CERN

Design inputs and concept

Specifications:

- Geometry:
  - Aperture of 1000 mm
  - About 100 km long
- Vacuum: 10^{-9} mbar
  → Low outgassing materials
  → In-situ bake out at 150 °C
- Mechanics:
  - Vacuum/atmospheric pressure
  - Gravity
- Environment
  - Corrosion resistant
- As cheap as possible

Design inputs and concept

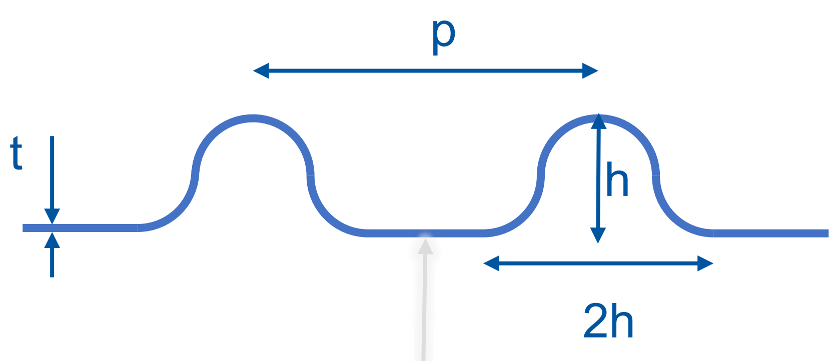
Mechanical aspects of **thin-walled corrugated tubes**

- Withstand external pressure
- Stainless steel material
- No need of bellows
- Easier bake out
- Less raw material
- lighter forming equipment (thinner wall)

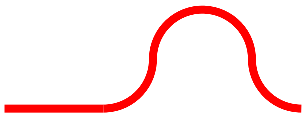
Mechanical aspects

The design is driven by the buckling pressure of a corrugated tube.

Simplified geometry with two parameters.



Unfolded length of one pitch: Lr

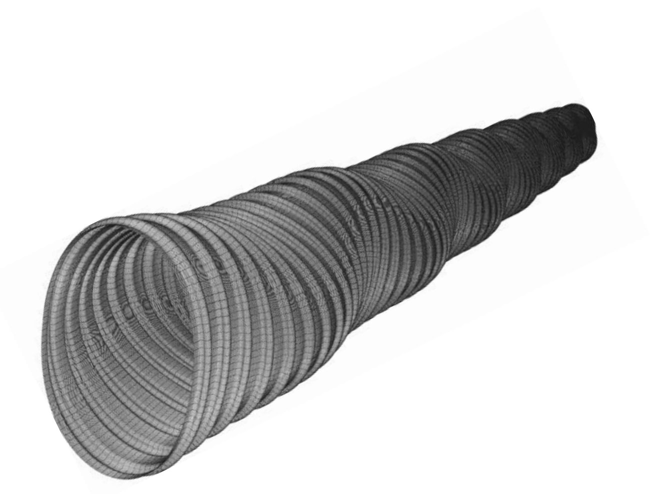


Equivalent thickness for the material quantity: $t_{eq}=t*L_r/p$

A flat section between each corrugation accommodates baffle interfaces and simplifies tooling insertion if required

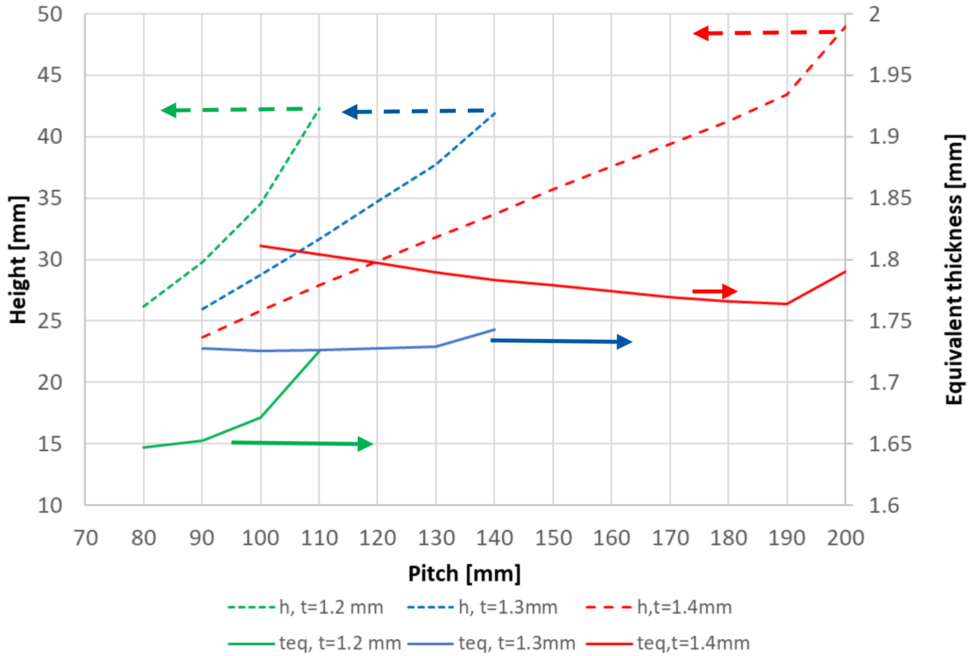
For long thin tube, typical buckling mode 2 is observed.

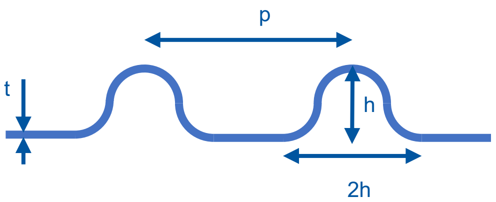
Safety coefficient of 3 is included.



Mechanical aspects

Wall thickness in the range 1.2-1.5 mm can be considered for a buckling differential pressure of 3 bars.





1.5 mm thick wall chamber could be a good starting point considering welding, convolution height.

Mechanical aspects

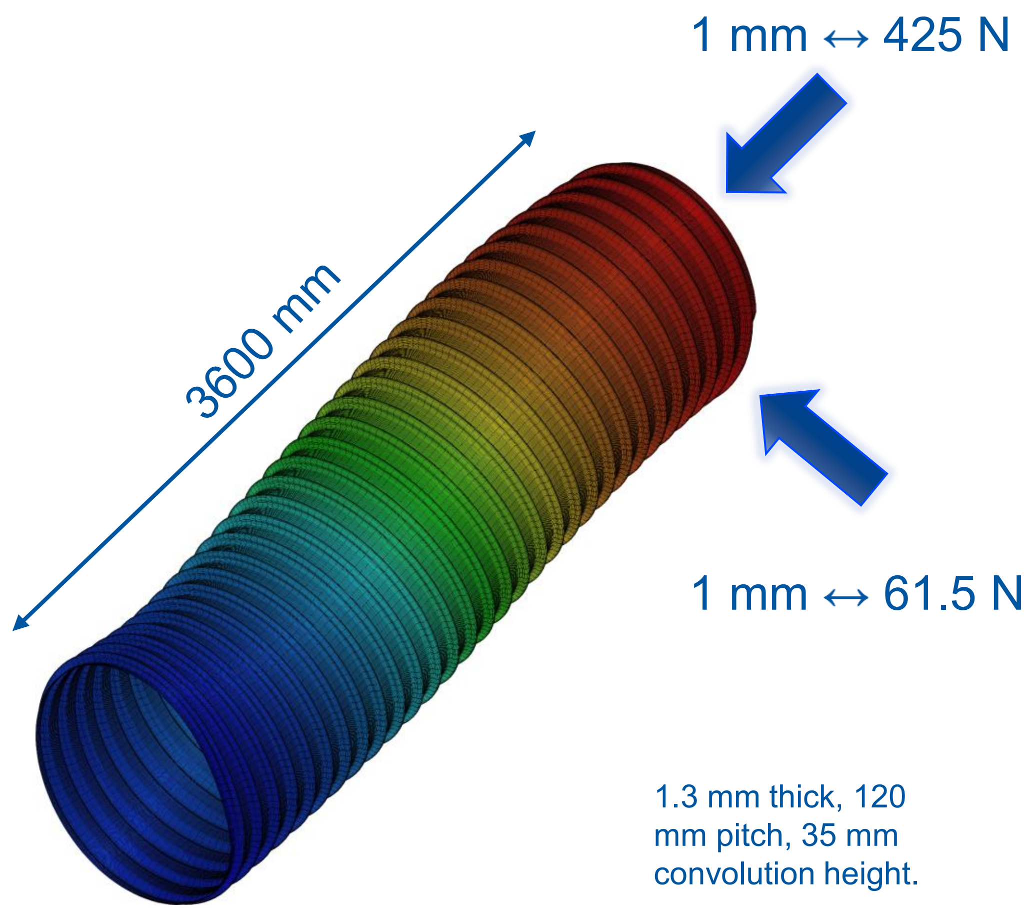
Specific stiffness:
- Axial (E.S): 1.53E6 N
- Transversal (E.I): 2.4E11 N.mm^2

Specific weight: 48 kg/m

Bakeout induced axial force: -3.3 kN
(< 95 kN thrust force)

Euler buckling force (in case of accidental venting during bakeout), assuming simple supports distanced by 7.5 m : -42 kN

→ Global column instability not expected.

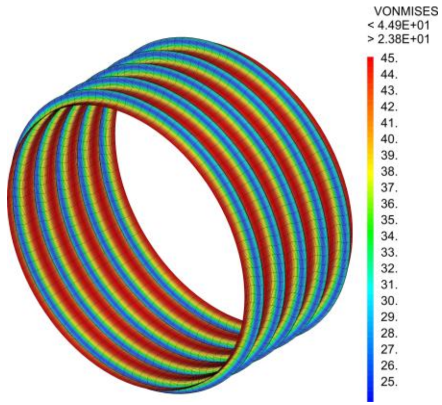


1.3 mm thick, 120 mm pitch, 35 mm convolution height.

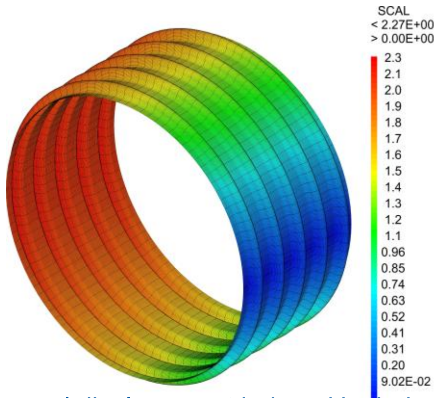
Mechanical aspects

Behaviour during bakeout (150°C) :

- Stress of about 50 MPa
- Diameter dilatation of about 2.3 mm



Von Mises equivalent stress field during bakeout



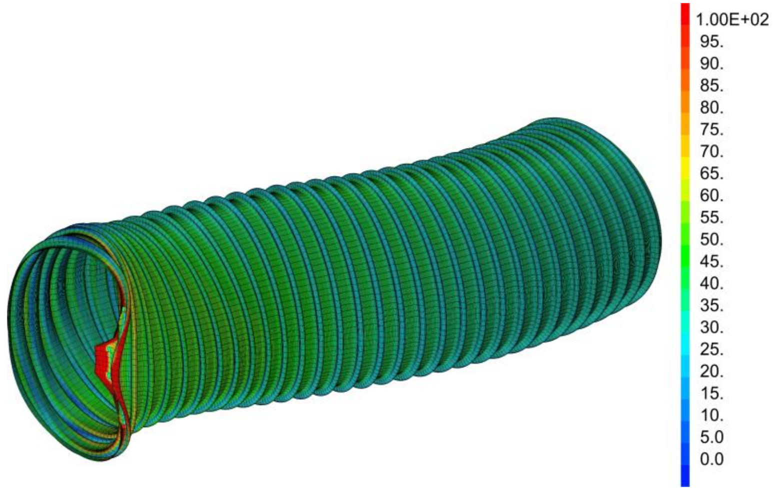
Transversal displacement induced by bakeout

Von Mises equivalent stress during bakeout under gravity (singularity at support removed)

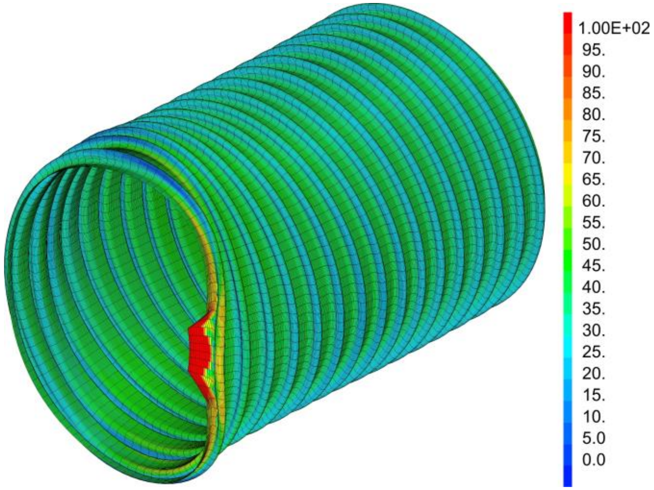
Mechanical aspects

Behaviour during bakeout with gravity:

- Assumption of a 14 m long tube
  - Supported at 3.25 m from the extremities
    - Sag ~ 18.3 mm
    - Stress in the 60 MPa (support area excluded)
  - Supported at 3.25 m from the extremities with central crutch
    - Sag ~ 2.5 mm
    - Stress in the 50 MPa (support area excluded)



Von Mises equivalent stress field during bakeout under gravity with supports distanced by 7.5 m (deformed shape factor: 100)

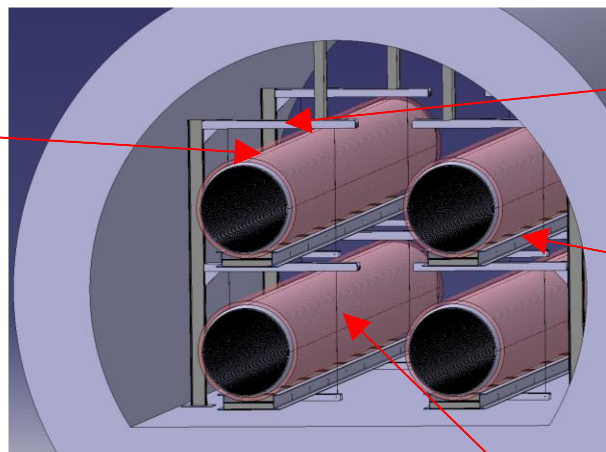


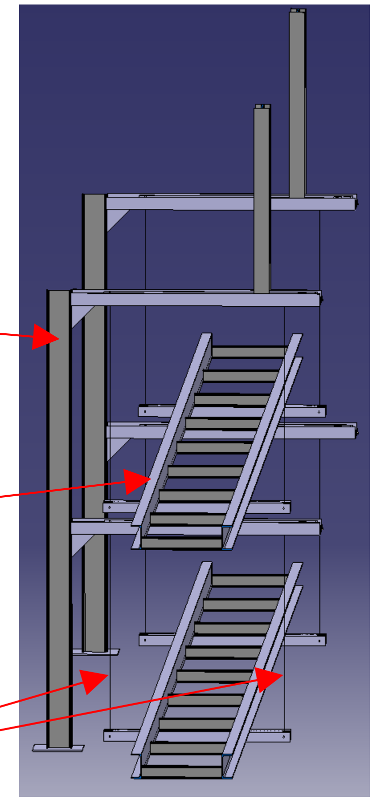
Von Mises equivalent stress field during bakeout under gravity with additional central support (deformed shape factor: 100)

A support proposal

The proposed design, based on a suspended vacuum chamber, aims at reducing vibrations on the baffles.

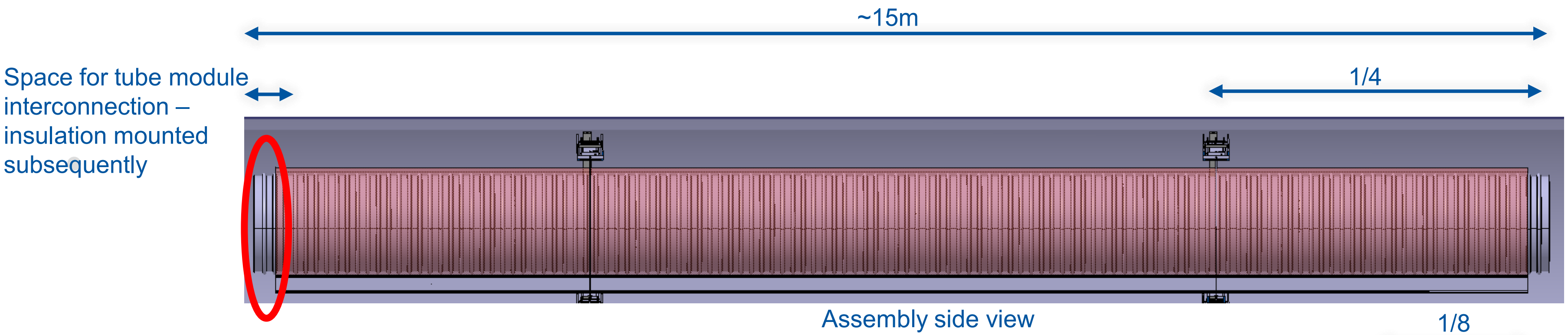
Basic concept is based on harmonic oscillator and aims at lowering the first eigen frequencies.



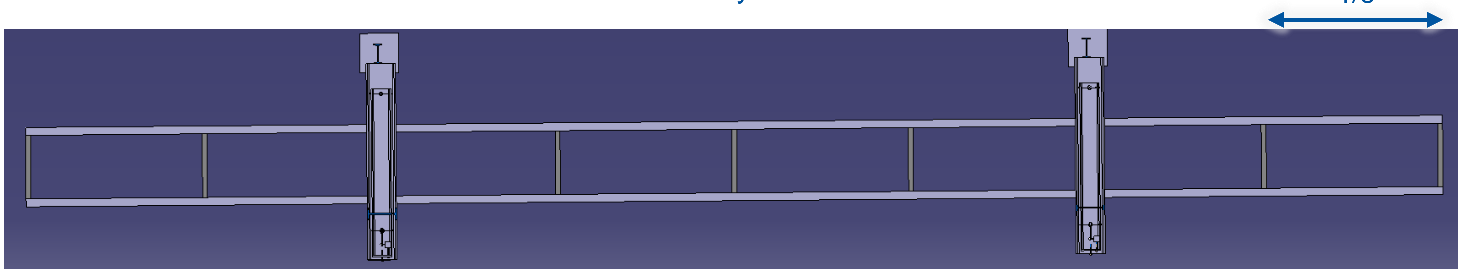


A support proposal

Elementary module would be composed of a ~15m long chamber, insulated and installed on a the supporting frame.
Supporting beam would be mounted and pre-aligned before module installation.



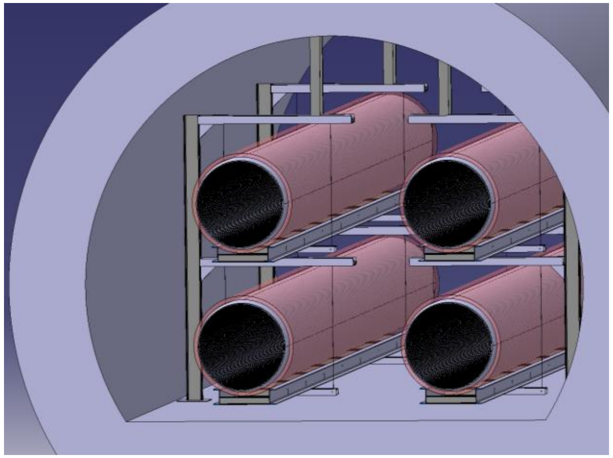
Assembly side view

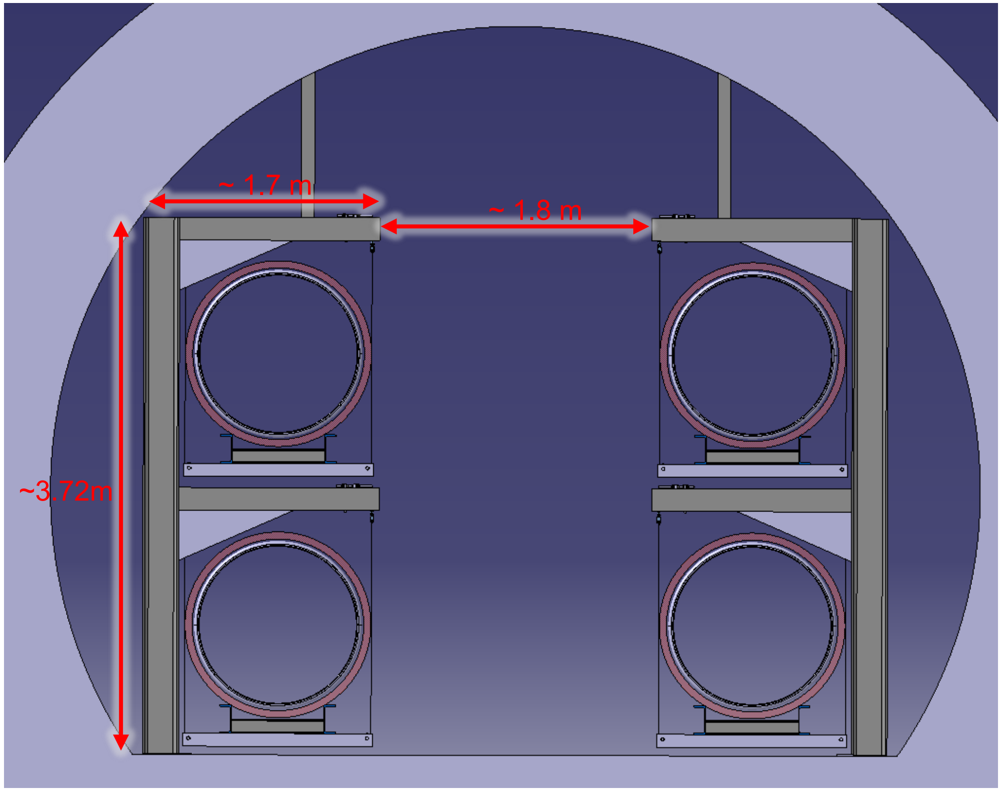


Support top view

Preliminary implementation in a tunnel cross-section

- Passage width: 1,8 m
- Depending on the tunnel floor heigh

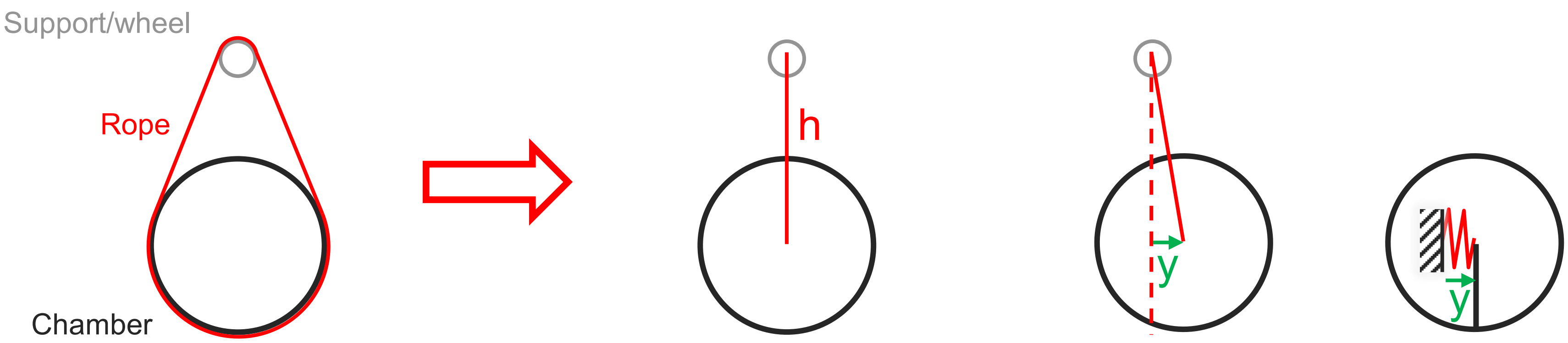




Mechanical aspects

Column Stability for hanging structure

During the thermal treatment, the chamber is in compression without vacuum → subjected to column buckling.



The chamber behaves as a pendulum that corresponds in lateral direction to an elastic foundation.

Specific mass

Specific foundation stiffness: $K_s = \frac{m_l \cdot g}{h}$

Pendulum height

Expected buckling force for infinitely long column on elastic foundation:

$$F_{cr} = \sqrt{4 \cdot K_S \cdot E \cdot I}$$

For h = 1 m, EI = 2.4E11 N.mm^2 and m= 48 kg.m^{-1}: F_{cr} ~ 21.25 kN

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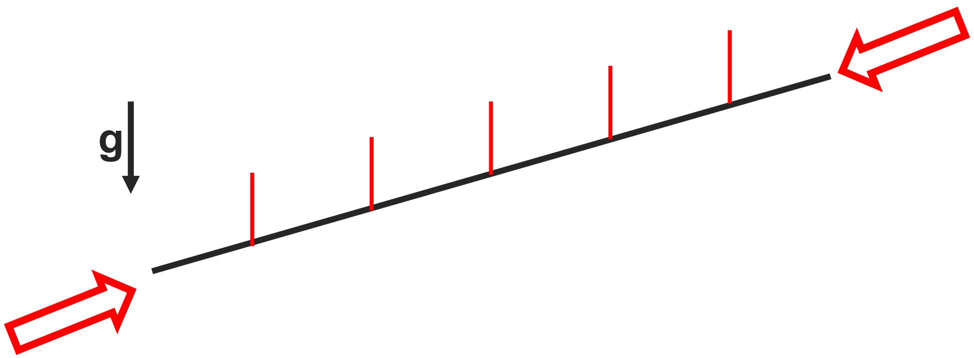
Mechanical aspects

Column Stability for hanging structure

Two models:

- Beams in 2D with equivalent springs to model the pendulum effect; eigen mode study

- Beams in 3D with gravity and initial imperfection; non linear large displacement study

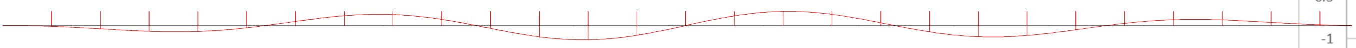


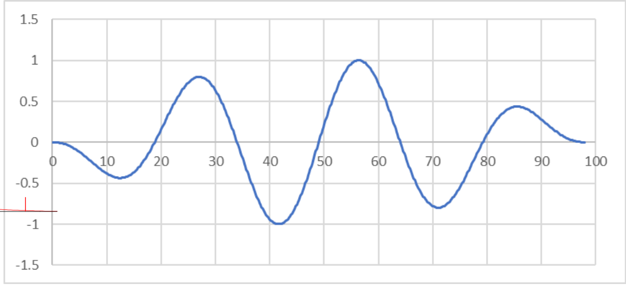
Mechanical aspects

Column Stability for hanging structure

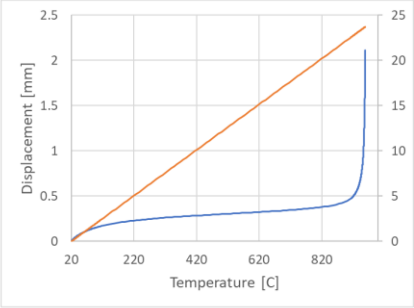
100 m model:

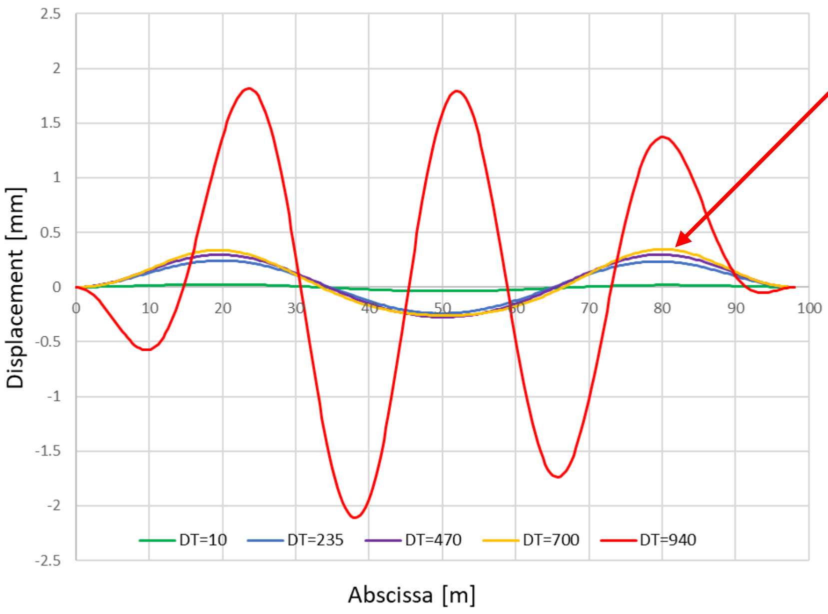
- 2D eigen value model: buckling force: 22.15 kN

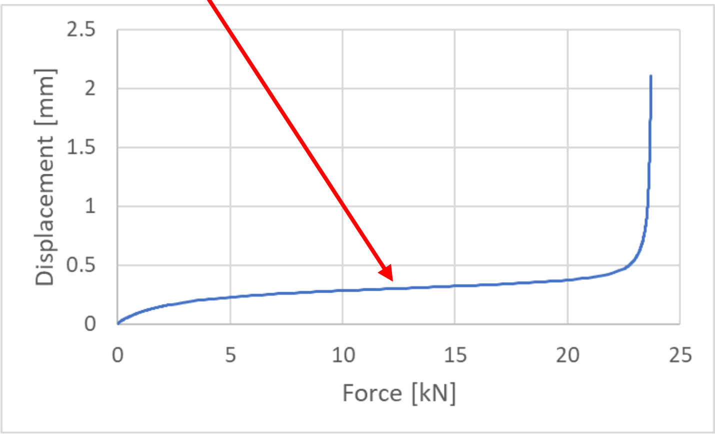




- 3D non linear model:
  - Instability at ~ 23 kN (930 C)
  - Plateau with stable deformation related to initial imperfection





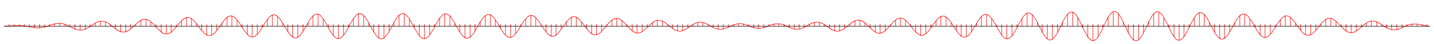


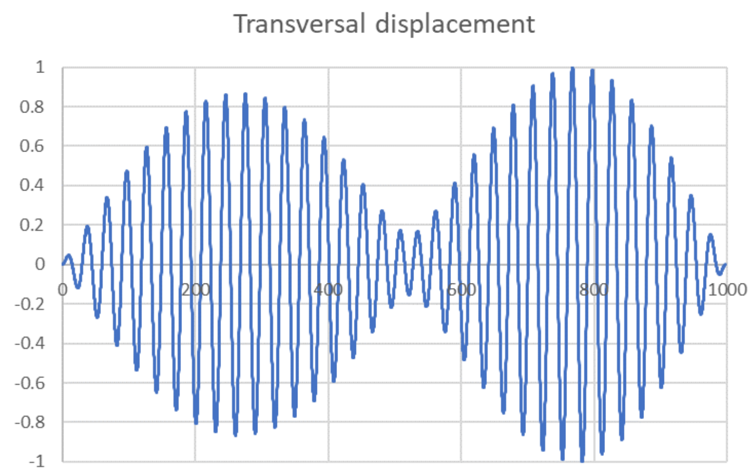
Mechanical aspects

Column Stability for hanging structure

1000 m model:

- 2D eigen value model: buckling force: 21.3 kN





No significant difference between the 100 and 1000 m models.
Very good agreement between the two models and the theoretical values.
The chamber remains stable during the heat treatment in the 200-300 C range (Safety coefficient: 3-4).

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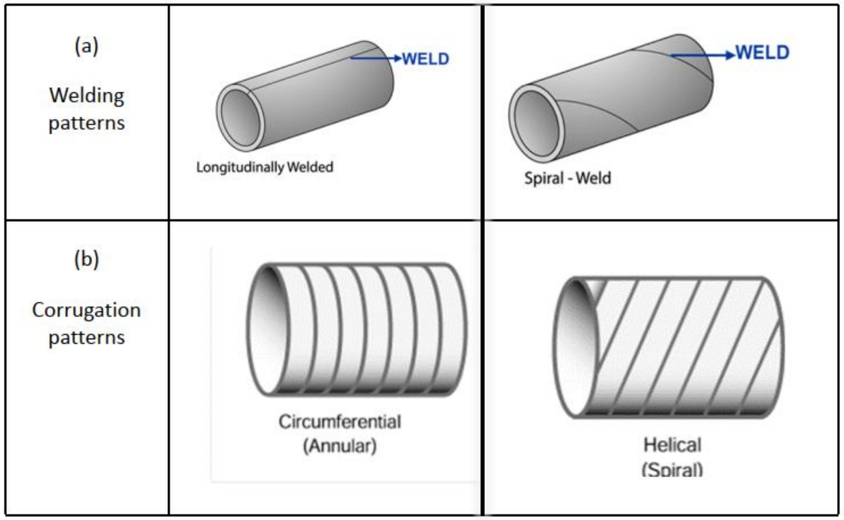
Annular vs spiral corrugations



https://www.prdcompany.com/corrugated-metal-pipe/

https://www.ail.ca/product/corrugated-steel-pipe/

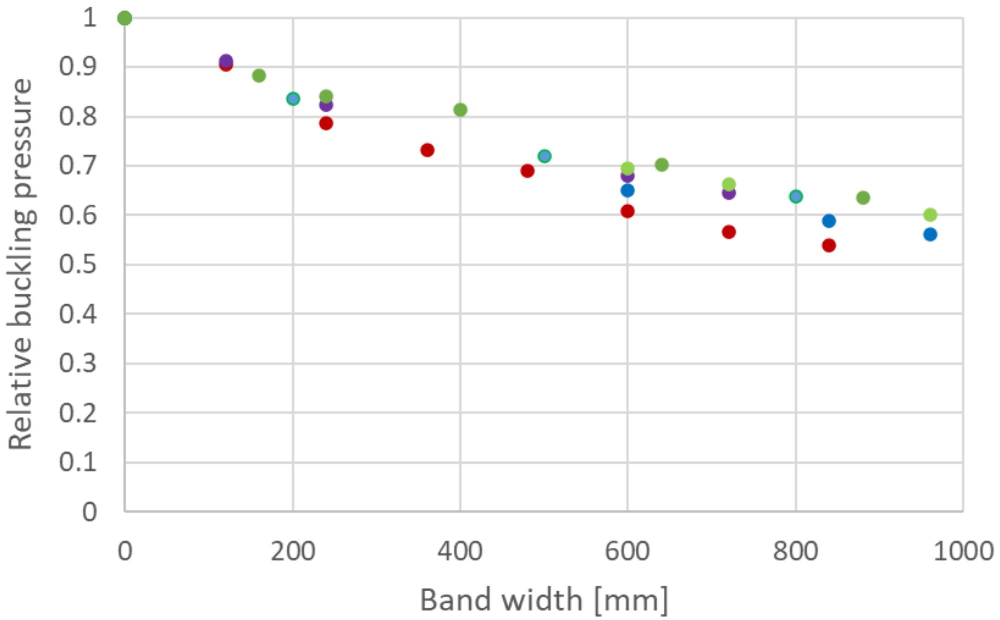
Spiral corrugations

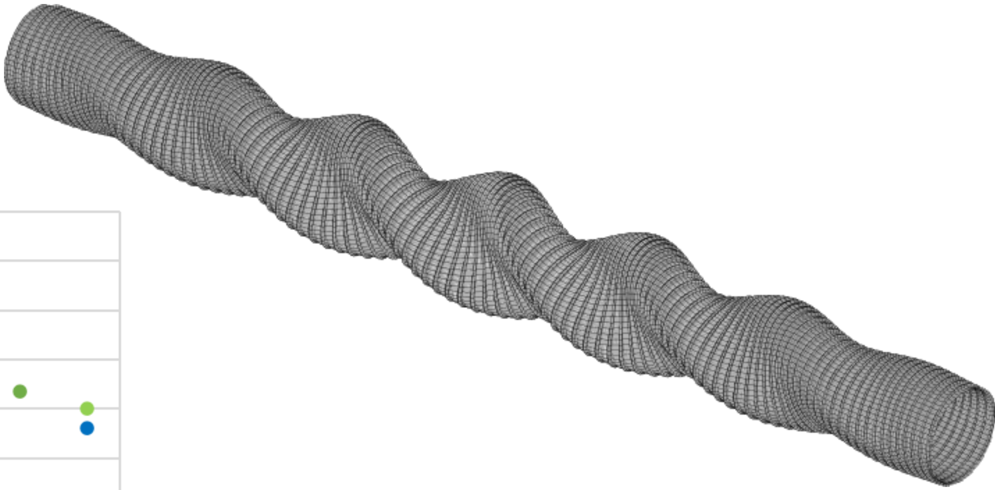
Spiral corrugations

Drawbacks

Decrease of mechanical performance:

- Higher longitudinal stiffness
- Lower buckling strength





Influence of band width (helice angle) on the relative buckling pressure for different convolution parameters

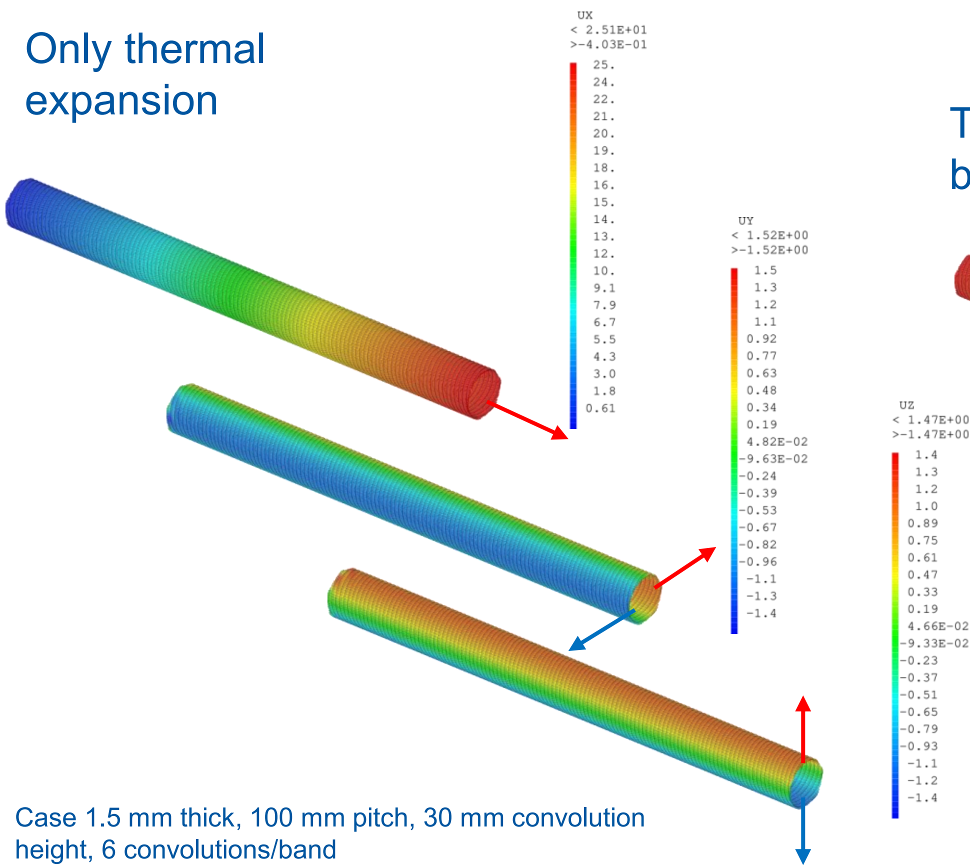
Spiral corrugations

Drawbacks

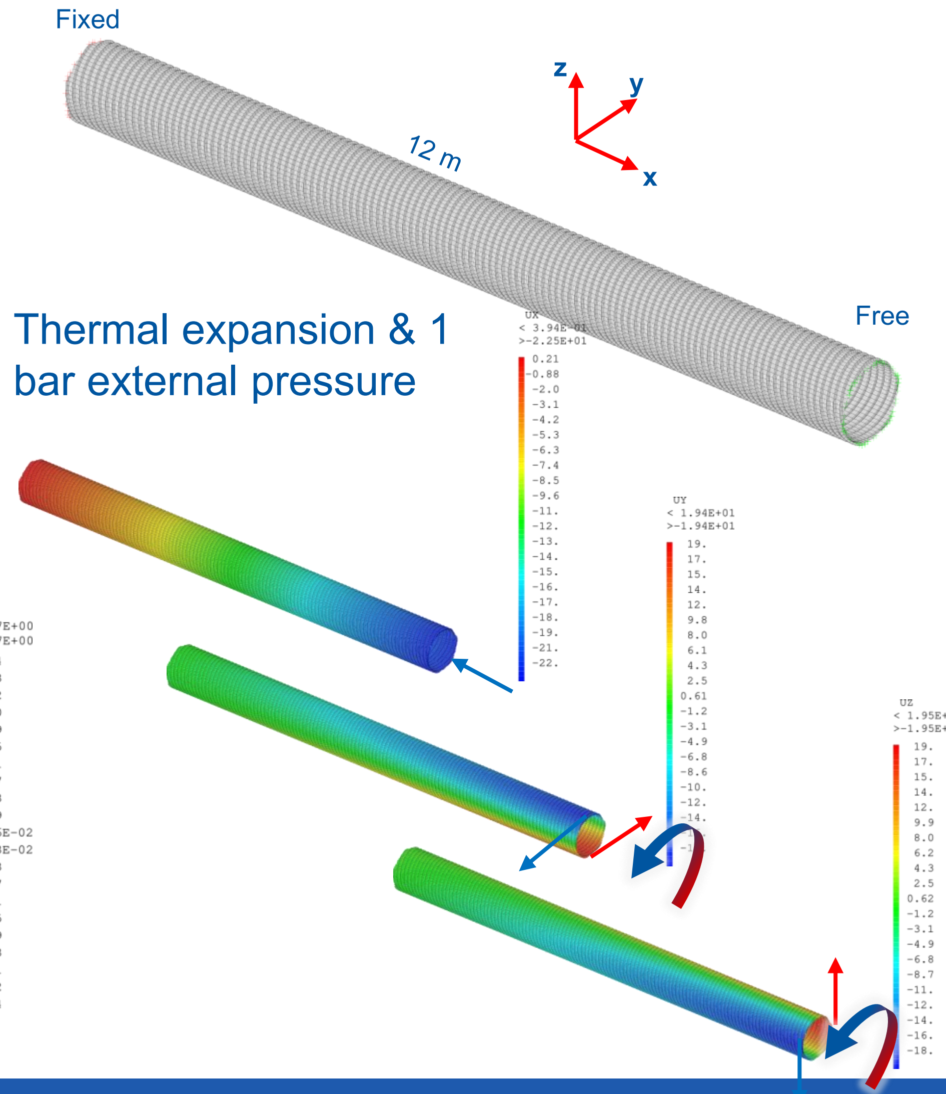
Axial/torsional coupling:

- Axial force induces rotation or torque.

Only thermal expansion



Thermal expansion & 1 bar external pressure



Case 1.5 mm thick, 100 mm pitch, 30 mm convolution height, 6 convolutions/band

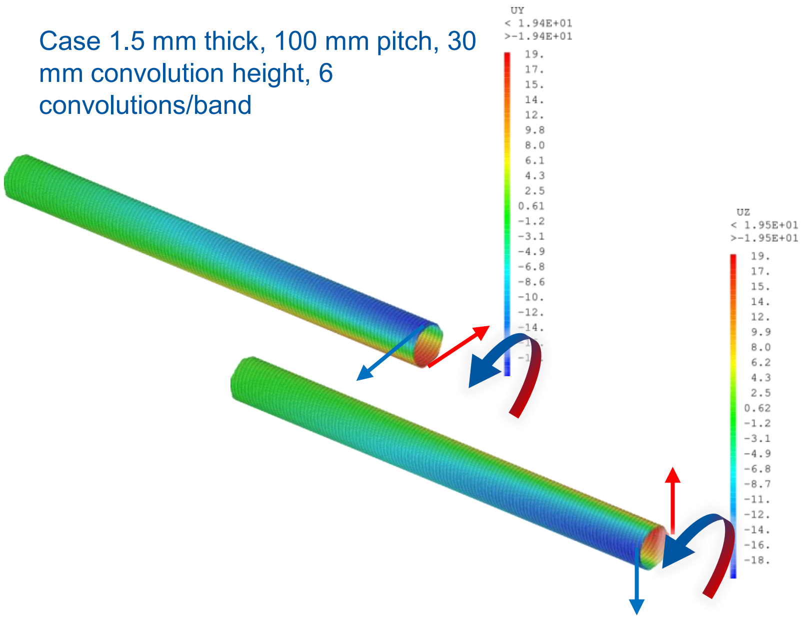
Spiral corrugations

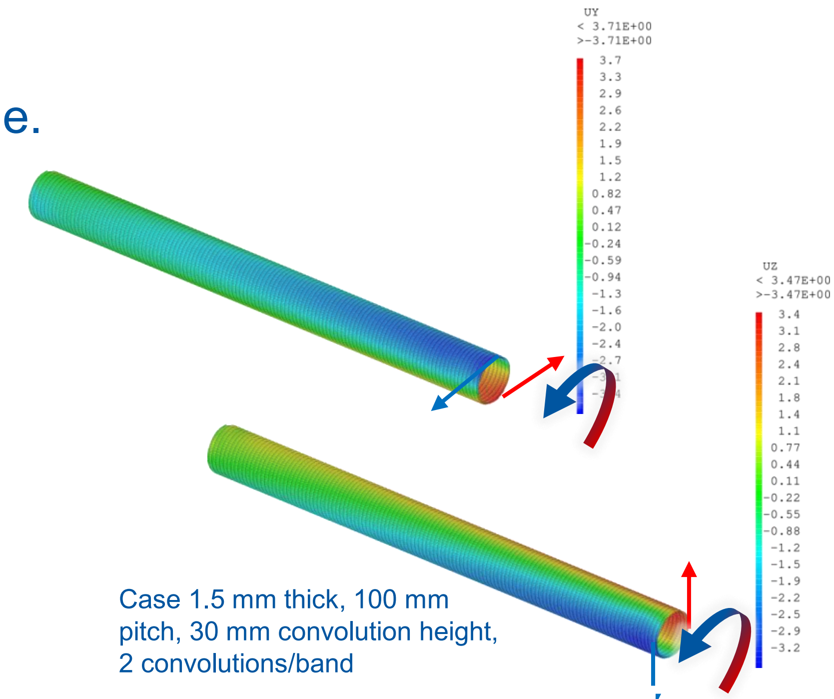
Drawbacks

Axial/torsional coupling:

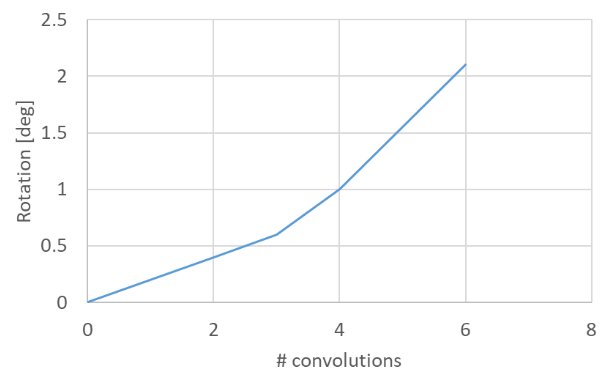
- Axial force induces rotation or torque.

Case 1.5 mm thick, 100 mm pitch, 30 mm convolution height, 6 convolutions/band





Case 1.5 mm thick, 100 mm pitch, 30 mm convolution height, 2 convolutions/band

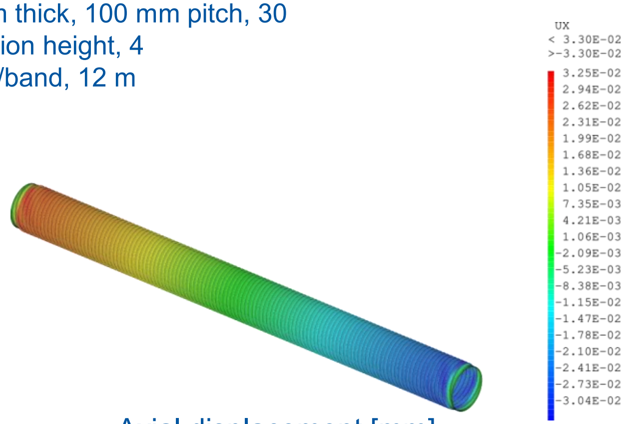


Spiral corrugations

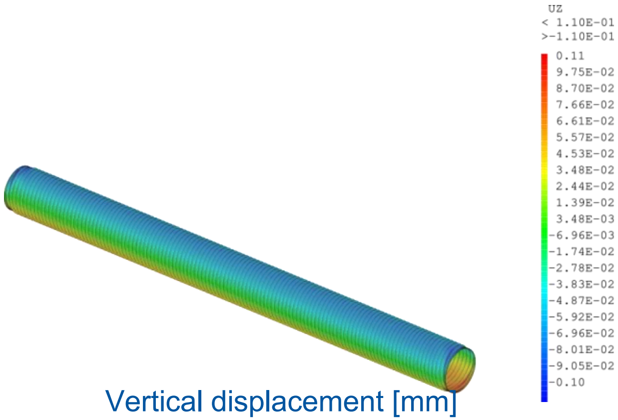
Reaction forces – effect of boundary conditions

Clamped both extremities, under vacuum

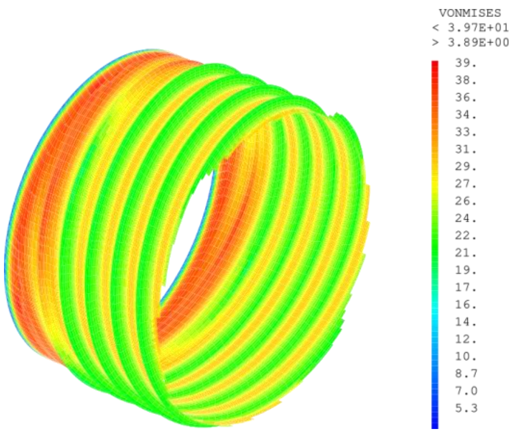
Case 1.5 mm thick, 100 mm pitch, 30 mm convolution height, 4 convolutions/band, 12 m



Axial displacement [mm]



Vertical displacement [mm]



Equivalent Von Mises Stress

Axial moment: -6343 N.m
Axial force: 4820N

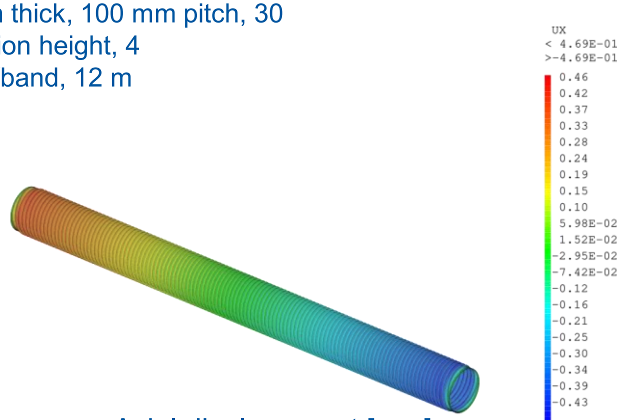
Stress in the 30 MPa range.

Spiral corrugations

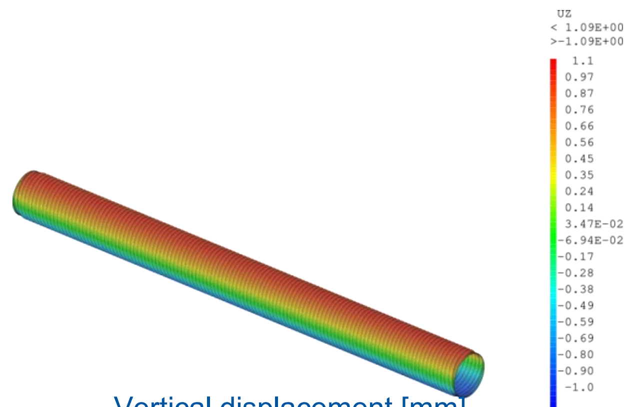
Reaction forces – effect of boundary conditions

Clamped both extremities, under vacuum during bakeout at 150 C

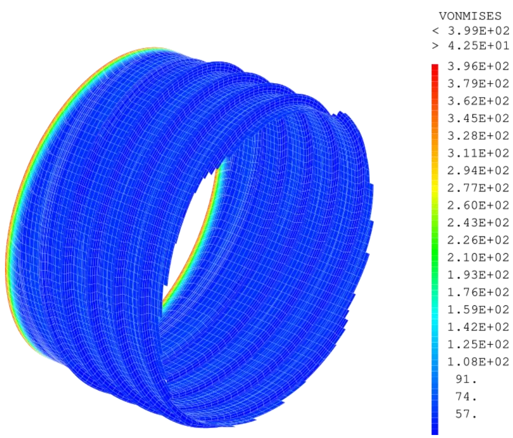
Case 1.5 mm thick, 100 mm pitch, 30 mm convolution height, 4 convolutions/band, 12 m



Axial displacement [mm]



Vertical displacement [mm]



Equivalent Von Mises Stress

Axial moment: -62626 N.m
Axial force: -35340 N

Stress in the 60 MPa range.

For comparison:

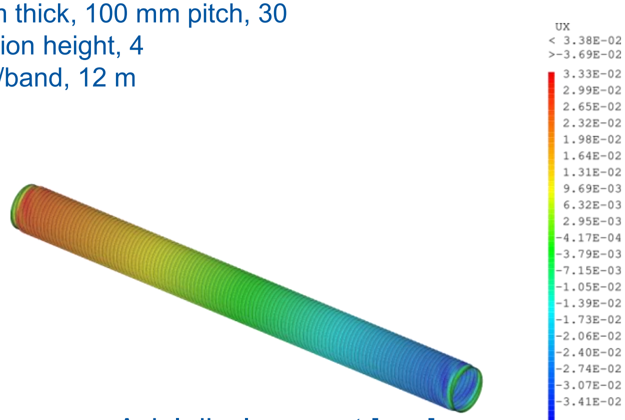
- Torque generated by friction under weight ~ 50 kg/m * 6 m * 9.8 * 0.1 * 0.5 ~ 150 N.m
- Buckling in torsion (2πEI/L): ~1.5E5 N.m

Spiral corrugations

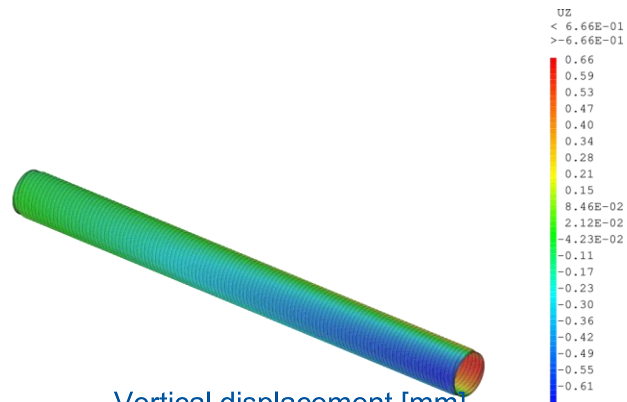
Reaction forces – effect of boundary conditions

Clamped at one extremity, fixed axially and free to rotate at the other, under vacuum

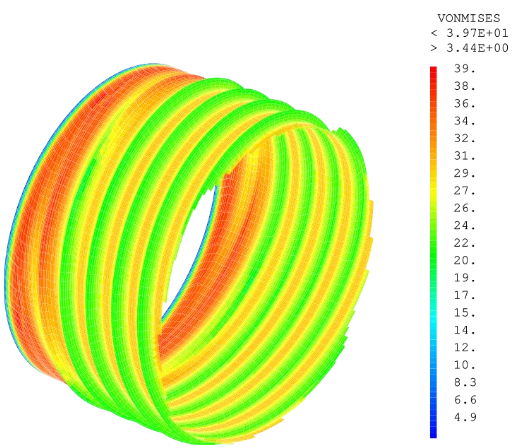
Case 1.5 mm thick, 100 mm pitch, 30 mm convolution height, 4 convolutions/band, 12 m



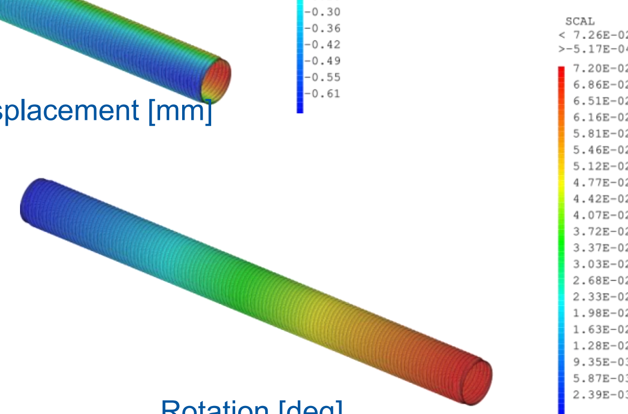
Axial displacement [mm]



Vertical displacement [mm]



Equivalent Von Mises Stress



Rotation [deg]

Axial force: ~ 7900 N
Rotation: ~ 1.3 mrad

Stress ~ 30 MPa

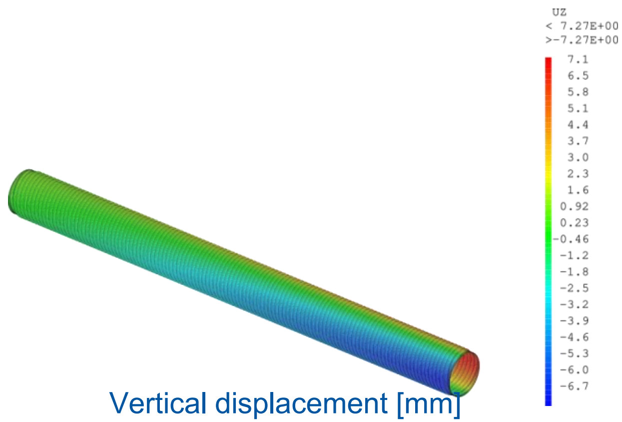
Spiral corrugations

Reaction forces – effect of boundary conditions

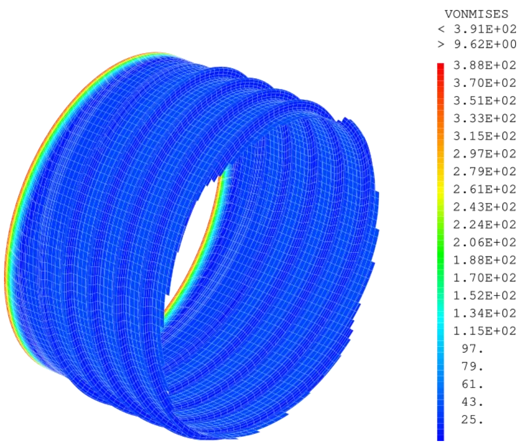
Clamped at one extremity, fixed axially and free to rotate at the other, under vacuum during bakeout at 150 C

Case 1.5 mm thick, 100 mm pitch, 30 mm convolution height, 4 convolutions/band, 12 m

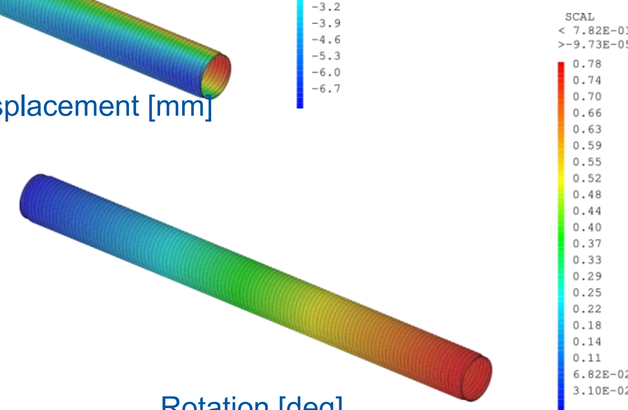
Axial displacement [mm]



Vertical displacement [mm]



Equivalent Von Mises Stress



Rotation [deg]

Axial force: ~ -3100 N

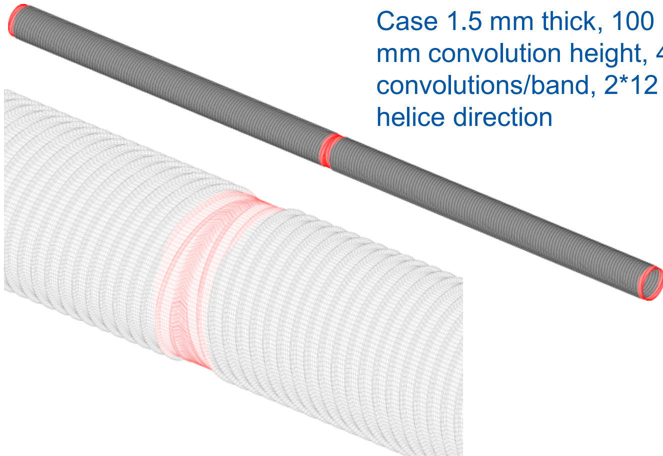
Rotation: ~ 14 mrad

Stress ~ 30 MPa

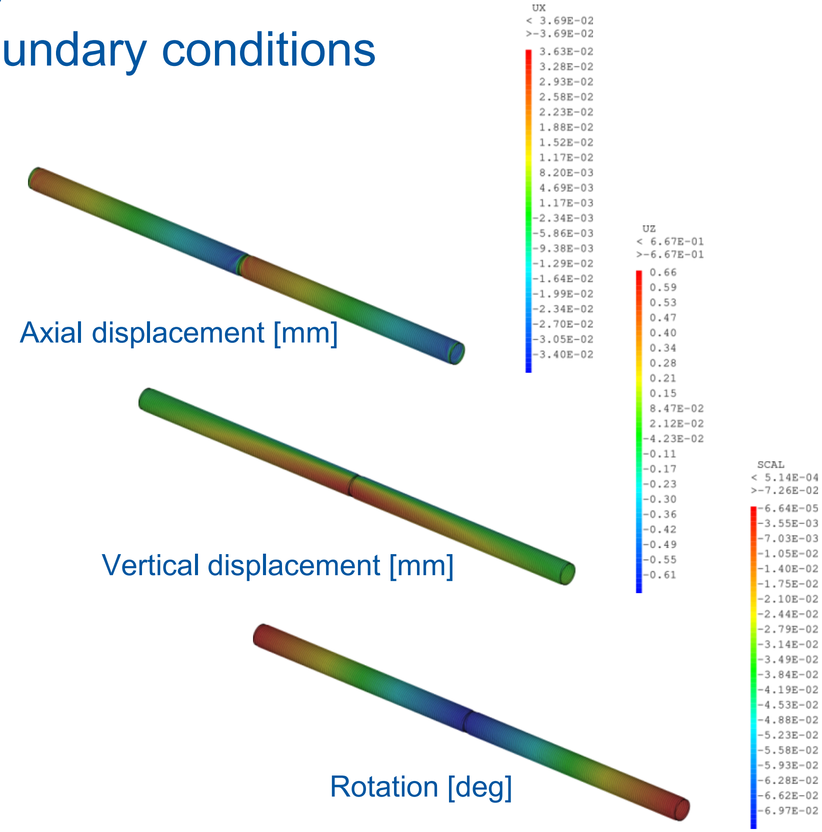
Spiral corrugations

Reaction forces – effect of boundary conditions

Clamped both extremity, under vacuum



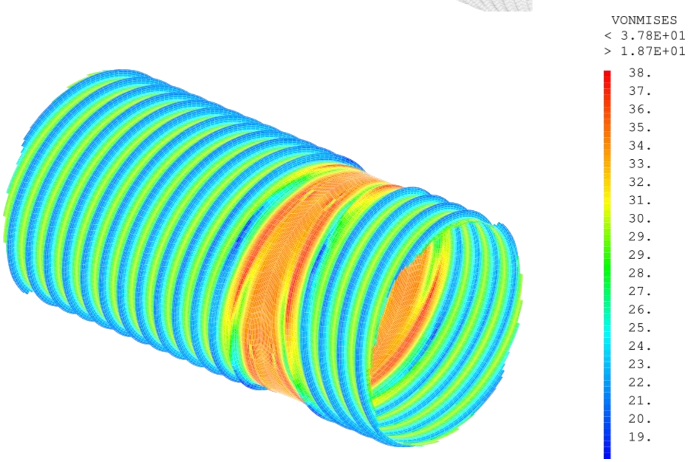
Case 1.5 mm thick, 100 mm pitch, 30 mm convolution height, 4 convolutions/band, 2*12 m, opposite helice direction



Axial displacement [mm]

Vertical displacement [mm]

Rotation [deg]



Equivalent Von Mises Stress

Axial force: ~ -7900 N
Rotation: ~ 1.3 mrad
Net Torque ~ 0 N.m

Stress ~ 30 MPa

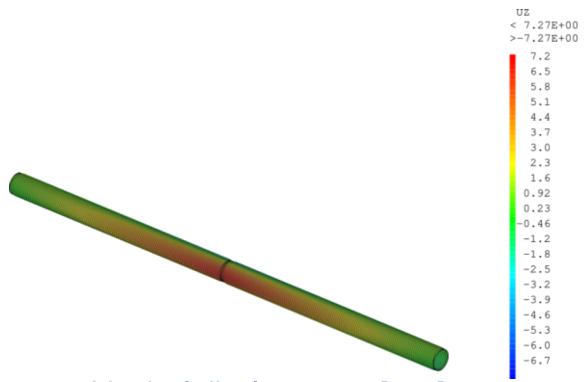
Spiral corrugations

Reaction forces – effect of boundary conditions

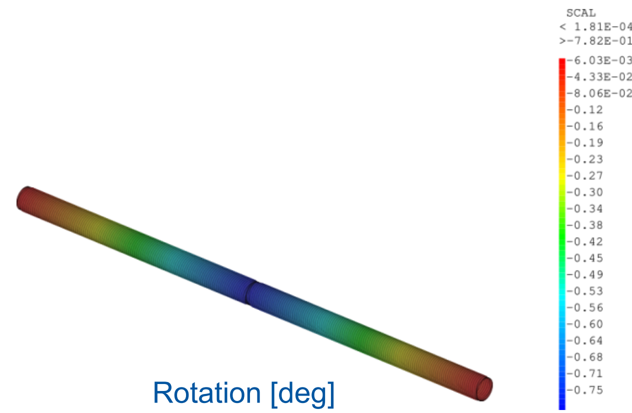
Clamped both extremity, under vacuum during bakeout

Case 1.5 mm thick, 100 mm pitch, 30 mm convolution height, 4 convolutions/band, 2*12 m, opposite helice direction

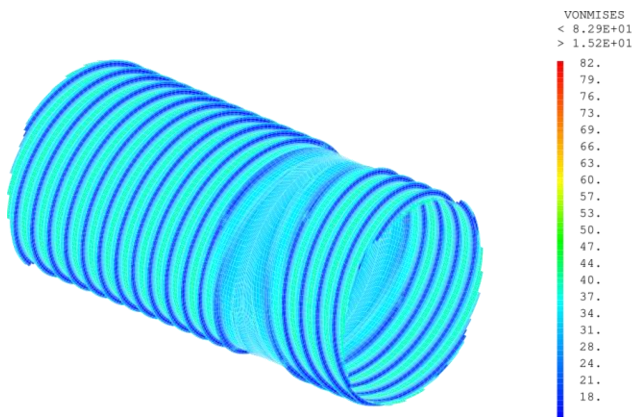
Axial displacement [mm]



Vertical displacement [mm]



Rotation [deg]



Equivalent Von Mises Stress

Axial force: ~ -3100 N
Rotation: ~ 14 mrad
Net Torque ~ 0 N.m

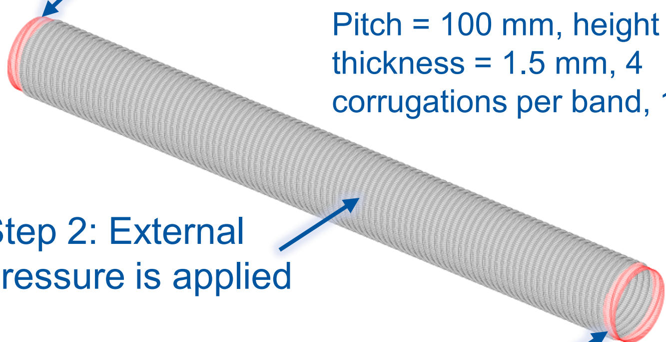
Stress ~ 30 MPa

Spiral corrugations

Specific stiffnesses of the chamber

Stiffnesses of 10 & 15 m long vacuum chambers and 4 helicoidal pitch (1.613m) segment.

Clamped extremity



Pitch = 100 mm, height = 30 mm, thickness = 1.5 mm, 4 corrugations per band, 10 m

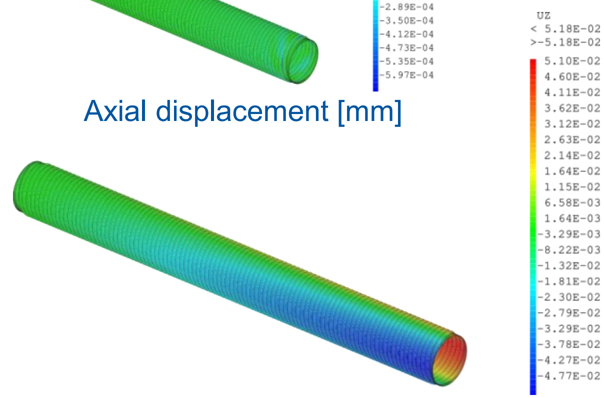
Step 2: External pressure is applied

Step 1: Different boundary conditions (imposed/free displacement, rotation)

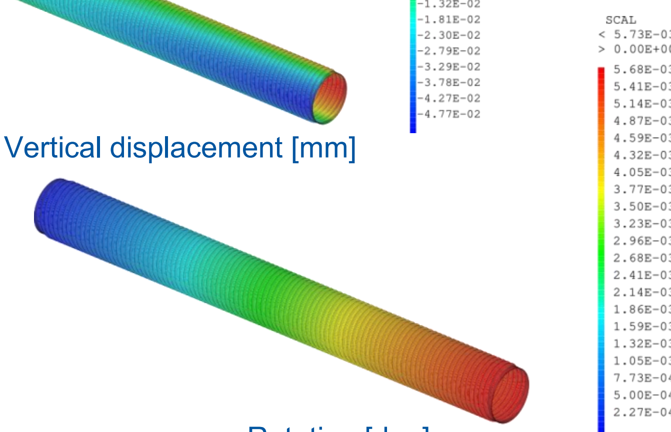
Displacements / reaction forces and moments are extracted after the two steps.

Case of fixed axial displacement, imposed rotation [0.1 mrad], no vacuum

Axial displacement [mm]



Vertical displacement [mm]



Rotation [deg]

Spiral corrugations

Specific stiffnesses of the chamber

Results for the 10 m long chamber

Boundary conditions		**After displacement**	**After displacement and under vacuum**
Rotation [mrad]	Axial displacement [mm]		
0.1	Free	M_α= 82.5 N.m Δ_x= -0.177 mm	M_α= -14790 N.m Δ_x= -3.1 mm
0.1	0 (fixed)	M_α= 605 N.m F_x = 295 N	M_α= -5730 N.m F_x = 5120 N
0 (fixed)	1	M_α= 2950 N.m F_x= 1670 N	M_α= -3380 N.m F_x= 6500 N
Free	1	α= -0.49 mrad F_x= 230 N	α= 0.57 mrad F_x= 7900 N
Free	Free		α= 18.7 mrad Δ_x= -34.9 mm
Fixed	Fixed		M_α= -6330 N.m F_x= 4830 N

Spiral corrugations

Beam model

Definition of an equivalent 1D beam:

1^{st} step: definition and determination of the axial/torsion coupling

Modification of the constitutive law:

$$F = ES*U/L + k.\ \alpha/L$$

Coupling term

$$C = GJ*\alpha/L + k.U/L$$

2^{nd} step: consideration of the vacuum effect

- Contraction and twist of the chamber if free
- Tension/torque if the chamber is fixed.

Modification of the constitutive law:

$$F = ES*(U/L-\varepsilon_0) + k.\ (\alpha/\ L-\theta_0)$$

$$C = GJ*\ (\alpha/\ L-\theta_0) +\ k*(U/L-\varepsilon_0)$$

Vacuum force is introduced by the free strains in axial and rotation

The sign of k and θ_0 depends on the helice direction (left or right-hand).

Spiral corrugations

Beam model

Definition of an equivalent 1D beam:

3rd step: Thermal strain.

$$F = ES^*(U/L - \varepsilon_0 - \varepsilon_{th}) + k.(\alpha/L - \theta_0)$$

$$C = GJ^*(\alpha/L - \theta_0) + k^*(U/L - \varepsilon_0 - \varepsilon_{th})$$

Thermal strain: $\varepsilon_{th} = 1.6E\text{-}5 \cdot \Delta T$

Implementation in a FE code by modifying the stiffness matrix of the beam elements.

Parameter	Value	Unit
Torsion stiffness (GJ)	6.11E+07	N.m²
Coupling axial-torsion (k)	2.98E+07	N.m
Axial stiffness (ES)	1.68E+07	N
Bending stiffness (EI)	2.98E+5	N.m²

Free strain under vacuum	Value	Unit
Axial ε_0	-3.4306E-03	m/m
Rotation θ_0	1.7767E-03	rad/m

Displacement | Rotation

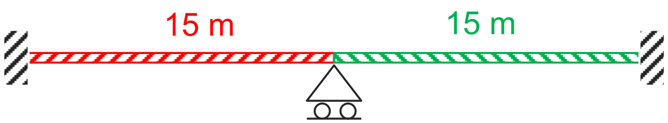
Force / Moment

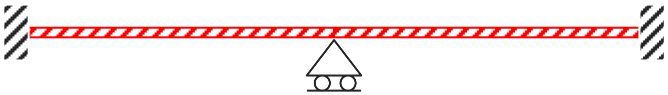
$$\begin{pmatrix} \frac{E\cdot S}{L} & 0 & 0 & \frac{k}{L} & 0 & 0 \\ 0 & 12\frac{E\cdot I}{L^3} & 0 & 0 & 0 & 6\frac{E\cdot I}{L^2} \\ 0 & 0 & 12\frac{E\cdot I}{L^3} & 0 & -6\frac{E\cdot I}{L^2} & 0 \\ \frac{k}{L} & 0 & 0 & \frac{G\cdot J}{L} & 0 & 0 \\ 0 & 0 & -6\frac{E\cdot I}{L^2} & 0 & 4\frac{E\cdot I}{L} & 0 \\ 0 & 6\frac{E\cdot I}{L^2} & 0 & 0 & 0 & 4\frac{E\cdot I}{L} \end{pmatrix}$$

Spiral corrugations

Beam model

The model has been cross-checked with 3D shell model (10 m, 15m, 1.6 m) and the applied to different configurations





	Room temperature	150 °C
Configuration 1	F = 4688 N M = -6325 N.m	F = -30256 N M = -68300 N.m
Configuration 2	F = 7773 N M = 0 N.m Rotation (middle) = 1.55 mrad	F = 3060 N M = 0 N.m Rotation (middle) = 16.77 mrad
Configuration 3	F = 4688 N M = -6325 N.m	F = -30256 N M = -68300 N.m

Spiral corrugations

Beam model

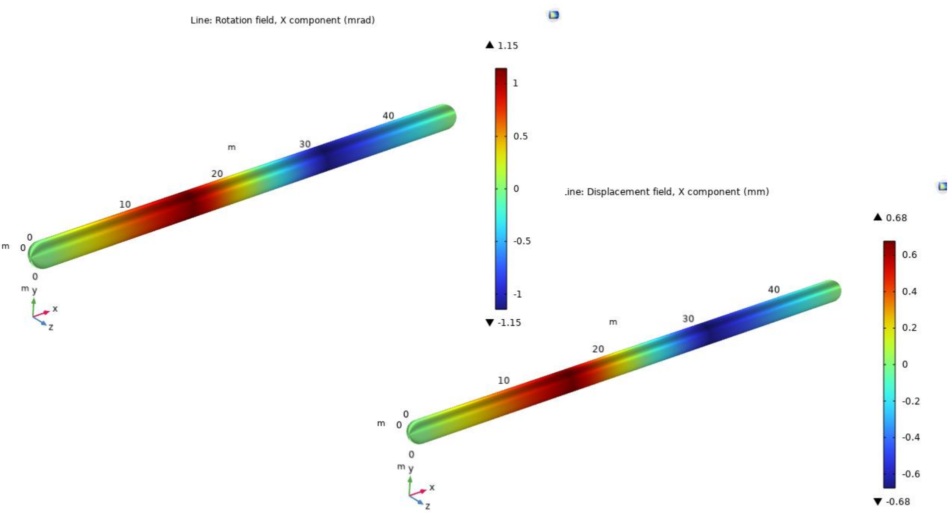
Application to different configurations

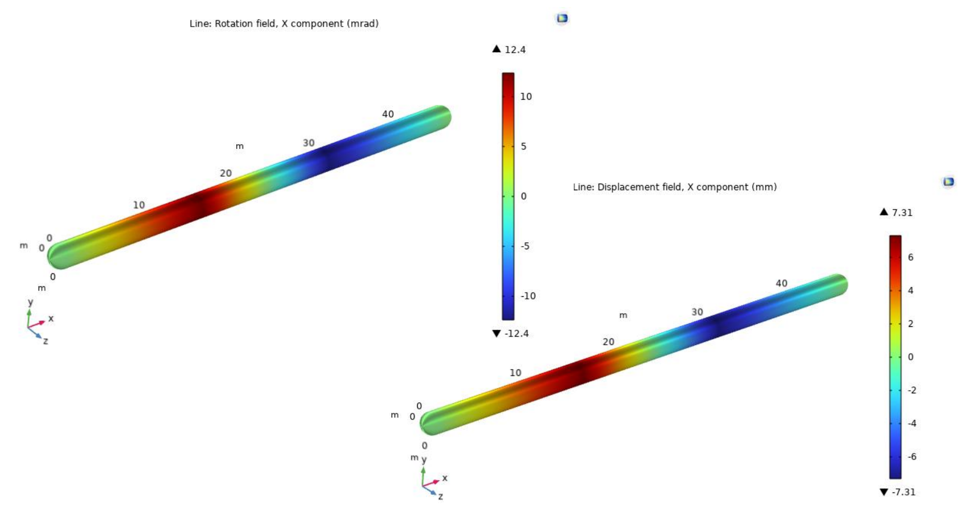
Room temperature

F = 7722 N
M = -314 N.m
Rotation = 1.15 mrad
Axial displacement = 0.68 mm

150 °C

F = 2508 N
M = -3398 N.m
Rotation = 12.4 mrad
Axial displacement = 7.3 mm





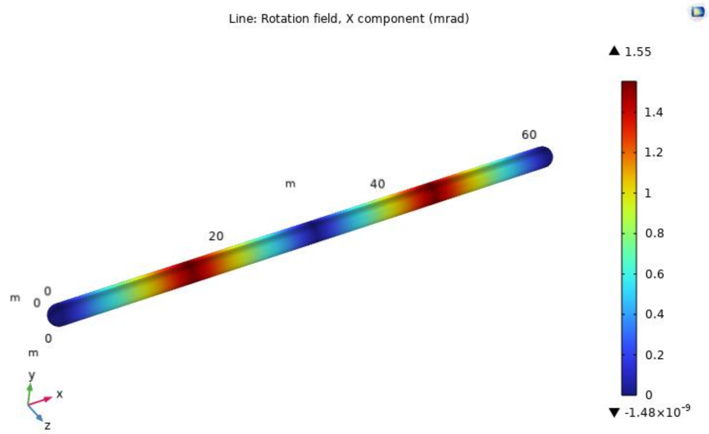
Spiral corrugations

Beam model

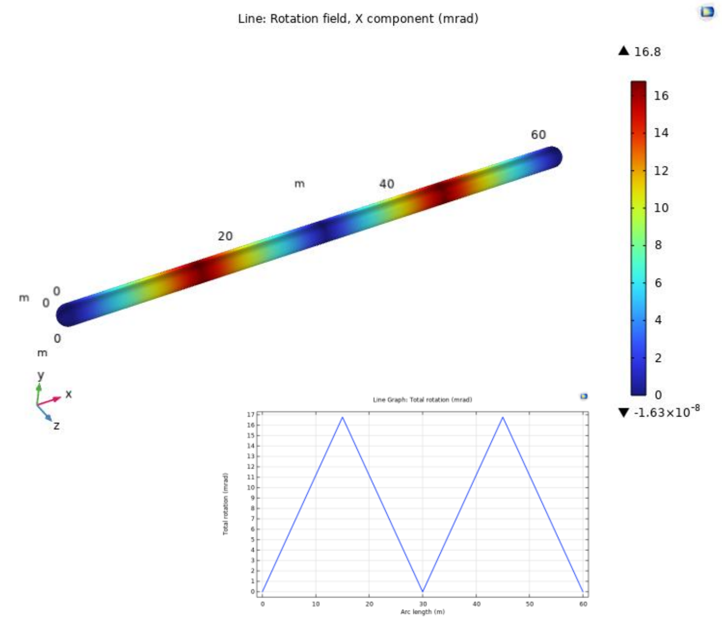
Application to different configurations

4 chambers with alternate helice direction equivalent to 2 chambers

Room temperature



150 °C



Conclusion

The integration of the corrugations to the sheet before the tube forming, leading to helicoidal corrugations, presents some advantages for the manufacturing.

But in addition to the corrugation effects:
- Limited bending stiffness → dedicated supports,
- Vacuum induced axial force,

the helicoidal corrugations leads to:
- Significant reduction (~50%) of the buckling strength against external pressure,
- Strong axial/torsion coupling,
- (less convenient interface to the supports).

Stresses in the chamber remain acceptable, but reaction forces in the supports can be large and strongly depend on the support configuration.

A 1D beam model has been developed to account this coupling and can be used to assess the reaction forces under vacuum and during bakeout.

Effect of the coupling can be reduced with alternated helice direction.

Despite easier manufacturing and cleaning process with spiral corrugations, vacuum chambers with annular convolutions seem required.