Mechanical design for vacuum technologies of particle accelerators

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Outline:

Vacuum chamber design

- External pressure
- Electromagnetic forces

Vacuum system as a mechanical system

- Bellows expansion joints
- Supports

Material choice

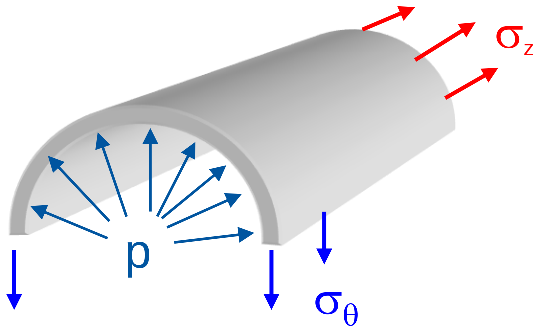
General guideline for mechanical design of vacuum components

Mechanical loads

Vacuum/pressure

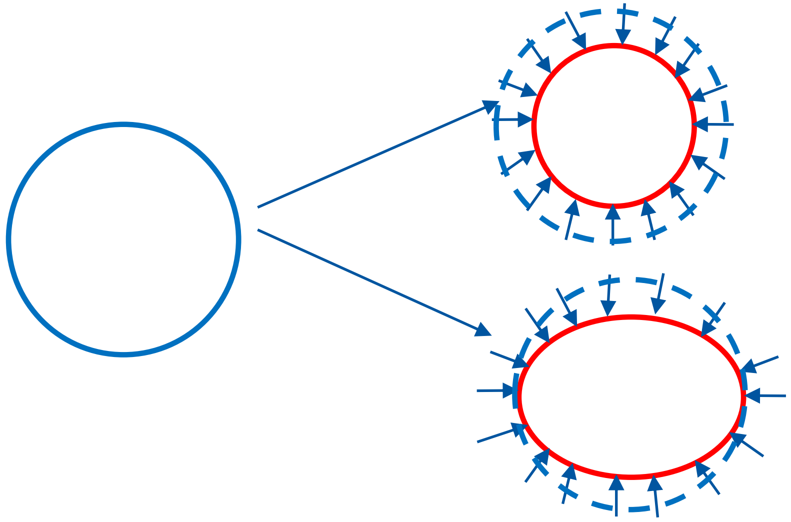
For a simple thin tube (radius R, thickness t):

Hoop stress: $$\sigma_\theta = \frac{p \cdot R}{t}$$



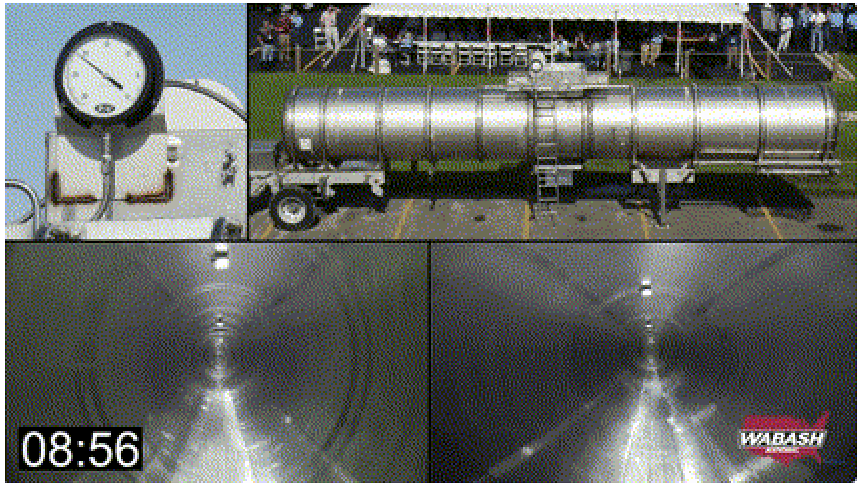
Longitudinal stress (for a close tube): $$\sigma_z = \frac{p \cdot R}{2 \cdot t}$$

Vacuum chamber collapse



Tube under external pressure

- Buckling modes (shape) depends on the boundary conditions.
- Sudden and brutal event.



Vacuum chamber collapse

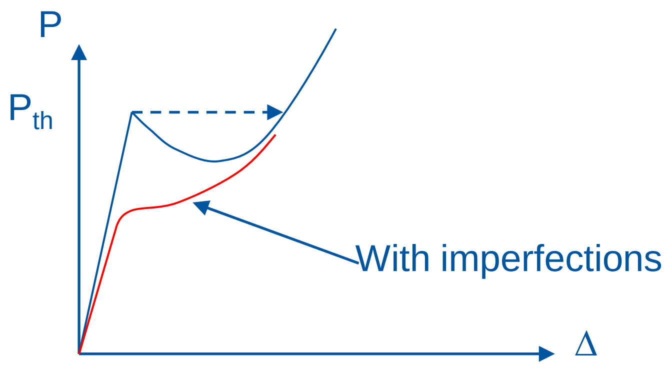
For an infinite elastic tube subjected to external pressure:

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

Safety factor of 3 is usually applied.

Design rule for stainless steel: $t \geq \frac{D}{100}$

At the critical pressure (3 bars), $\sigma_\theta \sim \frac{0.3 \cdot 100}{2} \sim 15$ MPa << σ_y !!!



Initial geometrical imperfection plays a critical role in buckling and shall be well considered.

Mechanical loads

Electromagnetic forces

Foucault's currents are governed by Maxwell's equation:

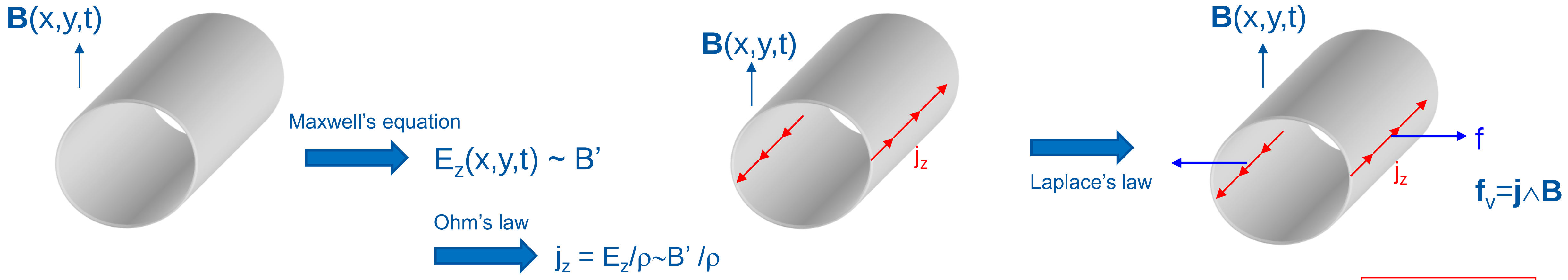
rot E=-∂**B**/∂t (-B')

j = **E**/ρ

B: magnetic field **j**: current density

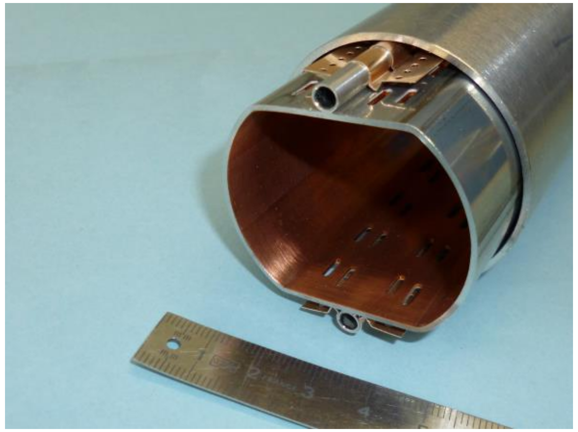
E: electric field ρ: electrical resistivity

In a long structure, subjected to a time dependent magnetic field B:



$f_v \sim B'B/\rho$

Orders of magnitude for cryogenic applications (beam screen)



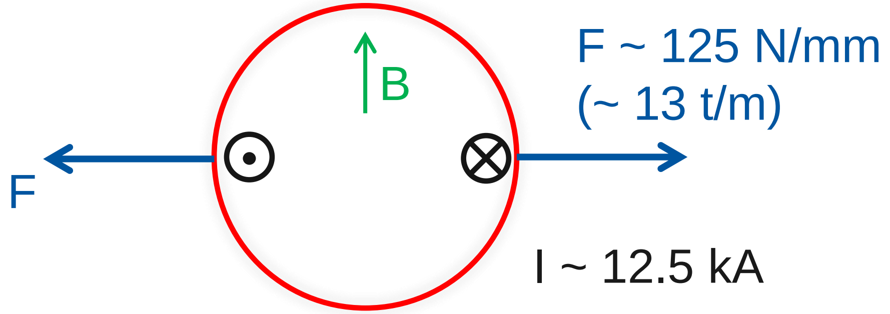
For a given magnetic configuration, force intensity ~ t/ρ

For a (colaminated) copper (0.1 mm thick) /stainless steel (1 mm thick) beam screen at cryogenic temperature:

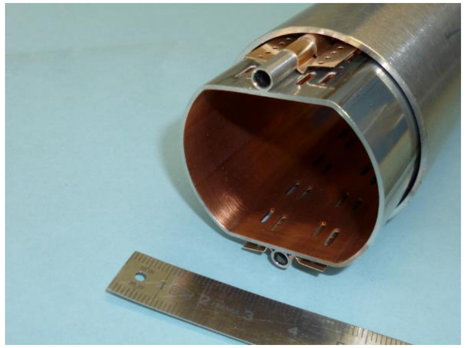
$$(t/\rho)_{st.st.} / (t/\rho)_{Cu} \sim (1/5E\text{-}7)/(0.1/1E\text{-}9) \sim 0.02$$

→ Lorentz' force are driven by copper

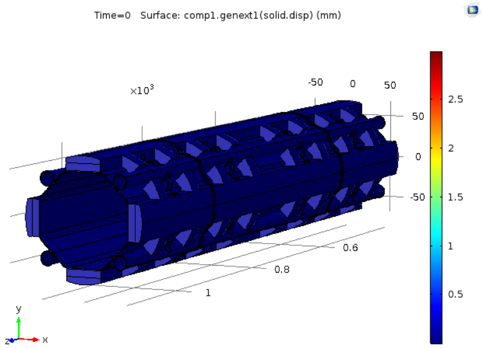
In a copper tube, 0.1 mm thick, radius of 25 mm, subjected to a magnetic field of 10 T with a decay of 100 T/s:



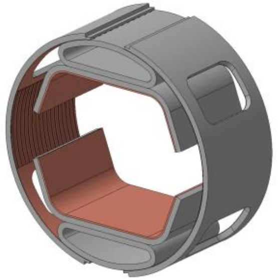
Some examples



LHC dipole:
- Coil aperture: ∅56 mm.
- Operation temperature: 4.5-20 K.
- Lorentz forces: ~ 10 kN/m (8.3 T).



HL-LHC focusing quadrupole:
- Coil aperture: ∅150 mm.
- Operation temperature: 60-80 K.
- Lorentz forces: ~ 320 kN/m (130 T/m).

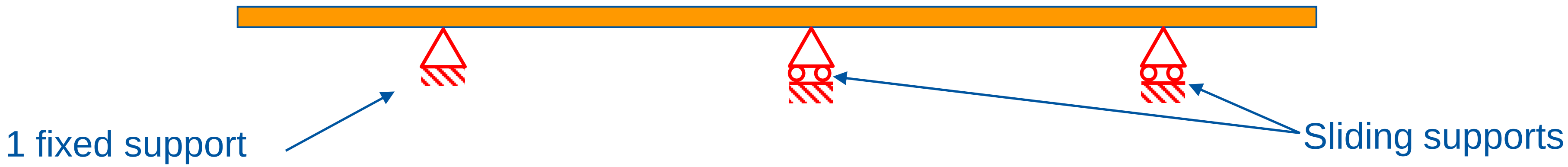


FCC-hh dipole:
- Coil aperture: ∅50 mm.
- Operation temperature: 60-80 K.
- Lorentz forces: ~ 180 kN/m (16 T).

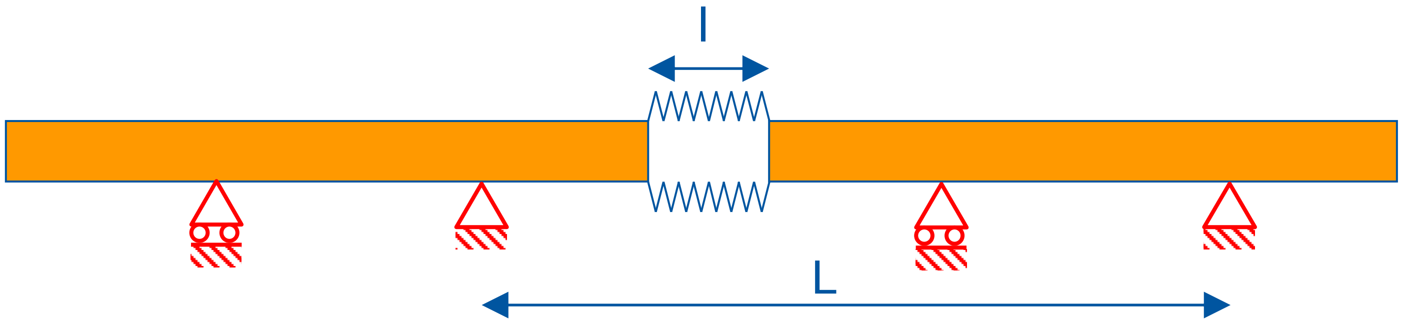
MedAustron dipole chamber:
- Coil aperture: ∅72 mm.
- Operation temperature: room temperature.
- Inconel 625 (High strength, high resistivity)

→ High strength materials and extremely good welding quality are required.

Mechanical System



Only 1 longitudinally-fixed support has to be used.



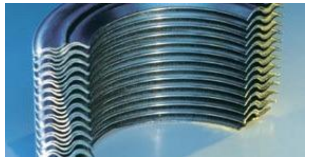
Bellows required to cope with:

- Mechanical and alignment tolerances
- Decoupling adjacent elements
- Thermal elongation (bakeout): $\Delta = \alpha L \Delta T$ $(l << L)$

Design of bellows expansion joints

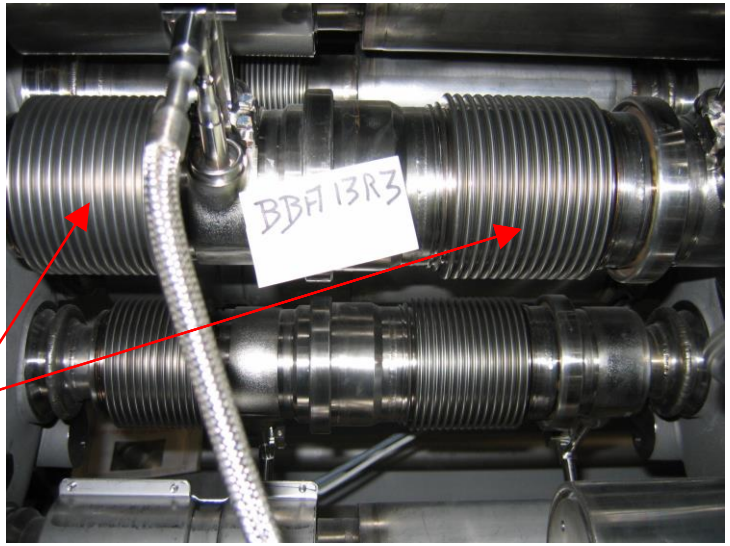
Bellows are used as the vacuum enclosure in the interconnections.

(Hydro)formed bellows are the preferred technology (less welds, cleaning, stability).


Edge welded bellows


Formed bellows

Initial thickness:
0.15 mm



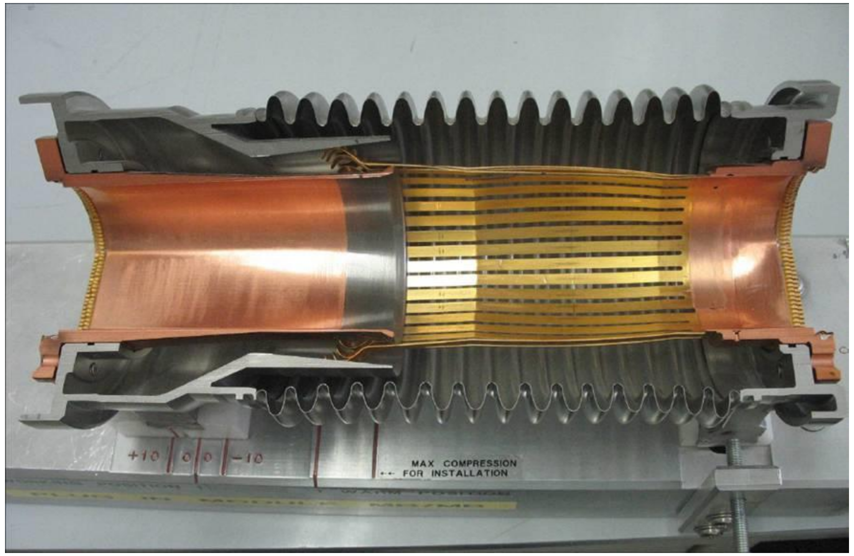
Thickness: 1 mm

Stainless steel is the most commonly used material for vacuum bellows.

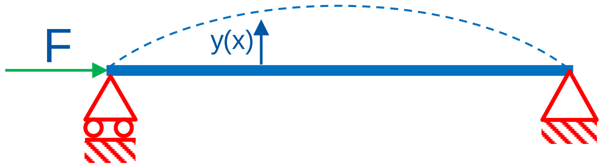
They should be as thin as possible to be as flexible as possible.

Mechanical System – Shielded bellows

To carry the image current with a low impedance and to avoid important cross section variation (leading to High Order Modes), shielded bellows are usually required.



Shielded bellows for the LHC cryogenic beam vacuum interconnections



Euler's critical load: $F_{cr} = E \cdot I \cdot \left(\frac{\pi}{L_r}\right)^2$

Initial geometrical imperfection plays a critical role in buckling and shall be well considered.

Mechanical System – Column buckling

This phenomenon can occur for a line under internal pressure (not necessary with a bellows).

Buckling pressure can read, in a general formulation (similar to Euler's formula):

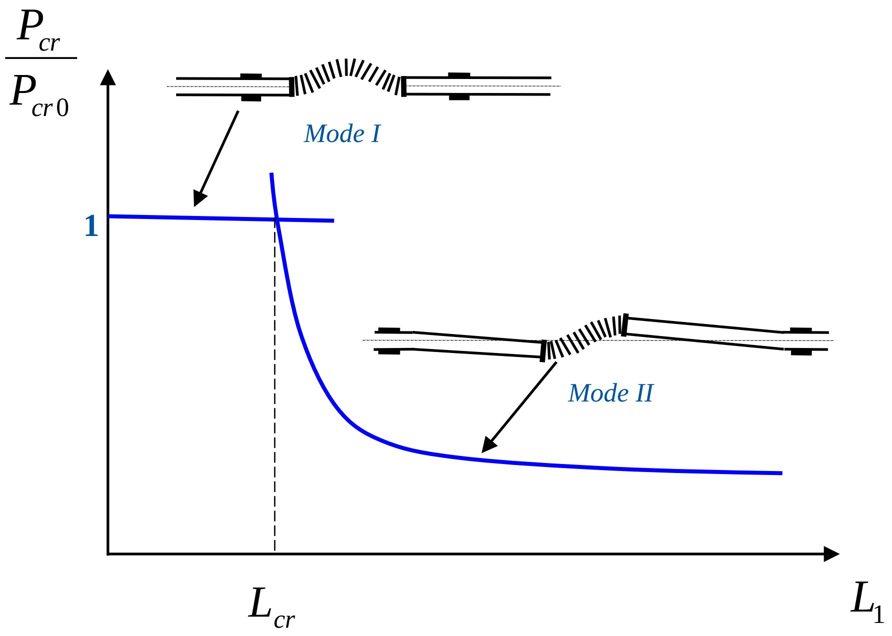
Bending stiffness

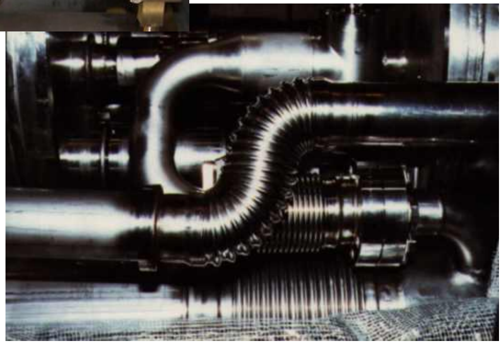
$$P_{cr} = \frac{\pi^2 C_b}{L_r^2 R_m^2}$$

Reduced length (depends on boundary conditions)

Radius

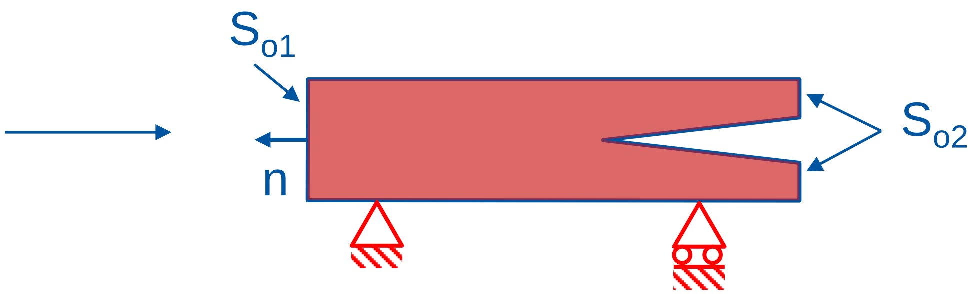
→





Mechanical System - Supports

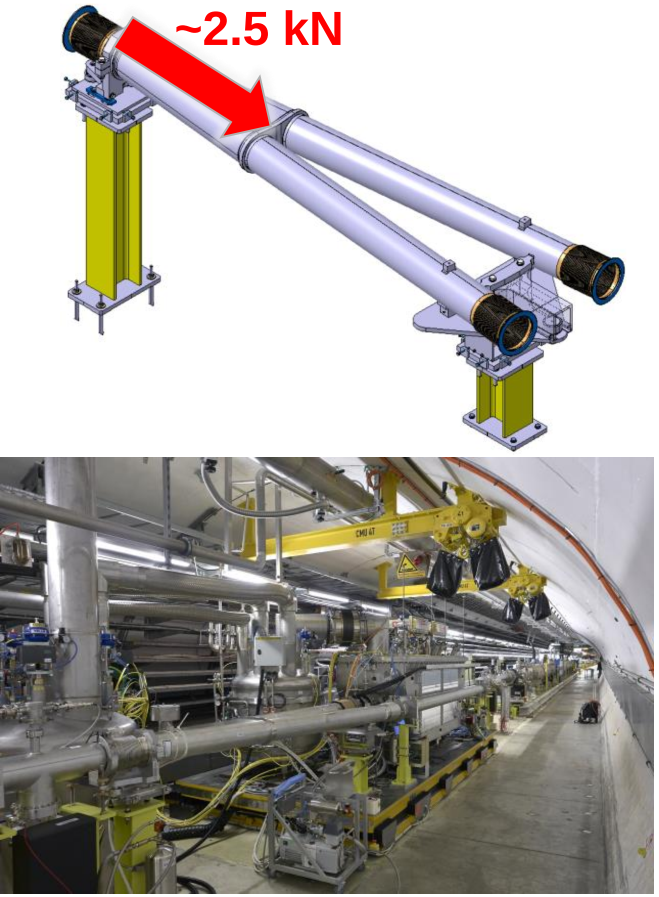
Pressure thrust force



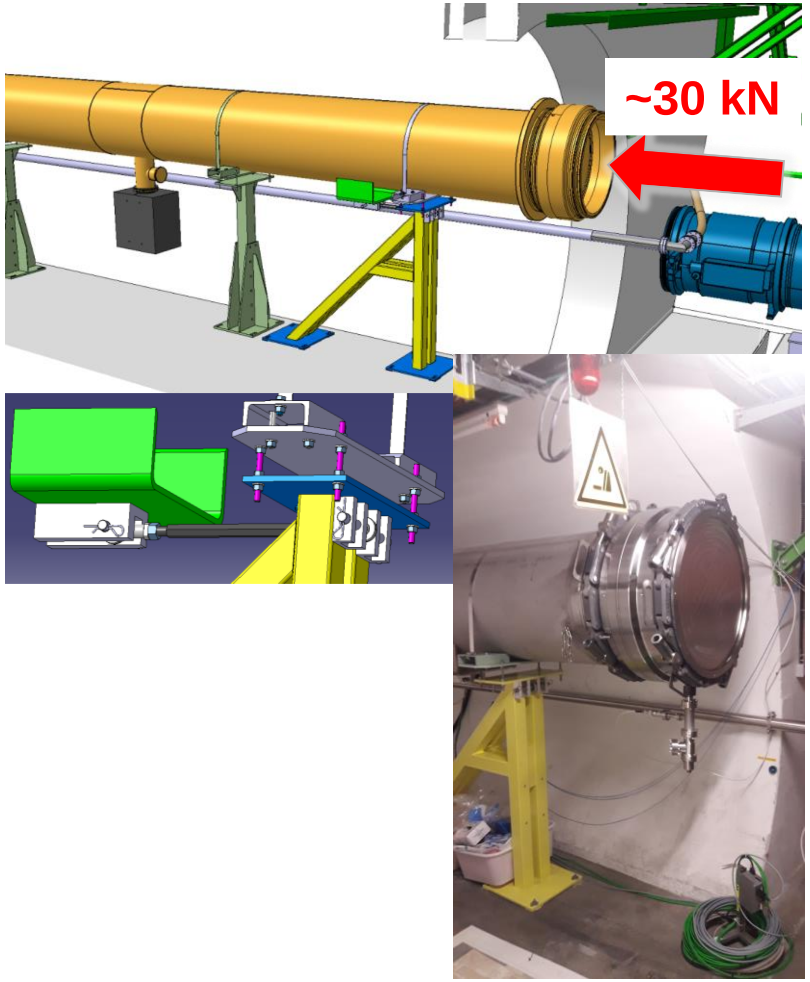
$$\vec{F}_{\rightarrow support} = p \cdot \sum_i S_{opened_i} \cdot \vec{n}_i$$

p = 0.1 MPa

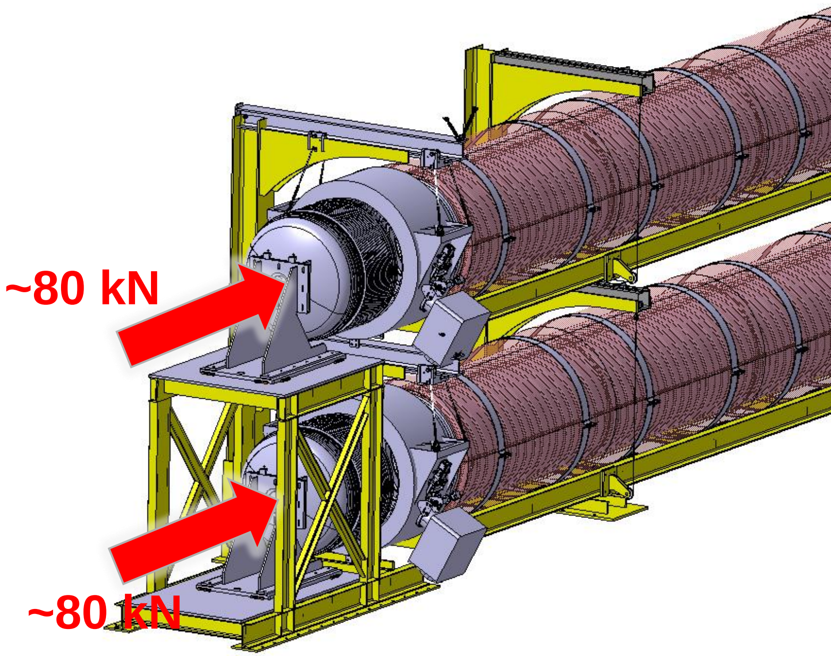
Mechanical System - Supports



Support with mobile Y-chamber for the crab cavity test stand in SPS



Support of the LHC dump windows



Support of the extremity module for the Einstein telescope pilot sector

Materials for vacuum chambers

	Symbol	Unit	Beryllium	Aluminium	Titanium G5	316L	Copper	Inconel
Density	ρ	$g \cdot cm^{-3}$	1.85	2.8	4.4	8	9	8.2
Heat capacity	C	$J \cdot K^{-1} \cdot Kg^{-1}$	1830	870	560	500	385	435
Thermal conductivity	λ	$W \cdot K^{-1} \cdot m^{-1}$	200	217	16.7	26	400	11.4
Coefficient of thermal expansion	α	$10^{-6} \cdot K^{-1}$	12	22	8.9	16	17	13
Radiation length	X_0	cm	35	9	3.7	1.8	1.47	1.7
Melting temperature	T_f	K	1560	930	1820	1650	1360	1530
Yield strength	σ_y	MPa	345	275	830	300	200	1100
Young modulus	E	GPa	230	73	115	195	115	208
Electrical resistivity	ρ_e	$10^{-9} \cdot \Omega \cdot m$	36	28	1700	750	17	1250

Indicative values at room temperature

A few material selection criteria

Several figures of merit, characterizing the material, can be used depending on the final application.

- Mechanical Stability for transparent vacuum chamber: $X_0 \cdot E^{1/3}$
- Mechanical Stability for vacuum chamber subjected to fast magnetic field variation: $\rho_e \cdot E^{1/3}$
- Fatigue under fast magnetic field variation $\rho_e \cdot \sigma_y$

For beam-material interaction induced heating:

- Temperature rise in transient regime: $\rho \cdot X_0 \cdot C \cdot T_f$
- Thermal fatigue: $\dfrac{\rho \cdot X_0 \cdot C \cdot \sigma_y}{E \cdot \alpha}$
- Temperature rise in steady state: $X_0 \cdot \lambda \cdot T_f$

Manufacturing techniques

Machining

Machining allows complex shapes with good tolerances.

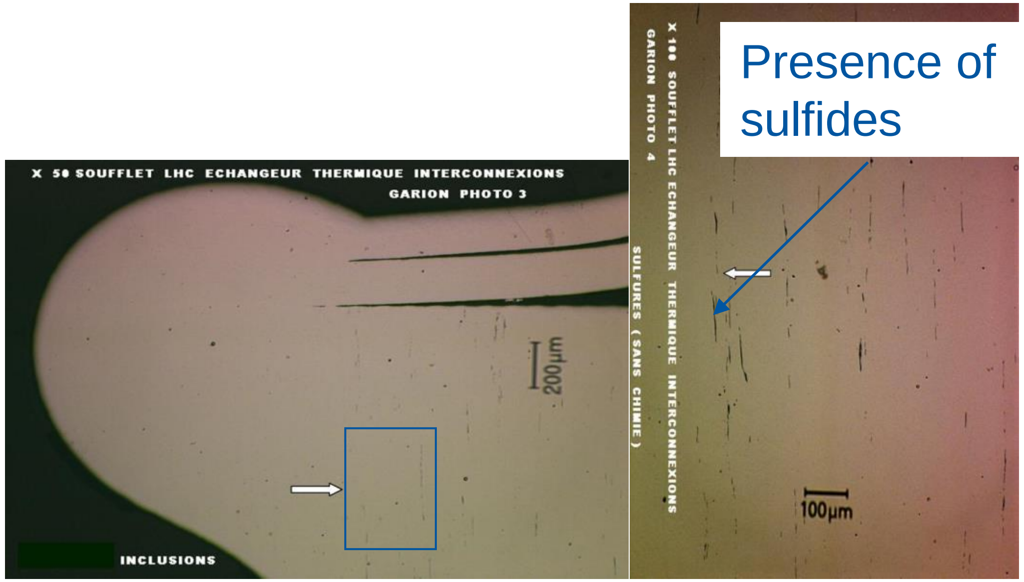
But **metallurgical defects can be opened during machining**

→ the quality of components for vacuum applications depends on the raw material quality:

→ low impurity alloy (ESR)

→ forged material

→ No machining perpendicular to the rolling direction



Sheet metal work

Quite simple shape at “low” cost.

Metallurgical defects are still embedded in the raw material.

But it requires usually a good weldability of the material.

Manufacturing techniques

Welding

Welding processes used for UHV applications:

- TIG
- Electron beam
- Laser

The quality of the welds will highly depend on the quality of the raw material.

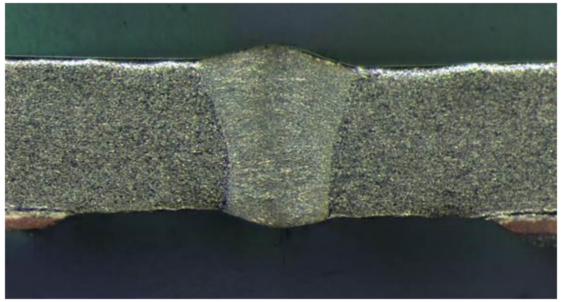
Some guidelines for UHV applications:

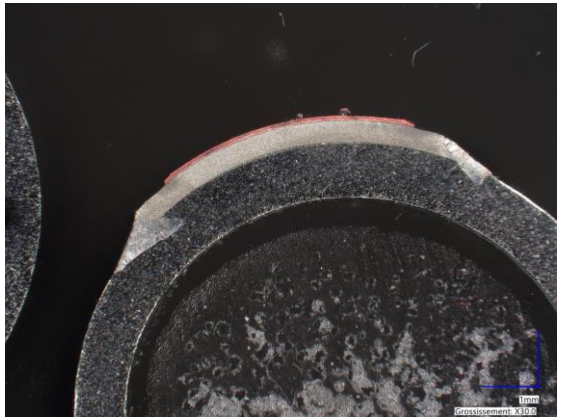
For mechanical strength a reduction factor of 0.7 is allowed

The butt welds have to be performed on the vacuum side (or fully penetrant).

The fillet welds shall not be fully penetrant.

If required mechanical strength reason, a continuous weld on the vacuum side can be made in combination with stitch welds on the opposite side.



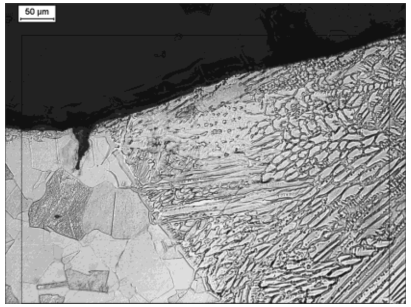


Metallography for butt and fillet weld qualification

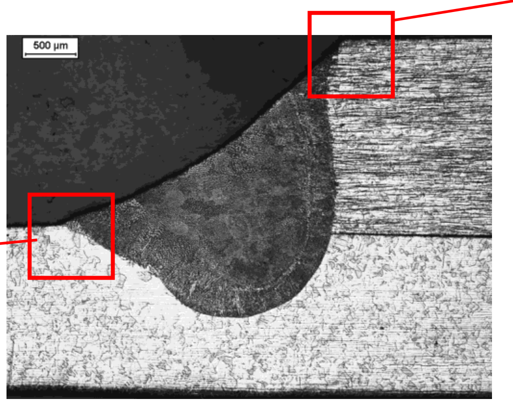
Manufacturing techniques

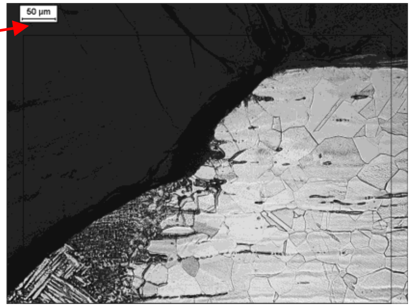
Welding

Typical defects:



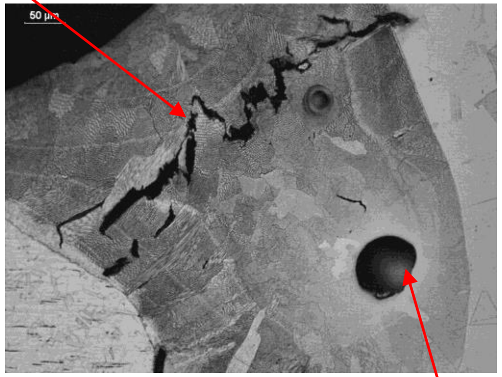
Cold cracking



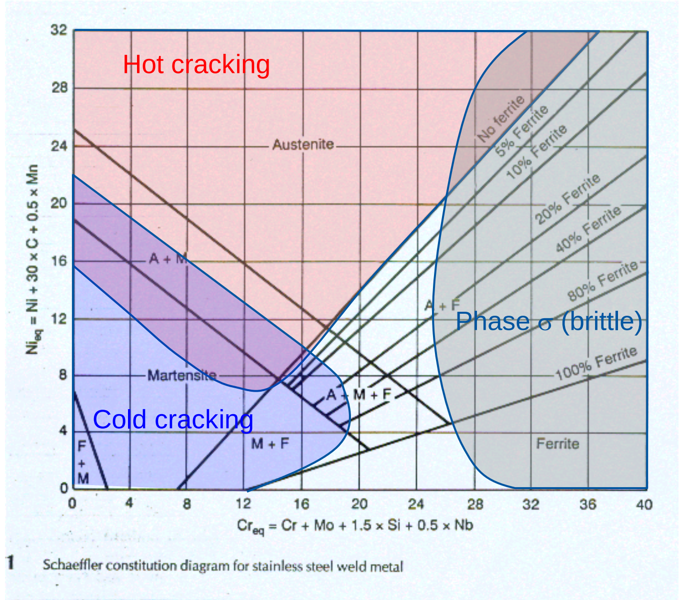


Lack of fusion

Hot cracking



Porosity



Schaeffler diagram for stainless steels

Manufacturing techniques

Soldering/brazing

2 types of soldering:

Soft soldering: T <450 °C
SnAg (96-4): T ~ 230 °C

Brazing: T>450°C
AgCu (eutectic 72-28): 780 °C
AgCuTi : ~ 830 °C
AgCuInTi : ~ 715 °C

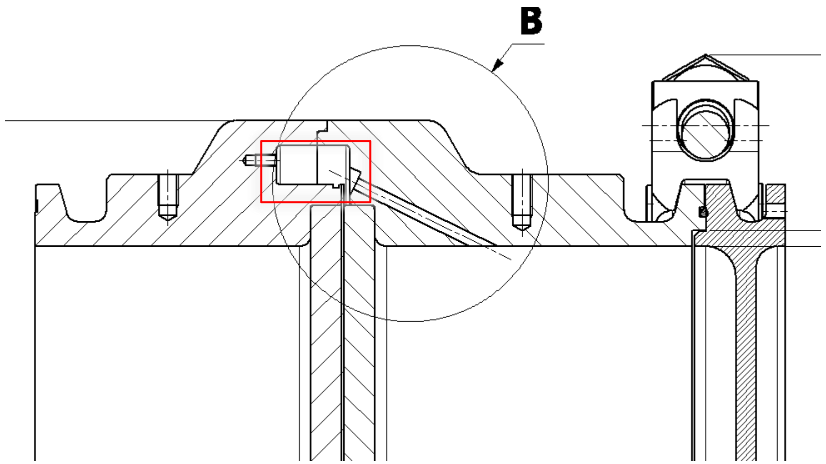
Brazing of copper/copper and copper/tungsten

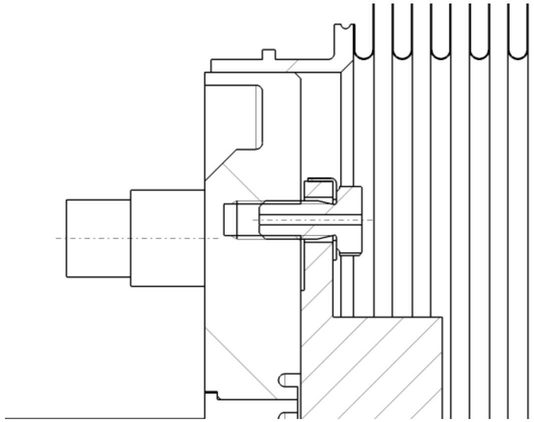
Design rules:

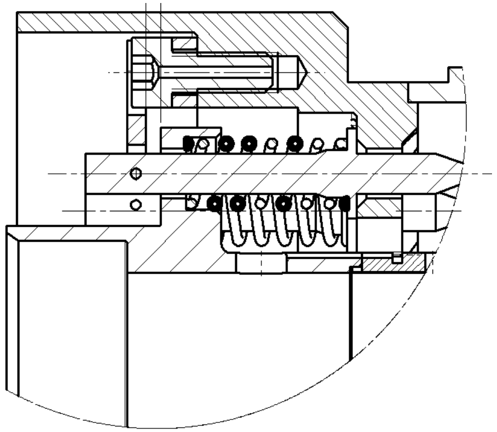
- σ_y : ~ 40MPa for the soft soldering and ~400MPa for brazing (Maximum shear ~ $\sigma_y/2$)
- Gap between the 2 pieces: ~0.05 mm
- **no flux with halogens** (corrosion of thin-walled stainless steel shells)

Process: furnace under vacuum

Mechanical assembly







Venting holes to avoid trapped volumes.

Through holes. If not possible, vented screws are used.

Silver plating of nuts (or screws).

Summary

A vacuum system is also a mechanical system that requires studies based on structural and material mechanics.

It is usually composed of very sensitive components that have, most of the time, to be optimized and whose behavior depends on the manufacturing quality.