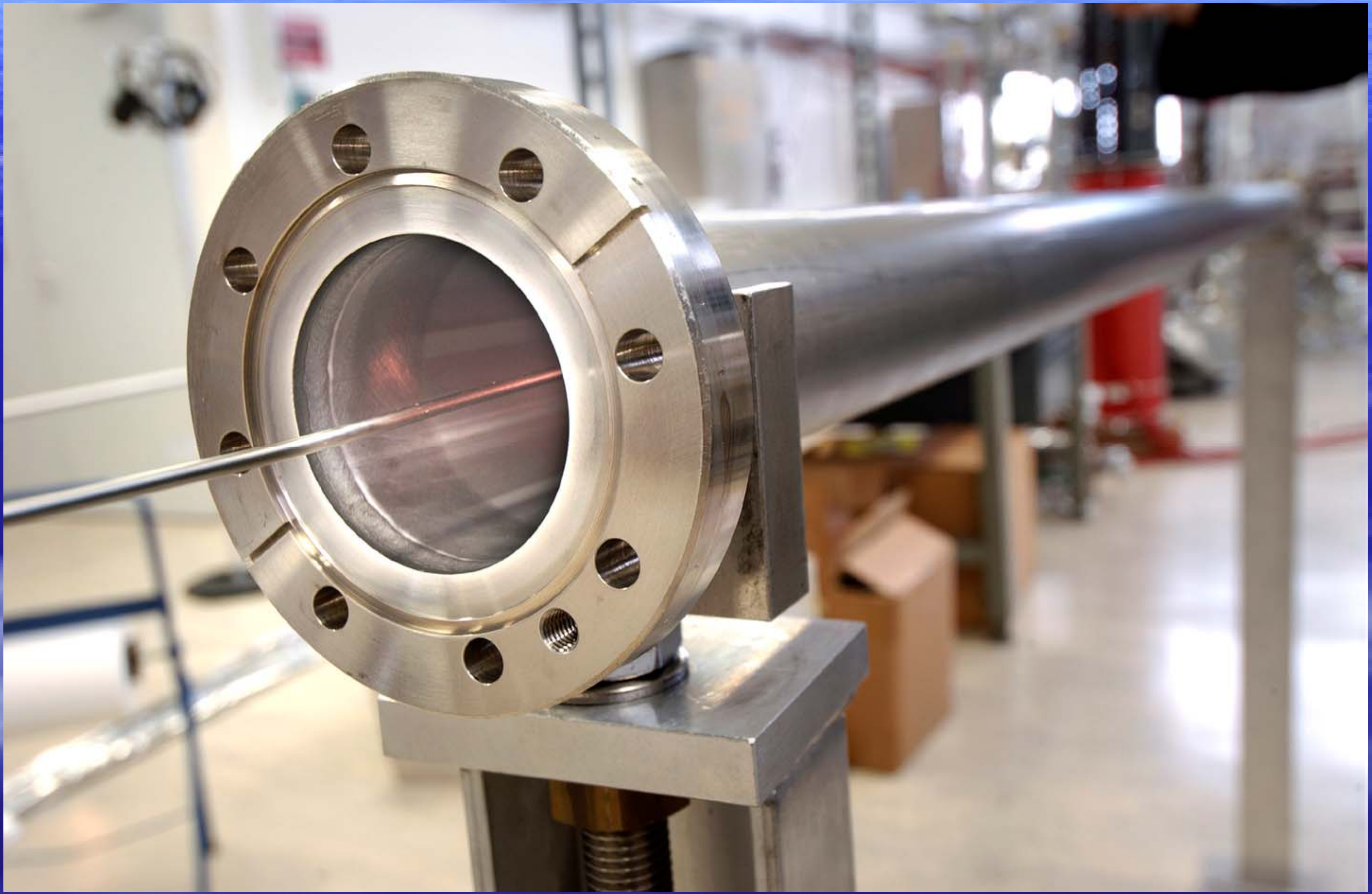
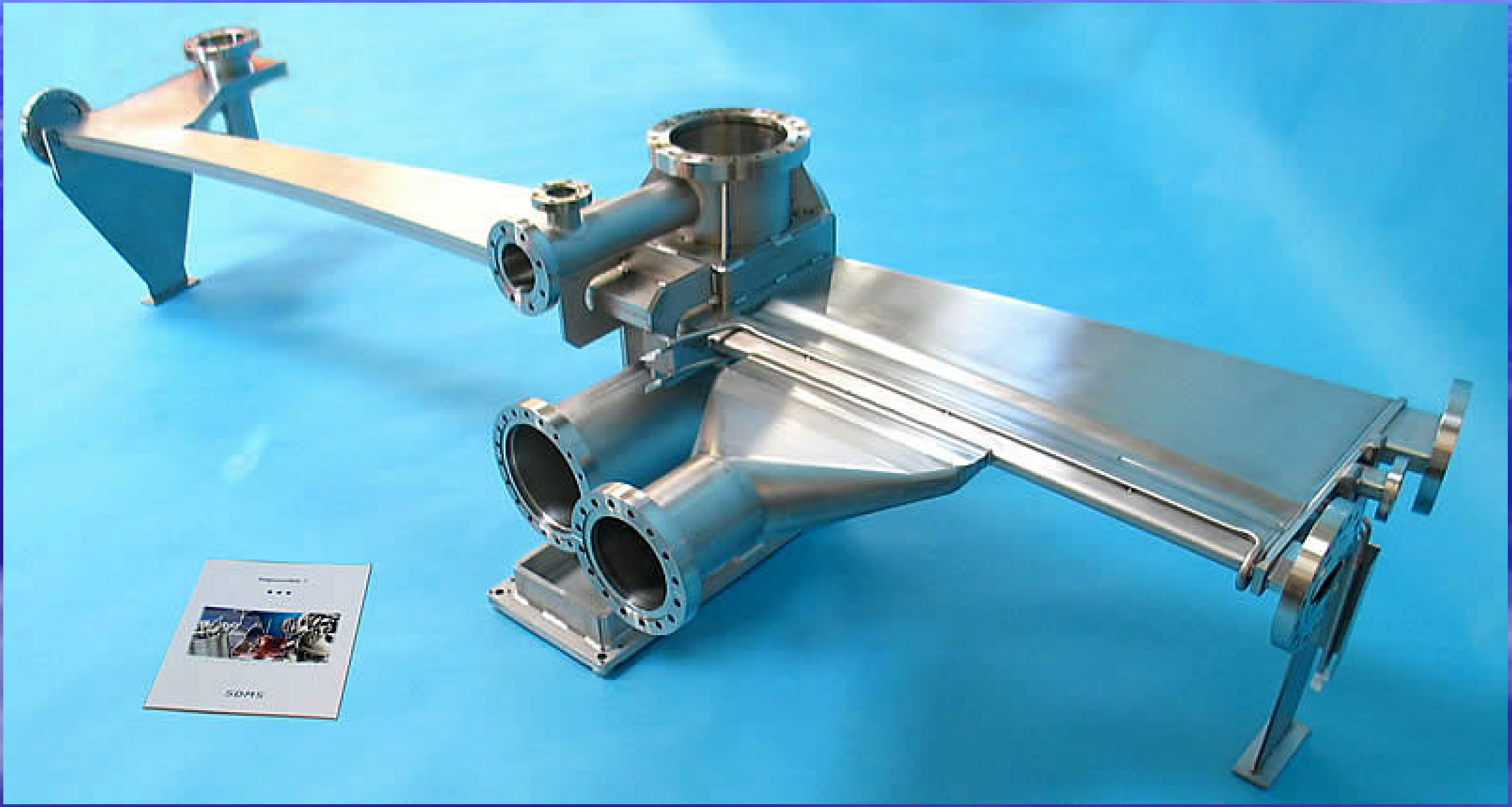
# Design Rules of Vacuum Chambers

C. Hauviller/CERN

# LHC



# SOLEIL



# LHC

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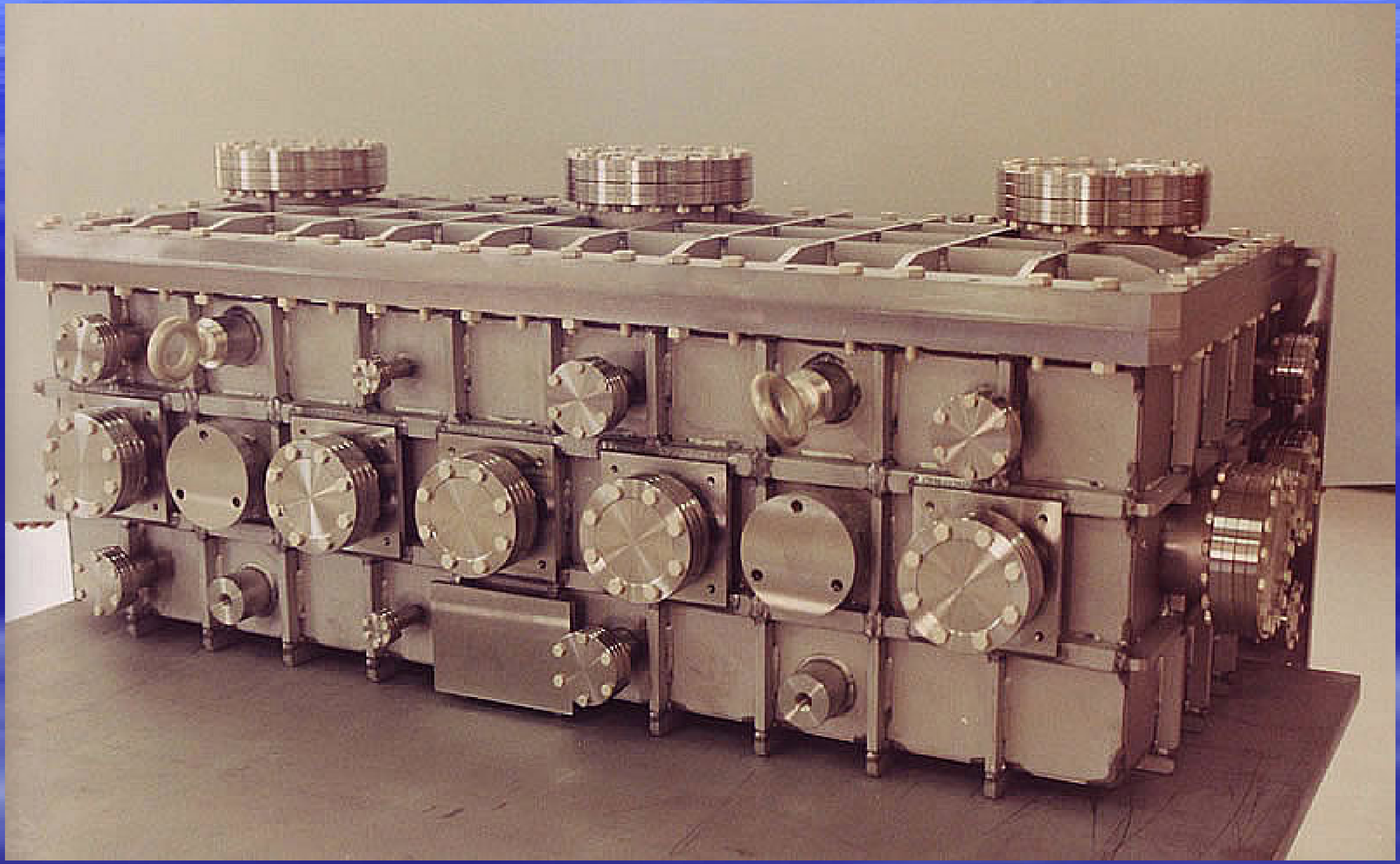
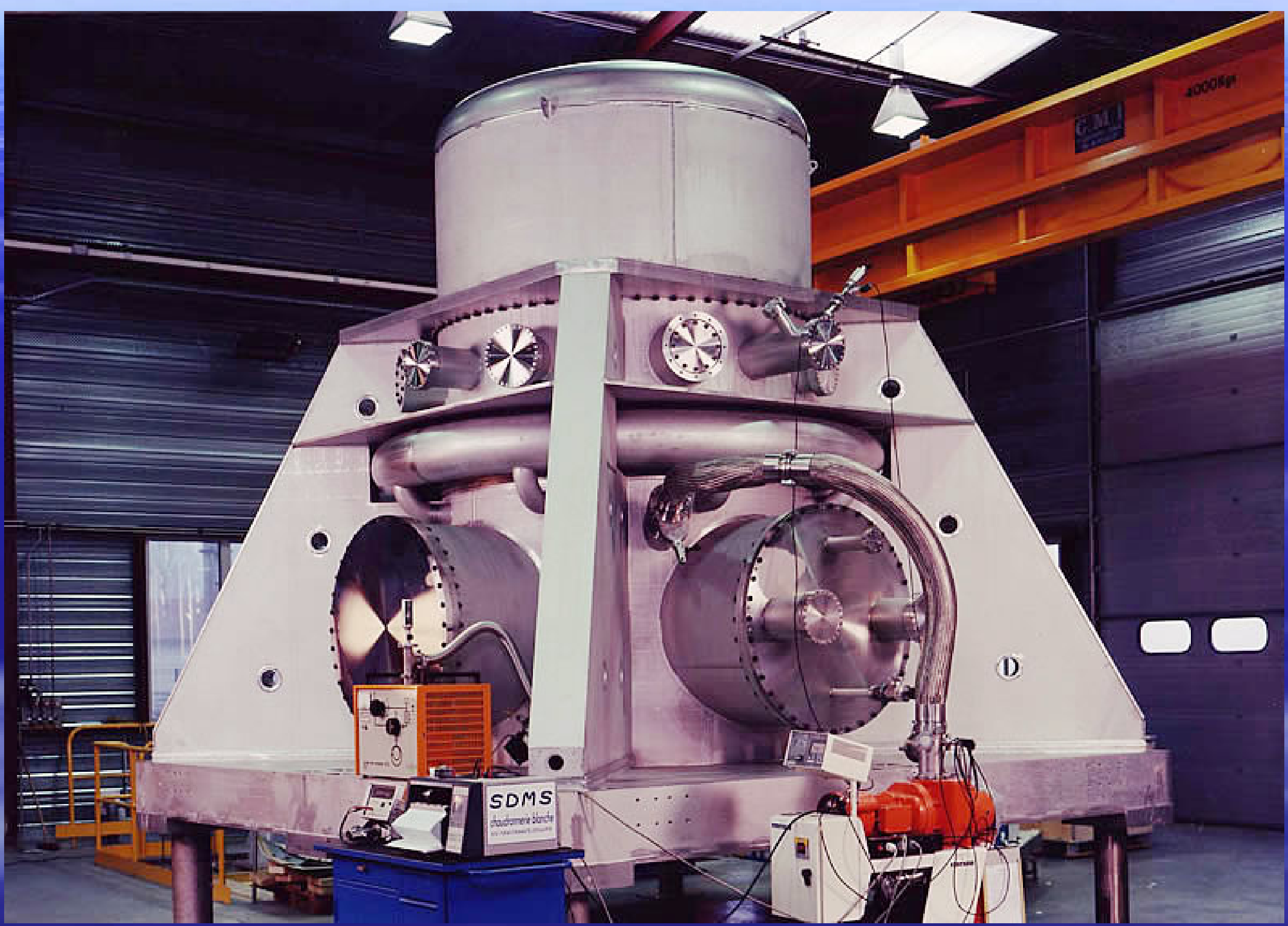


# VIRGO



# Introduction

- Mechanical design of a vacuum chamber
  - define all the boundary conditions
  - parameters settled by the other systems
- Material: a long debate
- Conceptual design followed by detailed design
- Manufacturing
- Controlled by a quality assurance plan

# Introduction

- Not exhaustive
  - Accelerator equipment on beam lines.
  - Vacuum vessels for the services.
  - Static

- Methodology, methods, hints.

- Classical rule: 70% of the final cost defined at the end of the design

# Table of contents

# Boundary conditions

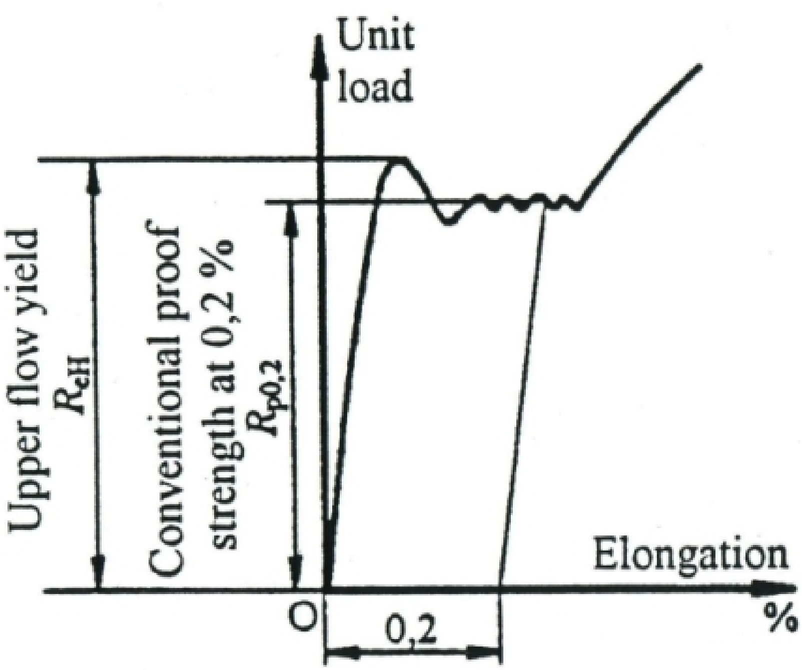
- Environment
  - Not necessary exhaustive
  - Outside
    - External envelope
    - Fitting a vacuum chamber/beam pipe of a particle accelerator inside an optimized gap of magnets
    - Space for supports
    - Space and access to the pumping ports and to the pumping and diagnostics equipment.
  - Inside
    - Beam envelope
    - Conductance in case of lumped pumps
    - Cryogenic system:
      - inner piping
      - insulation layers
      - extra space to tackle with the movements
  - Pressure, forces
    - 1 bar
    - Over-pressure ?
    - Closed end forces

# Boundary conditions

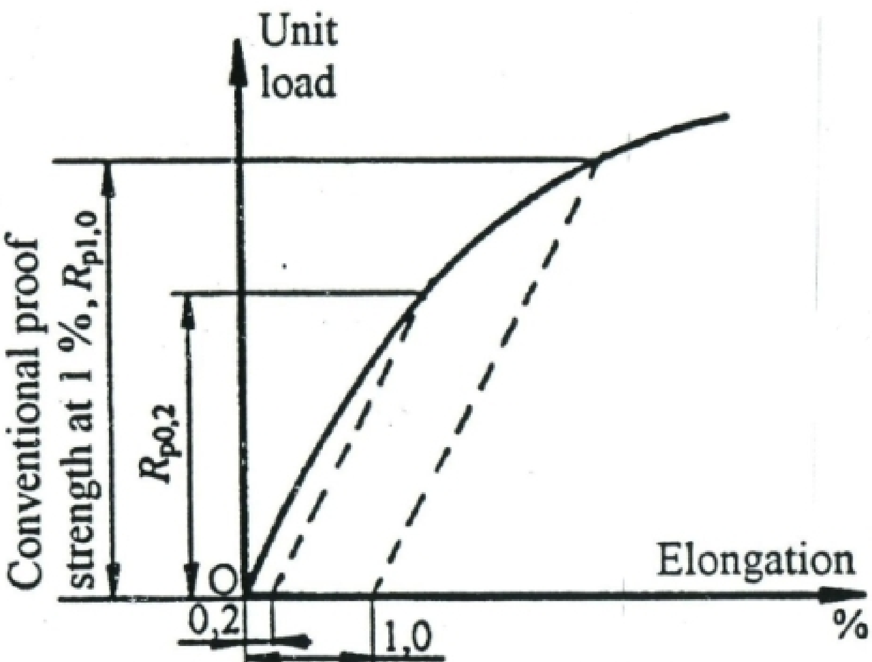
- Temperature
  - Operating temperature (usually room temperature).
  - Bake-out temperature (usually between 150°C and 300°C)
  - Exceptional temperature in case of an incident (like a cool-down due to cryogen losses)
  - Transitories

- Specific cases
  - Heat loads
  - Electrical impedance
  - Electric isolation
  - Activation of material by the particles
  - Secondary beam going through a window
  - Particules escaping the beam pipe and to be analysed by surrounding detectors

- Main material parameters
  - Modulus of rigidity (Young's modulus) E (GPa)
  - Elastic limit $\sigma_{0.2}$
  - Rupture limit $\sigma_r$



Steels except austenitic stainless steels



Austenitic stainless steels, Aluminium alloys

# Materials

- Rule of thumb: upper temperature limit of usage of a metalis: 70% of its melting temperature in Kelvin.

- Vapor pressure depends upon the temperature and the pressure: Zinc, cadmium or magnesium or standard resins not acceptable when a bake-out is foreseen.

- Selection in case of many parameters: non-dimensional parameter
- Example of beam pipes for collider experiments.

| Material | Be | CFC | Al-Be | Al | Ti | Fe |
|---|---|---|---|---|---|---|
| E (GPa) | 290 | 200 | 193 | 70 | 110 | 210 |
| $X_0$(m) | 0.353 | 0.271 | 0.253 | 0.089 | 0.036 | 0.018 |
| $X_0E^{1/3}$ | 2.34 | 1.58 | 1.46 | 0.37 | 0.17 | 0.11 |

$X_0$ radiation length

CFC LEP

Beryllium + Aluminum
LHC

C. Hauviller/CERN

# Materials

- Good electrical or thermal conductivity: copper, aluminum
- Low elecrical conductivity: ceramics (aluminum oxide)

- Major advancements in metallurgy and surface physics: replace plain material by combination of materials
  - Examples:
    - Copper on stainless steel
    - Aluminum on CFC

- Technological properties : weldability

# Materials

- Cost break-down
  - Design
  - Raw material
  - Manufacturing
    - Machining
    - Assembly
  - Tooling
  - Quality controls

  (Workshop)

  - Assembly
  - Tooling
  - Quality controls

  (In-situ)

- Austenitic stainless steels: 316 LN, 316 L, 304 L
- Aluminum alloys: 5000 and 6000 series
- Copper: OFHC, Glidcop

# Legislation and codes

- No construction code dedicated to vacuum vessels but one for cryogenic vessels.
- Own regulations
- Common practice : treat a vacuum chamber as a pressure vessel with some arrangements.
  - At CERN : Safety code D2 for pressure vessels and pressurized pipelines.

- The European legislation for pressure vessels (free trade)
  - directive 97/23/EC of the European parliament and of the Council of 29 May 1997 on the approximation of the laws of the Member States concerning pressure equipment. "This directive applies to equipment subject to a maximum allowable pressure exceeding 0.5 bar" which "does not pose a significant hazard".

# Legislation and codes

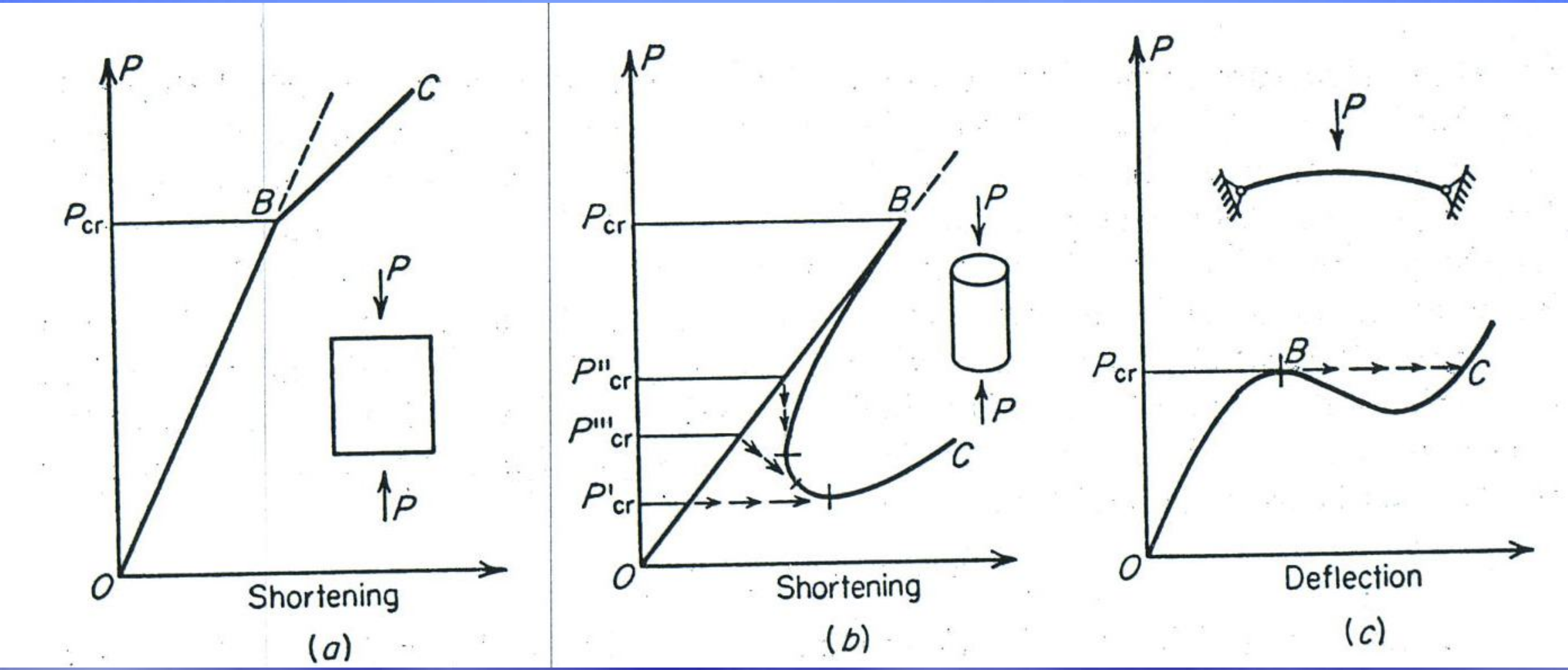
- Codes define common rules accepted by the clients, the manufacturers, the technical centers and the inspection bodies.

– Classical ones:
  - CODAP 2005 French code for construction of unfired pressure vessels issued by SNCT (Syndicat National de la Chaudronnerie, de la Tolerie et de la tuyauterie industrielle);
  - EN 13445 Unfired pressure vessels issued by CEN (European Committee for Standardization);
  - 2004 BPVC (Boilers and Pressure vessels code) Section VIII- Rules for Construction of Pressure vessels issued by ASME (American Society of Mechanical Engineers).
  - EN 13458-2 which treats specifically the “static vacuum insulated vessels” of the “cryogenic vessels”.

- Basics

  - Stresses in the elastic range.
  - Equivalent stress (according to Von Mises or Tresca criterion) should not exceed the elastic limit ($\sigma_{0.2}$)
  - Directive 97/23/EC states in particular that “the permissible membrane stress for predominantly static loads…must not exceed…2/3 of the yield limit (stainless steel and aluminum alloys)”.

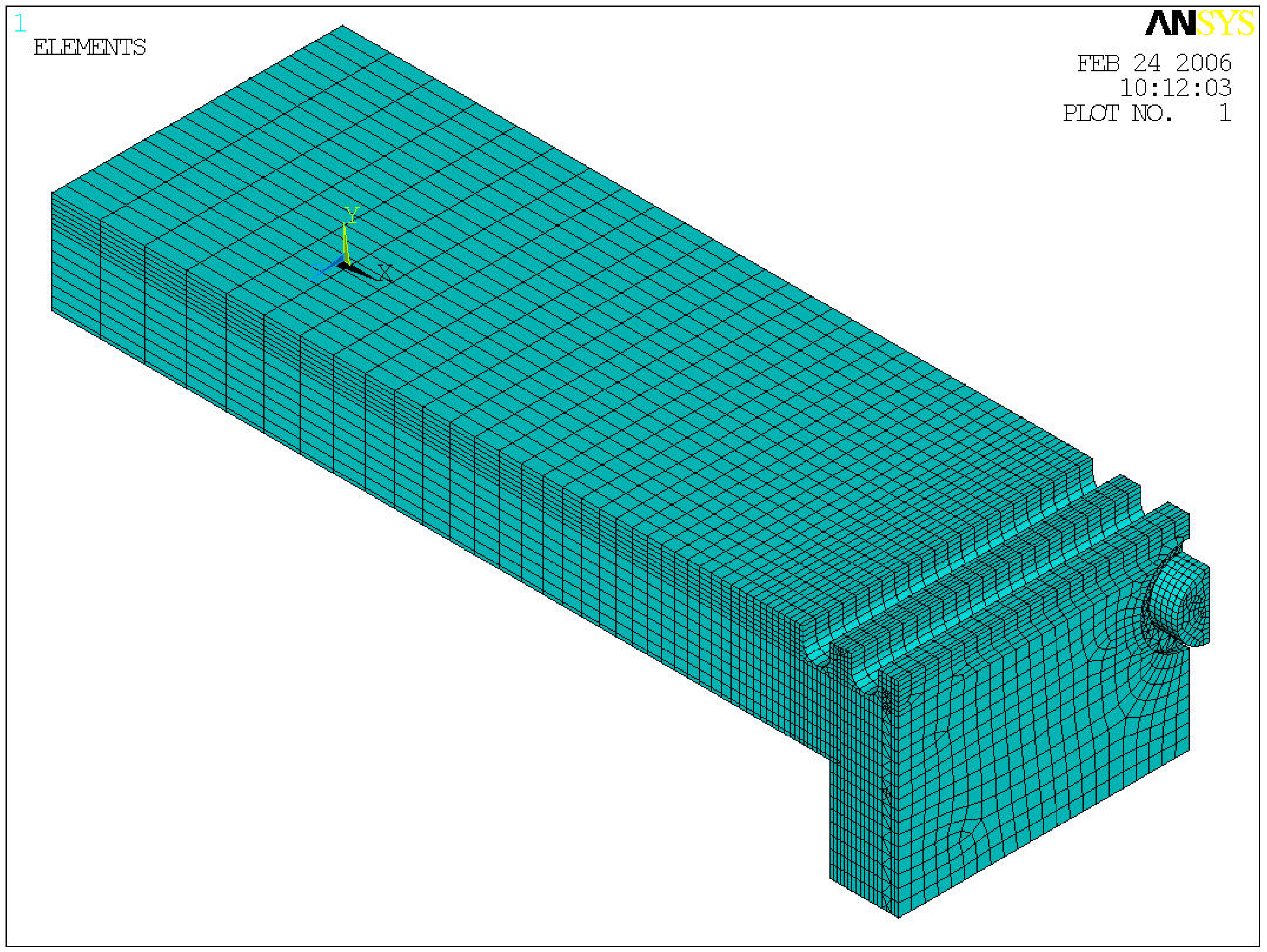
  - External pressure resulting in compressive membrane stresses.
  - Instability and bifurcation point on the behavioral curve: a potential buckling
  - Non-linear phenomenon influenced by defects.

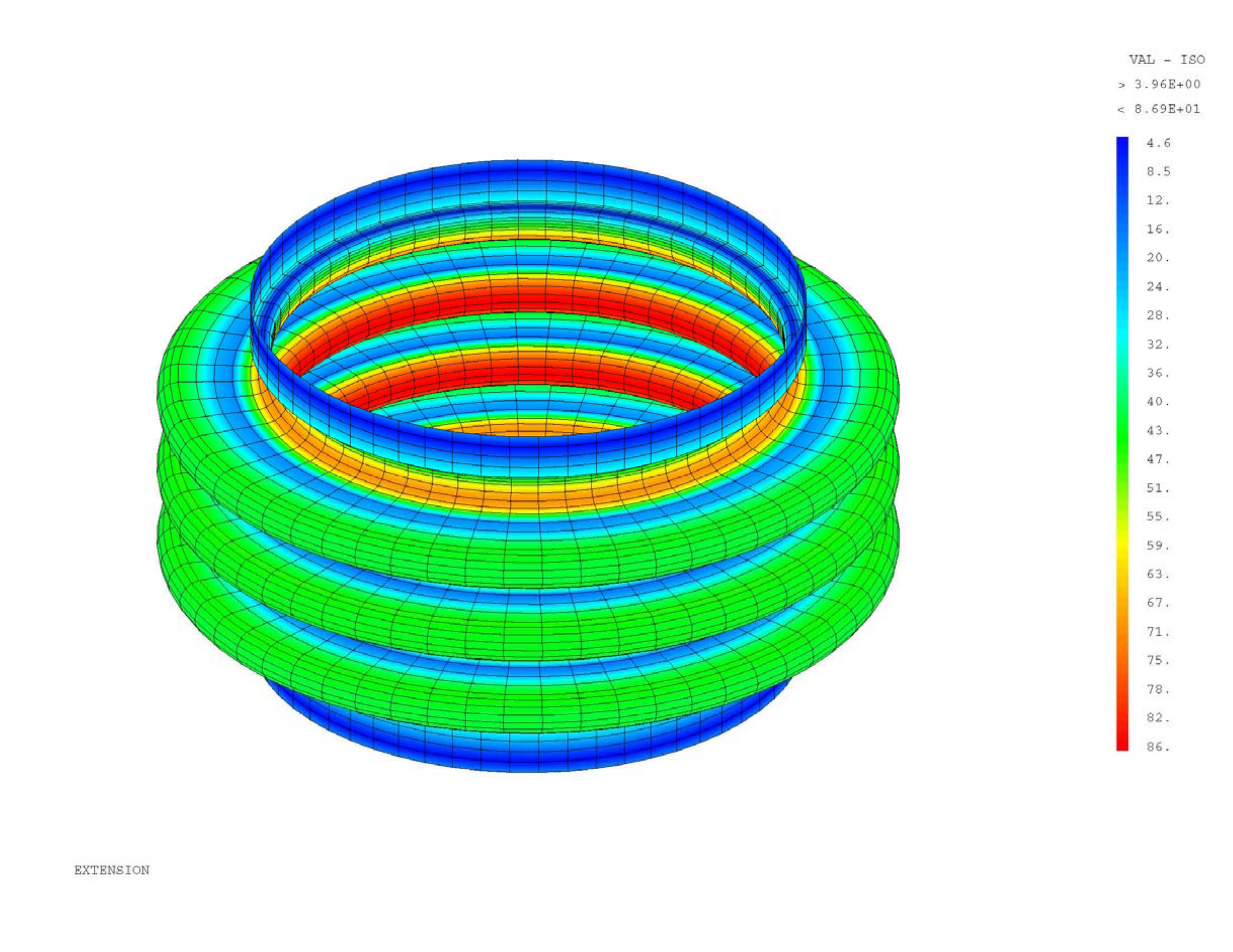



- A safety factor must be applied on any computed value:
  - pressure vessels codes like CODAP 3.0
  - EN 13458-2: 2.0 for outer jackets.

- Methods and techniques
  - Analytical methods
  - Structural analysis programs.
  - Finite Element Method (FEM) for detailed design (mechanical, thermal,…)
    - Two main families of elements:
    - Solid elements for the “thick” machined parts
    - Shell elements more efficient for thin shell structure (t/R<100).

# Solid 3D elements: a slice of machined vacuum chamber

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EXTENSION

- Analysis
  - Linear elastic analysis: displacements, strains and stresses
  - Buckling factors for the main modes
  - For thin shells, the non-linear pre-buckling analysis allows determining the shake-down factor on the linear buckling value; as high as 10 for very thin shells.

- Circular tubes
  - Stresses

$$\sigma_\theta = \frac{pR}{t}$$

$$\sigma_z = \frac{pR}{2t} + \frac{F}{2\pi Rt}$$

$$\sigma_e = \frac{1}{2}\left[3\left(\frac{pR}{t}\right)^2 + \left(\frac{F}{\pi Rt}\right)^2\right]^{\frac{1}{2}}$$

  - Buckling

$$p_{cr} = \frac{0.25E}{1-\nu^2}\left(\frac{t}{R}\right)^3$$

  - In practice, stainless steel tube

$t = D/100$

- Non-circular tubes
  - Quasi-rectangular shape approximated by beam

$$\frac{1}{32}\frac{pl^4}{Et^3} < w_{\max} < \frac{5}{32}\frac{pl^4}{Et^3}$$

$$\frac{1}{2}p\left(\frac{l}{t}\right)^2 < \sigma_{\max} < \frac{3}{4}p\left(\frac{l}{t}\right)^2$$

- Windows
  - Critical items
  - Best shape: spherical dome
    - Rigid external ring must be quite rigid. If the window is oriented in such way that it can buckle, the classical buckling pressure is

$$p_{CL} = \frac{2E}{\sqrt{3\left(1-\nu^2\right)}}\left(\frac{t}{R}\right)^2$$

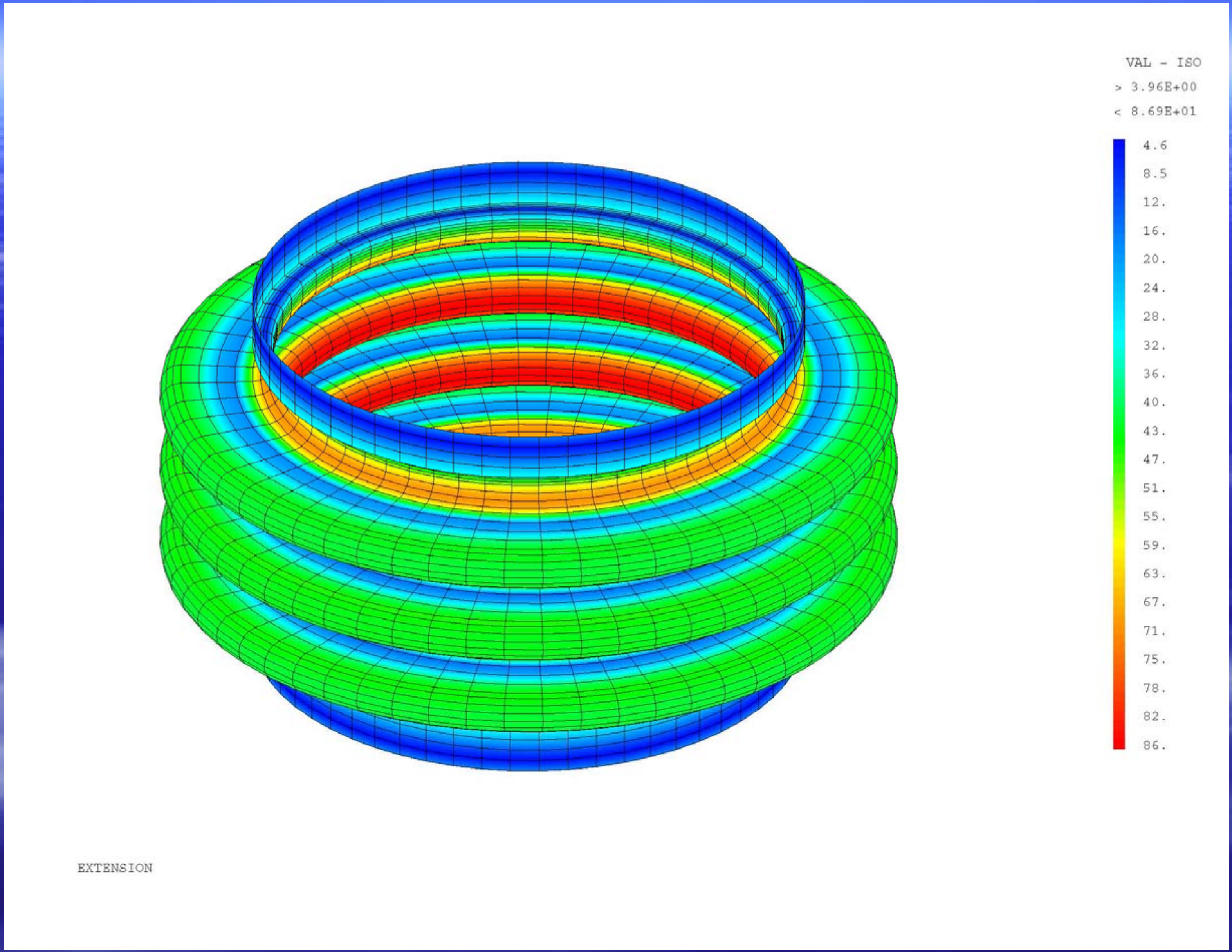
  - Flat window

$$w_{\max} = \frac{3}{16}\frac{p}{E\left(1-\nu^2\right)}\frac{R^4}{t^3}$$

  - Non-circular windows: Take care of corners

- Bellows
  - Critical items
    - minimize stresses due to displacements during commissioning and operation
    - ease assembly of parts
  - Manufacturing techniques
    - mechanically formed
    - hydroformed from thin tubes
    - assembled by welding alternatively a series of individual annular rings
  - Design
    - General codes for pressure vessels
    - Expansion Joint Manufacturers Association, Inc. (EJMA),
    - Project norm pr-EN 14917

# Design



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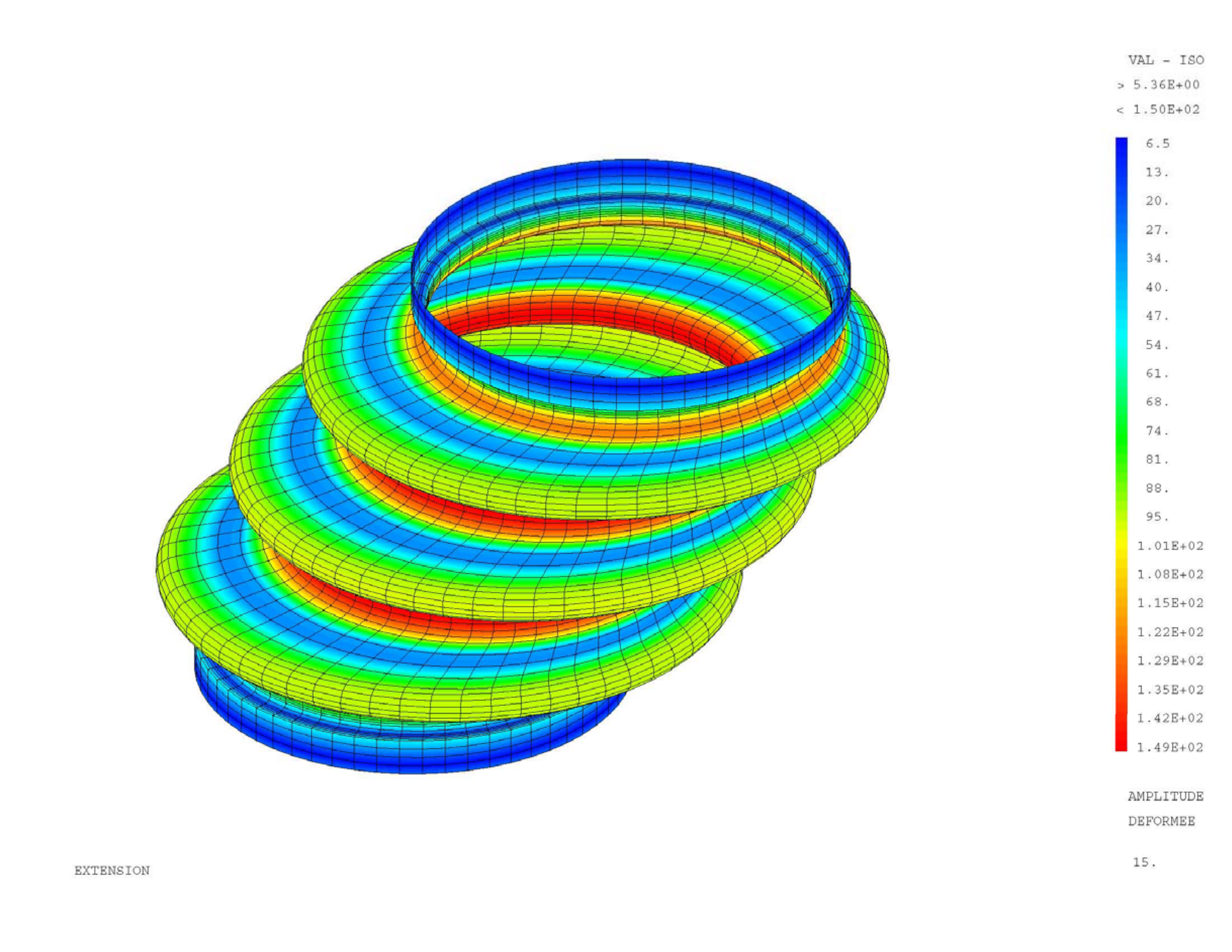
EXTENSION

# Design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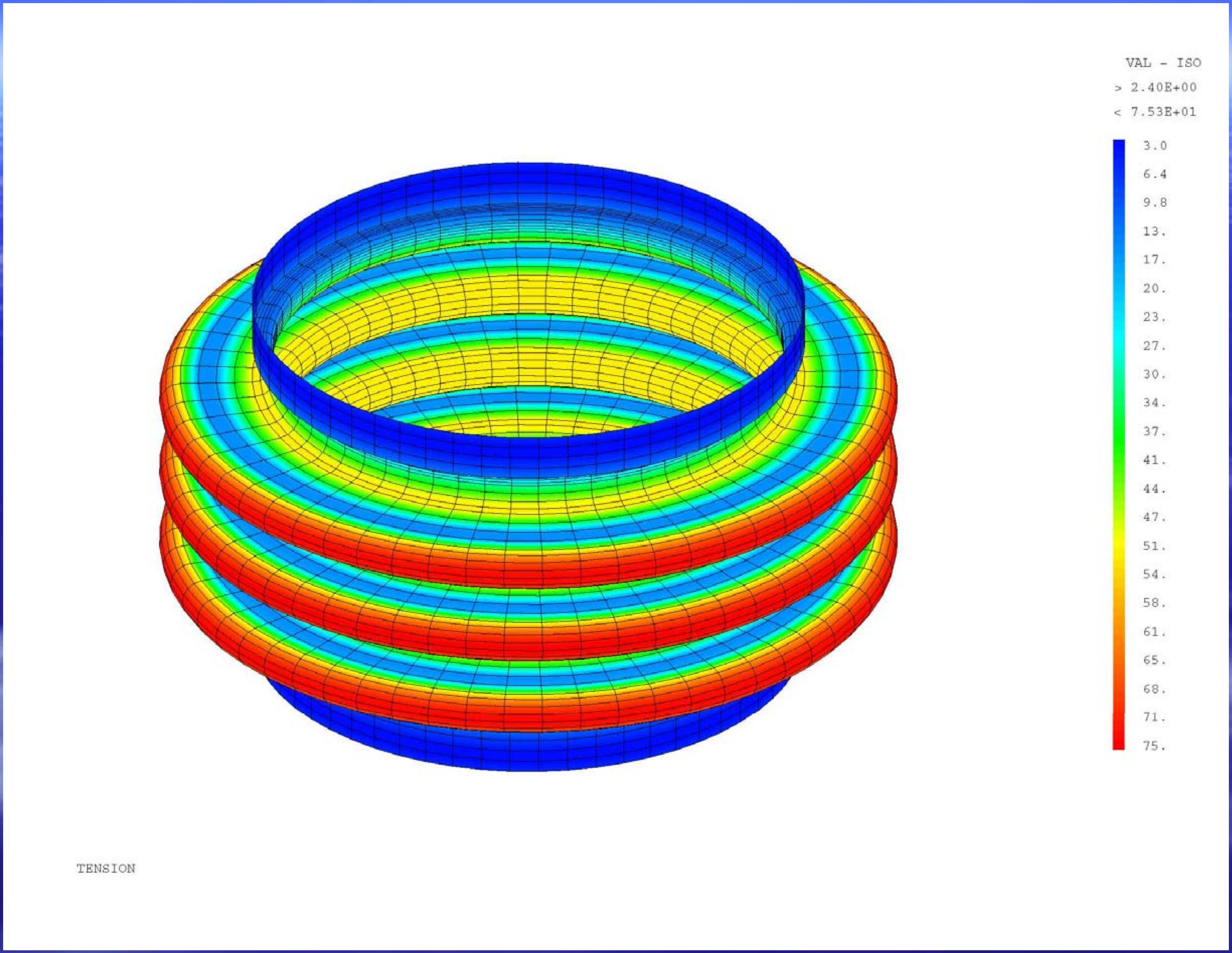
AMPLITUDE
DEFORMEE
15.
EXTENSION

# Design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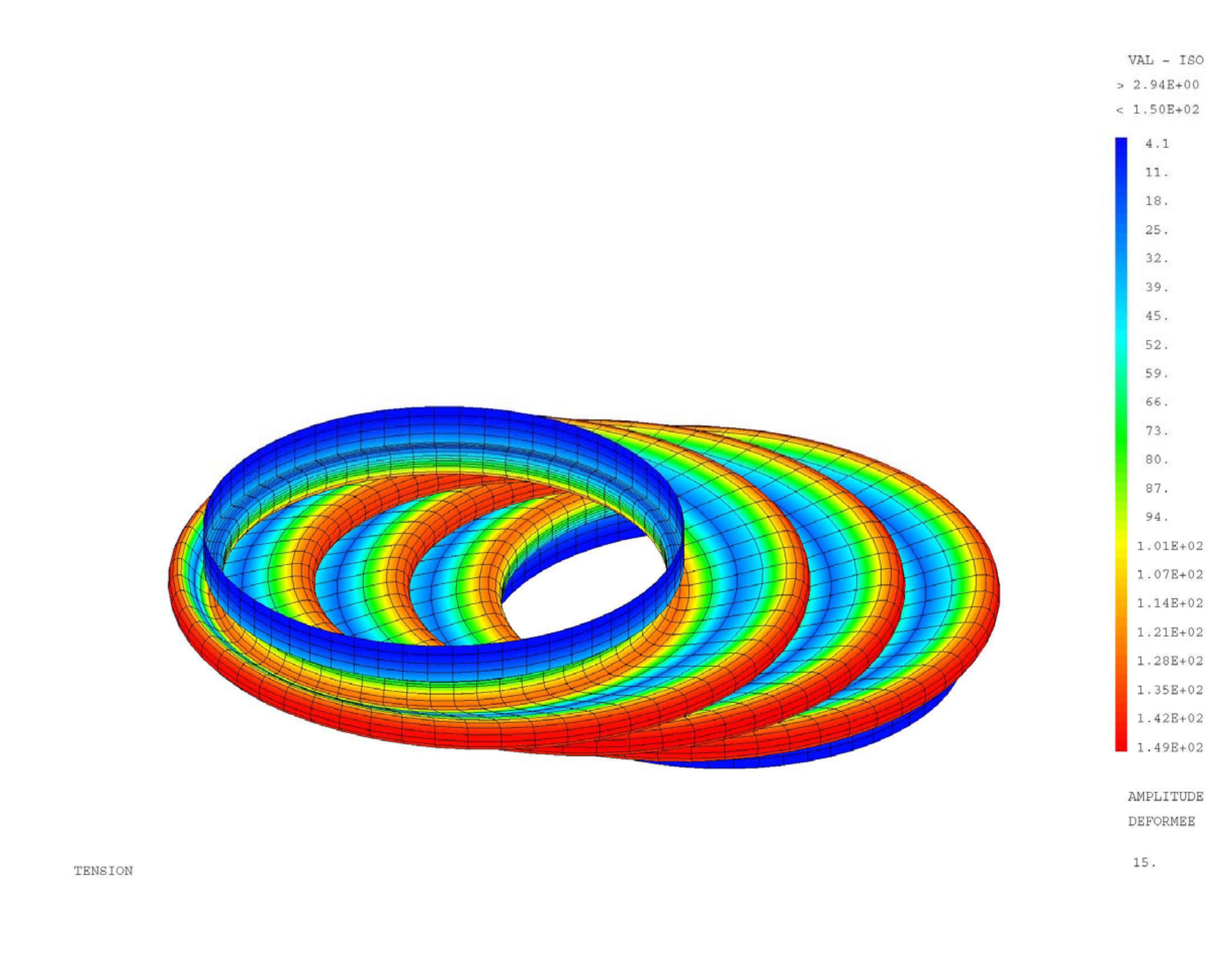
TENSION

# Design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AMPLITUDE
DEFORMEE
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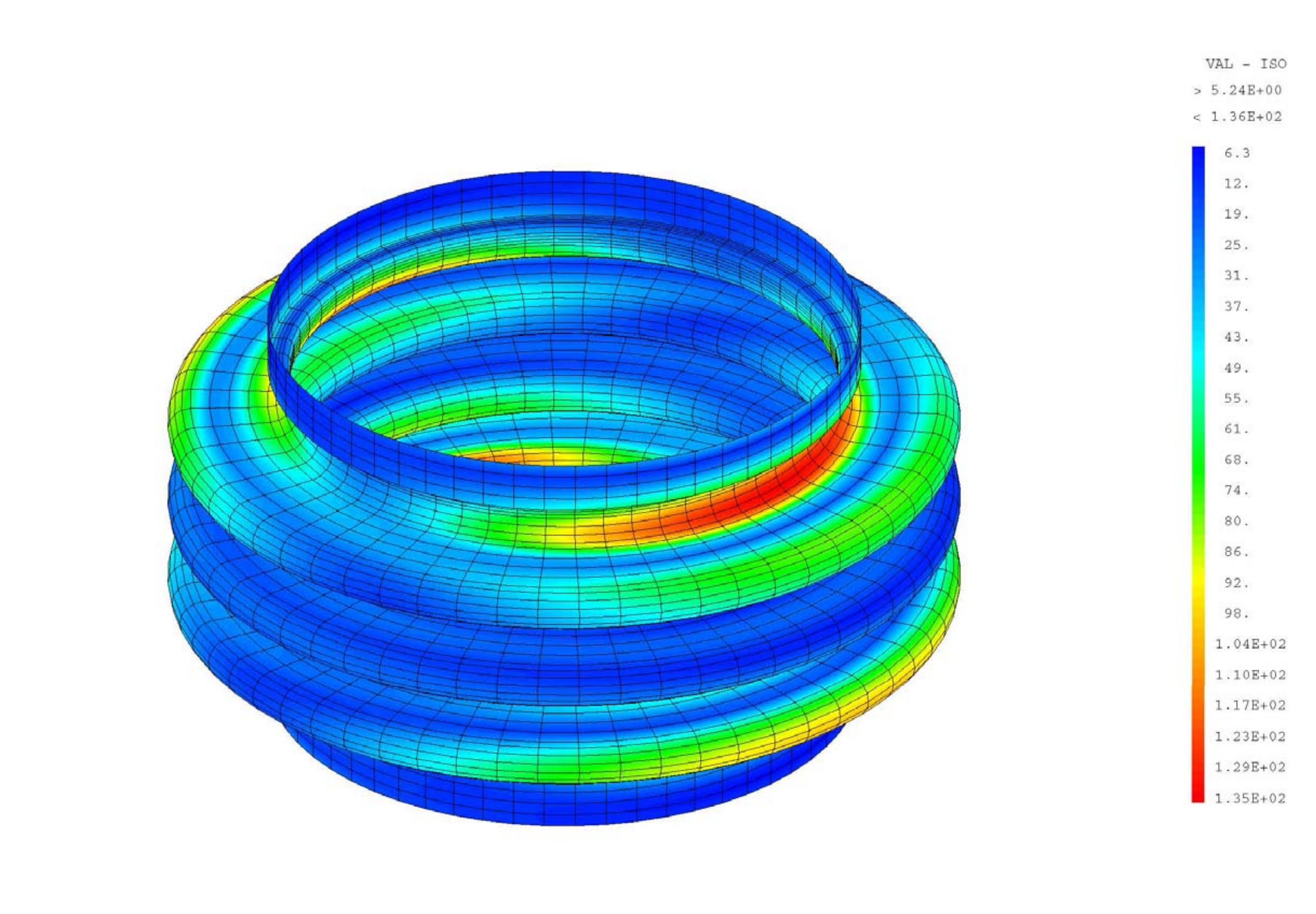
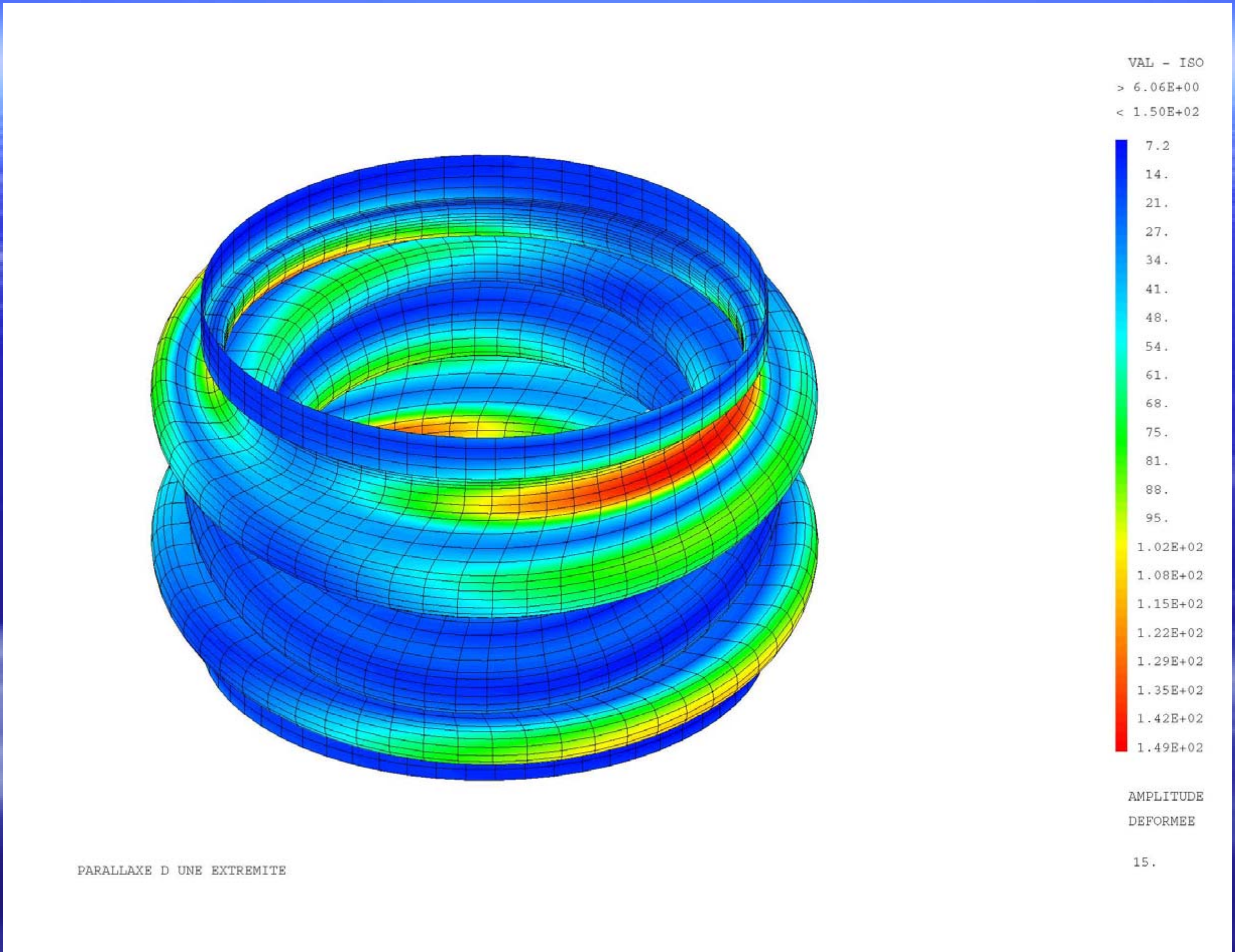
TENSION




Shell elements : a bellow

# Design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1.08E+02
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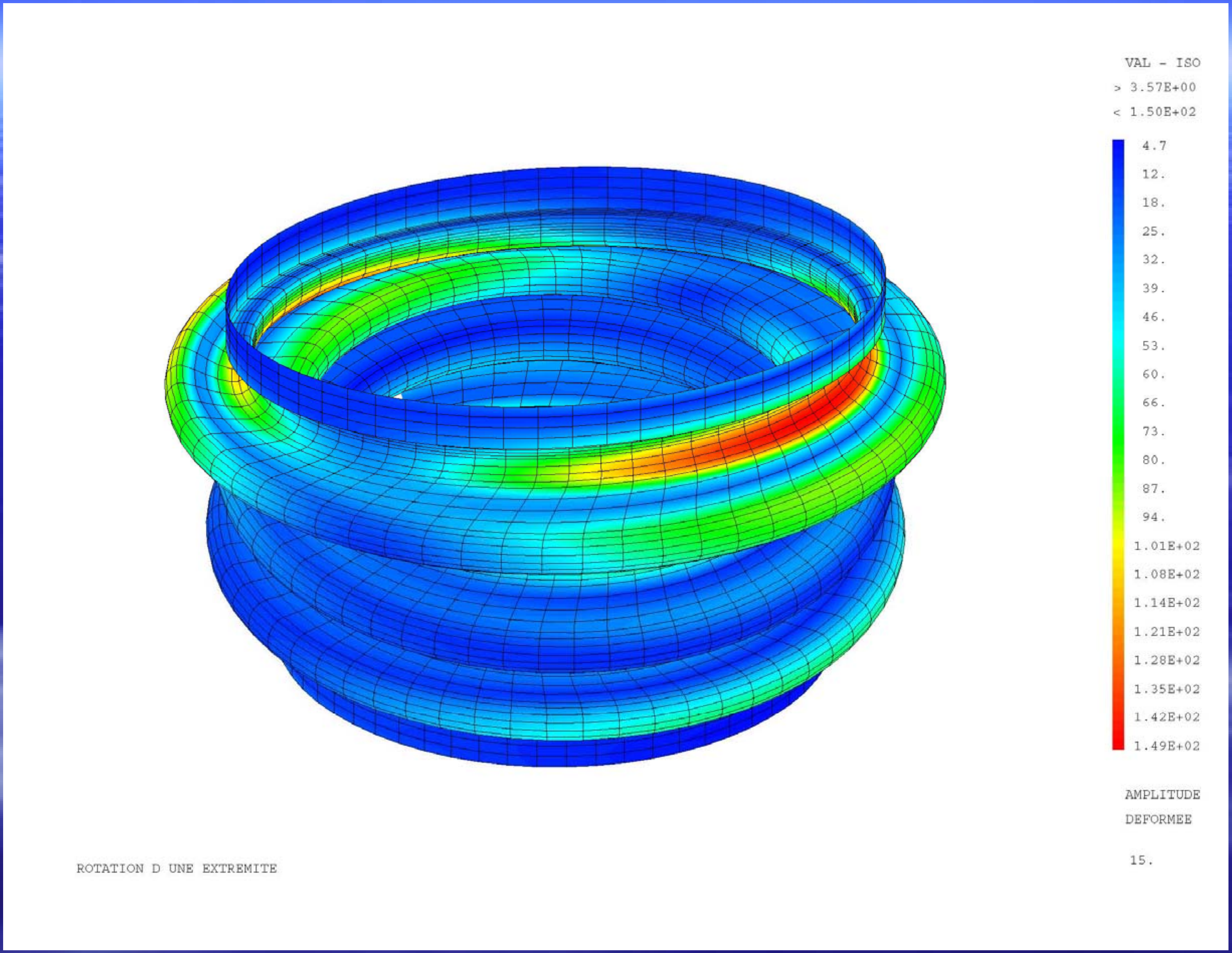
AMPLITUDE
DEFORMEE
15.
PARALLAXE D UNE EXTREMITE

# Design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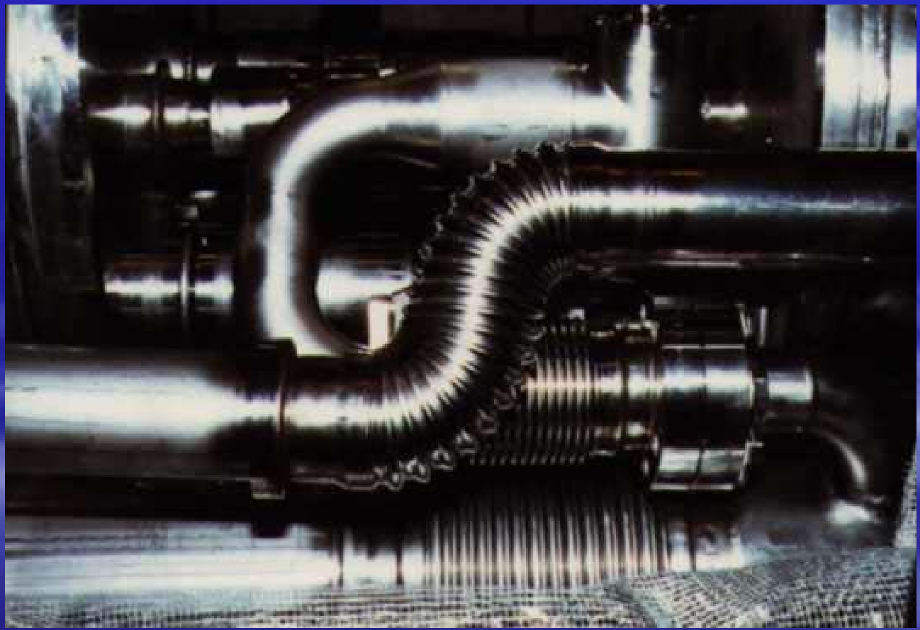
AMPLITUDE
DEFORMEE
15.
ROTATION D UNE EXTREMITE

# Design

- Lifetime
  - Axial expansion / compression cycling
  - Angular movement
  - Offsets (cardan)
  - Buckling



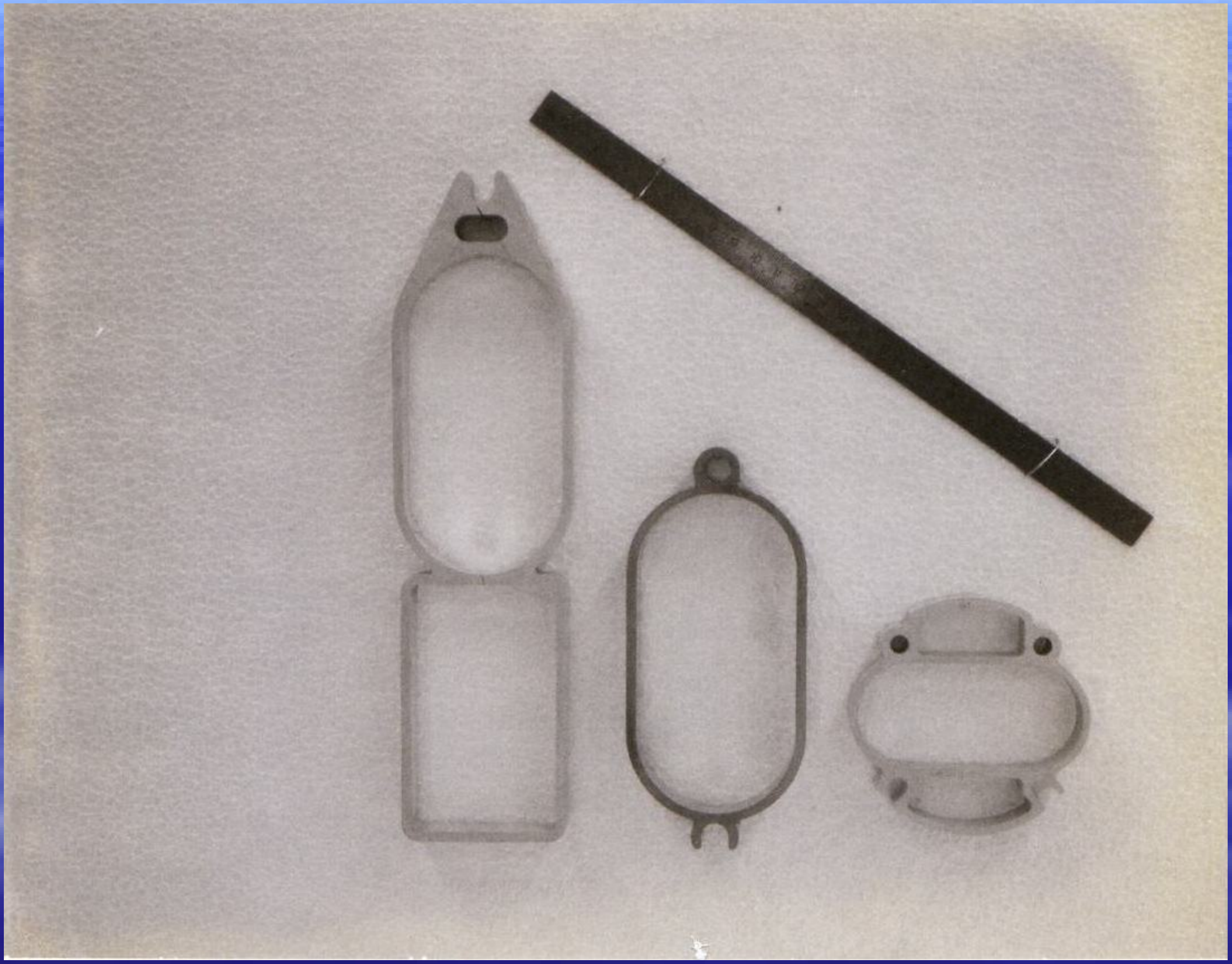
# Design

- More complex shapes of vacuum chambers
  - Any shape can be designed and analysed with the available tools
  - Be careful with the analysis of the results, in particular with the interpretation of the local stresses: true or generated by FEM mesh
  - Prefer curved surfaces to flat panels wherever possible

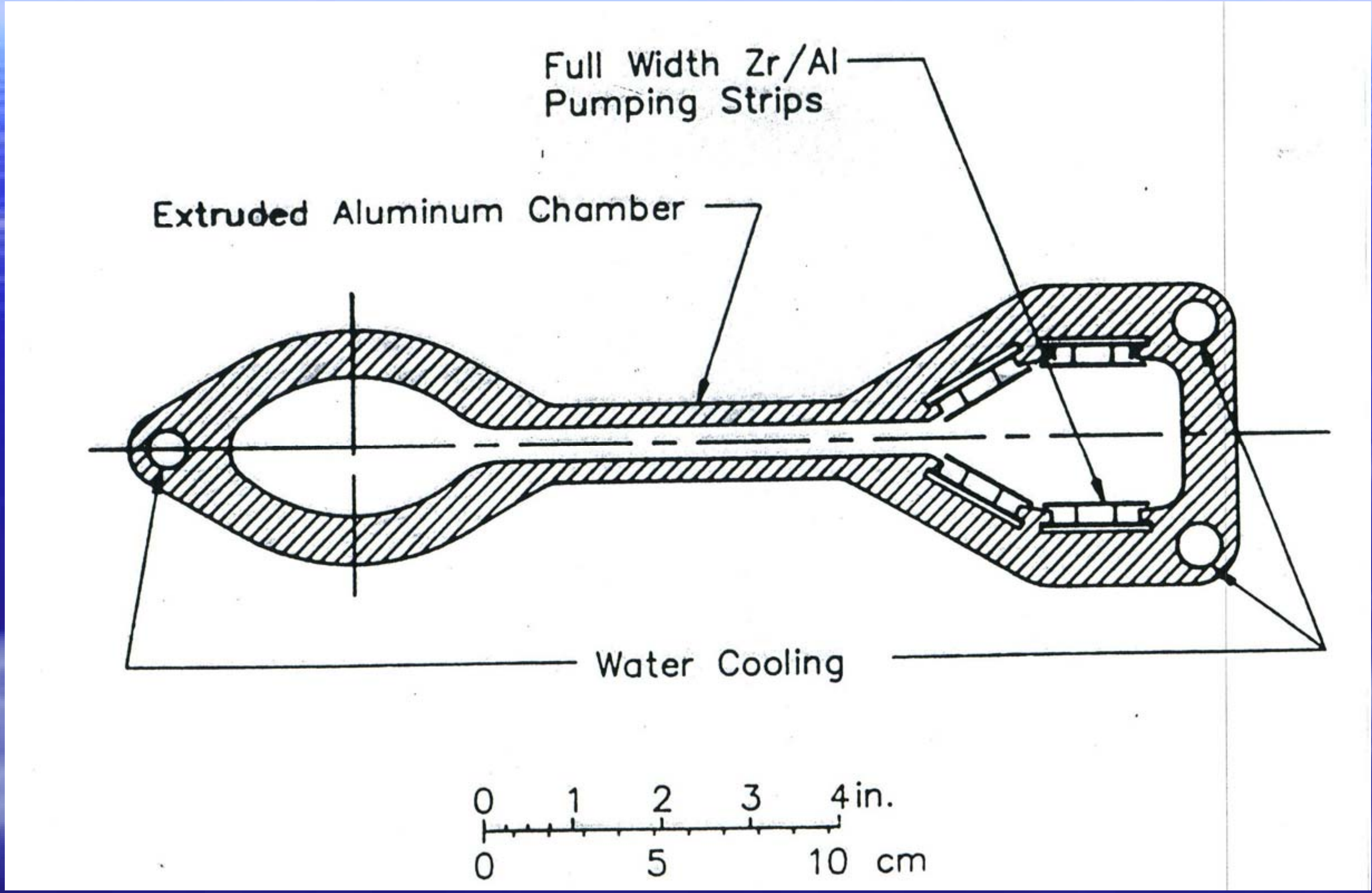
# Manufacturing and assembly

- Materials availability
  - Raw products: blanks, sheets
  - Semi-finished:
    - Extrusion (aluminum, copper)

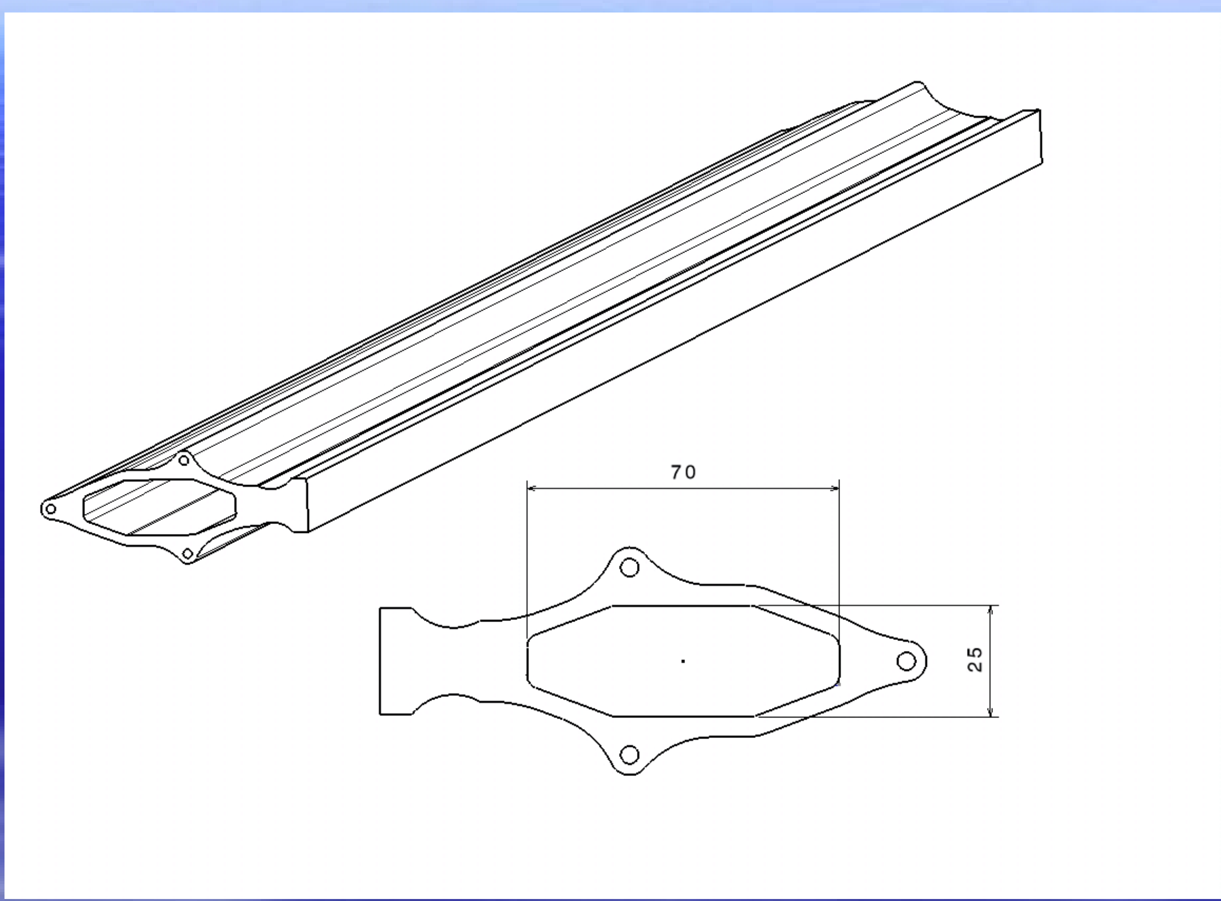
# TRISTAN



# ALS



Full Width Zr/Al
Pumping Strips
Extruded Aluminum Chamber
Water Cooling
0 1 2 3 4 in.
0 5 10 cm




Standard cross-section of the vacuum vessels of the SOLEIL storage ring

# Manufacturing and assembly

- Materials availability
  - Raw products: blanks, sheets
  - Semi-finished:
    - Extrusion (aluminum, copper)
    - Forgings (flanges)
    - Moldings
    - Sintering (ceramics, beryllium)

# Manufacturing and assembly

- Machining or sheet metal work
  - Defects internal to the metal: leaks if going through
  - Forging, extruding and laminating squeeze and enclose impurities
  - Machining could open the defects

## Material defect (AISI316LN with inclusions)

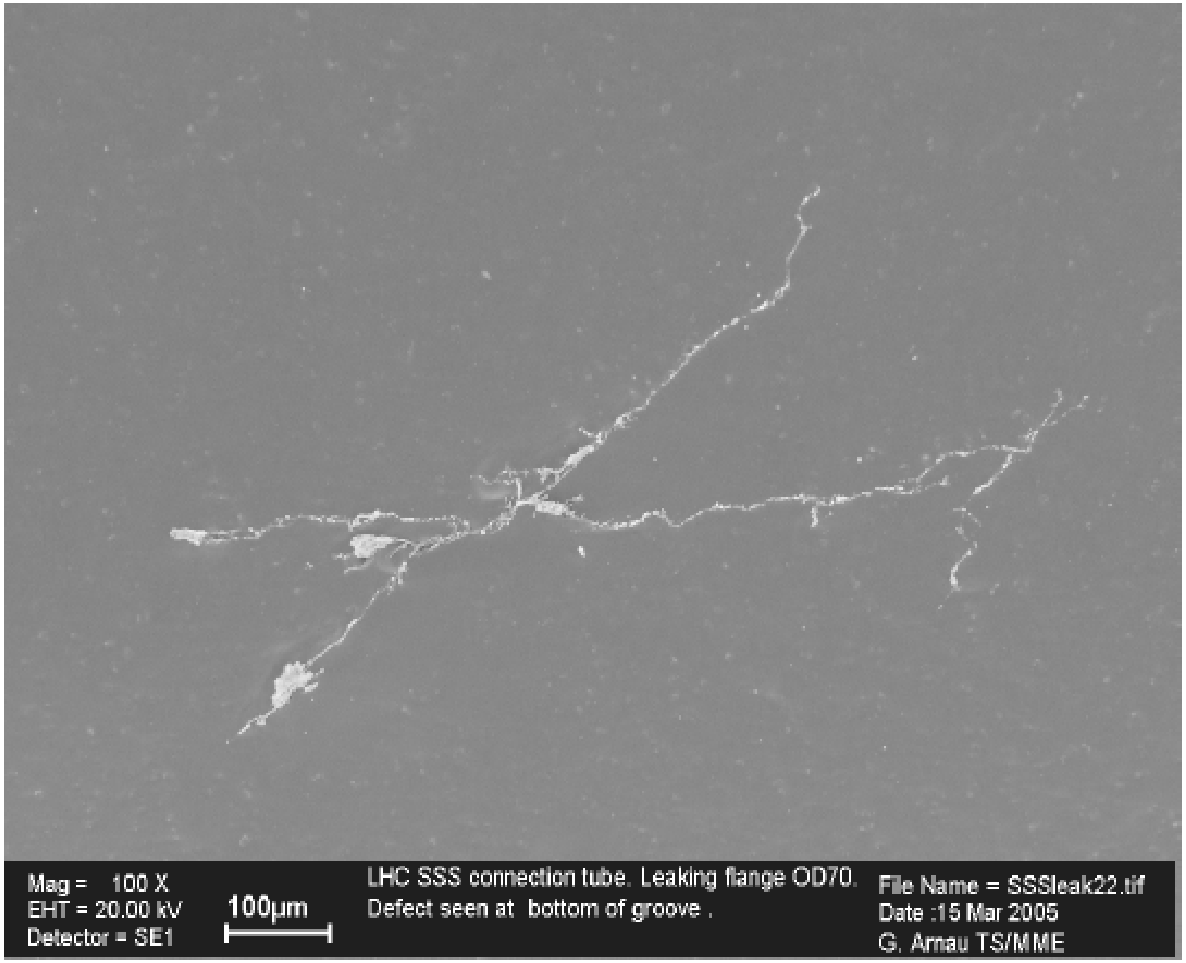
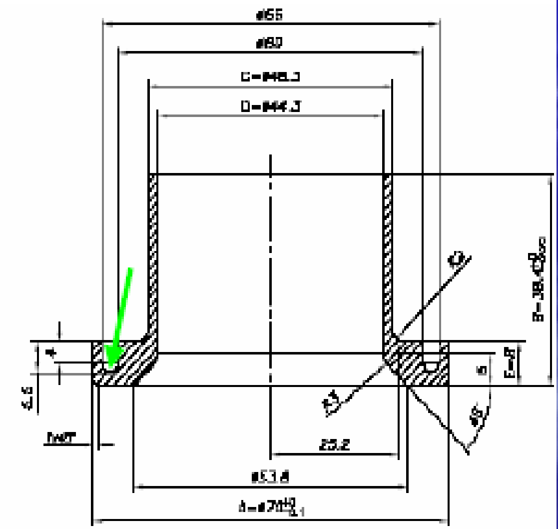
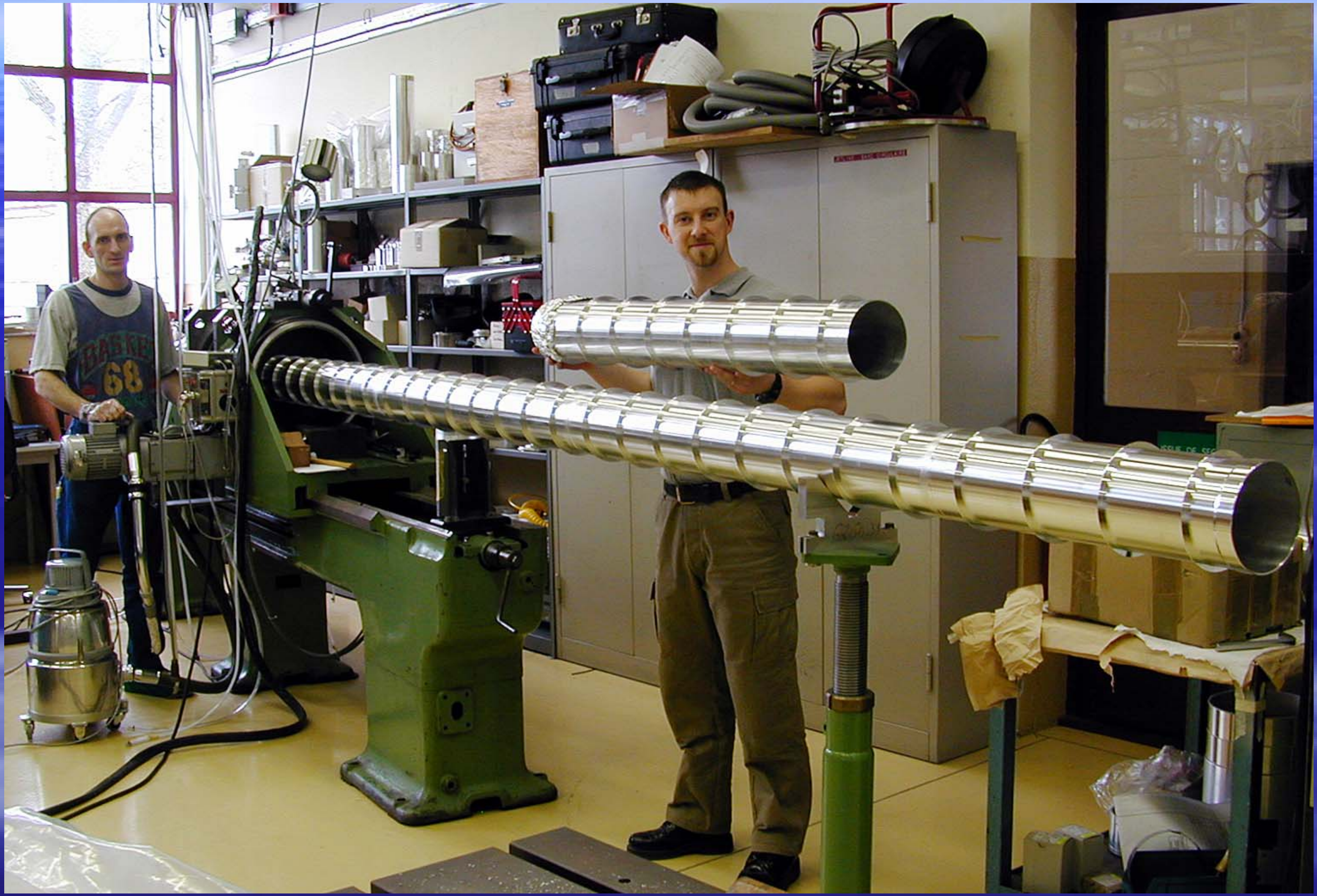



**Fig. 6.1.**
Mag.: × 100
Electro-polished sample.
Defect seen at the bottom of the groove at position pointed by He leak detection.



# Manufacturing and assembly



Aluminum ring-stiffened tubes (LEP…)

# Manufacturing and assembly

- Machining or sheet metal work
  - Defects internal to the metal: leaks if going through
  - Forging, extruding and laminating squeeze and enclose impurities
  - Machining could open the defects
  - Metal sheets leak-tight but potential problems in HAZ of welds

# Manufacturing and assembly

- Joining techniques
  - Main sources of leaks
  - Flanges or permanent seals (welds,…) ? How often ?

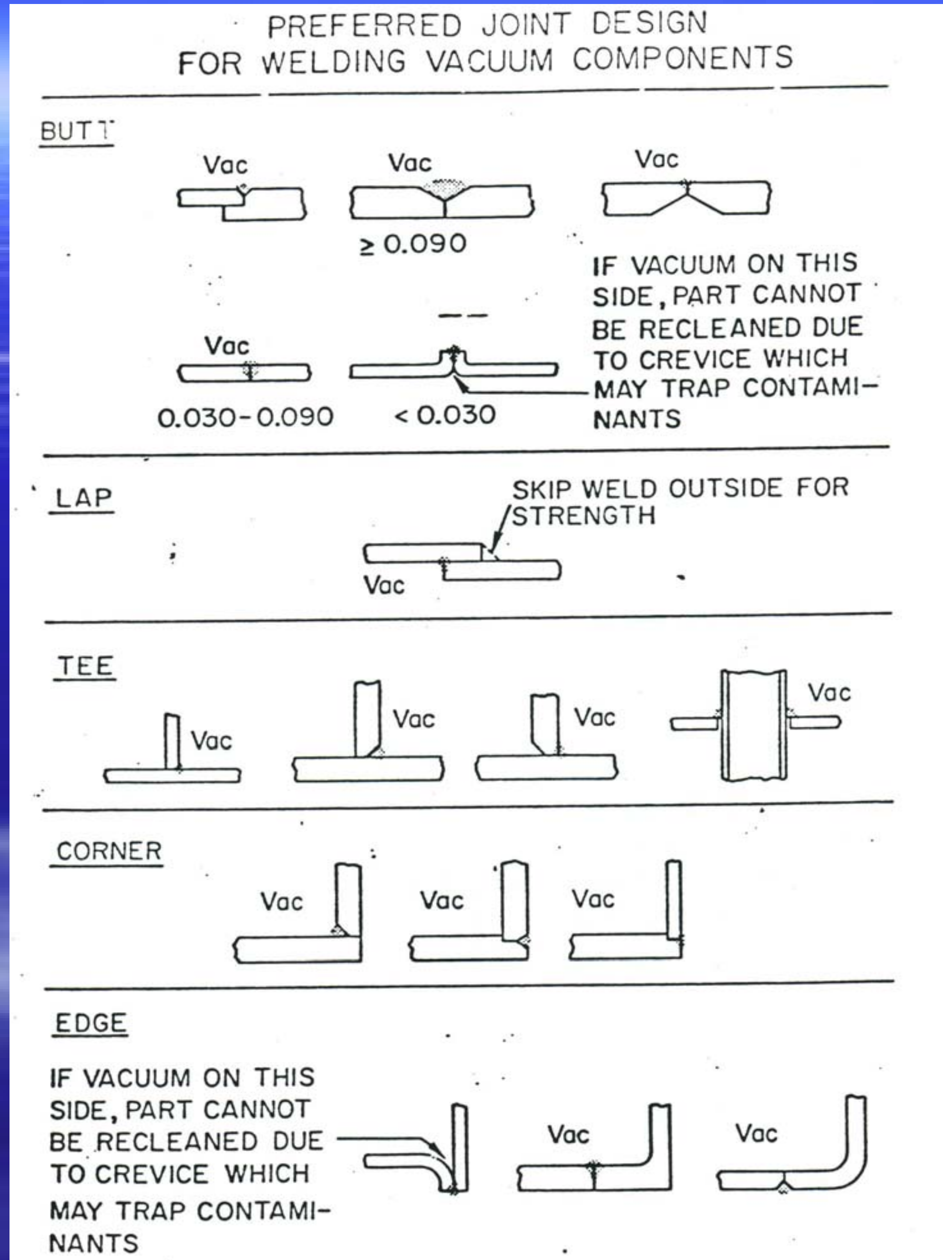
- Flanges
  - Industry standards
  - If specific design:
    - Stored energy and high forces: strong material
    - Sealing surfaces: quality and hardness
    - Seal: plastify locally to enforce leak tightness

# Manufacturing and assembly

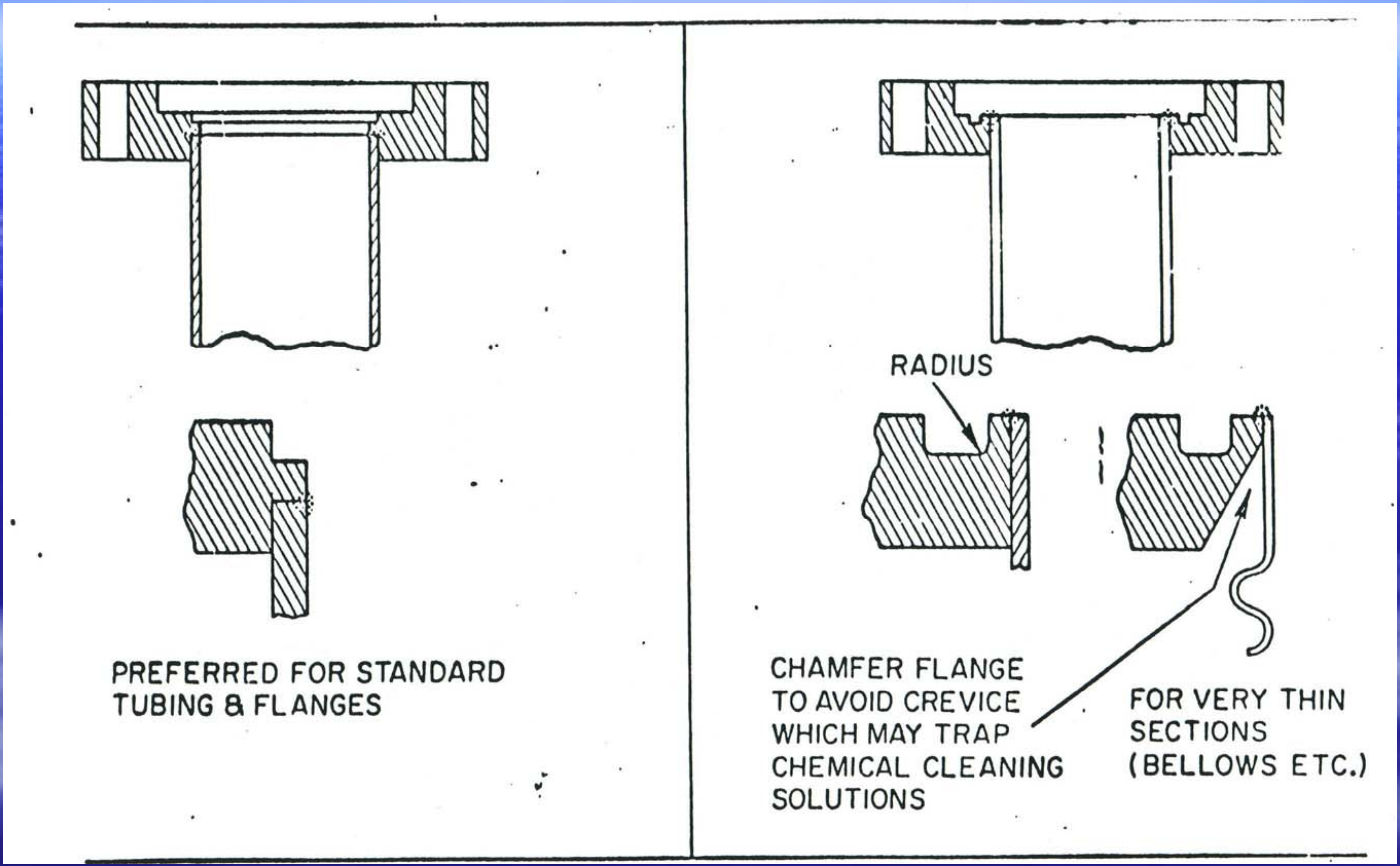
- Welding
  - Welds are sources of impurities and defects.
  - Weldability of the material ?
  - Design and execute according to the rules of the construction codes
    - Reduction factor: 0.85, 0.7

      Avoid localizing a weld in a highly stressed zone.
  - Specific rules for high vacuum chambers to avoid contamination and virtual leaks generated by pockets:
    - Welds on the vacuum side.
    - Trapped volumes between two welds forbidden.
    - Filler metal not recommended.
    - Grooves help to minimize heat propagation along the walls.
    - Crossing welds lead to a remelting of the bath creating defects.

# Manufacturing and assembly



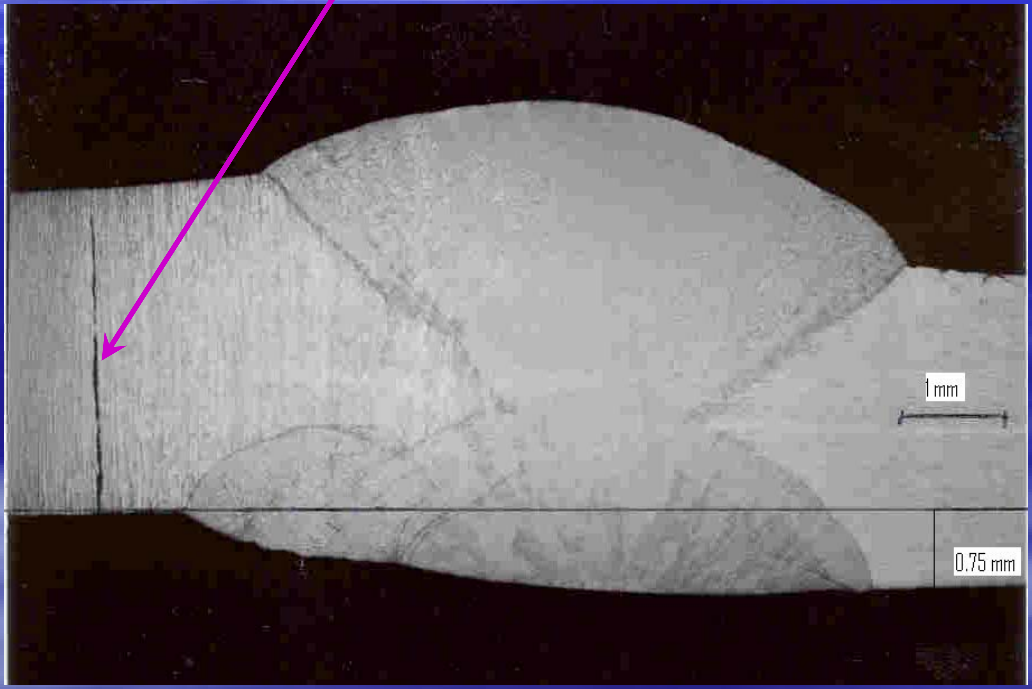
# Manufacturing and assembly



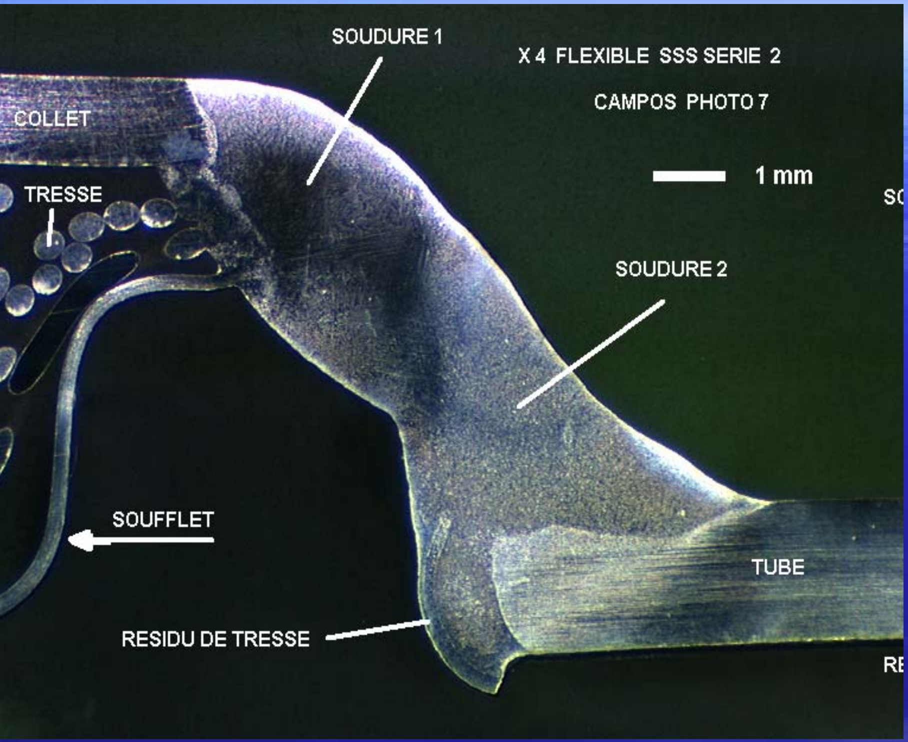

Vacuum flanges

# Manufacturing and assembly

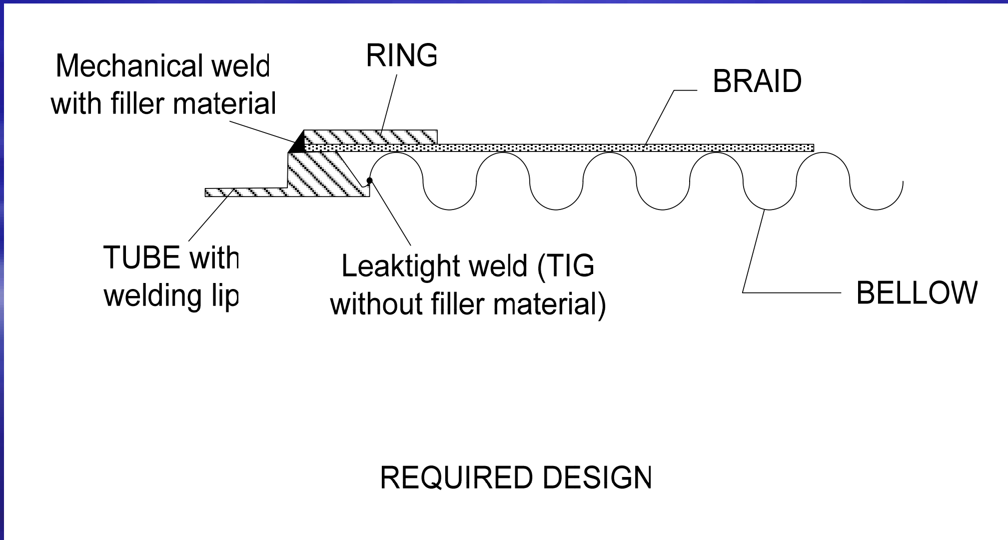
Material (304L) cracks close to weld




# Manufacturing and assembly




Welds too closed



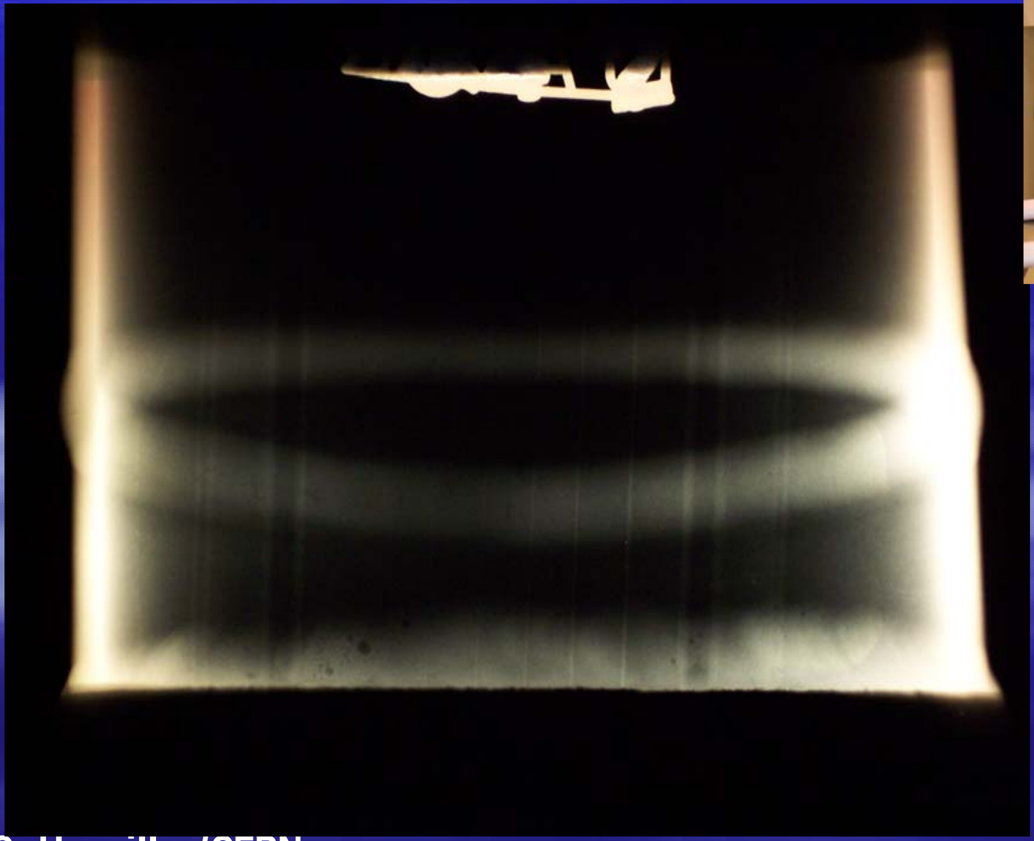
# Manufacturing and assembly

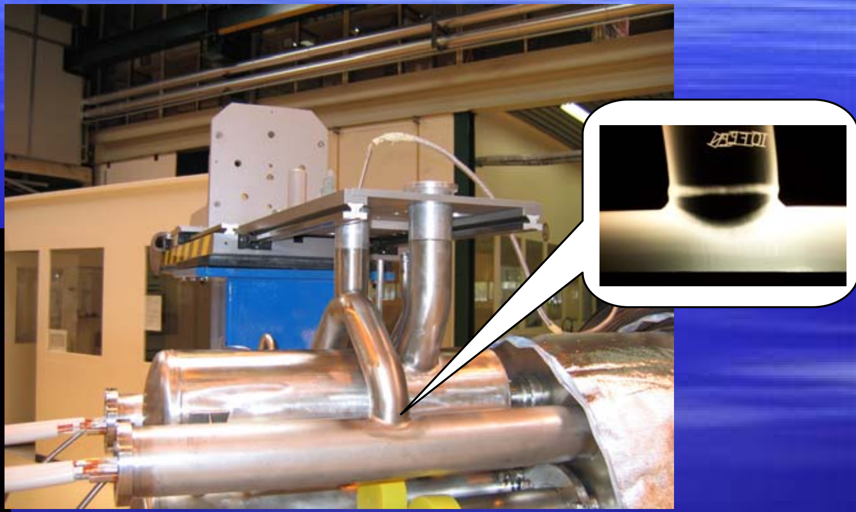
- Welding
  - The preferred and most used technology: TIG (Tungsten Inert Gas) welding. A very good inert gas (argon) protection is a prerequisite.
  - Electron beam welding not as flexible due to the need for a vacuum envelope.
  - Plasma welding is recommended for shells
  - Good mechanical preparation of the parts to be welded is the key to the success
  - Easier to weld in the workshop than in-situ
  - Not more than 99 % of the welds are leak-tight:

    visual inspection and X rays recommended or compulsory

# Manufacturing and assembly

X- ray inspections on welds





Stainless steel piping

Aluminum tube

# Manufacturing and assembly

- Brazing
  - Requires a furnace filled with a protective gas and jigs to keep the parts in position during the thermal cycle.
  - Solution to join dissimilar metals or ceramics together
  - Design of the interfaces to be brazed to be done according to strict rules taking onto account the expansion of the materials.
  - High quality cleaning after brazing : one classical problem is the appearance of corrosion on stainless steel following a deficient cleaning of the chloride-based flux.
- Gluing
  - Not common practice
  - Configuration of joints similar to brazing
  - Curing at RT or lower than brazing
  - Degazing
  - Prefer epoxies

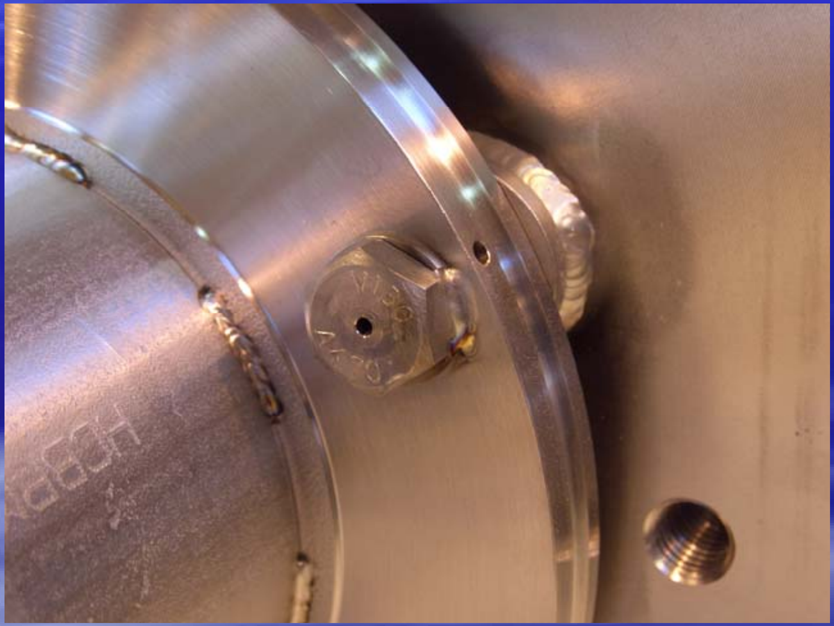
# Manufacturing and assembly

- Cleanliness
  - Cleanliness to minimize outgassing.
  - Well-known processes compatible with parts (materials, temperature, abrasion…).
  - Avoid polluting the parts during the fabrication, e.g. machining with silicon oils difficult to remove.
  - Suppress zones where puddles will remain and avoid closed volumes.

- Ease the leak detection
  - Painful step of the commissioning. Simple actions will ease the work:
    - provide access to the vacuum chamber, in particular to the joints,
    - avoid virtual leaks by suppressing closed volumes like bolts.
  - Time of flight technique for large chambers: provide easy way for helium to flow through radialy in order to minimize the perturbation when measuring over long distances.

# Manufacturing and assembly

Holes to open closed volumes



One leak tight weld the second interrupted.

# Quality assurance

- Clear technical specification and good quality drawings, using international standards.
- All the steps of the procurement, manufacturing and assembly detailed beforehand and controlled according to agreed procedures (construction codes contain specific chapters).
- Minimum requirement to choose a manufacturer is that he is certified ISO 9001: 2000.
- Include regular inspections at the premises of the contractor either by your technicians and/or by an accredited inspection body.

# Conclusion

- Designing a vacuum chamber is not very complex
- Be systematic if you want to get a good quality at the right price