INSTITUTE OF PLASMA PHYSICS
OF THE CZECH ACADEMY OF SCIENCES

STRUCTURAL MODEL OF HIGH-TEMPERATURE VACUUM-SEALING FLANGE

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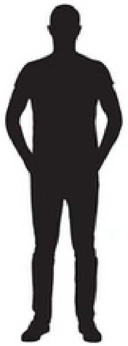
MINISTRY OF EDUCATION,
YOUTH AND SPORTS

CONTENTS

- **TOKAMAKs** are **scientific devices** to explore nuclear fusion
  - fusion of **hydrogen isotopes** (D+D, D+T)
  - hopefully **future energy source** of mankind!

- At IPP, we build a new tokamak called **COMPASS-Upgrade**
  - Expected time of first run ~ **2026**
  - Most important parameters

		Old COMPASS
Toroidal mag. field	5 T	2.1 T
Plasma current	2 MA	0.35 MA
Major radius	R = 0.894 m	0.56 m
Minor radius	a = 0.27 m	0.23 m



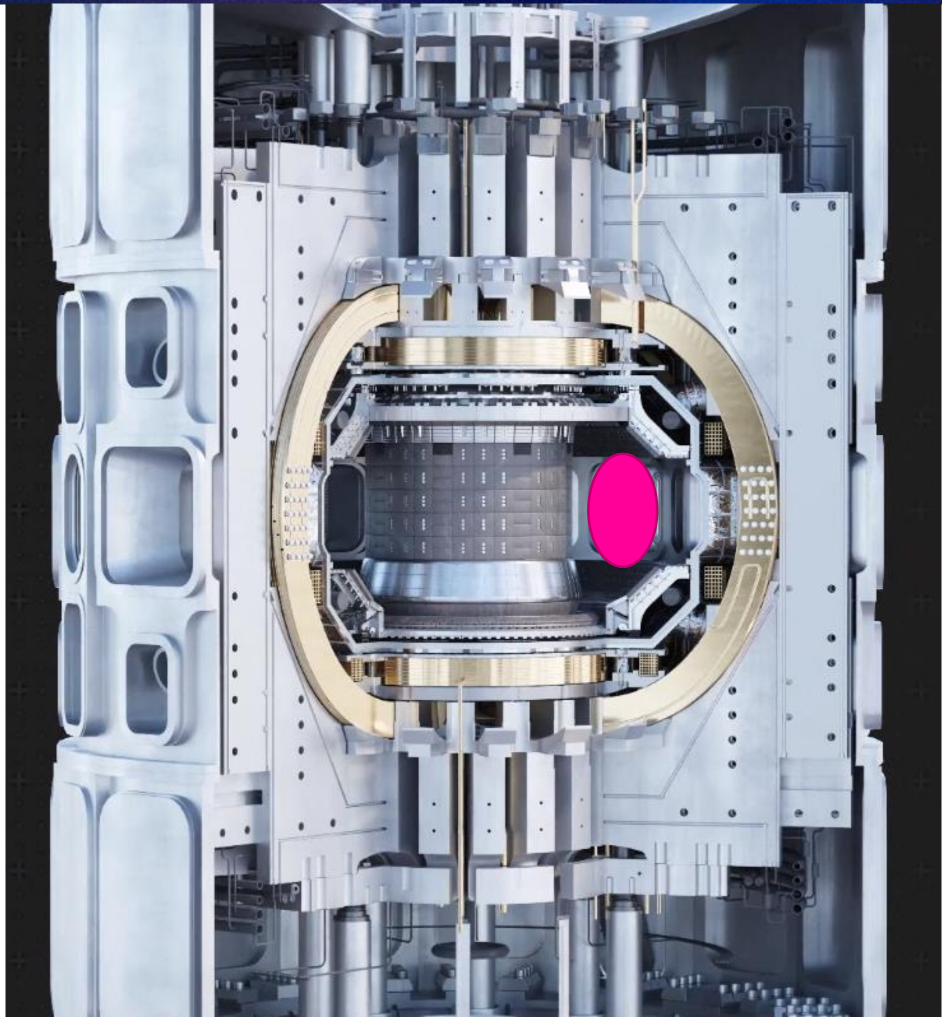


Fig. 1.: ¾ Section of tokamak COMPASS-U. Position of plasma is indicated by **pink elipse**.

- COMPASS-U vacuum vessel has a lot of (non-circular) ports
- Moreover, seals are required
  - To seal **ultra-high vacuum** (leak rate < 10-9 Pa.m3/s)
  - Withstand **high temperature (500 °C)**
- Only feasible option is to **use resilient metal seals!**

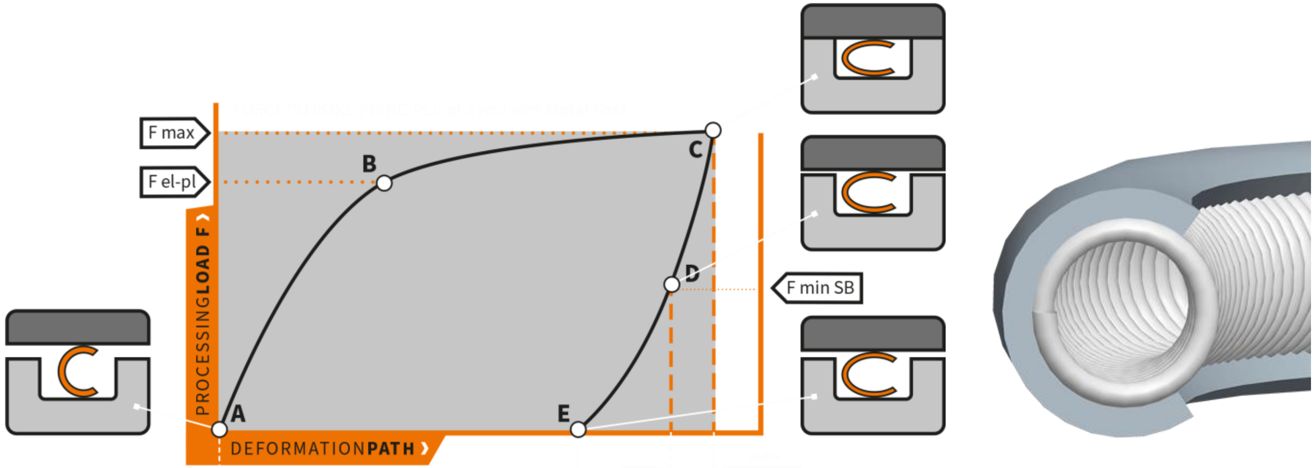


Fig. 2.: Illustration of resilient metal seals working diagram, illustration of seal cross-section
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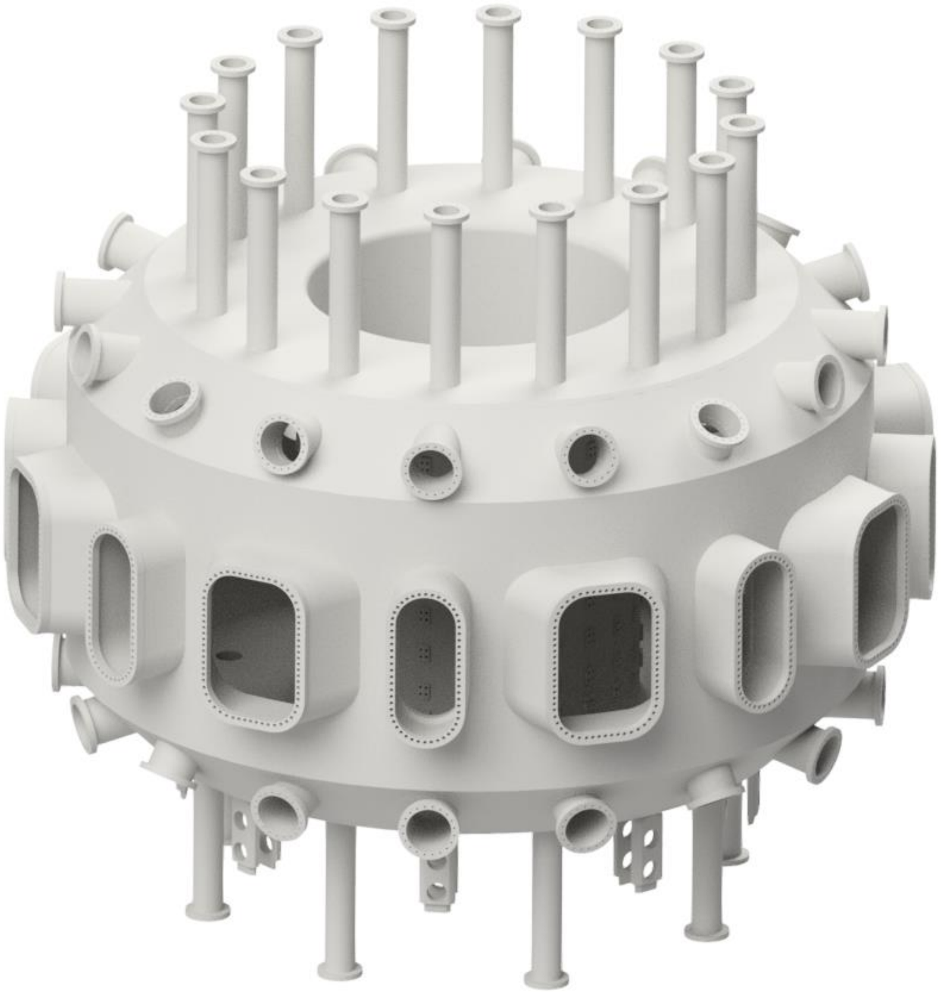

Fig. 3.: Render of COMPASS-U vacuum vessel, ports visible

METAL SEALED FLANGES

- What are the challenges?
  - **Huge compression force** required! (~350 N/mm)
  - Only **small springback** allowed (~0.05 mm)
  - Flanges are **inverted** (bolts inside, seal outside) and not blind
  - Different materials all-around

Bolts and flanges are on the edge of possible, therefore the design optimization and verification is crucial!

Fig. 4.: Different resilient metal seals (Parker Hannifin)

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FLANGE MODEL

- Circular flange, d ~ 200 mm, 22x M8 b
- Seal modeled as a 1 mm strip

- **Materials**
  - Stainless steel (AISI 310)
  - Nickel superalloy (Inconel 625)
  - Metal seal (elastoplastic material)

- **Physics used**
  - Solid mechanics
    - Contacts
  - Beam

- **Load cases**
  - Bolt preload
  - Temperature (20 °C – 500 °C)

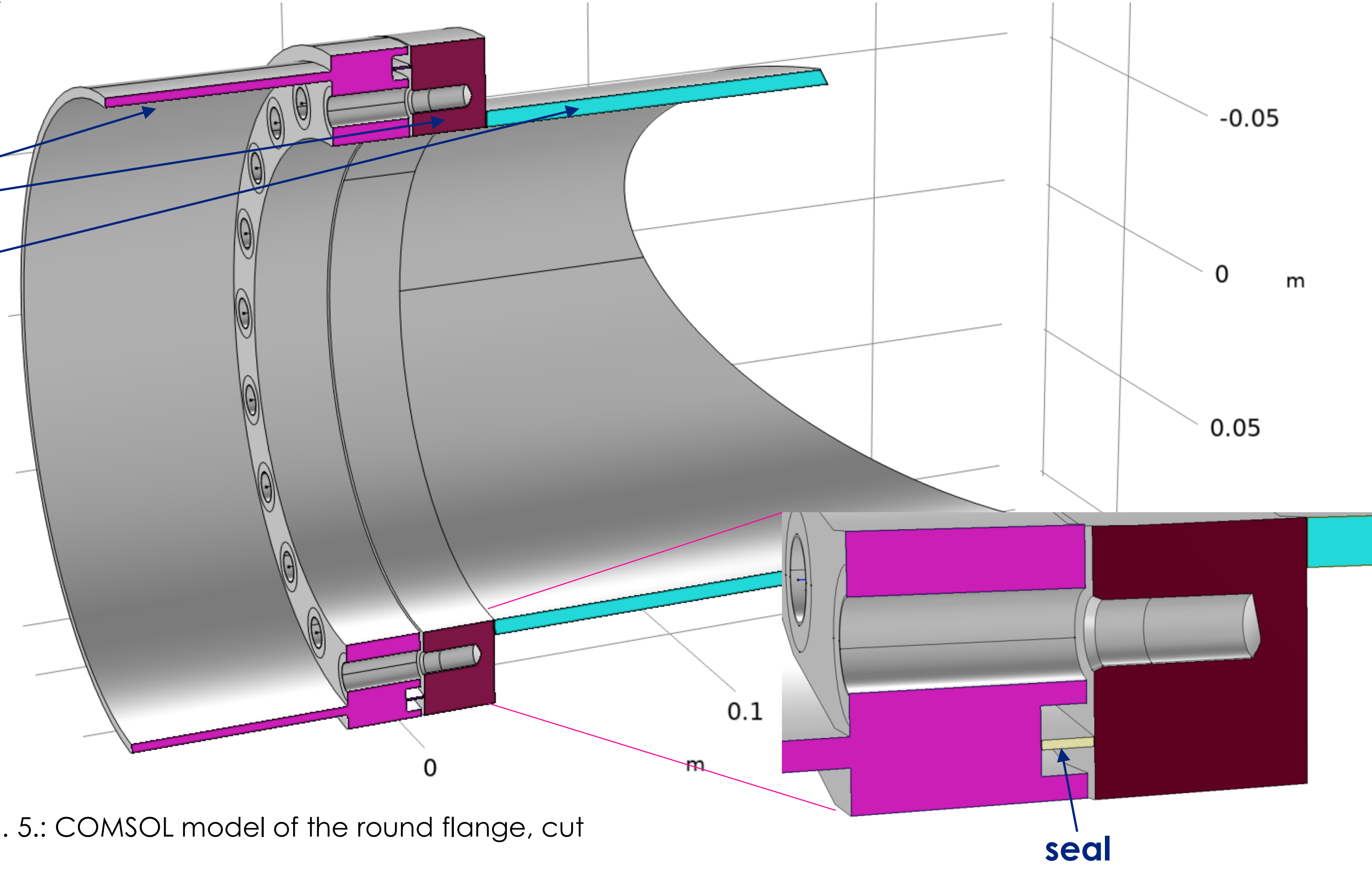


Fig. 5.: COMSOL model of the round flange, cut

BOLT BEAM MODEL

- Bolts are modelled as a beams
- Default multiphysics beam-solid coupling **doesn’t support thermal expansion.**
- Fortunately, COMSOL includes **Rigid connector**, which has much more settings!

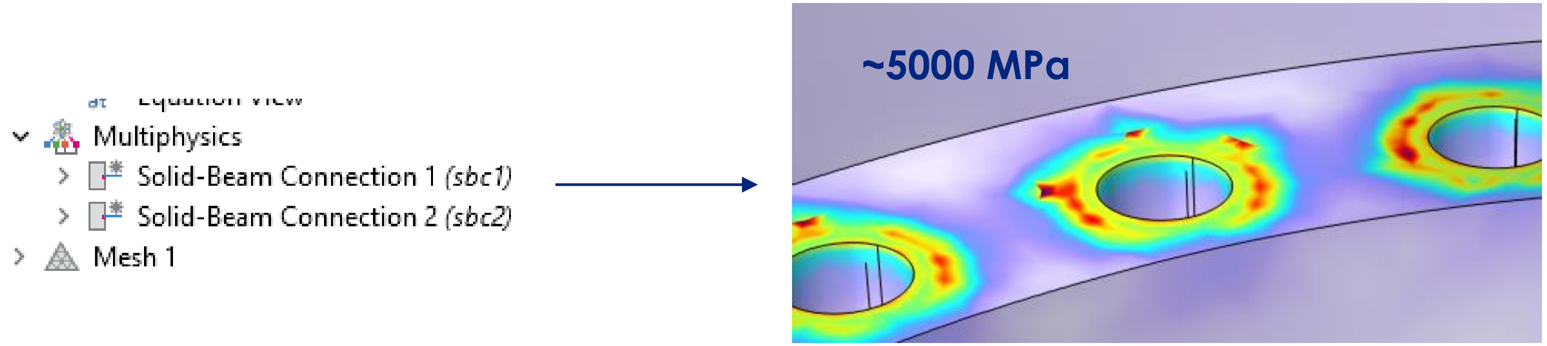


Fig. 6.: Solid-beam connection node with resulting non-physical stress

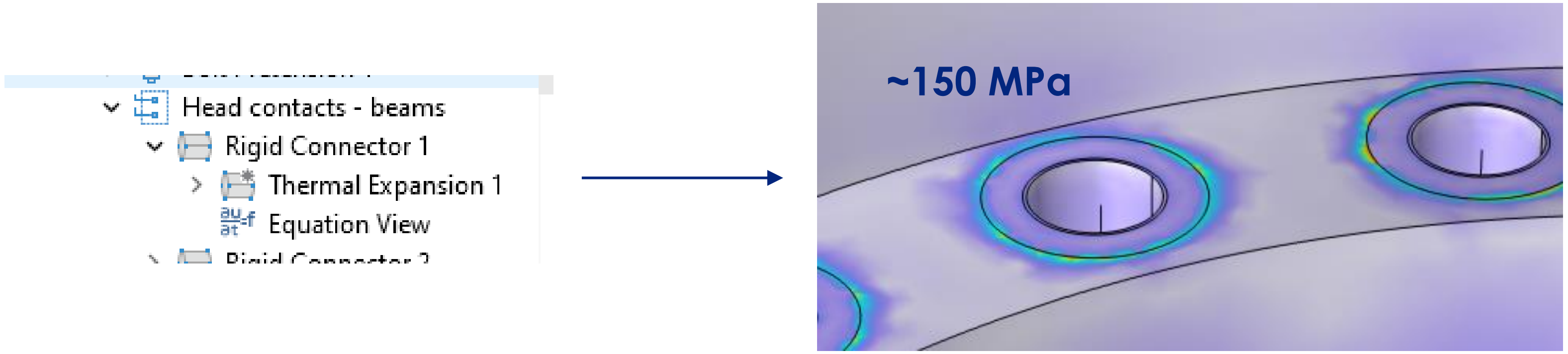


Fig. 7.: Rigid connector node with thermal expansion subnode set up

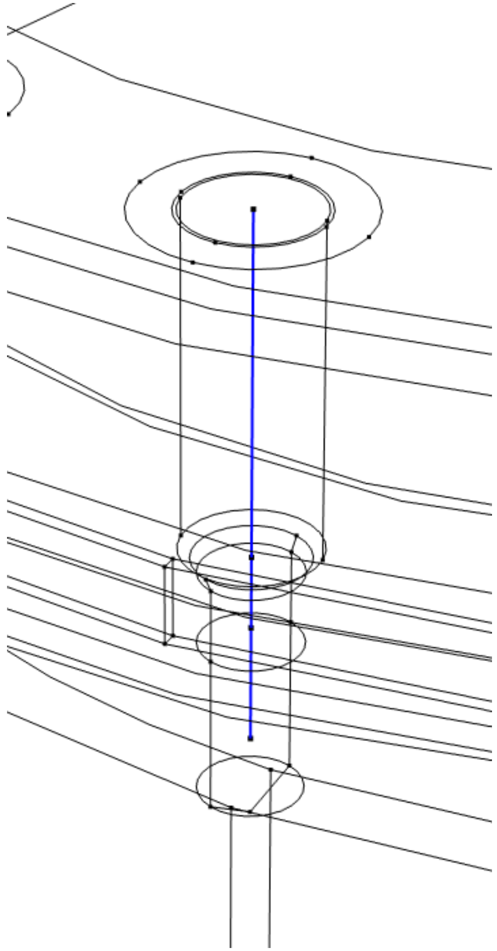


Fig. 8.: Used beam element in the bolt hole

- Main working mechanism of the resilient metal seal is the plastic deformation.
- We don’t have the Nonlinear Structural Material Module!

- Just use the „**External Materials**“ node!
  - Available in basic Solid mechanics module
  - Bit harder to use (you need to compile you own DLL)
  - But! COMSOL has a nice tutorials! [1] [2]

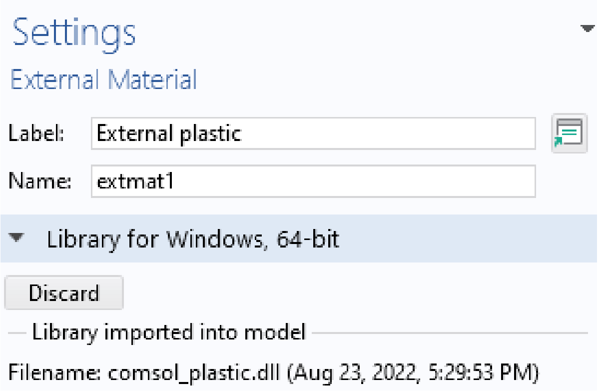
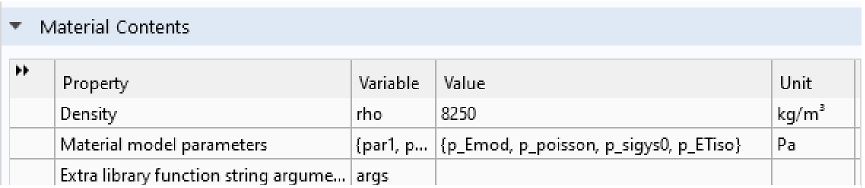


Fig. 9.: External material node setup



Material Contents

Property	Variable	Value	Unit
Density	rho	8250	kg/m³
Material model parameters	{par1, p...	{p_Emod, p_poisson, p_sigys0, p_ETiso}	Pa
Extra library function string argume...	args		

Fig. 10.: External material parameters setup

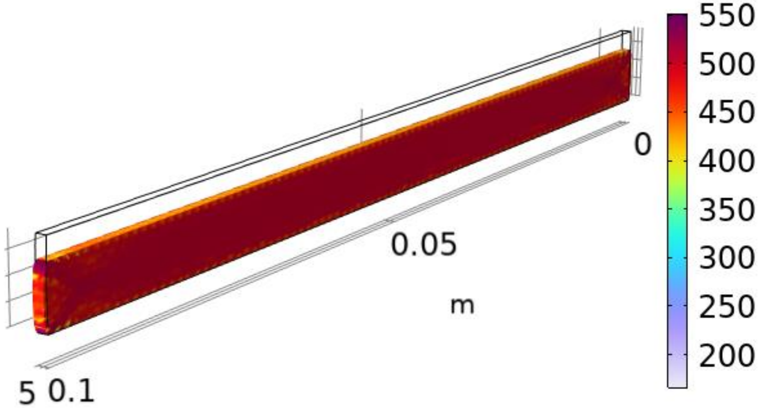


Fig. 11.: Seal testing submodel (to verify external material)

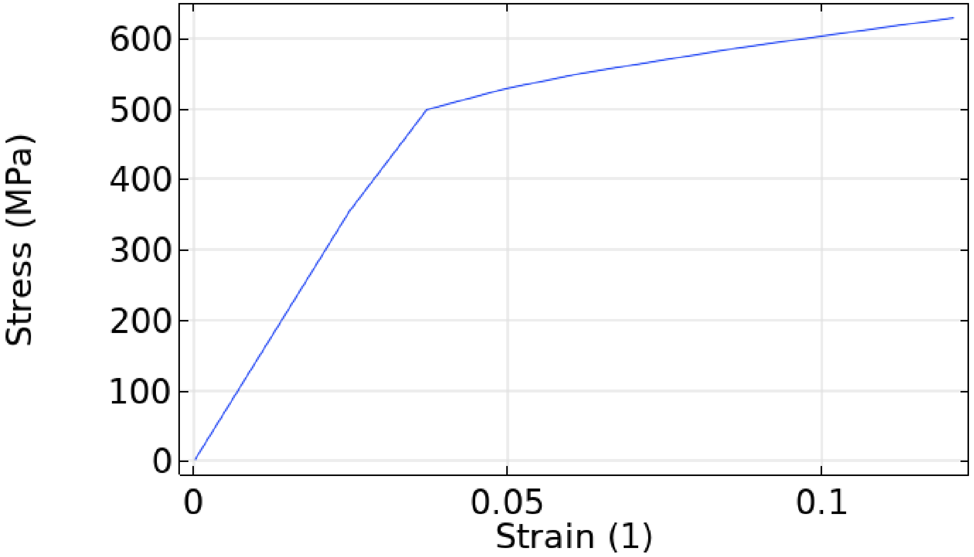


Fig. 12.: Resulting stress-strain relation from the submodel.

[1] https://www.comsol.com/model/external-material-examples-structural-mechanics-32331
[2] https://www.comsol.com/blogs/how-to-implement-elastoplasticity-in-a-model-using-external-materials/

MODEL RESULTS

- Flange computed for two load cases
  - Bolt pretension (15 kN) + Room temperature (300 K)
  - Bolt pretension (15 kN) + 500 °C (770 K)

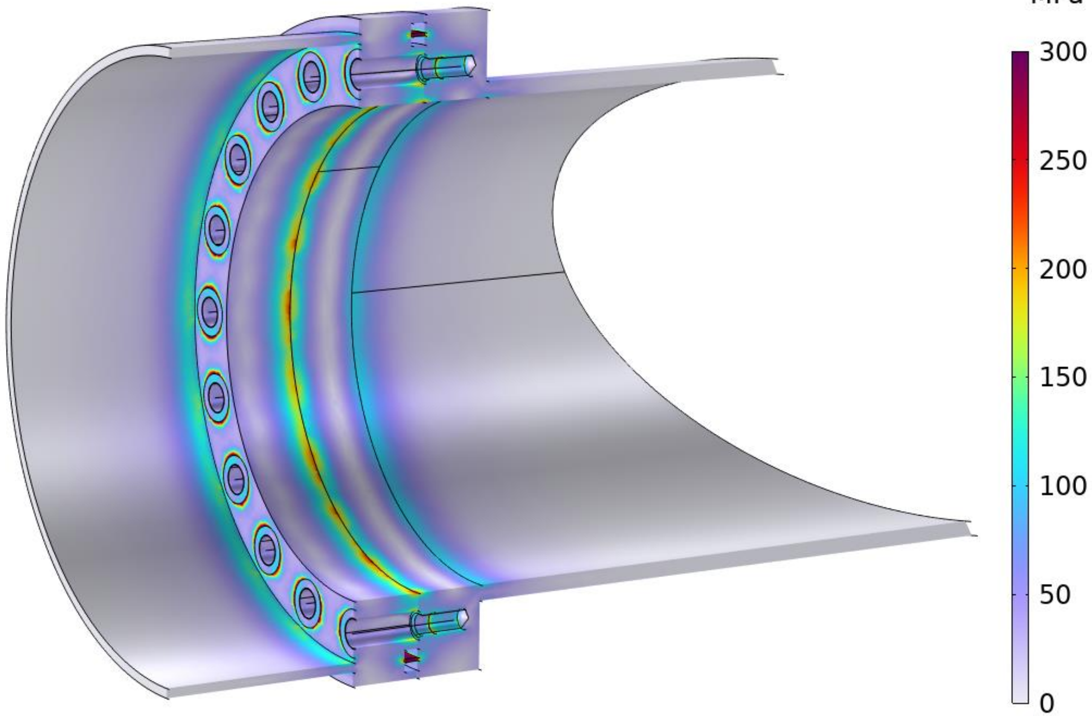


Fig. 13.: Resulting stress distribution in the flange and port, @300 K

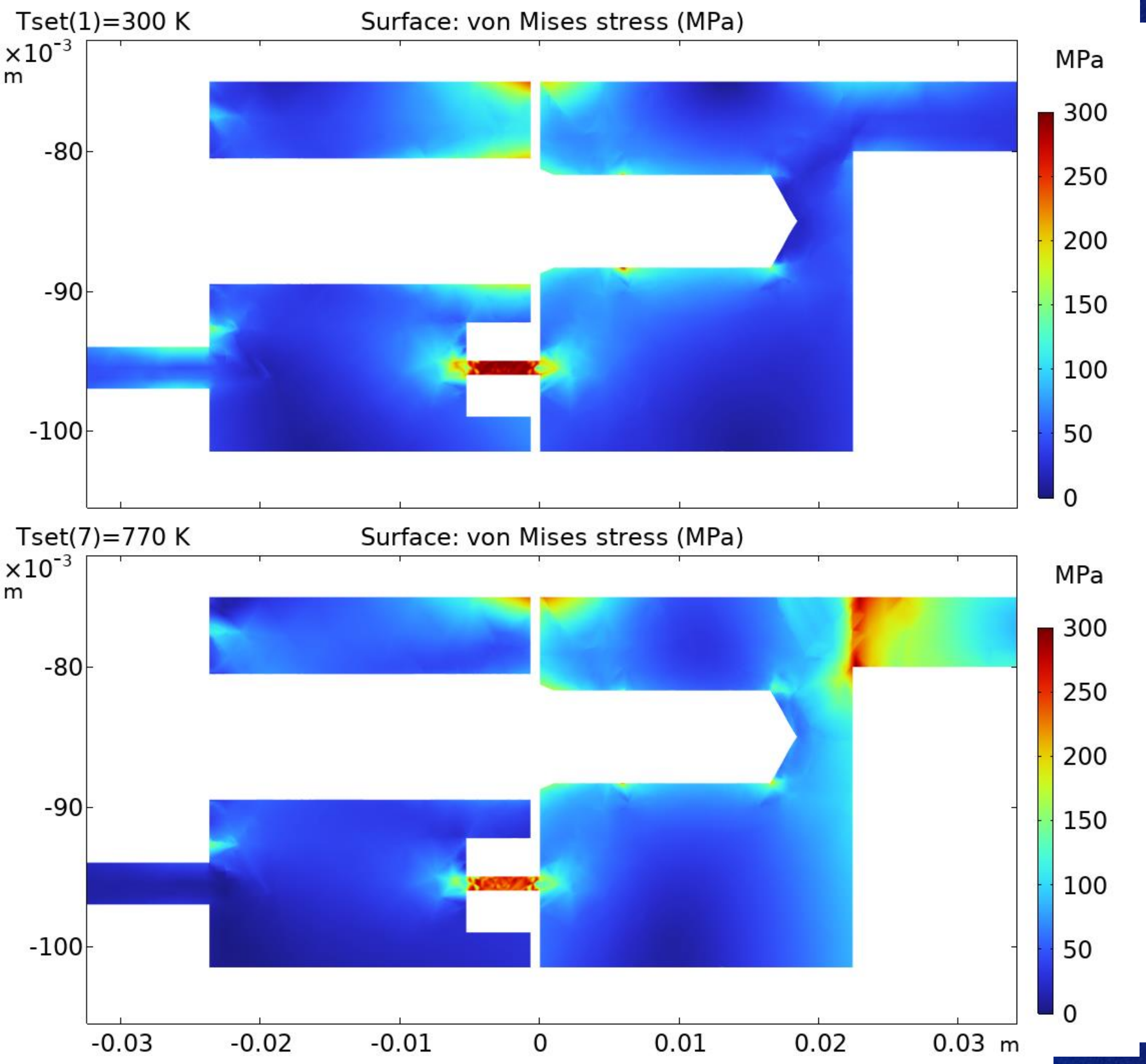


Fig. 14.: Resulting stress distribution, section, both load cases

- How to read the seal deformation?
  - Both sides move, we need to subtract.

- **Linear extrusion** is here to help!
  - Part of the nonlocal couplings family
  - It maps entities onto each other

- After setup, you can just do
  - deff = w – linext1(w)

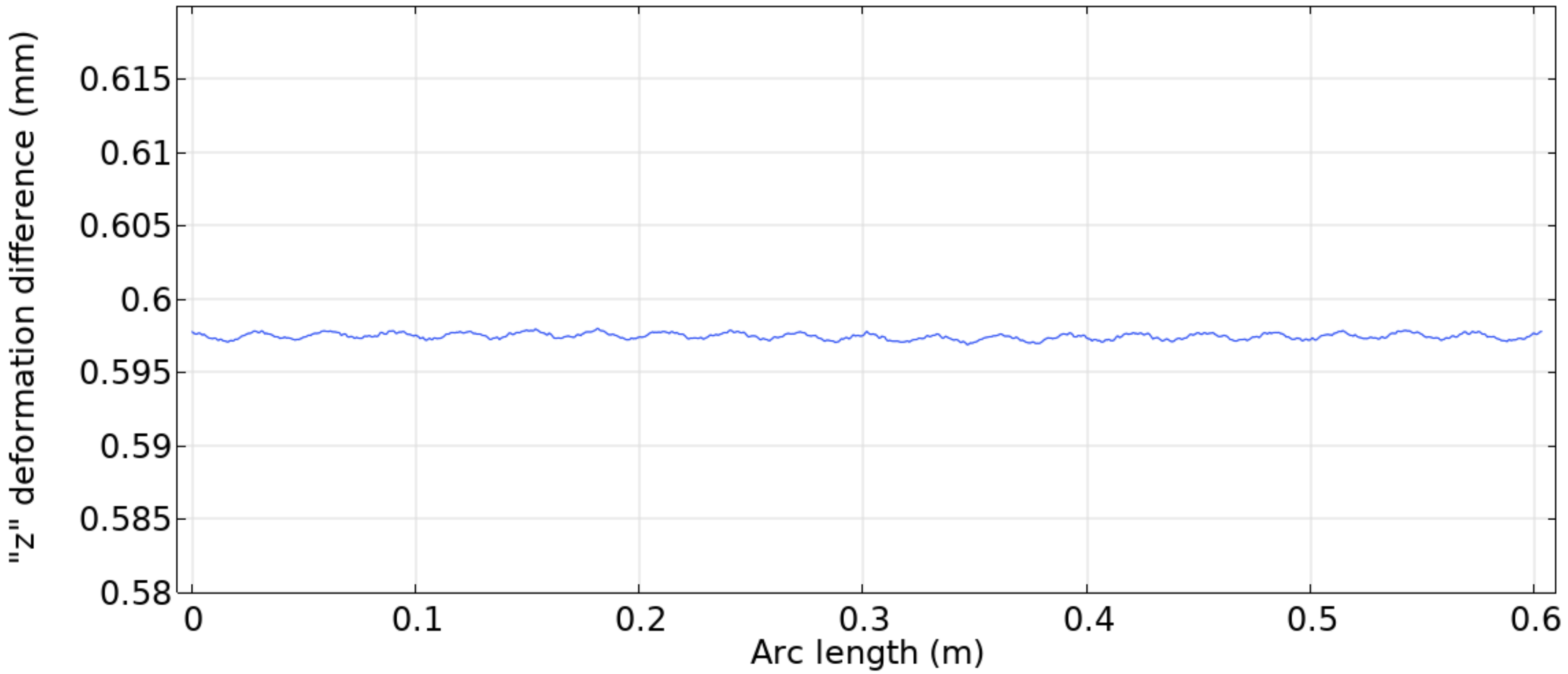


Fig. 15.: Seal compression along the port, @300 K

CONCLUSION

- We have optimized and verified the high-temperature flange design
  - Required bolt preload ~15 kN
  - Maximal springback reached < 0.05 mm
  - Bolt stress < 600 MPa

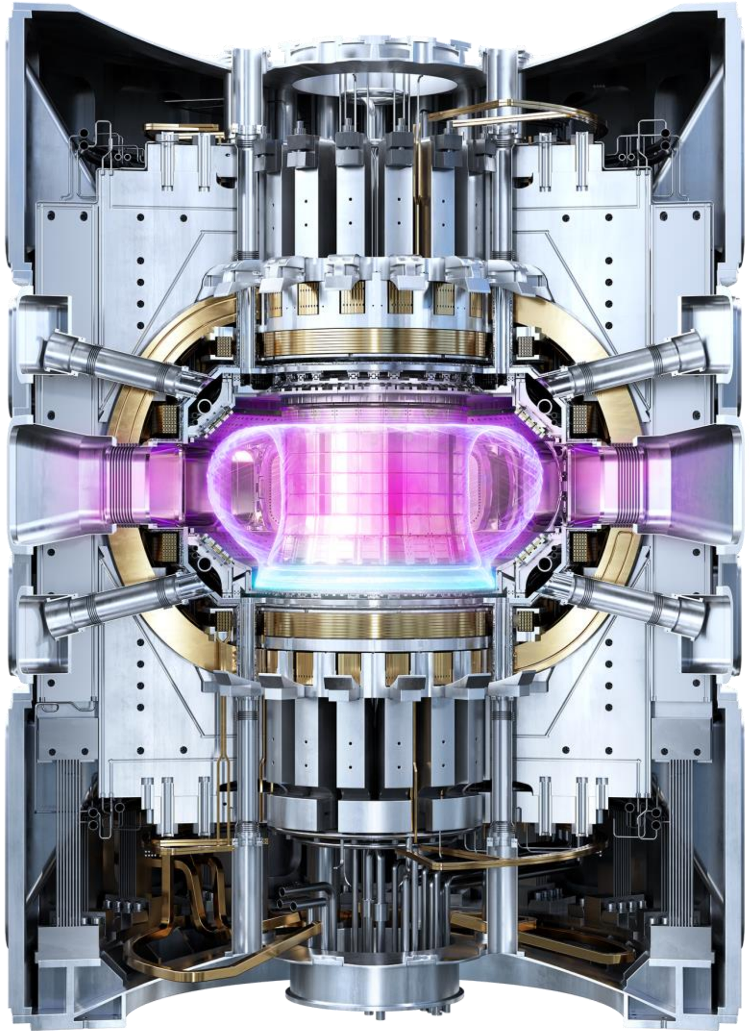


Fig. 16.: Tokamak COMPASS-U render