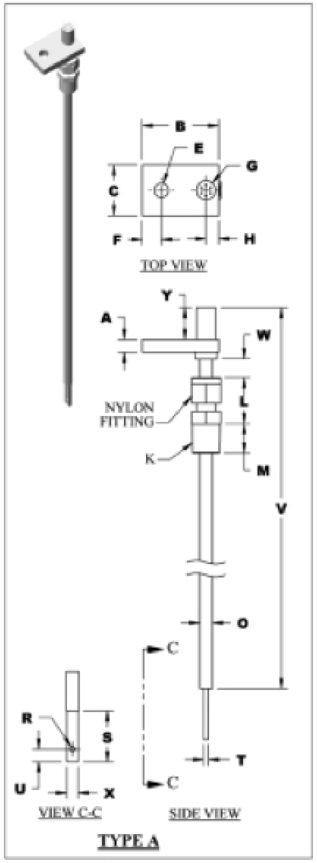
$$L_o = 2.45\times 10^{-8}\ \left(\mathrm{V}/\mathrm{K}\right)^2$$

(Constant for most metals and alloys)

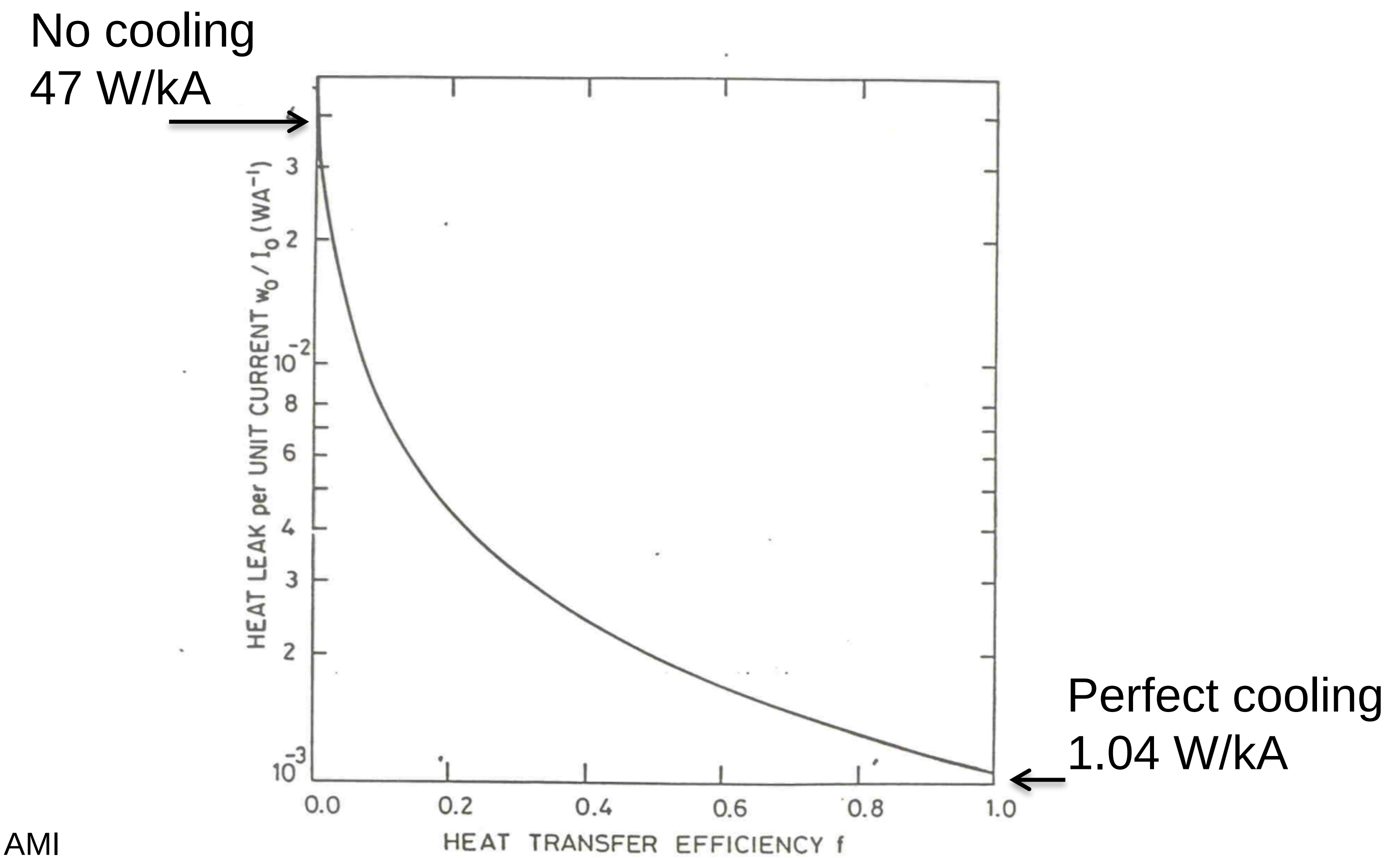
- ρ(T) and k(T) are correlated! (good electrical conductors are also good thermal conductors)
- Minimising heat in-leaks is independent of material choice for normal conducting materials

Substituting in the above equation and integrating it for variable f efficiencies…(next slide)

Heat load to bath per unit current



Example of off-the-shelf lead from AMI
(current rating up to 10 kA)



- Enhancing thermal performance can be achieved with materials which do not follow the WF law
- High Temperature Superconductors, for example, have zero resistivity and are relatively bad thermal conductors up to high temperatures. → *more in specific lecture*

End of 1st Part…

Insulation vacuum and construction aspects

Leaks

Units:

- A leak is a throughput, normally given symbol q_L

$$q_L = q_{pV} = \frac{pV}{t} = \frac{n}{t} RT = \frac{m}{t} . \frac{RT}{M}$$

- Common units are:
  - mbar.l/s atm.cc/s torr.l/s Pa.m^3/s (SI unit)
  - With a leak rate of 1 mbar.l/s a volume of 1 litre will change in pressure by 1 mbar in 1 second
  - Units of mbar.l/s equivalent to atm.cc/s

    Eg immersed in water:

    - A leak of 1 atm.cc/s would produce a bubble of 1 cm^3/s
    - A leak of 10^{-3} atm.cc/s would produce a bubble of 1 mm^3/s

- Flux through a leak will be different depending on the prevailing conditions (temperature, pressure, gas type)

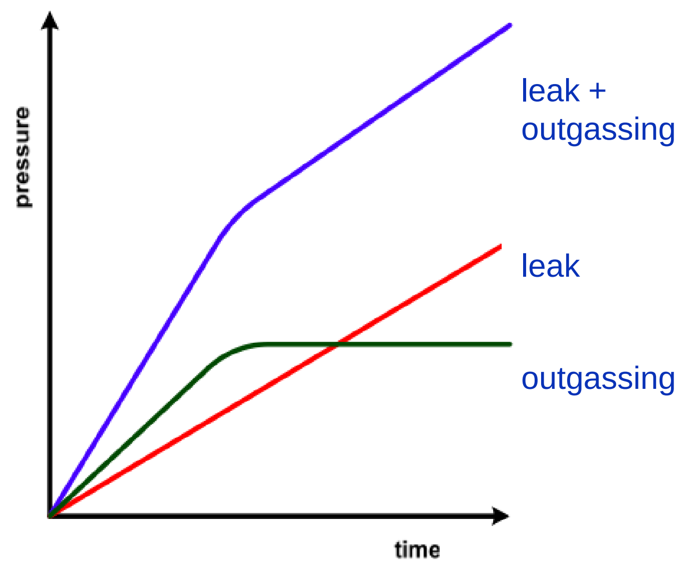
- Unless otherwise stated, a 'standard helium leak rate' in mbar.l/s implies:
  - Helium as tracer gas,
  - Under vacuum test,
  - Helium at 1 bar_{abs} and 100% concentration
  - System at 20 °C.

Leak tightness

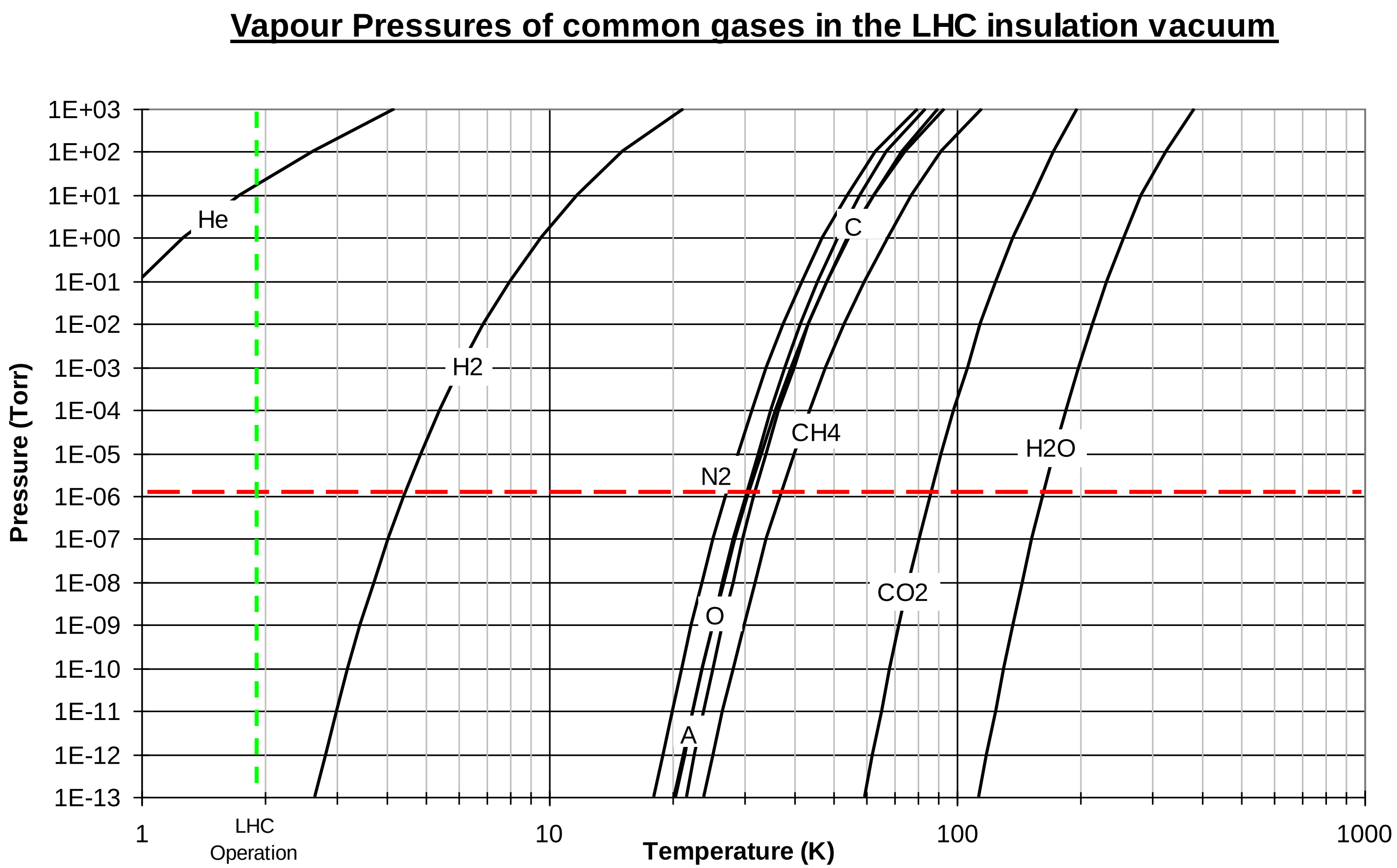
- No vacuum vessel is leak-tight, nor need it be
- Define the satisfactory leak rate needed to remain within the needed pressure in a given time:

$$q_L = \frac{\Delta p \cdot V}{\Delta t}$$

- Normally 2 sources of pressure increase: leaks and outgassing



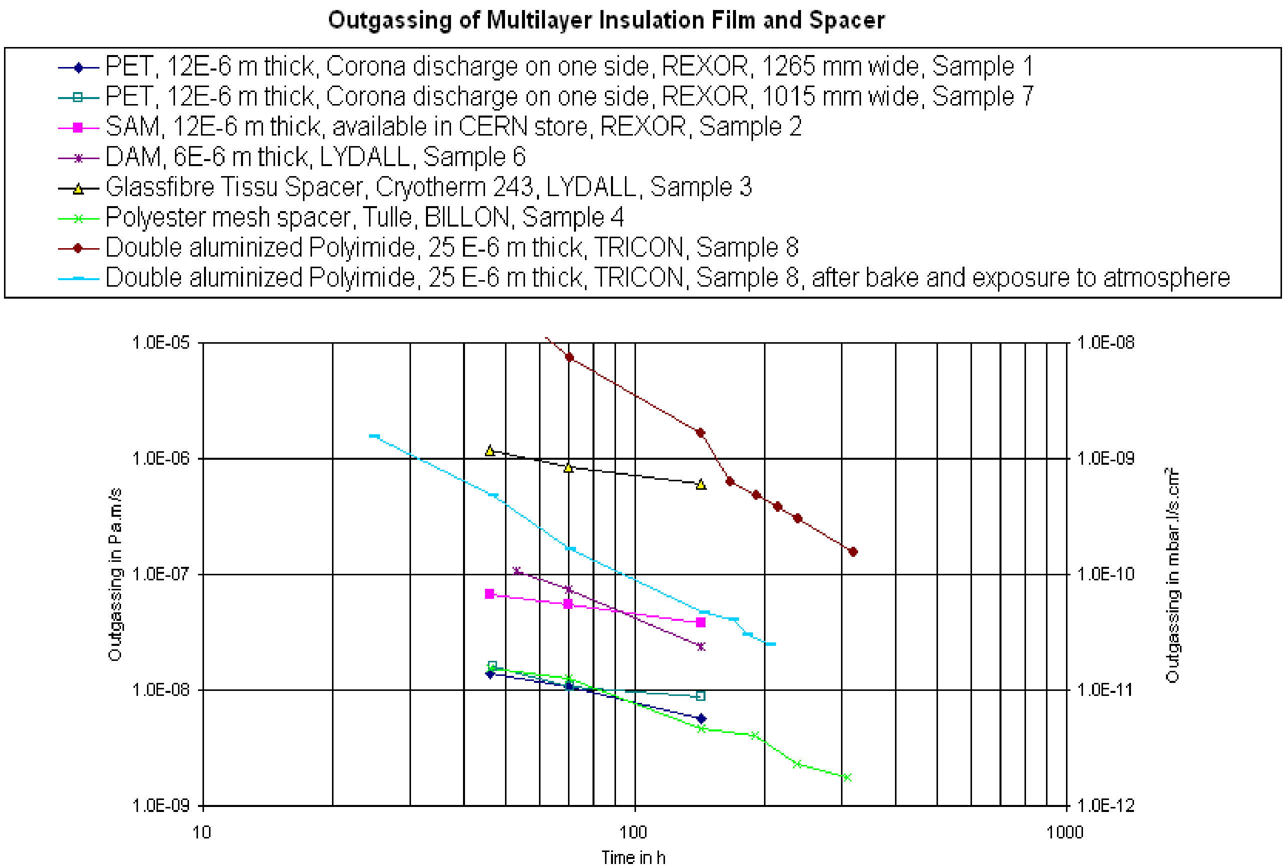
Cryopumping: cryo-condensation



- 2-4.5 K surfaces have high pumping speed & capacity
- Gas species have very low saturation vapour pressure except helium
- Without helium leaks, equilibrium pressures < 10-6 mbar are obtained

→ helium leaks are the real issue

MLI outgassing

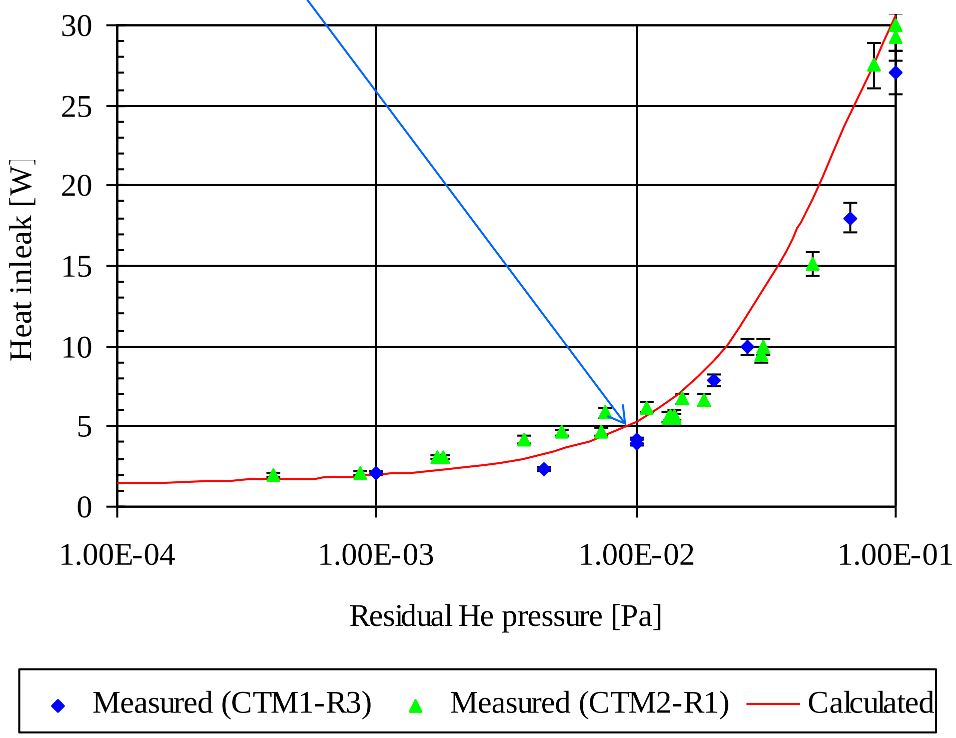


- Outgassing in cryostats is normally dominated by MLI outgassing
- For an LHC insulation vacuum sector (80 m^3, 250 m^2/m length of MLI, 214m length) exposed to ambient air for several weeks, we obtain ~ 1 e-3 mbar at RT after ~ 200 hrs pumping (S = 100 l/s). Equivalent to ~ 2 e-10 mbar.l/s/cm2 of MLI.

Insulation vacuum and heat loads from residual gas conduction

- Insulation vacuum is about minimising heat transfer due to residual gas conduction (wrt to radiative and conductive heat transfer)
- Only helium leaks can degrade the vacuum
- Determine the maximum acceptable degraded helium pressure for cryostat (only helium matters for LHC)
  - For LHC → ~ 10-4 mbar (10-2 Pa)

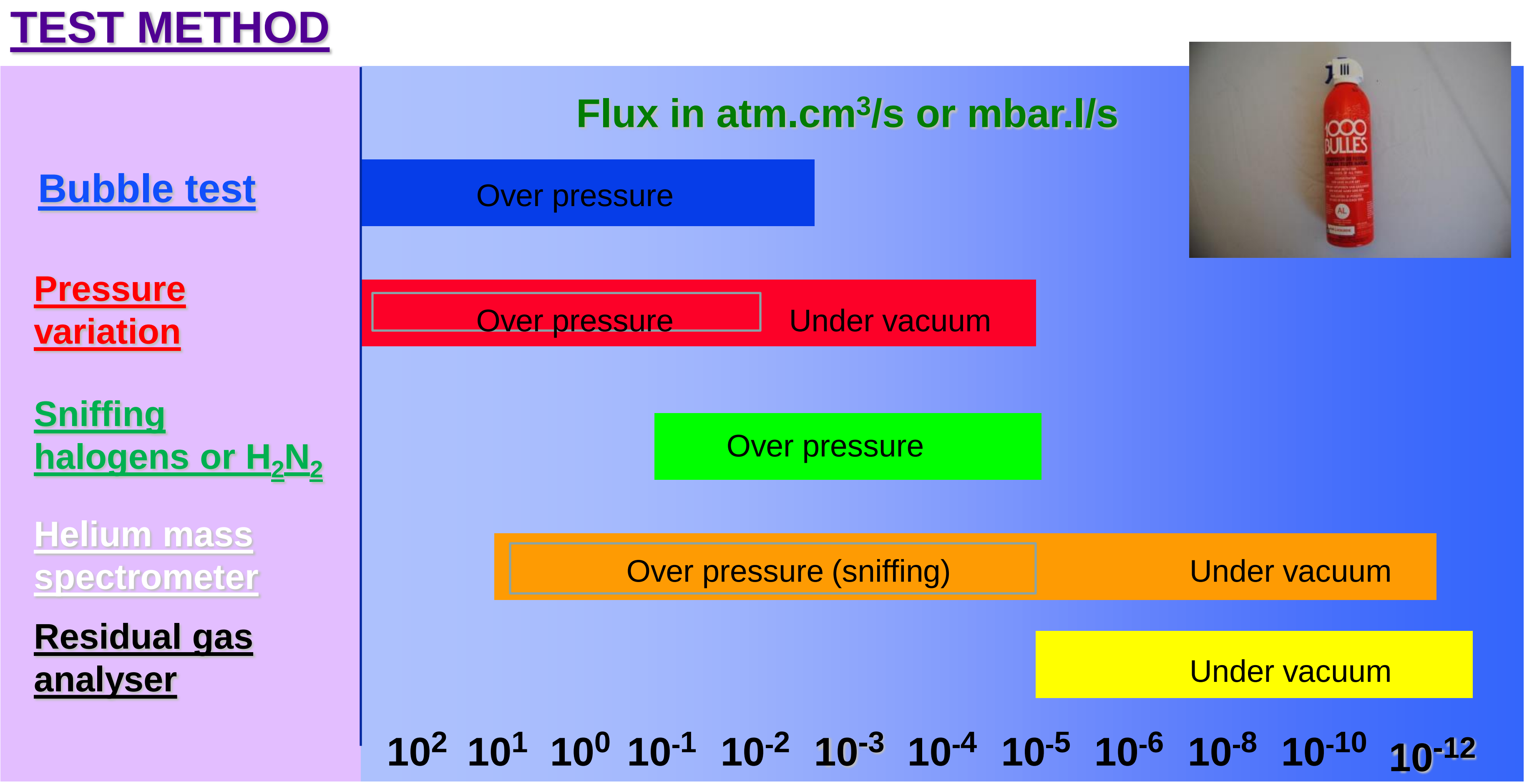
LHC dipole Cryostat Test Model results



LHC Strategy

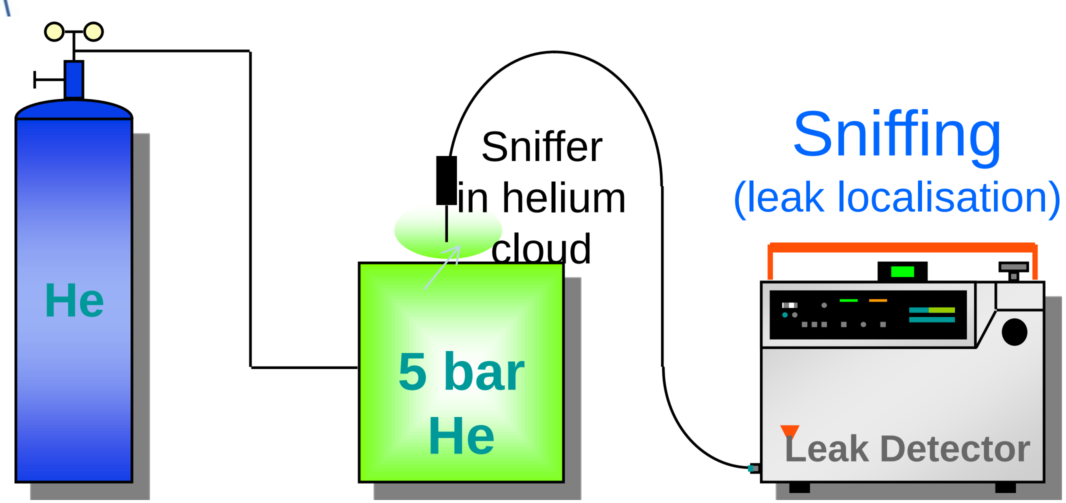
- Consider no mechanical pumping on insulation vacuum during operation
- Determine maximum helium degraded vacuum pressure → 10-2 Pa
- Determine helium cryosorption capacity of cold surfaces
  - For LHC ~ 100 mbar.l of helium @ 1 e-4 mbar per 214 m of cryostat
- Determine the leak rate that will saturate the cold surfaces of 1vacuum sector after 200 days of LHC operation → < 5 10-6 mbar.l/s
- Use fixed turbos during thermal cycles and as ‘backup’ in case the tightness specification cannot be immediately reached
- Apply cold/warm correlation for leak rates (considered to be up to x1000 at cold) → < 5 10-9 mbar.l/s per vacuum sector
- Allocate higher levels of leak tightness to sub-assemblies and components in one same vacuum sector → down to < 10-11 mbar.l/s

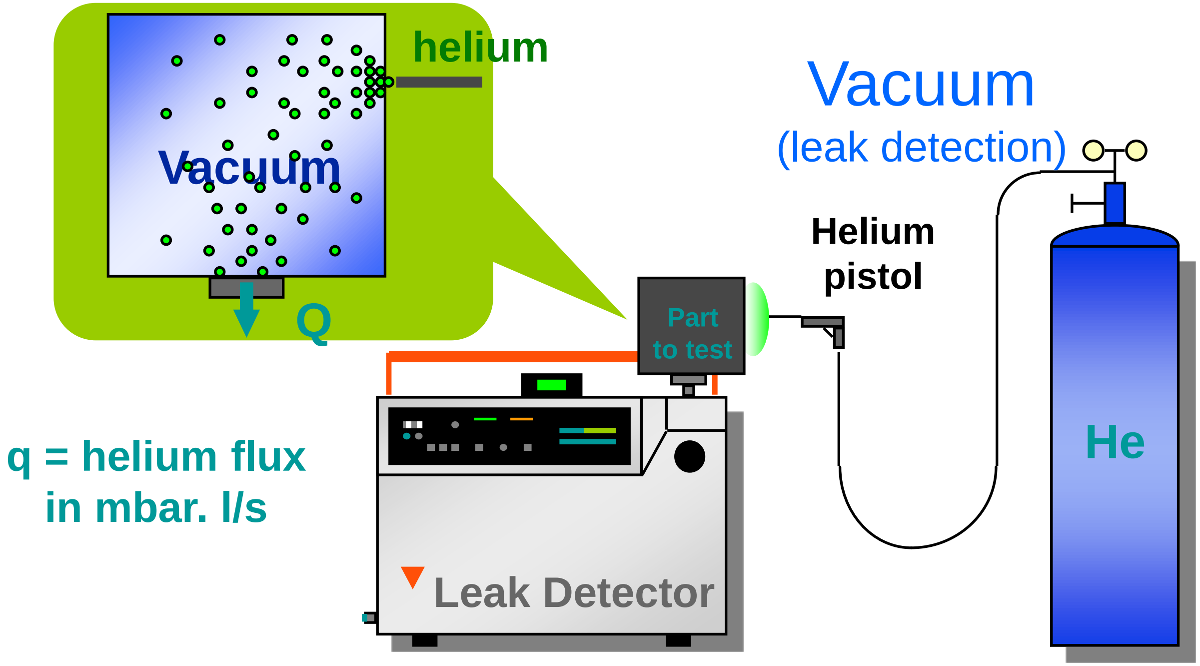
→ These very low levels of leak tightness on steel metal work and welded piping assemblies are extremely challenging for construction and testing, especially for large industrial productions (e.g. LHC)



Courtesy of P.Cruikshank

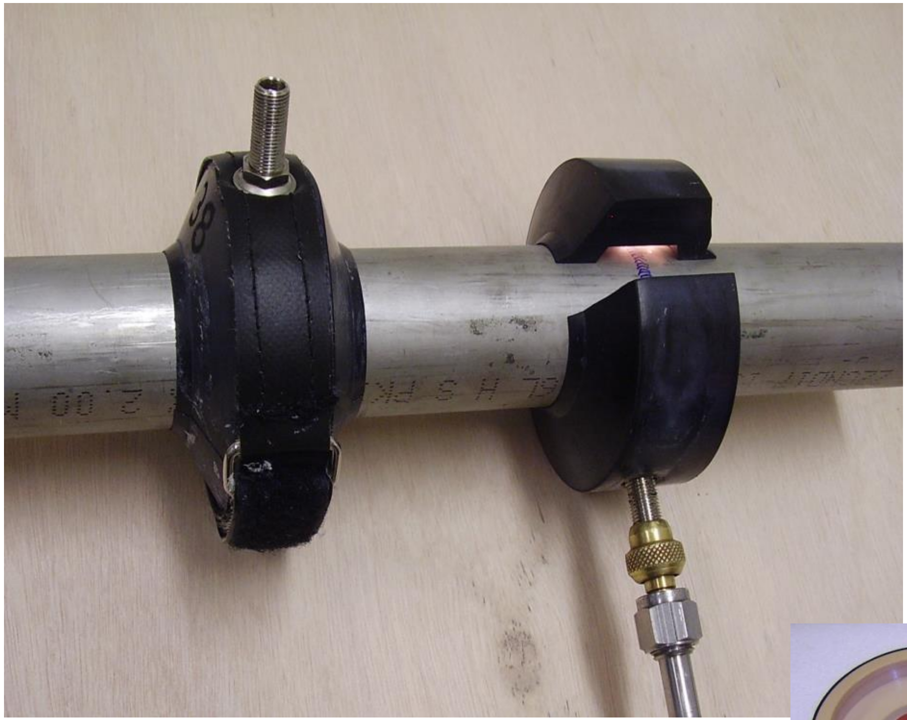
He leak detection methods

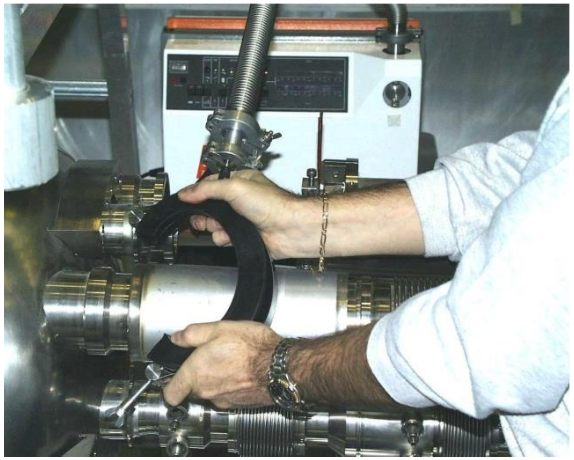




Courtesy of P.Cruikshank

Leak detection with clam-shell

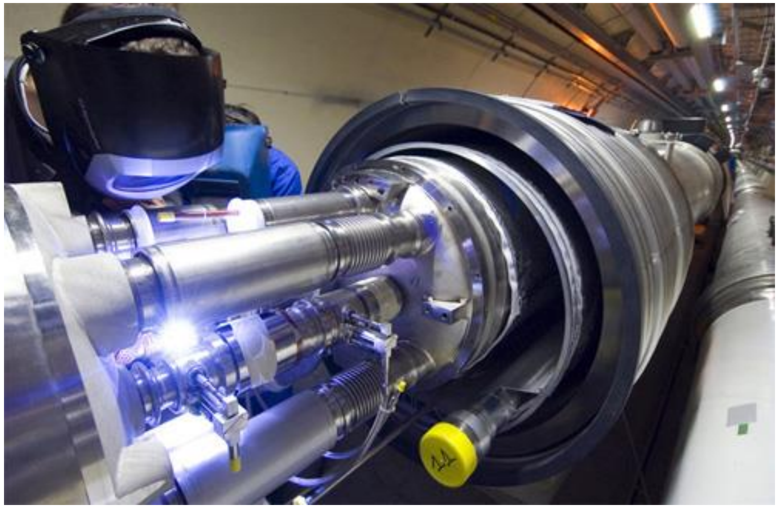


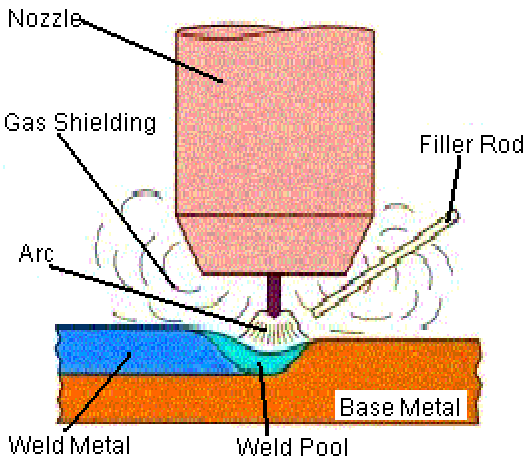


- A practical detection method for circumferential welds
- Pumping of reduced volumes
- Particularly interesting for helium polluted circuits (e.g. magnets cold tested in helium)

Clam-shells for pipe geometries for LHC

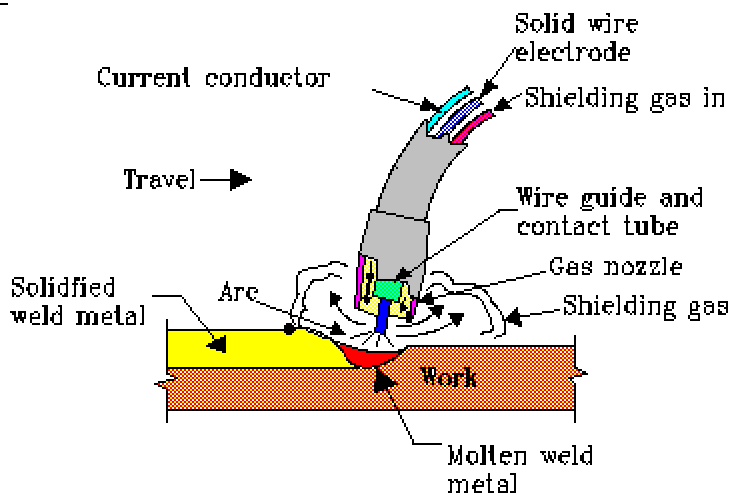
Welding





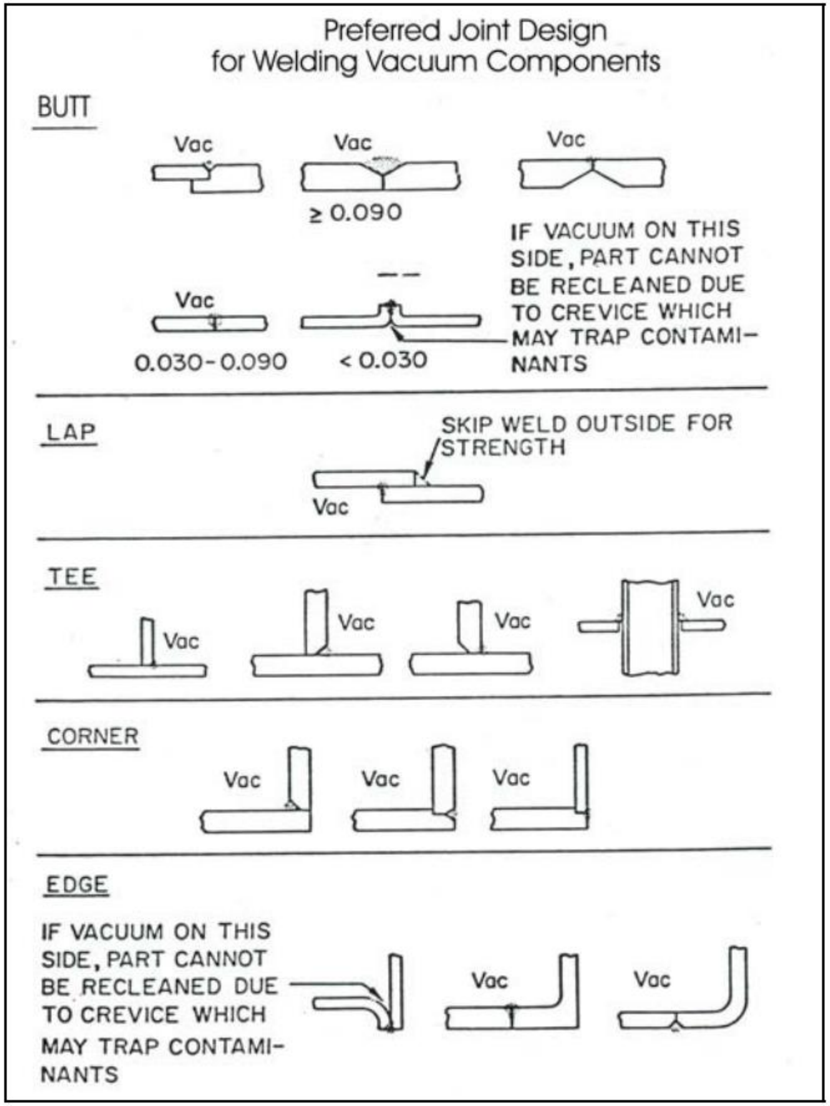
Tungsten inert gas welding

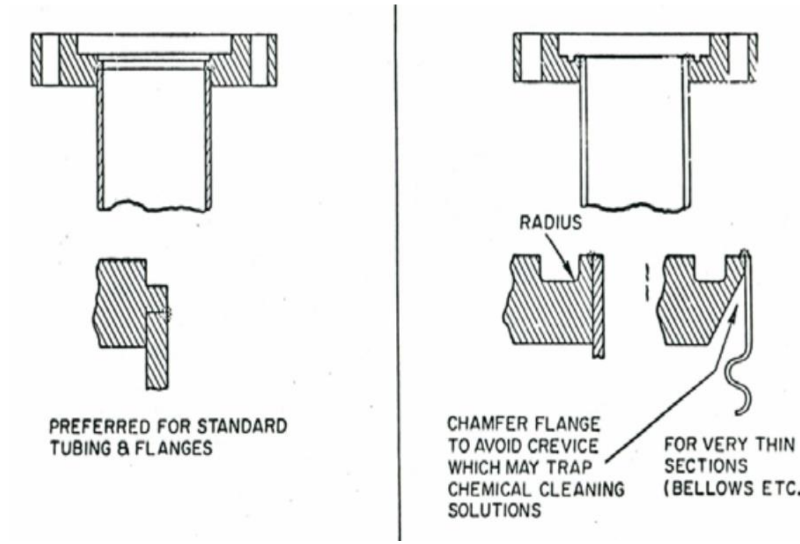
- Tungsten Inert Gas (TIG) and Metal Inert Gas Welding (MIG) are the most commonly used processes in cryostat fabrication
- Qualification of welding procedures and personnel required to fulfil mechanical requirements imposed by pressure vessel codes
- Design of welded seams must be carefully chosen to avoid sources of impurities and defects
- Non-destructive testing is often necessary



Metal inert gas welding

Design of vacuum facing welds

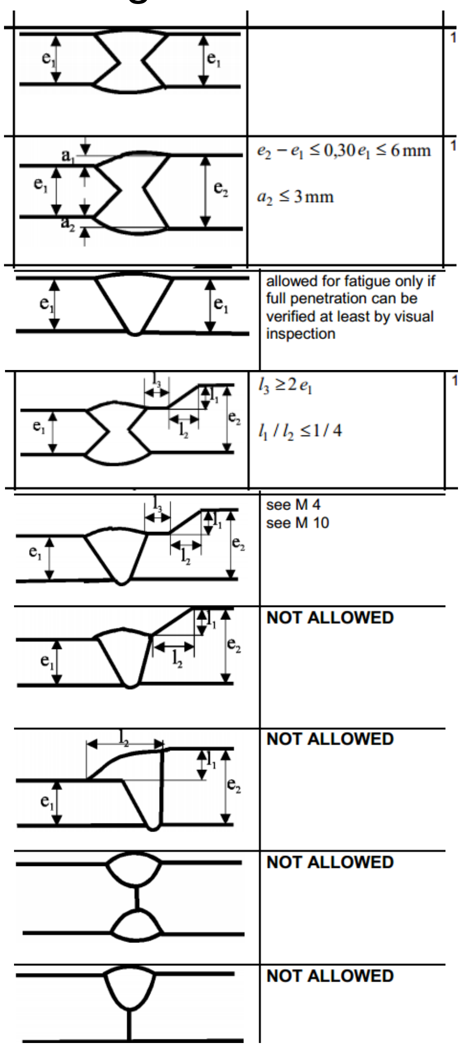


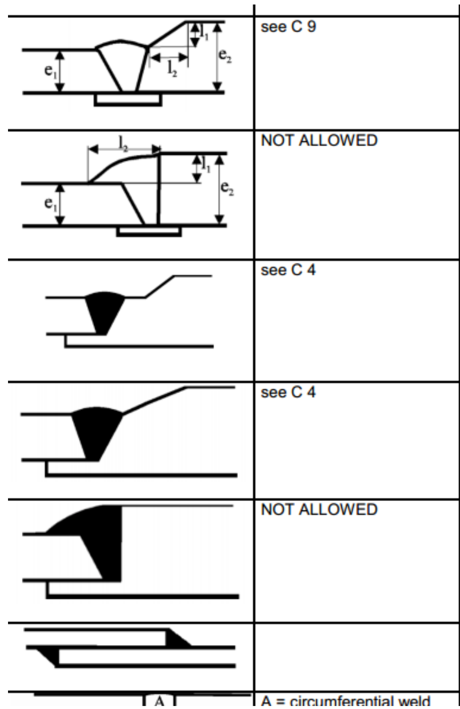


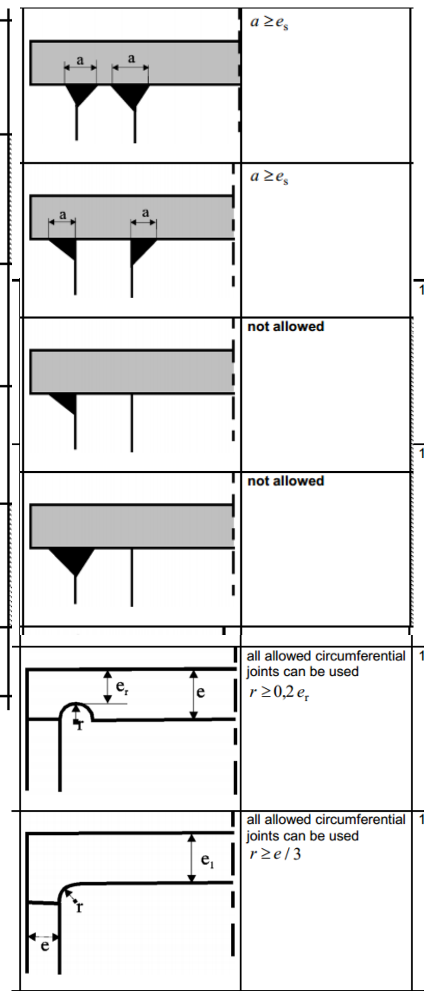
Design of pressure bearing welds

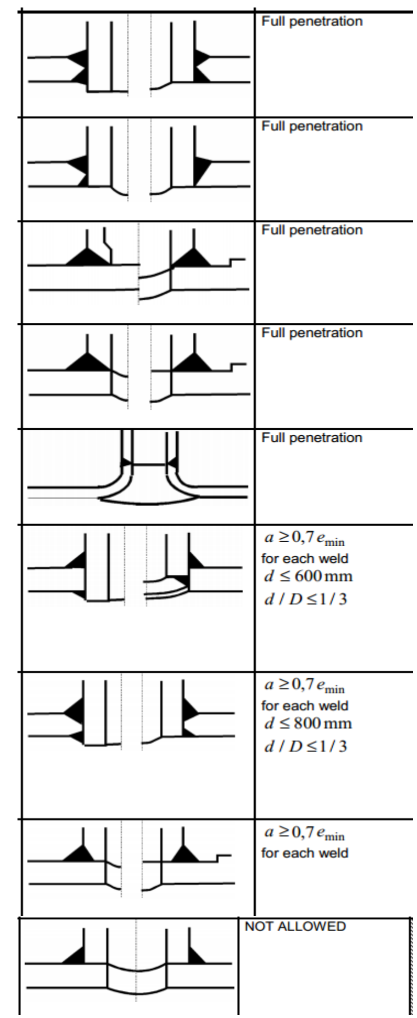
- EN 13445-3 annex A is a good reference for designing pressure bearing welds. EN 1708-1 is also a very useful hamonised standard. Some examples:

Longitudinal welds | Circular welds | Flat ends | Nozzles







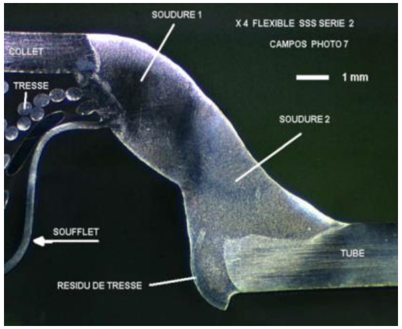


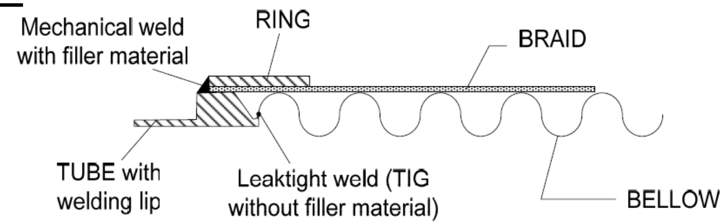
Welders and procedures qualification

	Steel	Aluminium
Welding procedure approval	EN ISO 15614-1:2004 Specification and qualification of welding procedures for metallic materials - Welding procedure test - Arc and gas welding of steels and arc welding of nickel and nickel alloys	EN ISO 15614-2:2005 Specification and qualification of welding procedures for metallic materials - Welding procedure test - Arc welding of aluminium and its alloys
Qualification of welders	EN 287-1:2004 Qualification test of welders - Fusion welding - Steels	EN ISO 9606-2:2004 Qualification test of welders - Fusion welding - Aluminium and aluminium alloys
Qualification of welding operators	EN 1418:1998 Welding personnel - Approval testing of welding operators for fusion welding and resistance weld setters for fully mechanized and automatic welding of metallic materials	

Some typical mistakes causing leaks

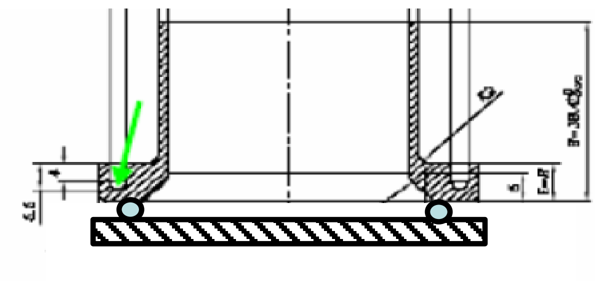
Flexible hose

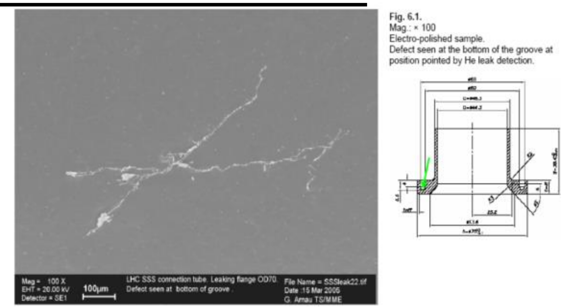




Same weld including braid/ring/bellows → separate weld functions

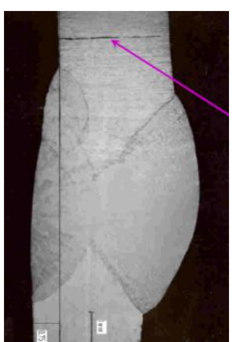
Flanges made of cold rolled material





Leak through material inclusions → QA of raw materials, or 3-D forged flanges (but expensive!)

Sheet metal work vessel

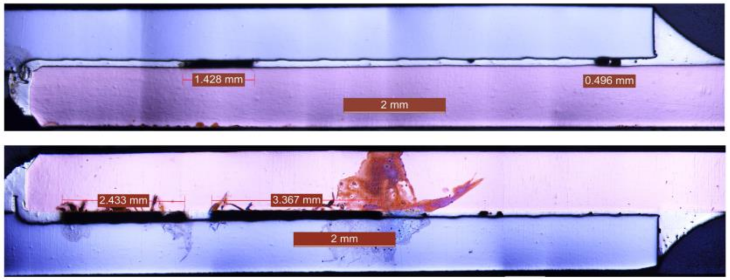


Leak through material crack → QA of raw materials,

Brazing

- Often the only solution to join different materials (ex: copper to stainless steel; stainless steel to ceramics…)
- Vacuum brazing (no flux required) gives the most reliable joints, but at a cost
- Thorough cleaning after brazing with flux is mandatory. Poor cleaning often results in the development of leaks in stainless steel due to corrosion!
- Useful standards for brazing specification and execution:
  - EN 13134:2000 Brazing - Procedure approval
  - EN 13133:2000 Brazing - Brazer approval
  - EN 12797:2000 Brazing - Destructive tests of brazed joints
  - EN 12799:2000 Brazing - Non-destructive examination of brazed joints
  - EN ISO 18279:2003 Brazing - Imperfections in brazed joints

Example of flame brazed stainless steel to copper transition for a thermal shield cooling circuit

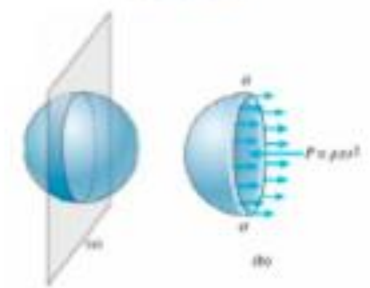


Mechanical considerations

Thin shells under internal pressure

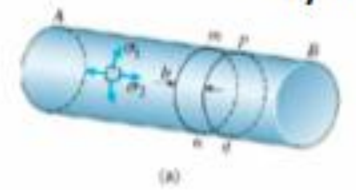
valid for $r \geq 10t$

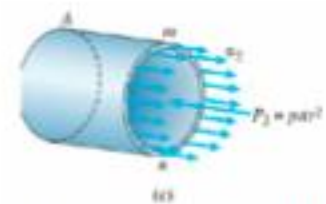
Sphere

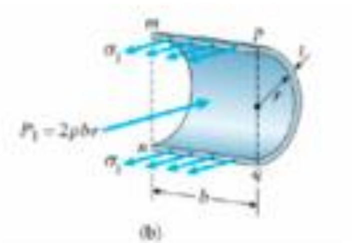


$$\sigma_1 = \sigma_2 = \frac{pr}{2t} \qquad \sigma_3 \cong 0$$

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 σ_a is the maximum allowable stress

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

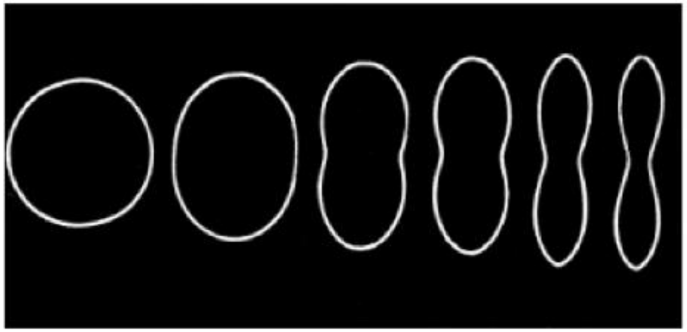
$$\frac{pr}{t} \leq \sigma_a$$

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

Radial buckling under external pressure

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

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



- 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:

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

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

- Alternatively, we need to add reinforcements

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


Stress relieving


Forged cradle

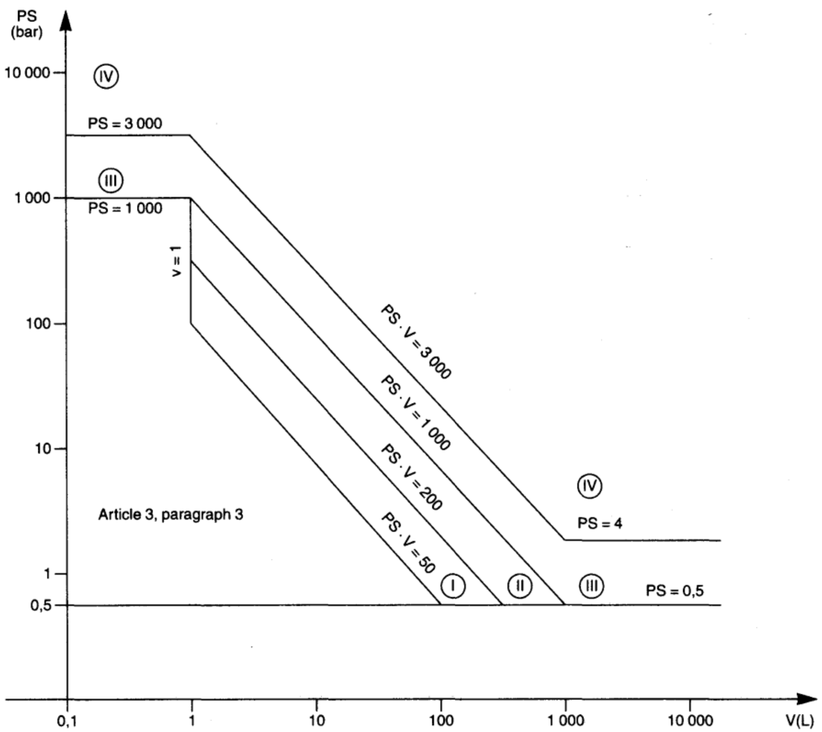

Final lathe machining


3-D dimensional control in Industry


Out-doors storage at CERN

Pressure vessel codes regulations

- Pressure European Directive 97/23/EC (PED) is obligatory throughout the EU since 2002
  - Applies to internal pressure **≥ 0.5 bar**
  - Vessels must be designed, fabricated and tested according to the essential requirements of Annex 1 (Design, safety accessories, materials, manufacturing, testing, etc.)
  - 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-dangeroureous 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 comformity with the PED, within their scope. Uselful codes for cryostat design and fabrication:
  - EN 13458-1:2002 Cryogenic vessels - Static vacuum insulated vessels - Part 1: Fundamental requirements
  - EN 13458-2:2002 Cryogenic vessels - Static vacuum insulated vessels - Part 2: Design, fabrication, inspection and testing + EN 13458-2:2002/AC:2006
  - EN 13458-3:2003 Cryogenic vessels - Static vacuum insulated vessels - Part 3: Operational requirements + EN 13458-3:2003/A1:2005
  - EN 13445-1:2009 Unfired pressure vessels - Part 1: General
  - EN 13445-2:2009 Unfired pressure vessels - Part 2: Materials
  - EN 13445-3:2009 Unfired pressure vessels - Part 3: Design
  - EN 13445-4:2009 Unfired pressure vessels - Part 4: Fabrication
  - EN 13445-5:2009 Unfired pressure vessels - Part 5: Inspection and testing
  - EN 13445-8:2009 Unfired pressure vessels - Part 8: Additional requirements for pressure vessels of aluminium and aluminium alloys

- Other codes such as the French CODAP or the American ASME Boiler and Pressure Vessel Code can be used, but proof of conformity is at the charge of the manufacturer

Useful material standards for cryostats

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

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

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

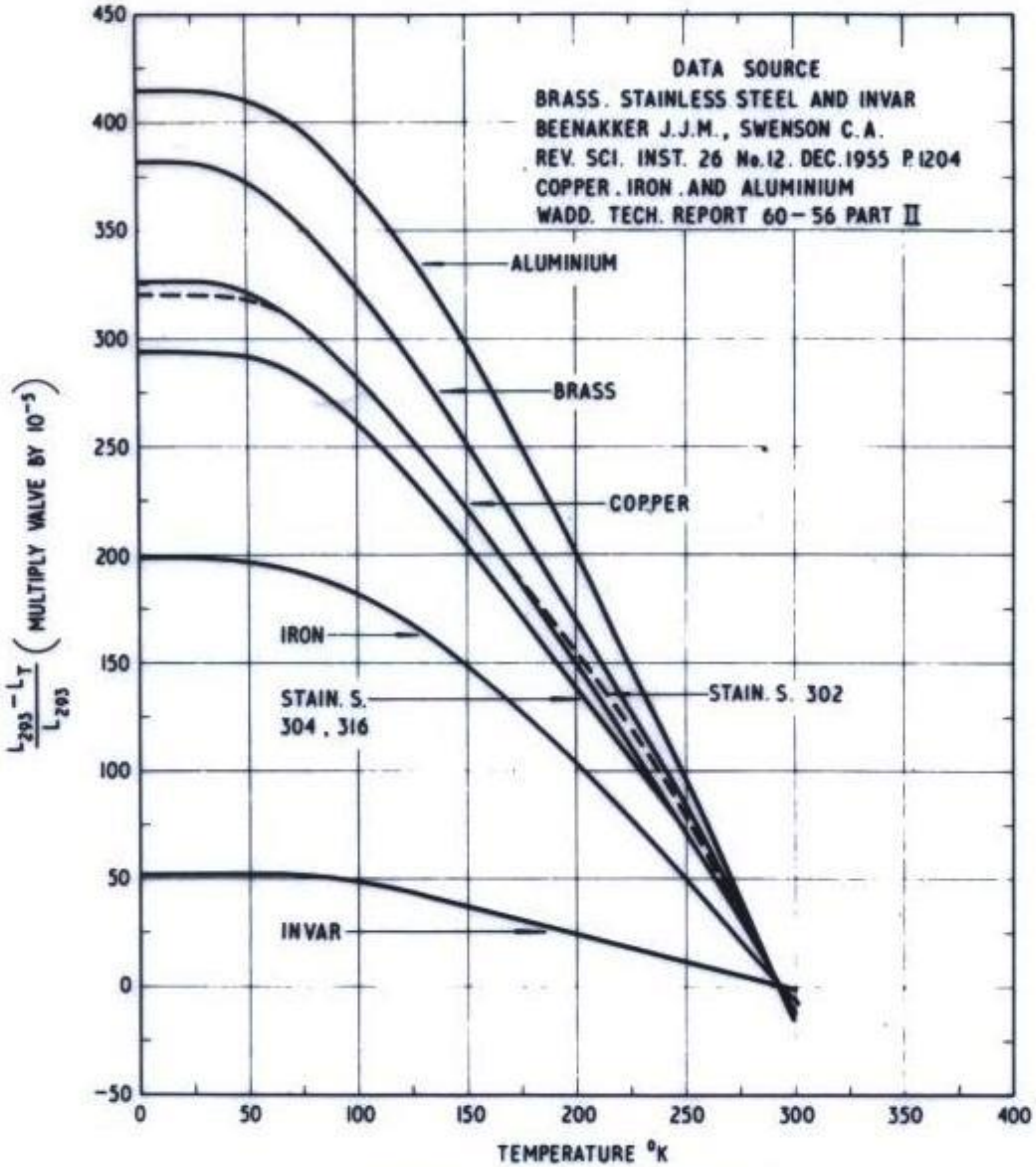
Material	$R_{p1.0}$ /R_m (MPa)	f (MPa)	f_{test} (MPa)
AW 5083-O/H111	125/270	83	119

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

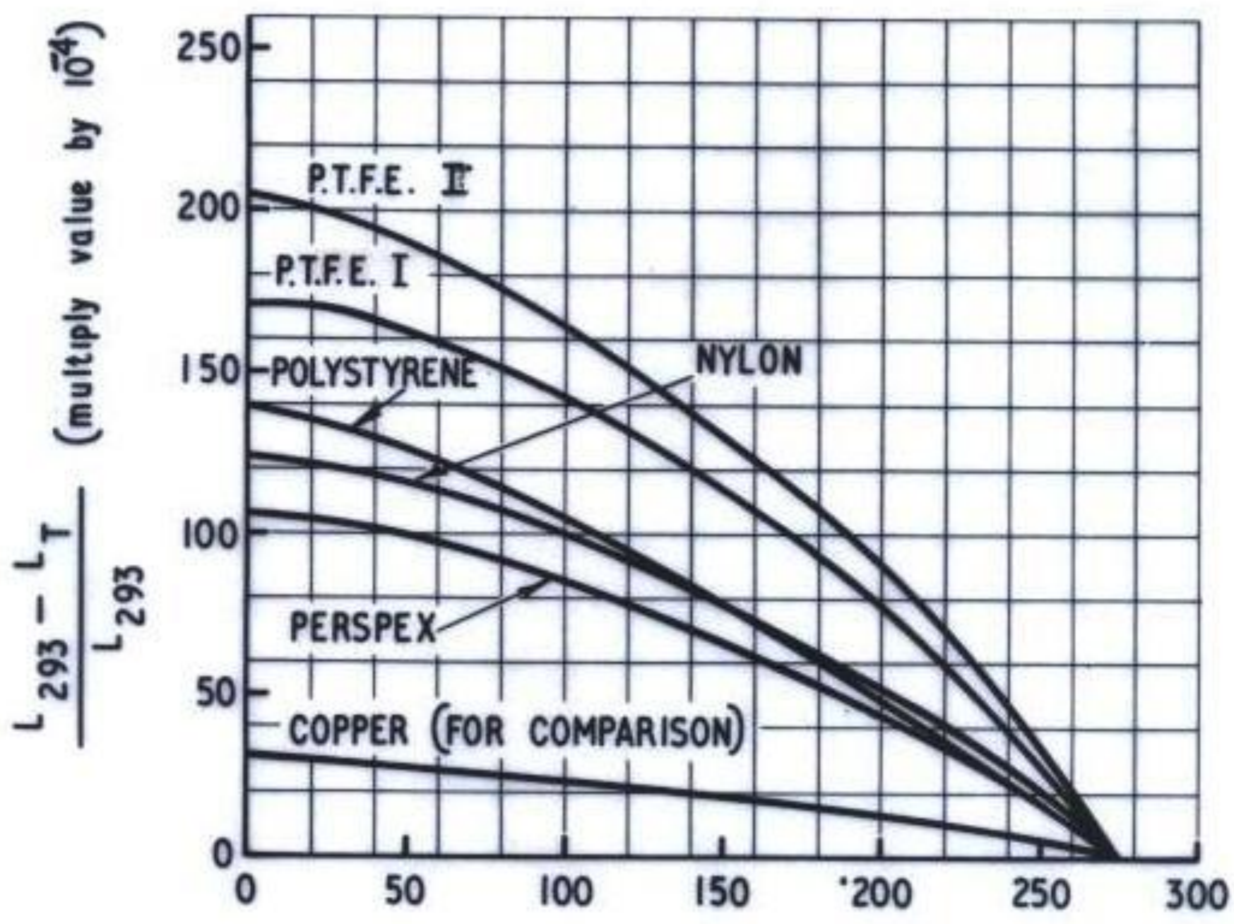
Thermo-mechanical considerations

Thermal expansion of some metals



THERMAL EXPANSION OF METALS

Thermal expansion of some plastics

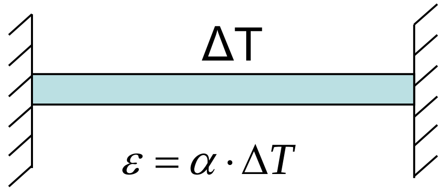


THERMAL EXPANSION OF PLASTICS

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

Thermal stress: 3 cases

A) Restrained component



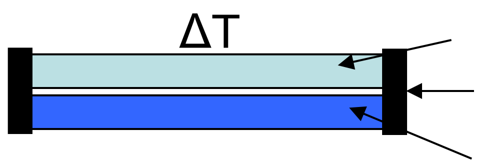
$$\varepsilon = \alpha \cdot \Delta T$$

$$\sigma = \frac{\alpha \cdot \Delta T}{E}$$

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

$E =$ Young modulus

B) Assembly of different materials



$$\varepsilon_1 = \frac{E_2 A_2}{E_1 A_1 + E_2 A_2}(\alpha_2 - \alpha_1) \cdot \Delta T$$

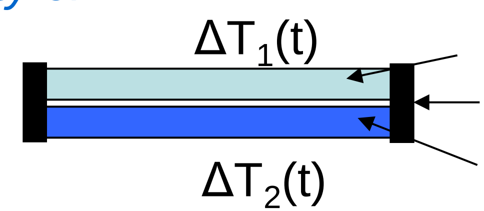
$$\sigma_1 = E_1 \varepsilon_1 = \frac{E_1 E_2 A_2}{E_1 A_1 + E_2 A_2}(\alpha_2 - \alpha_1) \cdot \Delta T$$

$$\varepsilon_2 = \frac{E_1 A_1}{E_1 A_1 + E_2 A_2}(\alpha_2 - \alpha_1) \cdot \Delta T$$

$$\sigma_2 = E_2 \varepsilon_2 = \frac{E_1 E_2 A_1}{E_1 A_1 + E_2 A_2}(\alpha_2 - \alpha_1) \cdot \Delta T$$

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

(different material diffusivity or different cooling)



Supporting systems

Supporting system

- Mechanical housing of cryogenic devices (supporting systems):
  - Supporting of (sometimes heavy) devices
  - Accurate & reproducible positioning (almost always)
  - Precise alignment capabilities (SC devices in accelerators)

- Many solutions available:
  - Tie rods
  - Suspended posts
  - Compression posts
  - …other

- Each having specific advantages/drawbacks depending on:
  - SC device's weight and cryostat assembly methods
  - Vacuum vessel external supporting (supported? Suspended?)
  - Adjustment of cold mass inside vacuum vessel
  - …

- For the LHC, the compression posts were preferred because of :
  - Heavy cold masses (~30 tons!) → supported on jacks on tunnel floor
  - Cryostat assembly based on sliding (or rolling through) of cold mass standing on supports
  - No need for adjustment, magnets individually fiducialised and machine aligned w.r.t. external cryostat-mounted fiducials

LHC dipole cryostat assembly

Assembly bench

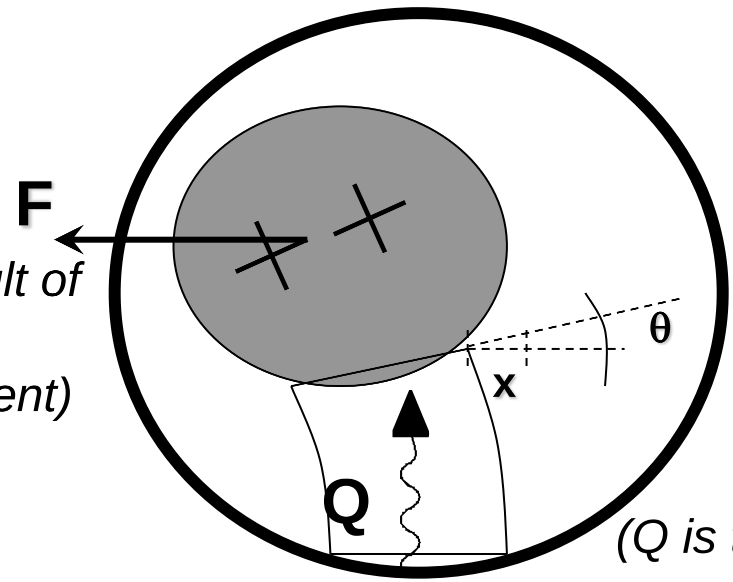
Pulling through sliding on vacuum vessel

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)

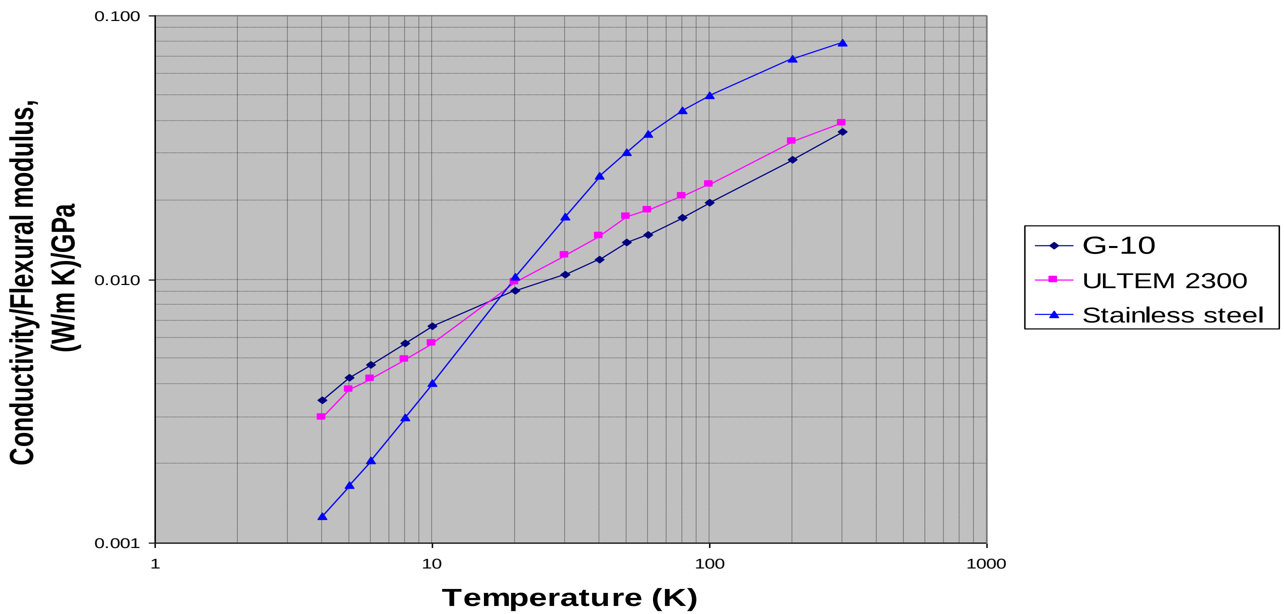


(The acceptable x and θ are alignment requirements)

(Q is to be within budget)

→ Flexural stiffness/conductivity is an interesting figure of merit in the choice of the material

Choice of the material



- St.steel → interesting below 20K
- G10 and Ultem 2300 → preferable at 20K < T < 300K
- Other interesting material: Carbon-fiber Epoxy → also interesting below 20 K (not shown in diagram)

For LHC, a Glass-fiber Epoxy Composite (GFRE) was chosen:

- Good conductivity/flexural stiffness
- Widely available on the market → cost effective for large production (5000 units!)

…but a specific thermal conductivity validation campaign was needed.

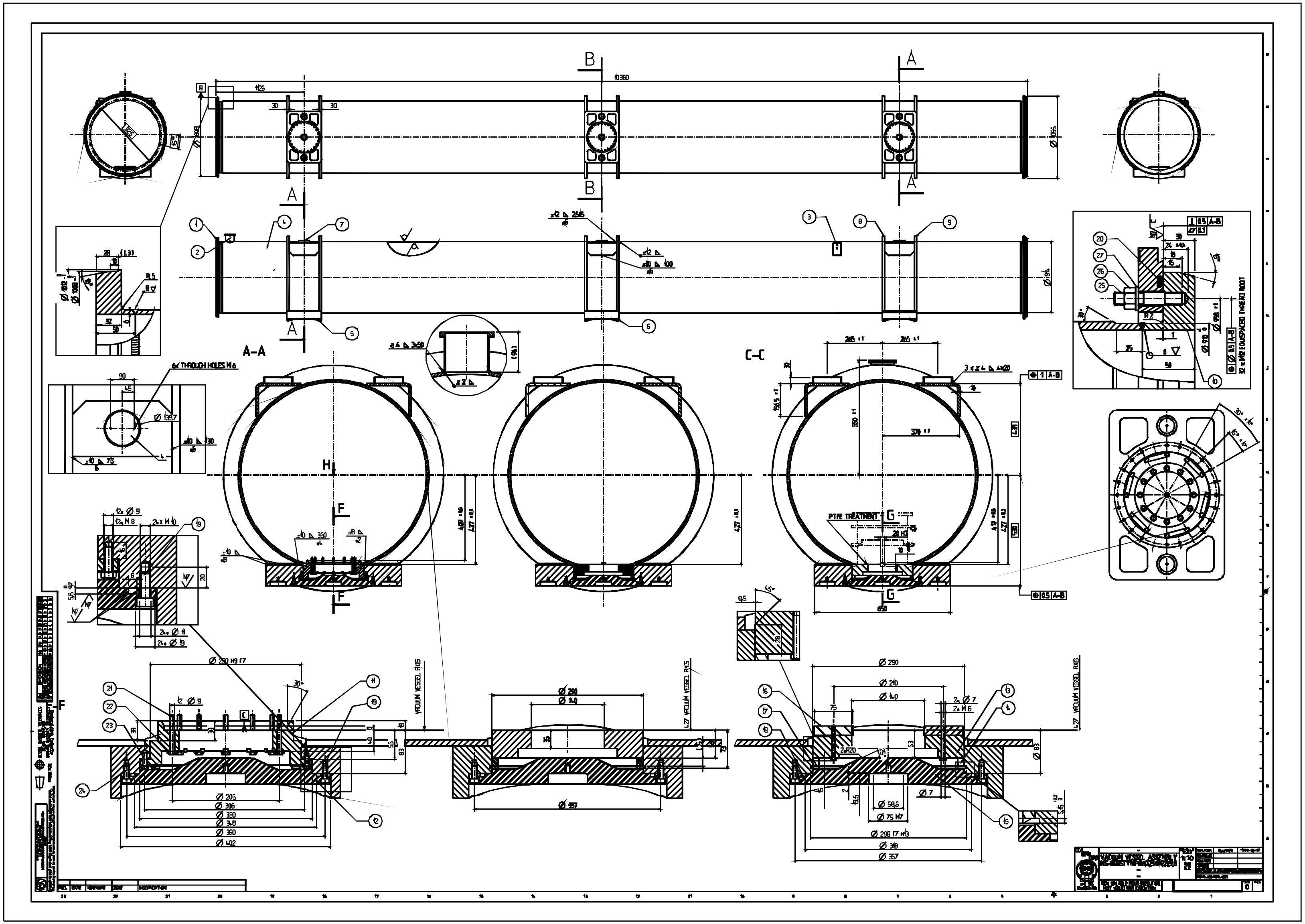
No. of supports, spacing and positions:

- 2 support posts whenever possible:
  - Isostatic: well known forces on cold mass/supports/vacuum vessel, not conditioned by handling
  - Optimise spacing to minimize vertical sag

- Add 3rd support post if necessary for long cold masses:
  - Limit vertical sag to acceptable values (cold mass straightness)
  - Hyper-static: precautions when handling, use of specific girders

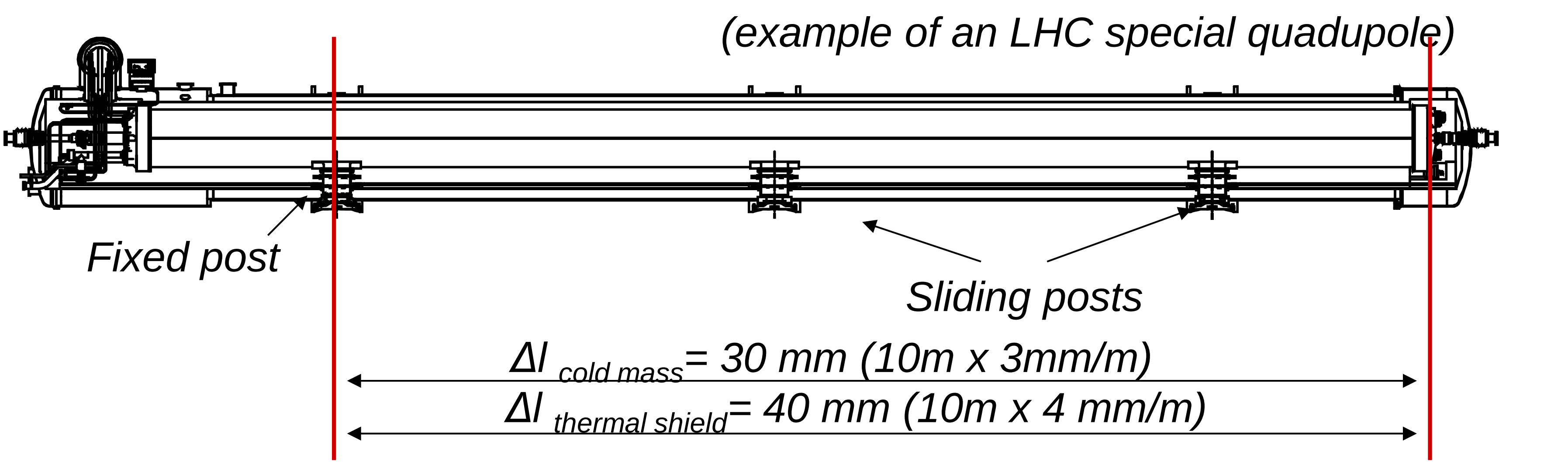
- Position of support posts on vacuum vessel:
  - Always above the external jacks → direct load transfer from cold mass to ground, hence the vacuum vessel is unstressed (only vacuum loads).

The LHC vacuum vessel, a 3 supports solution



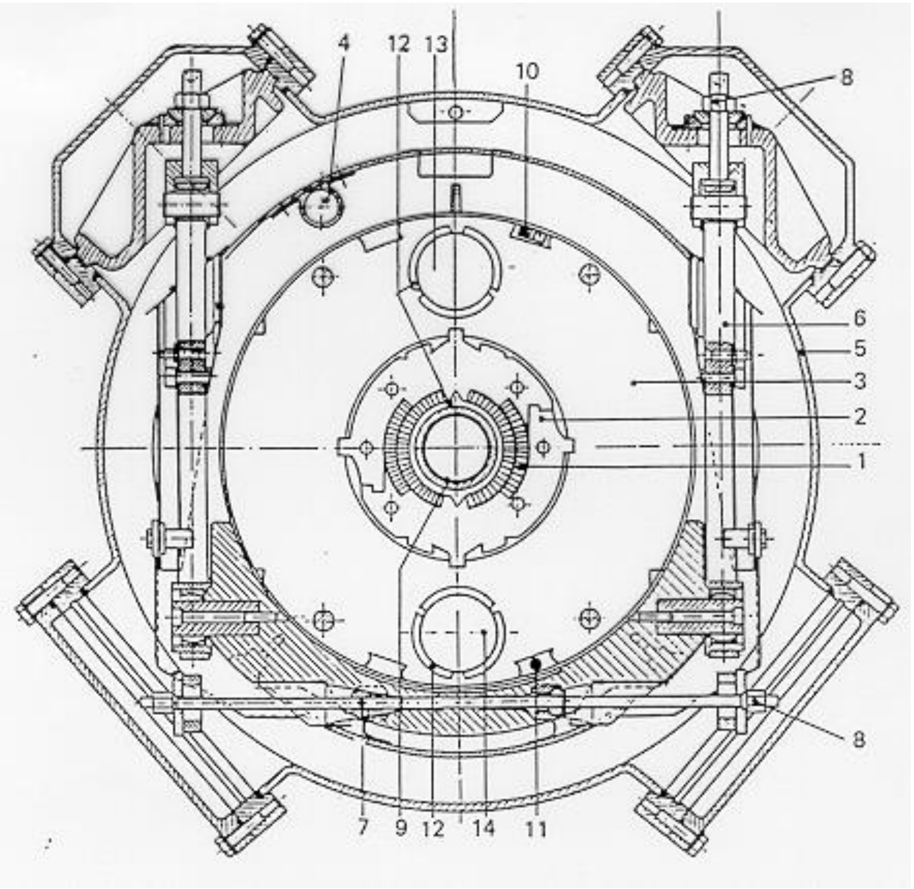
Longitudinal thermal contractions

- 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
- Flexible thermalisations anchors



Other solutions

HERA Dipole

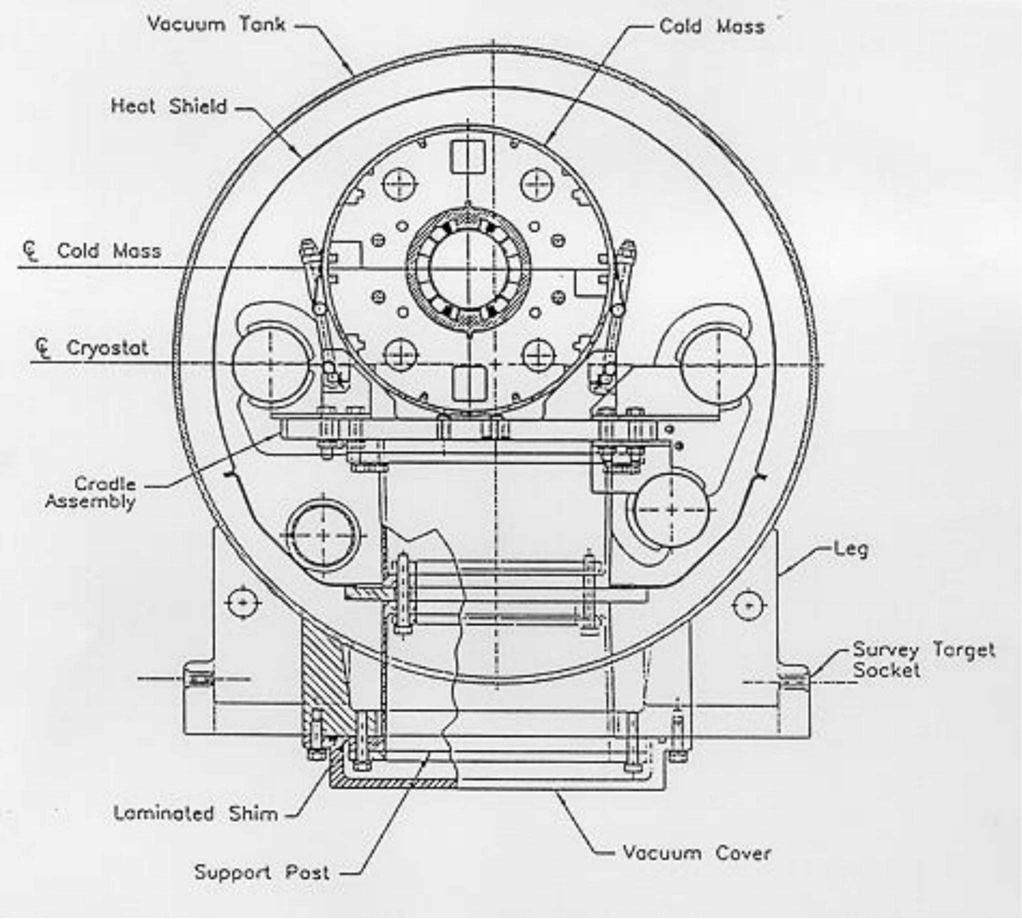


HERA Dipole Cross Section

(1) Two layer coil
(2) Laminated aluminum collars
(3) Laminated yoke
(4) Shield coooling tube
(5) Vaccum container
(6) Glass fiber tape
(7) Glass fiber rod
(8) Adjustment
(9) Beam tube with correction Coils
(10) Forward and return bus
(11) Correction coil bus
(12) One-phase helium
(13) Two-phase helium
(14) Aluminum filler

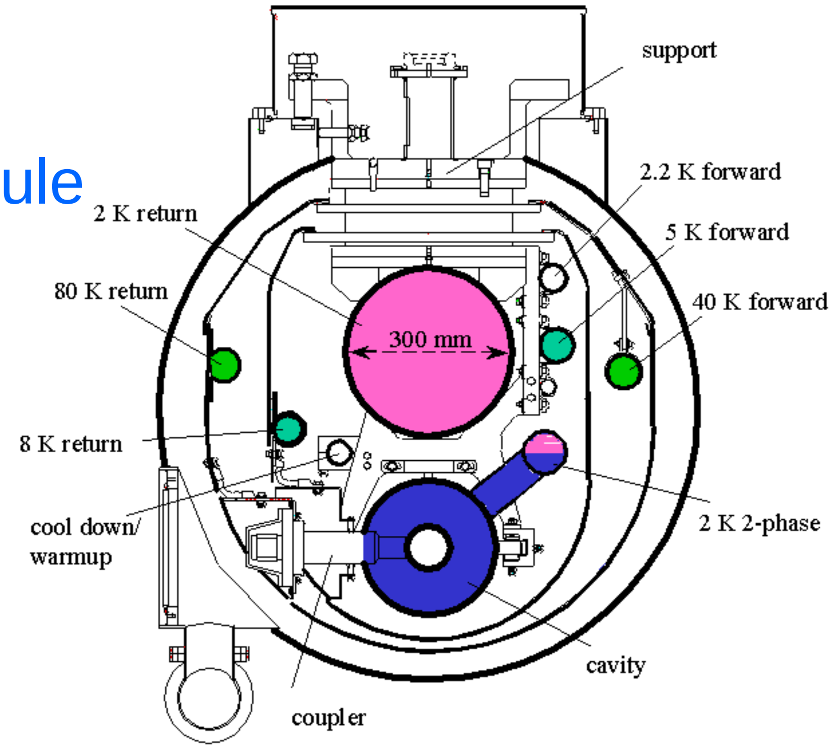
Other solutions

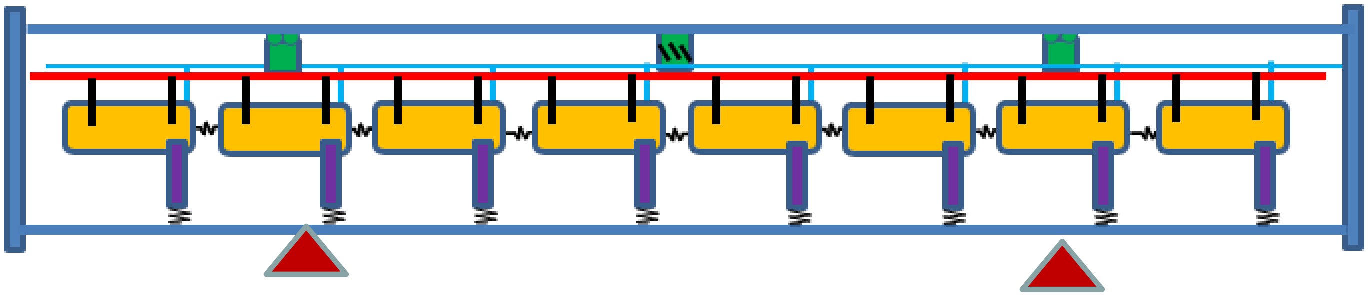
RHIC Dipole



Other solutions

Tesla/TTF/ILC cryomodule





RF coupler (with bellows)

Invar longitudinal positioner

Inertia beam

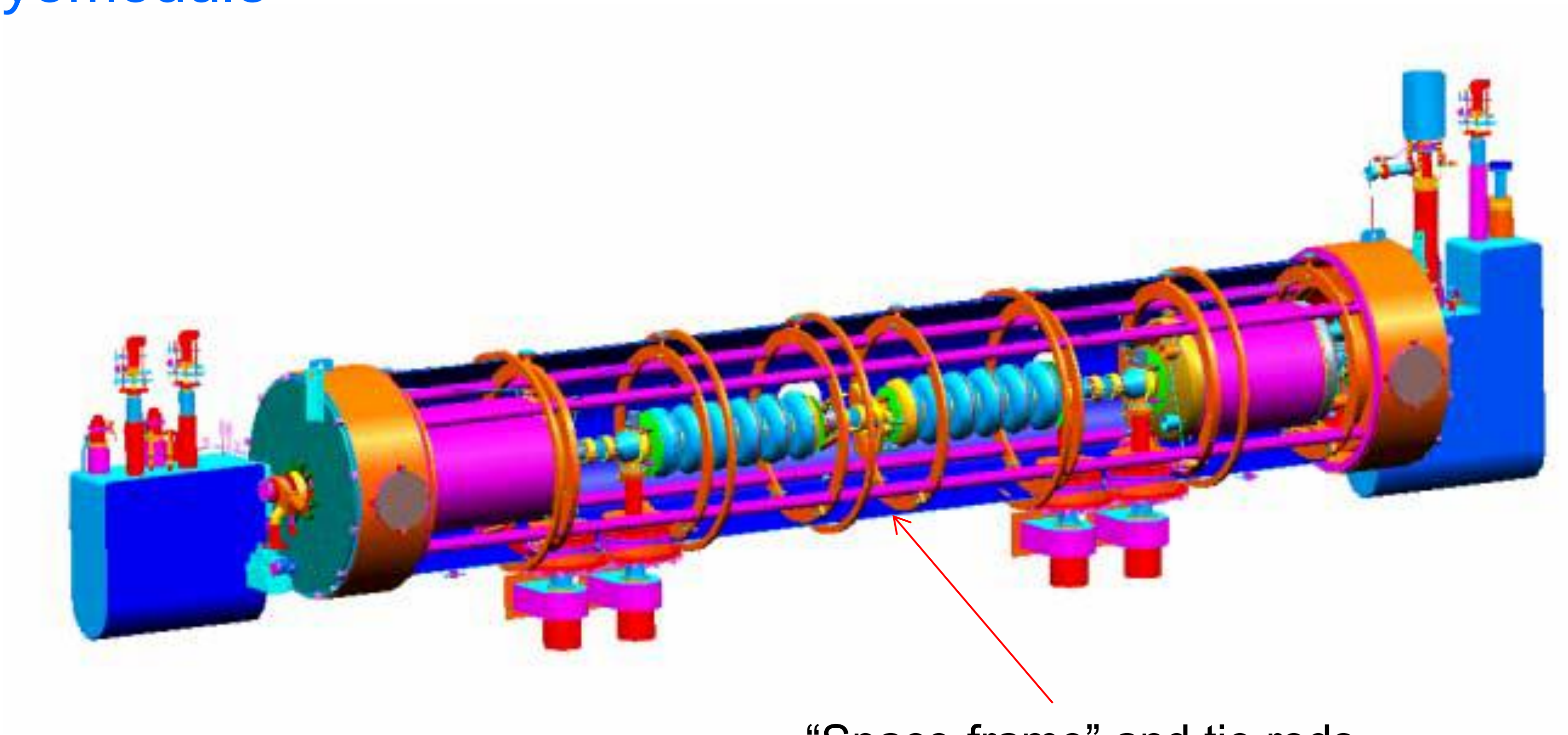
Fixed support

Sliding support

External supports (jacks)

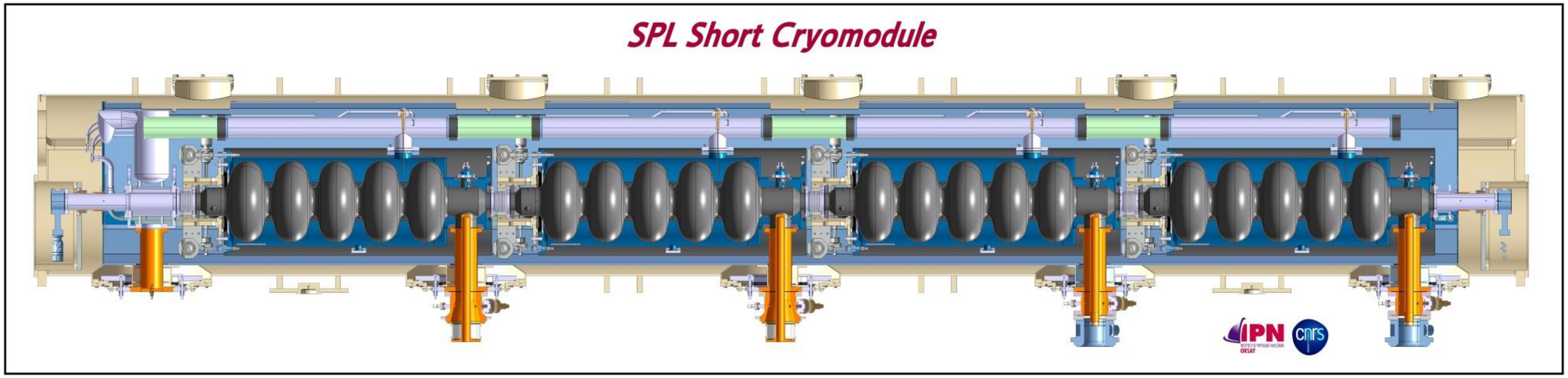
Other solutions

SNS high beta cryomodule

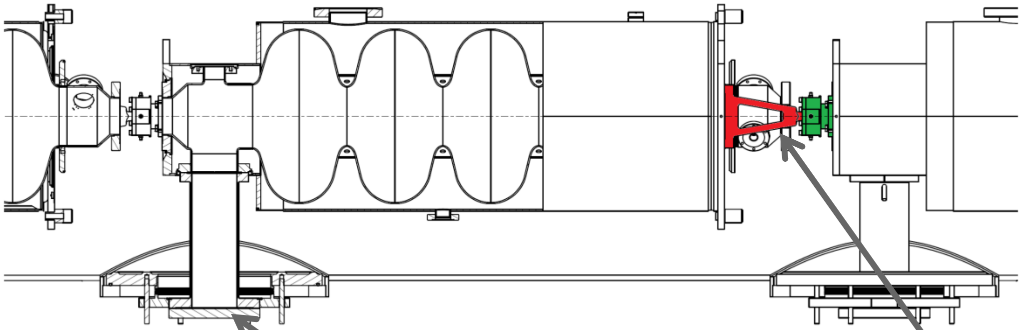


"Space-frame" and tie rods

Other solutions



SPL cryomodule



Vacuum vessel

Double tube of the power coupler as main support

Inter-cavity support ensures alignment

Pressure relief protection systems

Pressure relief protection systems

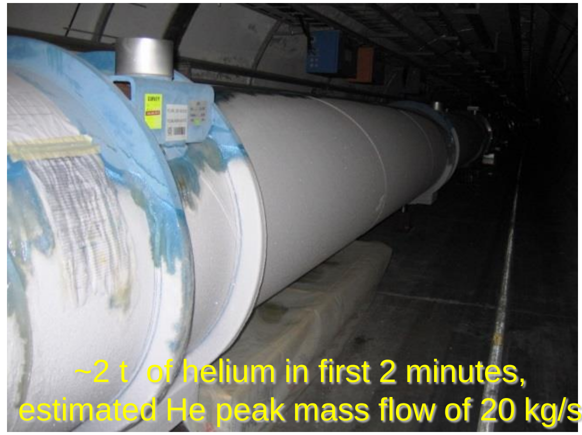
- Cryostats include large cold surfaces, inventory of cryogenic fluids, sometimes large stored energy (e.g. energized magnets)
  - a potentially unstable energy storage which will tend to find a more stable state of equilibrium
  - Through a thermodynamic transformation which can be sudden and uncontrolled with a dangerous increase of pressure
- Protect personnel (burns, ODH) and equipment (direct and collateral damage)
- Risk hazards:
  - Sources of pressure:
    - Compressors connected to cryo lines
    - Connection to higher pressure source (e.g. HP bottles)
    - 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
    - Heating/vaporization of cryogens from sudden release of stored energy in SC device (e.g. quench or arcing in a SC magnet circuit)
    - Uncontrolled air/nitrogen venting of insulation vacuum with sudden condensation on cold surfaces
    - Uncontrolled 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

Often the most critical

A typical example…LHC 19th sept.2008

The CERN Accelerator School

…5 MW arc in an interconnect



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

Insulation vacuum relief device

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

…uprooting of jacks

General approach

Risk analysis & mitigation:

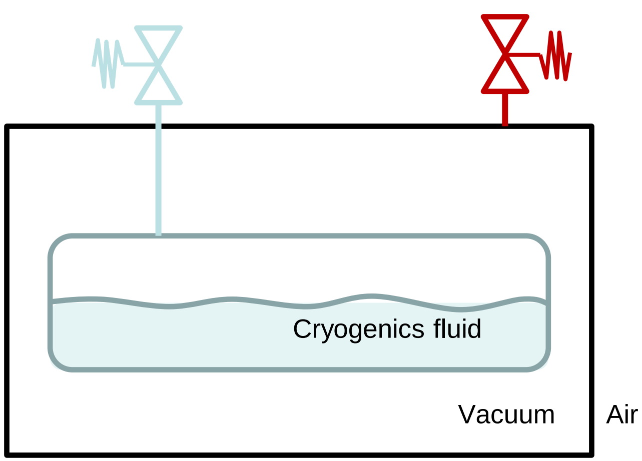
- Make a thorough risk analysis and evaluate risk hazards
- Identify mitigation measures (e.g. protections of exposed bellows and flanged connections)
- Identify severity of consequences and appreciate probability of the event
- Define the maximum credible incident(s) and design the safety relief system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

Design steps:

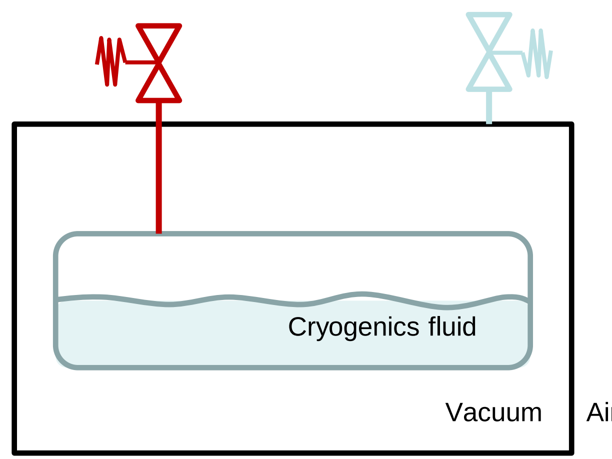
- Estimate the heat exchange and its conversion to mass flow rates to be discharged
- Check the sizing of piping (generally designed for normal operation) to the relief device and increase if necessary
- Choose the type of safety device (burst disks, valves, plates) and size the safety device (DN and set pressure). Make use of safety device manufacturers formulas and charts
- Size recovery piping downstream of safety device and check venting needs in the buildings where the release occurs (ODH issue)

Pressure Safety Relief Devices

- Vacuum vessel
  - Typical ΔPmax < PS (0.5 bar relative to atm. for vac.vessels)
  - Define DN of valve and set pressure, P_T



- Cryogenic fluid vessel
  - Typical ΔPmax < PS
  - PS depends on the device (~few bar for SC cavities, up to ~ 20 bar for magnets)
  - Define DN of valve and set pressure, P_T



According to European directive 97/23/EC and EN 13648 "Safety devices for protection against excessive pressure"

Cryogenic fluid vessel

- The cryogenic fluid volume must be protected against over-pressure consecutive to unexpected heat transfers

Hazard: breach in insulation vacuum:

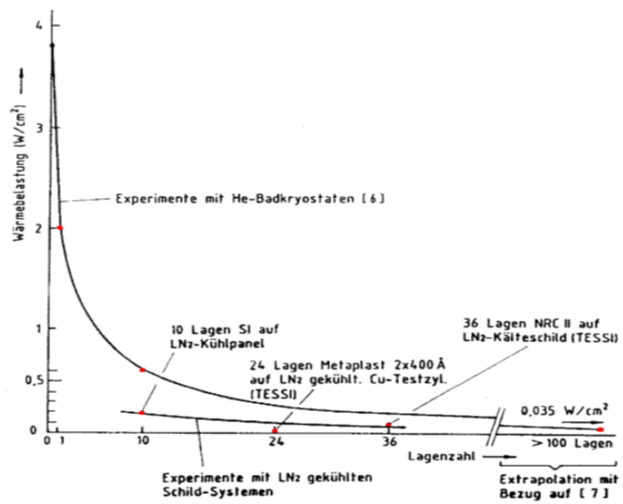
- Uncontrolled air/nitrogen venting of insulation vacuum with sudden condensation on cold surfaces

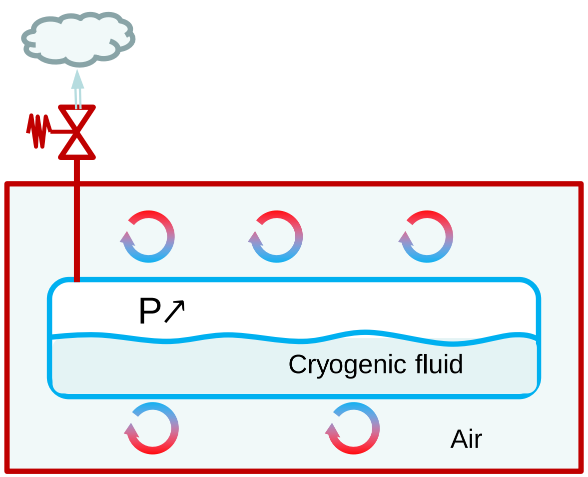
Heat flux:

- From 3 experimental sources internationally recognised:
  - W. Lehman and G. Zahn, "Safety Aspects for LHe Cryostats and LHe Transport Containers," ICEC7, London, 1978
  - G. Cavallari, et. al., "Pressure Protection against Vacuum Failures on the Cryostats for LEP SC Cavities," 4th Workshop on RF Superconductivity, Tsukuba, Japan, 14-18 August, 1989
  - M. Wiseman, et. al., "Loss of Cavity Vacuum Experiment at CEBAF," *Advances in Cryogenic Engineering,* Vol. 39, 1994, pg. 997.

Experimental values:

- 0.6 W/cm2 for a superinsulated tank of a bath cryostat
- Up to 4 W/cm2 for a bare surface tank of a bath cryostat





Cryogenic fluid vessel (cont.d)

- The safety device should be designed to relieve a mass flow equivalent to the highest heat load
- Calculate the mass flow, Q_m to be released by the safety device (EN13468-3.4)

2 cases for calculating mass flow Q_m:

- Below critical pressure (p<2.23 bar for helium):
  - Bi-phase with liquid boil-off → take Lv (latent heat)
- Above critical pressure (often the case):
  - Supercritical fluid expelled → use a "pseudo latent heat" Lv'

$$L' = v\left[\frac{\partial h}{\partial v}\right]_{P0} \text{ where } \frac{\sqrt{v}}{v\left[\frac{\partial h}{\partial v}\right]_{P0}} \text{ is maximum}$$

P0	[bara]	P0 < 40% Pc	40% Pc<P0<Pc	P0>Pc
Qm	[kg/s]	$Q_m = \frac{W}{L}$	$Q_m = \left(\frac{v_g - v_l}{v_g}\right)\frac{W}{L}$	$Q_m = \frac{W}{L'}$

- P0 : relieving pressure [bara]
- Pc : critical pressure [bara] (2.23 for He)
- Qm : mass flow in [$kg.s^{-1}$]
- W : heat load [W]
- L : latent heat in relieving conditions [$J.kg^{-1}$] (20.10^3 at 1 bar for He)
- vg/vl : specific volume of saturated gas/liquid at P0 [$m^3.kg^{-1}$]
- L' : specific heat input, see EN13468-3.4
- h : enthalpy of the fluid [J/kg]
- v : specific volume [$m^3.kg^{-1}$]

Cryogenic fluid vessel (cont.d)

- The minimum required flow area A is calculated with conservative assumptions on fluid properties
- For compressible fluids, the mass flow through a restriction depends on the downstream pressure until a fixed Pb/P0 ratio (0.49 for helium)

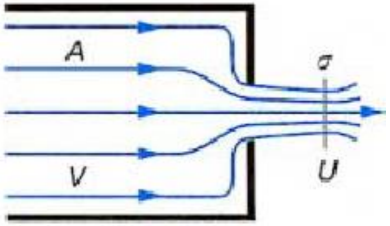
$$\frac{P_b}{P_0} \; ? \; \left(\frac{2}{k+1}\right)^{k/(k-1)} = 0.49 \text{ for He}$$

$\leq$ → Critical flow: $K_d = 1$

$\geq$ → Subcritical flow: $K_d = \sqrt{\dfrac{\frac{2k}{k-1}\left[\left(\frac{p_b}{p_o}\right)^{2/k} - \left(\frac{p_b}{p_o}\right)^{(k+1)/k}\right]}{k\left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}}}$

$$A \geq 3.469 \frac{Q_m}{K_d . C . \alpha . \sqrt{P_0 . \rho}}$$

- P0 : relieving pressure [bara]
- Pb : back pressure [bara]
- Qm : mass flow in [kg.h^{-1}]
- A : required minimum cross-sectional flow area [mm2]
- k : isentropic exponent [-] (1.67 for He)
- ρ : density at upstream conditions [kg. m^{-3}]
- α: discharge coefficient, depends on geometry.
- $C = 3.948\sqrt{k\left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}}$ (2.87 for He)

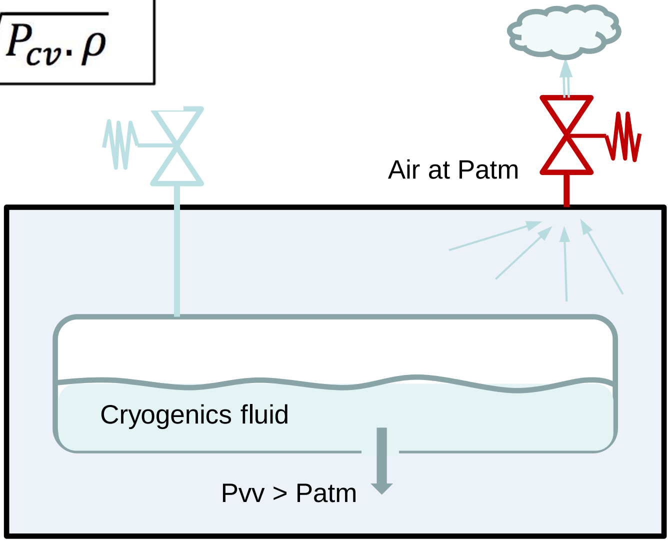


Vacuum vessel

- The vacuum vessel safety device is designed to relieve a mass flow equal to the highest incoming flow but at warmer temperature while keeping the vessel pressure within the PS
- Identify the worst case scenario (highest mass flow and coldest fluid)
- Often the worst case corresponds to a rupture of a cryogenic circuit:
  - ➢ The cryogenic fluid flows into the vacuum vessel → the fluid vaporizes/expands in contact with the warm walls → the internal pressure increases until the safety device set pressure → the device opens and the fluid is relieved to atmosphere
- Calculate the mass flow from the reservoir to the vacuum vessel
  - – Estimate the area of the breach in the cryogenic circuit
  - – Calculate the mass flow through an orifice

$$Q_{m1} = 0.2883\, A . Kd . C . \alpha . \sqrt{P_{cv} . \rho}$$

- Pcv : relieving pressure of cryogenic vessel safety device [bara]
- Qm : mass flow in [$kg.h^{-1}$]
- A : orifice in the cryogenic circuit [mm2]
- ρ : density at upstream conditions [$kg.\ m^{-3}$]
- α: discharge coefficient, depends on geometry. (0.73 for a hole)
- $C = 3.948\sqrt{k\left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}}$ (2.87 for He)
- k : isentropic exponent [-] (1.67 for He)
- Kd=1 (Pb<<P0 : critical flow)



Vacuum vessel (cont.d)

- Calculate the minimum required flow area, A for the safety device
  - Mass flow through the safety device = mass flow to the vacuum vessel
    - Qm1=Qm2
    - A > than the orifice area as Pb/P0 is lower and the gas is warmer.
  - The flow area is highly dependent on the relief temperature, usually difficult to estimate
    - First case T_{relief} = 300K
    - If the device is too big, investigations are needed to estimate T_{relief}

- Ps : relieving pressure [bara]
- Pb : back pressure [bara] (often atmospheric)
- Qm2 : mass flow in [kg.h^{-1}]
- A : required minimum cross-sectional flow area [mm2
- k : isentropic exponent [-] (1.67 for He)
- ρ : density at upstream conditions [kg. m^{-3}]
- α: discharge coefficient, depends on geometry.
- $C = 3.948\sqrt{k\left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}}$ (2.87 for He)

$$\frac{P_b}{P_0} \; ? \; \left(\frac{2}{k+1}\right)^{k/(k-1)}$$

≤ → Critical flow → $K_d = 1$

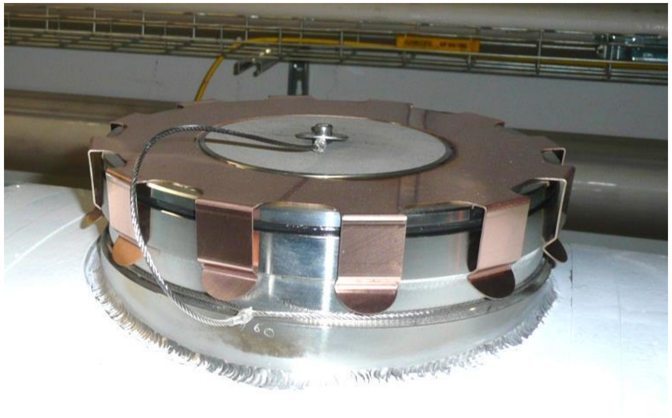
≥ → Subcritical flow → $K_d = \sqrt{\frac{\frac{2k}{k-1}\left[\left(\frac{p_b}{p_o}\right)^{2/k} - \left(\frac{p_b}{p_o}\right)^{(k+1)/k}\right]}{k\left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}}}$

$$A \geq 3.469\frac{Q_{m1}}{K_d.\mathrm{C}.\alpha.\sqrt{P_s.\rho}}$$

Examples of safety devices

Safety valves

Burst disks



LHC pressure release plates (DN200)

<u>Some suppliers:</u>
Herose, Rembe, Ramseyer, Leser…

Summary

- Since Dewar's invention, cryostats have evolved from simple containers for cryogens to sophisticated mechanical assemblies for SC accelerator devices for fundamental science as well as for industrial applications (e.g. NMR machines)
- Though the understanding of the heat transfer phenomena involved in a cryostat have considerably progressed since the time of Dewar, the main outstanding innovation was the introduction of MLI, in the 50^{ties}…
- …But the *enabling technologies*, have greatly evolved from "simple" "glass-blowing" to covering a wide range of disciplines, enhancing performance of modern cryostats:
  - Low thermal conductivity composite materials
  - Stainless steel (and low-carbon steel) sheet-metal work compatible with vacuum requirements
  - Vacuum and cryogenics technology
  - Leak-tight welding techniques
  - Leak detection with helium mass spectrometry
  - …
- The cryostat design engineer is confronted with a multidisciplinary environment in which he needs to master "a little of everything"
- …not to forget the industrialisation aspects when he is asked to produce cryostats in large series

Thank you for your attention!

Acknowledgements:

The work presented in this course is essentially the result of contributions from a number of colleagues and the work done during the design and construction of the LHC

I wish to acknowledge in particular for the material provided and for their contributions in preparing this course:

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