# Detailed 3D modeling of the DEMO TF coil design according to the SPC high current react & wind concept

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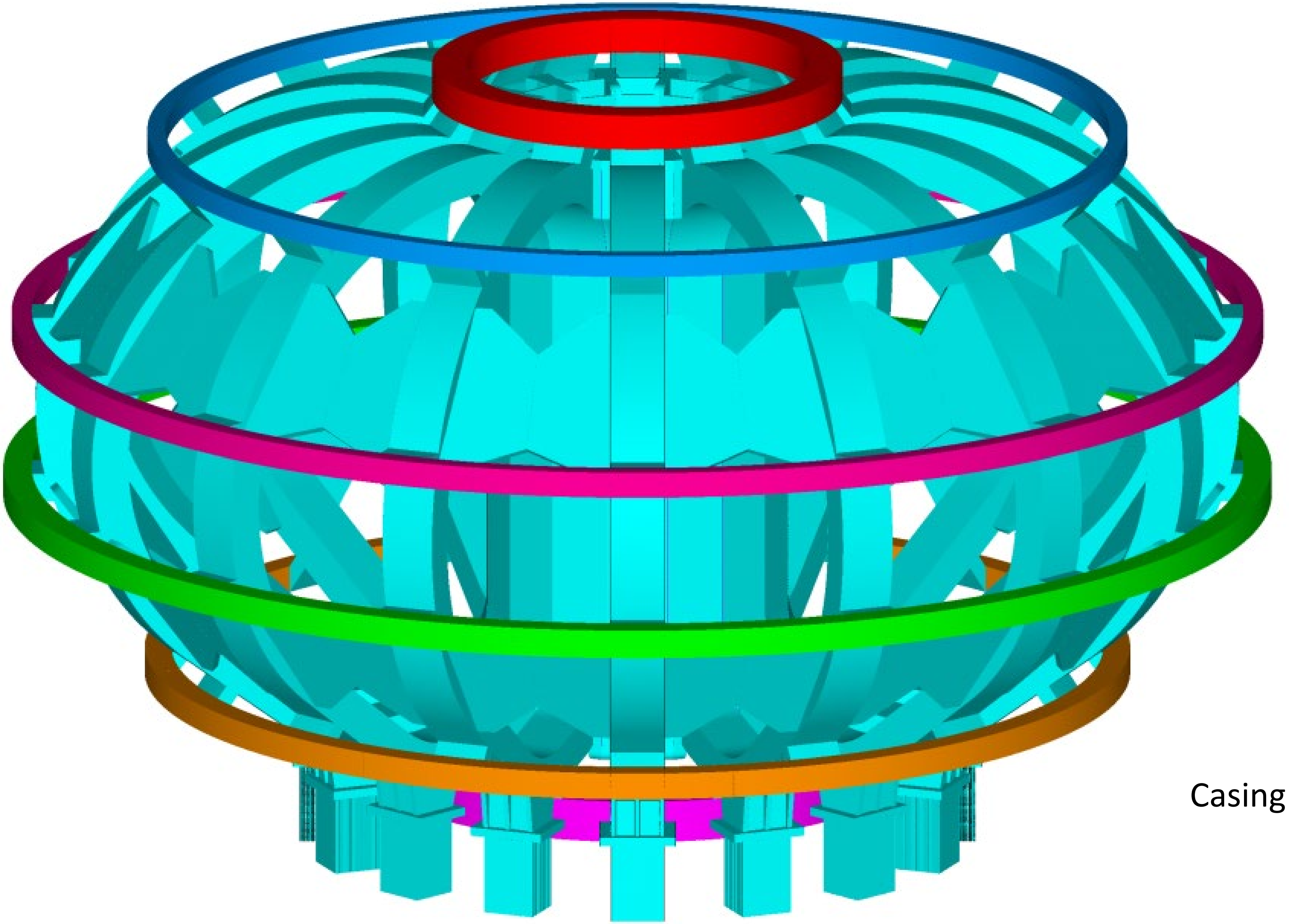
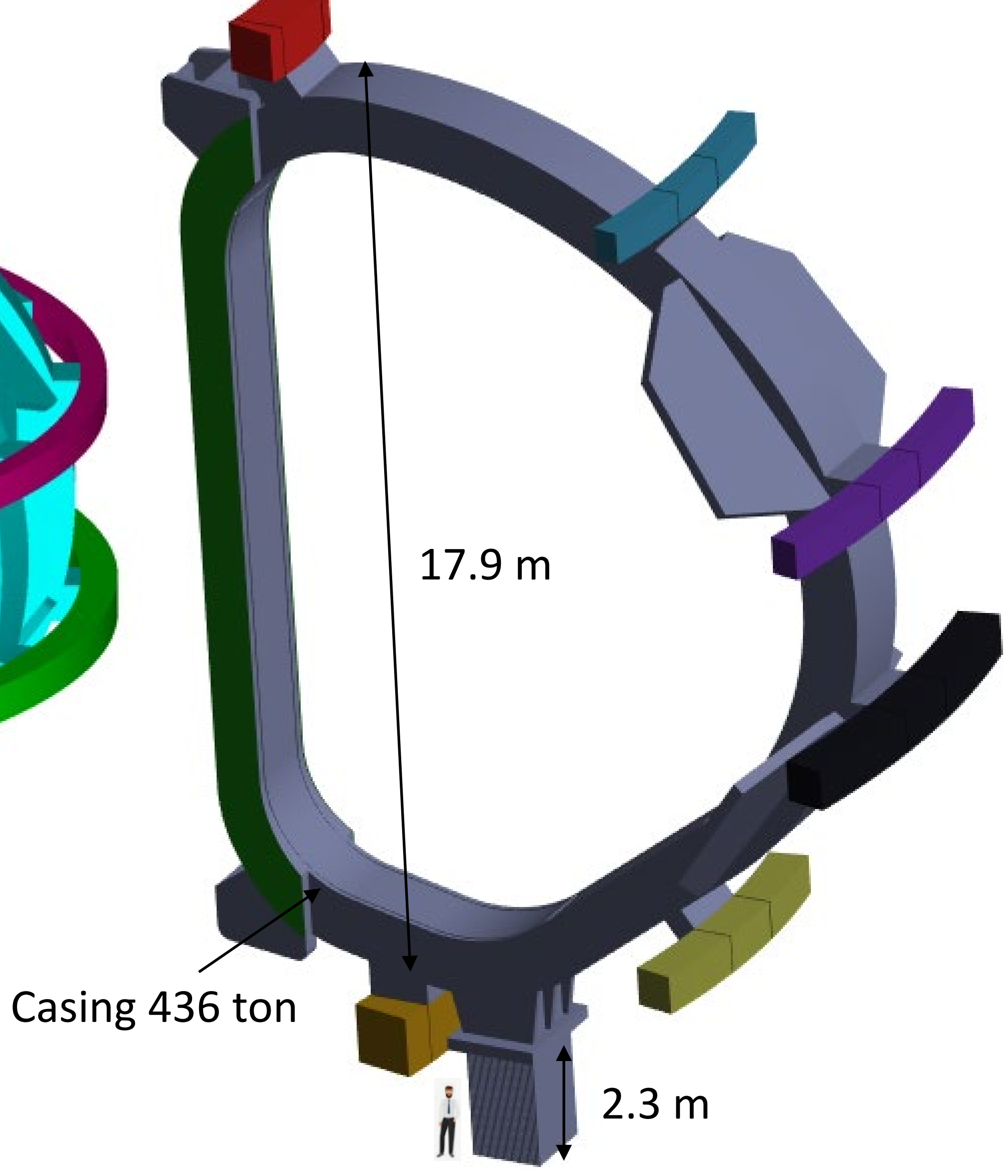
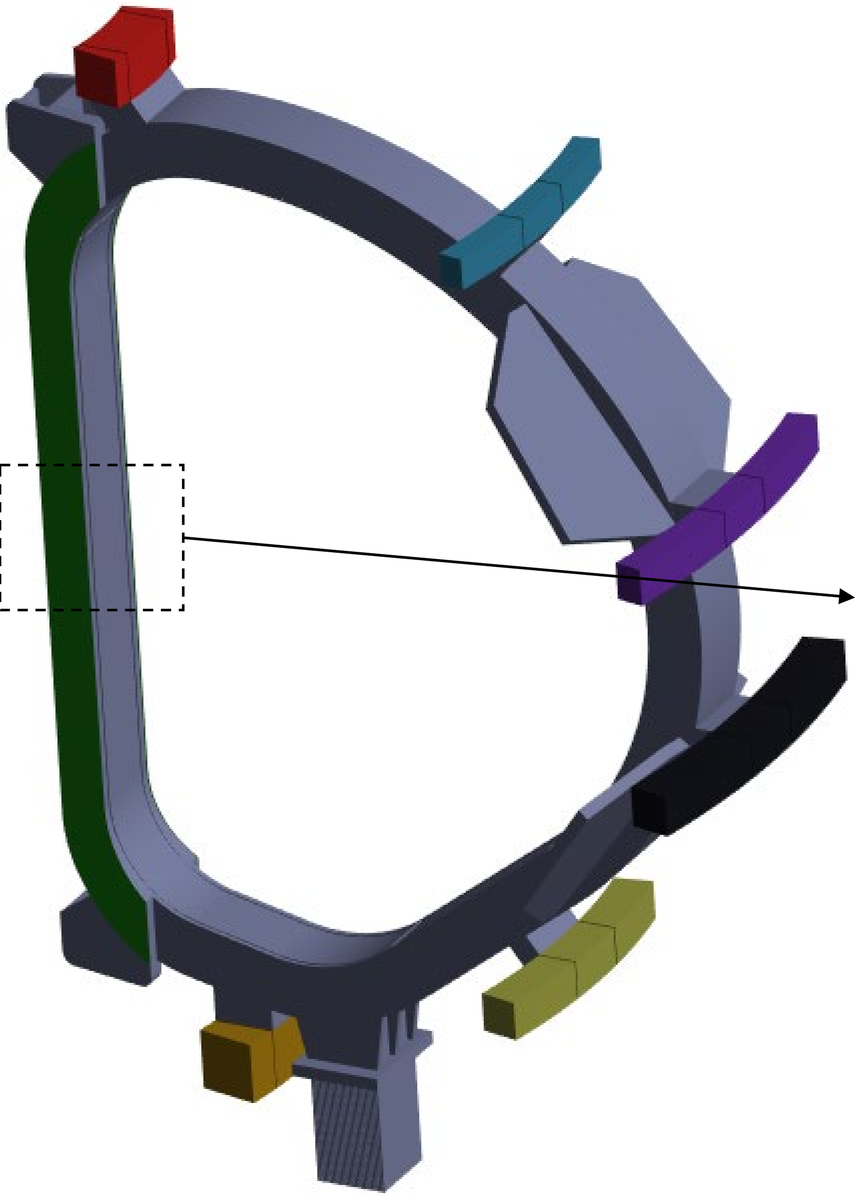
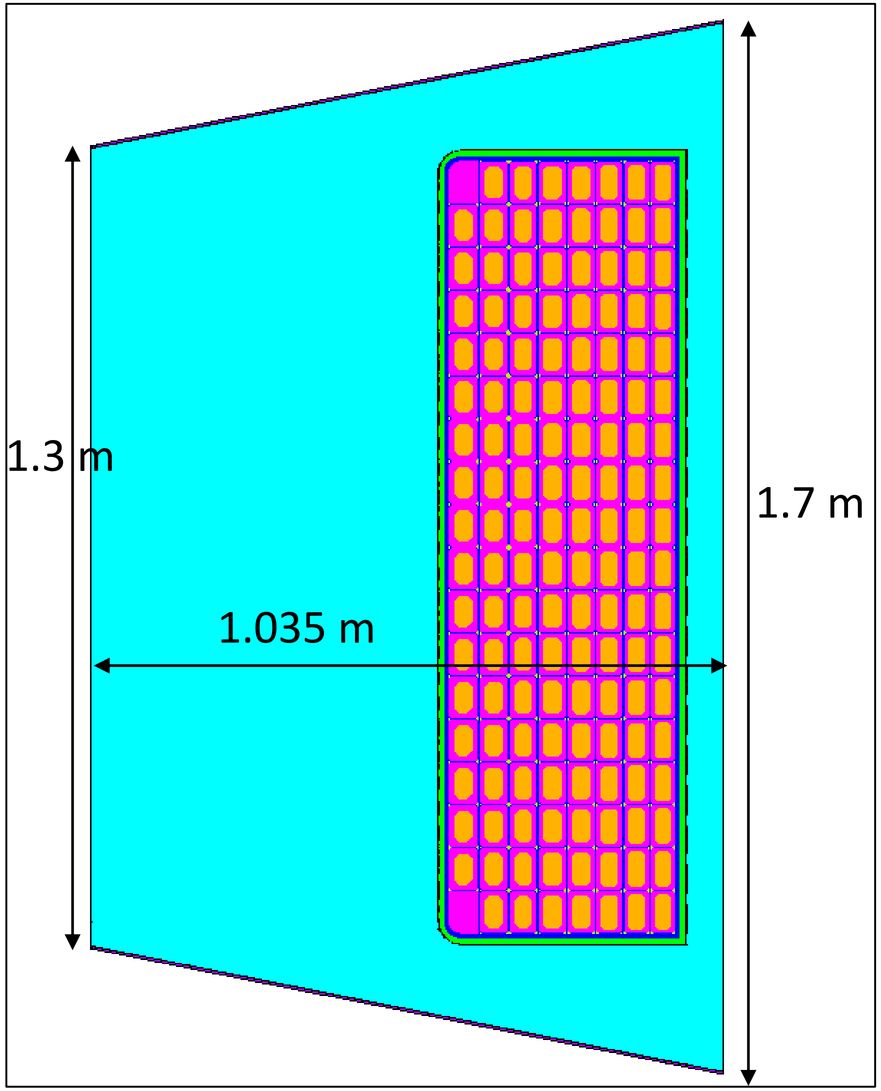
# 1. Introduction





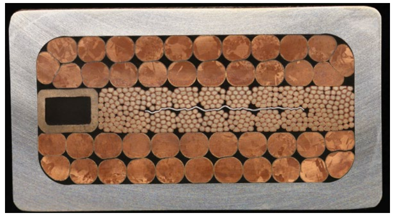
# 2. High current react & wind concept





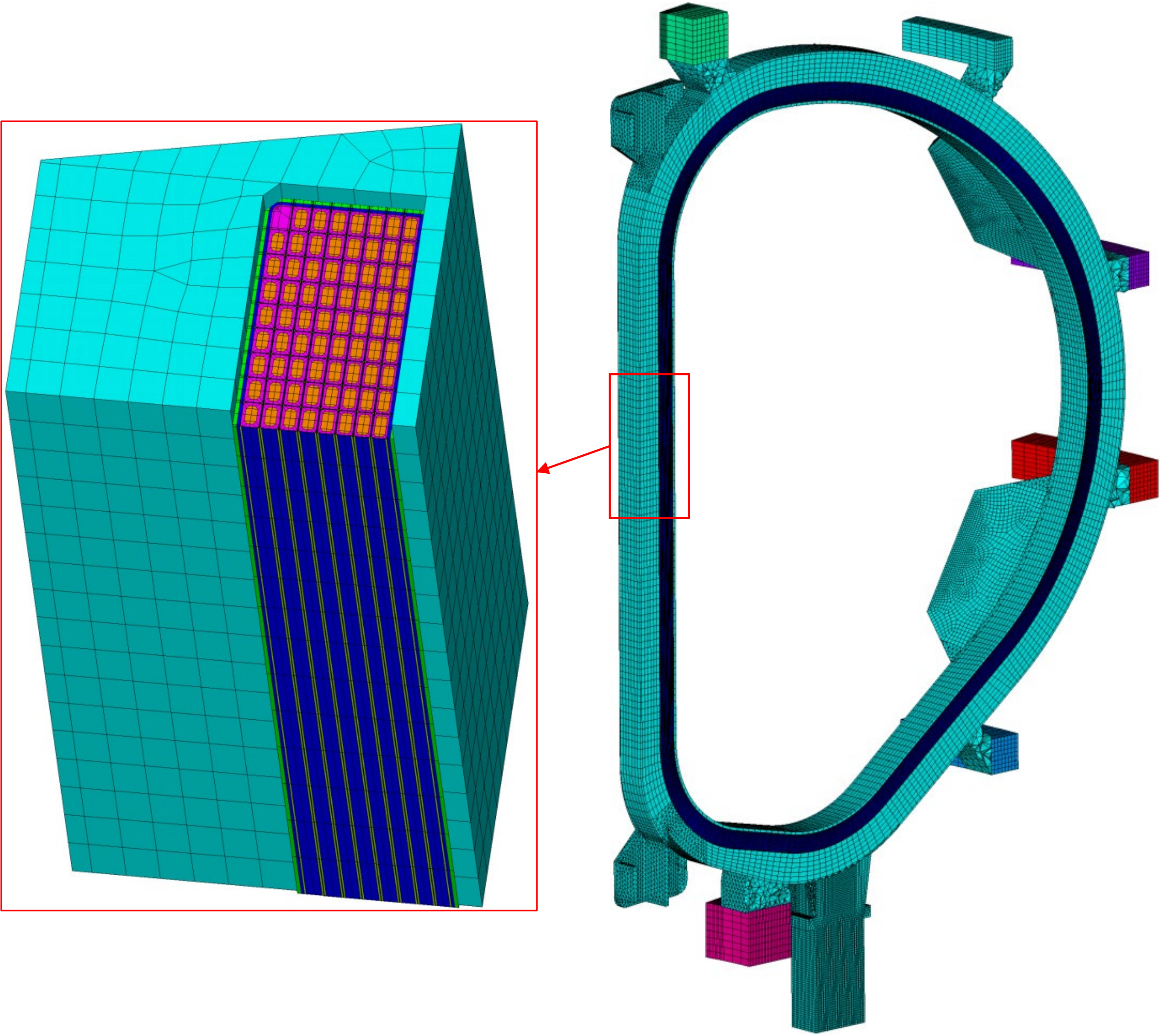

| | Nominal Current Baseline 2018 [4] | High Current Design |
|---|---|---|
| Operating current | 66 kA | **104.95 kA** |
| Layers/turns per layer | 12/19 | **8/18** |
| Total n. of turns | 226 | **142** |
| WP radial built with insertion gaps and ground insulation | 820 mm | **411 mm** |
| Toroidal width w/o insertion gaps and ground insulation | 1204 mm | **1260 mm** |
| Case lid at plasma side | 60 mm | **60 mm** |
| Case nose thickness | 520 mm | **563 mm** |
| Jacket thicknesses | up to 13.4 mm | **5 − 8.5 mm** |
| Total radial built | 1.4 m | **1.034 m**<br>**Δ = 366 mm** |
| Vacuum toroidal field at R | 5.26 T | **5.26 T** |

Courtesy of Kamil Sedlak ( SPC)



F. Damattè. TF WP design for the high current, nom. Field. MAG-S.01.01-T001-D001, EFDA_D_2P8XLN

# 3. 3D detailed model



Advantages of the global detailed model

- One model for the strength analysis of the casing and the Winding pack
- No need for the homogenization analysis of the Winding pack
- No need for a separate 2D models or separate 3D sub-models

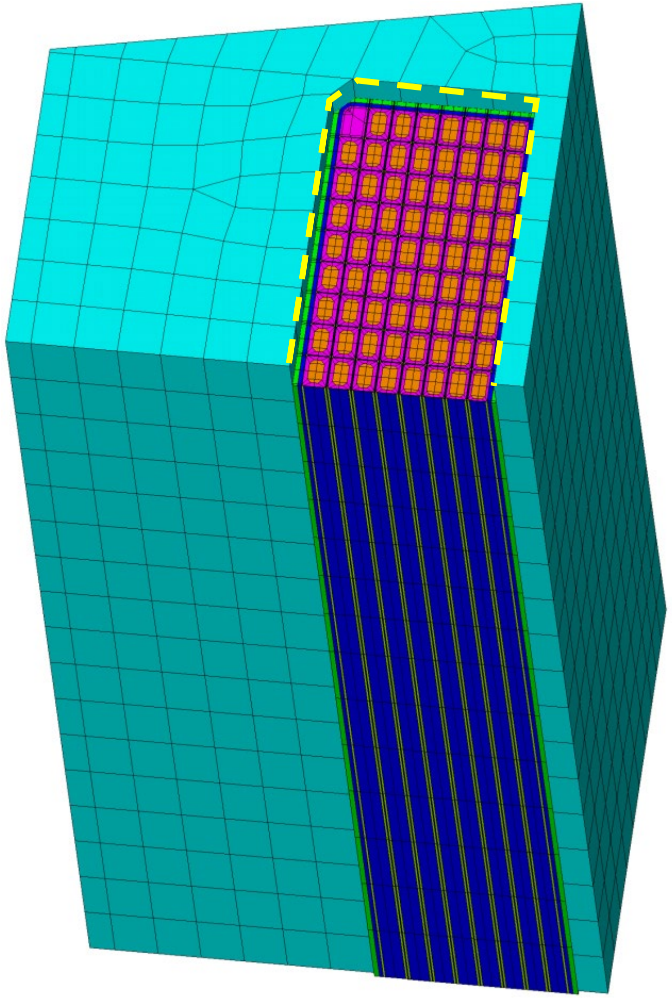
- The possibility of further developments, adding thermal simulations, cooling
- More realistic assumptions compared to 2D models

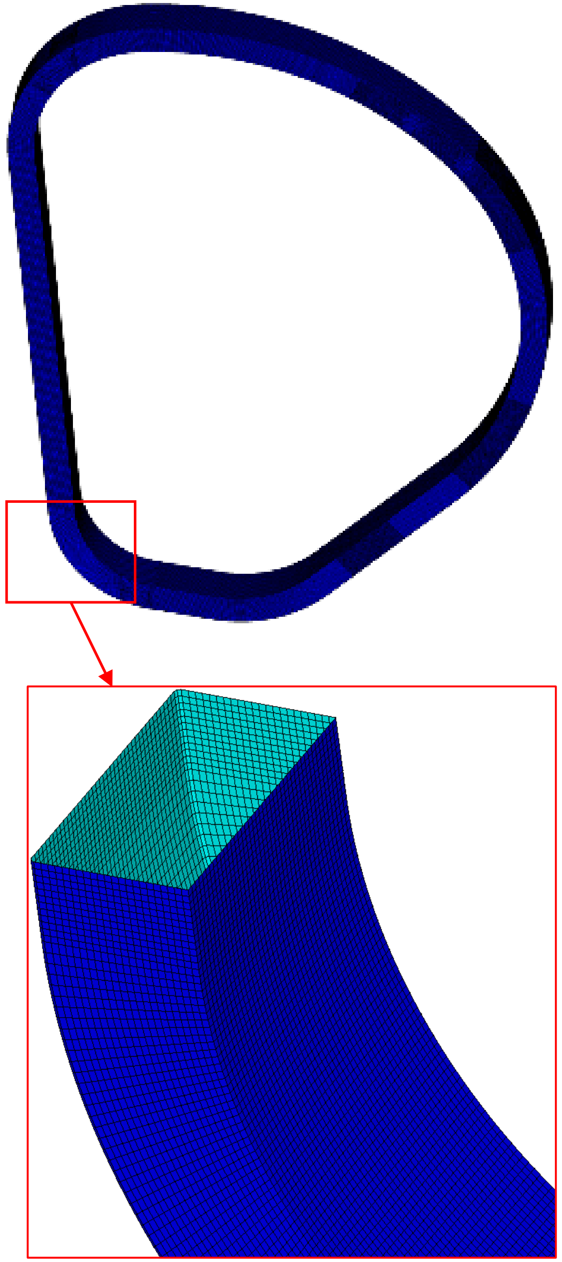
Drawbacks:

- Large computational cost?
- Much more difficult modeling

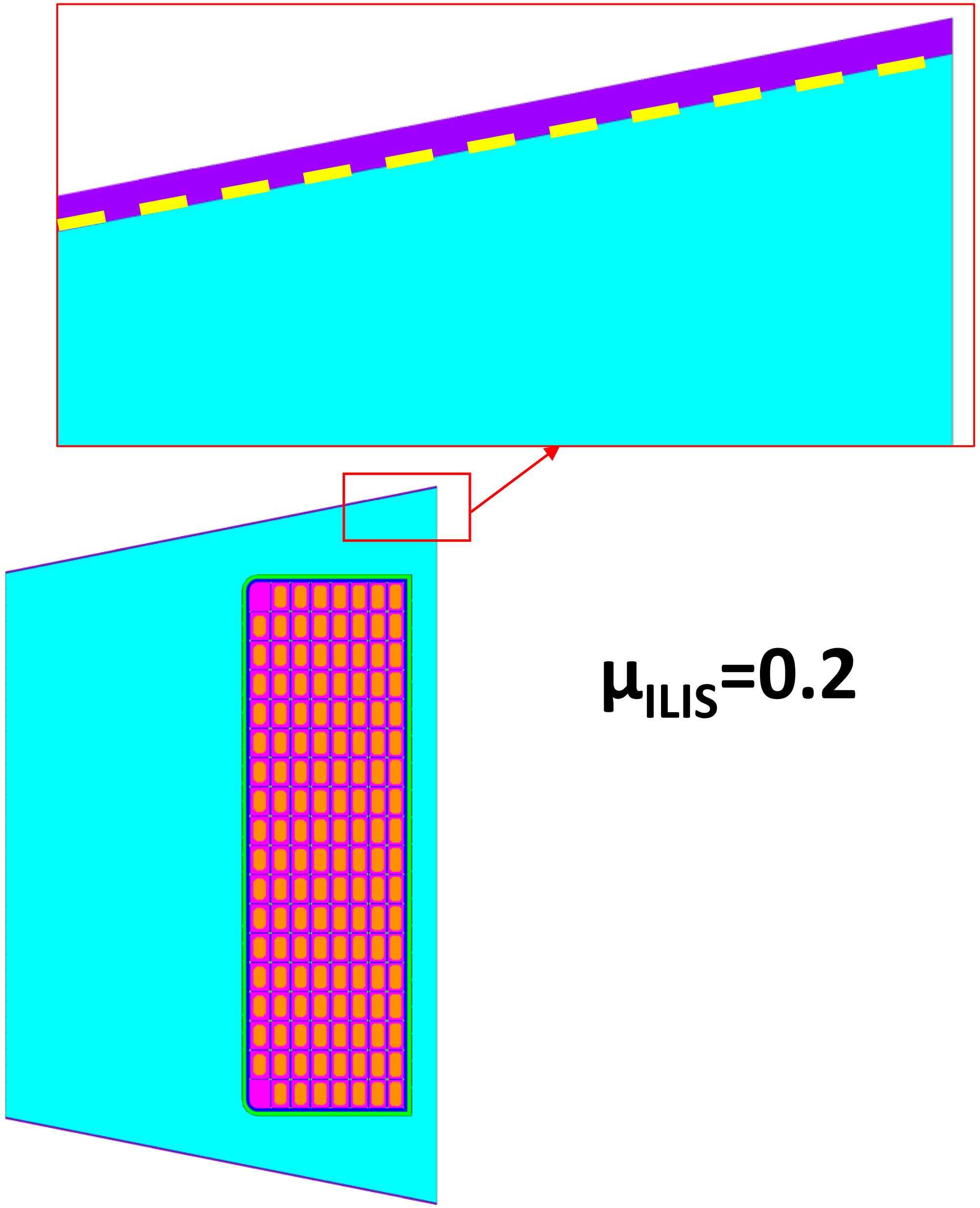
# 3. 3D detailed model

Contact between casing & the winding pack





Contact between casing and the intercoil structure (insulation)



$\mu_{ILIS}$=0.2

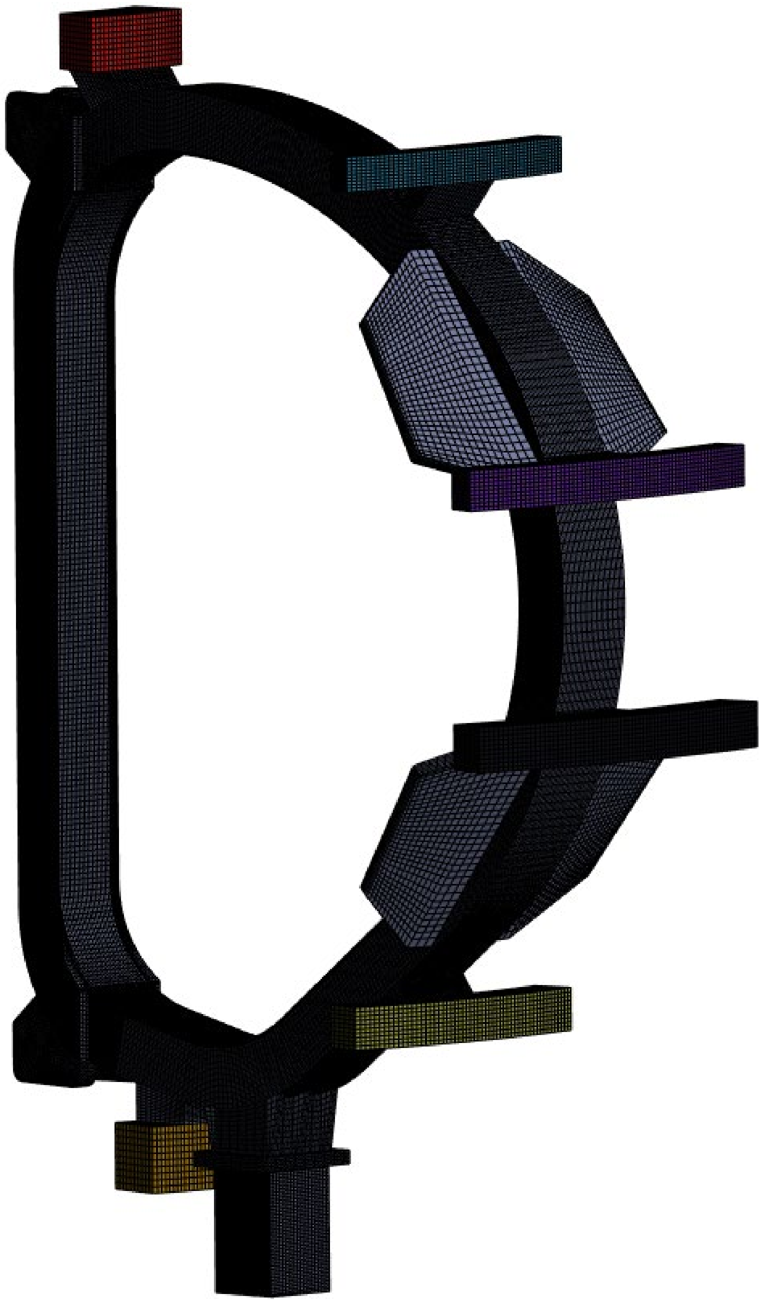
# 4. Modeling philosophy

APDL model

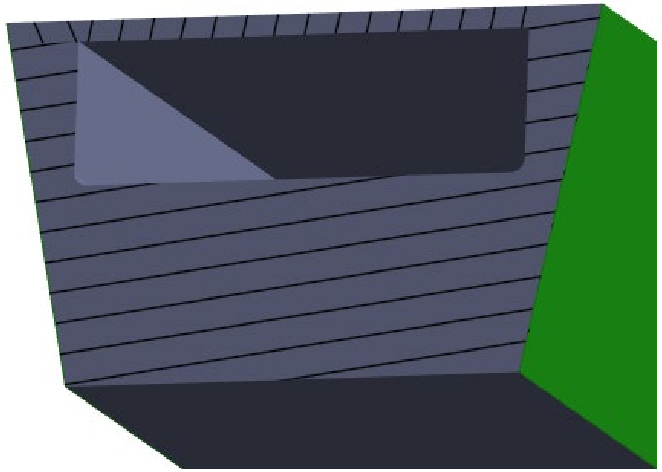
- CAD geometry meshed with GUI based „Meshing” tool
- Winding pack created via parametric APDL script
- Merging the two meshes via contact elements
- Solution
- Post-processing

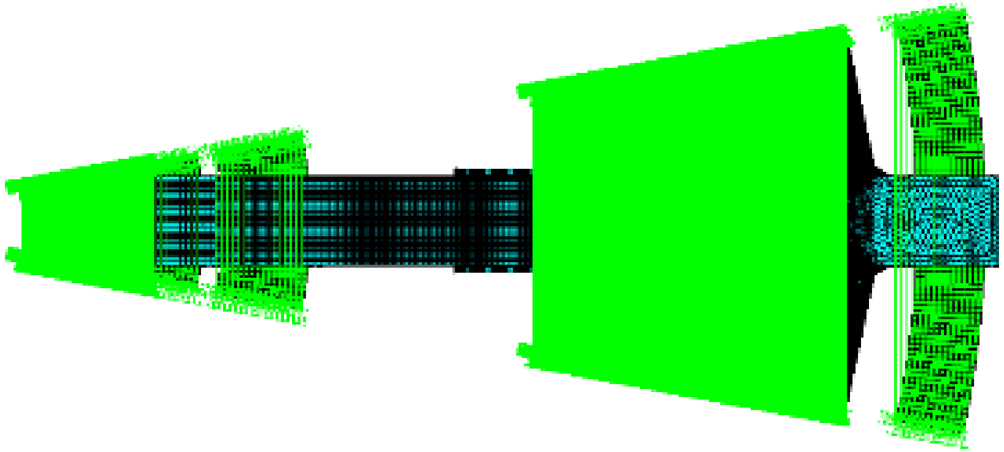
Top down approach

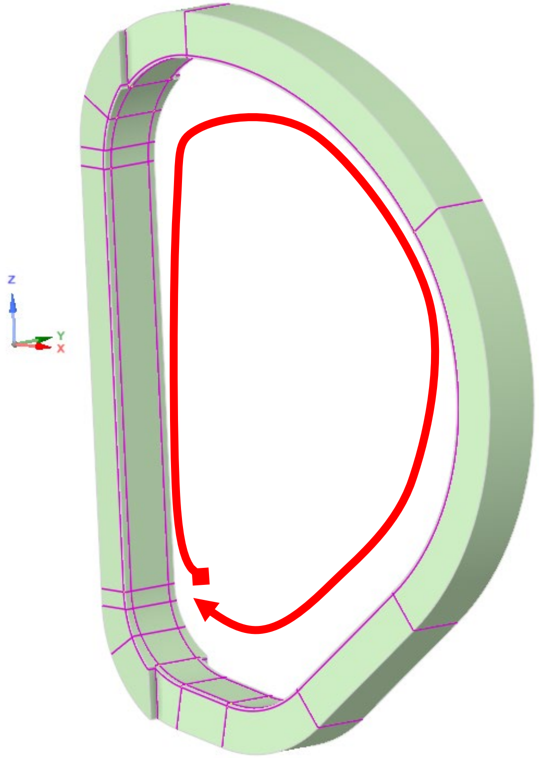
Bottom up approach

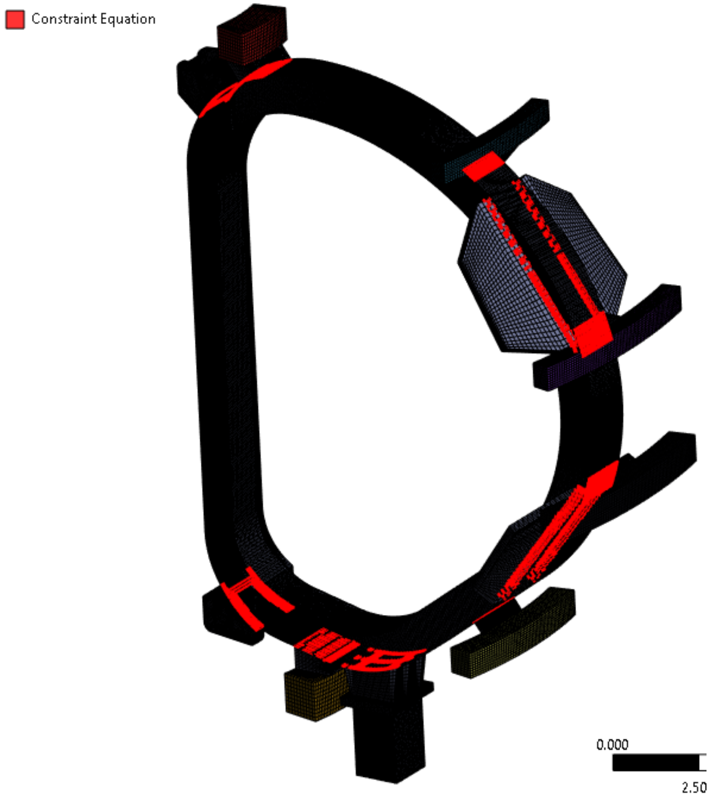


# 4. Modeling philosophy - casing





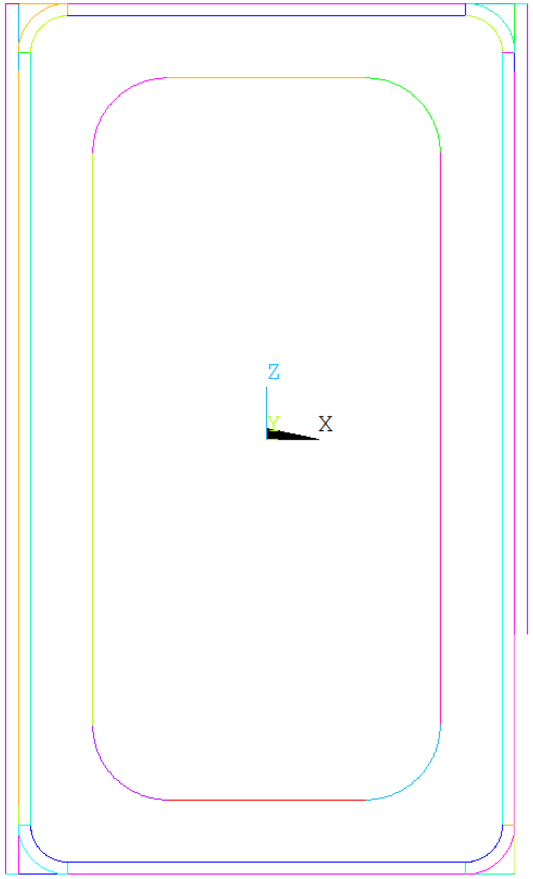


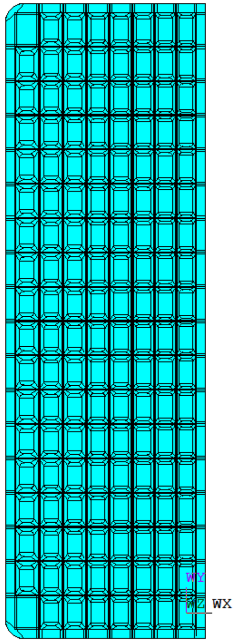


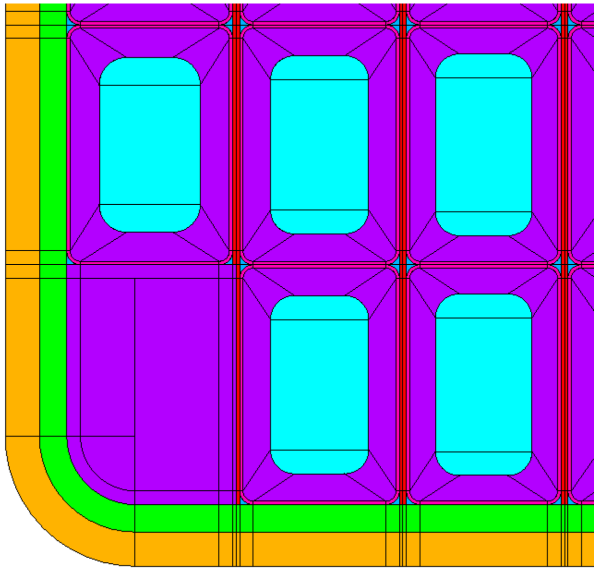

Sequence of steps:

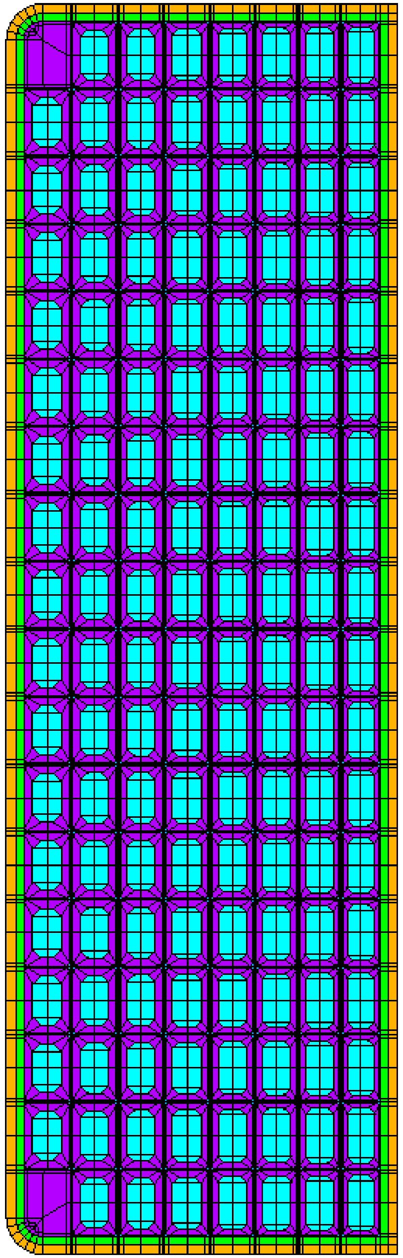
1. Geometry cutting into swappable shapes
2. Meshing the casing around the circumference, ensuring periodic meshing
3. Meshing PF coils, gravity support
4. Connecting the parts with MPC contact (constraint equations)
5. Applying periodic PBC & fixed support conditions.

# 4. Modeling philosophy - WP



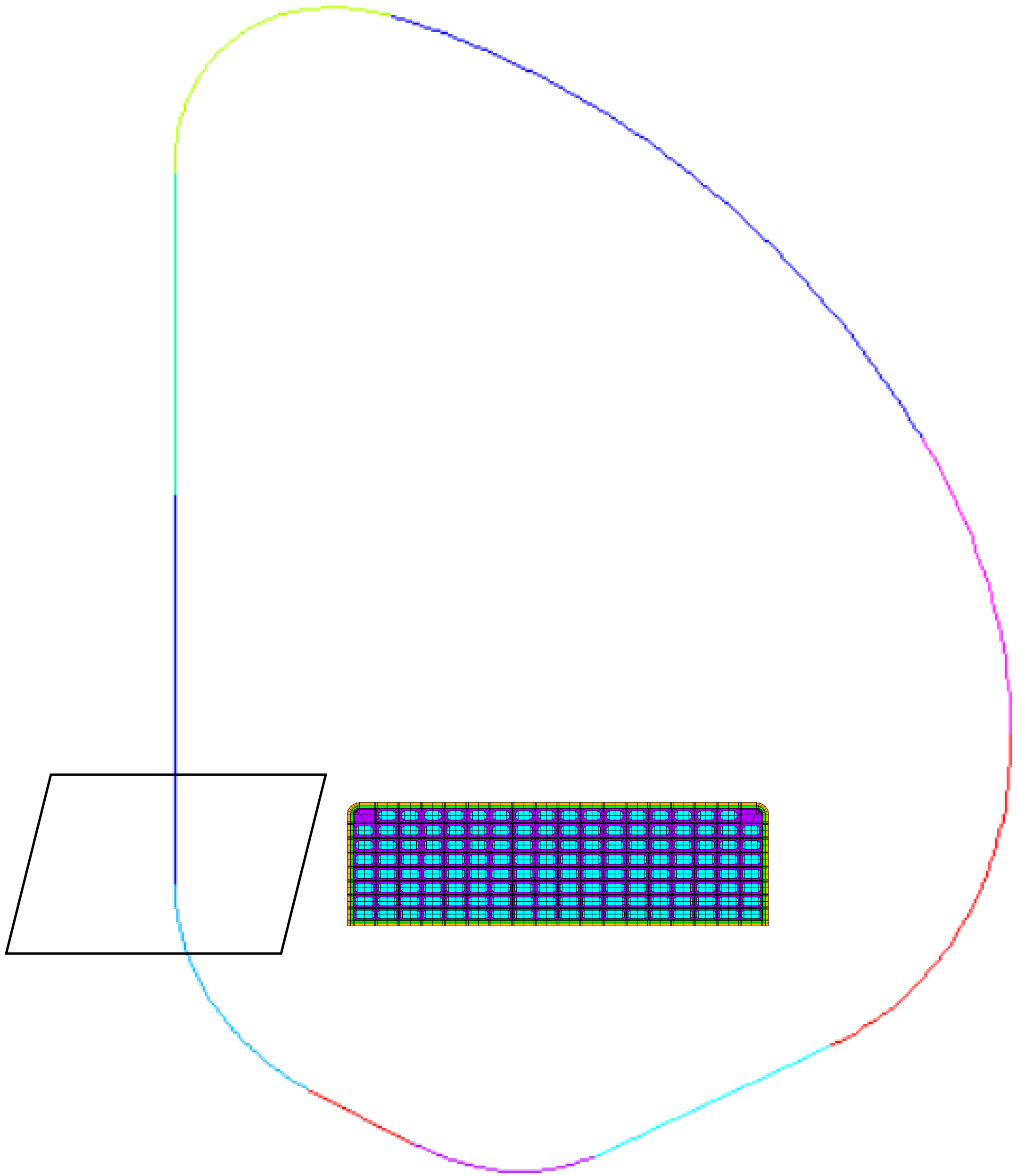





Sequence of steps:

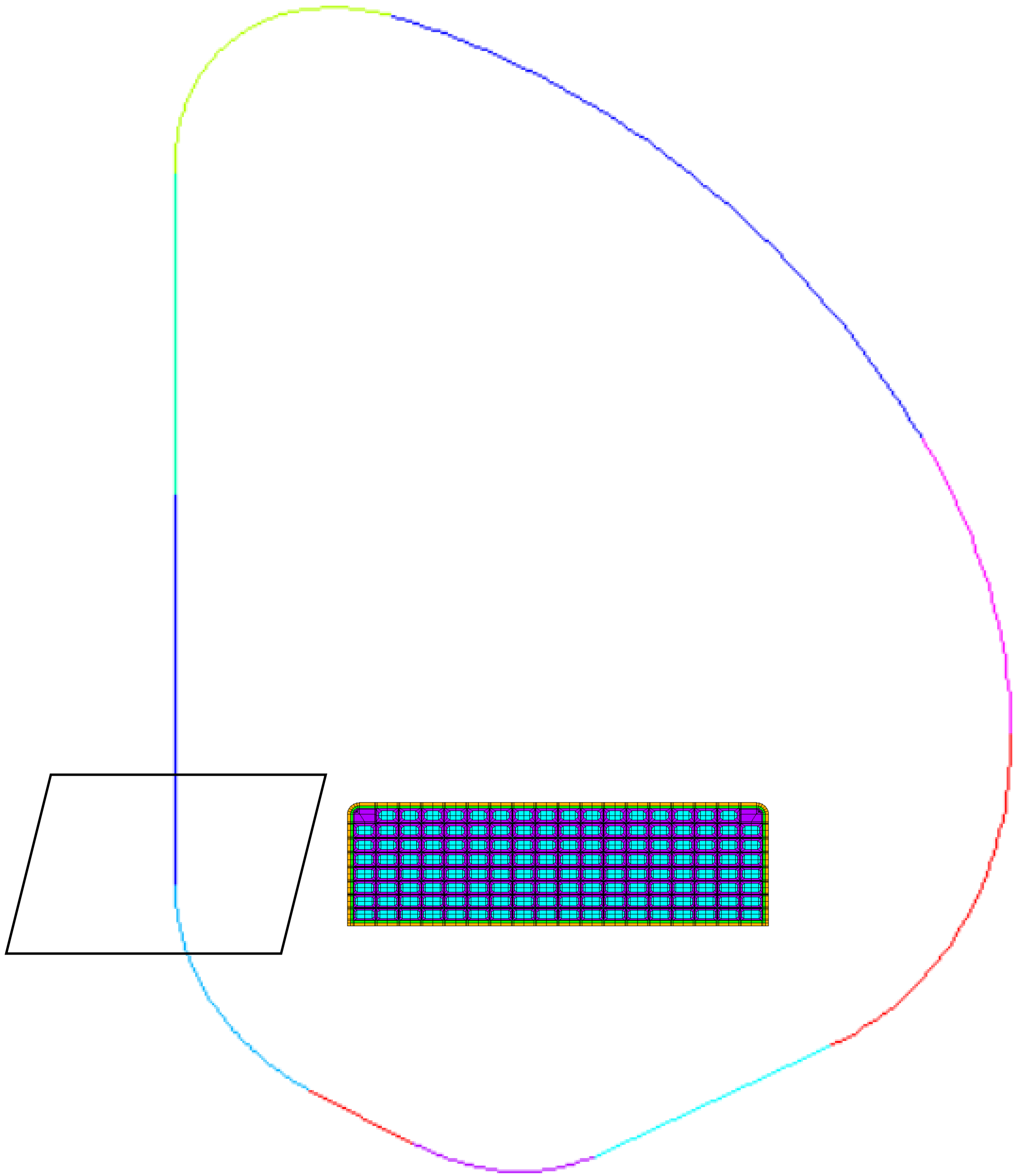
1. Parametrizing the basing cable cross-section, and meshing (line divisions)
2. Generating the other turns
3. Generating the layers
4. Filling the empty spaces
5. Generating the insulations around
6. Merging the duplicated nodes

# 4. Modeling philosophy - WP



1. Standard mesh extrusion works, but it is very slow in Ansys APDL (hours)
2. To speed up the algorithm, using low-level functions **NGEN & EGEN**, to created directly nodes and elements in the Cartesian and cylindrical CS along the centerline

# 4. Modeling philosophy - WP



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2. To speed up the algorithm, using low-level functions **NGEN & EGEN**, to created directly nodes and elements in the Cartesian and cylindrical CS along the centerline

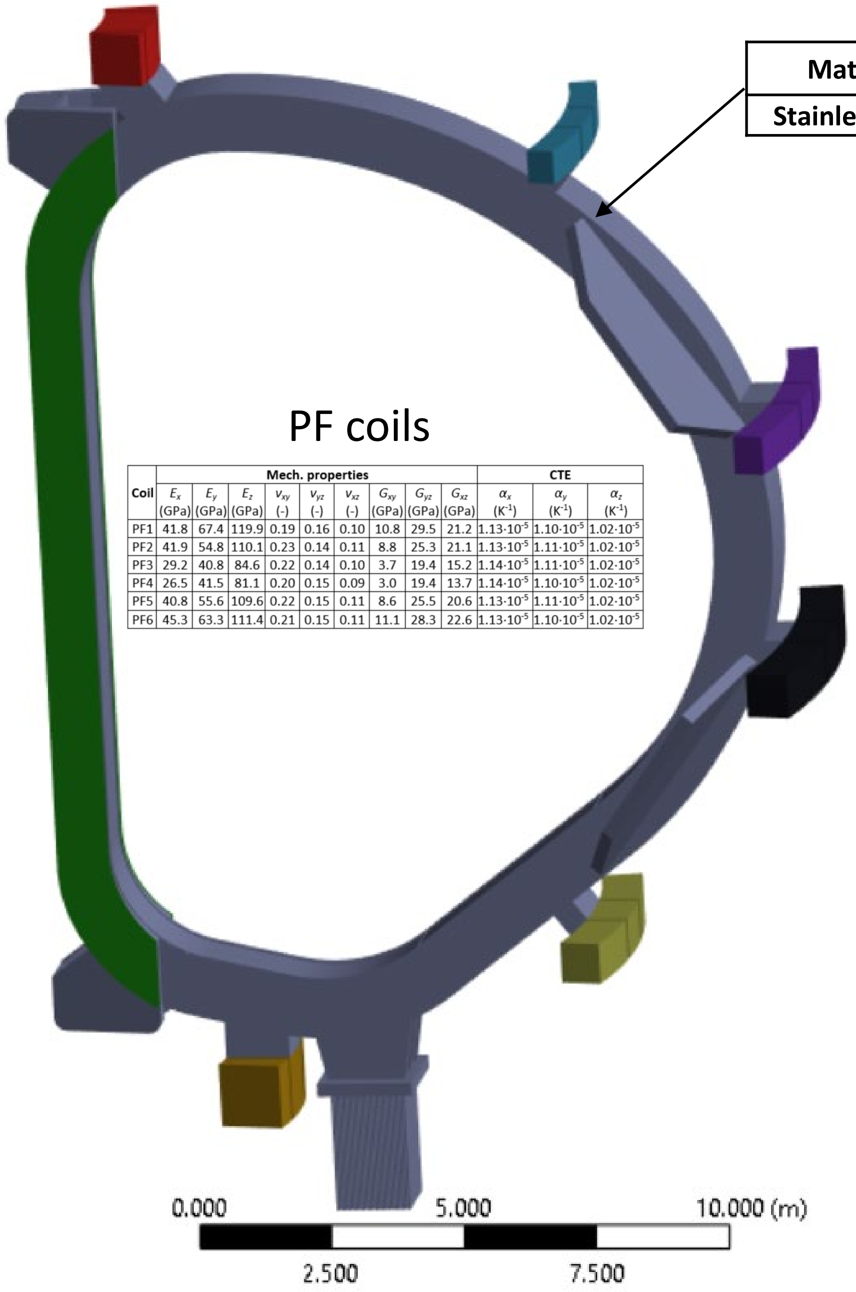
```
nsel,r,loc,z,ddz1 $ *get,nnode1,node,0,count
NGEN,    nn_d1,nnode1,all  ,     ,     ,   ,   , ddz1,
EGEN,    nn_d1,nnode1, all ,     ,     ,     ,     ,     ,     ,    ,   ,
cm,EGEN_V1,elem $ esel,r,mat,,11 $ cm,Strand_V1,elem $ cmsel,s,EGEN_V1

nsel,r,loc,z,LL1-1e-4,LL1+1e-4 $ *get,nnode1b,node,0,count
esel,r,cent,z,LL1-ddz1,LL1
NGEN,    nn_d1+1,nnode1b,all  ,     ,     ,   ,   , ddz1b,
EGEN,    nn_d1+1,nnode1b, all ,     ,     ,     ,     ,     ,     ,    ,   ,
cm,EGEN_V1b,elem $ esel,r,mat,,11 $ cm,Strand_V1b,elem $ cmsel,s,EGEN_V1b
```

# 4. Modeling philosophy - material properties

| Material | Mat | Stiffness | | $\alpha_{293\text{-}4K}$ [1/K] |
|---|---|---|---|---|
| **Stainless steel** | 1 | $E_{4K}$=205 GPa, $\nu_{4K}$=0.29 | $E_{293K}$=196 GPa, $\nu_{293K}$=0.29 | $10.4 \cdot 10^{-6}$ |

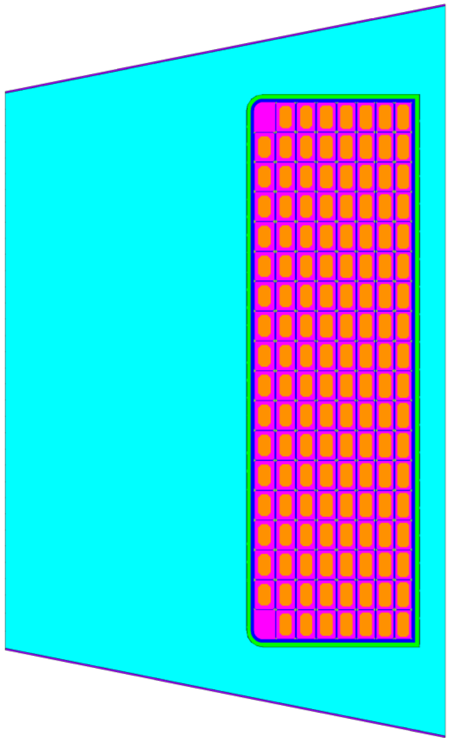
| Material | Mat | Stiffness | $\alpha_{293\text{-}4K}$ [1/K] |
|---|---|---|---|
| **Cable** | 2 | E=0.1 GPa, $\nu$=0.3 | $10.4 \cdot 10^{-6}$ |

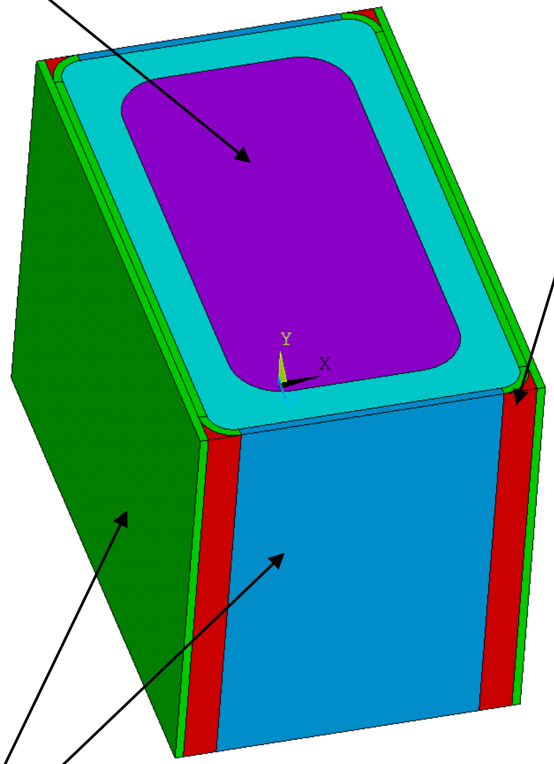
| Mate2rial | Mat | Stiffness | $\alpha_{293\text{-}4K}$ [1/K] |
|---|---|---|---|
| **Epoxy resin** | 3 | E=7 GPa, $\nu$=0.3 | $17.3 \cdot 10^{-6}$ |




PF coils

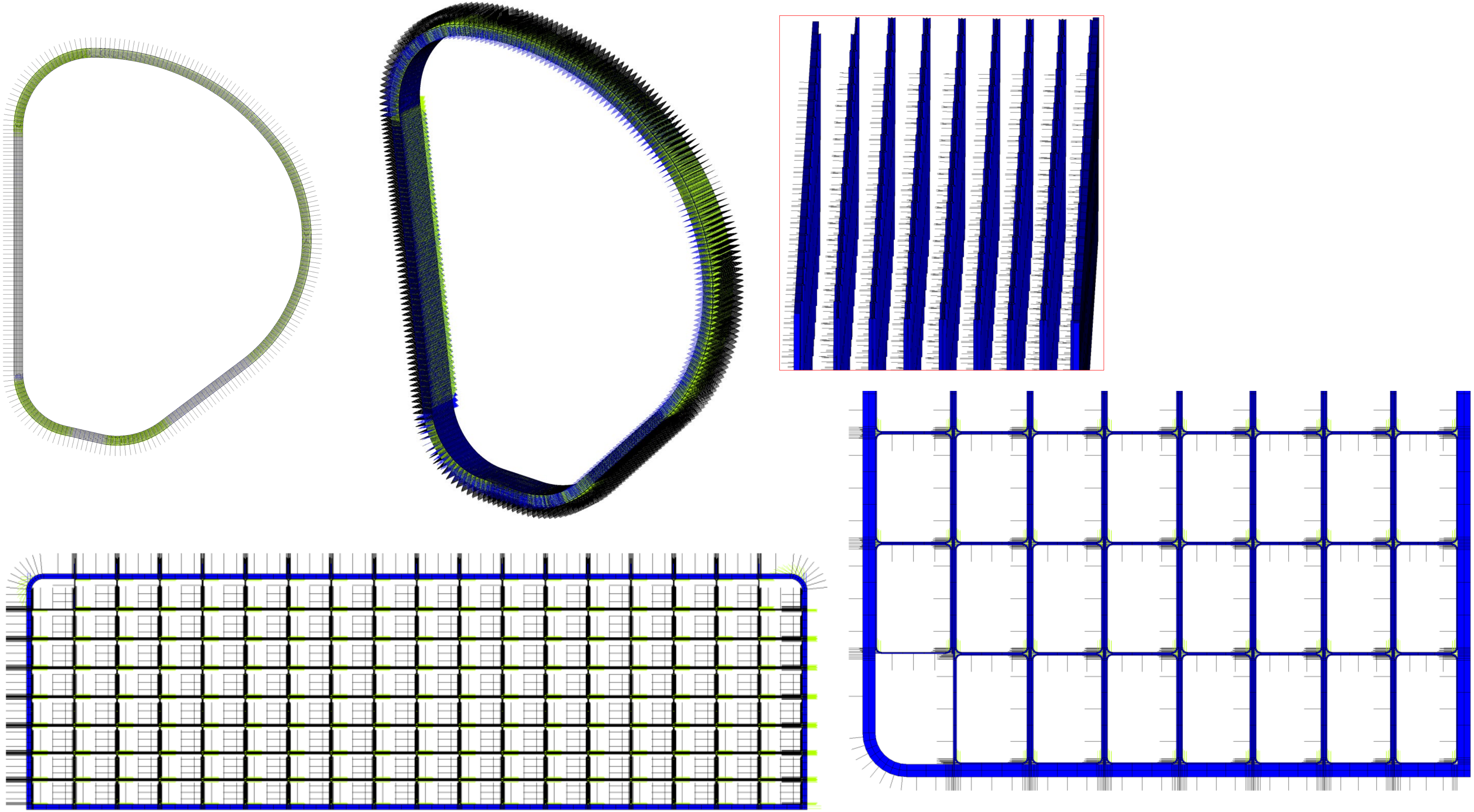
| Coil | Mech. properties | | | | | | | | | CTE | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $E_x$ (GPa) | $E_y$ (GPa) | $E_z$ (GPa) | $\nu_{xy}$ (-) | $\nu_{yz}$ (-) | $\nu_{xz}$ (-) | $G_{xy}$ (GPa) | $G_{yz}$ (GPa) | $G_{xz}$ (GPa) | $\alpha_x$ ($K^{-1}$) | $\alpha_y$ ($K^{-1}$) | $\alpha_z$ ($K^{-1}$) |
| PF1 | 41.8 | 67.4 | 119.9 | 0.19 | 0.16 | 0.10 | 10.8 | 29.5 | 21.2 | $1.13 \cdot 10^{-5}$ | $1.10 \cdot 10^{-5}$ | $1.02 \cdot 10^{-5}$ |
| PF2 | 41.9 | 54.8 | 110.1 | 0.23 | 0.14 | 0.11 | 8.8 | 25.3 | 21.1 | $1.13 \cdot 10^{-5}$ | $1.11 \cdot 10^{-5}$ | $1.02 \cdot 10^{-5}$ |
| PF3 | 29.2 | 40.8 | 84.6 | 0.22 | 0.14 | 0.10 | 3.7 | 19.4 | 15.2 | $1.14 \cdot 10^{-5}$ | $1.11 \cdot 10^{-5}$ | $1.02 \cdot 10^{-5}$ |
| PF4 | 26.5 | 41.5 | 81.1 | 0.20 | 0.15 | 0.09 | 3.0 | 19.4 | 13.7 | $1.14 \cdot 10^{-5}$ | $1.10 \cdot 10^{-5}$ | $1.02 \cdot 10^{-5}$ |
| PF5 | 40.8 | 55.6 | 109.6 | 0.22 | 0.15 | 0.11 | 8.6 | 25.5 | 20.6 | $1.13 \cdot 10^{-5}$ | $1.11 \cdot 10^{-5}$ | $1.02 \cdot 10^{-5}$ |
| PF6 | 45.3 | 63.3 | 111.4 | 0.21 | 0.15 | 0.11 | 11.1 | 28.3 | 22.6 | $1.13 \cdot 10^{-5}$ | $1.10 \cdot 10^{-5}$ | $1.02 \cdot 10^{-5}$ |






| Material | Mat | Stiffness | $\alpha_{293\text{-}4K}$ [1/K] |
|---|---|---|---|
| **VPI epoxy glass** | 5 | Ex=12 GPa, Ey=Ez=20 GPa, Gxy=Gyz=Gxz=6 GPa, $\nu_{xy}$=0.198, $\nu_{yz}$=0.17, $\nu_{xz}$=0.198 | $\alpha_X = 24.7 \cdot 10^{-6}$ $\alpha_Y = \alpha_Z = 6.9 \cdot 10^{-6}$ |

# 4. Modeling philosophy - material properties



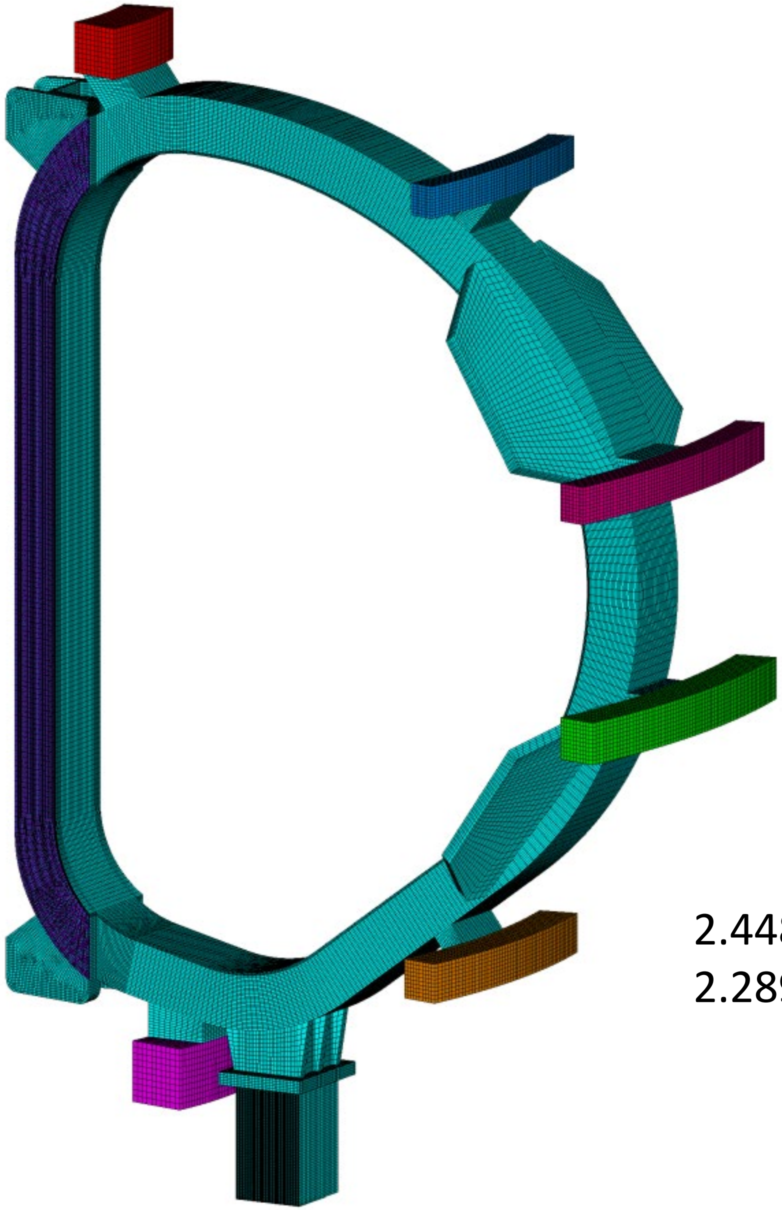
# 4. Modeling philosophy

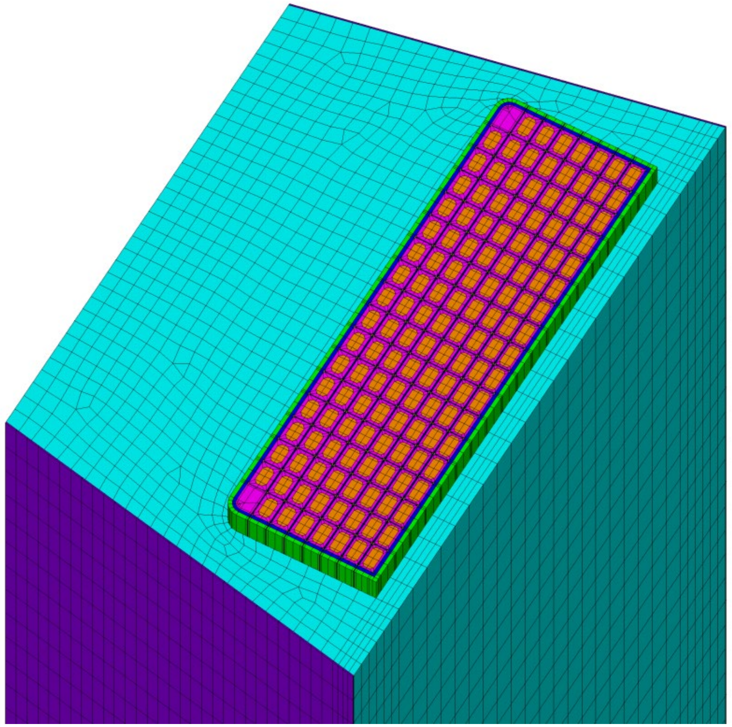
APDL model

- CAD geometry meshed with GUI based „Meshing” tool
- Winding pack created via parametric APDL script
- Merging the two meshes via contact elements
- Solution
- Post-processing

Top down approach

Parametric model

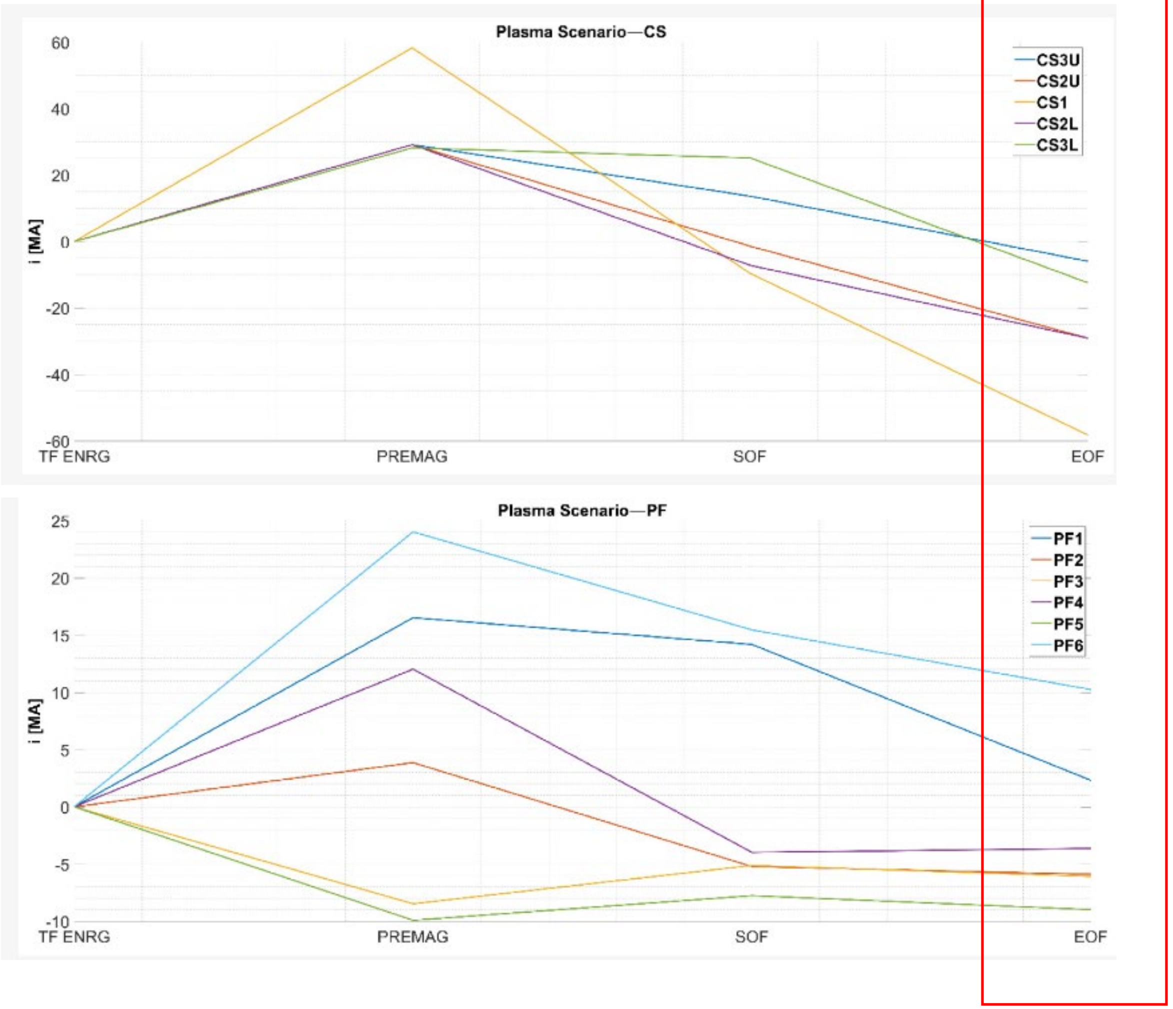




2.4486e6 elements
2.289353e6 nodes (6.8e6 DOF)

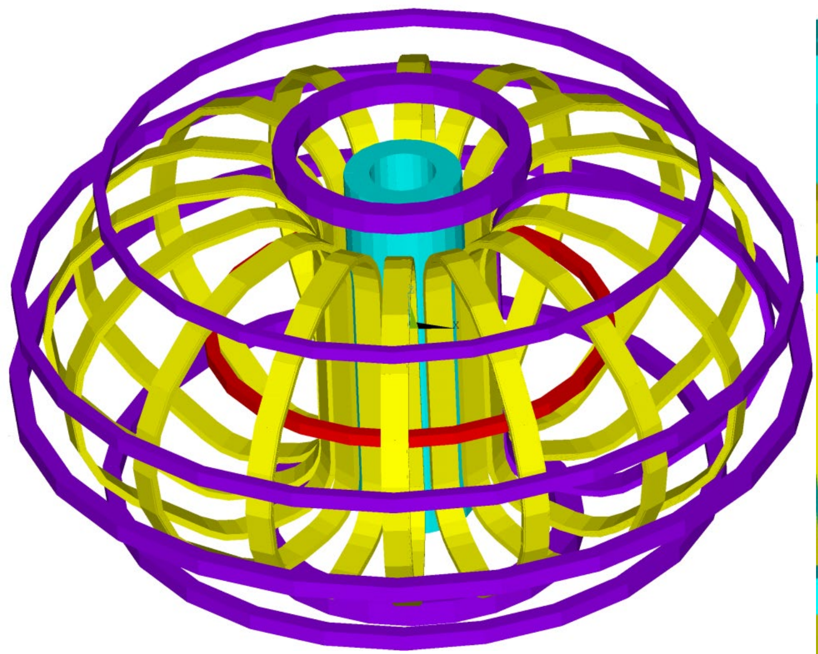
# 4. Modeling philosophy

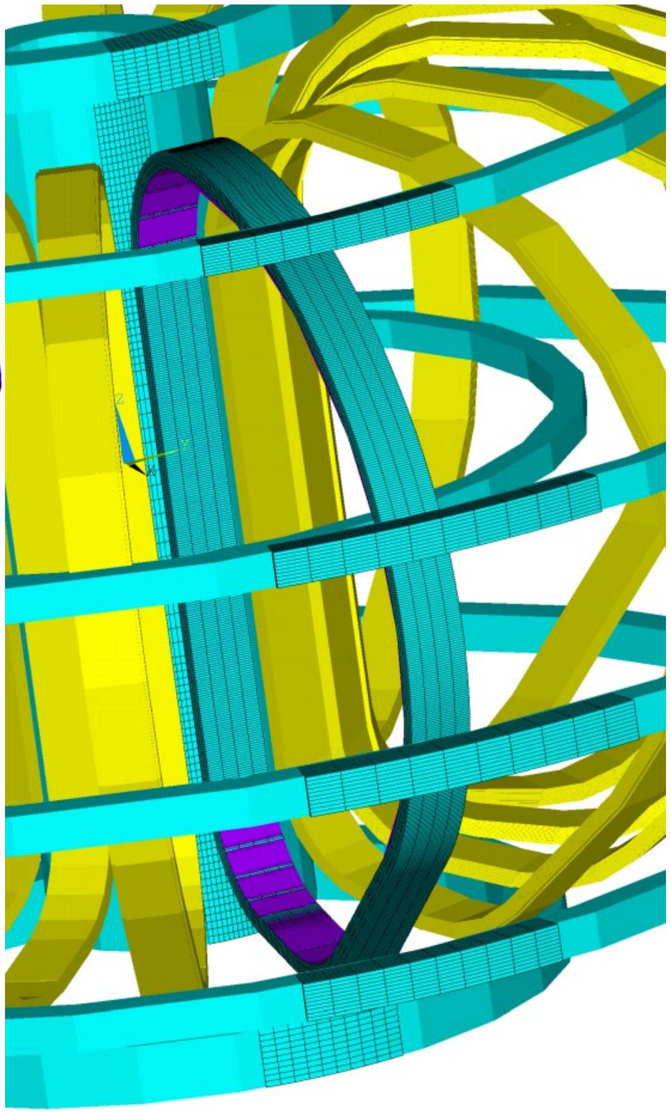
Load steps:
1) Cool-down to 4.2 K
2) Powering (EOF scenario – end of flat top)

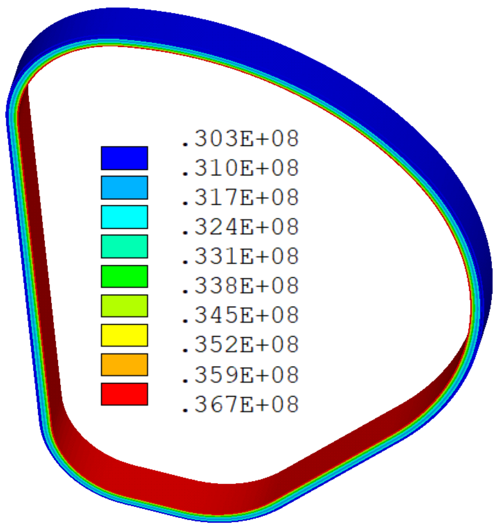


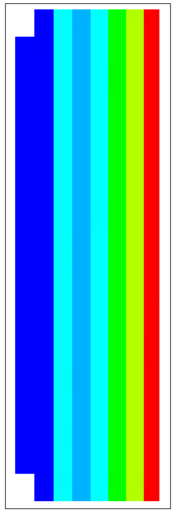

*L. Gianini, D.P. Boso, V. Corato. A Combined Electromagnetic and Mechanical Approach for EU-DEMO Toroidal Field Coils. Applied Sciences 2022: 12 6*

# 4. EOF Lorentz forces





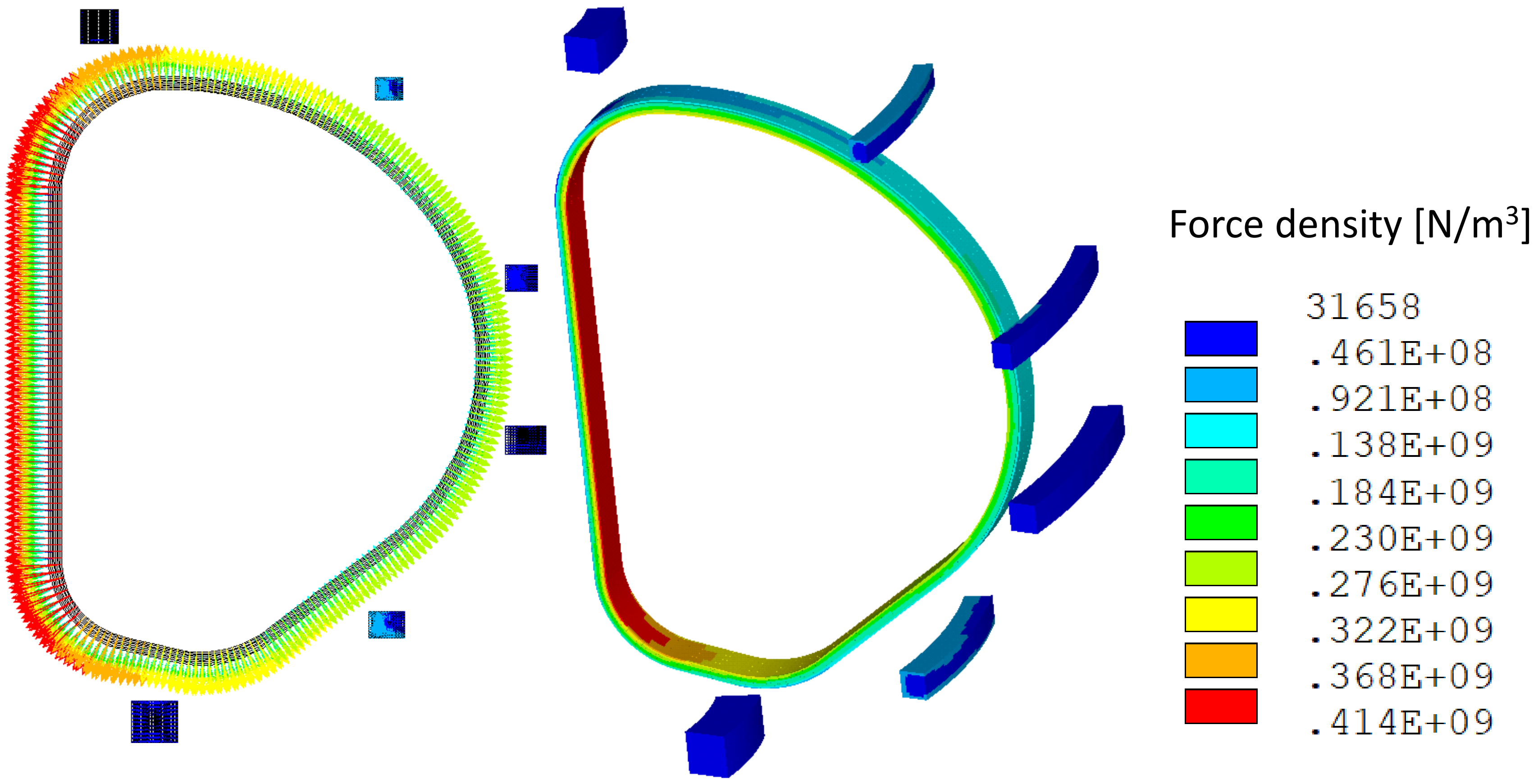


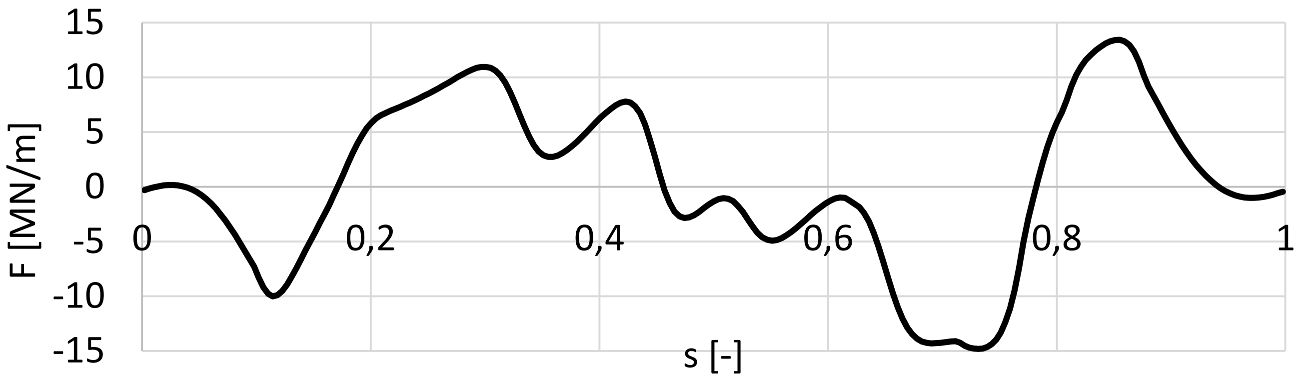



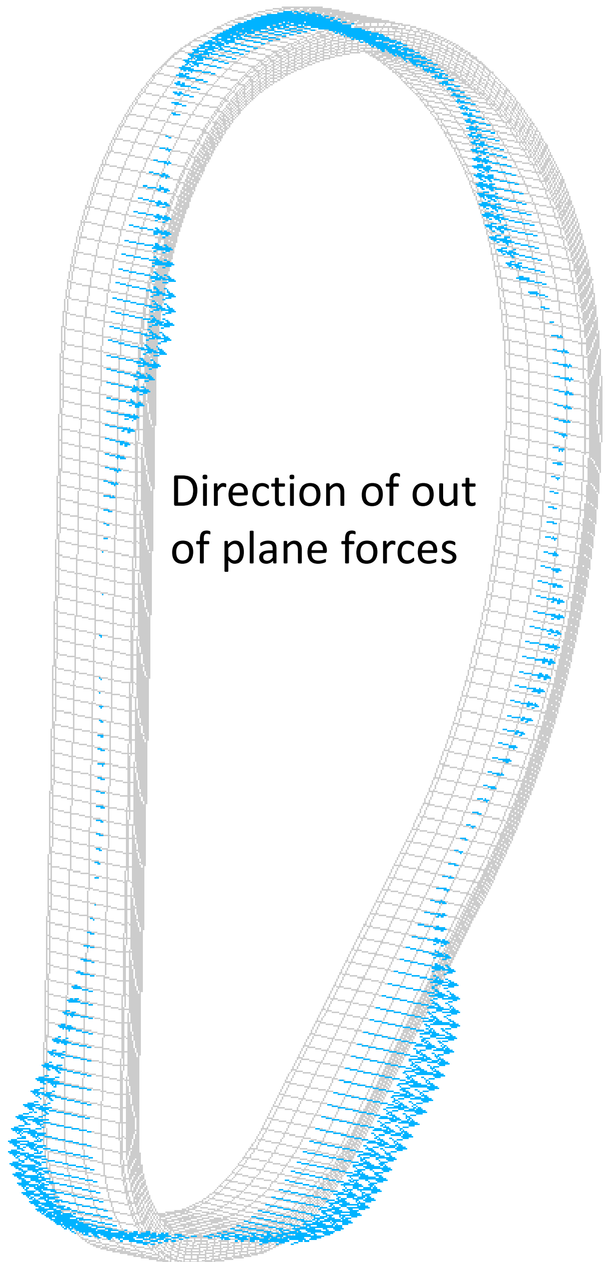
$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \iiint_V dV \frac{\mathbf{J} \times \hat{\mathbf{r}}'}{|\mathbf{r}'|^2}$$

| Coil | Cross-section | | | EOF | |
|---|---|---|---|---|---|
| | dim_r [m] | dim_z [m] | A [m$^2$] | j [A/mm$^2$] | I [MAt] |
| CS3U | 1.18 | 2.986 | 3.523480 | -1.6858 | -5.94 |
| CS2U | 1.18 | 2.986 | 3.523480 | -8.2617 | -29.11 |
| CS1 | 1.18 | 5.972 | 7.046960 | -8.2631 | -58.23 |
| CS2L | 1.18 | 2.986 | 3.523480 | -8.2617 | -29.11 |
| CS3L | 1.18 | 2.986 | 3.523480 | -3.5306 | -12.44 |
| PF1 | 1.002 | 1.002 | 1.004004 | 2.3107 | 2.32 |
| PF2 | 0.523 | 0.63 | 0.329490 | -17.8761 | -5.89 |
| PF3 | 0.579 | 0.74 | 0.428460 | -14.1904 | -6.08 |
| PF4 | 0.82 | 0.821 | 0.673220 | -5.4069 | -3.64 |
| PF5 | 0.77 | 0.771 | 0.593670 | -15.1262 | -8.98 |
| PF6 | 1.205 | 1.205 | 1.452025 | 7.0591 | 10.25 |
| Plasma | 0.6 | 0.6 | 0.360000 | 49.6111 | 17.86 |
| TF_L1 | 0.0409 | 1.26 | 0.051534 | 36.6574 | 1.8891 |
| TF_L2 | 0.044 | 1.26 | 0.055440 | 34.0747 | 1.8891 |
| TF_L3 | 0.045 | 1.26 | 0.056700 | 33.3175 | 1.8891 |
| TF_L4 | 0.0466 | 1.26 | 0.058716 | 32.1735 | 1.8891 |
| TF_L5 | 0.0476 | 1.26 | 0.059976 | 31.4976 | 1.8891 |
| TF_L6 | 0.0472 | 1.26 | 0.059472 | 31.7645 | 1.8891 |
| TF_L7 | 0.0487 | 1.26 | 0.061362 | 30.7862 | 1.8891 |
| TF_L8 | 0.0495 | 1.12 | 0.055440 | 30.2886 | 1.6792 |

# 4. EOF Lorentz forces

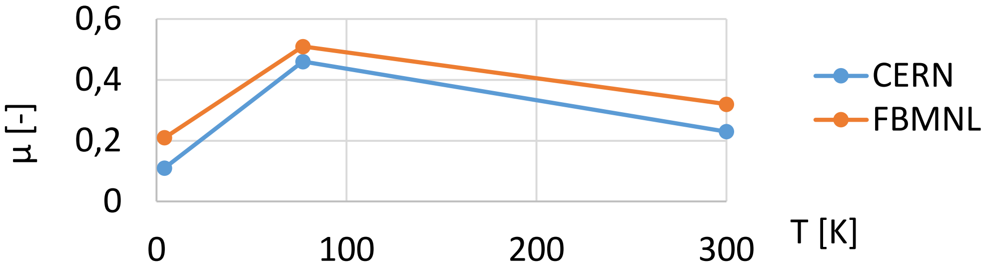


# 5. Friction coefficient WP-casing

K. Artoos et al. The measurement of the friction coefficient down to 1.8 K for LHC magnets. LHC note 303. CERN MT/94-06



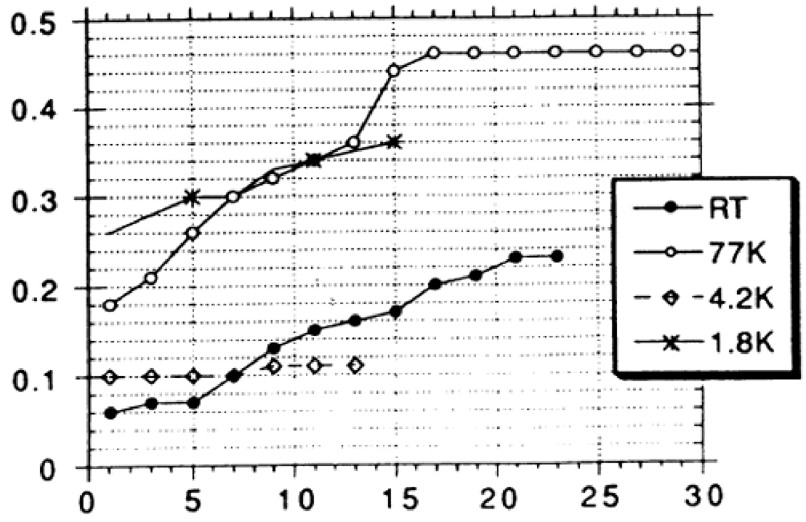
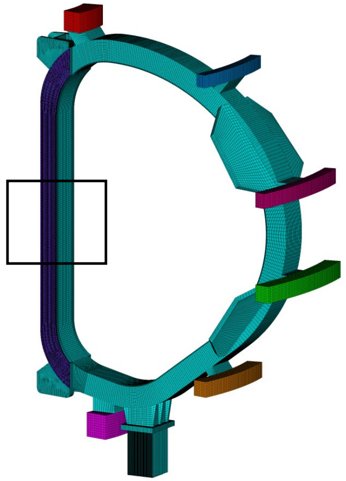
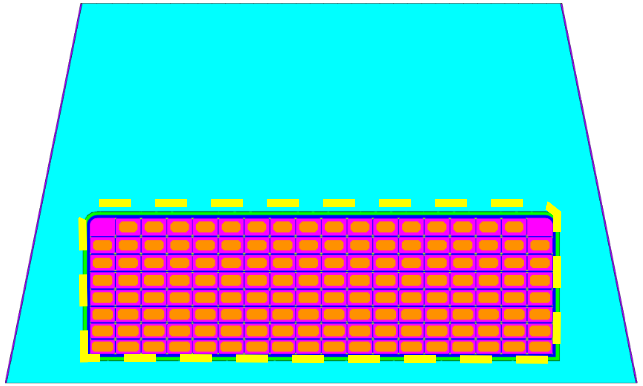
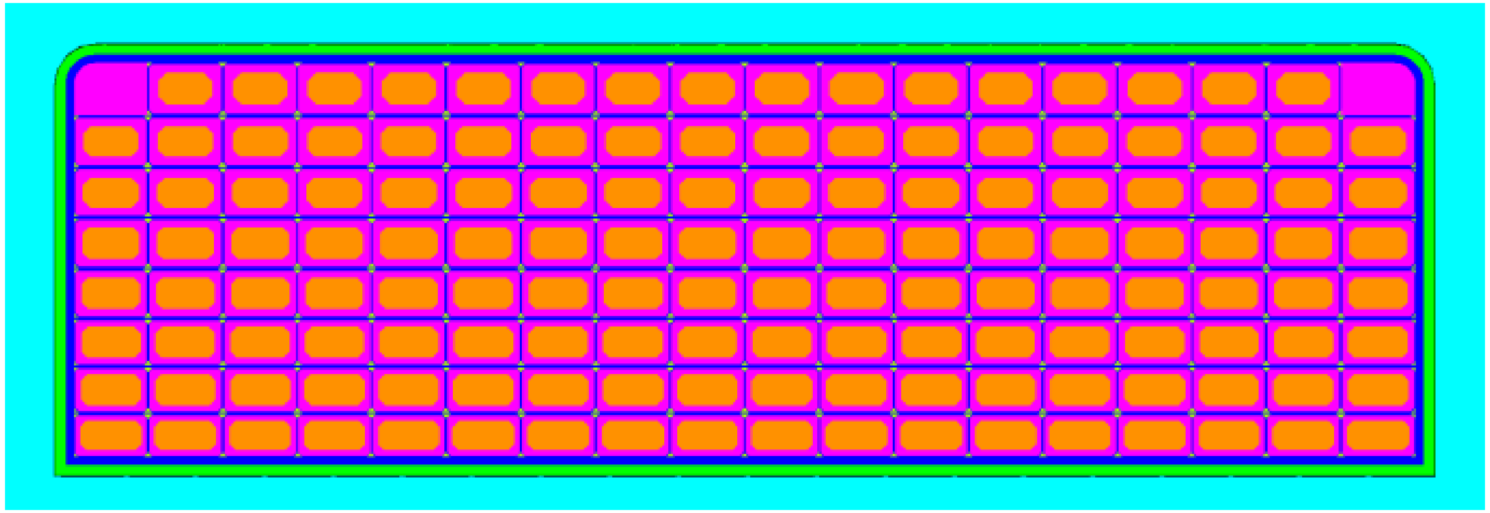




Figure 5 μ versus nb cycles- 304 L/vetronite G10

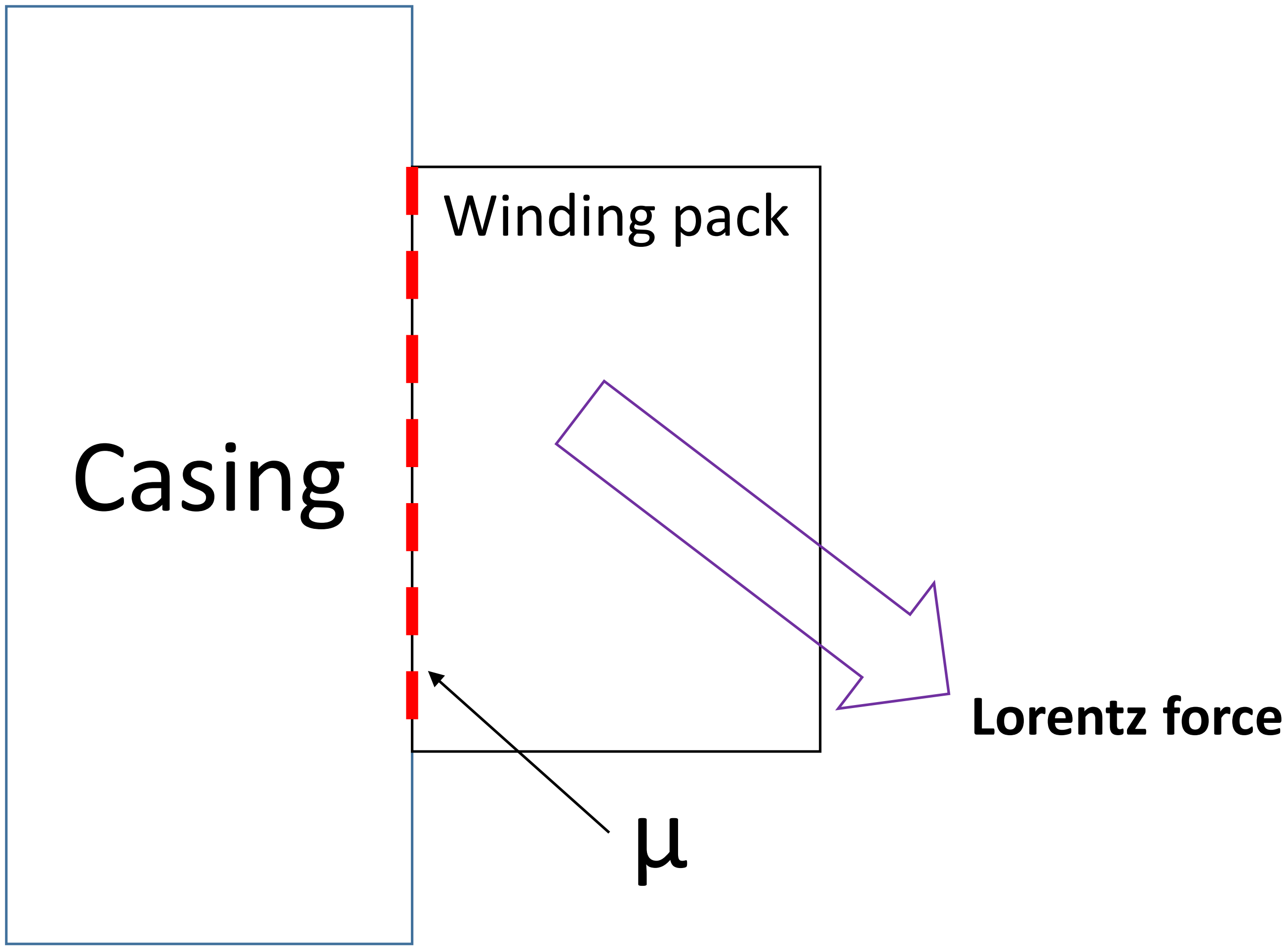


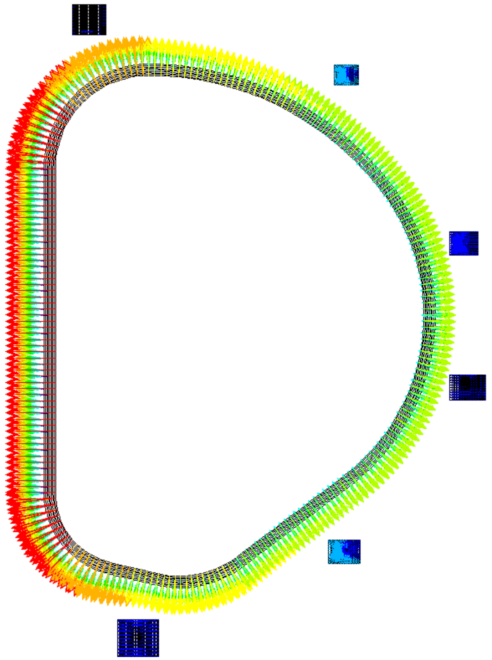


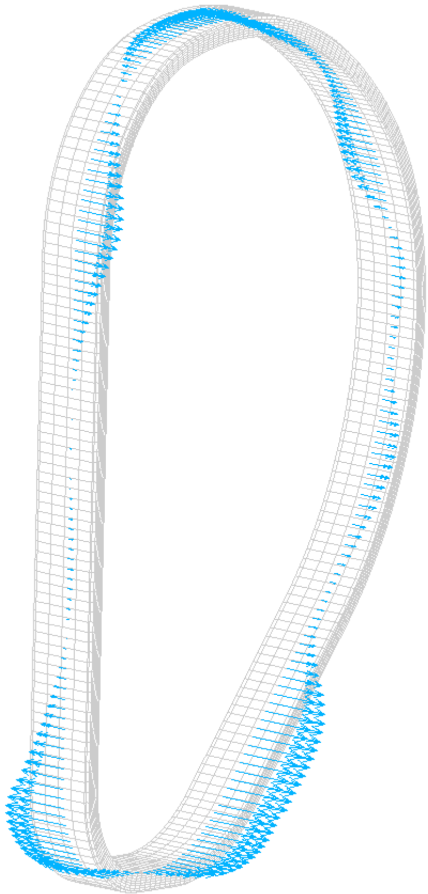


**Usually applied value is 0.2**

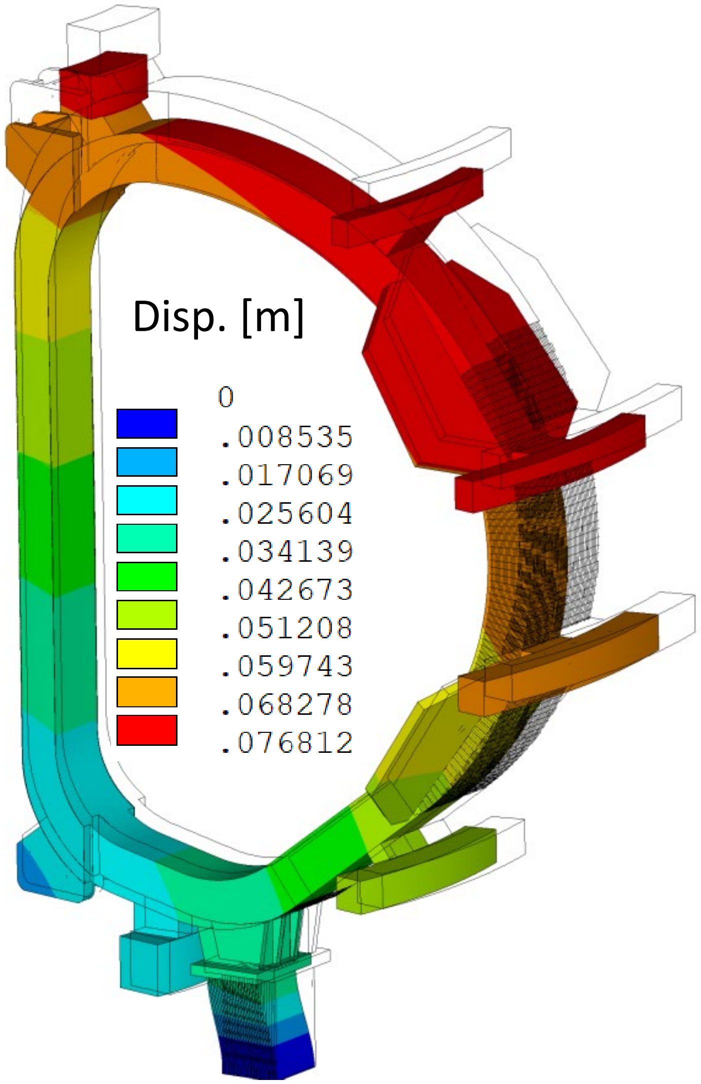
# 5. Friction coefficient WP-casing



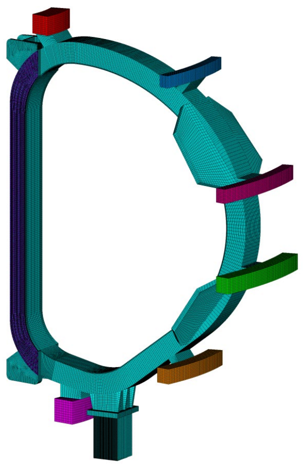



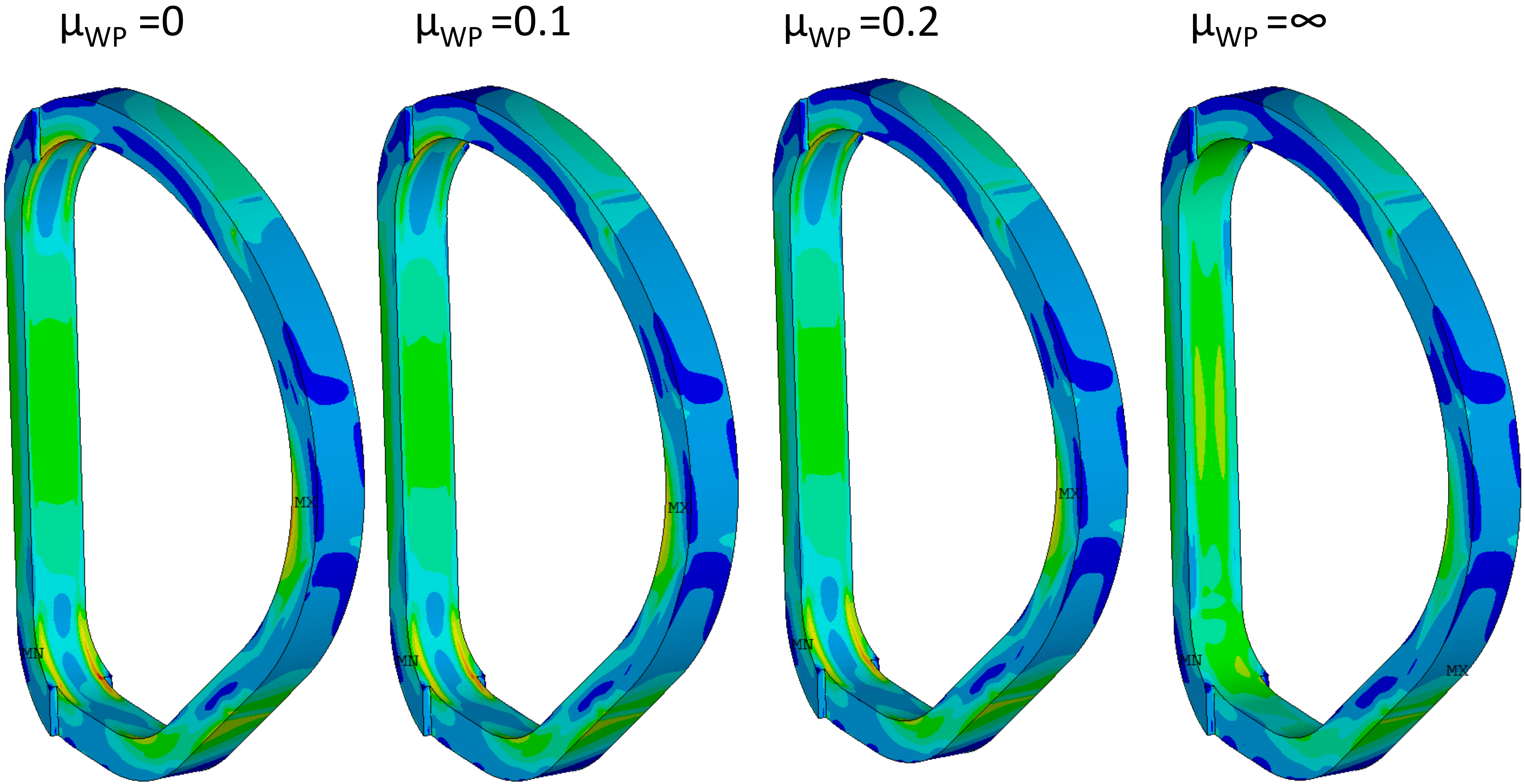


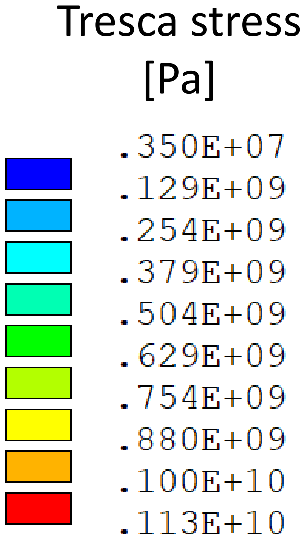
# 6. Results – cool-down



# 6. Results – powering - casing

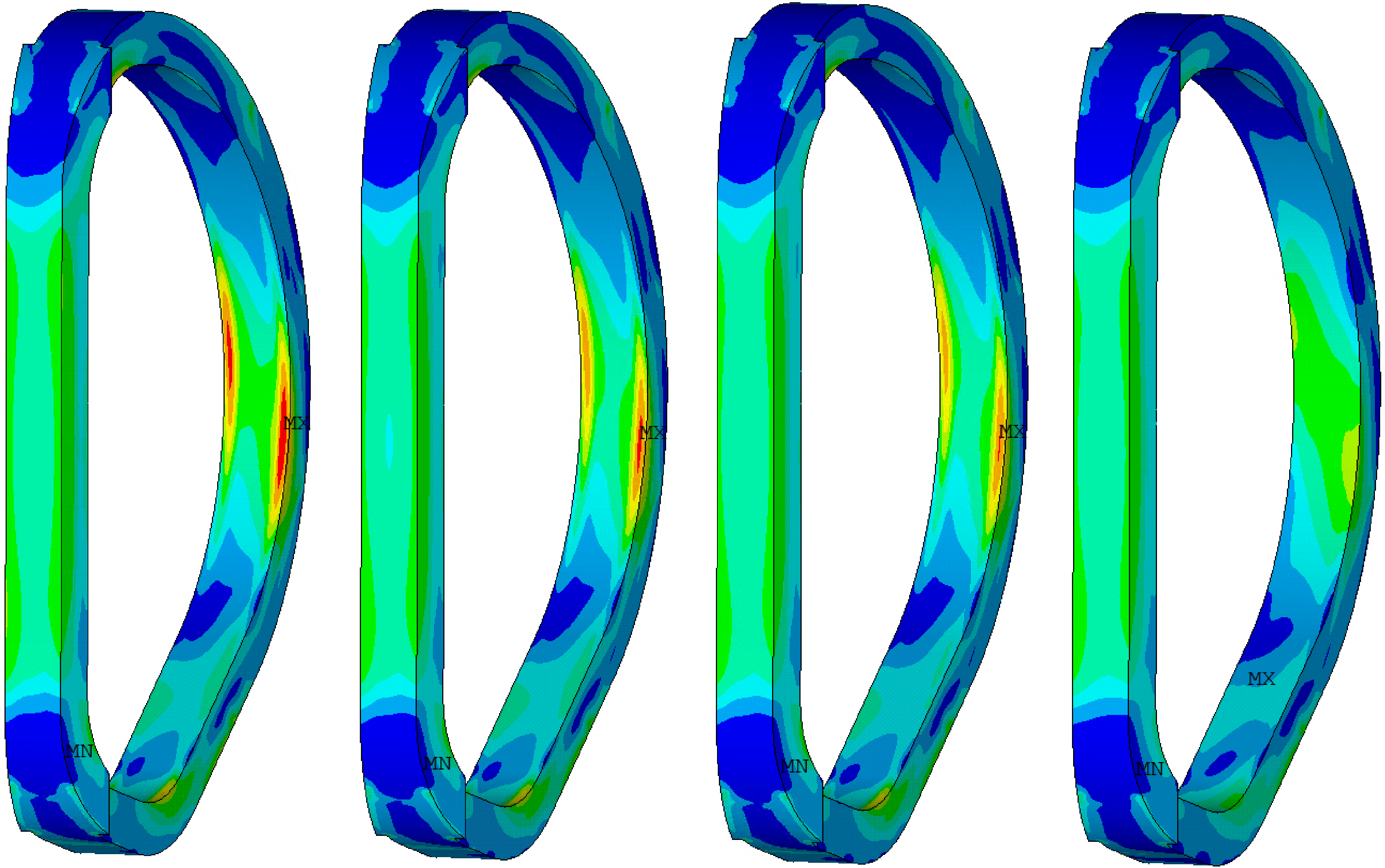


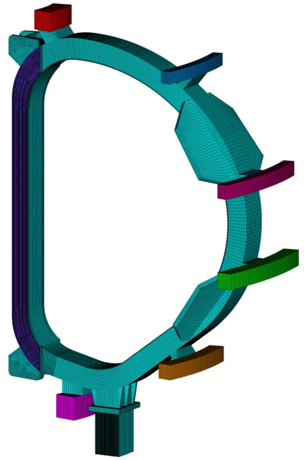


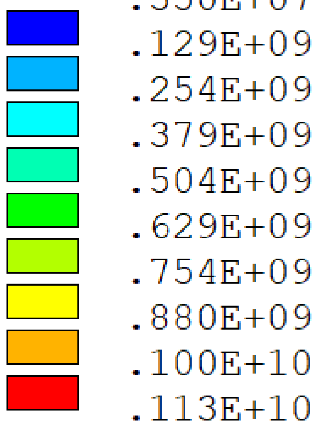



# 6. Results – powering - casing

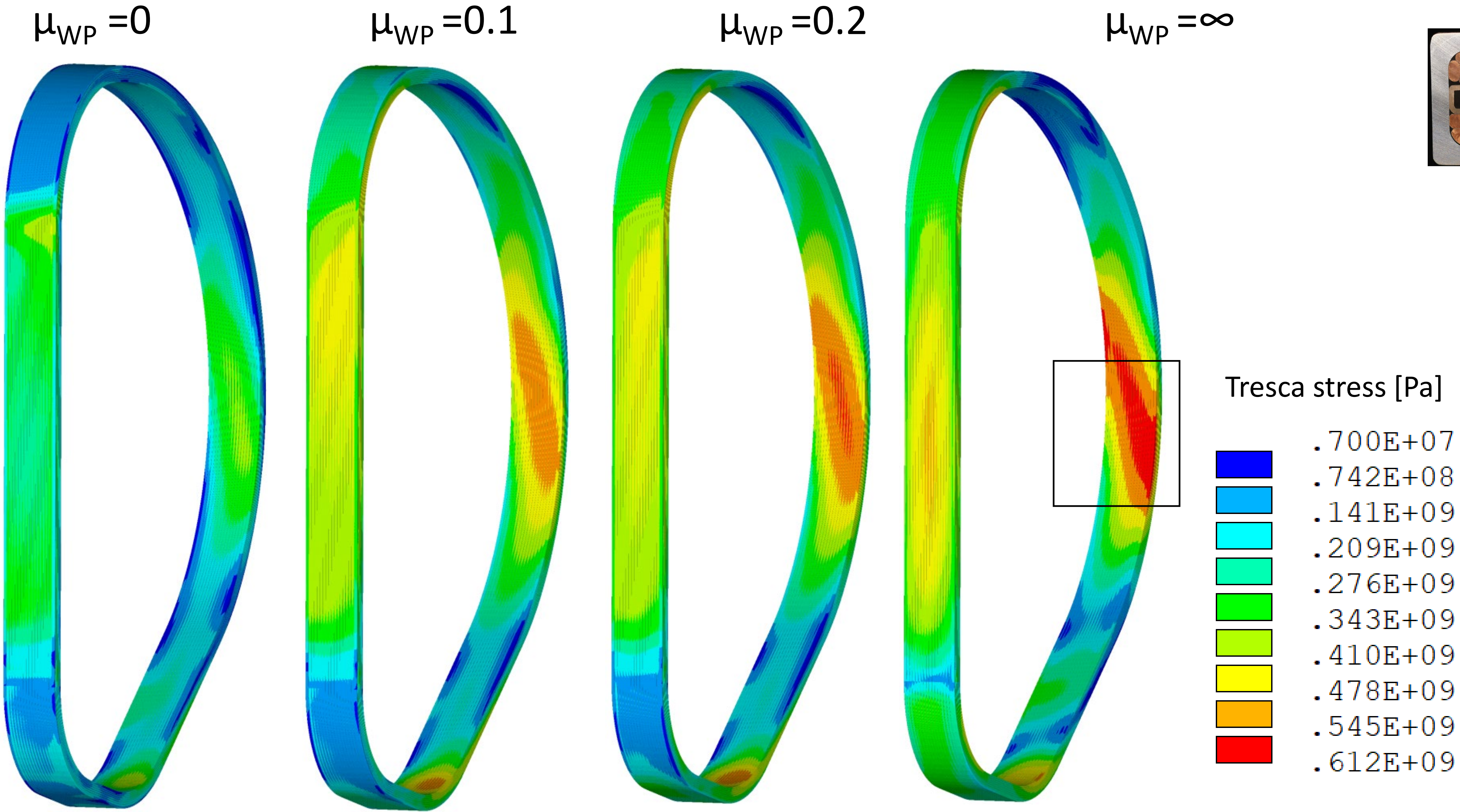
$\mu_{WP} = 0$ $\mu_{WP} = 0.1$ $\mu_{WP} = 0.2$ $\mu_{WP} = \infty$

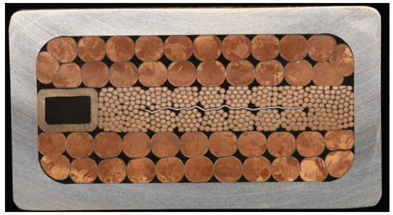


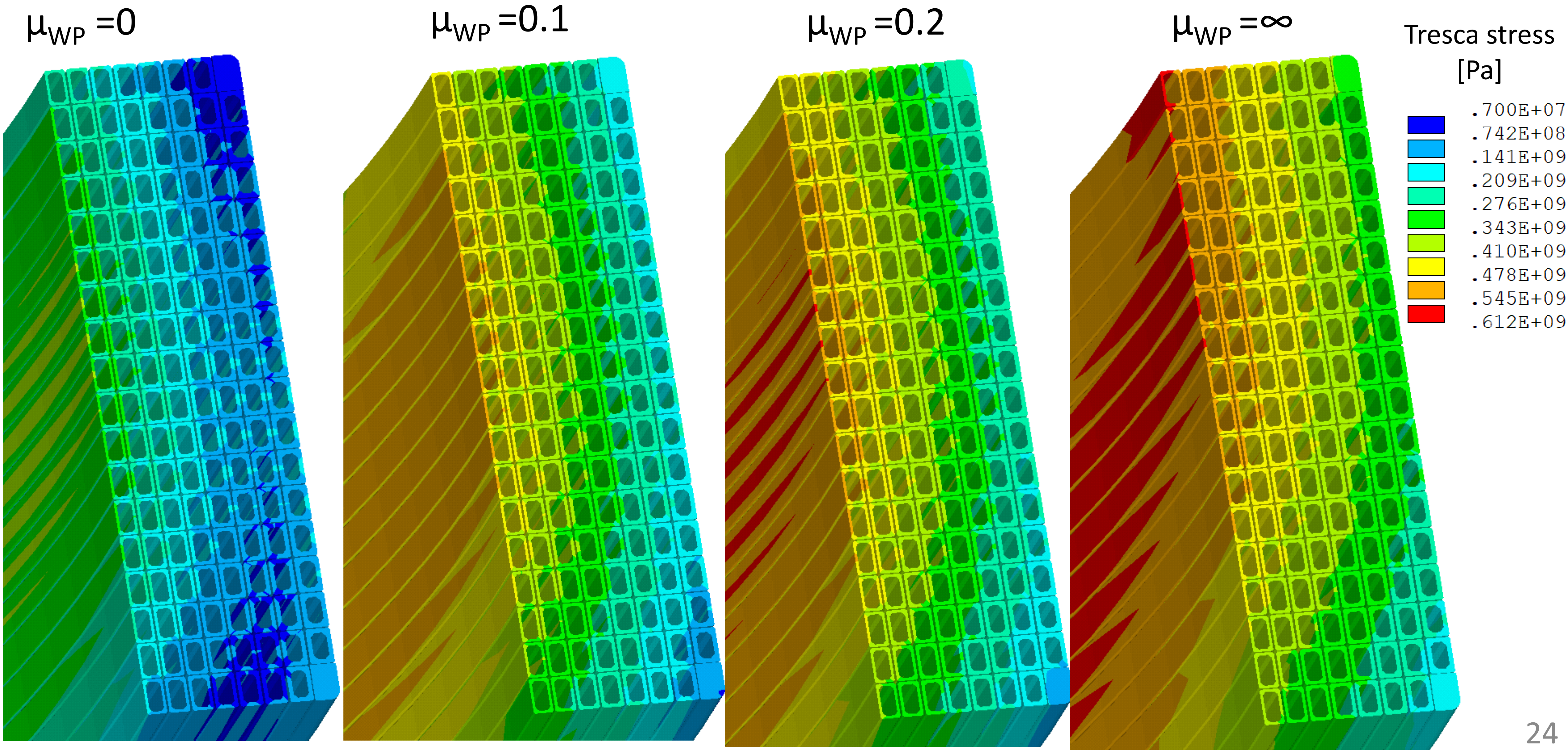


# 6. Results – powering - jackets

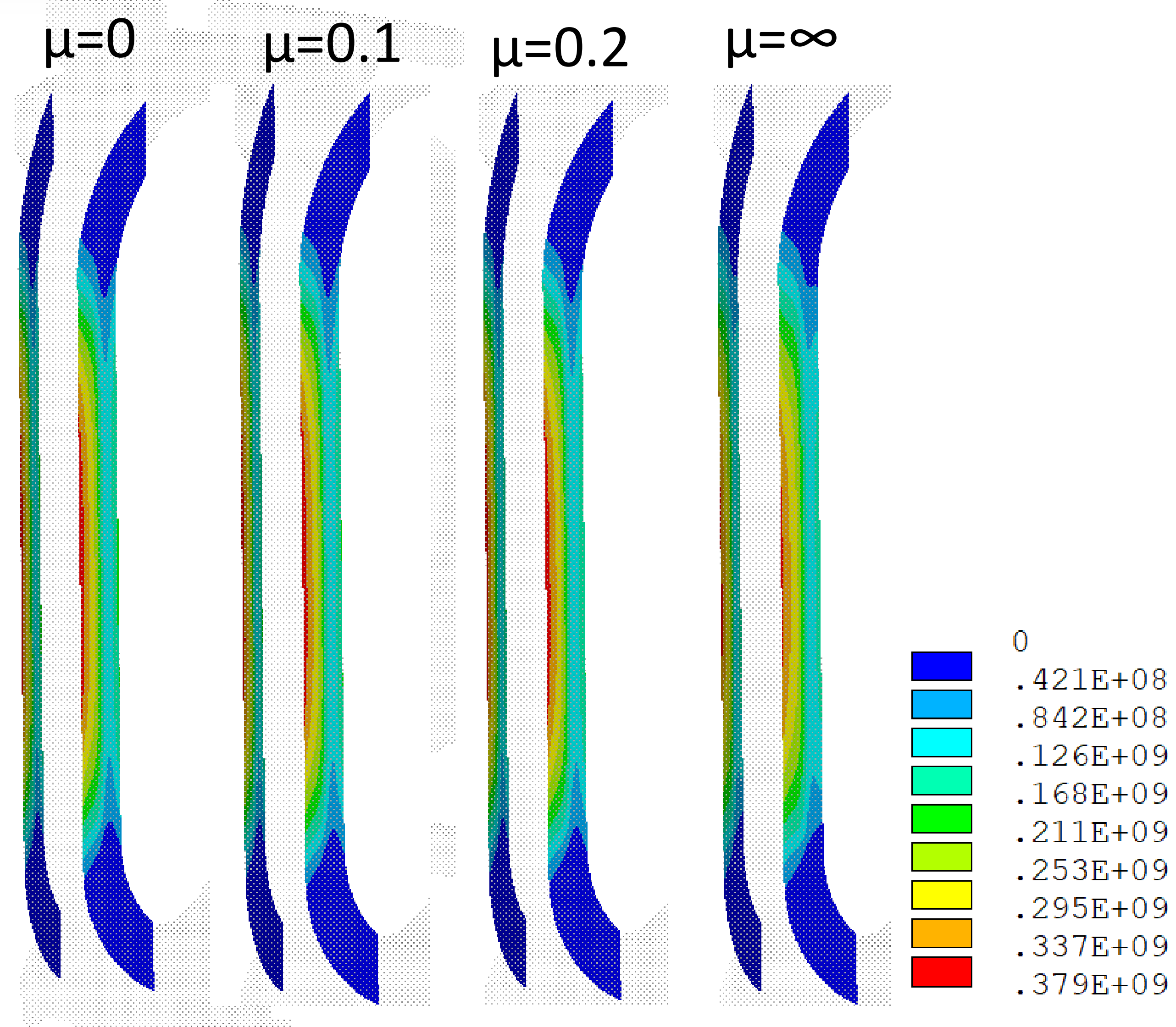


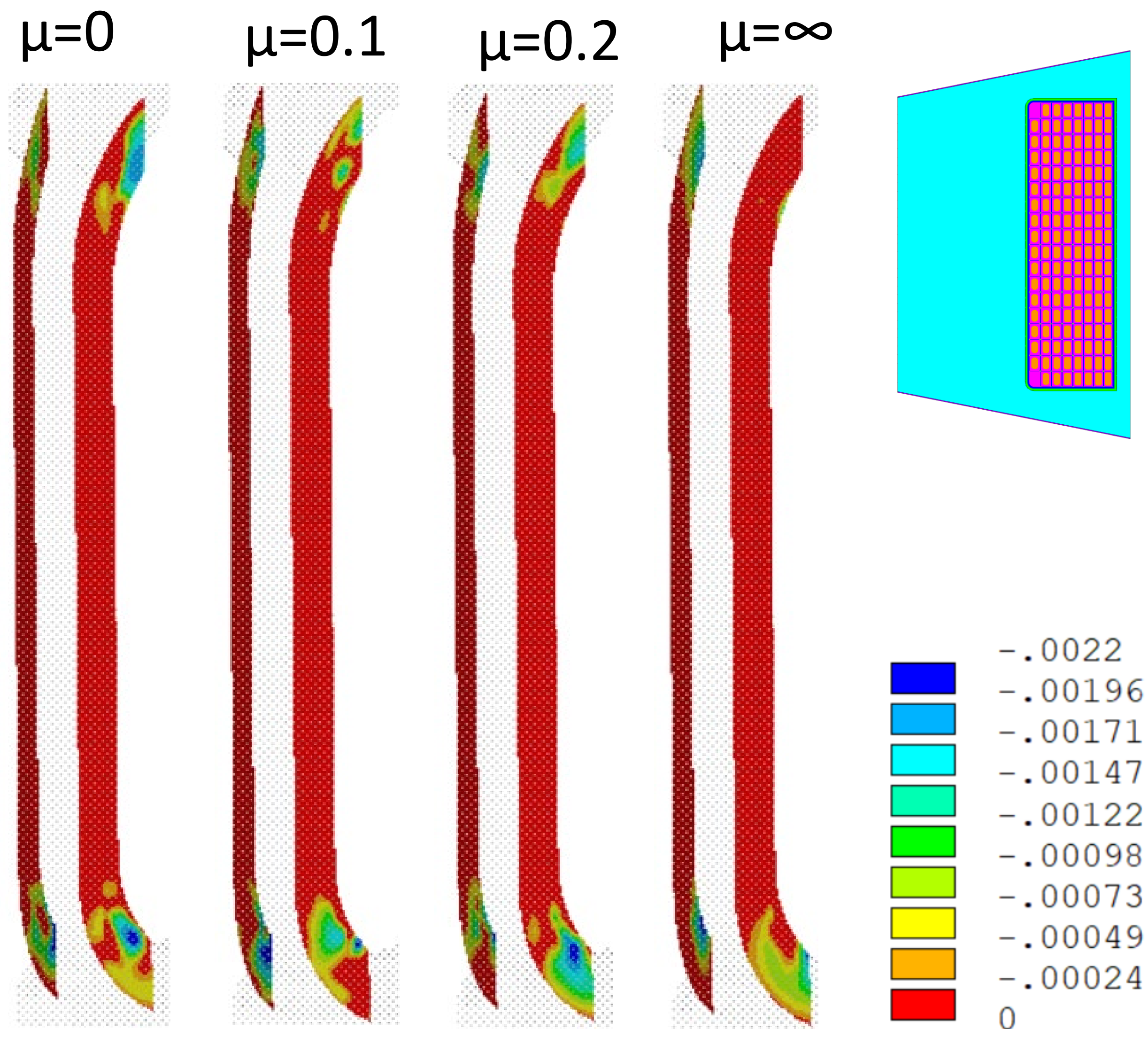
# 6. Results – powering - jackets



# 6. Results – intercoil contact




Contact pressure [Pa]




Contact gap [m]

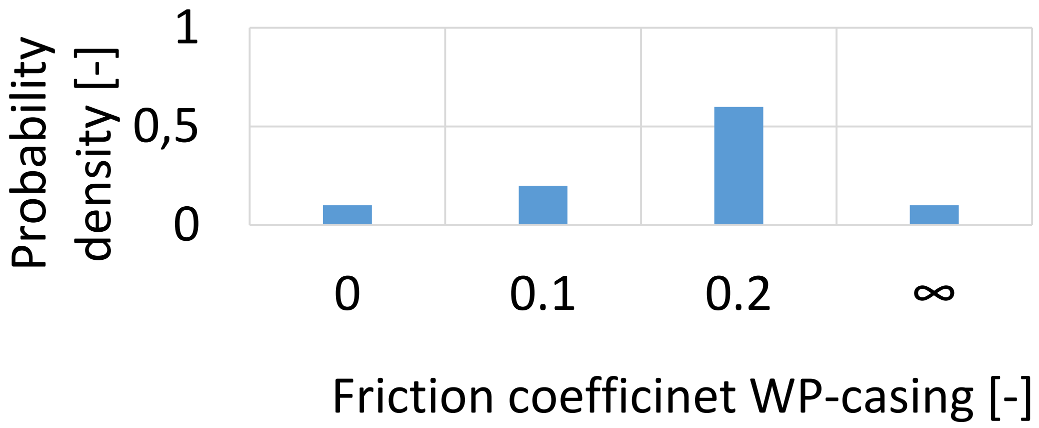
# 7. Probabilistic approach

| x (μ) | $x_1$ | $x_2$ | $x_3$ | .. | $x_N$ |
|---|---|---|---|---|---|
| P(x) | $P_{x1}$ | $P_{x2}$ | $P_{x3}$ | .. | $P_{xN}$ |

$$\mu = E(x) = \sum_{i=1}^{n} x_i P(x_i)$$

$$\sigma = \sqrt{\sum_{i=1}^{n} (x_i - \mu)^2 P(x_i)}$$

| $\mu_f$ (x) | 0 | 0.1 | 0.2 | ∞ |
|---|---|---|---|---|
| P(x) | 0.1 | 0.2 | 0.6 | 0.1 |
| Stress distribution Tresca | $\sigma_{T1}(x,y,z)$ | $\sigma_{T2}(x,y,z)$ | $\sigma_{T3}(x,y,z)$ | $\sigma_{T4}(x,y,z)$ |

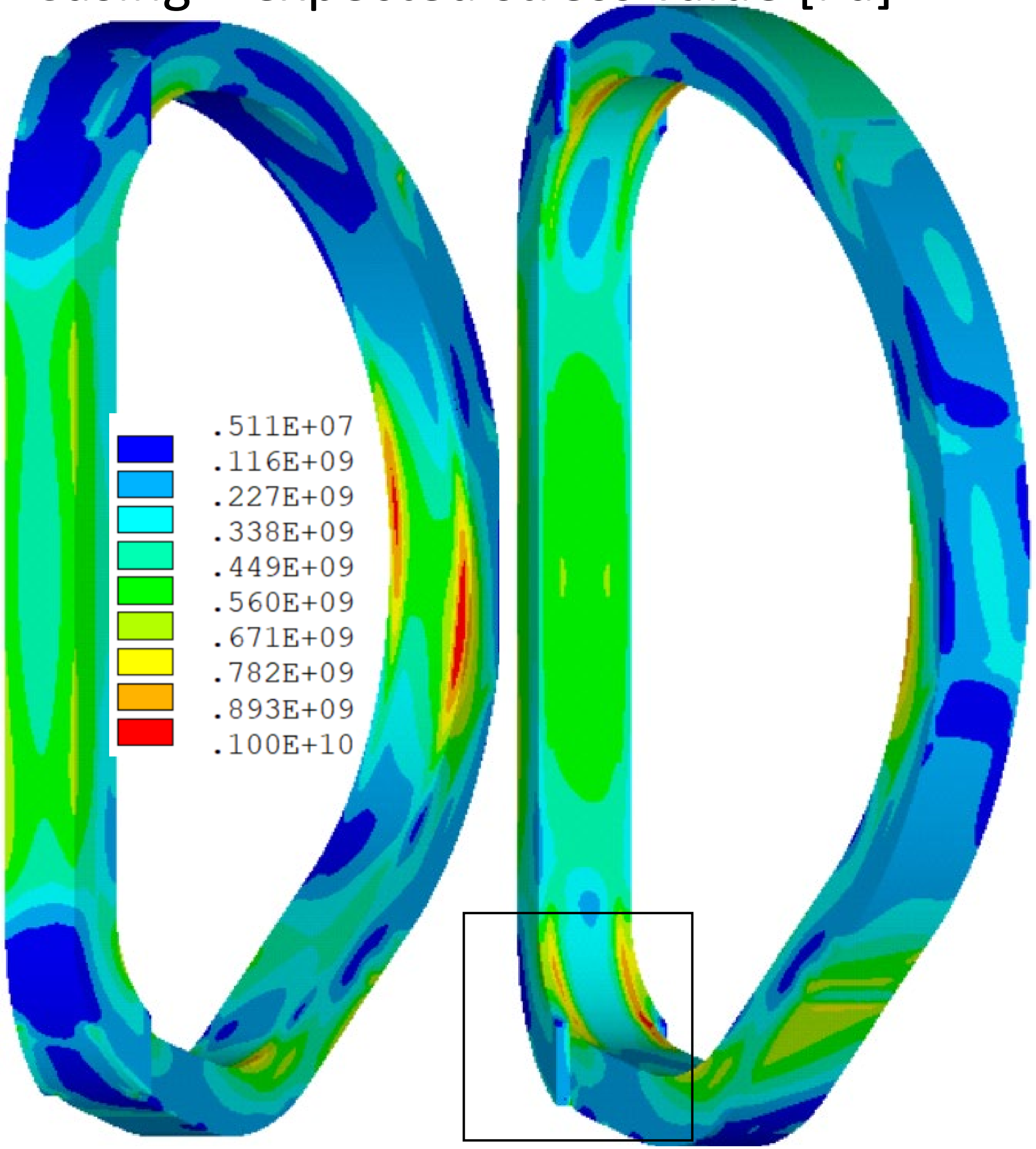



$$\sigma_E(x,y,z) = \sigma_{T1}(x,y,z)P_{x1} + \sigma_{T1}(x,y,z)P_{x2} + \sigma_{T1}(x,y,z)P_{x3} + \sigma_{T1}(x,y,z)P_{x4}$$

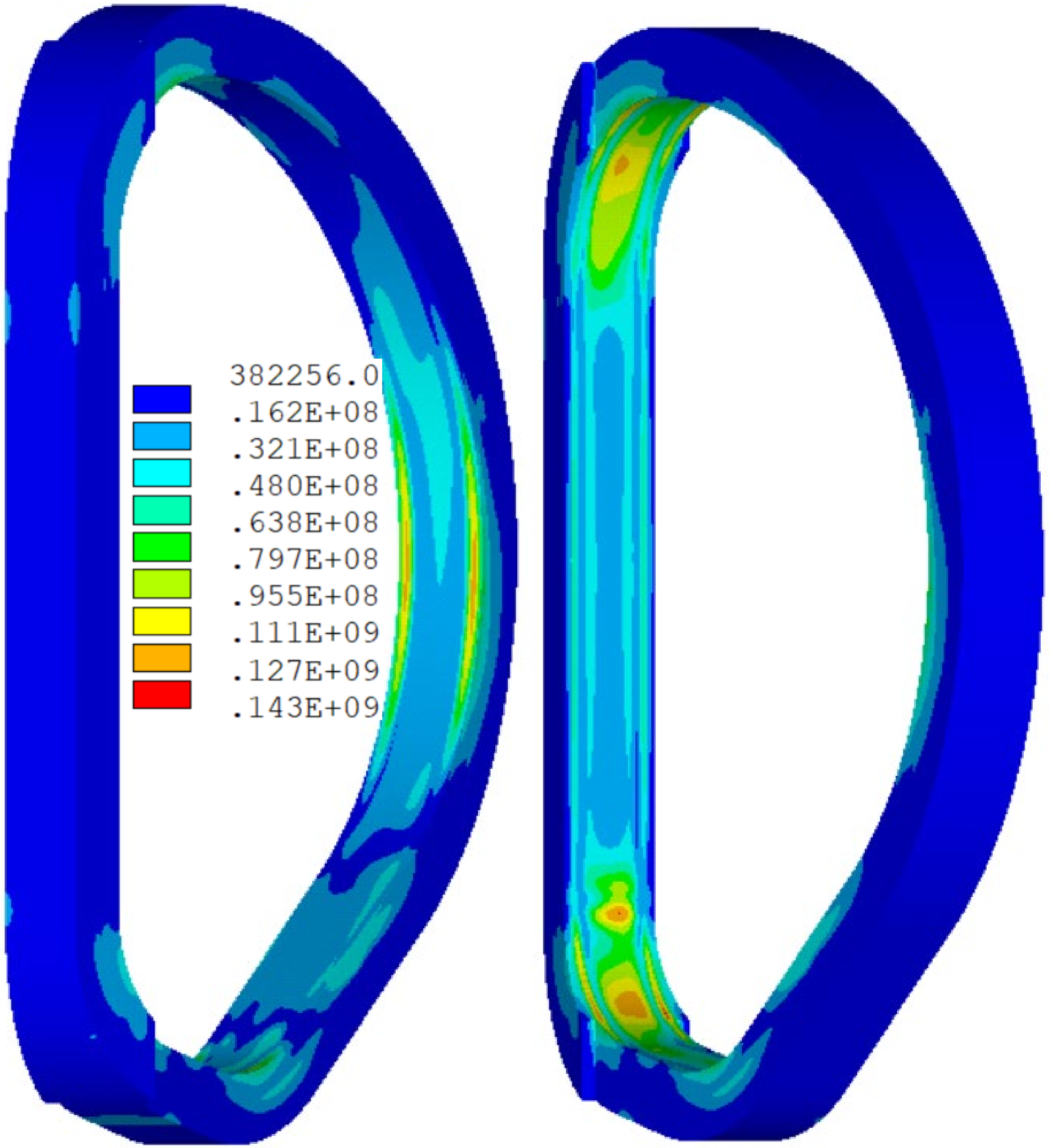
$$\sigma = \sqrt{(\sigma_{T1} - \sigma_E)^2 P_{x1} + (\sigma_{T2} - \sigma_E)^2 P_{x2} + (\sigma_{T3} - \sigma_E)^2 P_{x3} + (\sigma_{T4} - \sigma_E)^2 P_{x4}}$$

# 7. Probabilistic approach - casing

Casing – expected stress value [Pa]

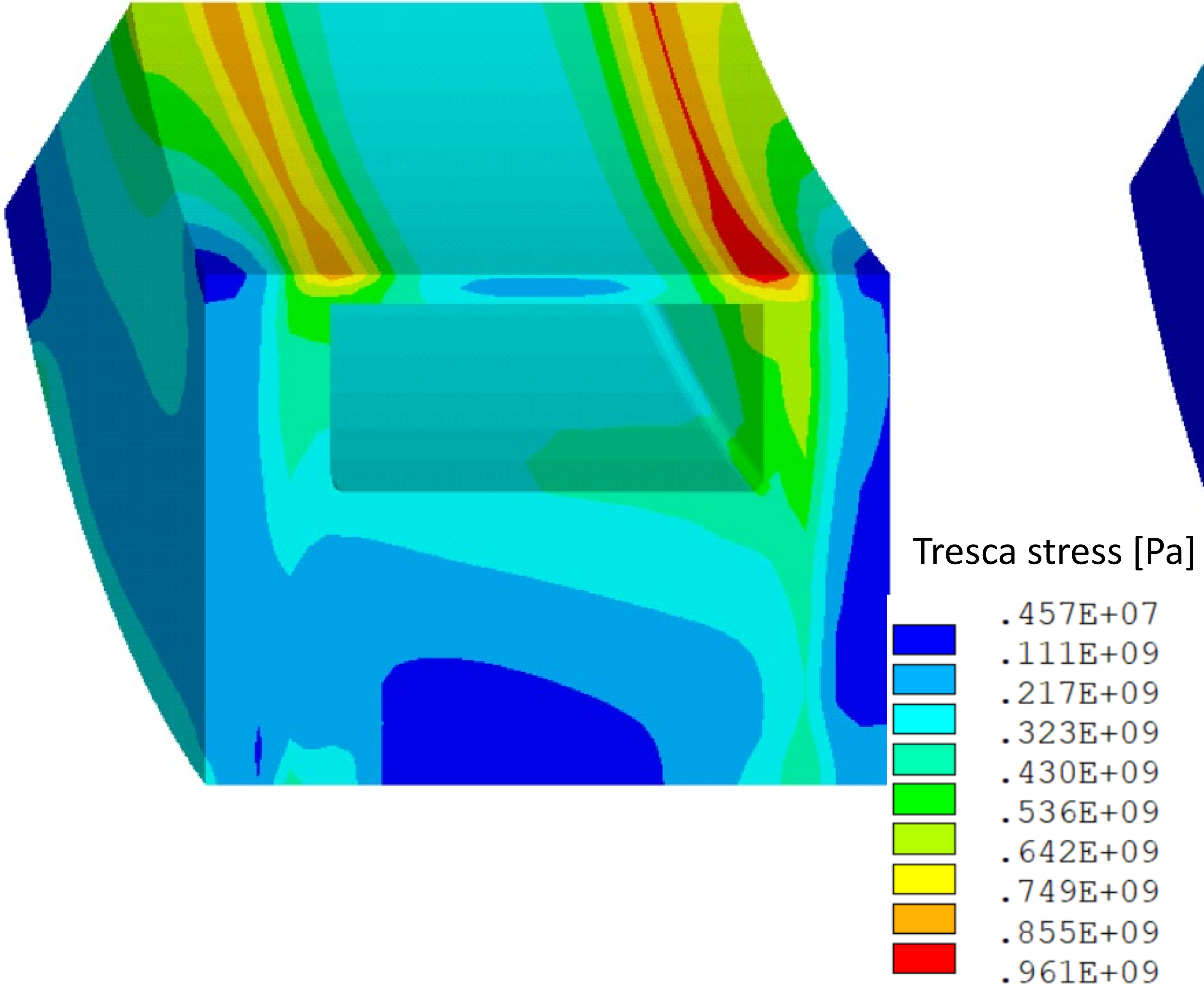



Casing – standard deviation of stress [Pa]

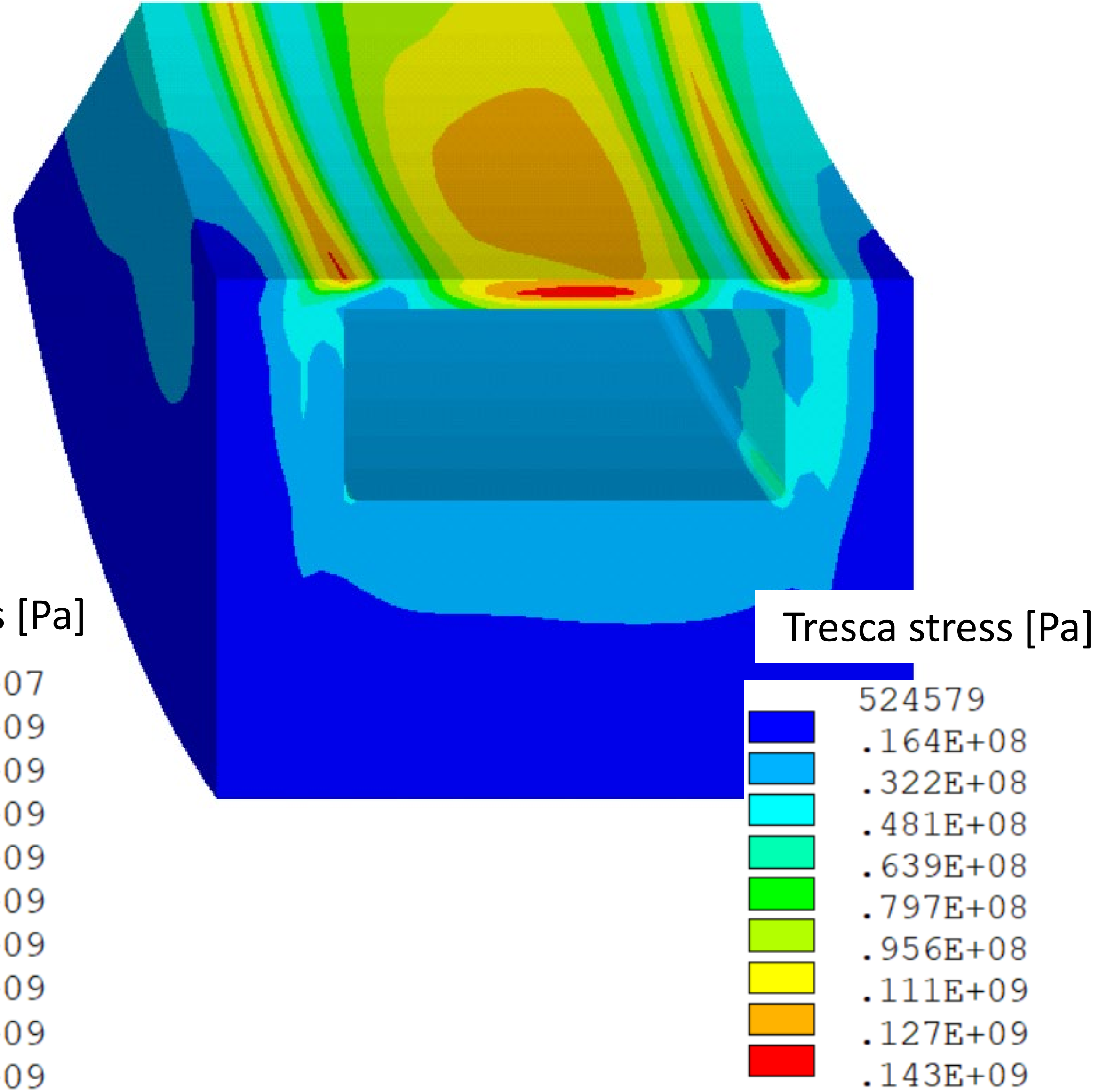


# 7. Probabilistic approach - casing

Casing – expected stress value [Pa]

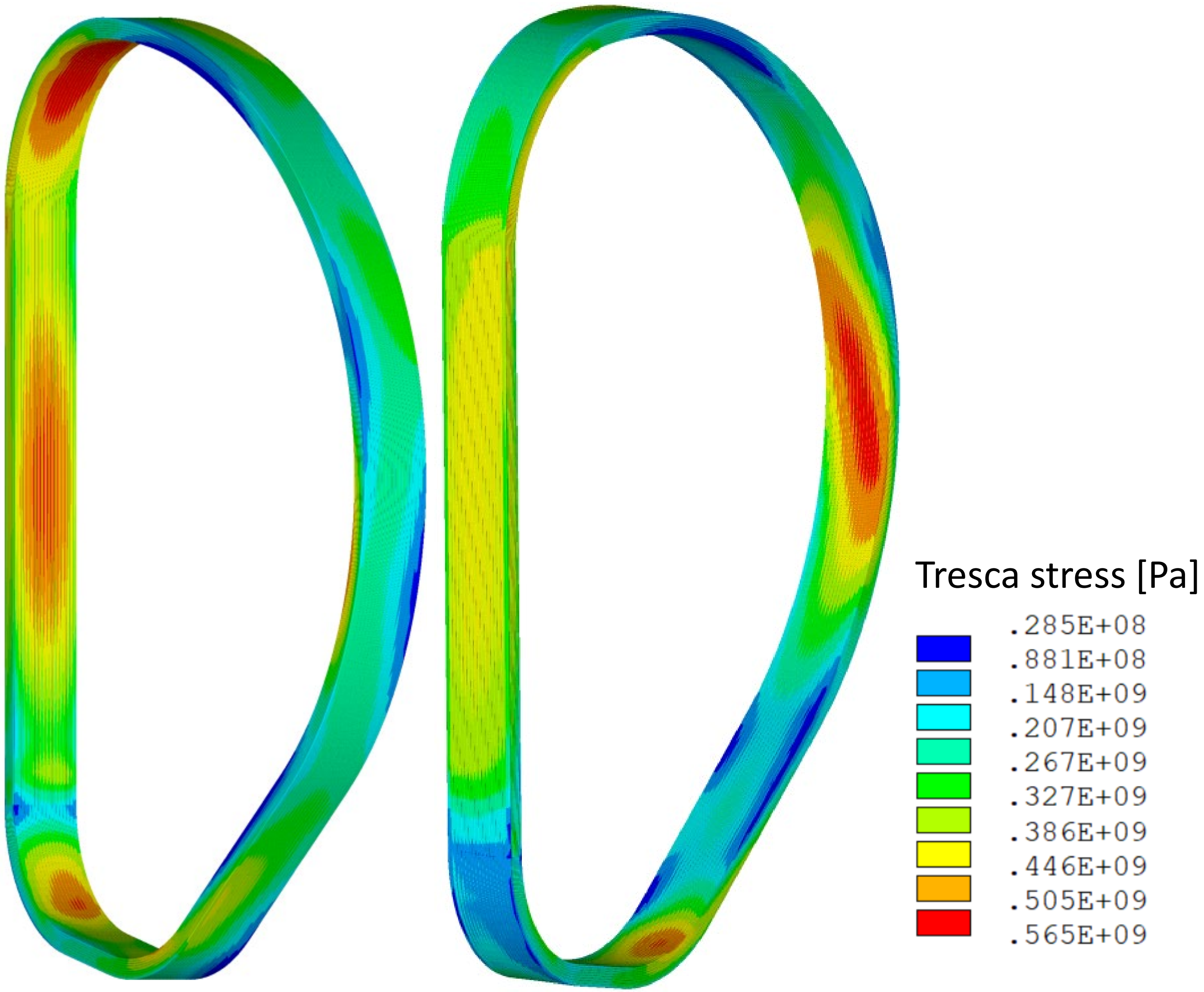



Casing – standard deviation of stress [Pa]

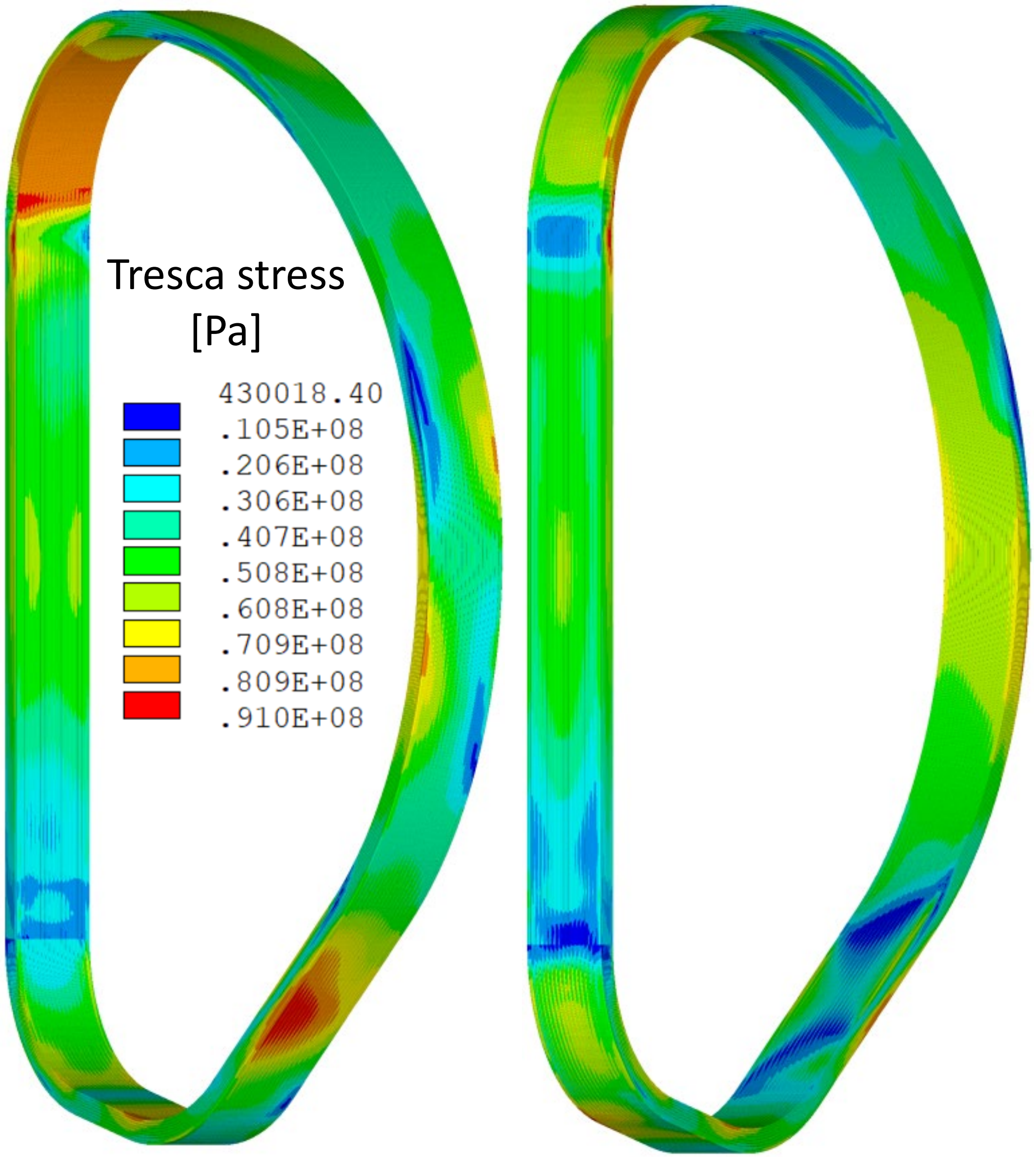


# 7. Probabilistic approach - jackets

## Jackets – expected stress value [Pa]



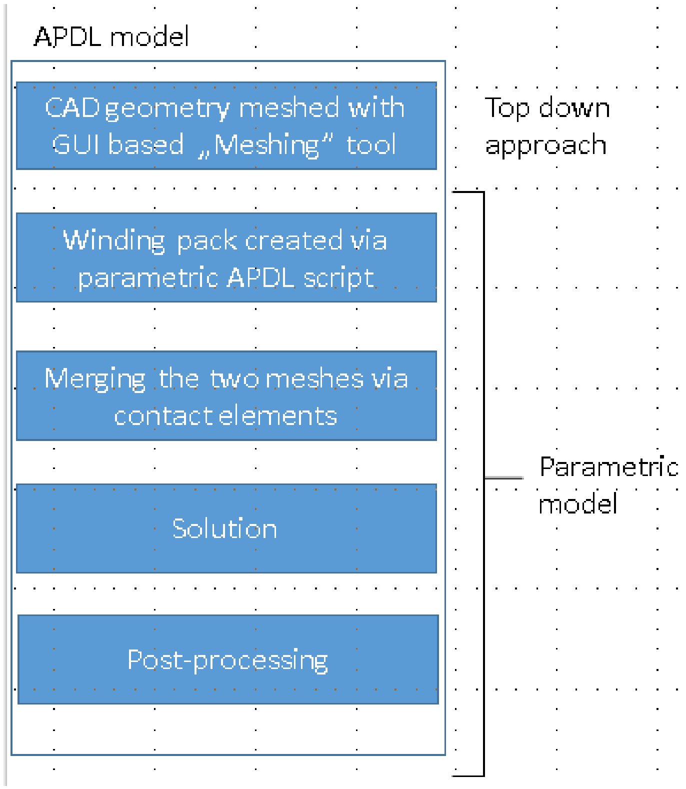

## Jackets – standard deviation of stress [Pa]



# 8. Conclusions/future work

1. Detailed 3D mechanical models are possible to build and solve on a standard workstations
2. The model is robust numerically and can solve with general frictional contacts

## Future work




1. Making the whole model parametric (casing). Performing parametric studies and comparing the results with 2D model parametric studies.
2. Expanding the model to add the thermo-hydraulic effects

# Thank you for your attention

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.