INSTITUTE OF PLASMA PHYSICS OF THE CZECH ACADEMY OF SCIENCES

Cryostat structural analysis

Presentation for preliminary market consultations

based on presentation for Internal tender design review 15. 5. 2025

This work has been carried out within the framework of the project COMPASS-U: Tokamak for cutting-edge fusion research (No. CZ.02.1.01/0.0/0.0/16_019/0000768) and co-funded from European structural and investment funds.

EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research, Development and Education

MINISTRY OF EDUCATION, YOUTH AND SPORTS

REVISIONS

Revision	Date	Description	Slides	Responsible
1	7. 05. 2025	Tender preliminary design review	No. edited slides	Šimůnek
2	19. 05. 2025	Tender design review	Reorganized	Šimůnek

List of load cases

Static loads (with vacuum at room temperature)	
S1	Atmospheric Pressure, Earth Gravity, 300 t Tokamak weight
S2	Unsymmetric atmospheric pressure
S3	Ports load by diagnostics
Thermal loads (thermal-mechanical effects)	
T1	Thermal gradient of cryostat base
T2	Thermal effects of local vacuum breach
T3	Vacuum Vessel heating to 500°C
Operation loads (electromagnetic and plasma effects)	
O1	Load from Error Field Correction (EFC)
O2	Downwards disruption
~~O3~~	Lateral disruption
~~**Magnetic forces**~~	
~~M1~~	Volumetric magnetic force due to elevated magnetic permeability of AISI 304L and welds
~~M2~~	Volumetric force from induced currents during plasma break-down

Conducted analysis by a buyer

Combined load cases (Structural mechanical effects)	
L1	S1
L2	S1 + O1
L3	S1 + S3
L4	S1 + S2 + O2
~~L5~~	S1 + S2 + O2 + O3
L6	T1
L7	S1 + T1 + O2
L8	S1 + T2
L9	S1 + T3

~~Strikethrough~~ load cases
not analyzed due to negligible forces or not fully specified

general axisymmetric FE model

BOUNDARY CONDITIONS

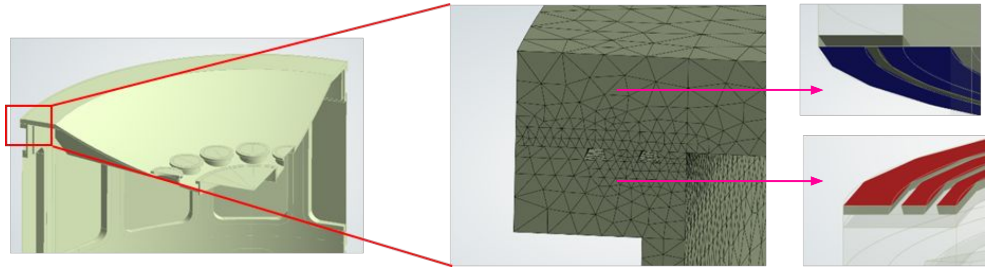
- Used for most Load cases
- ¼ model with axisymmetric BC
- Fixed support on legs bottom side
- M42 Bolts connecting legs and cryostat base
- Ports connected to flanges with bonded contact

MATERIALS

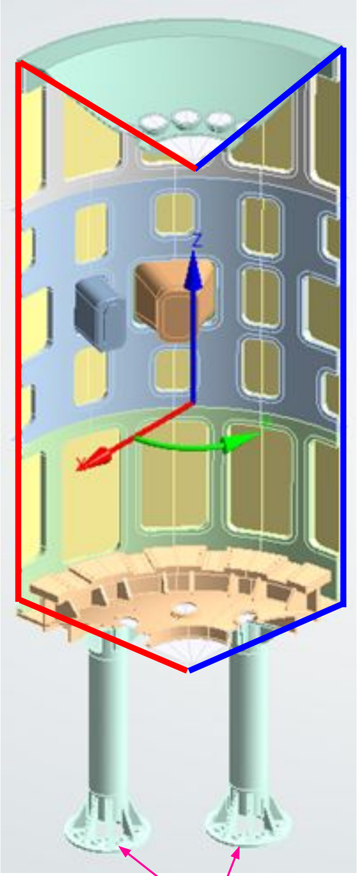
- All structural parts: 304L
- EFC: OFHC (homogenous prop.)

Section's flanges detailed mesh

Non-linear contact

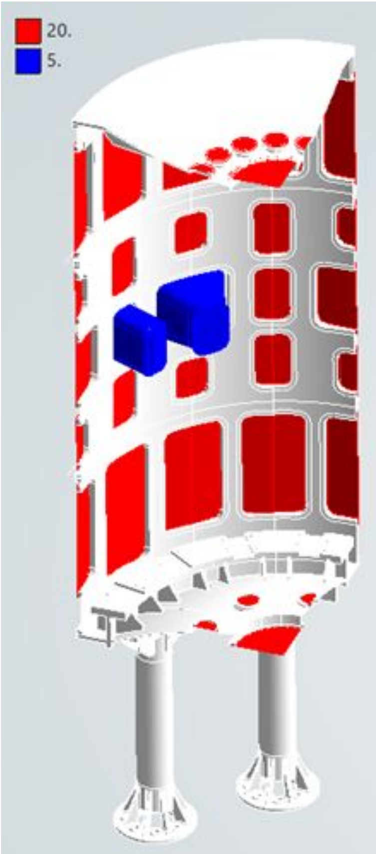


Axisymmetric BC



Fixed support

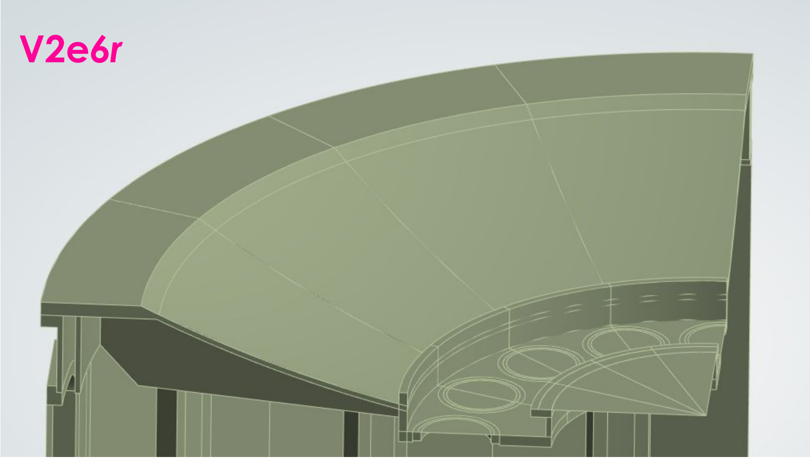
Solid (gray) + Shell (ports) with thickness

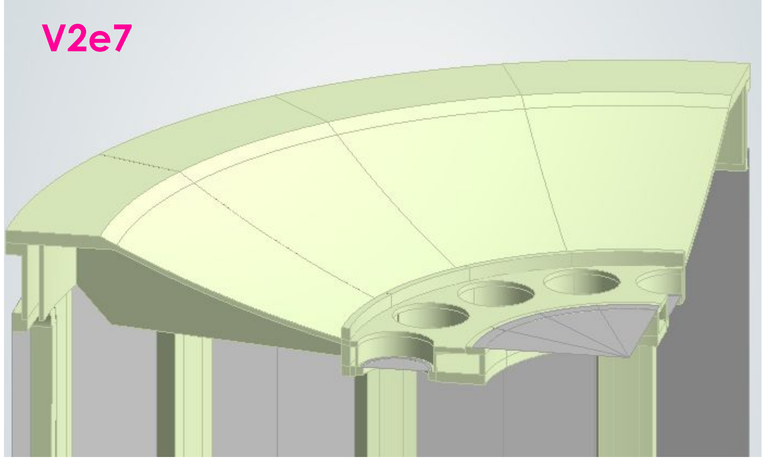


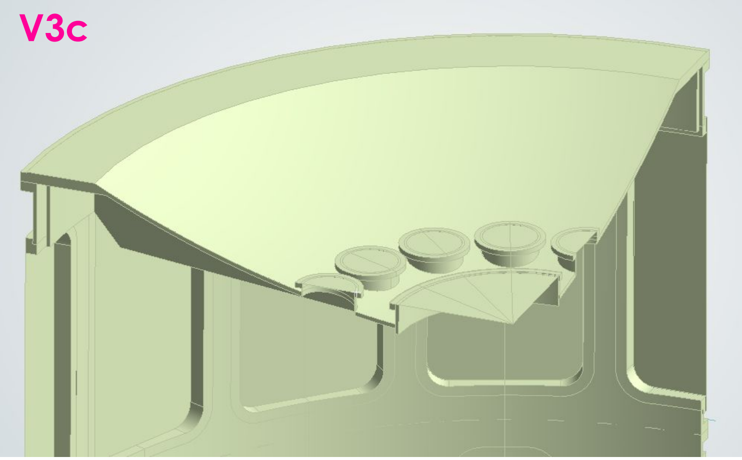
Quadratic mesh

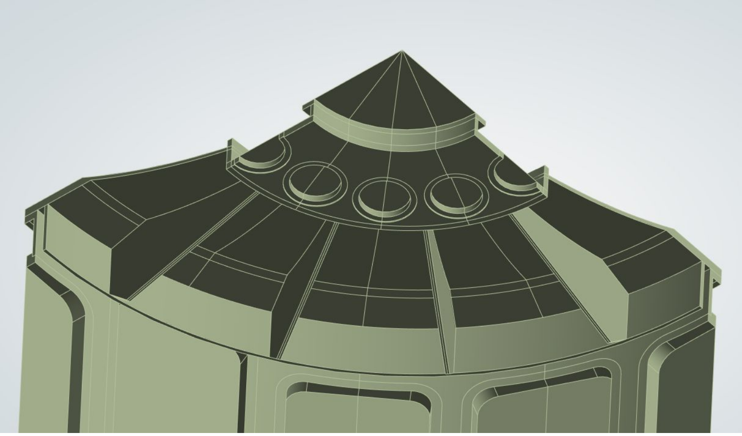
EFC

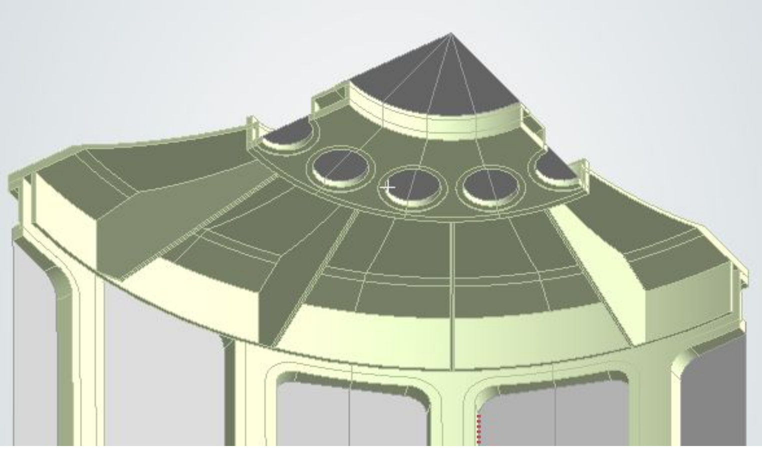
Cryostat Upper lid competing designs

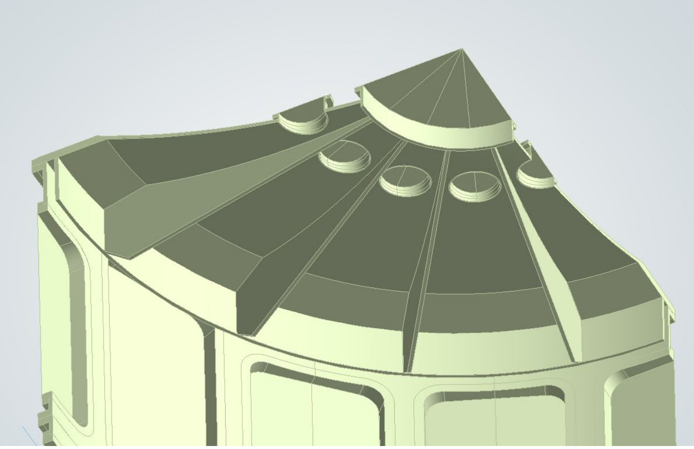












LC L1: S1

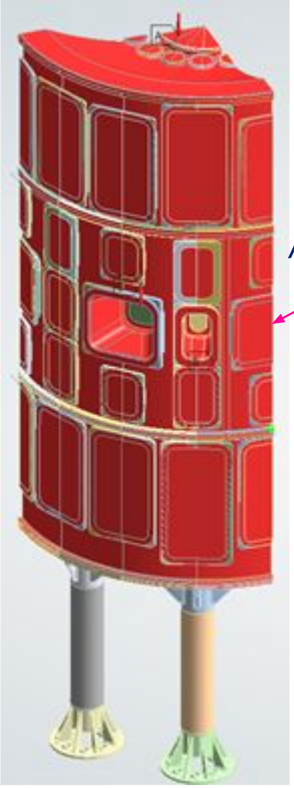
Static load

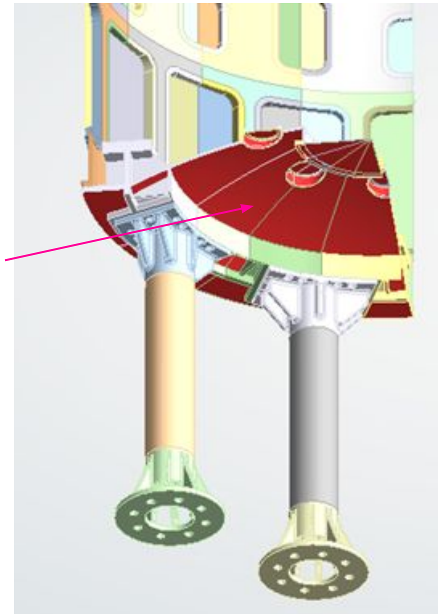
BOUNDARY CONDITIONS

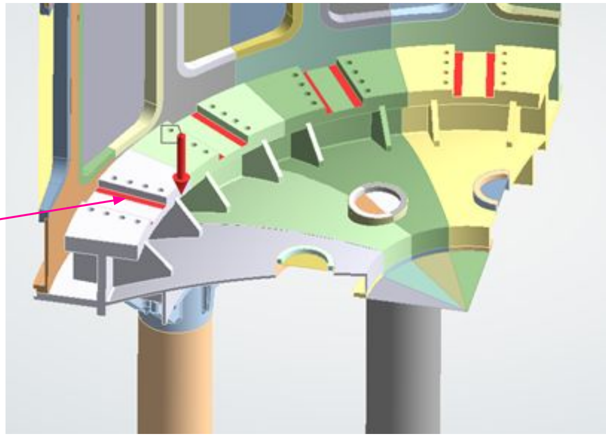
- Used general ¼ axisymmetric model

LOADING

- Bolt pretension
  - M42 bolts 300 kN
- Atmospheric pressure
  - 0.102 MPa at outer surfaces
- Earth gravity
- 300t Tokamak weight
  - 0.75 MN for ¼ model





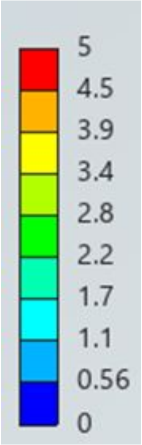


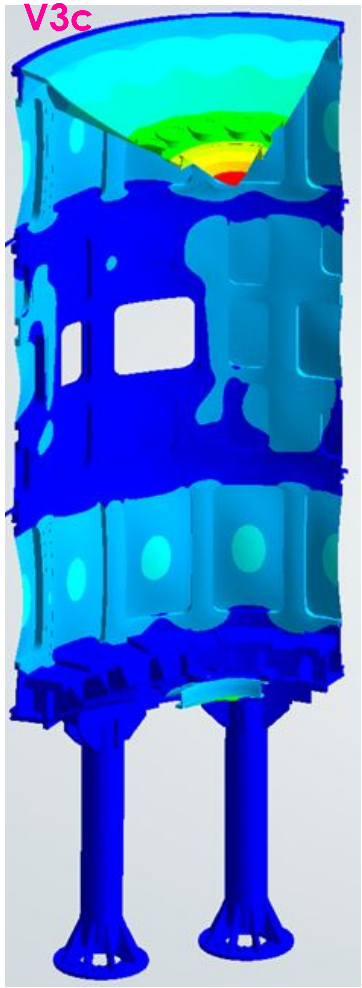
LC L1: S1

UTOT and Stress

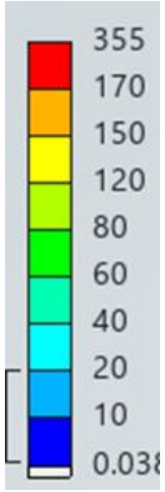
Atmospheric pressure + tokamak weight + gravity

UTOT [mm]





von-Mises [MPa]

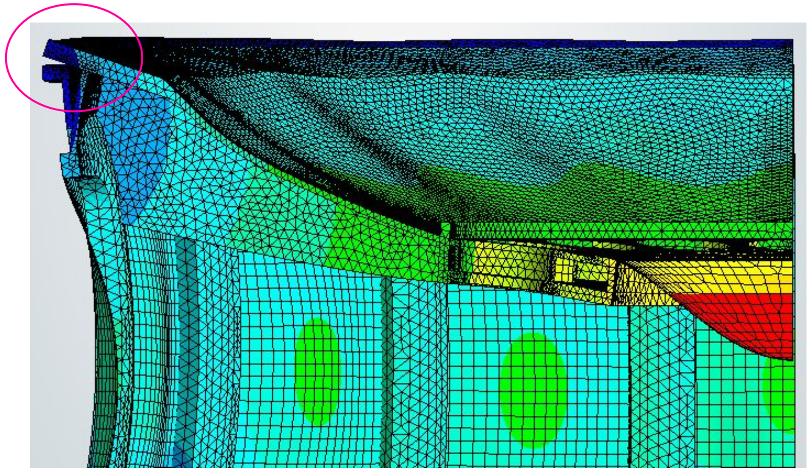


Conclusion:
Static structural deformations creates stresses within material yield strength of 170 MPa

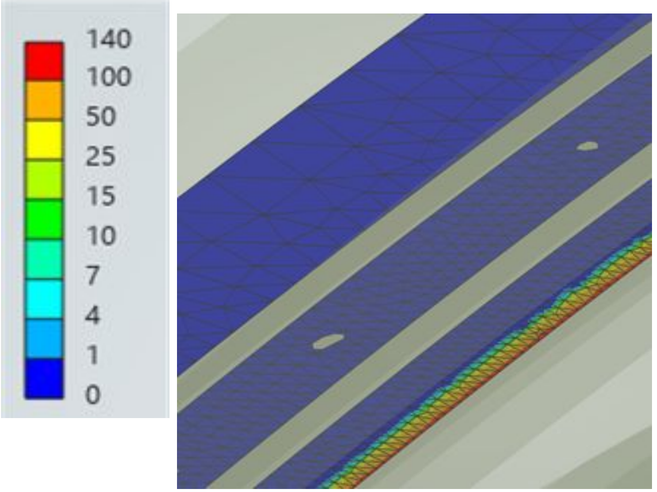
Atmospheric pressure + tokamak weight + gravity

- Upper lid to top Cryostat section Contact contact status

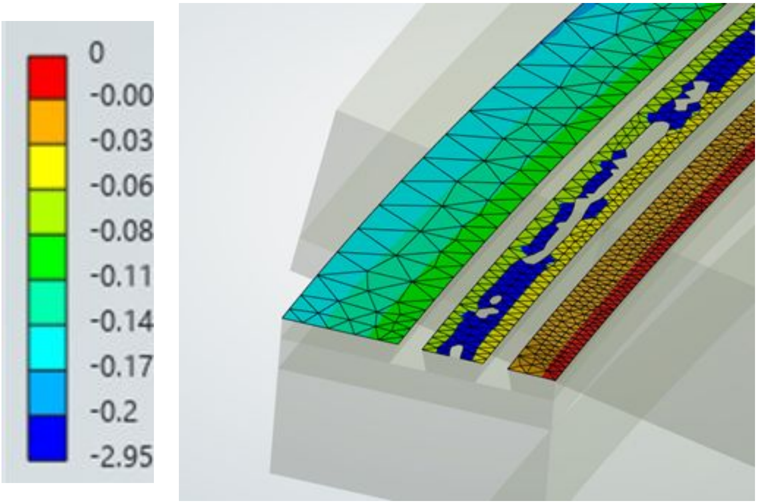
Flange opening due to atmospheric pressure



Contact pressure [mm]



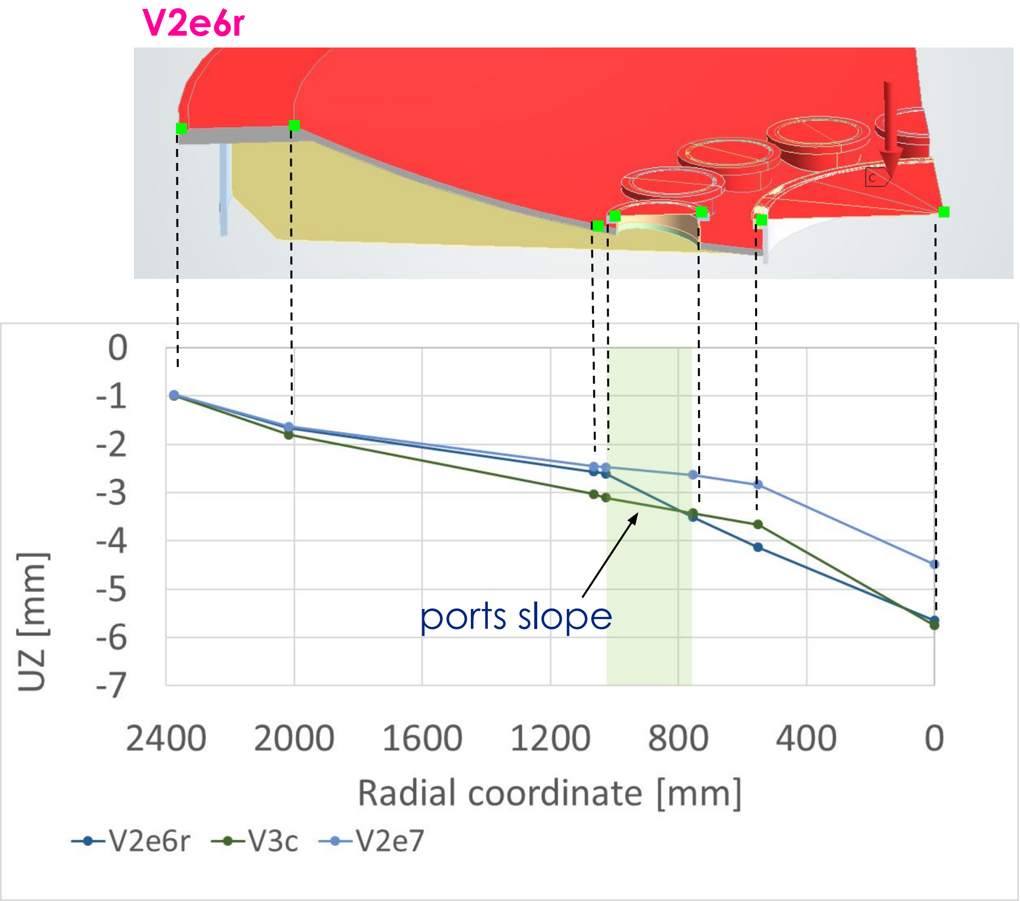
Contact Gap [mm]

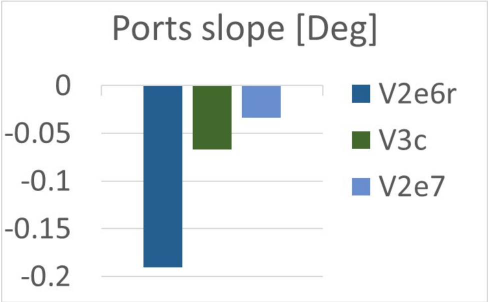


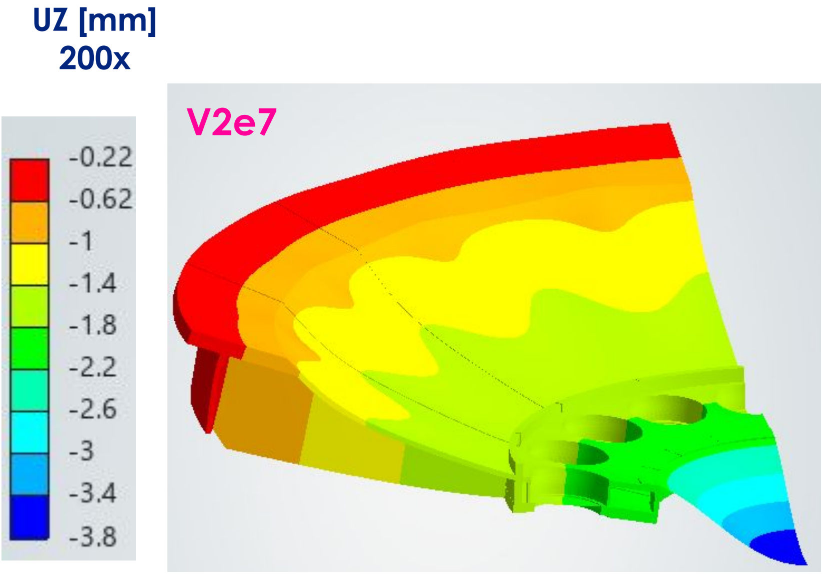
Conclusion:
Flanges gaps are small enough to be within rubber seal working range

Cryostat top ports deformations

Atmospheric pressure + tokamak weight + gravity





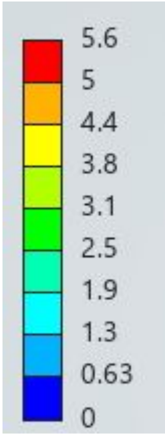


Conclusions:
Lowest top ports slope has a V2e7 variant of cryostat Upper lid with 0.03 degree

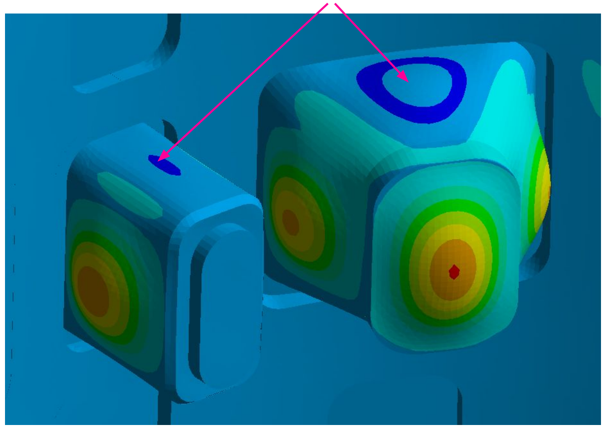
MN and MX Port Plugs UTOT and stress

Atmospheric pressure + tokamak weight + gravity

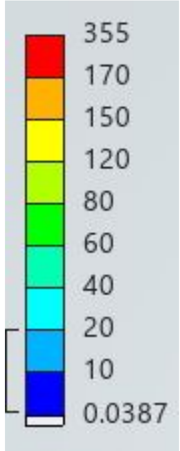
UTOT [mm]
20x

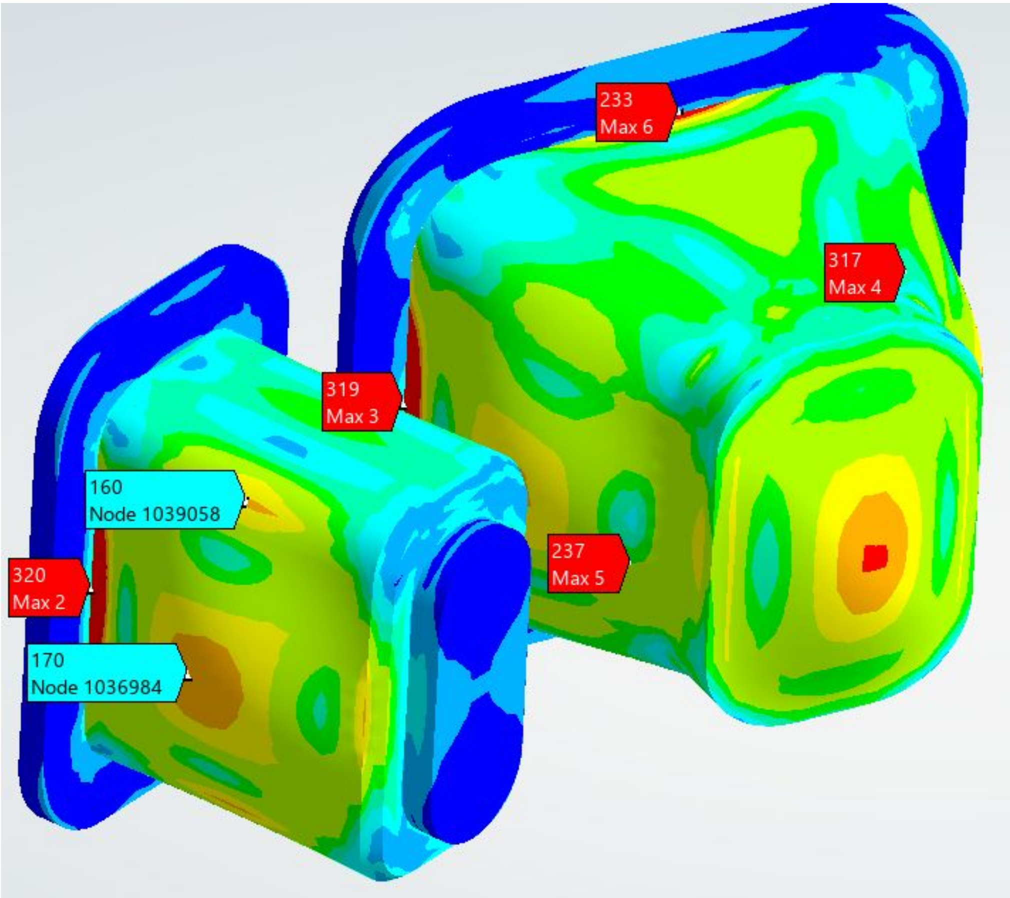


5 mm thickness



von-Mises [MPa]
20x

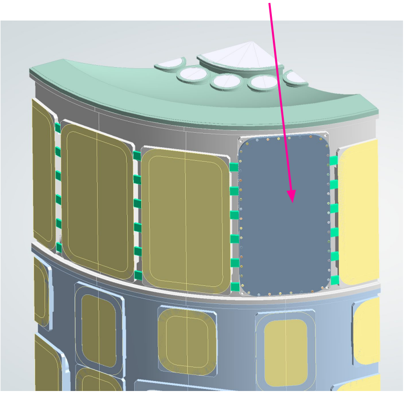




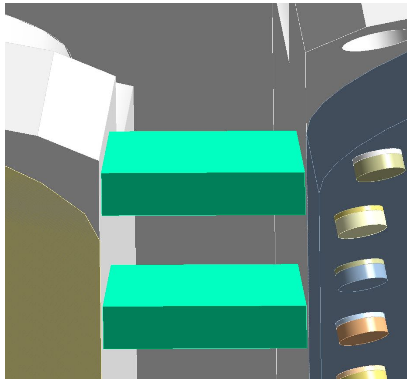
Conclusions:
High stresses in port plugs due to atmospheric pressure.
Some design modifications are necessary.

Upper divertor port flanges bolts check

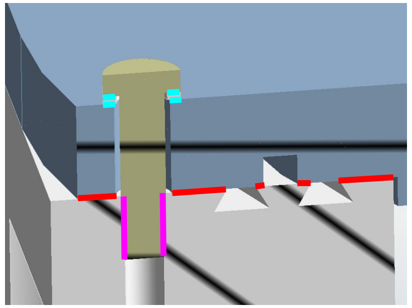
Checking M12 bolts of the DUC port



Ribs in alternative variants



Detailed model with non-linear contacts



Analysis variants
a) Bolts preload 18 kN
b) Bolts preload 18 kN + ribs
c) Bolts preload 42 kN
d) Bolts preload 42 kN + ribs

Bolts Strength check of Cryostat ports - upper long port

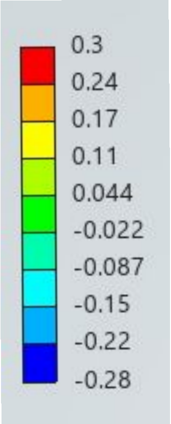
- Motivation: validate strength of M12 mounting bolts for the DUC port
- DUC is the most loaded port!
- M12 bolts with 50 mm pitch
- More variants tested
  - Higher preload requires higher strength grade bolts

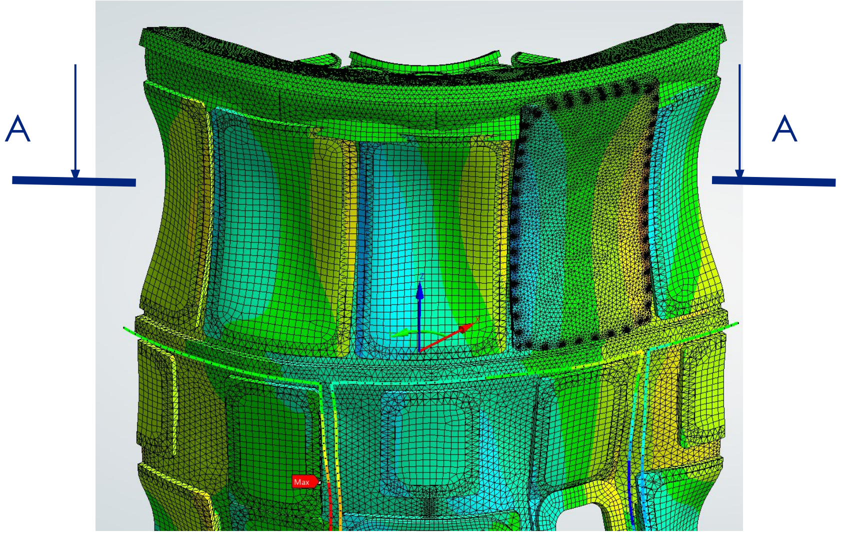
LC L1: S1

UY Deformations

Atmospheric pressure + tokamak weight + gravity

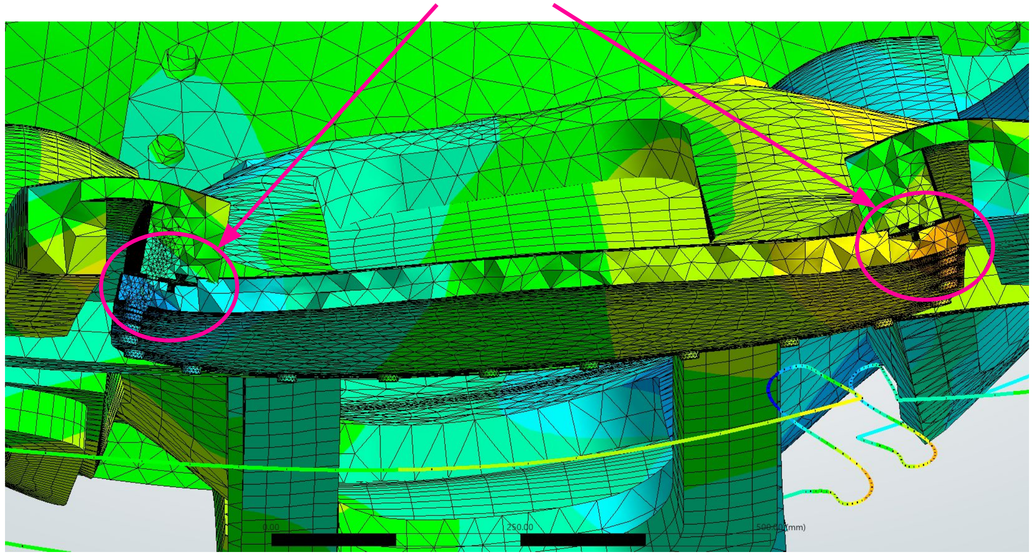
UY cyl [mm]
200x





a) Preload 18 kN
There is a contact sliding of 0.15 mm and large bolts bending which exceeding bolts strength

Section A-A



Conclusions:

- 18 kN preload is not sufficient to hold shear forces from atmospheric pressure
- 42 kN preload is required with higher grade A5-70 bolts
- Added ribs:
  - Highly reducing cryostat radial deformations (by 50%)
  - Lowering overall stress between flanges
  - Recommended but higher preload 42 kN is still required

Analysis variants

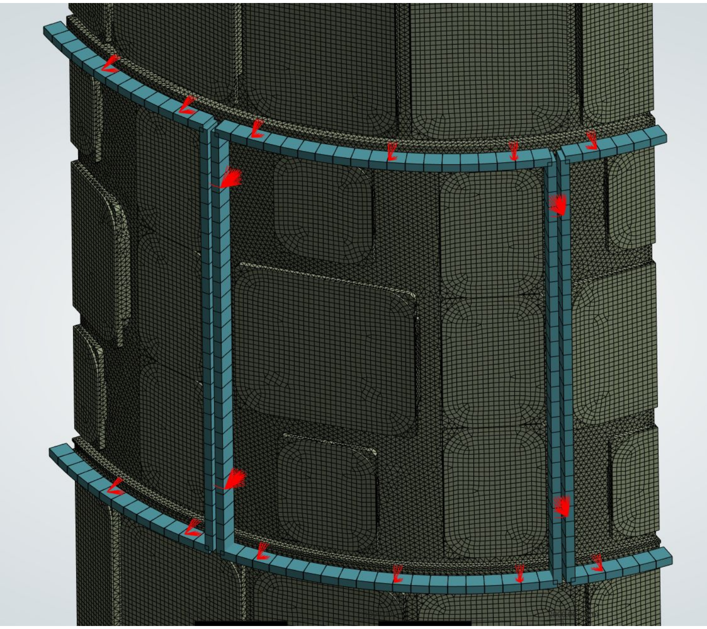
a) Bolts preload 18 kN X
b) Bolts preload 18 kN + ribs X
c) Bolts preload 42 kN ✅
d) Bolts preload 42 kN + ribs ✅

LC L2: S1 + 01

Static + EFC Load

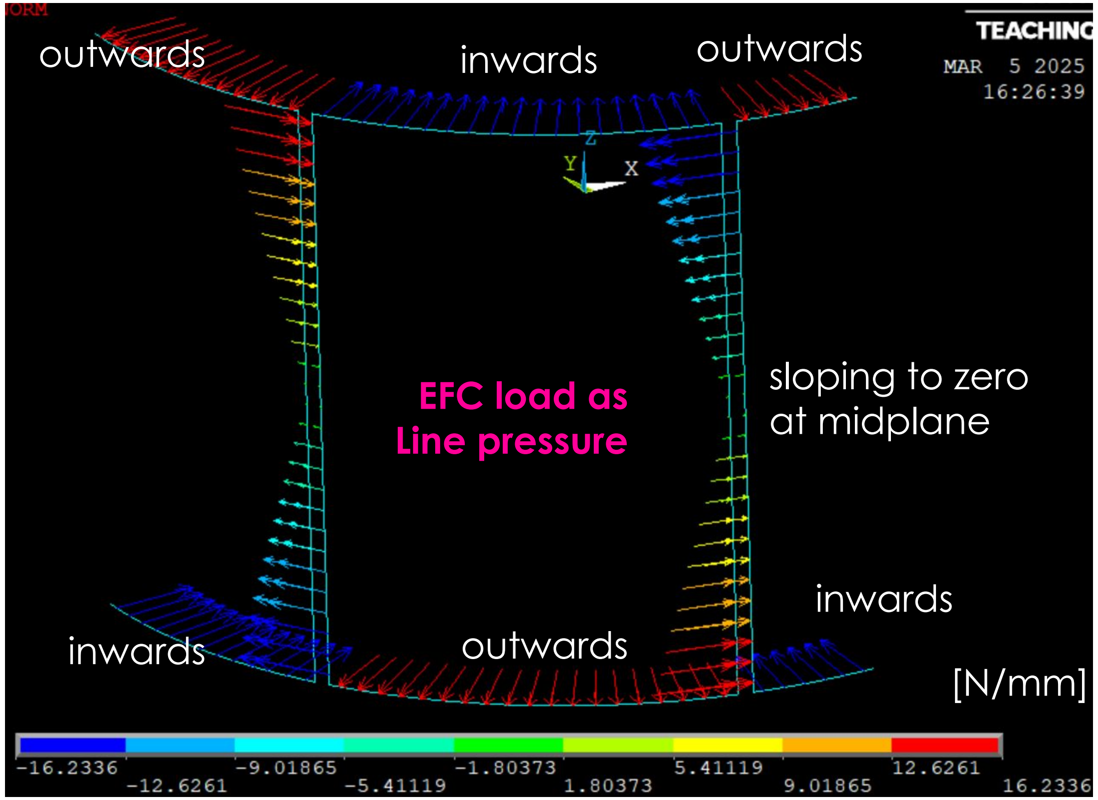
BOUNDARY CONDITIONS

- Used general ¼ axisymmetric model
- Including EFC coils modelled by a Beam elements with OFHC material
- Beam nodes connected to cryostat body by rigid Constraint Equations



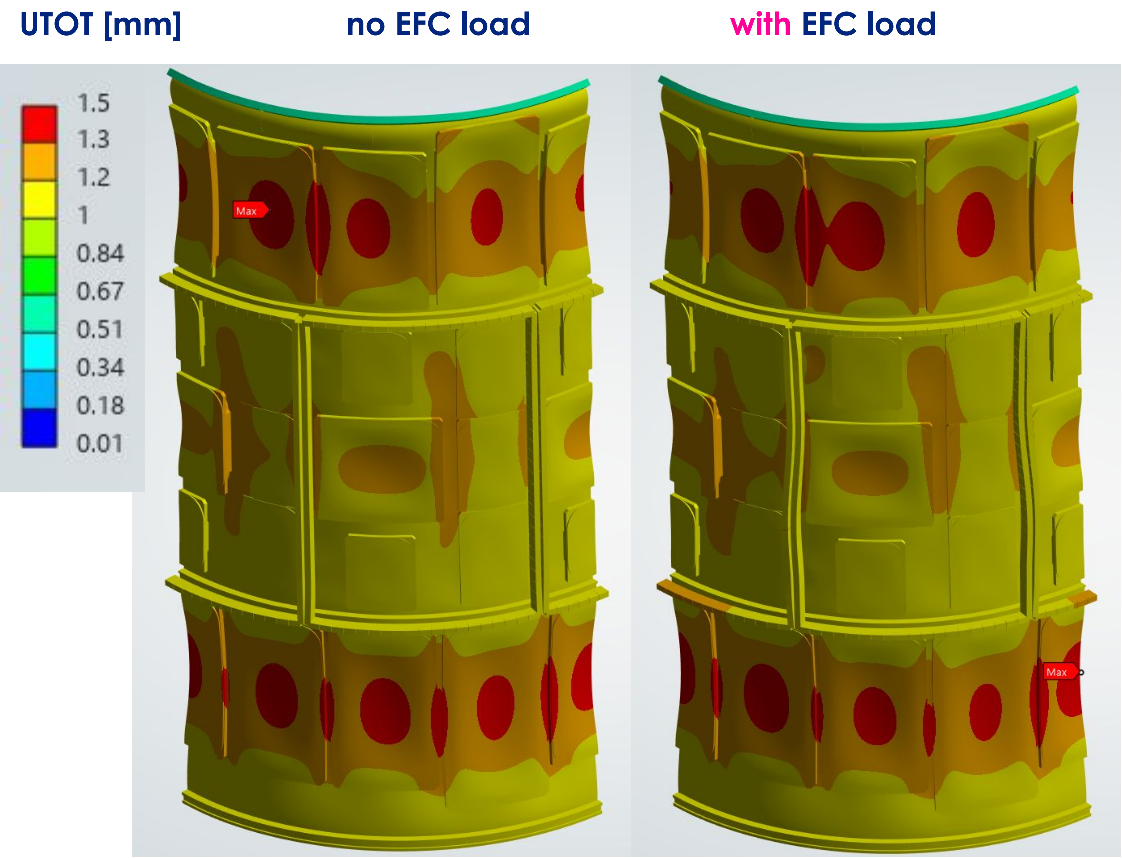
LOADING

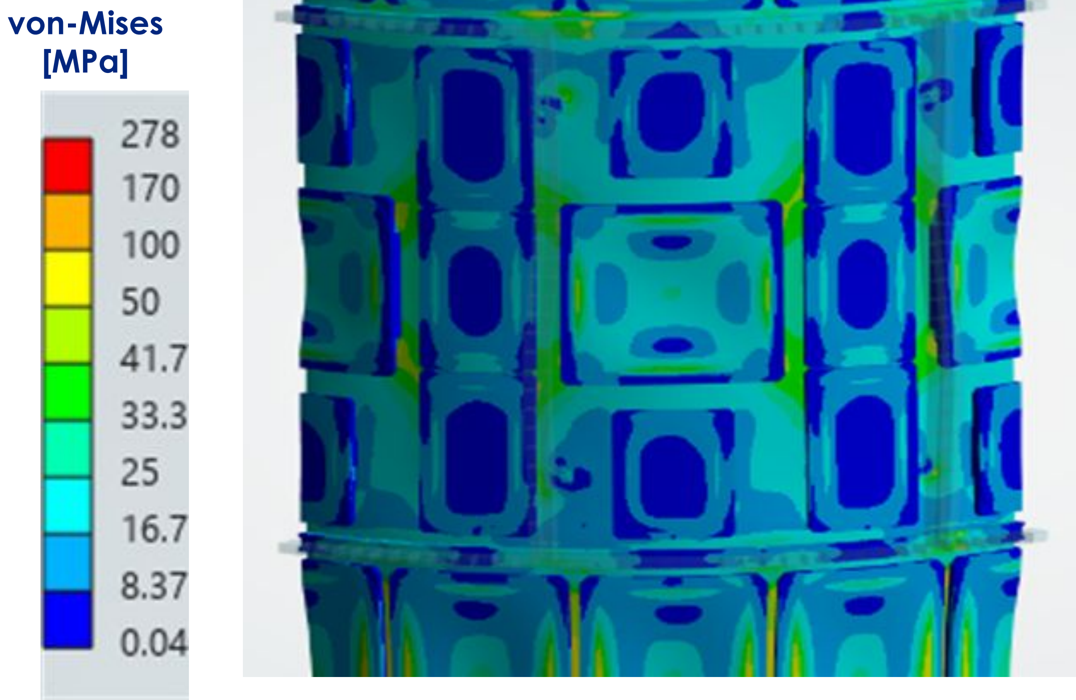
- S1 (static load)
- EFC load as a line pressure of 16kN/m



LC L2: S1 + 01

Static + EFC load





Conclusions:
EFC load makes almost no difference on overall deformations and does not not increase stresses

LC L3: S1 + S3

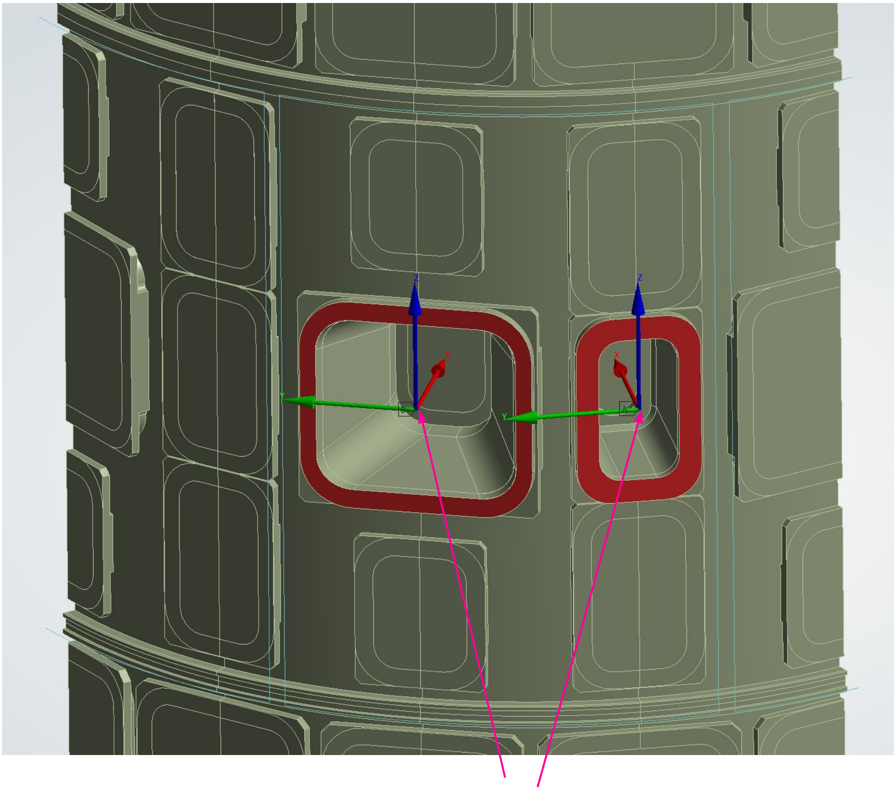
Static + Ports load

BOUNDARY CONDITIONS

- Used general ¼ axisymmetric model

LOADING

- S1 (static)
- Simulated weight of diagnostics
- Load applied to MN and MX ports separately via constraint equations at ports center
- Load at each
    - Moment up to 80 kNm Clockwise and anticlockwise
    - Force downwards 1 kN



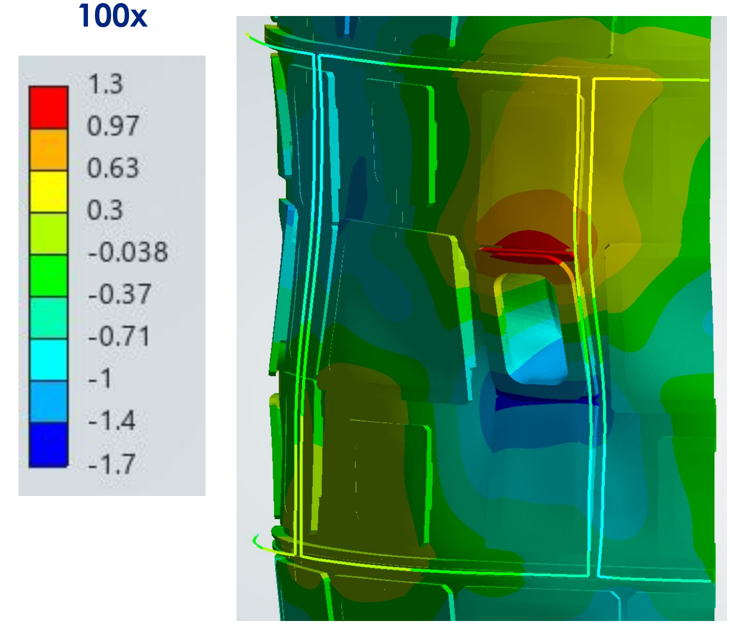
Port load
Moment and Force

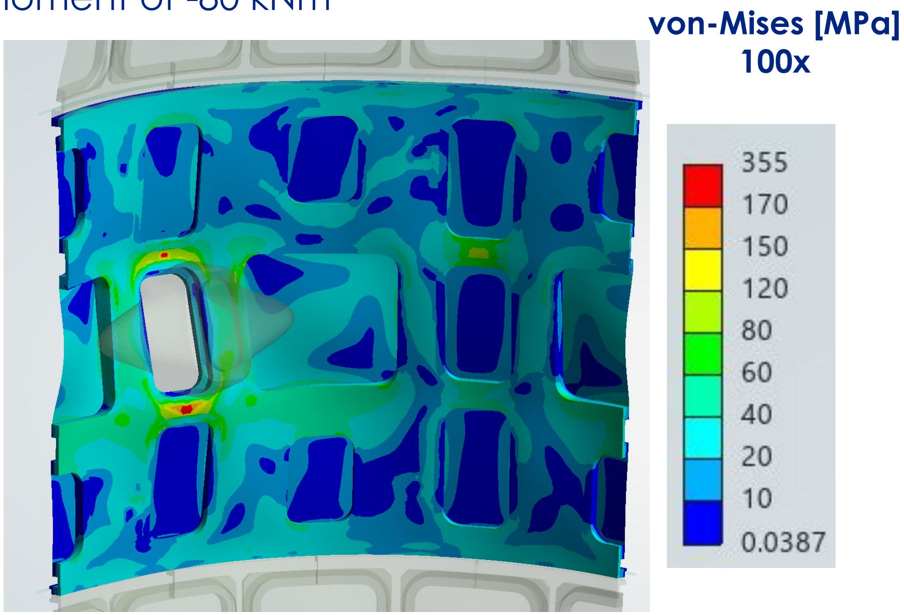
LC L3: S1 + S3

MN port load

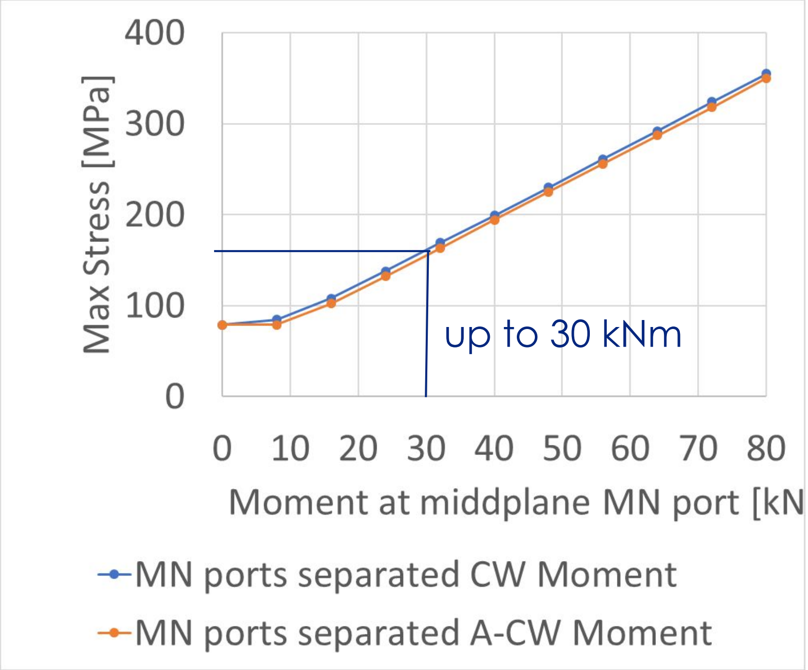
Static + MN port load

Anti-Clockwise moment of -80 kNm





Max equivalent stress at the middle Cryostat hull from varying Moment from -80 to 80 kNm



Conclusions:
MN port can withstand moment up to aprox 30 kNm (3 tons on 1m lever) in configuration with surrounding Blank ports

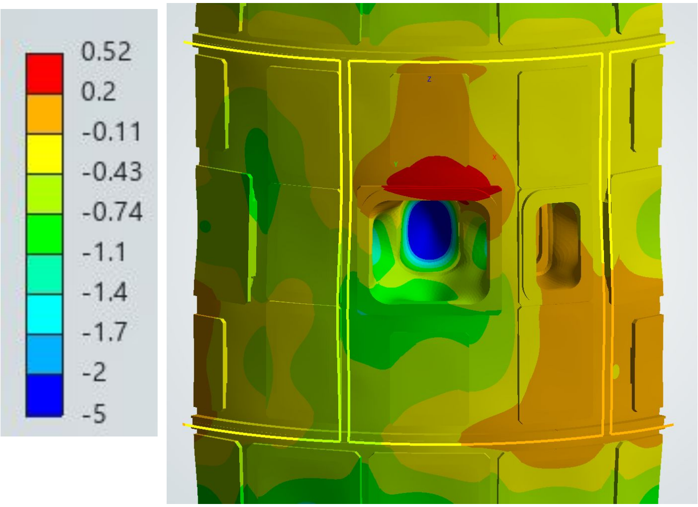
LC L3: S1 + S3

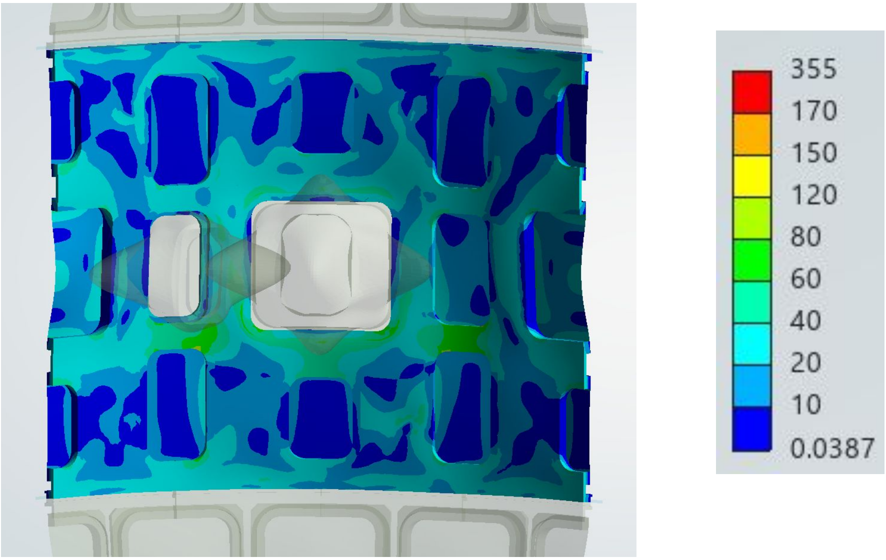
MX port load

Static + MX port load

UX (cyl) [mm]
100x

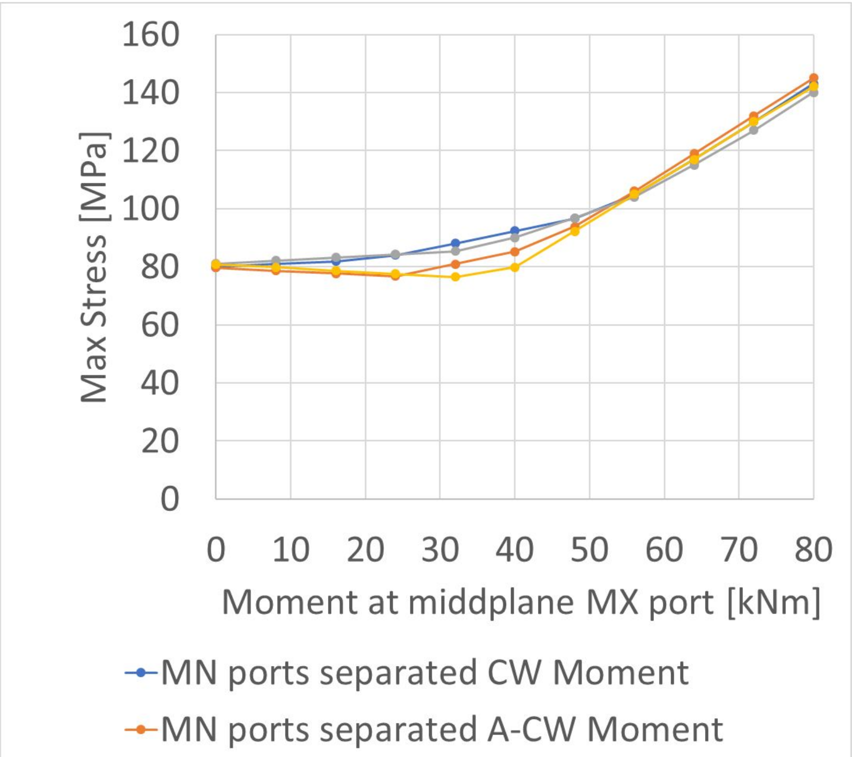
Anti-Clockwise moment of -80 kNm





von-Mises [MPa]
100x

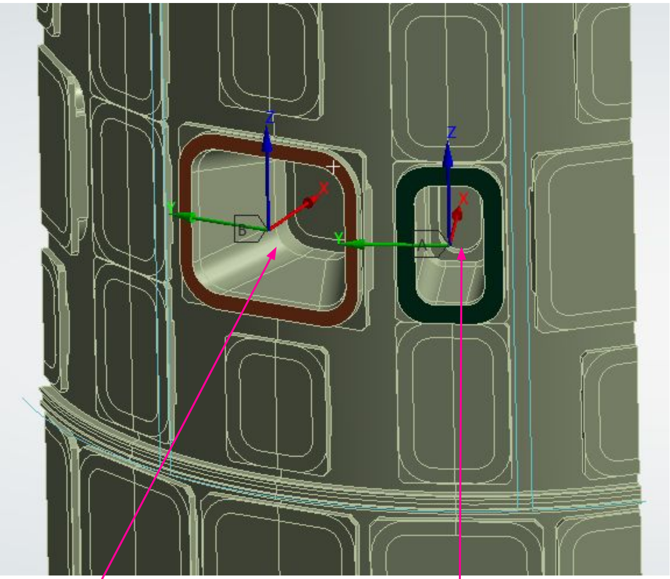
Max equivalent stress at the middle Cryostat hull from varying Moment from -80 to 80 kNm



Conclusions:
Load at MX port does not create any significant stress concentrators and MX port can withstand up to 80 kNm in both directions in configuration with surrounding Blank ports

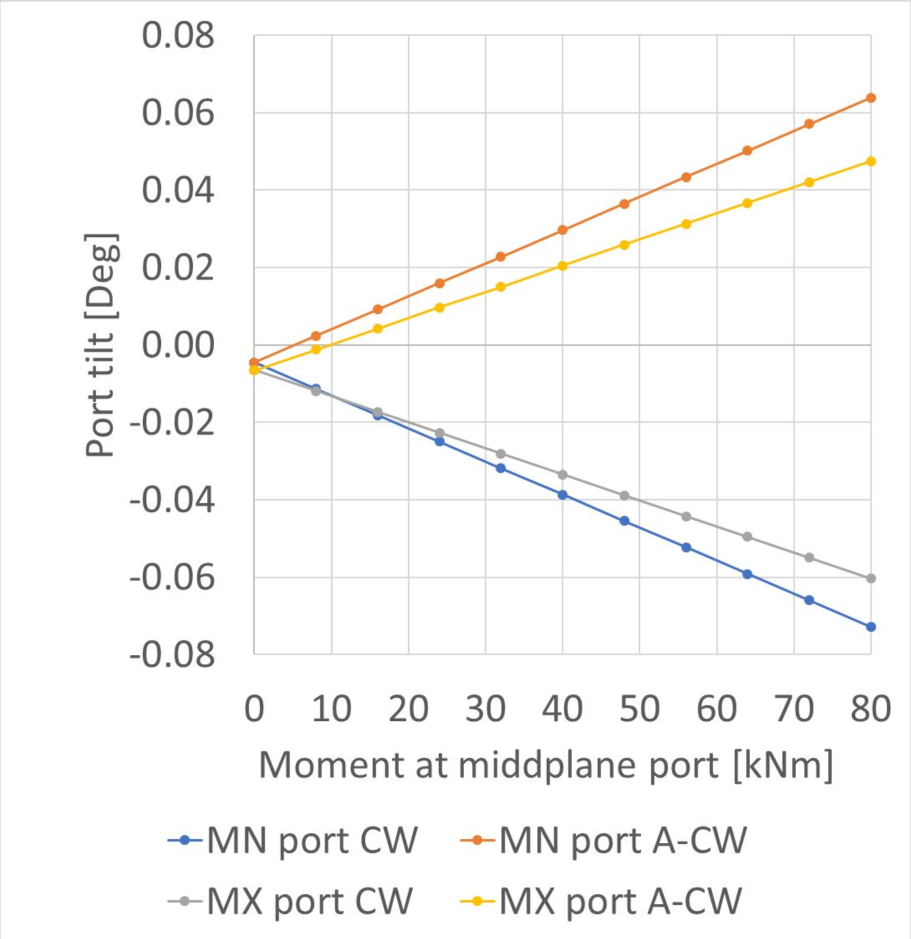
Ports tilt from moment load

Static + MX and MN port load



Port Tilt measured (rotation around axis Y) at Remote points used to insert force and moment at the ports.

Average tilt at independently loaded MX and MN ports by varying Moment from -80 to 80 kNm



Conclusions:
Worst case with excessive applied moment creates everage port tilt of 0.06 deg

With more reasonable moments up to 20 kNm is maximal average tilt of 0.02 deg.

With surrounding blank ports.

LC L4: S1 + S3 + O2

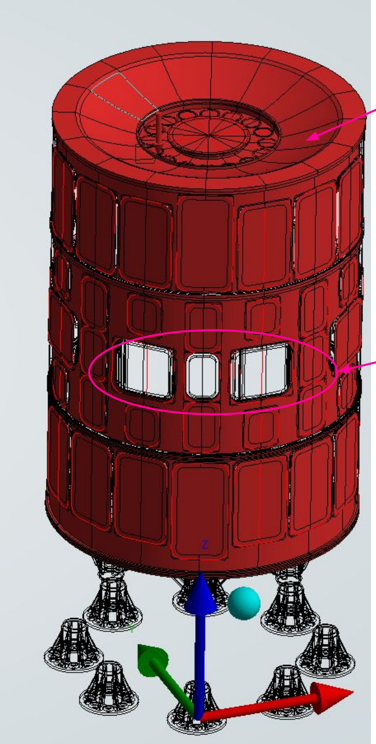
Static + Non-Sym atm. pres. + Downwards Disruption

BOUNDARY CONDITIONS

- Used full geometric model due to non-symmetric loading

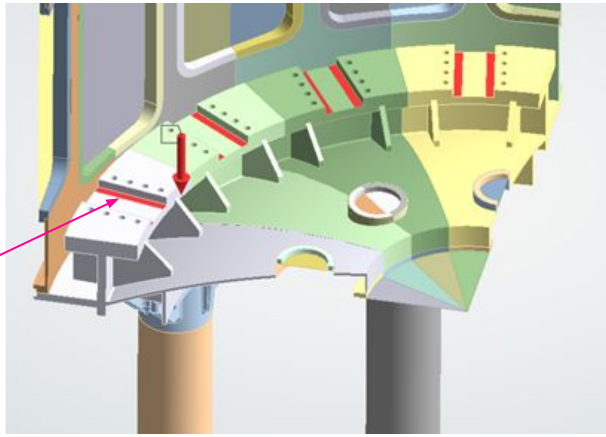
LOADING

- S1 (static)
- S3 (Non symmetrical atmospheric pressure)
  - Due to MN and 2 MX neighboring ports being open
  - Vacuum barrier at VV
- O2 (Downwards disruption)
  - 11.2 MN on full model
    - (overly estimated magnitude)



0.102 MPa

3 Neighboring opened ports without atmospheric pressure

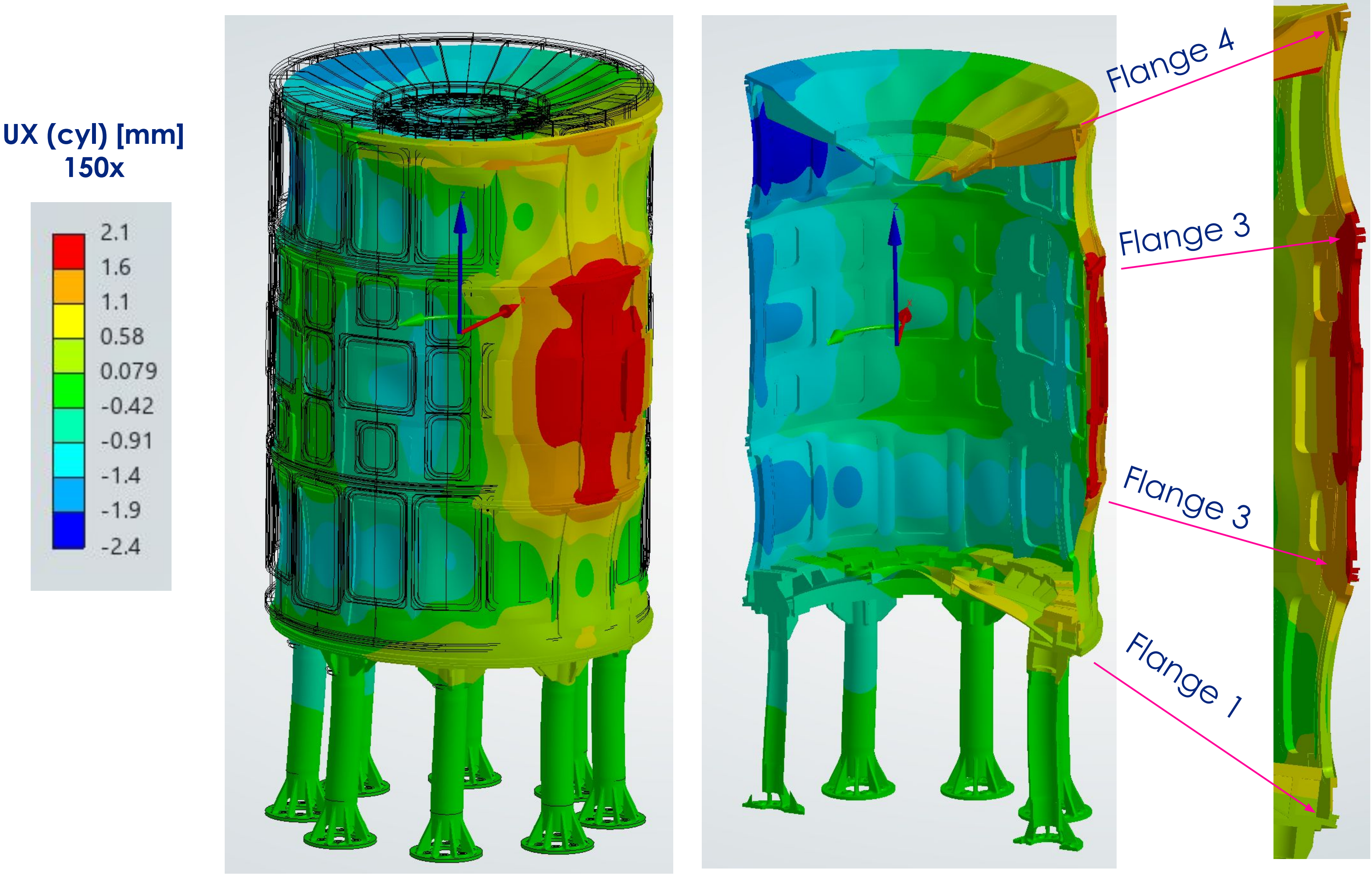


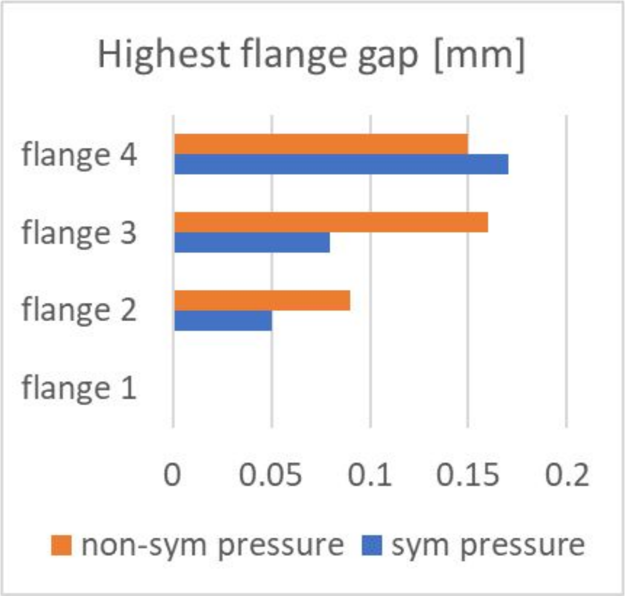
Load at SS interface:
3 MN (Tok weight) + 11.2 MN Downwards disruption

LC L4: S1 + S3 + O2

Radial Deformations from combined load

Static + Non symmetric atmospheric pressure + Downwards disruption





Conclusions:
Overall Cryostat tilting ~1.5 mm towards 3 open ports

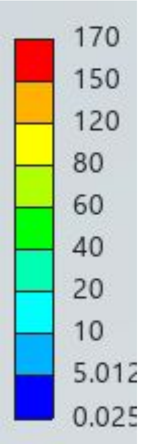
Gap at flanges are within rubber sealing working range

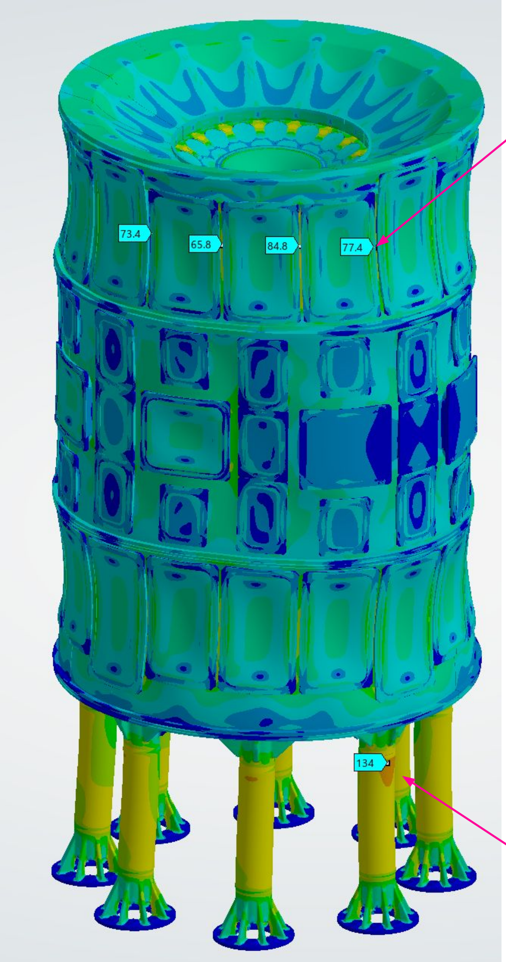
LC L4: S1 + S3 + O2

Stress from combined load

Static + Non symmetric atmospheric pressure + Downwards disruption

von-Mises [MPa]
150x





Stresses on cryostat hull between ports: Non-sym atm. Pressure does not increase the stress

Increased Legs stress due to Cryostat tilting

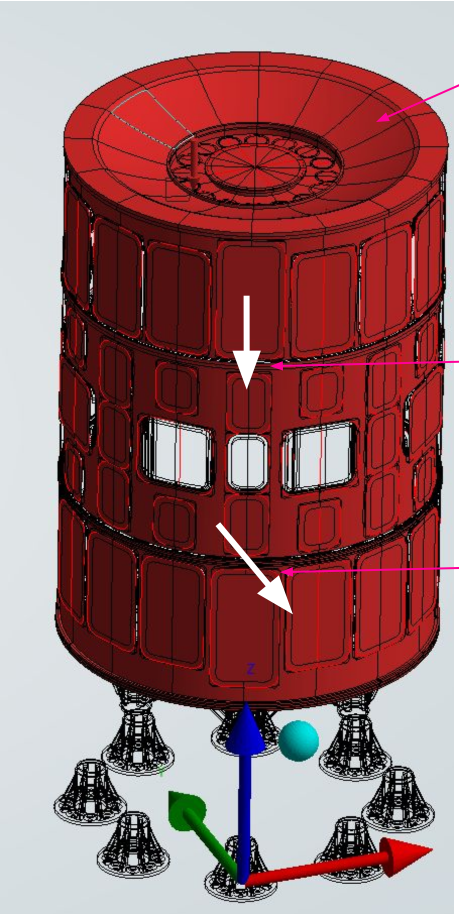
Conclusions:
Stresses on cryostat sections between flanges are not enlarged

Increased legs stress due to Cryostat tilting to 150 MPa (close to limit)

LC L5: S1 + S2 + O2 + O3

Non symmetric loads

based on V2e6r



Non-Symmetric loads

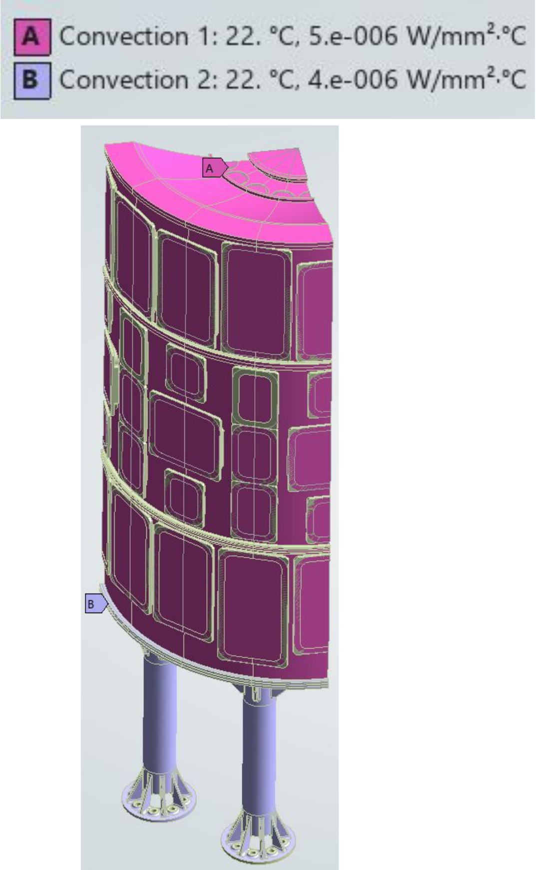
- S1
- S2 non symmetric atmospheric pressure
- O2 Downwards disruption
  - 11.2 MN (Update required)
- O3 Lateral disruption
  - Not yet specified

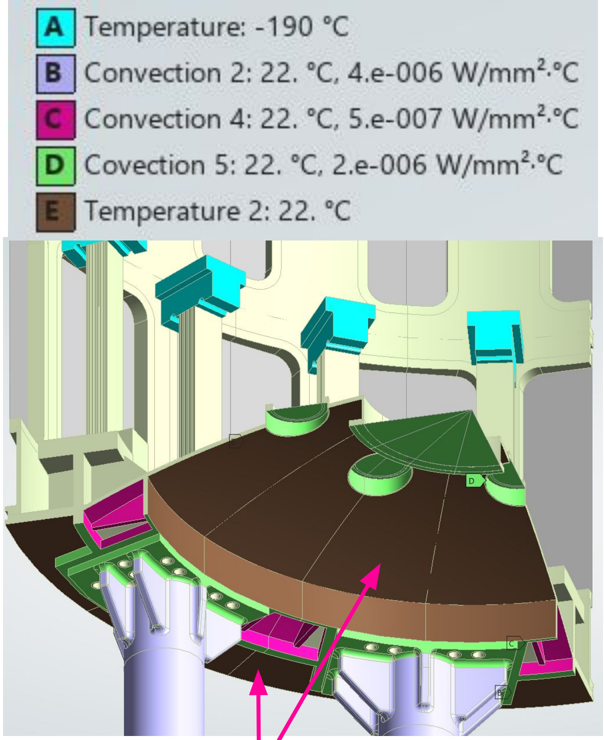
Thermal gradient

MOTIVATION
- Check thermally induced structural stress and deformations from Steady-State Thermal gradient between SS flexible support temperature and room temperature

BOUNDARY CONDITIONS
- Used general ¼ axisymmetric model
- Added Support structure legs
- Applied thermal convections to outer cryostat surfaces

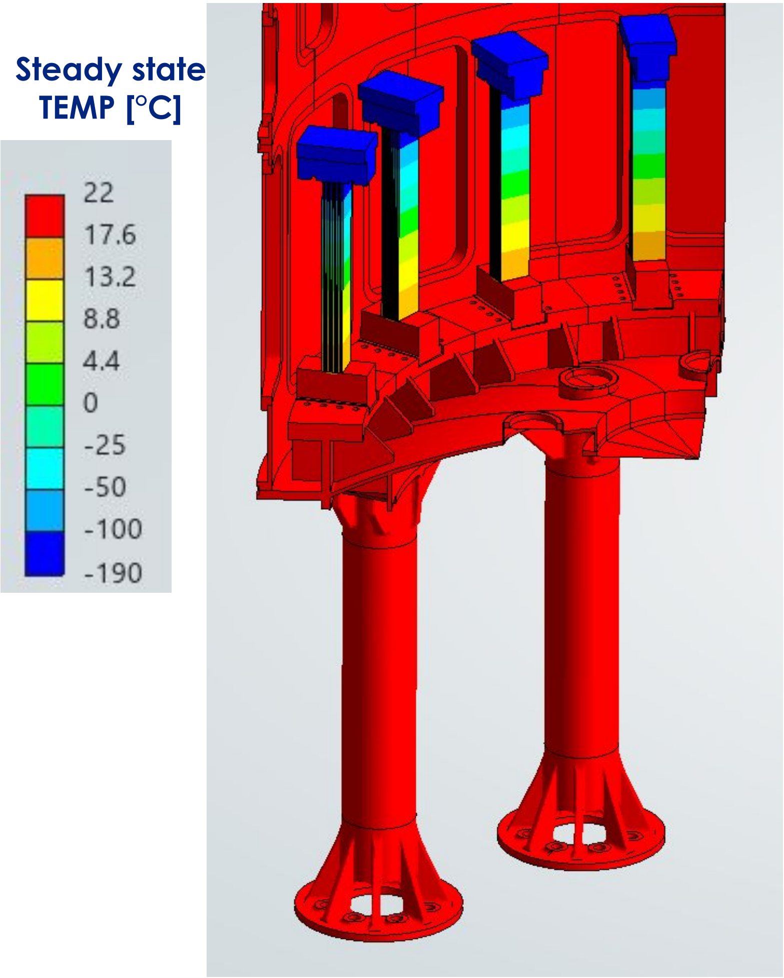
LOADING
- Temperature of -190C at Support structure upper legs
- Heating on the lower lid
  - (to avoid water condensation)

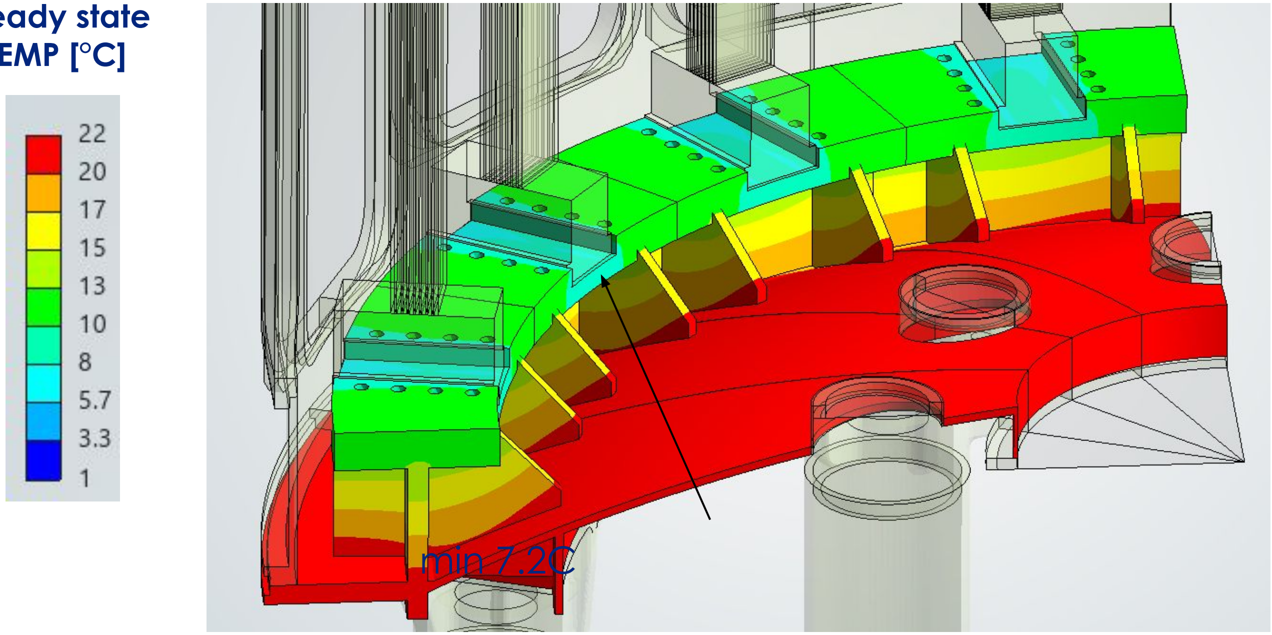




Steady state Temperature

Thermal gradient



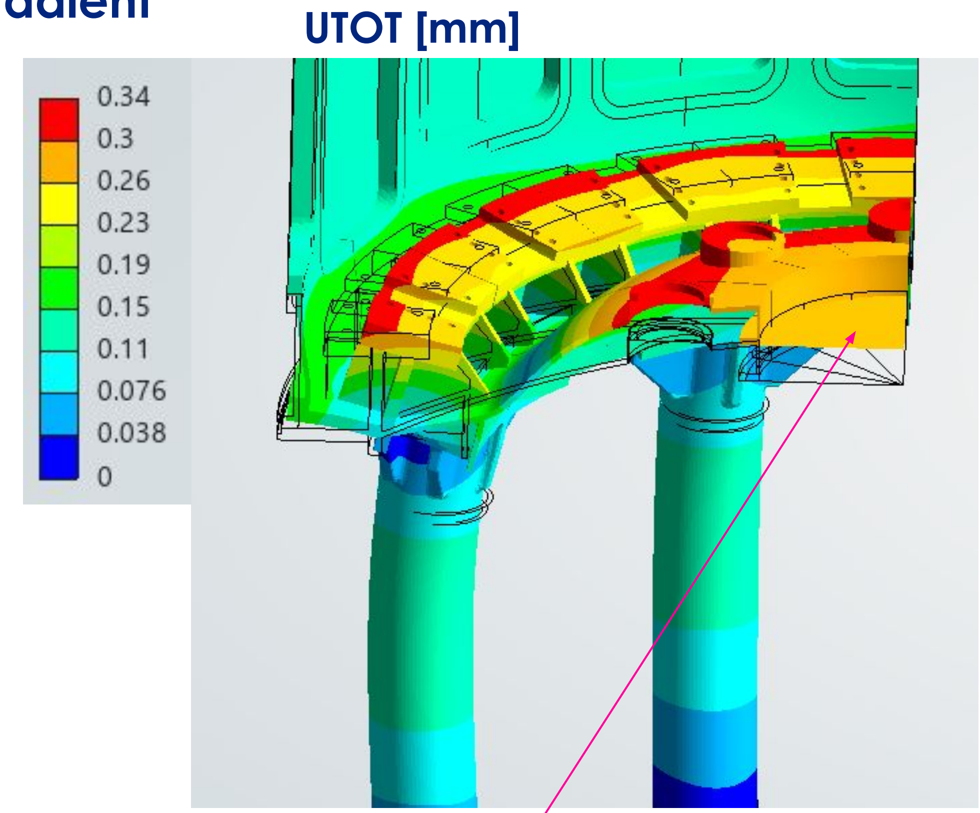


Conclusions:
Largest thermal gradient is 15°C on the cryostat base body.
Without the underside heating the gradient was up to 20°C

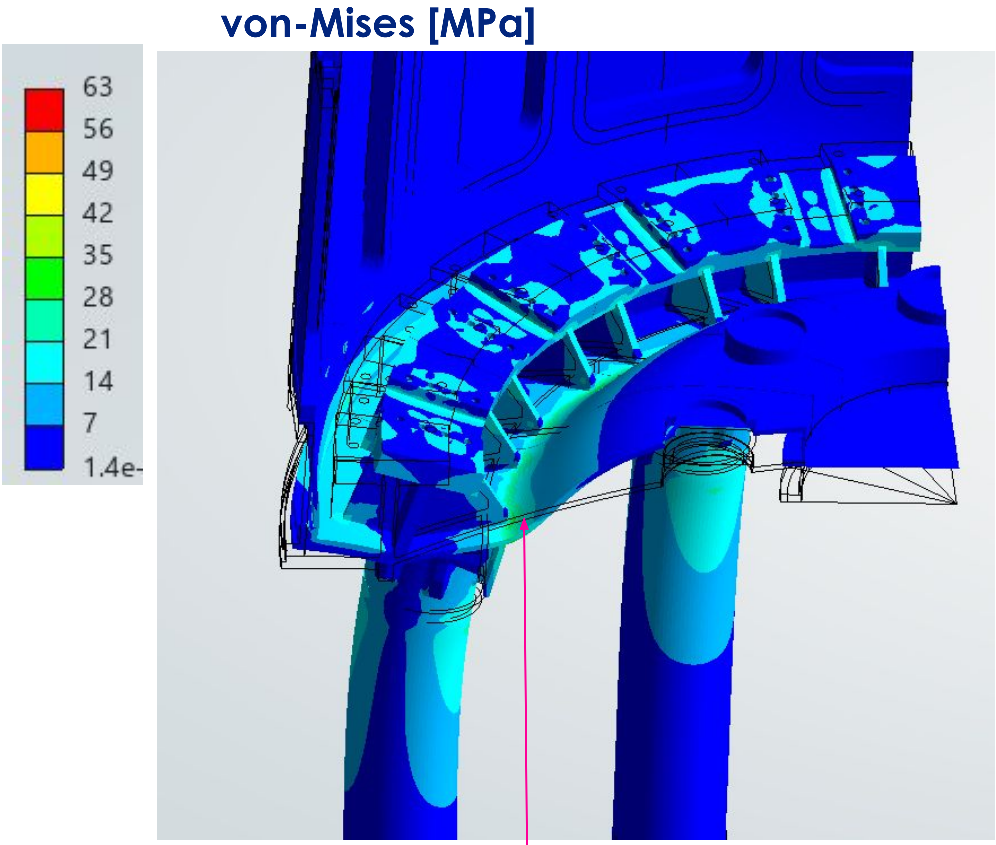
LC L6: T1

Deformations (500x) and stress

Thermal gradient



Upwards deflection of lower lid due to Concave shape, which does not allow downwards bending.



Highest stresses are between ring and concave part with approx 40 MPa

LC L7: S1 + T1 + O2

MOTIVATION

- Check stress from combined load case

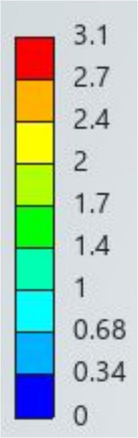
LOADING and BOUNDARY CONDITIONS

- S1 (static)
- T1 (Thermal gradient)
- O2 (Downwards disruption)

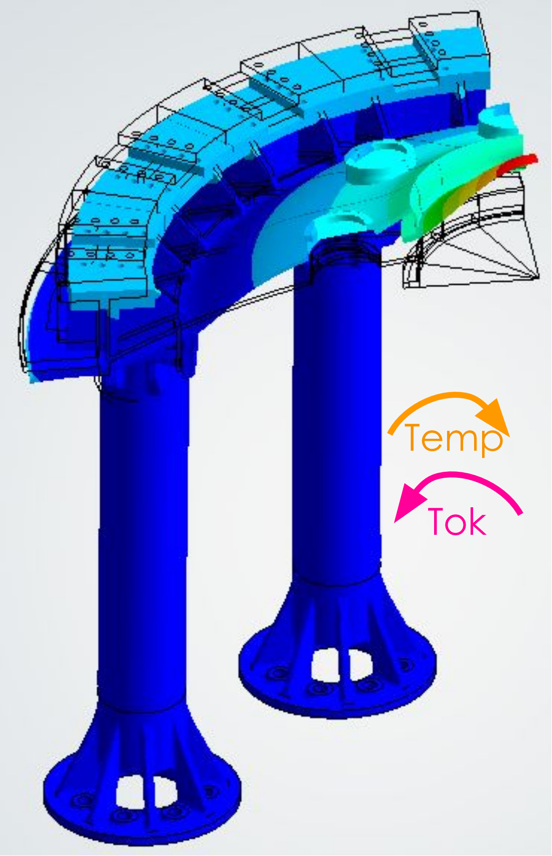
LC L7: S1 + T1 + O2

Combined load - UTOT

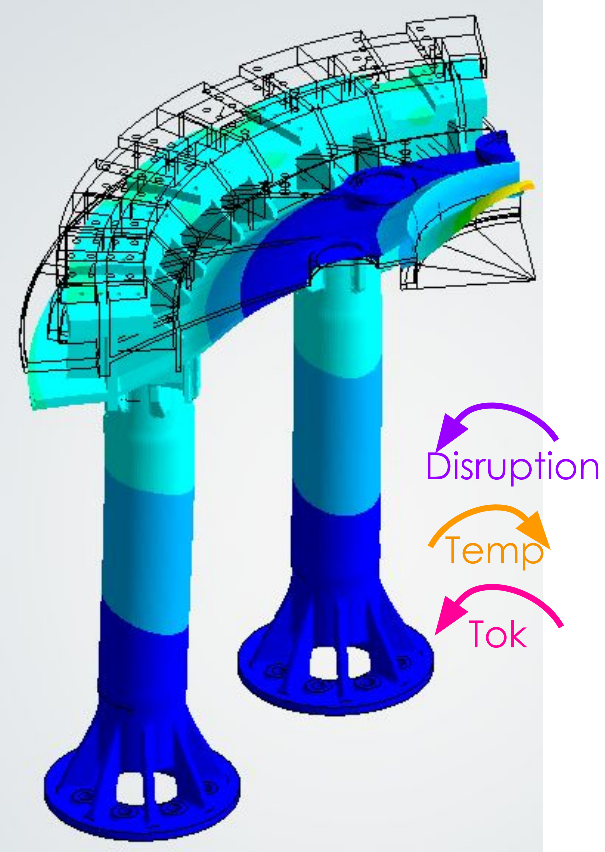
UTOT [mm]
300x



Atmos + TOK weight + T1 Temp



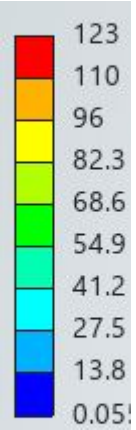
Atmos + TOK weight + T1 Temp + downwards disruption 11.2 MN



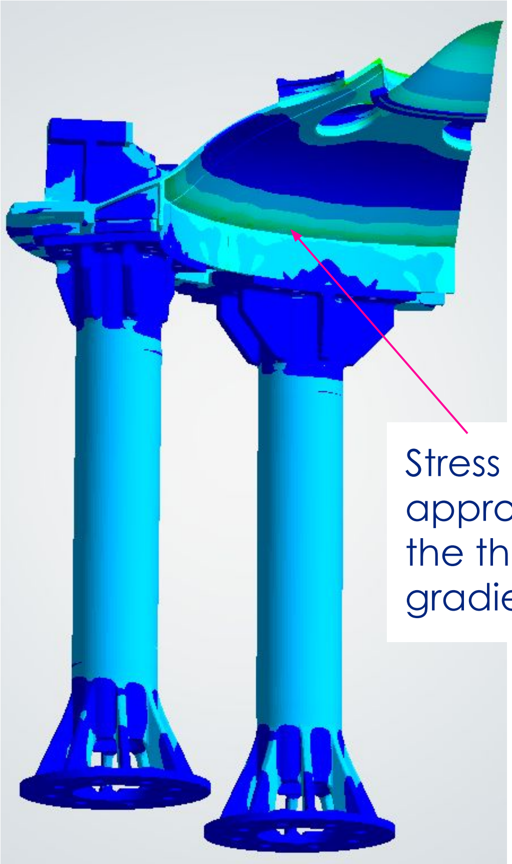
BC3 temp rotates Cryo Base inwards - acting as a compensation for the TOK weight

LC L7: S1 + T1 + O2 — Combined load - stress

von-Mises [MPa]
300x



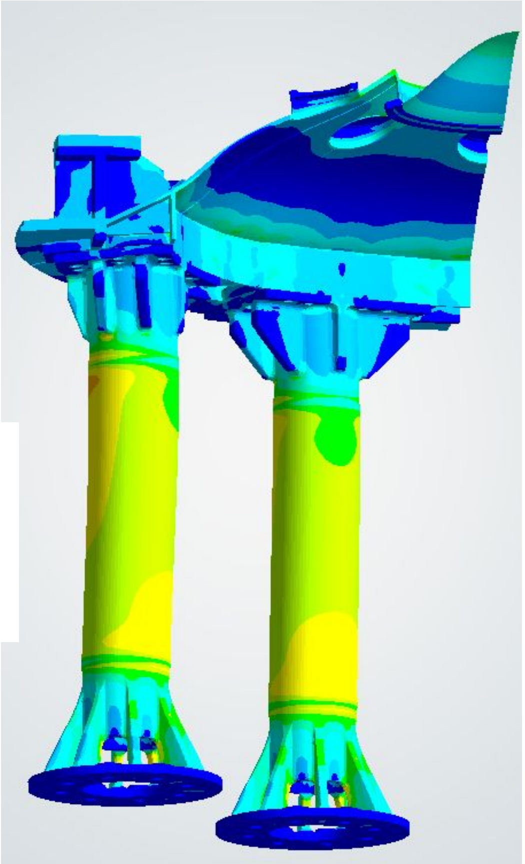
Atmos + TOK weight + T1 temp



Stress increased by approx 40MPa from the thermal gradient

Stress from legs Bending is neutralized

Atmos + TOK weight + T1 temp + downwards disruption 11.2 MN



Disruption adds bending and compression stress to the legs

LC L8: S1 + T2

Vacuum breach

MOTIVATION

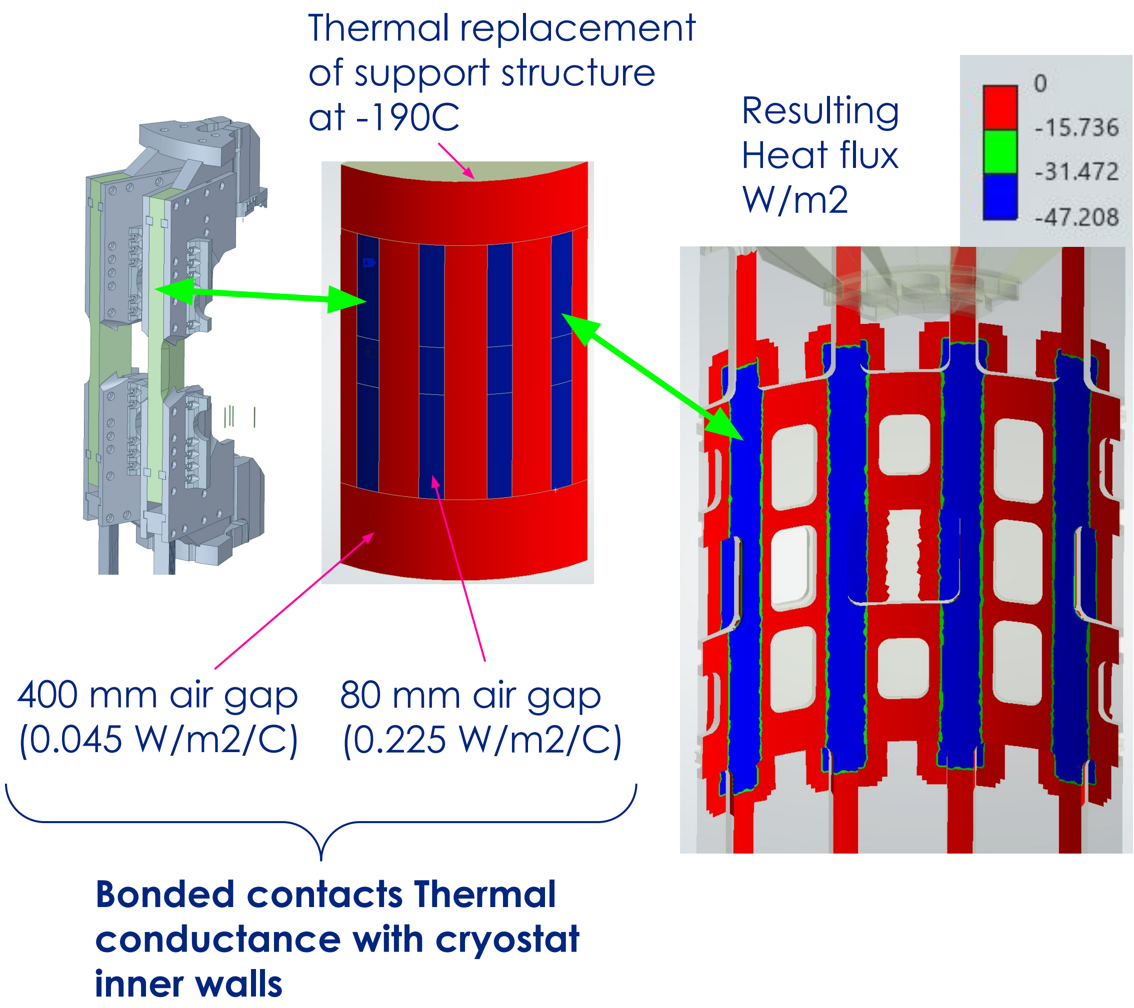
- Check stresses from thermal gradient created by **cryostat vacuum breach** which locally lowers temperature of cryostat sections closest to support structure and combine them with static load

BOUNDARY CONDITIONS

- Used general ¼ axisymmetric model
- Added simplified cylindrical SS geometry
- Convection 5W/m2 to RT on outer surfaces

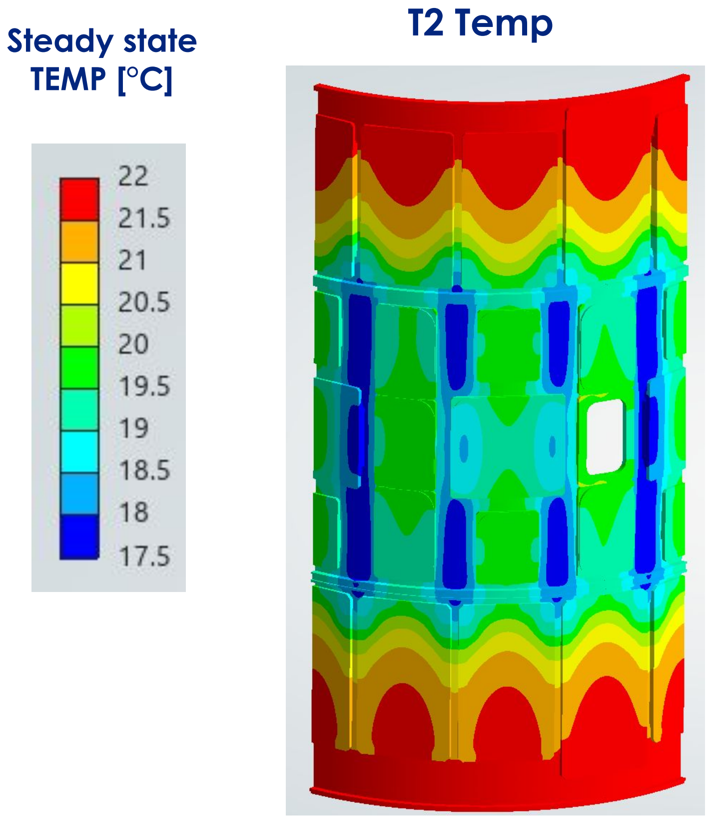
LOADING

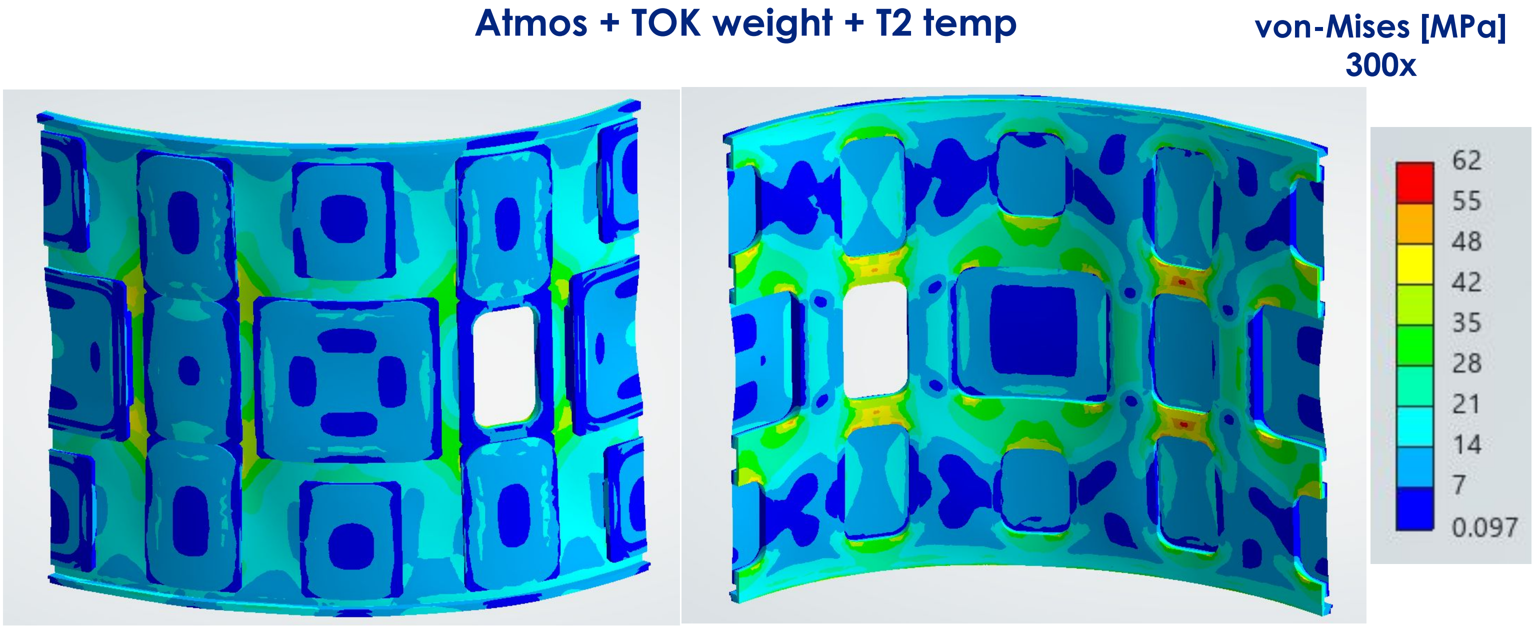
- S1 (static)
- T2 (Thermal effects of local vacuum breach)
  - Simulated conductance of air gap between Support structure and cryostat inner surfaces



LC L8: S1 + T2

Vacuum breach





T2 increased maximal equivalent stress by only 6 MPa

Conclusions:
Vacuum breach does lower locally temperature of cryostat to 17°C which creates increased stress by only 6 MPa.

LC L9: S1 + T3

Vacuum Vessel heating

MOTIVATION

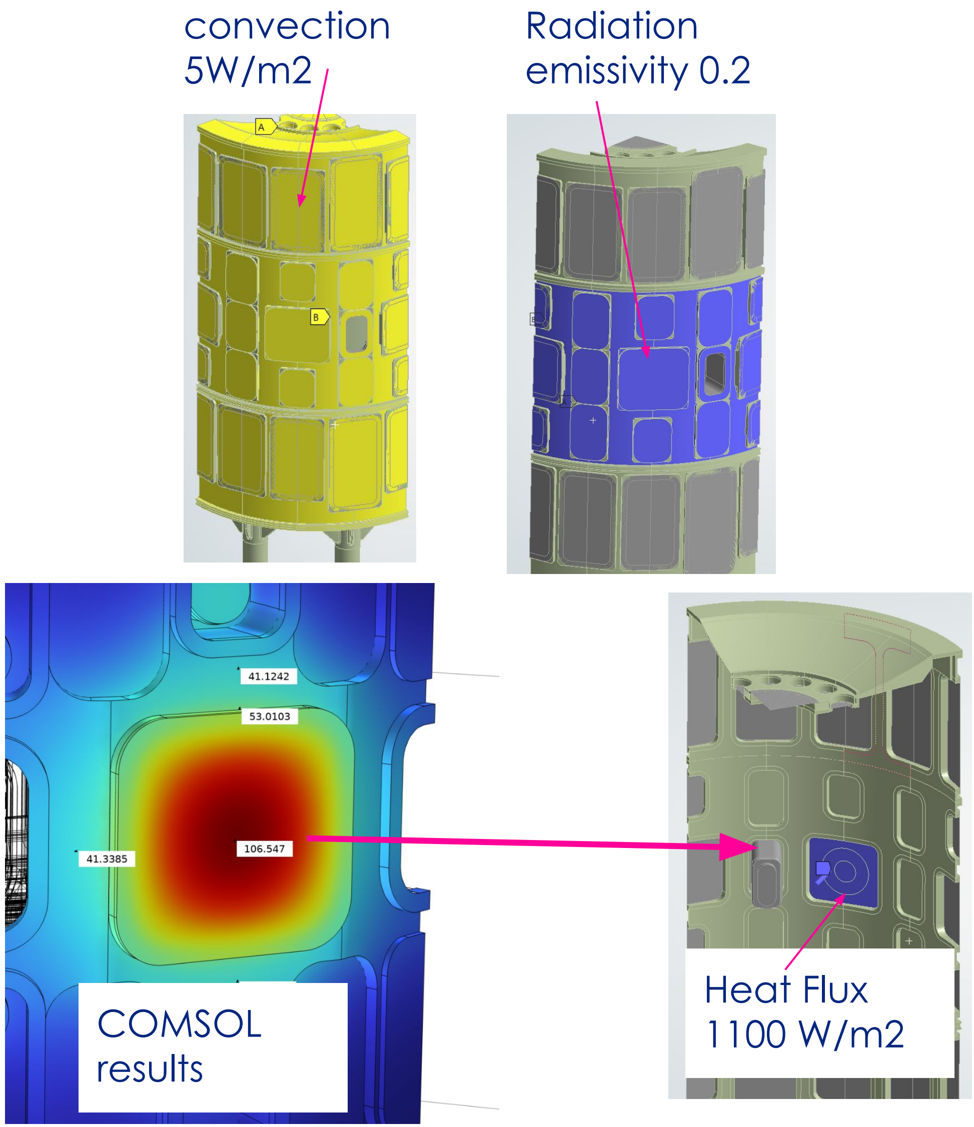
- Check thermal stresses on MX port from load case T3 during **Vacuum Vessel heating** to 500°C and combine it with static load S1

BOUNDARY CONDITIONS and LOADING

- Used general ¼ axisymmetric model
- Radiation and Convection on outer surfaces

LOADING

- S1 (static)
- T3 (Vacuum Vessel heating to 500°C)
  - Applied Heat Flux to inner face of Blank MX port
    - Best approximates thermal gradient from P. Bartoň COMSOL analysis results



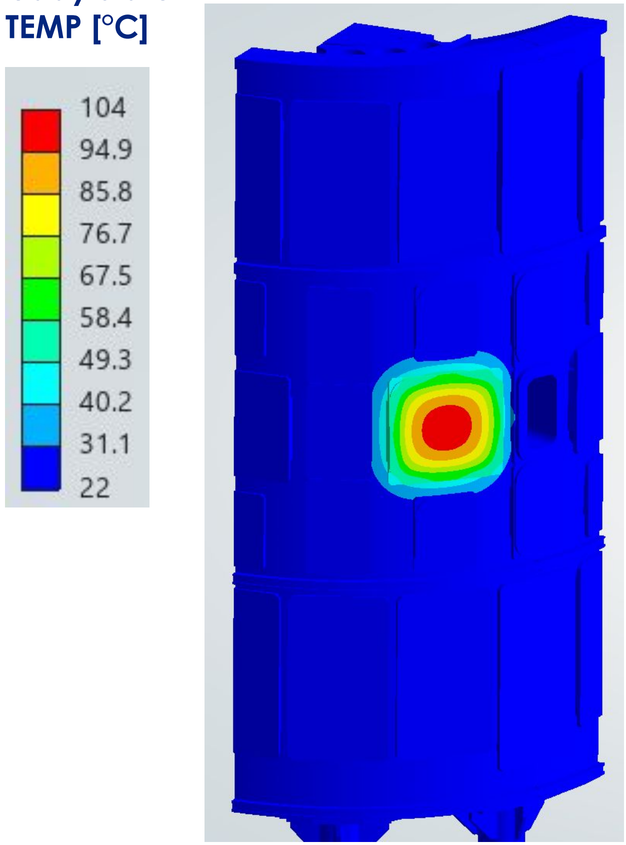
LC L9: S1 + T3

Vacuum Vessel heating

Vacuum Vessel heating

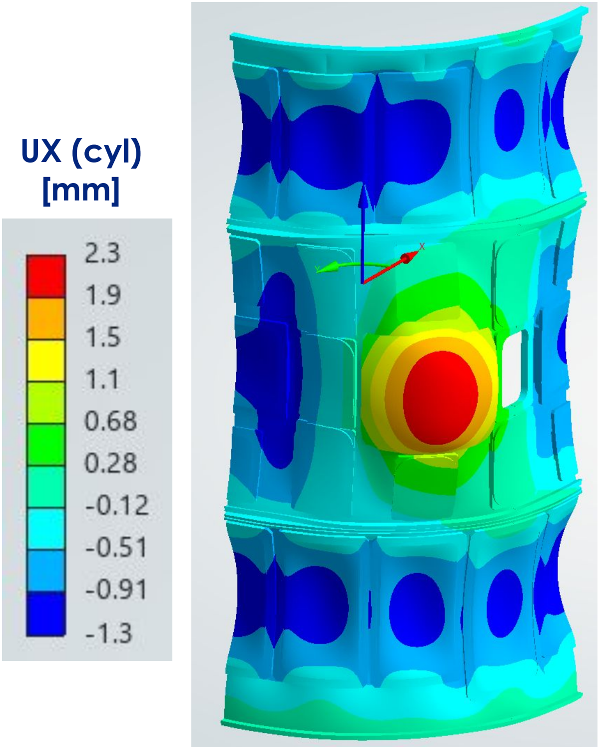
T3 Temp

Steady state TEMP [°C]

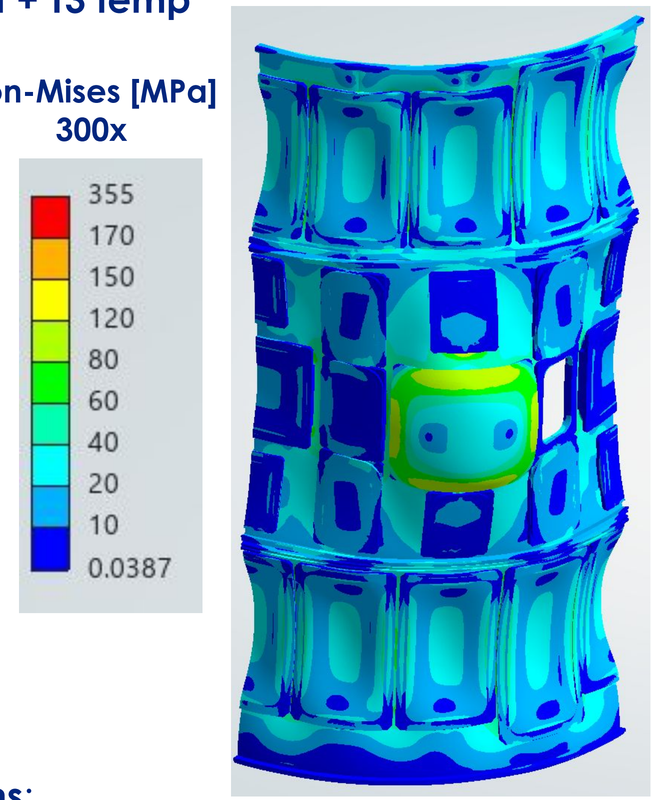


Atmos + TOK weight + T3 temp

UX (cyl) [mm]



von-Mises [MPa] 300x



Conclusions:
Blank MX port is heated up to 104°C which thermally expand MX port by approx 3 mm in radial direction.
Induced stress from thermal and static load is below 150 MPa