Mechanical analysis of the DEMO TF with 2D and 3D models: homogenized and fully detailed – comparison of accuracy

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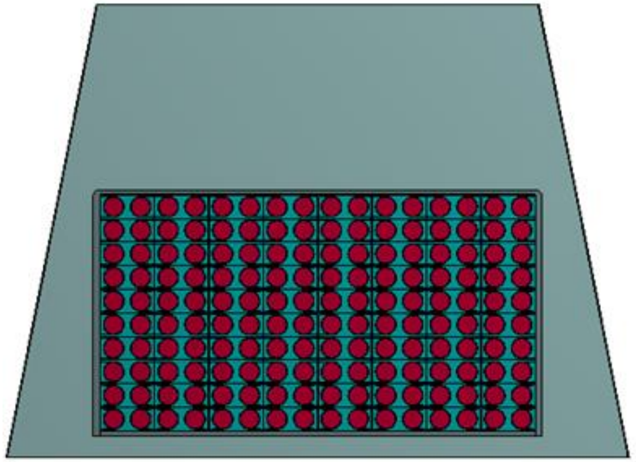
Outline:

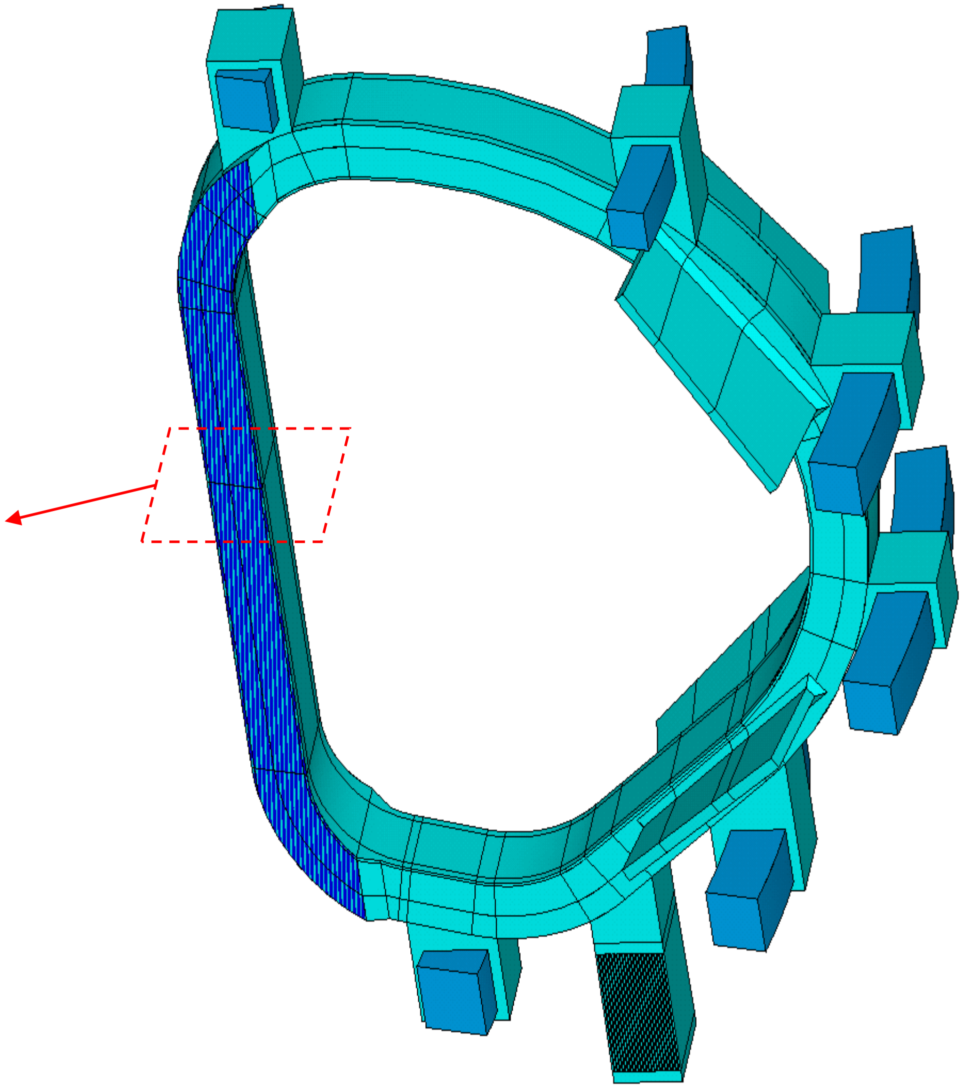
1. Motivation
2. Electromagnetic modeling
3. Homogenization
4. 3D mechanical model – homogenized
5. 3D mechanical model – detailed
6. Homogenized vs detailed model
7. 2D cuts from the detailed model
8. Conclusions

1. Motivation (1/5)

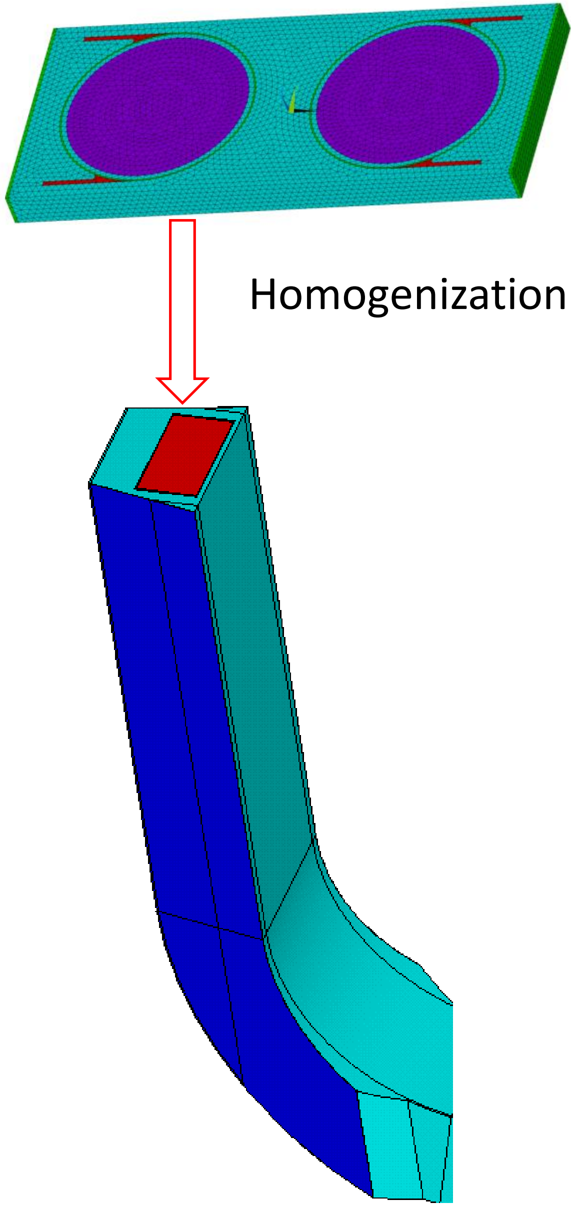
2D model in the equatorial plane (z=0)



3D model



Homogenization



1. Motivation (2/5)

2D model of the inboard leg at the equatorial plane

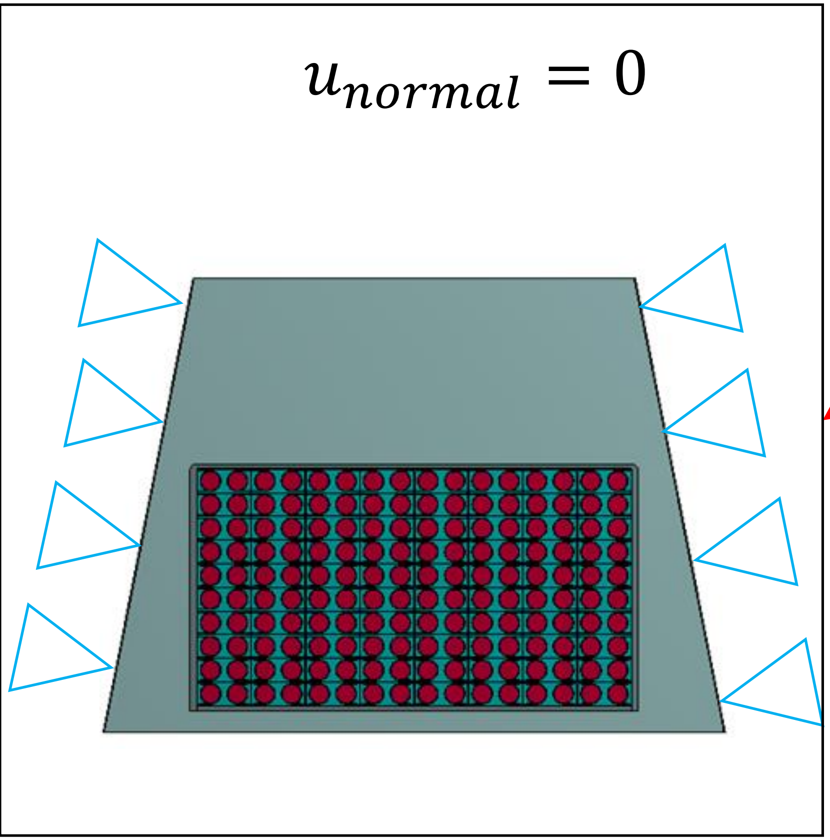
[13] Mechanical Analysis of the JT-60SA TF Coils
[16] Electromagnetic and mechanical analysis of a toroidal field coil winding pack for EU DEMO
[26R] TFC-PREDIM: A FE dimensioning procedure for the TF coil system of a DEMO tokamak reactor
[30R] 2019 Progress of the CFETR design
[31R] Progress in the conceptual design of the CFETR toroidal field coil with rectangular conductors
[32R] Conceptual magnet design study for fusion nuclear science facility

3D submodel of a piece of the inboard leg around the equatorial plane

[17R] An Electromagnetic and Structural Finite Element Model of the ITER Toroidal Field Coils
[20R] Analysis of the ITER TF Winding Pack During Cold Tests at Reduced Current
[24R] Detailed structural analysis of a graded TF coil winding pack for EU DEMO
[25R] MECHANICAL ANALYSIS OF THE ENEA TF COIL PROPOSAL FOR THE EU DEMO FUSION REACTOR

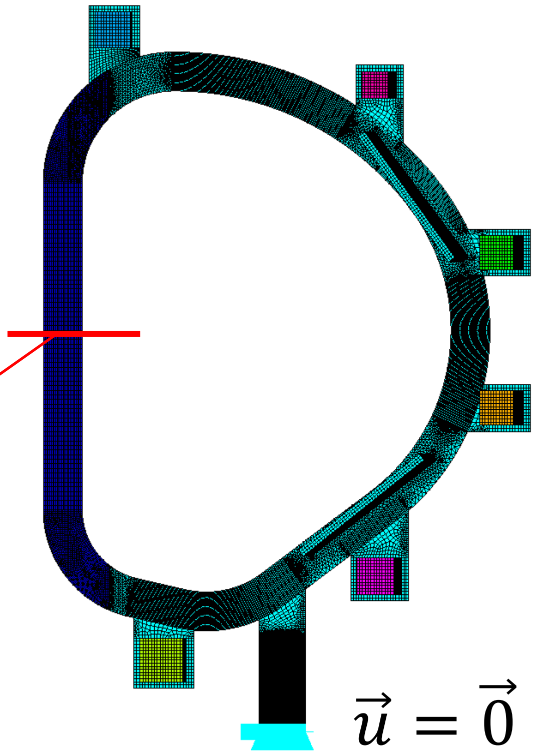
1. Motivation (3/5)

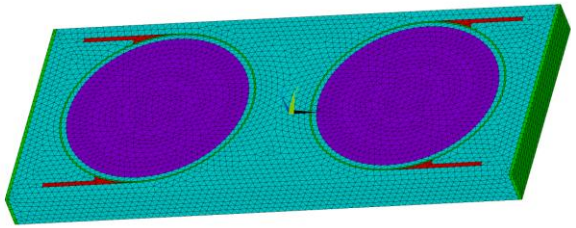
2D model in the equatorial plane (z=0)



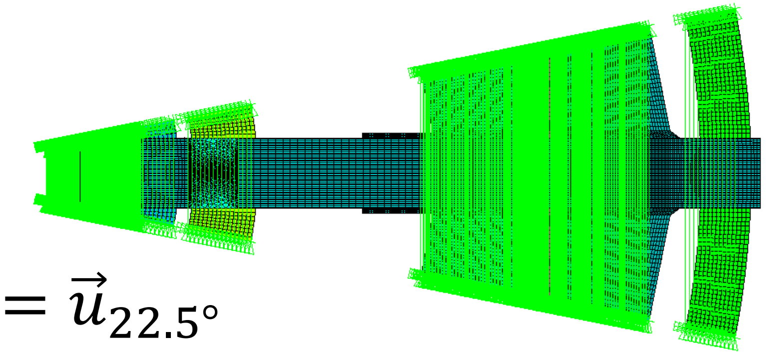
F_Z
transfered

3D model





Homogenization

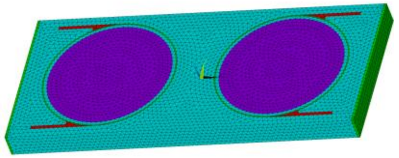


$\vec{u}_0 = \vec{u}_{22.5°}$

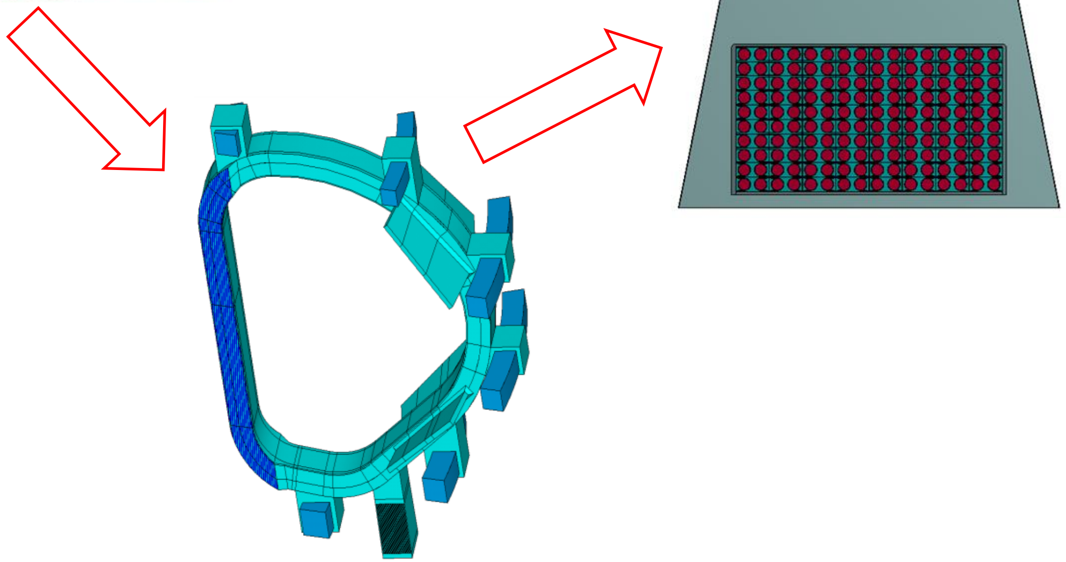
1. Motivation (4/5)

Usual approach:

1) Homogenization of the WP
2) 3D model with homogenized TF (no stress in the WP)
3) 2D model in the worst cross-section – stress in the WP



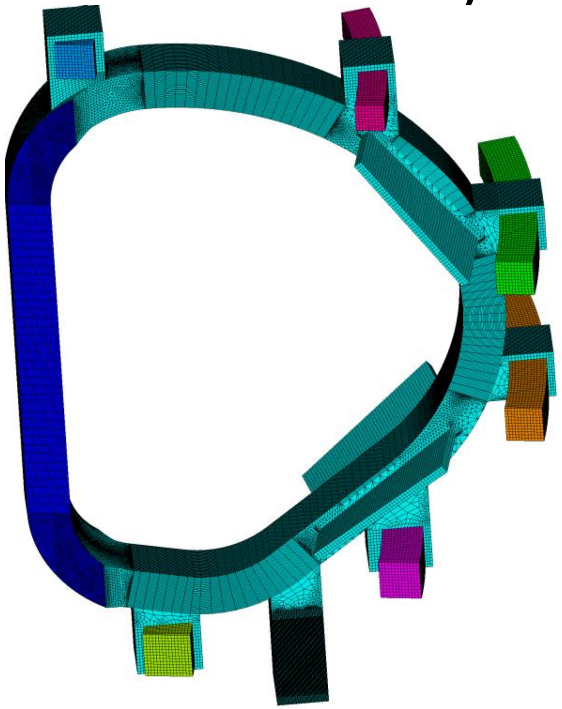
2D model

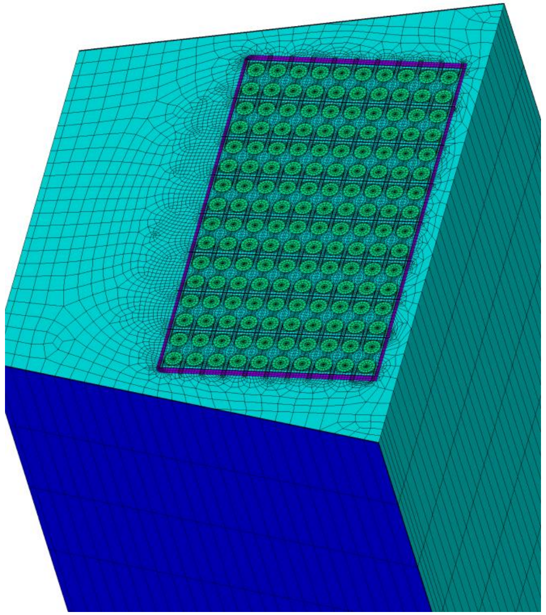


3D model

Detailed model:

1) No homogenization
2) No 2D model
3) **Only 1 detailed 3D model**





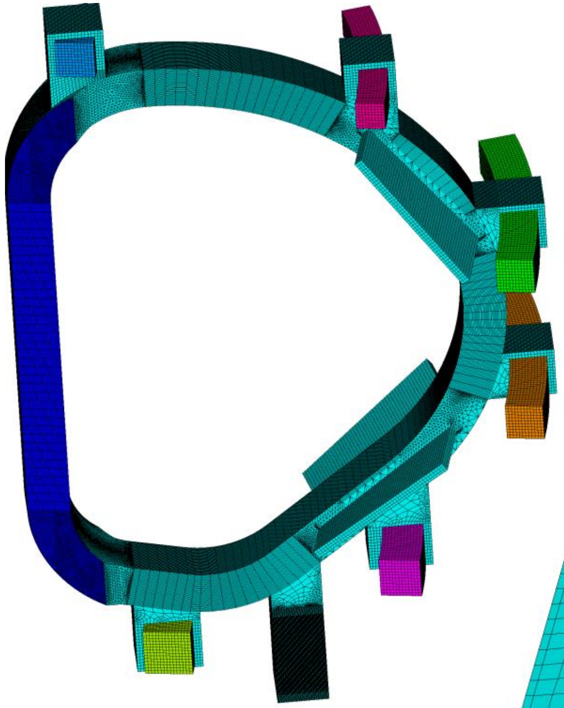
"3D global model is too large to model in detail".

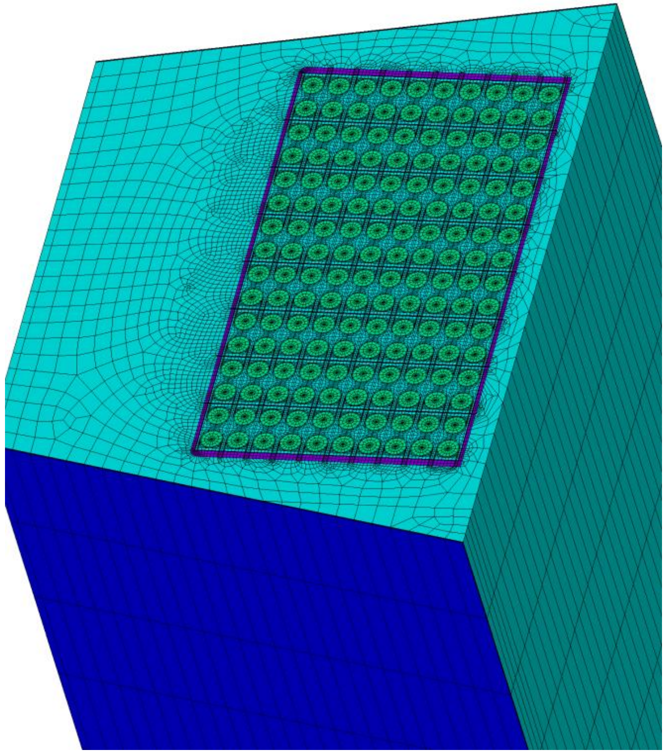
Progress in the conceptual design of the CFETR toroidal field coil with rectangular conductors

„It is impossible to model the winding pack (WP) in detail"

[14R] Electromagnetic and mechanical analysis of CFETR toroidal field coils

1. Motivation (5/5)

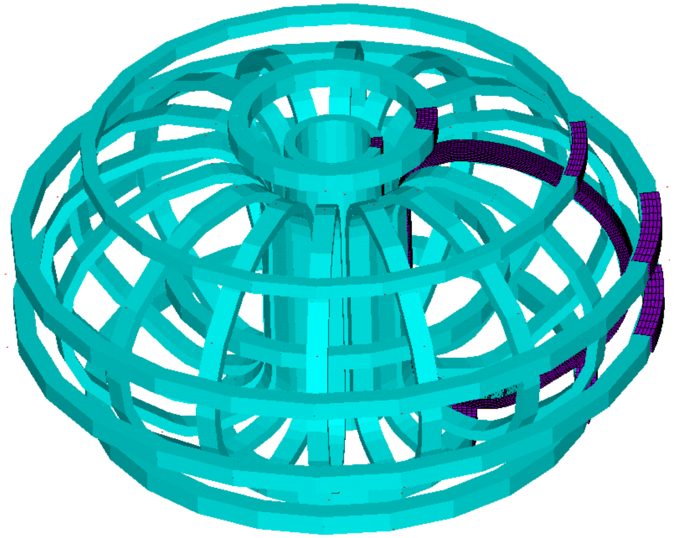




What question can such model answer?

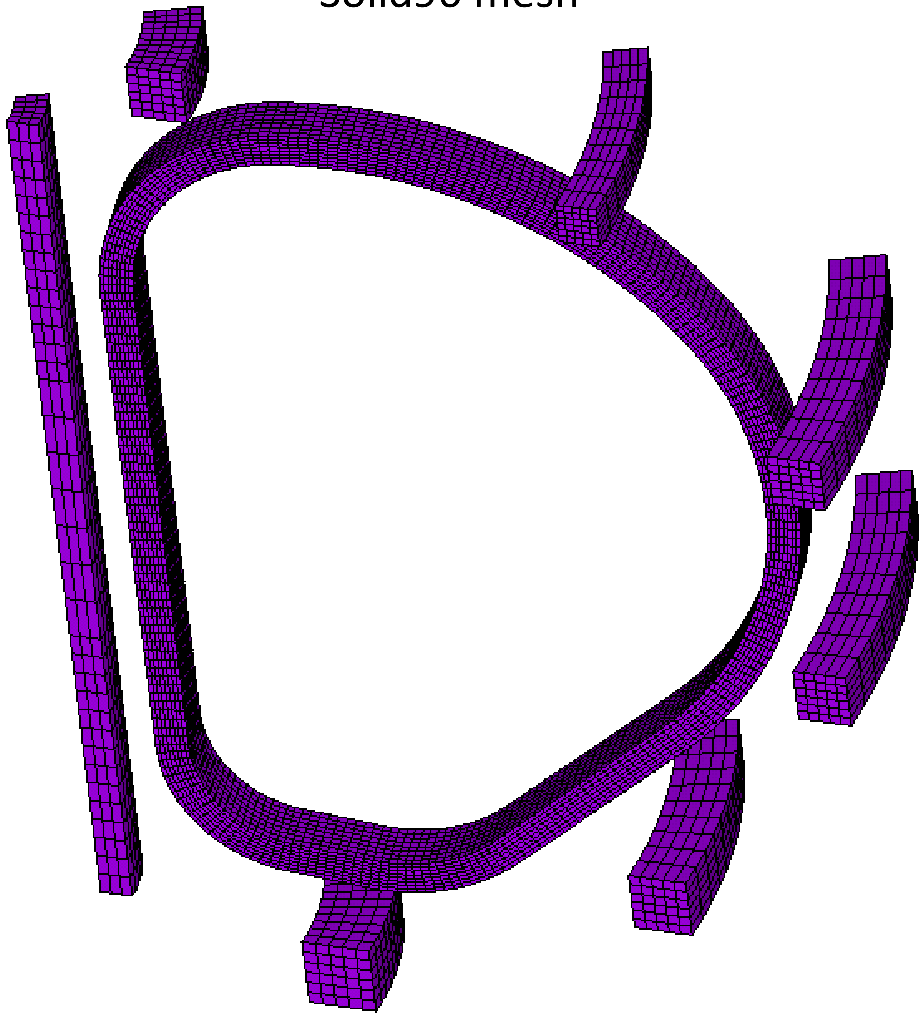
1) Does the state of strain on the 2D cross-section satisfy the generalized plane strain assumption? (Is the axial strain constant?)
2) Is the maximum stress located at the equatorial plane?
3) From such a the state of stress can be obtained at any cross-section
4) More realistic solution and the possibility of further insight into the design

2. Electromagnetic modeling (1/10)

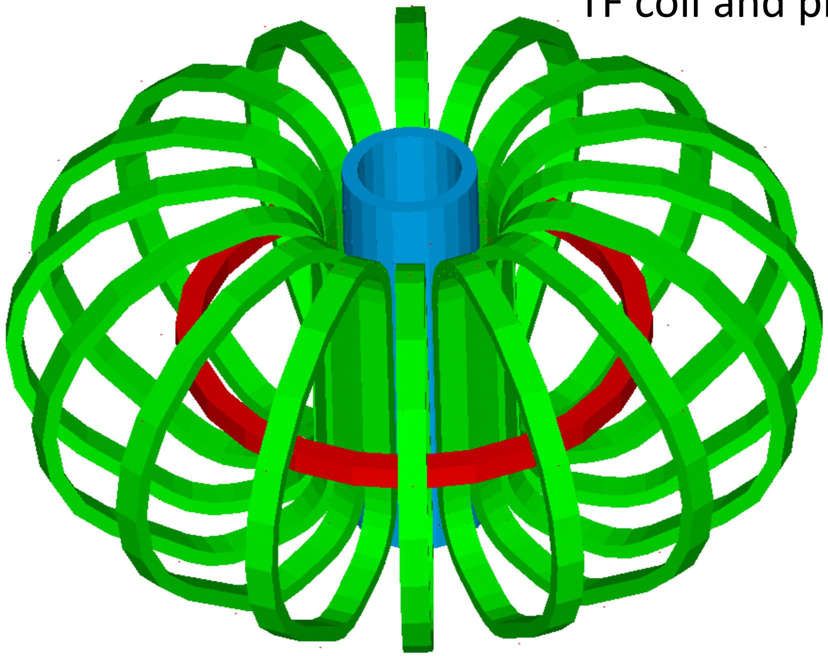


The EM model
CS, PT, TF, Plasma modeled with Sourc36
CS, PF, TF for Lorentz forces modeled with Solid96

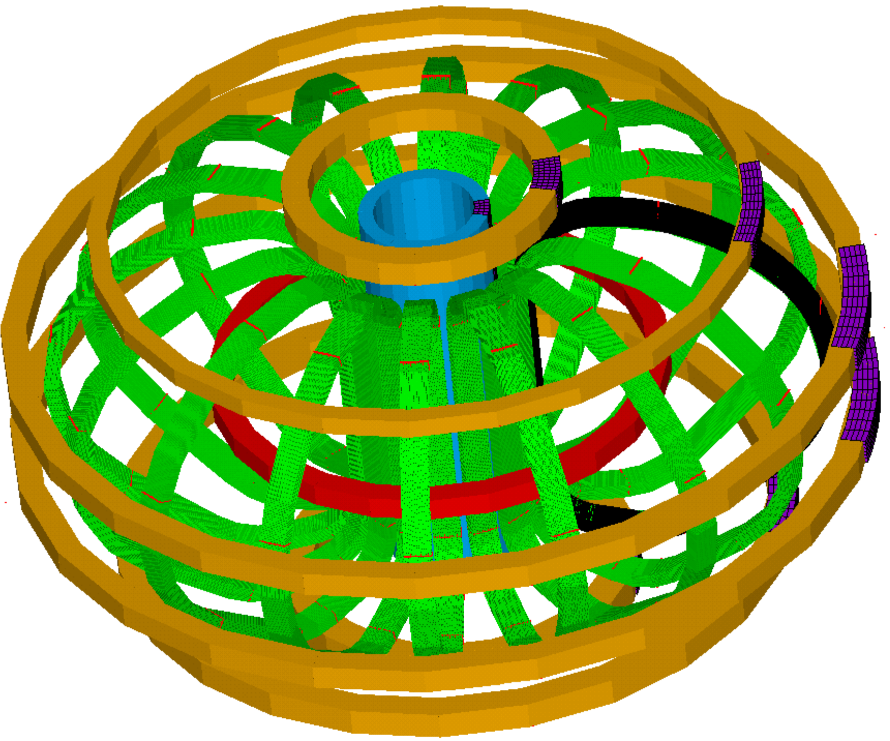
Solid96 mesh

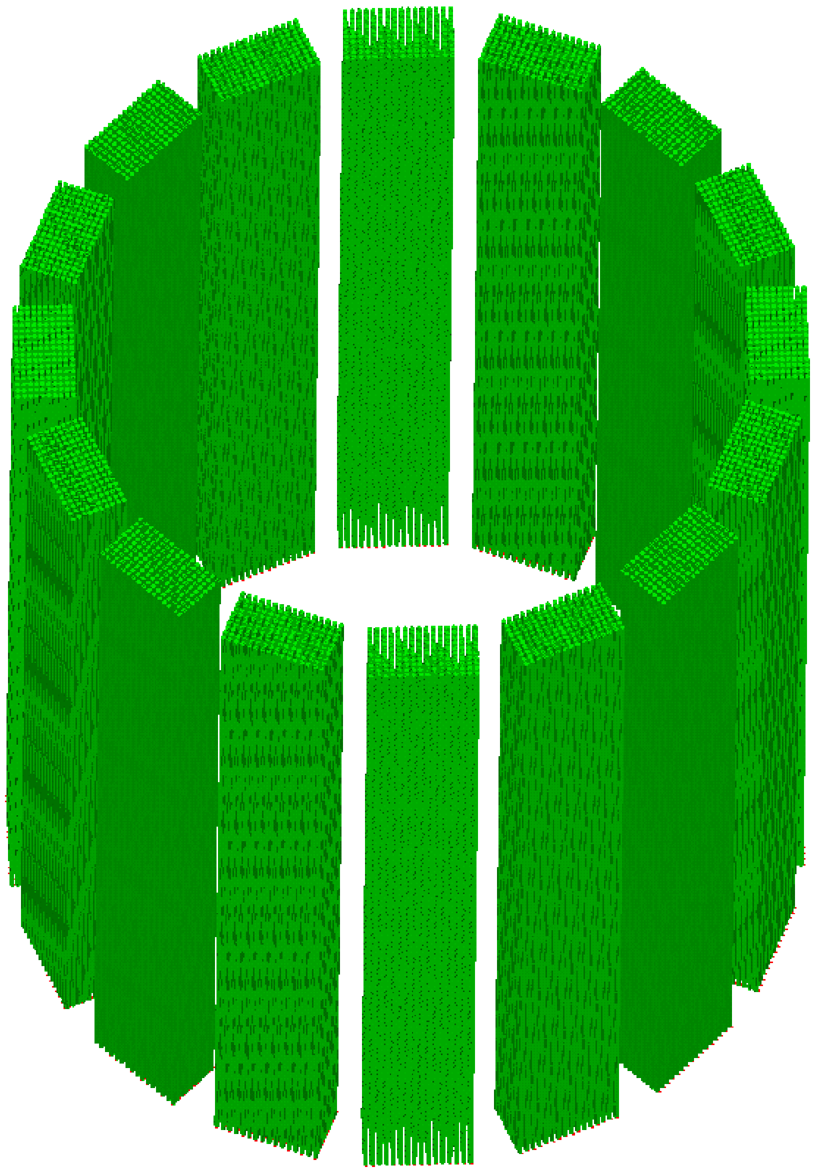


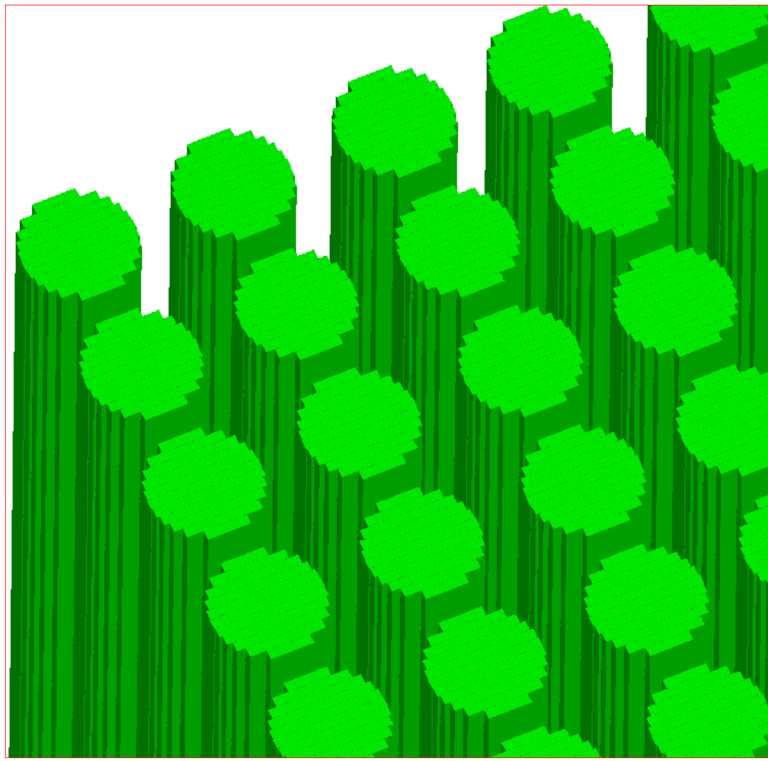
TF coil and plasma



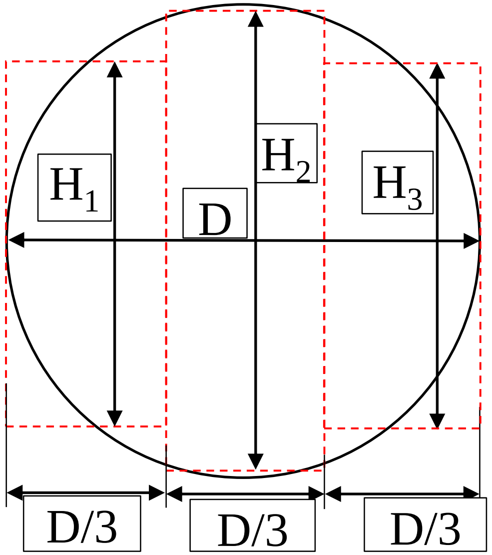
2. Electromagnetic modeling (2/10)

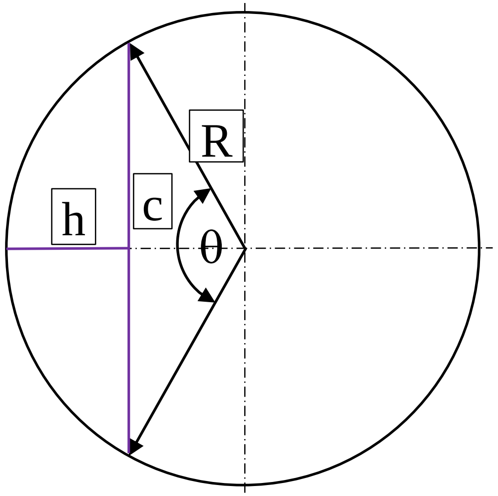






2. Electromagnetic modeling (3/10)





$$h = \frac{D}{N} = \frac{2R}{N} \qquad c = 2\sqrt{R^2 - (R-h)^2}$$

$$c = 2\sqrt{R^2 - \left(R - \frac{2R}{N}\right)^2} = 4R\frac{\sqrt{N-1}}{N}$$

$$\theta = 2\,\mathrm{asin}\left(\frac{c}{2R}\right)$$

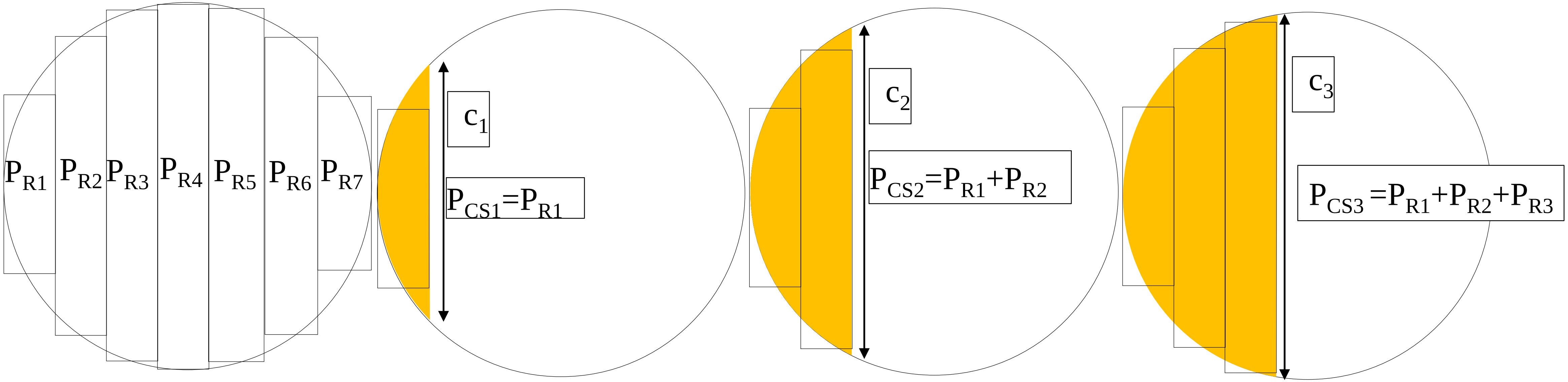
$$P_{CS} = \frac{R^2}{2}(\theta - sin\theta)$$

$$H_1 = \frac{P_{R1}}{h} = \frac{P_{CS}}{h} = \frac{3}{2}R(\theta - sin\theta)$$

$$P_{MID} = \pi R^2 - 2P_{R1} = R^2[\pi - 2(\theta - sin\theta)]$$

$$H_{MID} = \frac{P_{MID}}{h} = \frac{3P_{MID}}{2R} = \frac{3}{2}R[\pi - 2(\theta - sin\theta)]$$

2. Electromagnetic modeling (4/10)



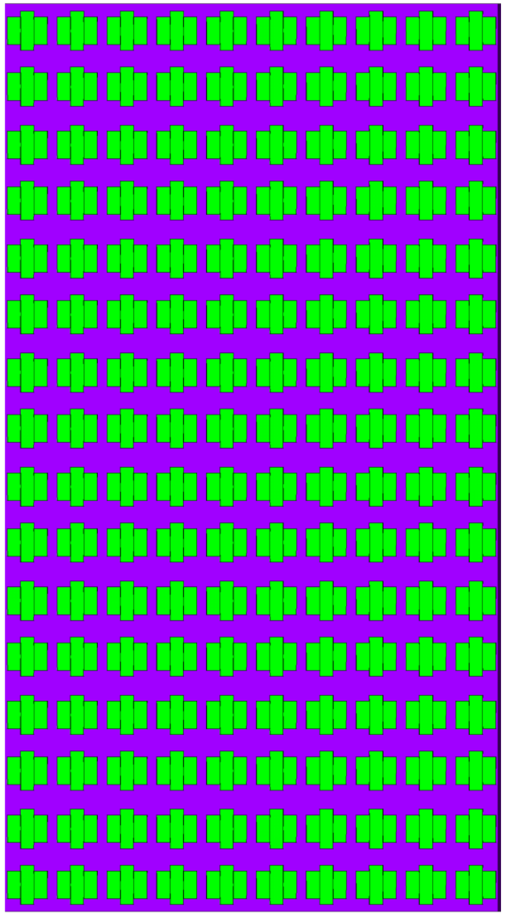
$$M = \frac{N-1}{2} + 1 \qquad c_i = 2\sqrt{R^2 - (R - i * h)^2} \qquad \theta_i = 2\,\mathrm{asin}\left(\frac{c_i}{2R}\right) \quad , \qquad P_{CSi} = \frac{R^2}{2}(\theta_i - sin\theta_i)$$

$$P_{Ri} = \begin{cases} P_{CSi}, & i = 1 \\ P_{CSi} - P_{CSi-1}, & i = 2..(N-1)/2 \end{cases}$$

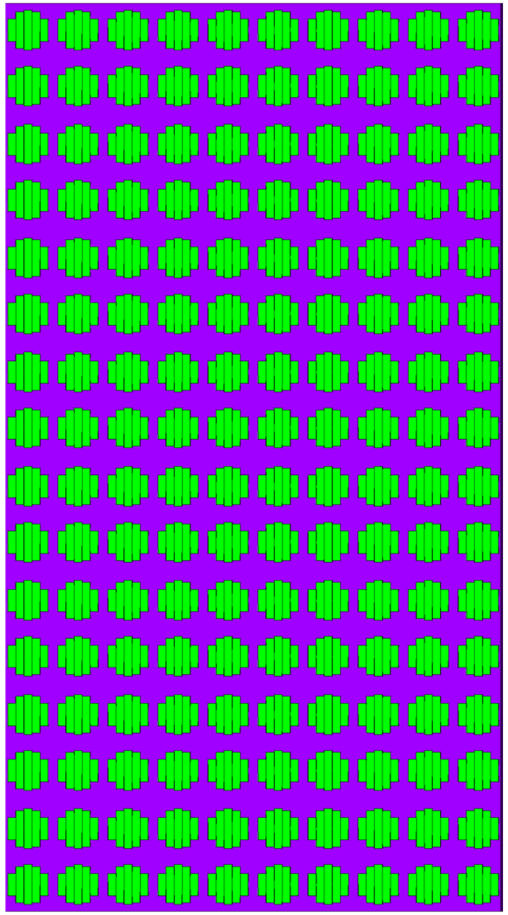
$$H_i = \frac{P_{Ri}}{h} = \frac{NP_{Ri}}{2R}$$

$$P_{mid} = P_M = \pi R^2 - 2 * P_{CS(N-1)/2} \quad , H_{Mid} = H_M = \frac{P_{mid}}{h}$$

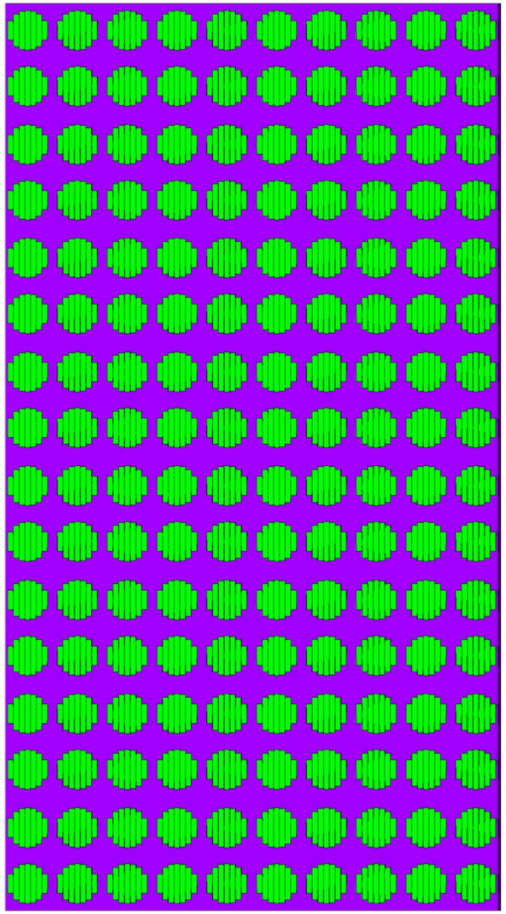
2. Electromagnetic modeling (5/10)



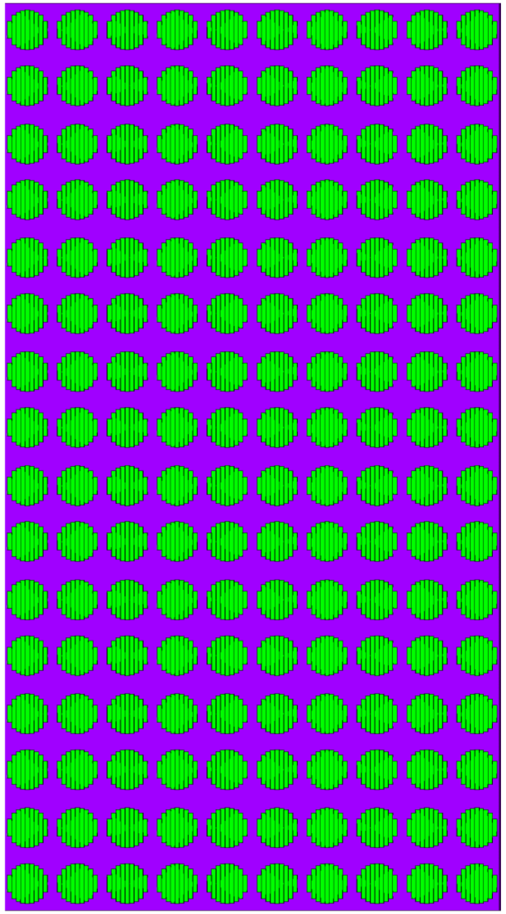
N=3



N=5

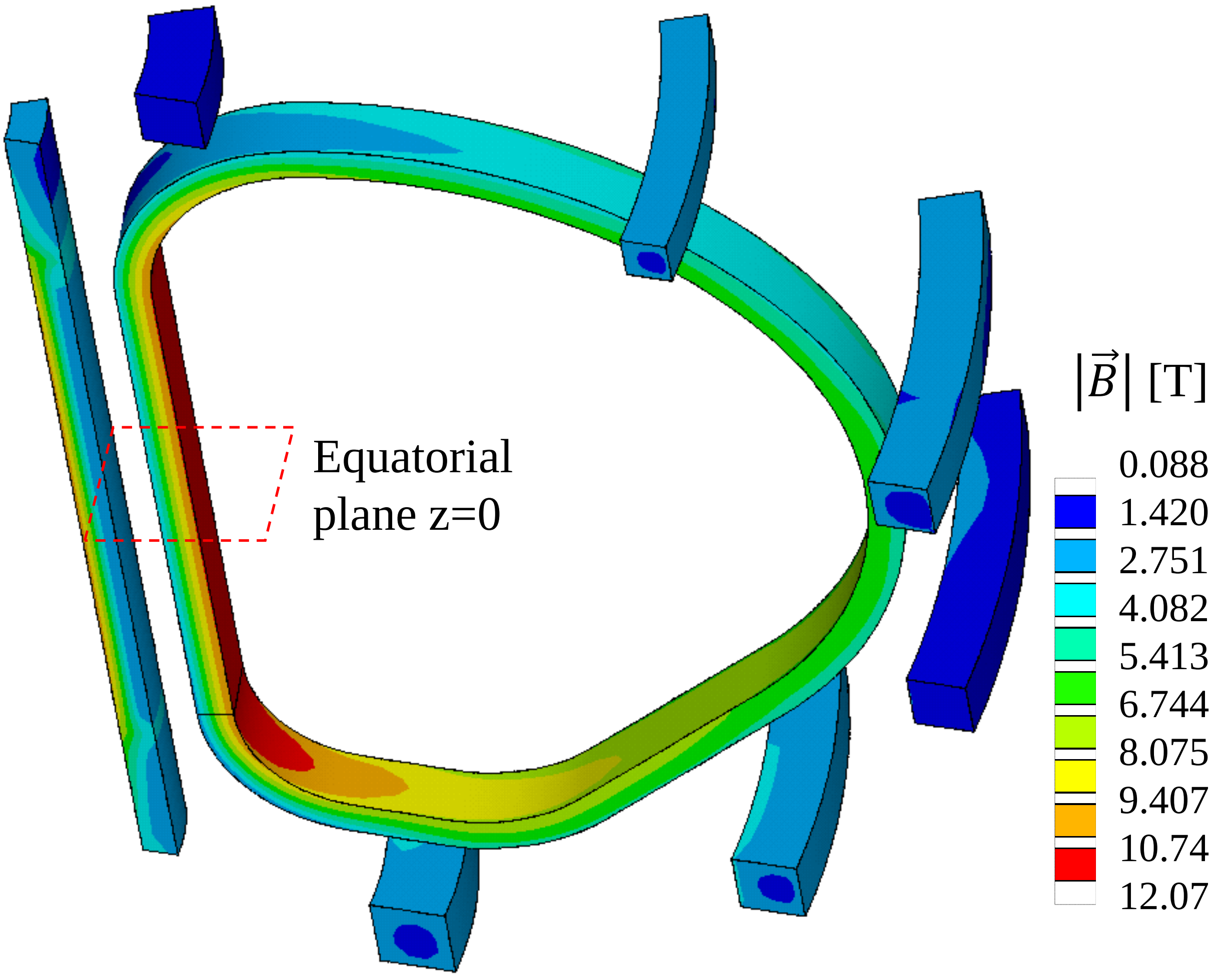


N=7

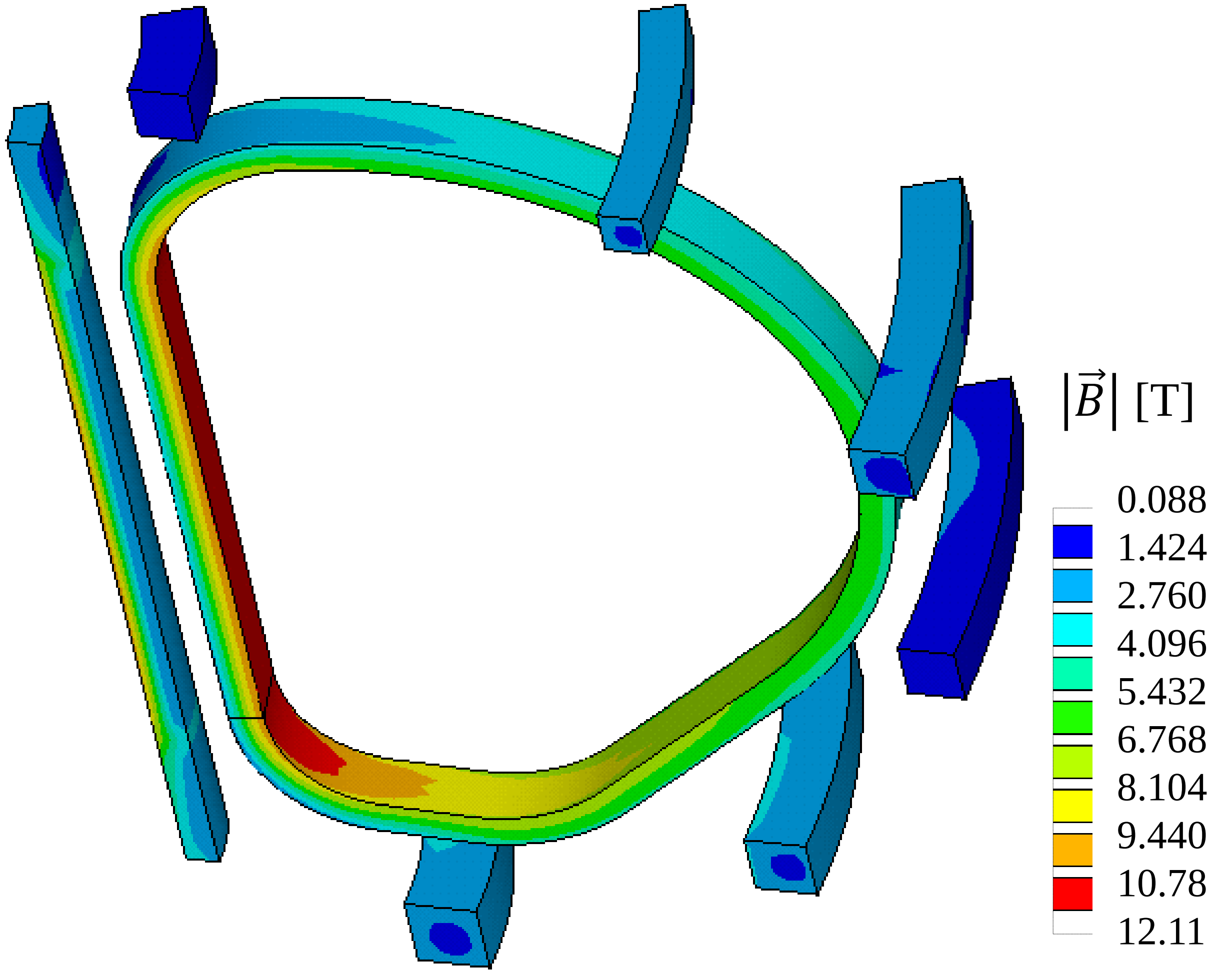


N=9

2. Electromagnetic modeling (6/10)

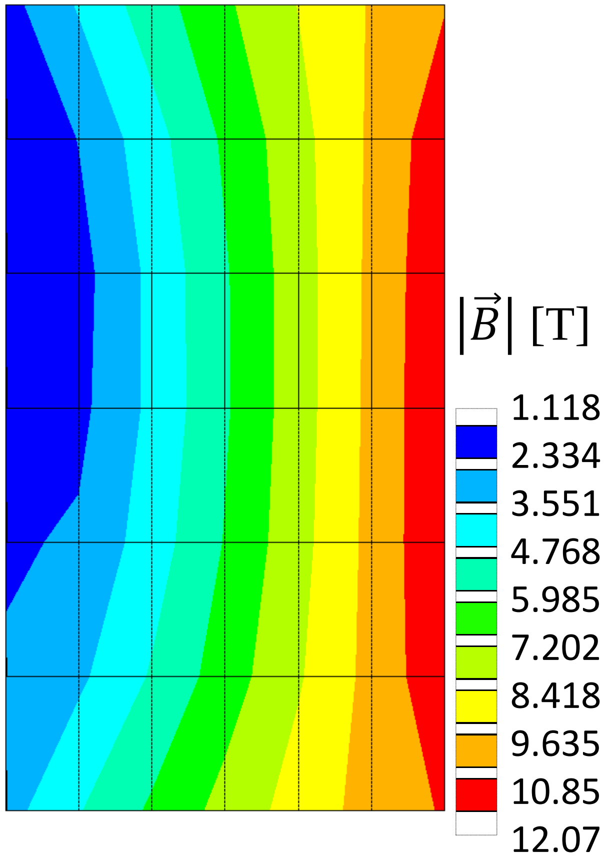


Homogenized model

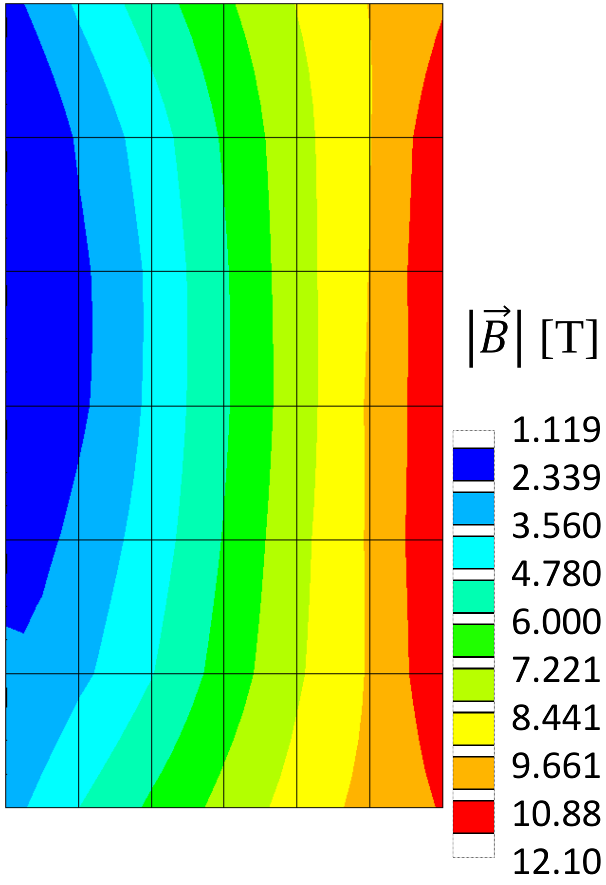


N=13

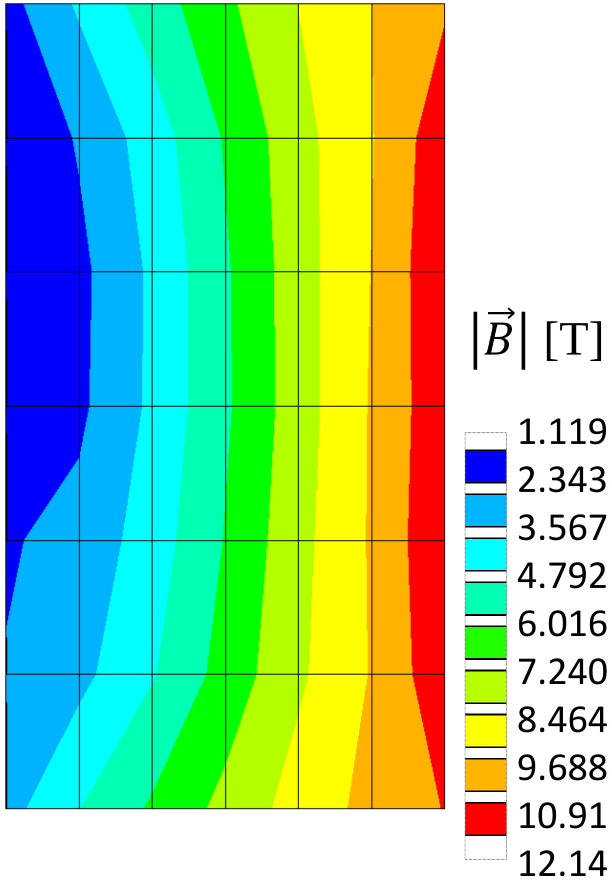
2. Electromagnetic modeling (7/10)



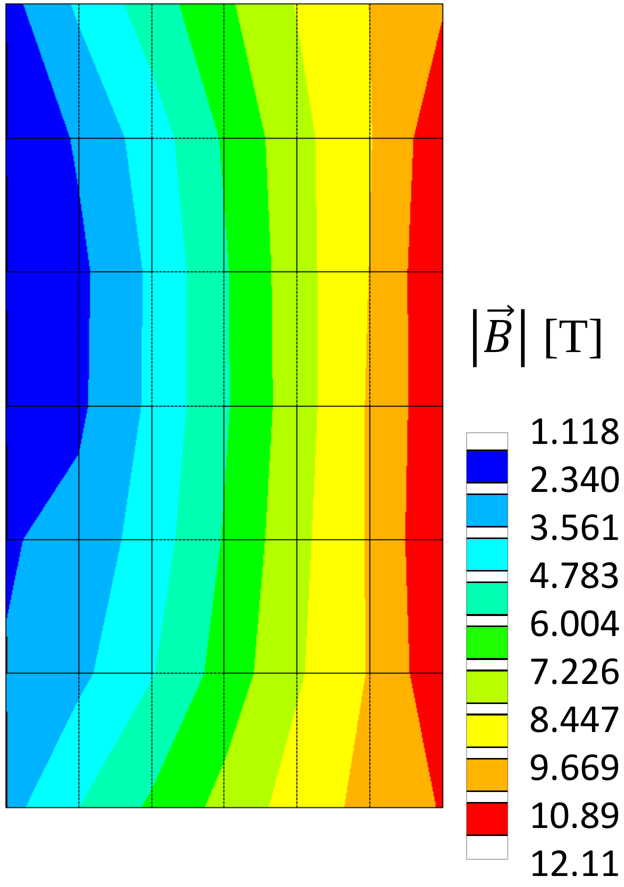
Homogenized model



N=1



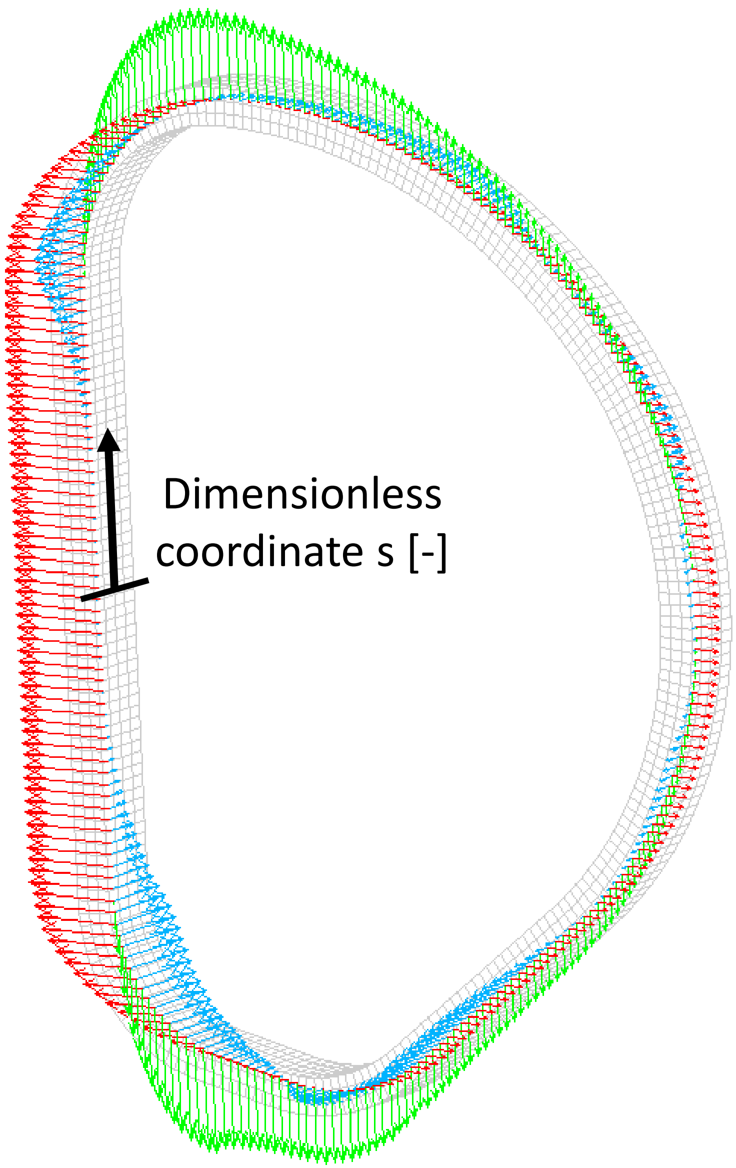
N=3

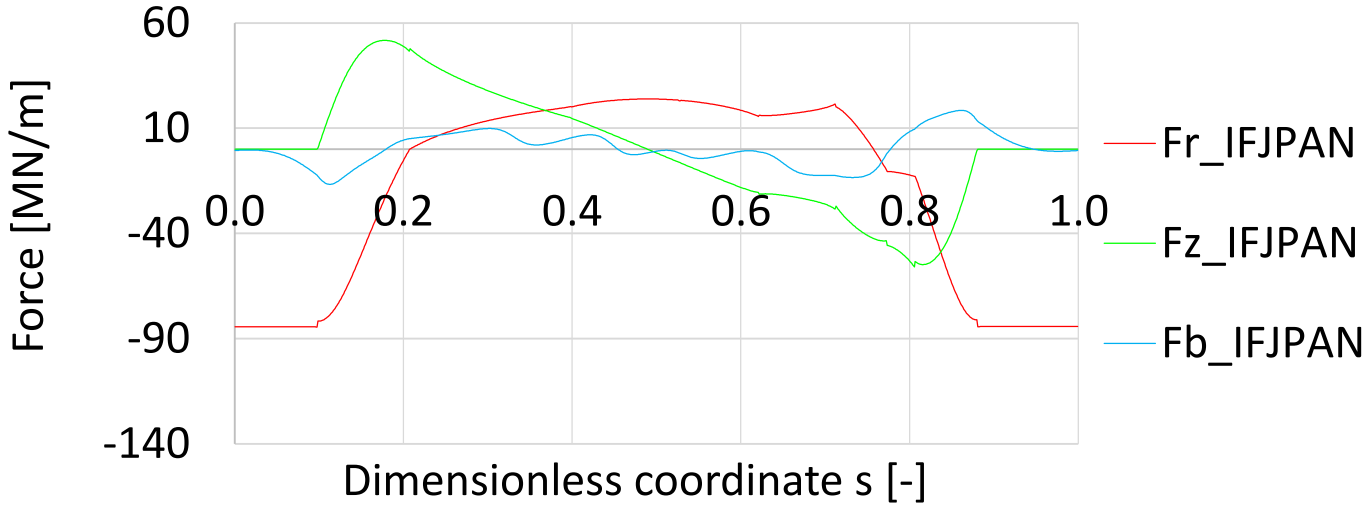


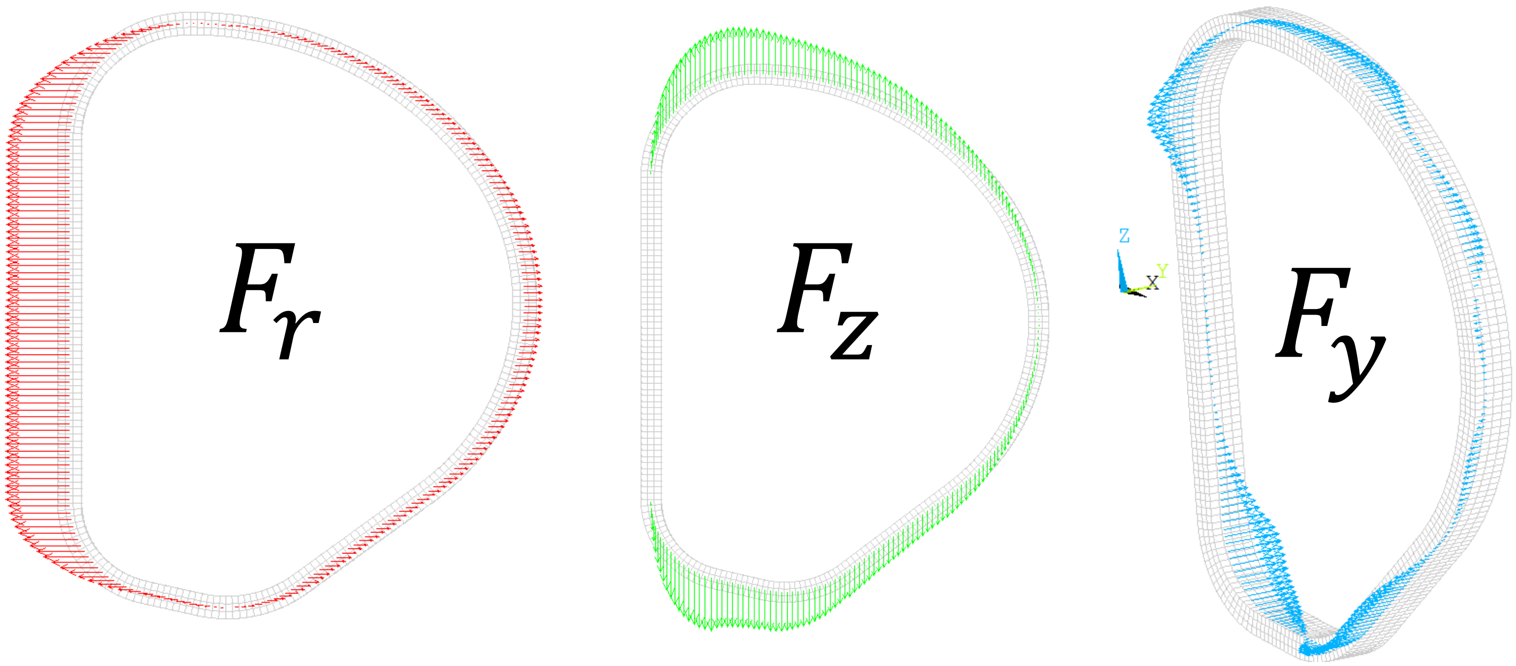
N=13

2. Electromagnetic modeling (8/10)

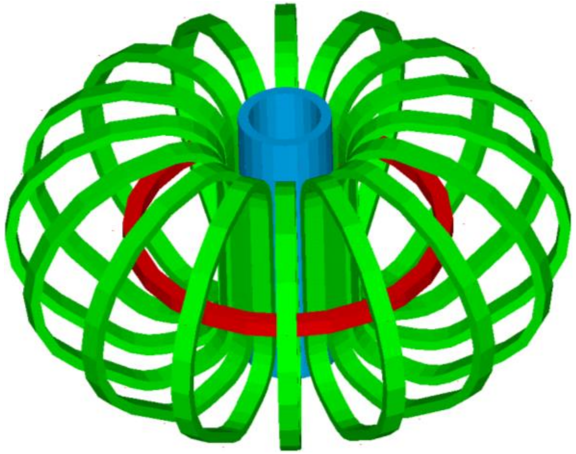
$$\vec{f} = \vec{j} \times \vec{B}$$





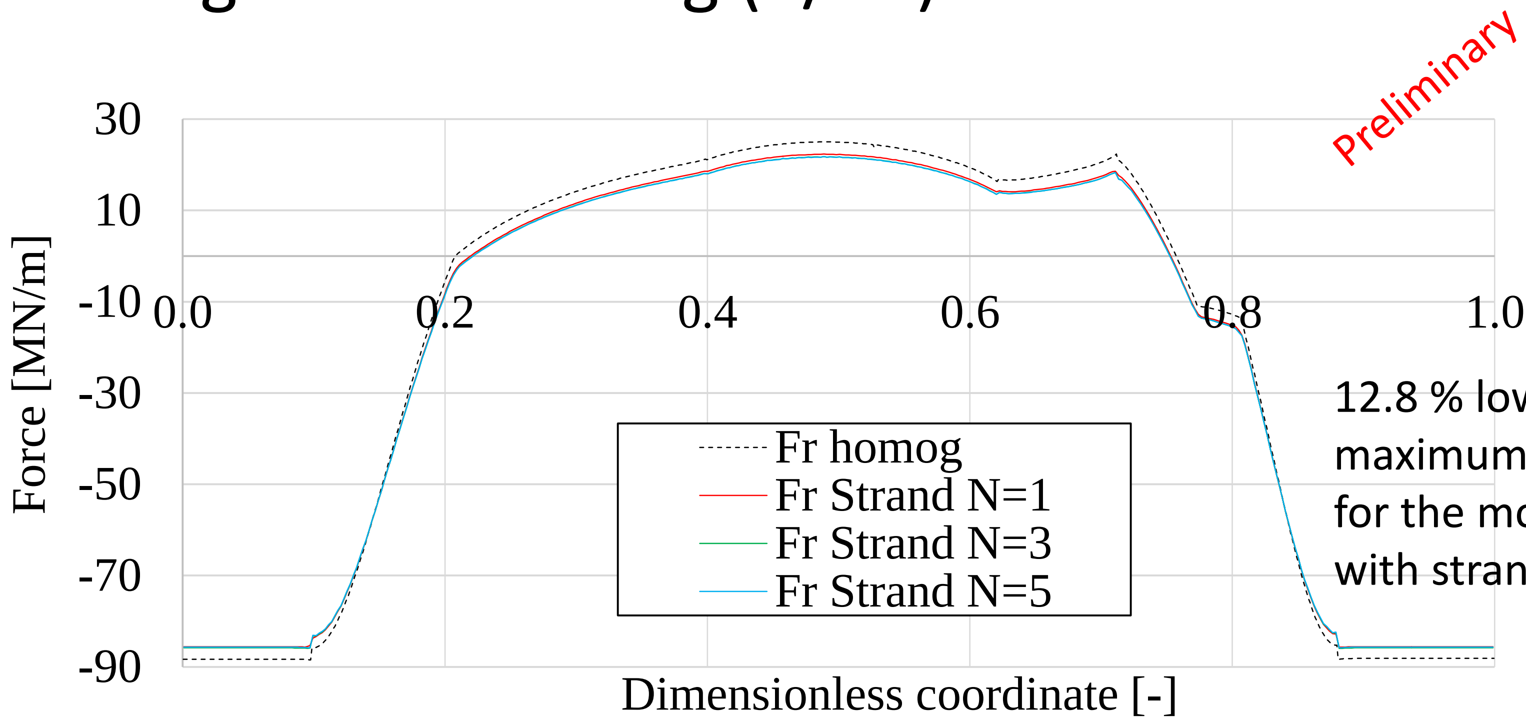


2. Electromagnetic modeling (9/10)

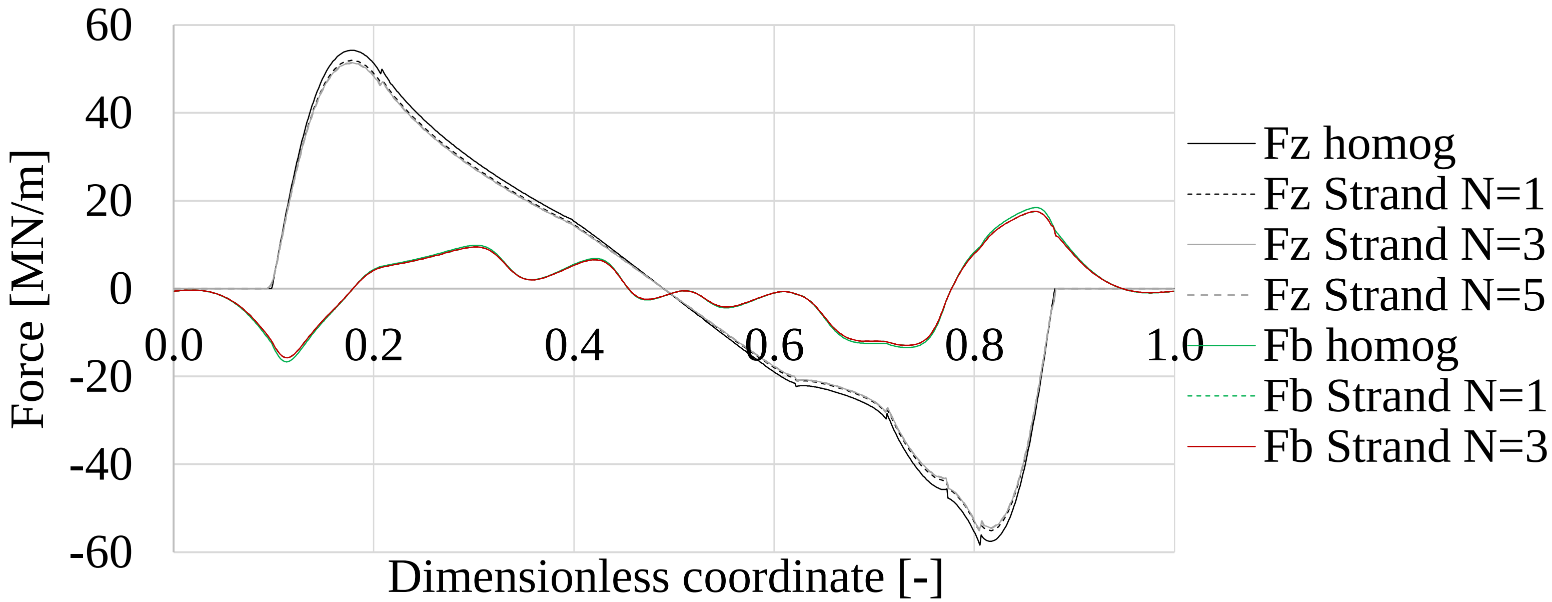


Single conductor for TF

TF strands modeled

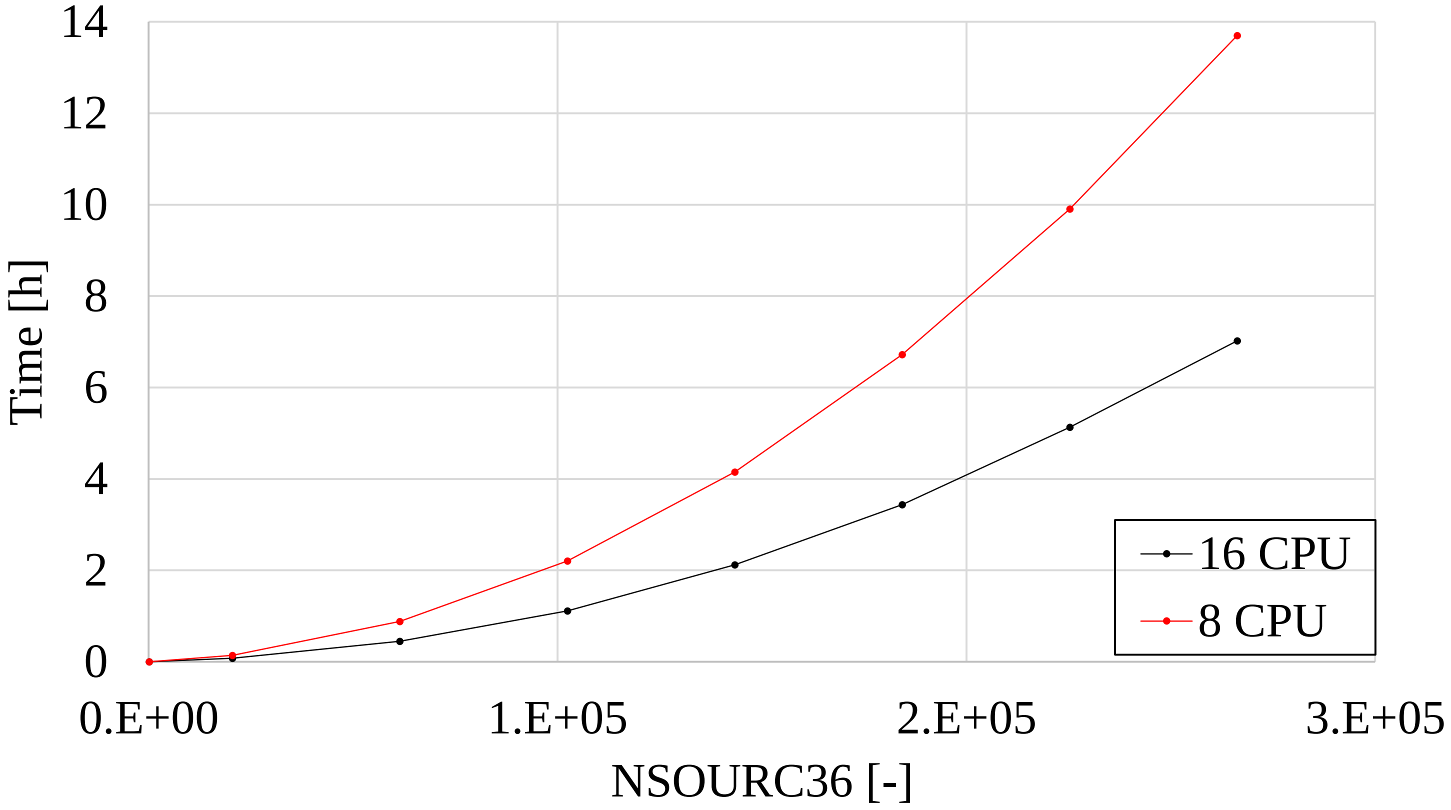


12.8 % lower maximum force for the model with strands

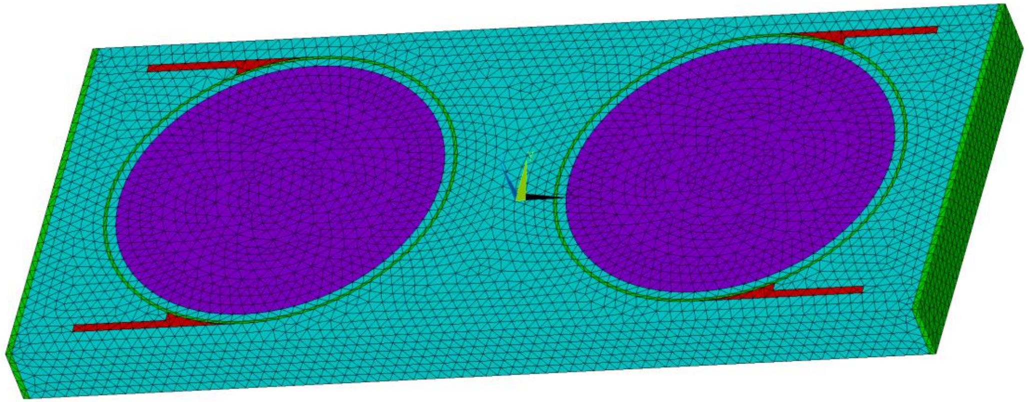


2. Electromagnetic modeling (10/10)

DELL 7920:
16 x 3.5 GHz CPU
792GB RAM DDR4, 2666 MHz



3. Homogenization (1/2)



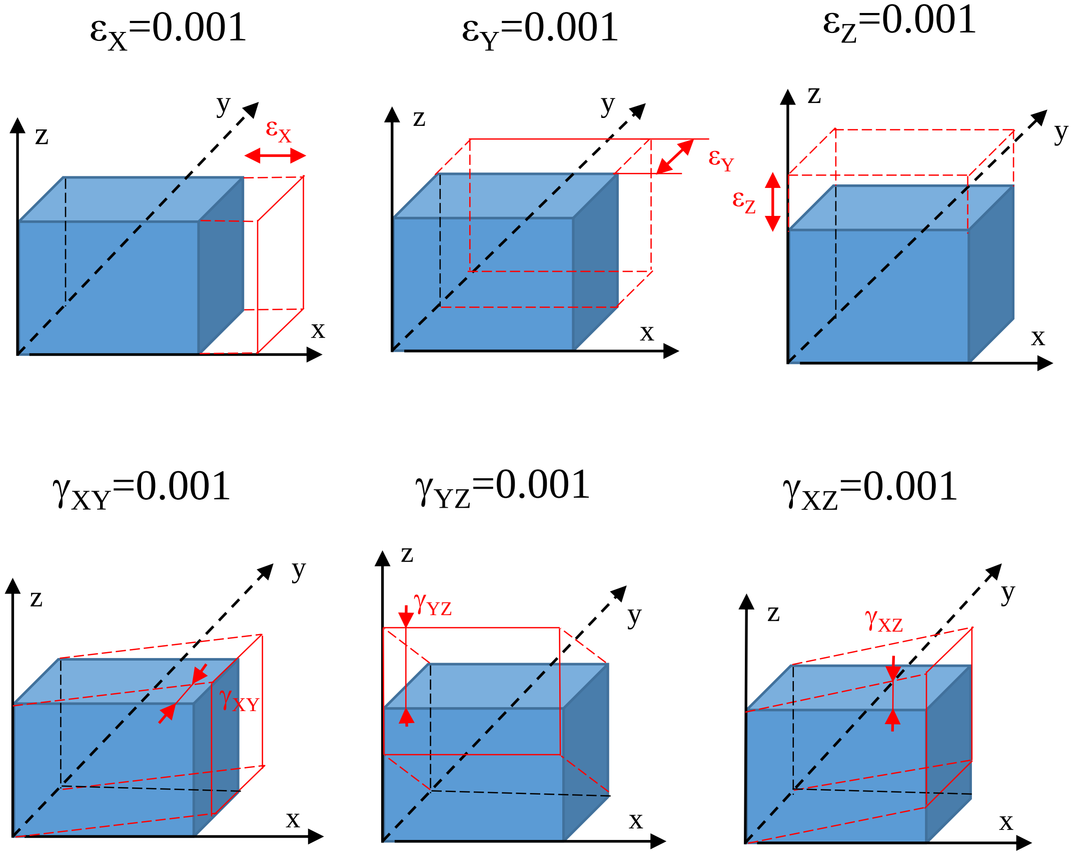
E=7 GPa, ν=0.3 (Resin)

E=1 GPa, ν=0.3 (CICC cable)

E=205 GPa, ν=0.29 (steel)

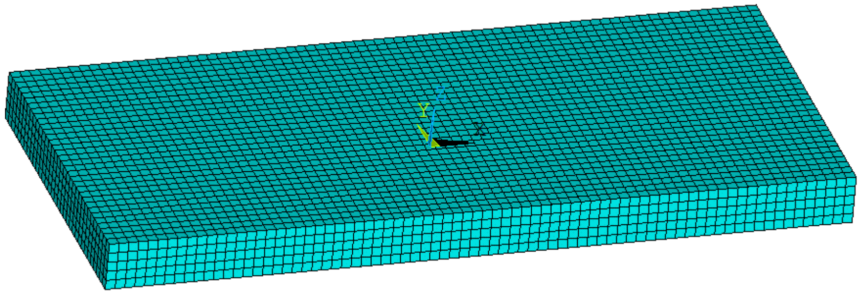
G10

E_X=12 GPa, E_Y=E_Z=20 GPa,
G_{XY}=G_{YZ}=G_{XZ}=6 GPa,
ν_{XY}=ν_{XZ}=0.2, ν_{YZ}=0.17

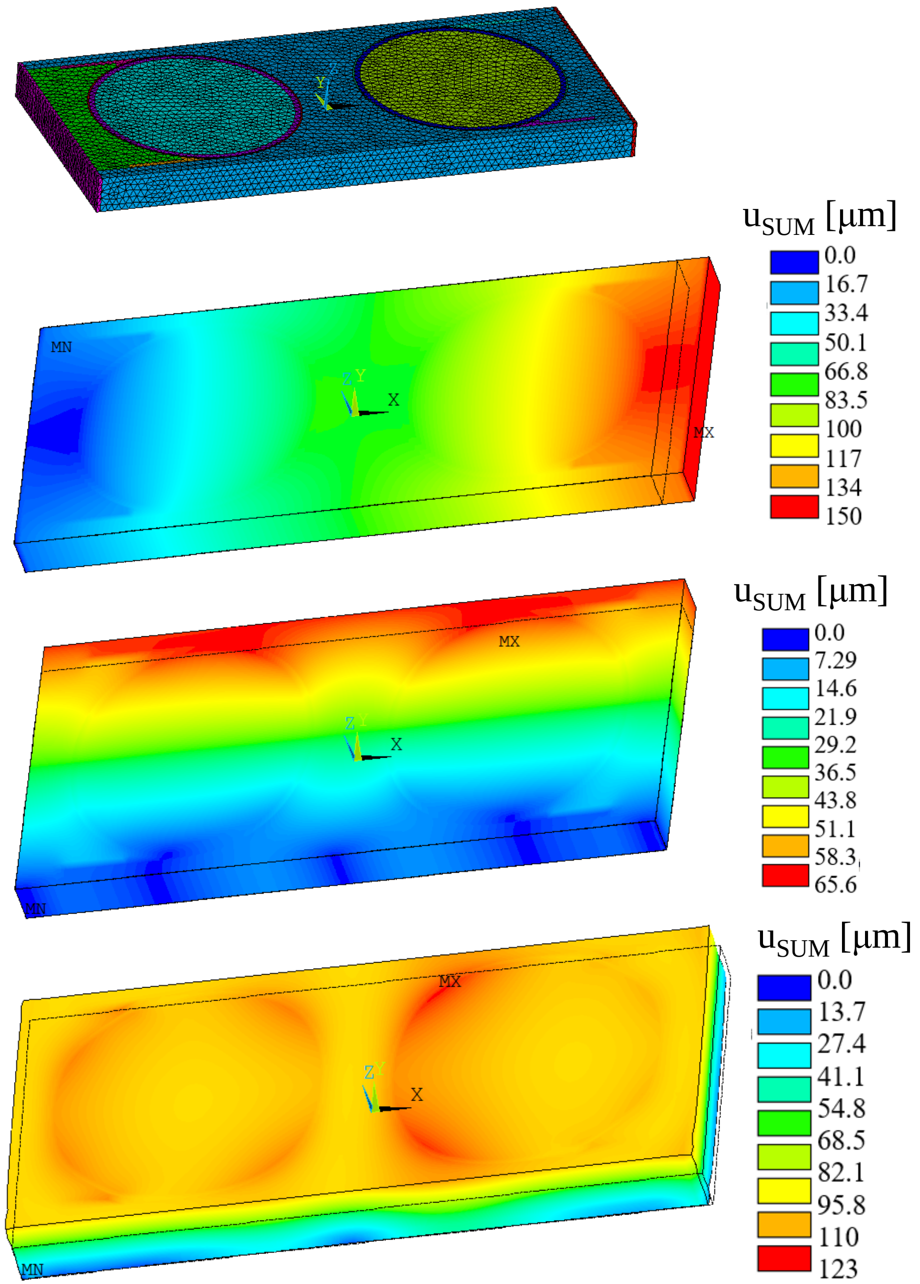


Constant
E_X
E_Y
E_Z
ν_{XY}
ν_{YZ}
ν_{XZ}
G_{XY}
G_{YZ}
G_{XZ}

Homogenized model



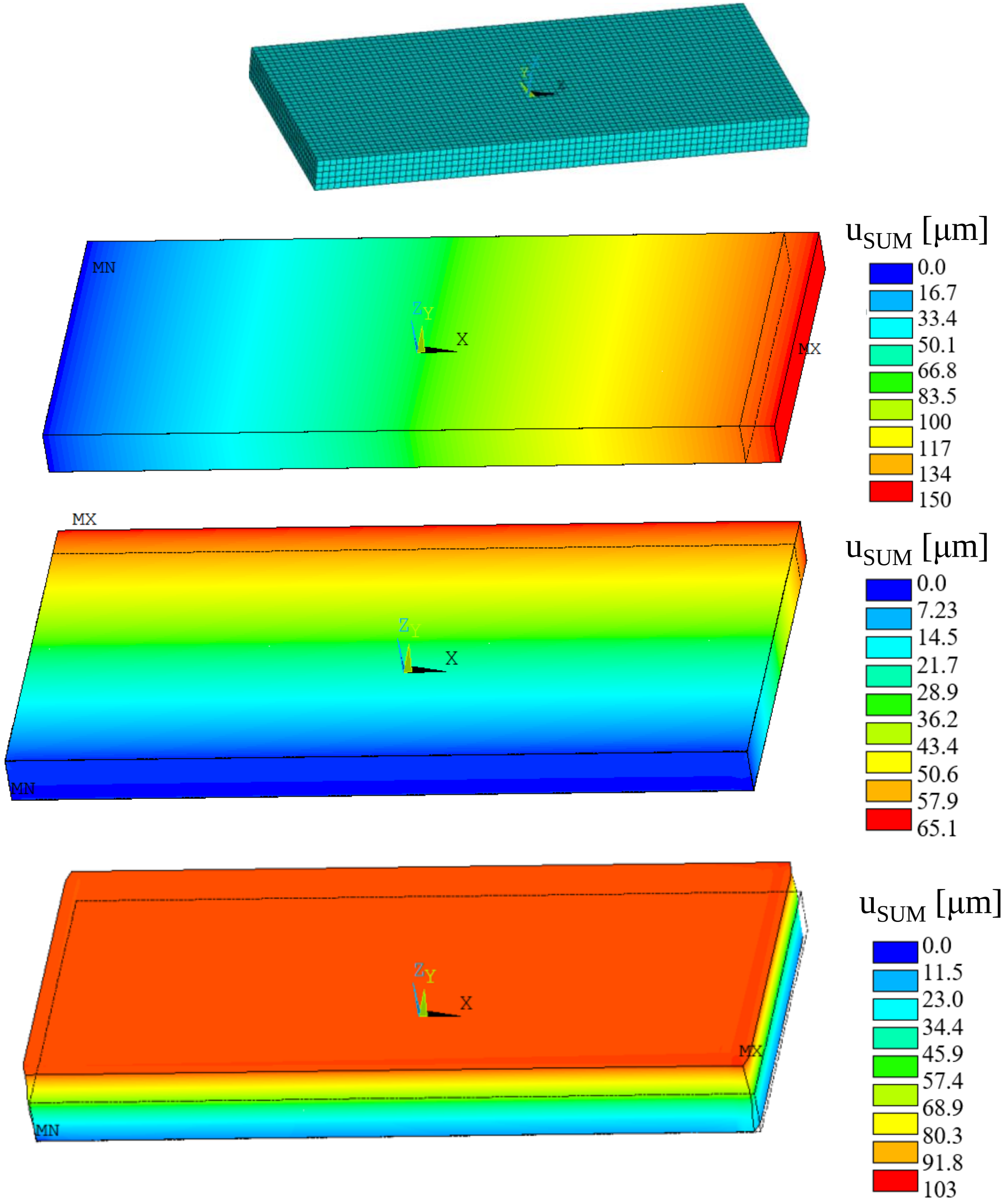
3. Homognization(2/2)



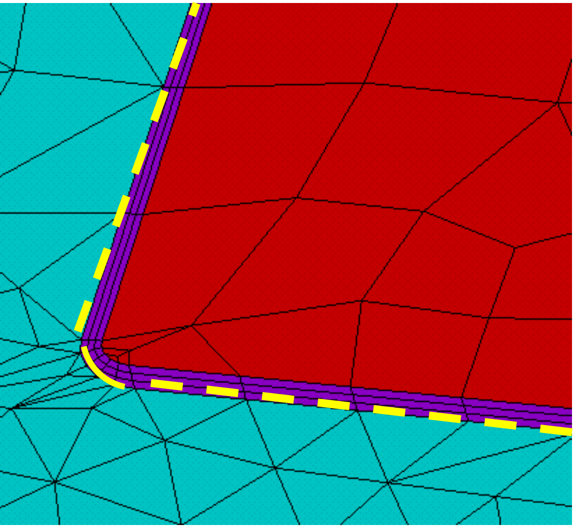
ε_X=0.001

ε_Y=0.001

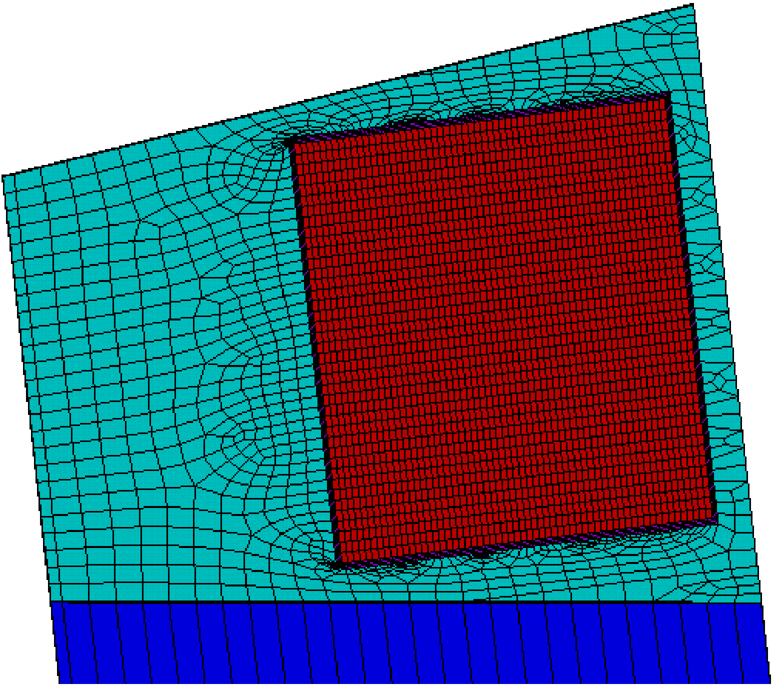
ε_Z=0.001

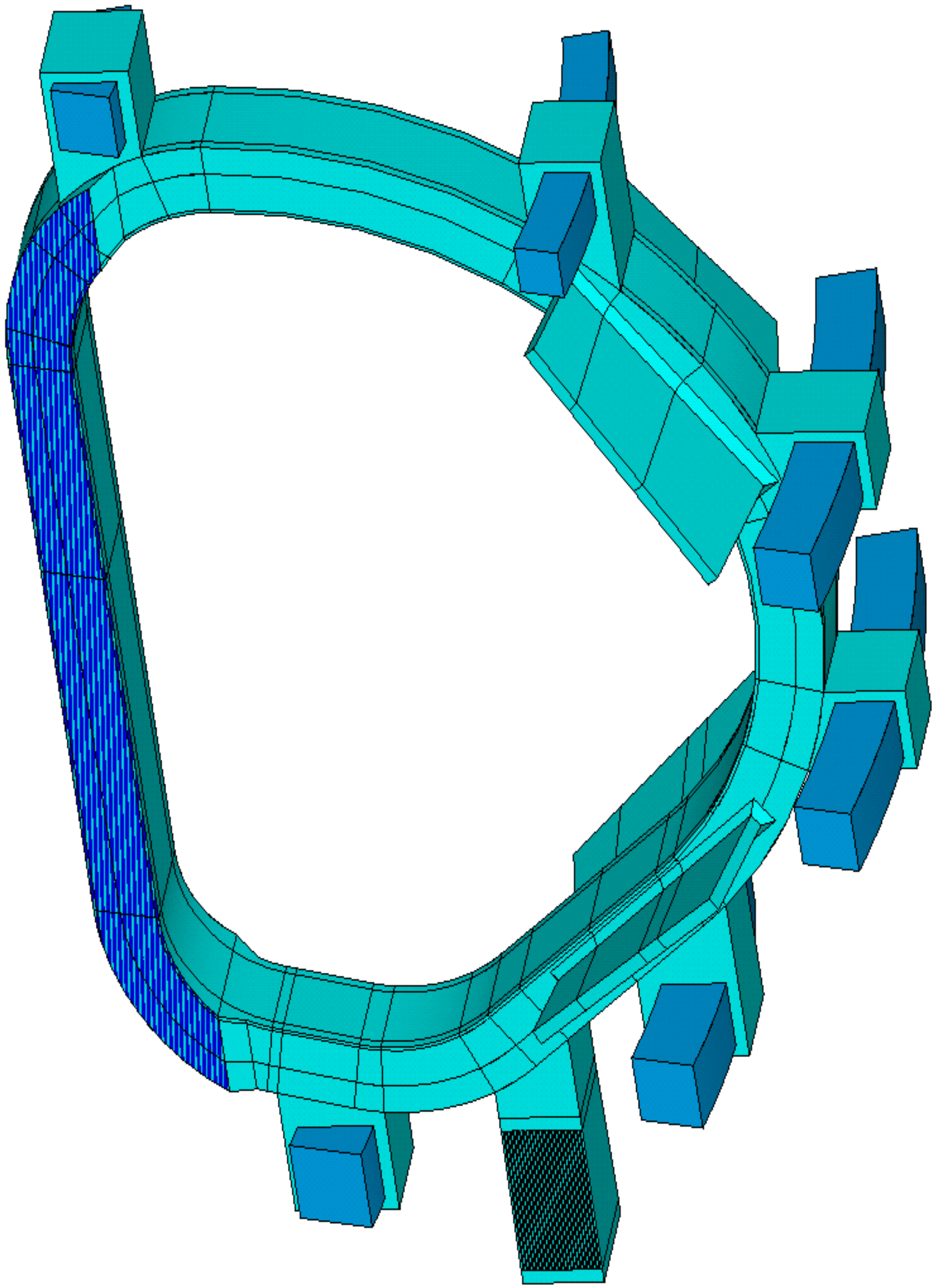


4. 3D mechanical model - homogenized

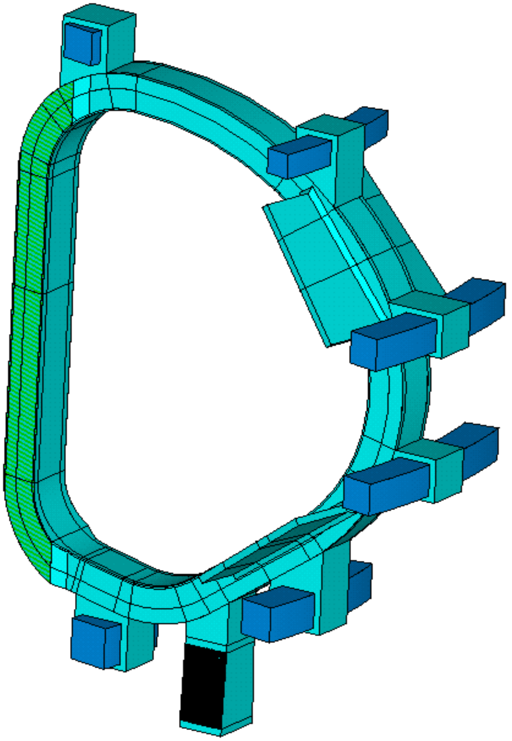


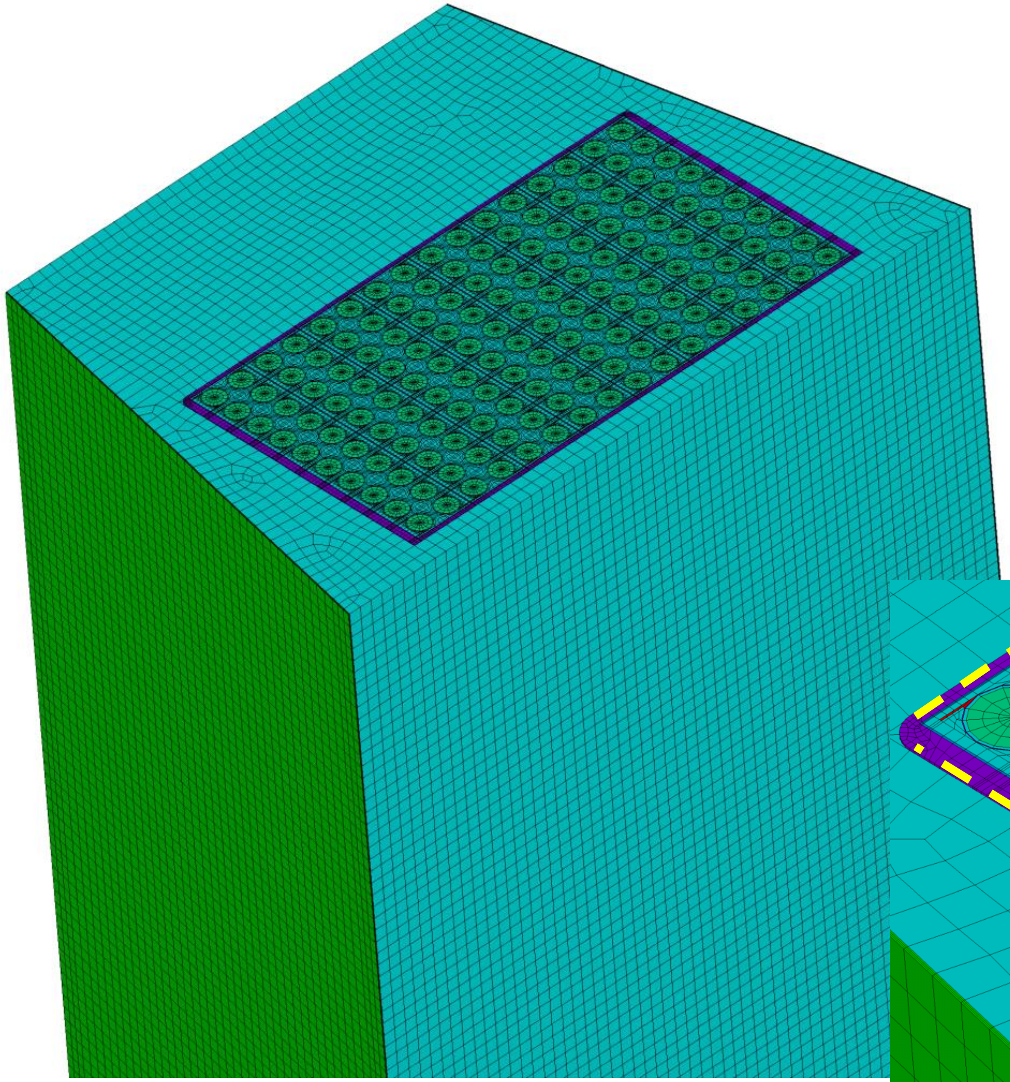
Frictional contact

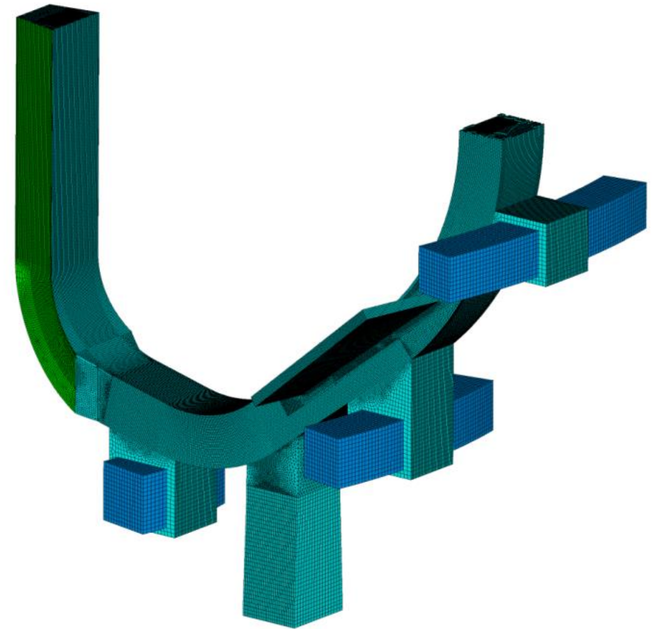




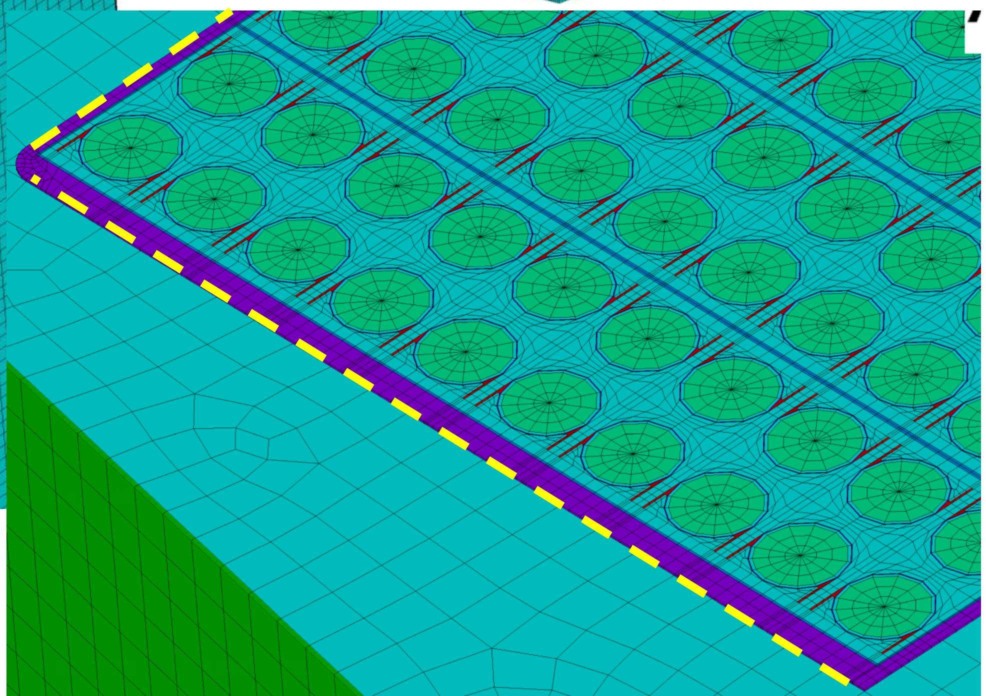
5. 3D mechanical model – detailed (1/5)



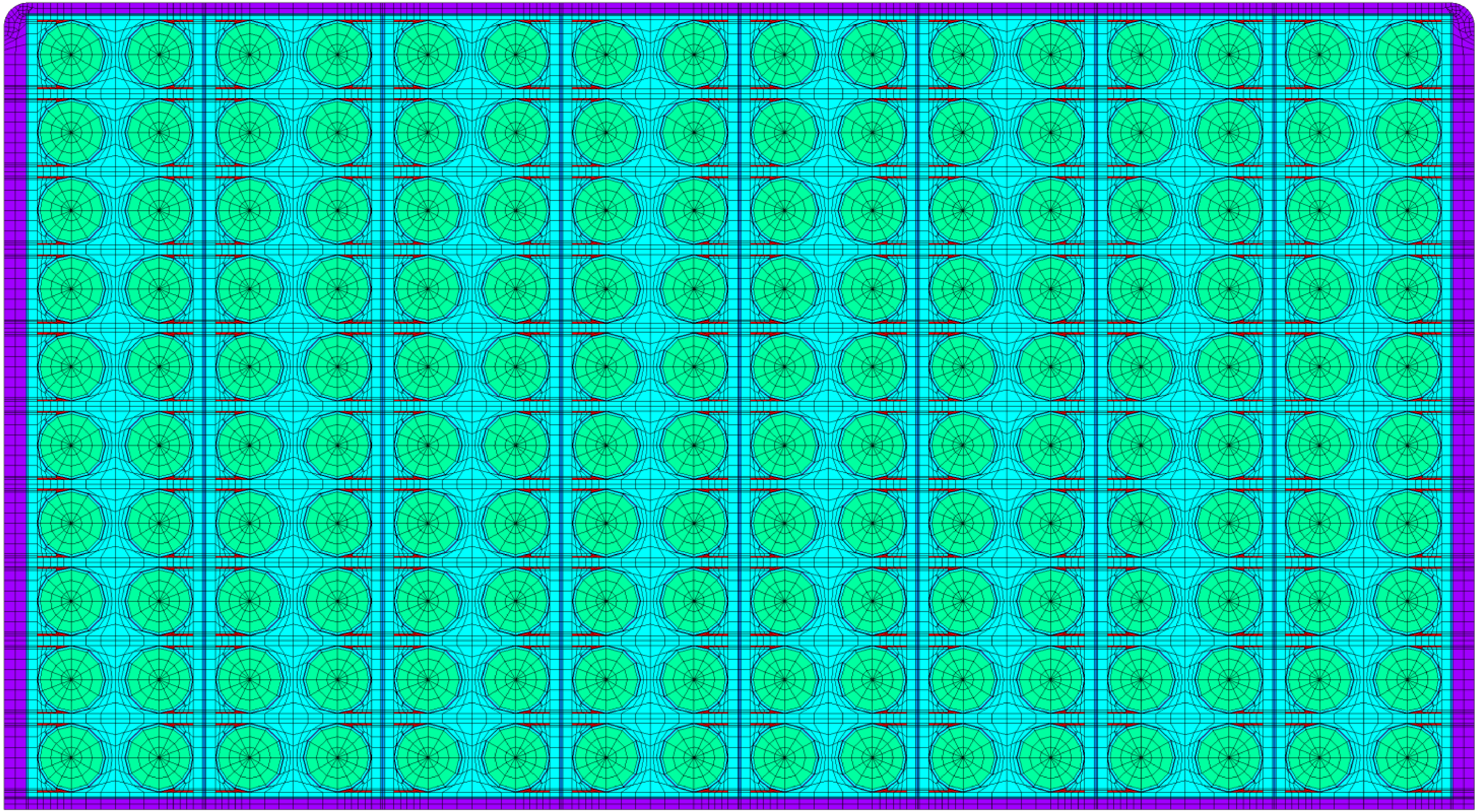




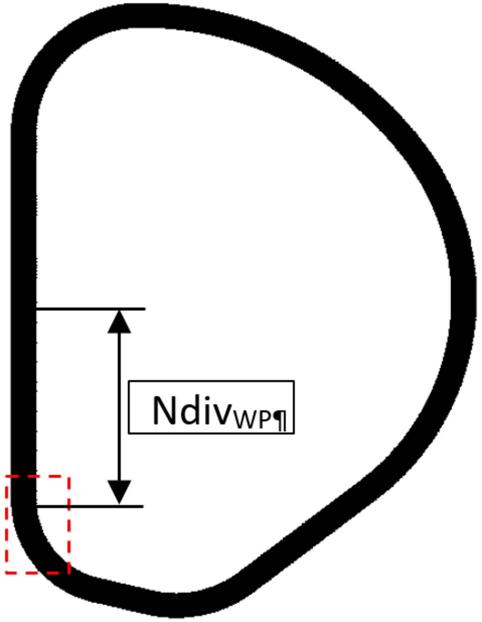
Frictional contact

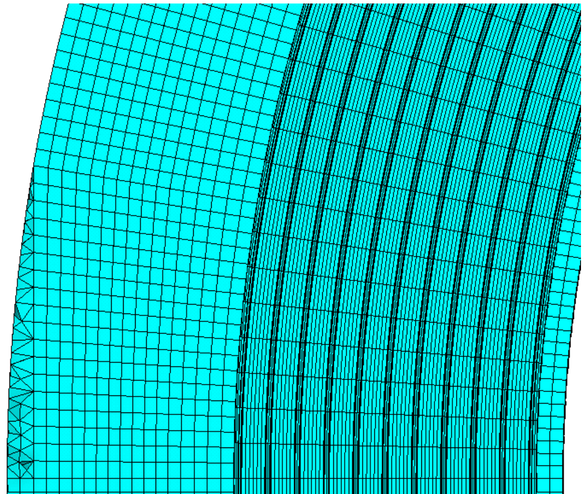


5. 3D mechanical model – detailed (2/5)

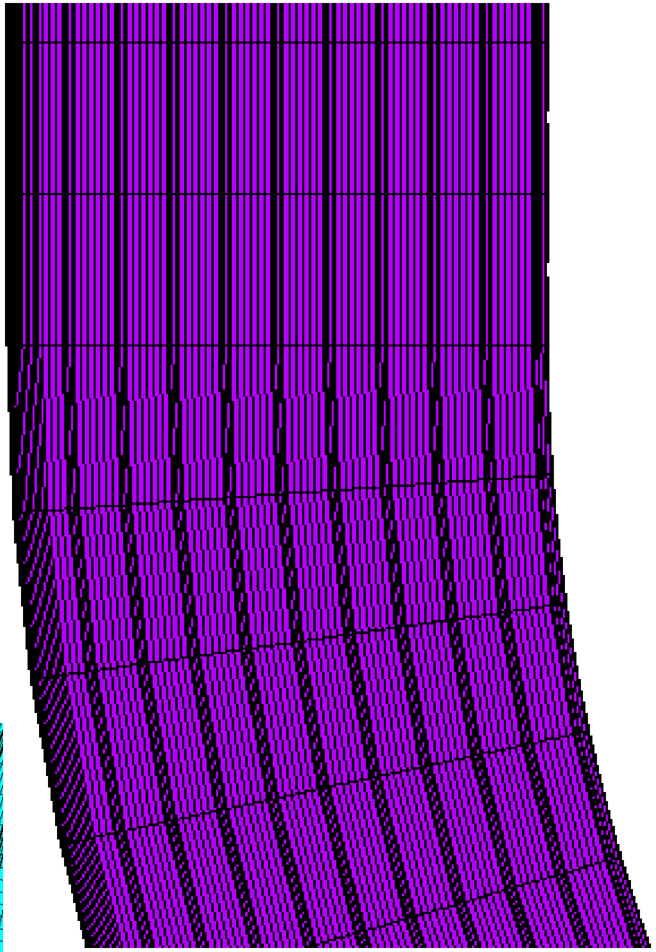


5. 3D mechanical model – detailed (3/5)





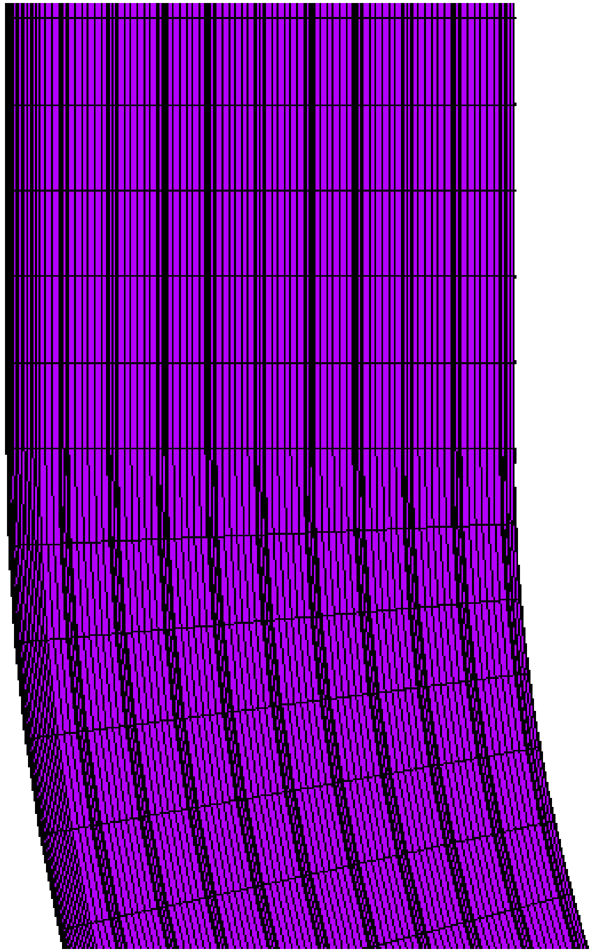
Mesh M1



$Ndiv_{WP}$=30

E_{ALL} [mln]=11.4
N_{ALL} [mln]=9.9

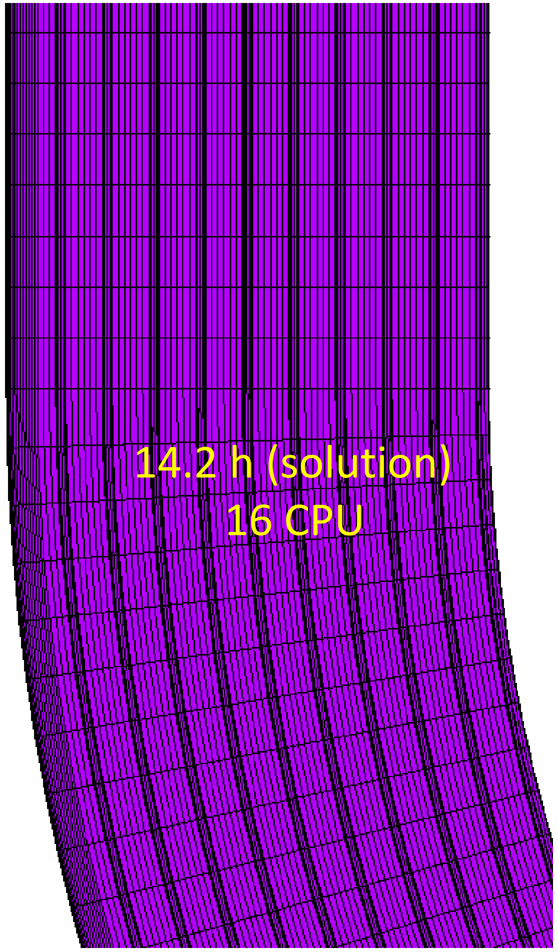
Mesh M2



$Ndiv_{WP}$=50

E_{ALL} [mln]=16.2
N_{ALL} [mln]=14.4

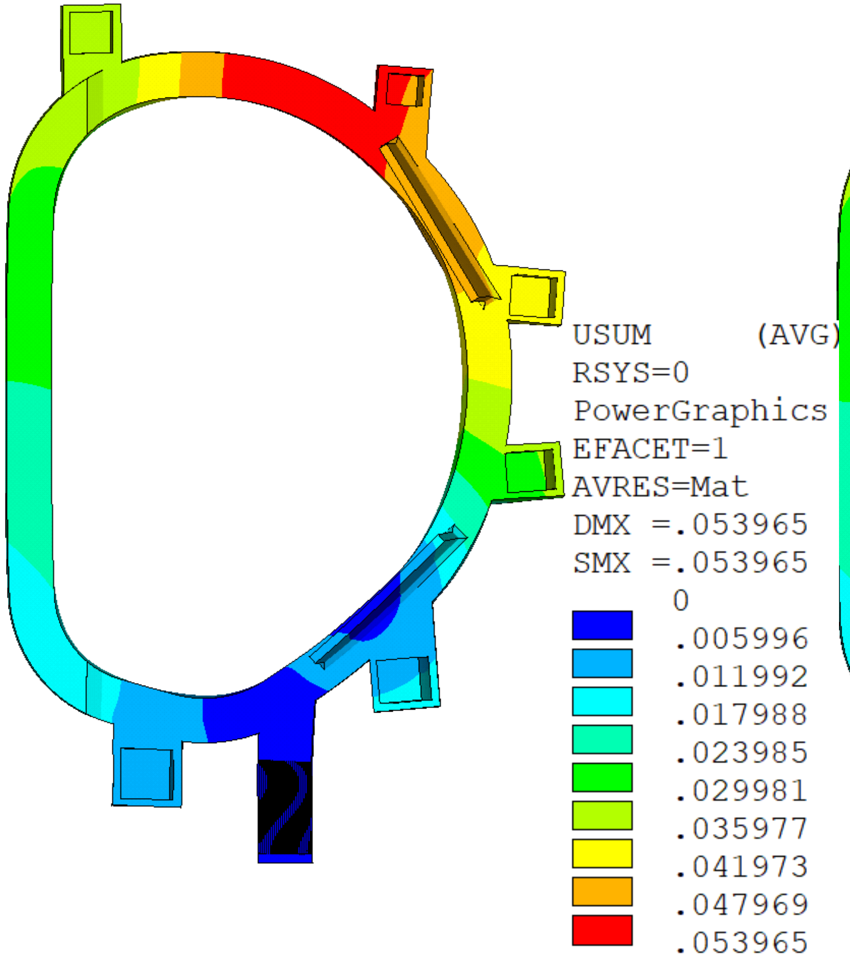
Mesh M3



$Ndiv_{WP}$=80

E_{ALL} [mln]=23.3
N_{ALL} [mln]=21.2

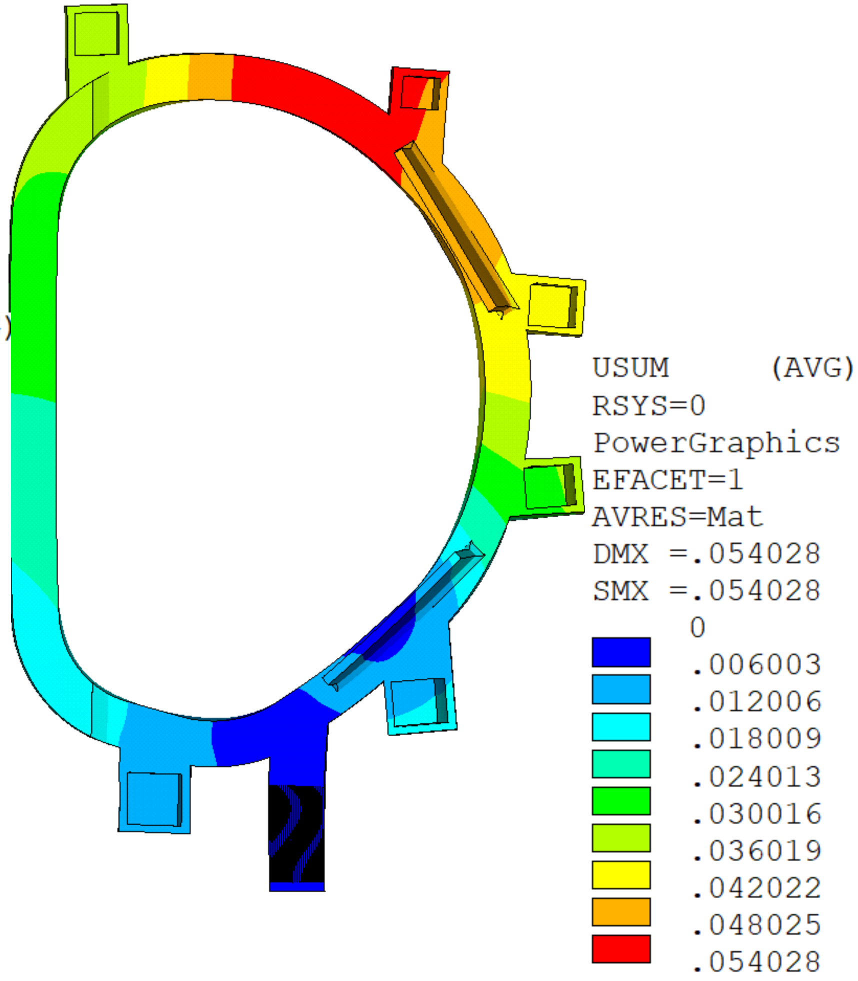
5. 3D mechanical model – detailed (4/5)



Mesh M1

E_{ALL} [mln]=11.4

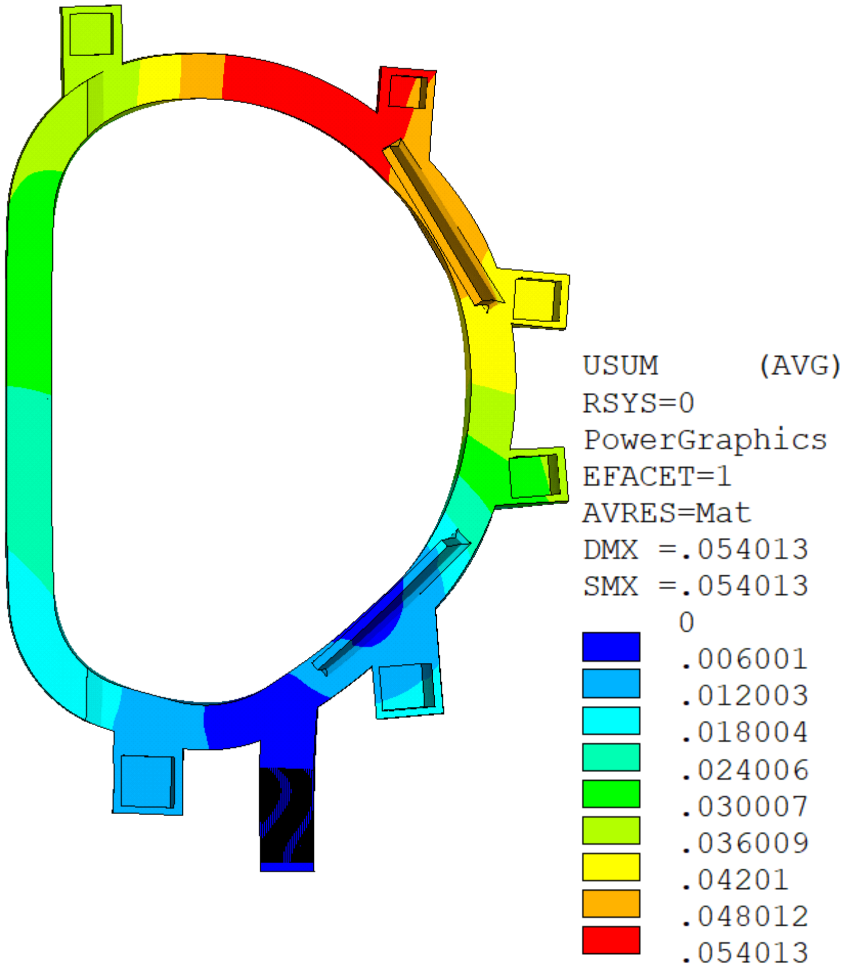
N_{ALL} [mln]=9.9



Mesh M2

E_{ALL} [mln]=16.2

N_{ALL} [mln]=14.4

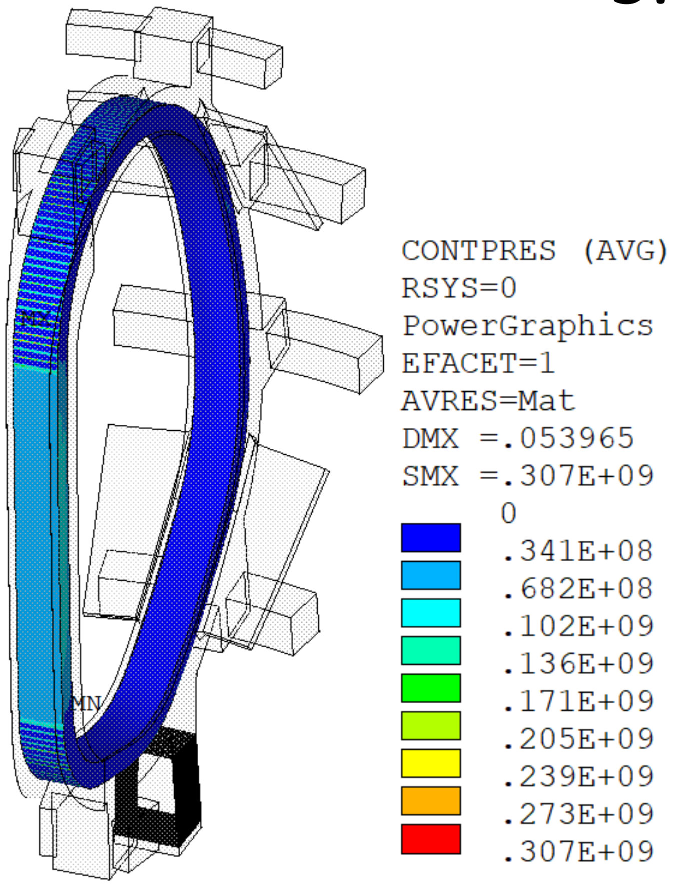


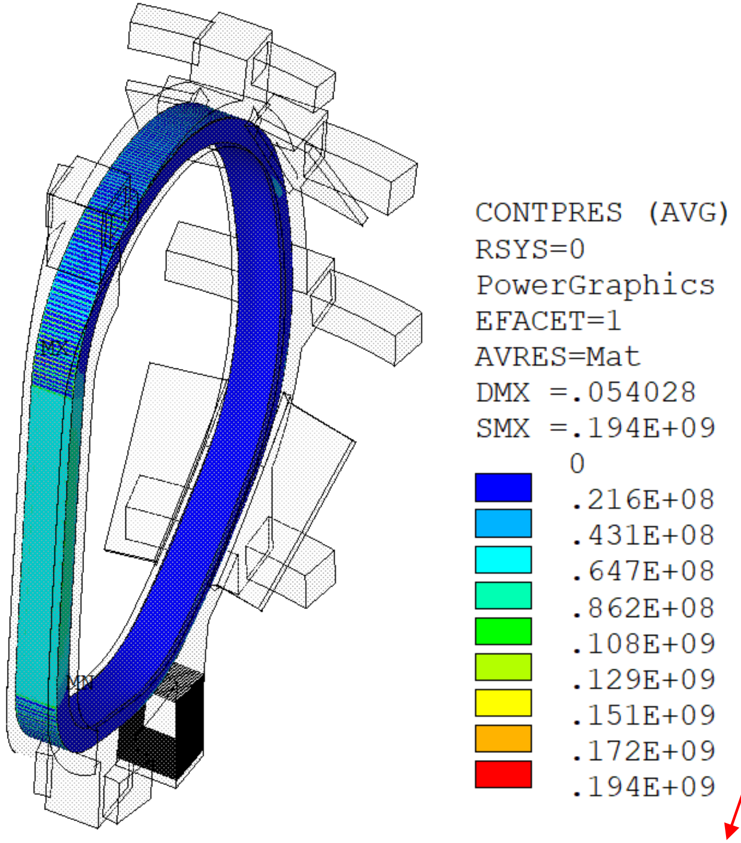
Mesh M3

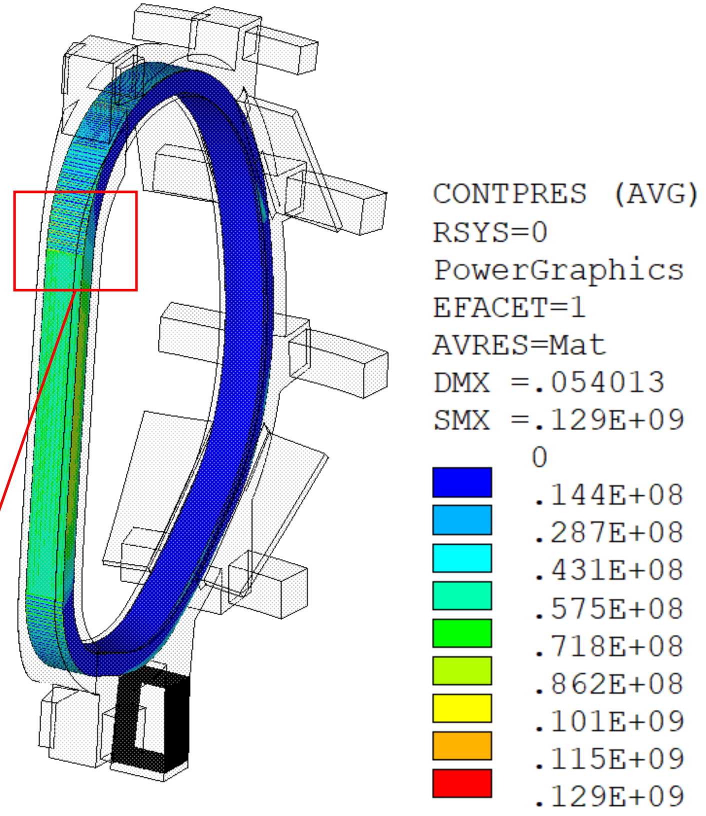
E_{ALL} [mln]=23.3

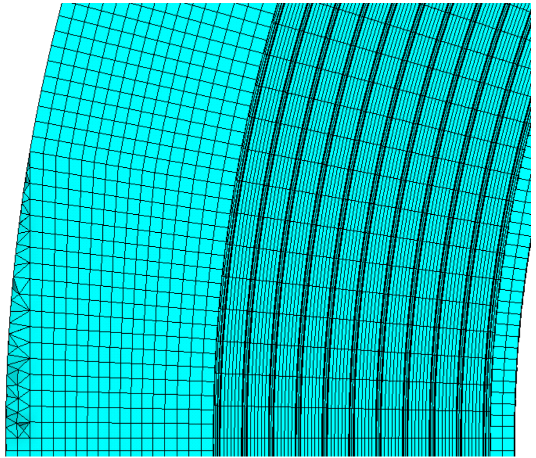
N_{ALL} [mln]=21.2

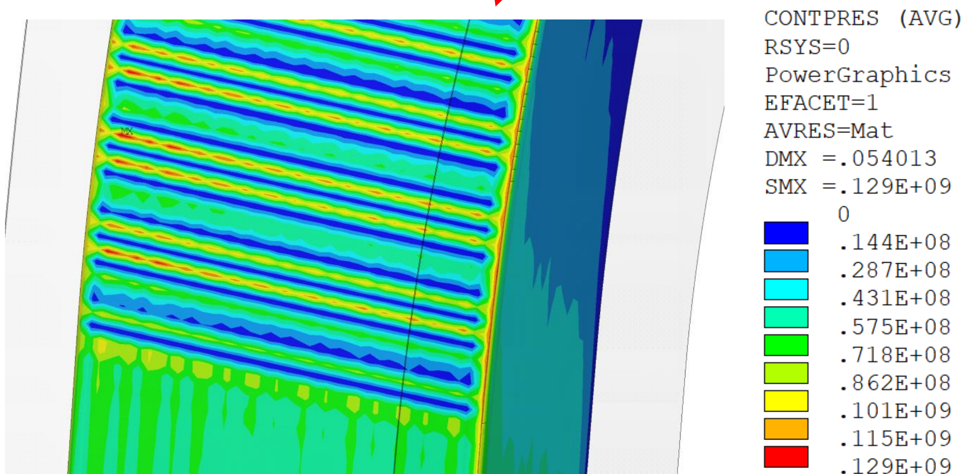
5. 3D mechanical model – detailed (5/5)





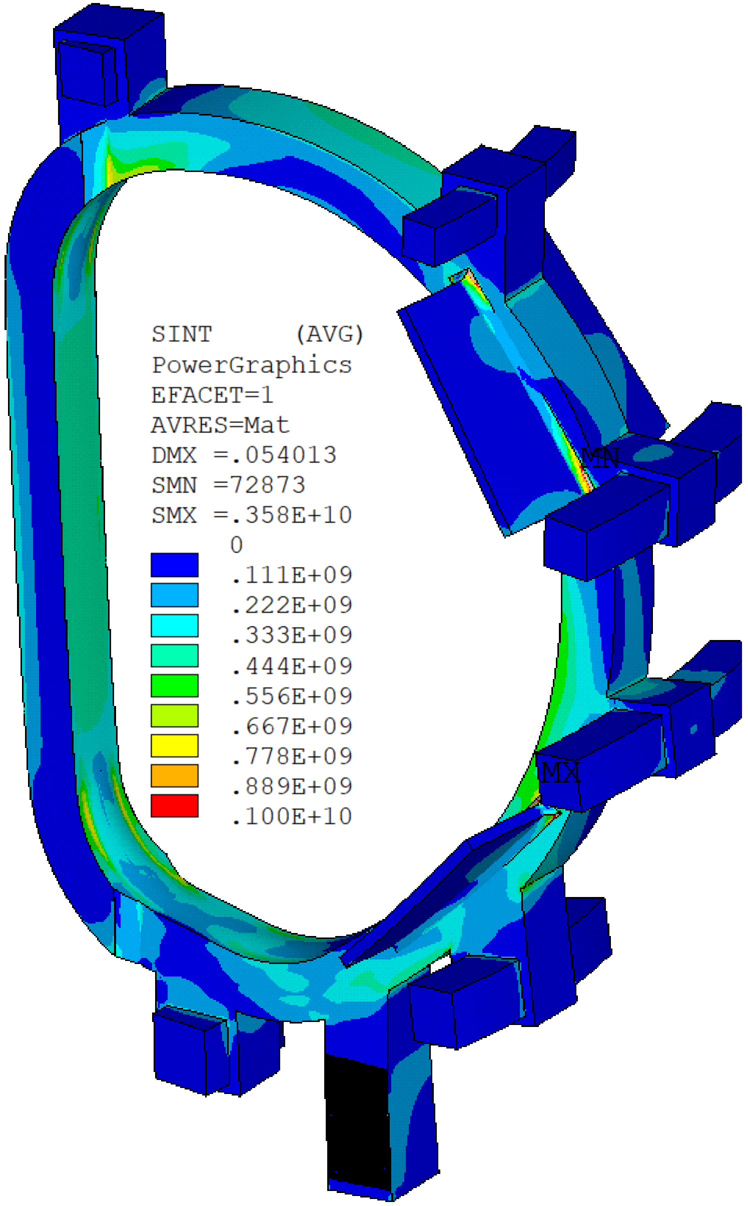




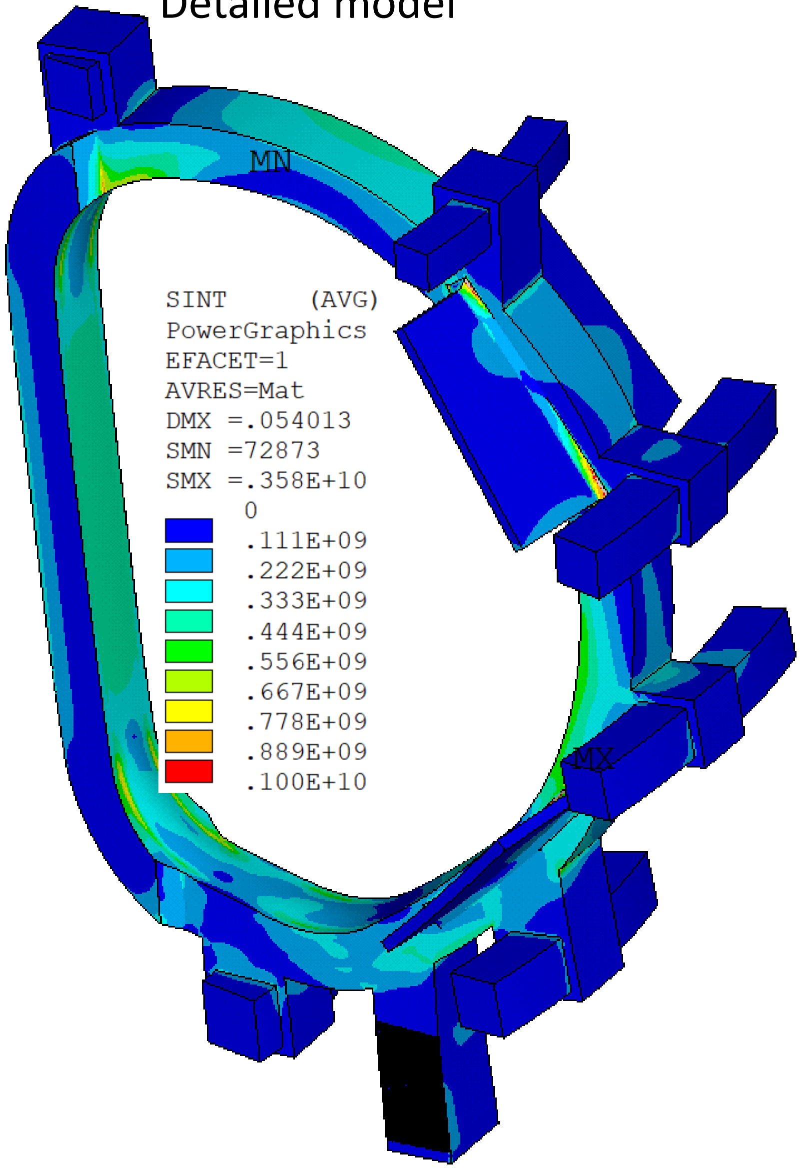


6. Homogenized vs detailed model - results

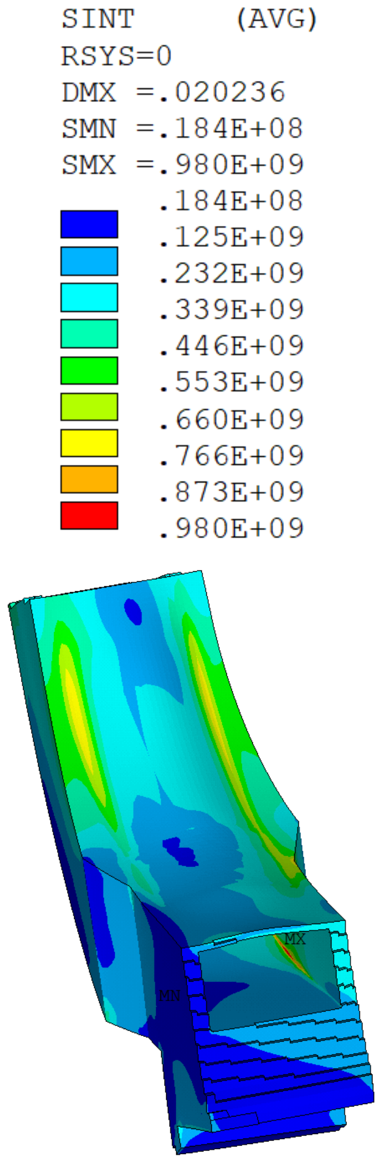
Homogenized model



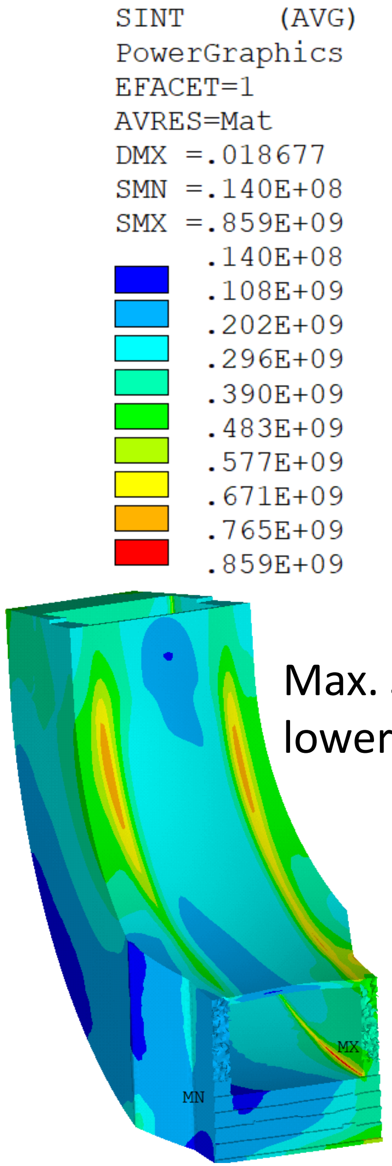
Detailed model



Homogenized model

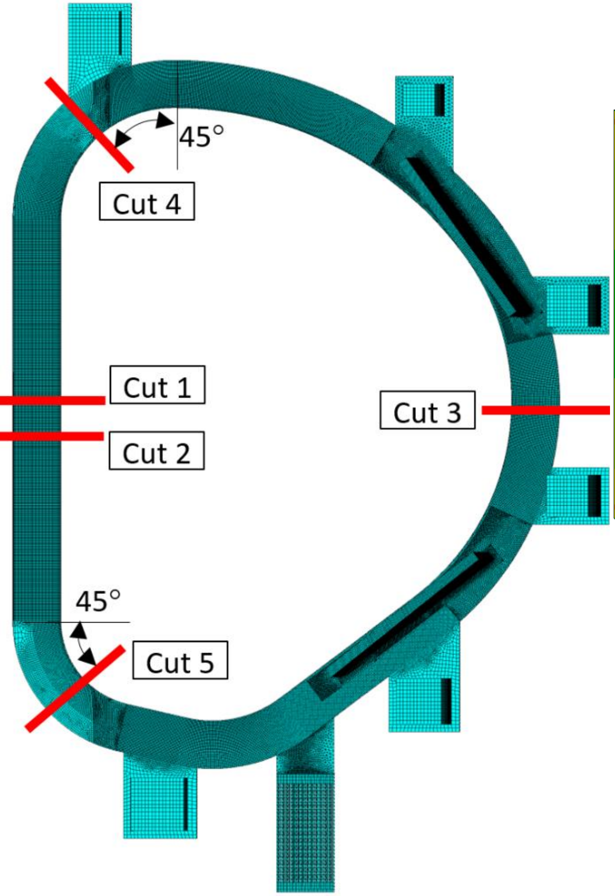


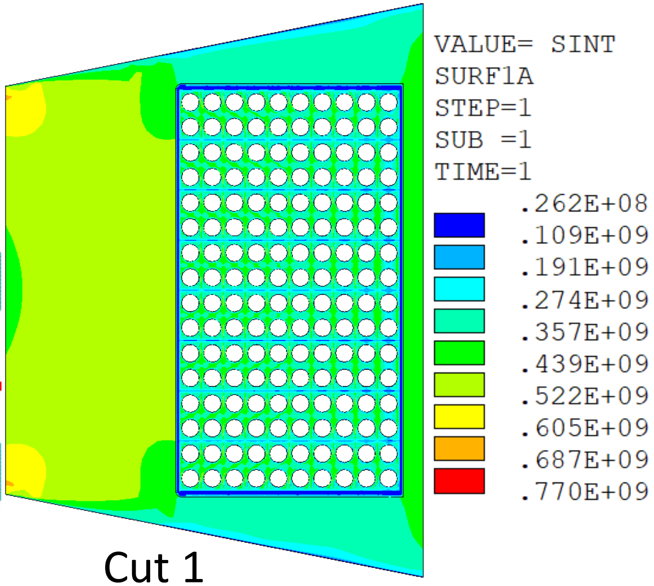
Detailed model



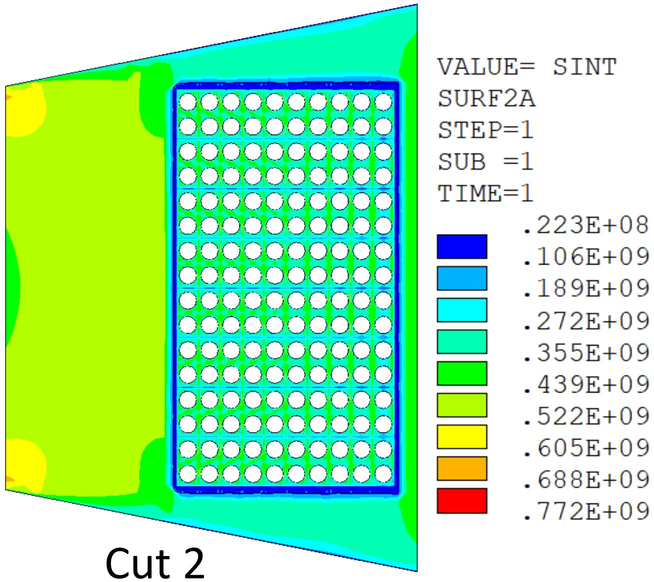
Max. Stress
lower by 12 %

7. 2D cuts from the deetailed model (1/2)

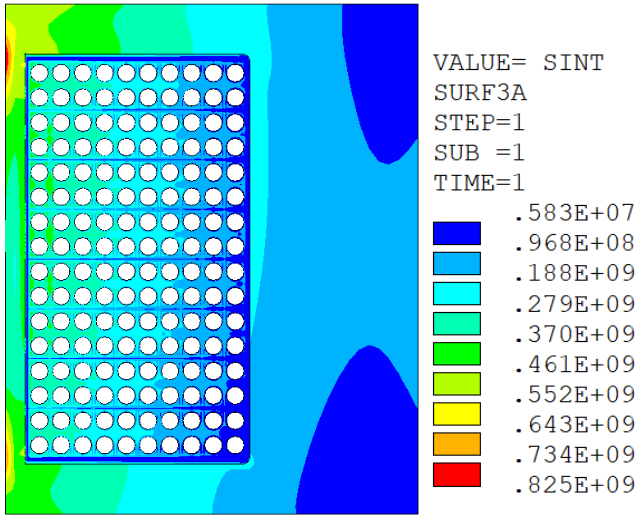




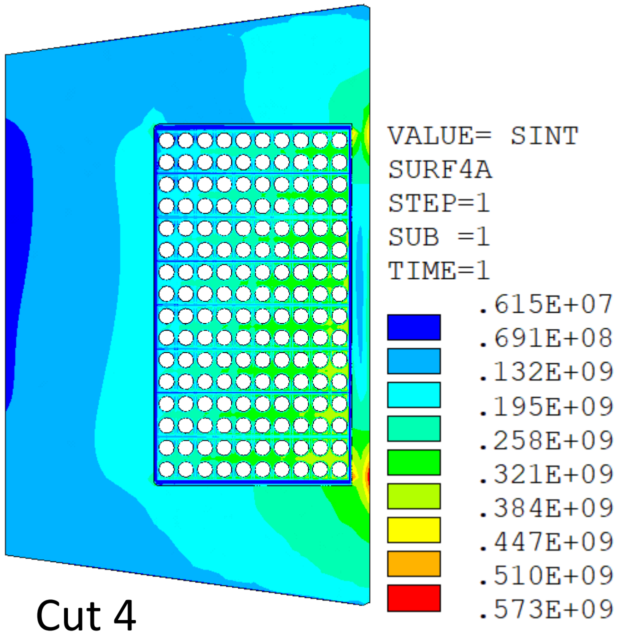
Cut 1



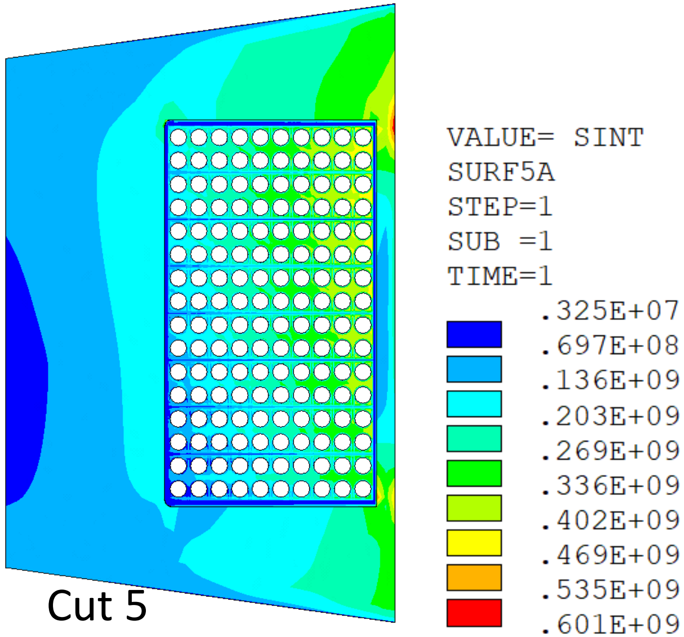
Cut 2



Cut 3

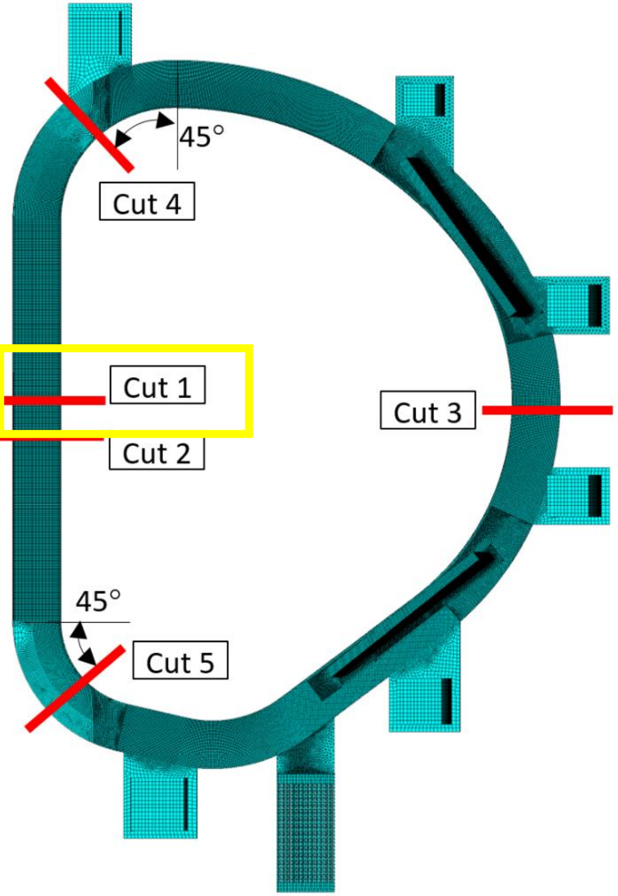


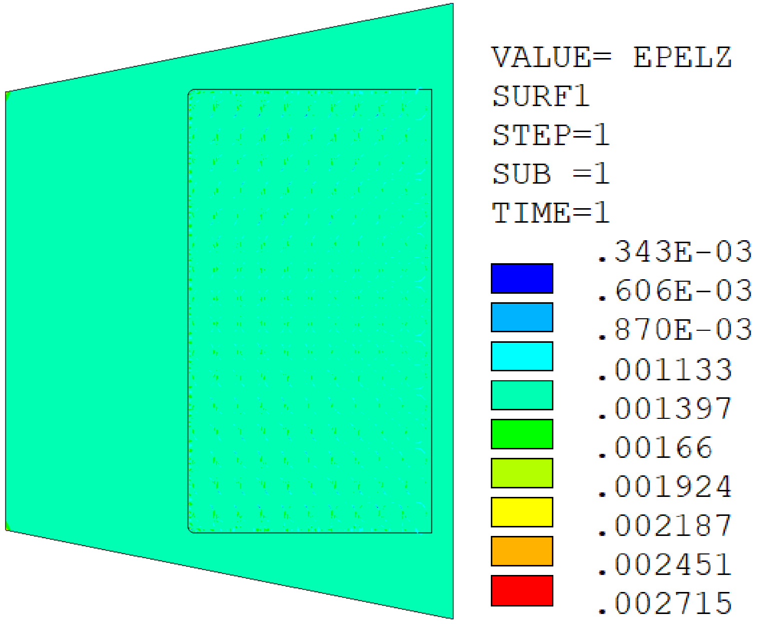
Cut 4

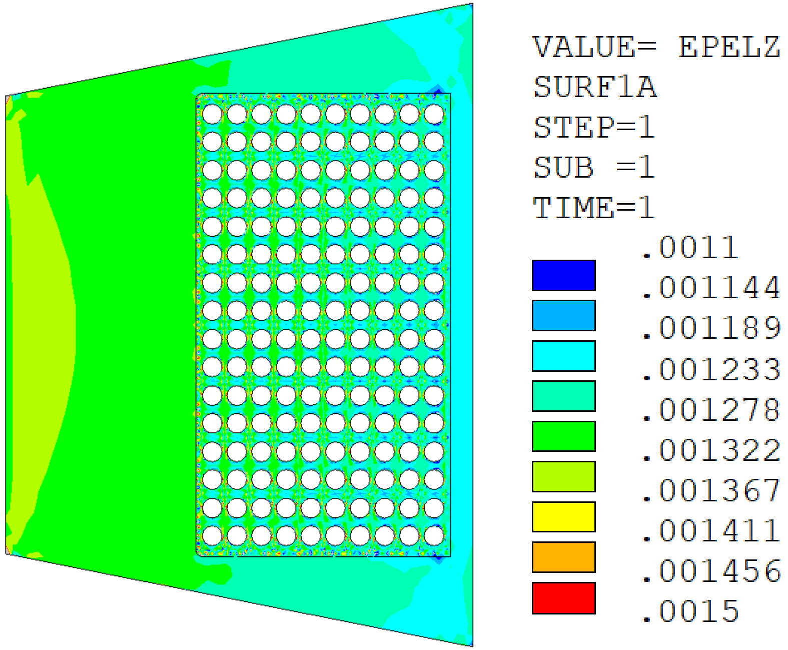


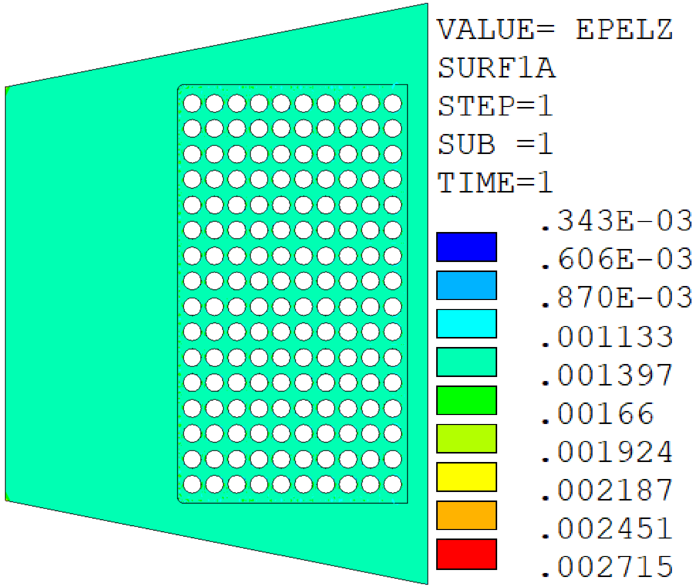
Cut 5

7. 2D cuts from the deetailed model (2/2)









Axial strain varies by at least ~30% - the condition of constant axial strain therefore is not satisfied – generalized plane strain model should not be used

8. Conclusions

- 3D electromagnetic and mechanical models down to the stran level can be developed and solved with reasonable computational cost

- Detailed EM model suggest that Lorentz forces on the TF coil can be ~12% smaller compared to the simple model for which a single conductor represents the TF coil

- The detailed mechanical model shows that the axial strain (eps_z) on the equatorial plane is not constant and variation of at least 30% is present, showing that the assumptions for the 2D model are not satisfied well

Acknowledgements

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Thank you for your attention