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HYBRID EVENT

Reshaping the DEMO Tokamak's TF Coil with high fidelity Multiphysics CAE and advanced mesh morphing

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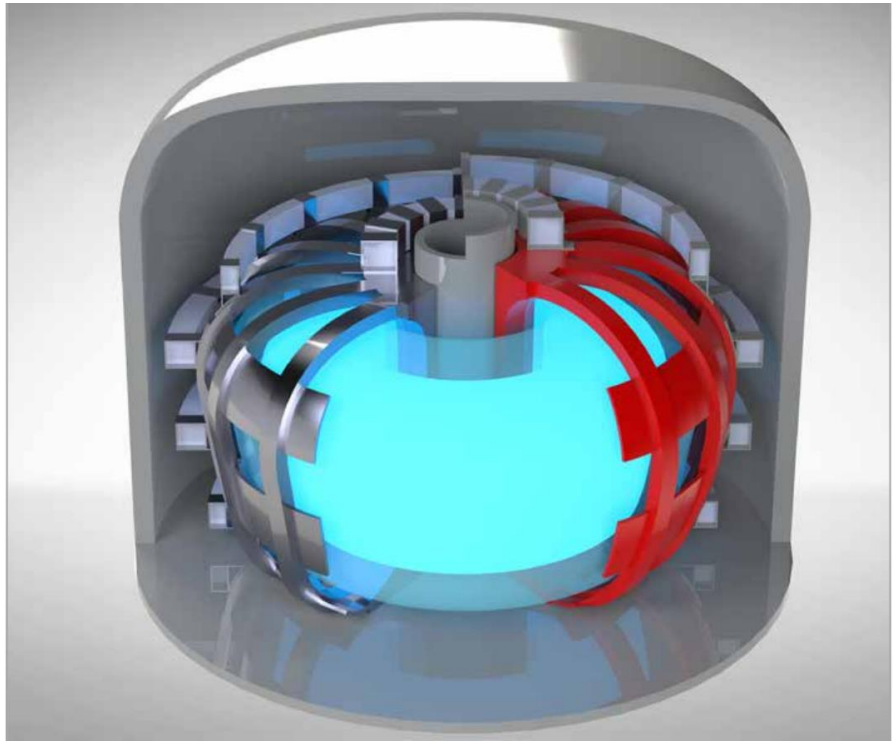
You are welcome to visit us!

I have heard that with fusion we can have our own stars

Have a look at the 3D printed prototype showing the effect of shape optimization



Visit the RBF Morph booth in the CAE Conference & Exhibition 2021

Introduction

- A DEMOnstration powerplant: the next step in EU's ambitious nuclear fusion power generation project
- DEMO will produce net electricity, design more challenging as compared to ITER: foreseen plasma power four times higher
- New technologies and concepts required. Divertor Tokamak Test (DTT) facility currently under design.

Introduction

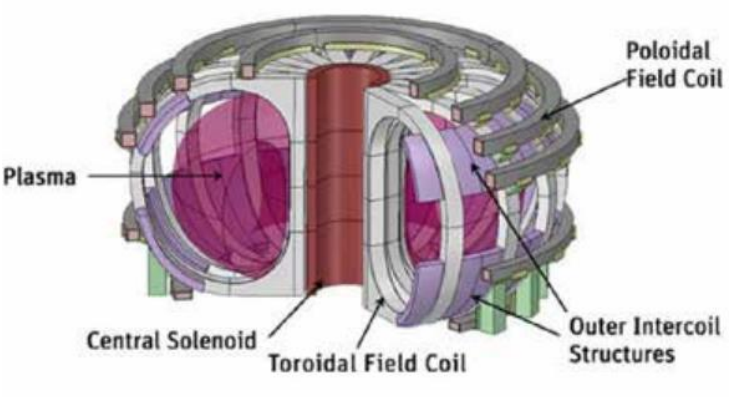
- DEMO is a challenge from a technical and technological point of view for several reasons:
  - Multiphysics involved, often leading to a trade-off of opposing requirements
  - Unprecedented range of operation for each sub-system of the assembly
- In this presentation, we show an optimization strategy for the Toroidal Field (TF) coils of the Advanced Divertor Configurations (ADCs).

Introduction

- Target: best compromise between electromagnetic and structural compliance
- Ansys simulation tools to reach the final goal:
  - **APDL** for the electromagnetic and structural analysis of the basic ADC configurations for a preliminary stress assessment
  - **Workbench** + **RBF Morph** + **APDL** to define an optimal shape (iso-stress profile) for each TF coil progressively mixing the initial and the iso-stress shape of each ADC coil to find the best compromise between the two.

DEMO architecture

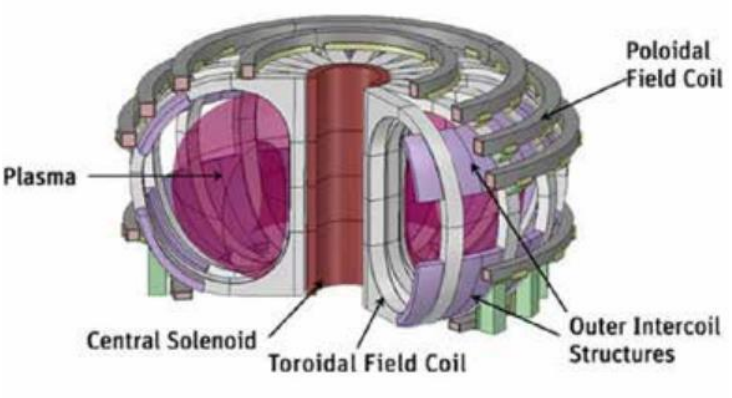
- Fusion reaction takes place inside the plasma: large amount of energy at the expense of a small portion of mass.



- Plasma is confined in a toroid chamber by magnetic fields
- Magnetic fields generated by superconductors: TF, PF, CS
- Superconductors arranged in arrays called Winding Packs (WP), cooled with supercritical helium

DEMO architecture

- Coils subject to enormous Lorenz forces
- Superconductors contained in steel casing to:
  - Shape the superconducting loops appropriately
  - Bear the impressive loads involved
- ADC designed to fulfill the first. We want to improve the latter.

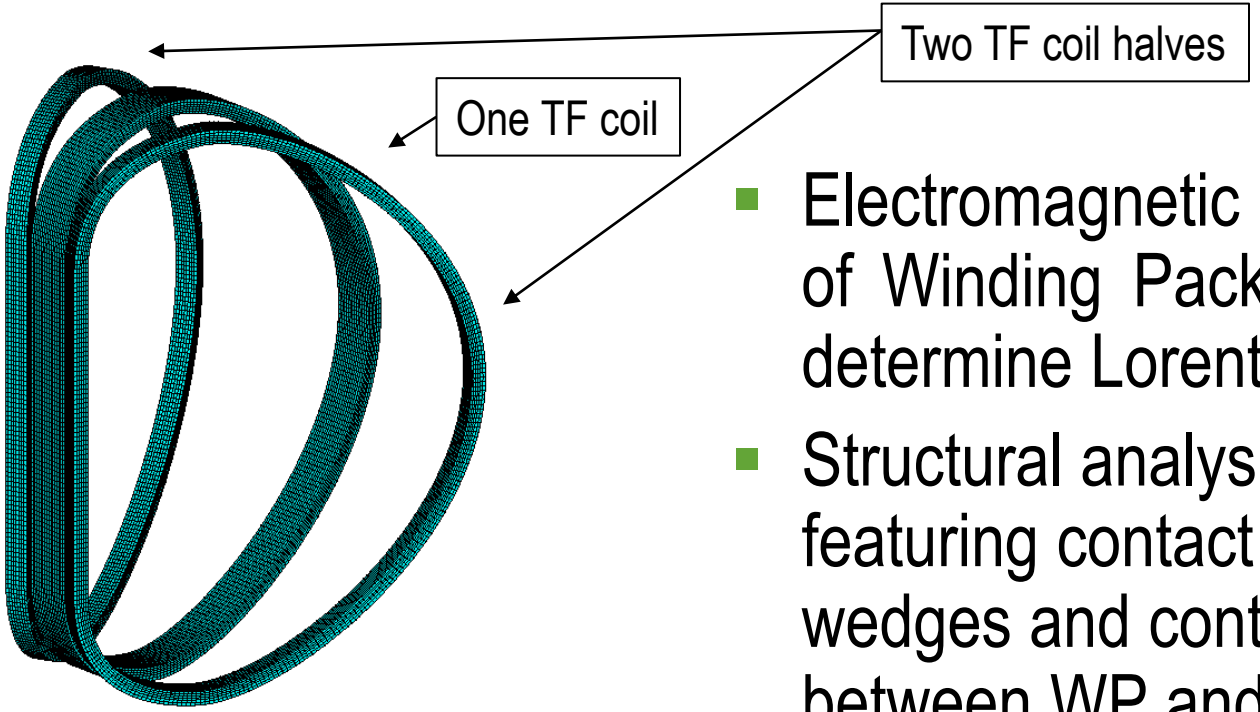


- First step: ADC configurations used for Electromagnetic and structural analyses

SN, DN, SF, SX Stress results

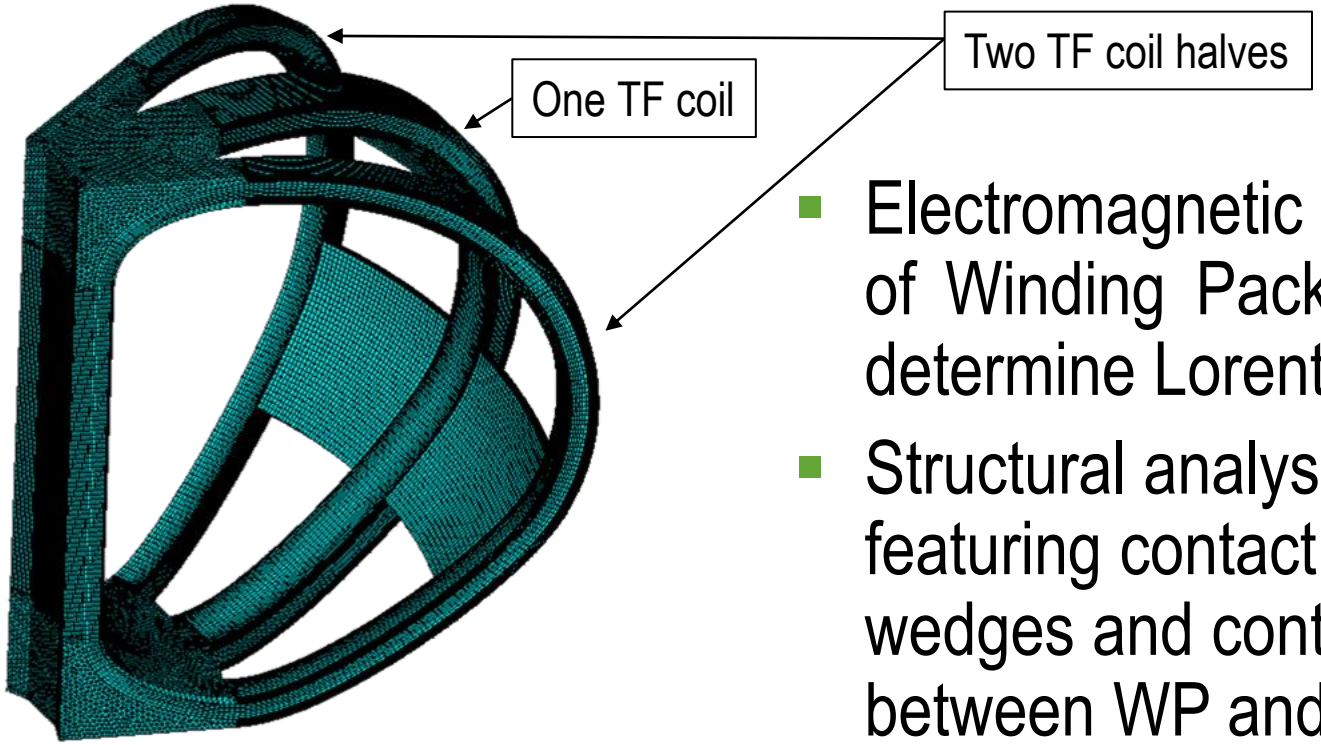
- Results were achieved on a numerical mesh counting ~1 Mil elements
- Basic configurations of all the ADCs studied: Single-Null (SN), Double-Null (DN), Snow-Flake (SF) and Super-X (SX)
- Electromagnetic analysis followed by structural study in APDL
- EM considering current flowing in TF coils only as happening during the magnetization stage. Lorentz forces on superconductors sent to structural analysis on same mesh

TF coil : EM model



- Electromagnetic analysis of Winding Pack (WP) to determine Lorentz forces
- Structural analysis featuring contact between wedges and contact between WP and casing

TF coil : structural model



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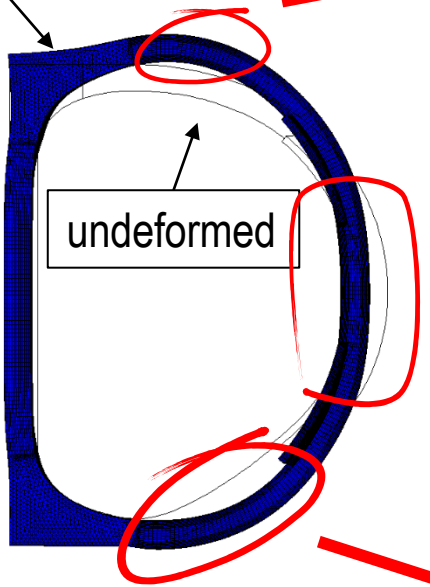
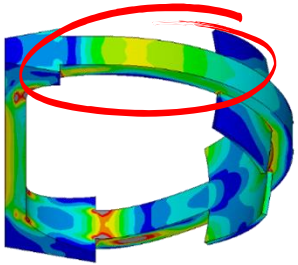
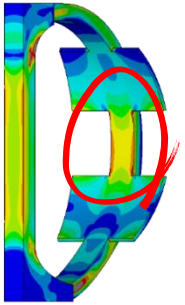
SN magnetization stage



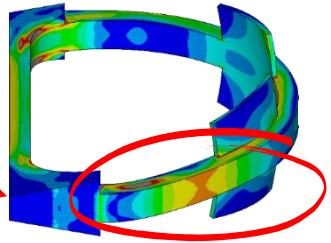


Von Mises stress:
- view from above

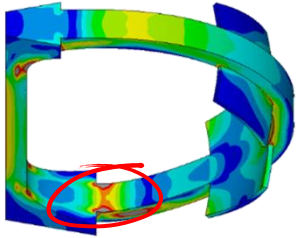
- view from one side

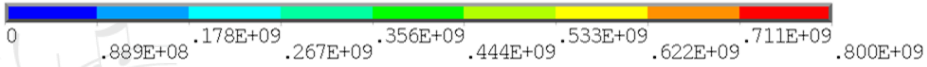


- view from below

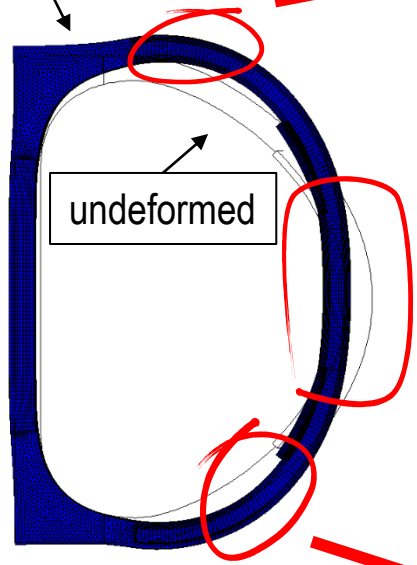


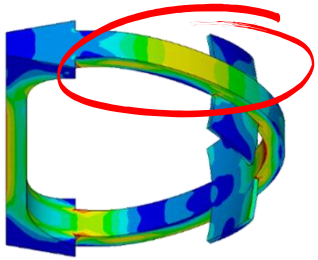
- view from above



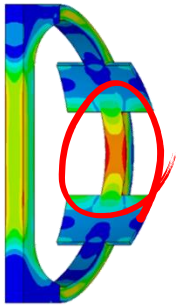


DN magnetization stage

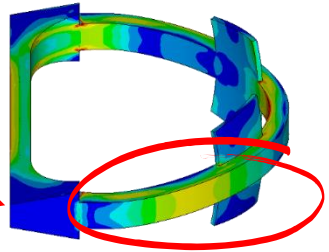




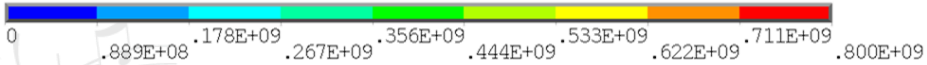
Von Mises stress:
- view from above



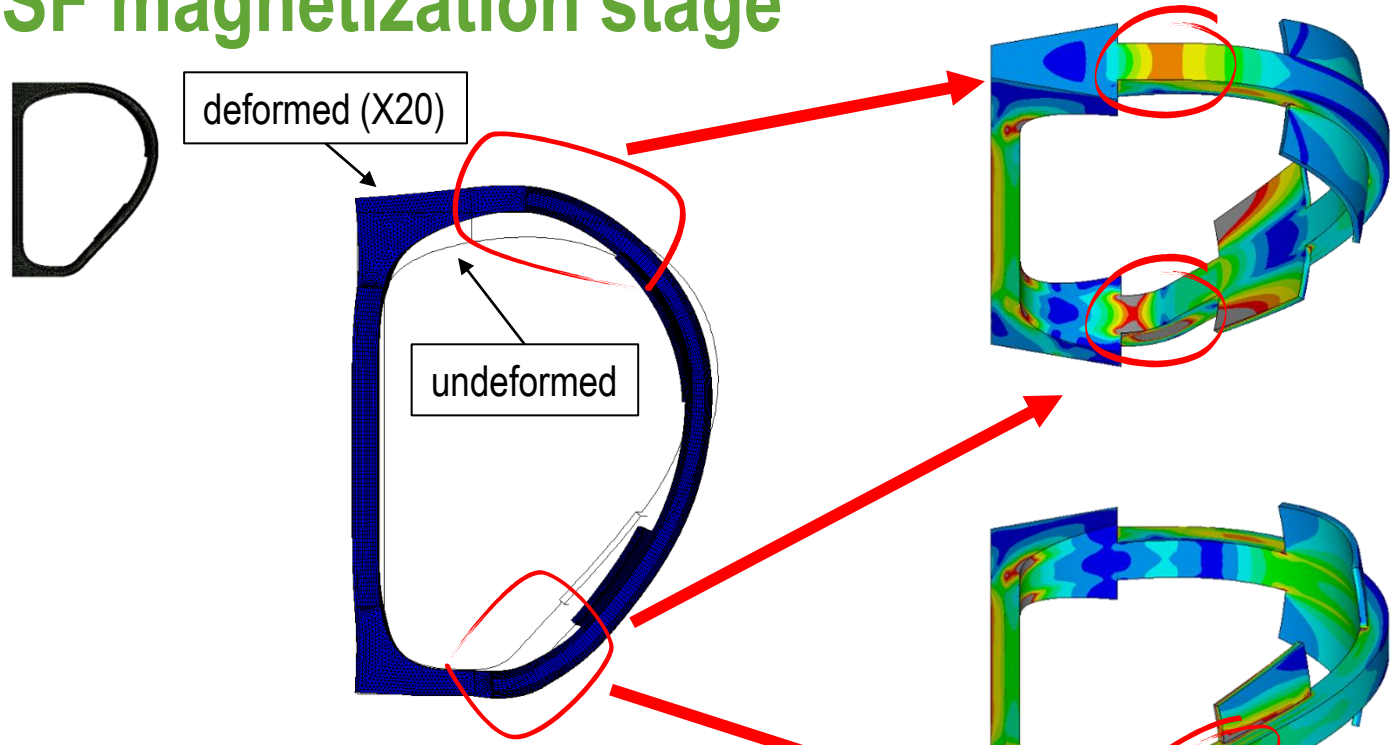
- view from one side



- view from below

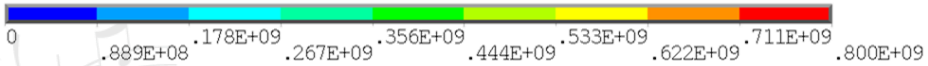


SF magnetization stage



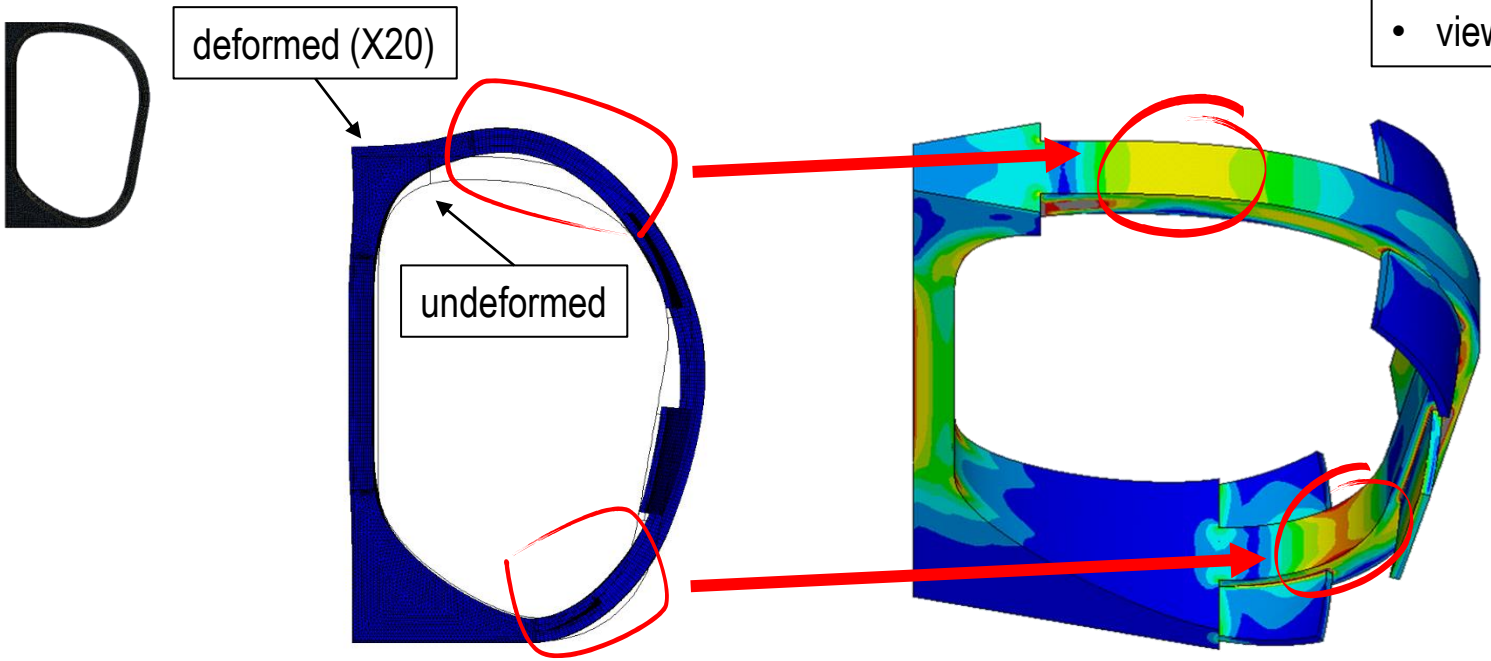
Von Mises stress:
- view from above

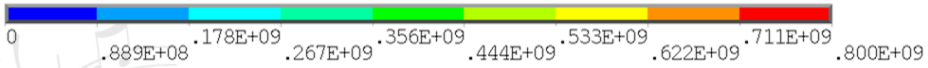
- view from below



SX magnetization stage

Von Mises stress:
- view from above





ADC baseline stress results

- For each coil resultant radial force (RX) and resultant angular moments around the toroidal direction (MY):

Resultant component	SN	DN	SF	SX
RX (radial) [MN]	-860.211	-910.373	-917.155	-943.783
MY [MN•m]	341.530	0.182	9.053	1146.301

- Von Mises (VM) stresses over ADC casings reveals that large areas of material are above the assumed stress limit (700 MPa)

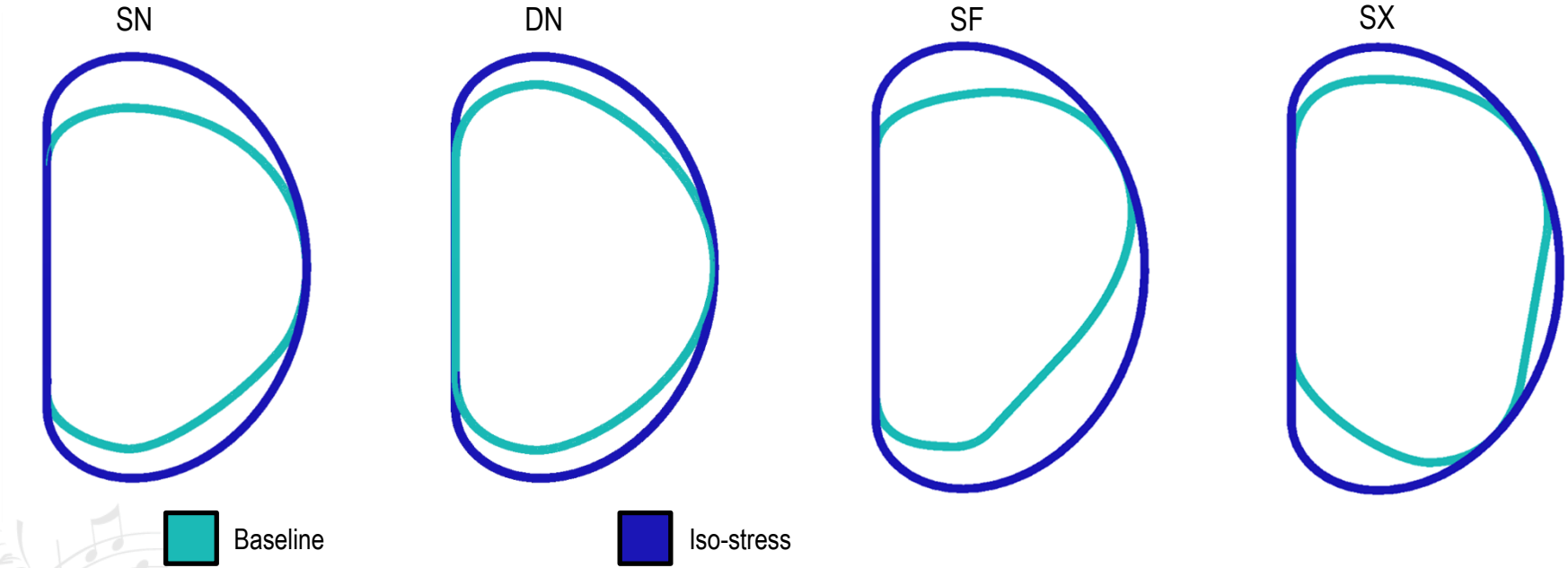
Iso-stress shape of the coil

- The optimal shape of a coil, structurally, has membrane stresses only when loaded
- Optimal iso-stress design has radius of curvature proportional to the radial coordinate at each point on the coil track*
- We can imagine for each ADC configuration an iso-stress profile, with the constraint of being always external and tangential wrt baseline

*Knoepfel, Heinz E. 2000. "Magnetic fields: a comprehensive theoretical treatise for practical use". John Wiley & Sons, New York, pp. 423-427

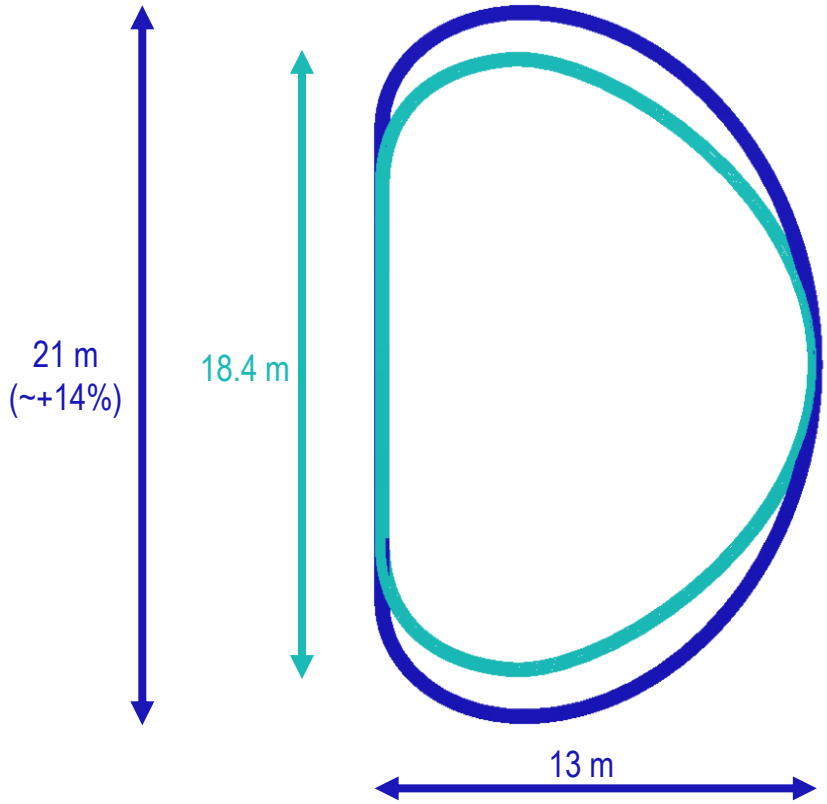
Iso-stress shape of the coil

- Iso-stress shape is symmetric with respect to the horizontal plane



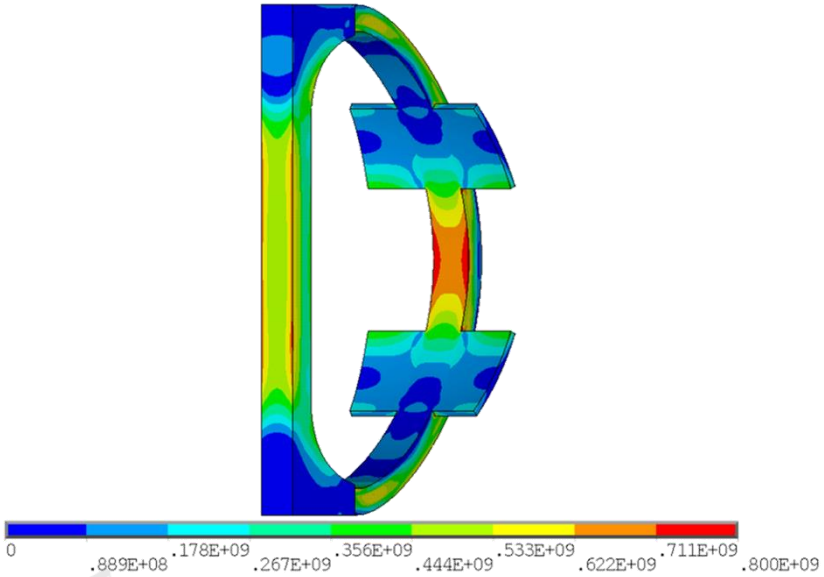
Bending-free design of the coils

- Both configurations of the DN (baseline and bending-free) are perfectly symmetric wrt the horizontal plane
- Bending-free configuration is more elongated than the original one, being equal the radial size

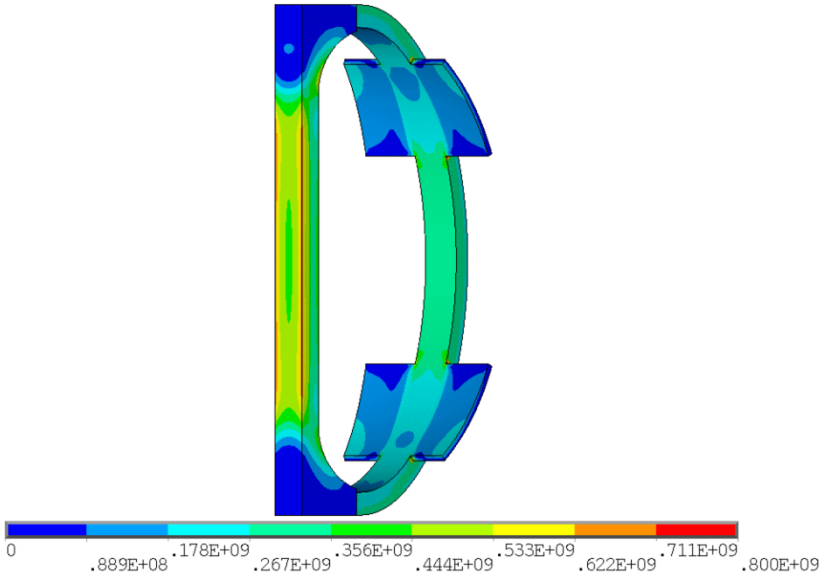


Bending-free design of the coils

Baseline



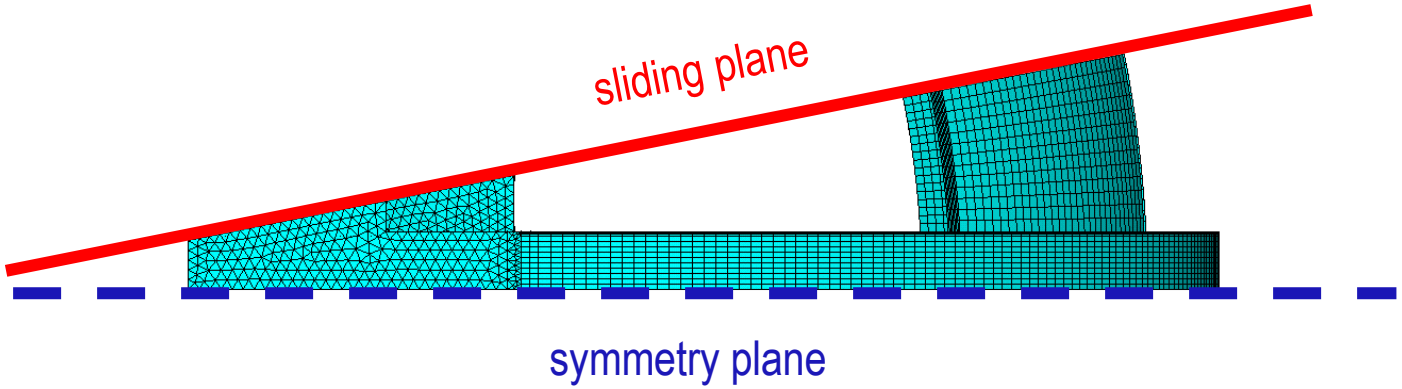
Bending-free



Optimisation Workflow: aim

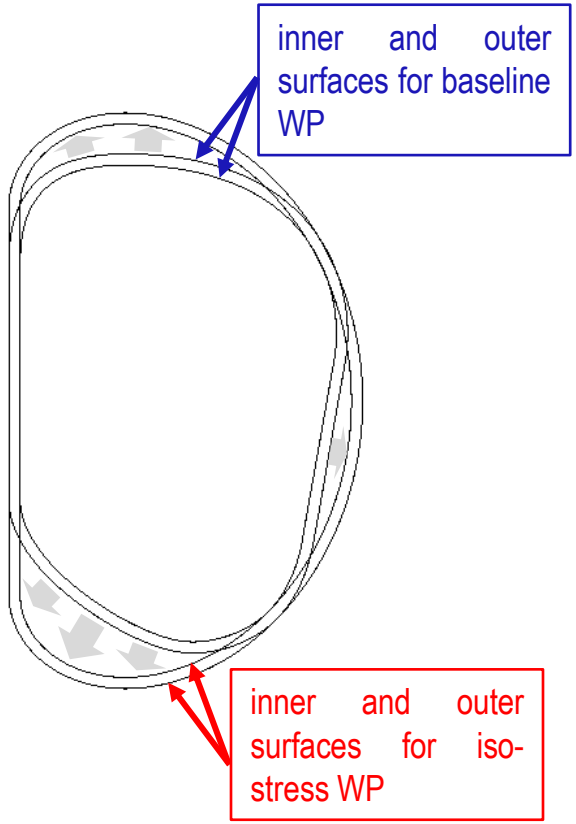
- Definition of a shape for the TF coils of the 4 cases (SN, DN, SF, SX) in-between the initial configuration and the iso-stress shape such to experience a stress state below a certain limit (σ_{VM} = 450 MPa) during magnetization
- A continuous transformation from the baseline to the iso-stress shape for each ADC case needs to be established
- A discrete number of TF coil configurations are extracted and considered for electromagnetic analysis (EM) and stress assessment

Optimisation Workflow: simplified model



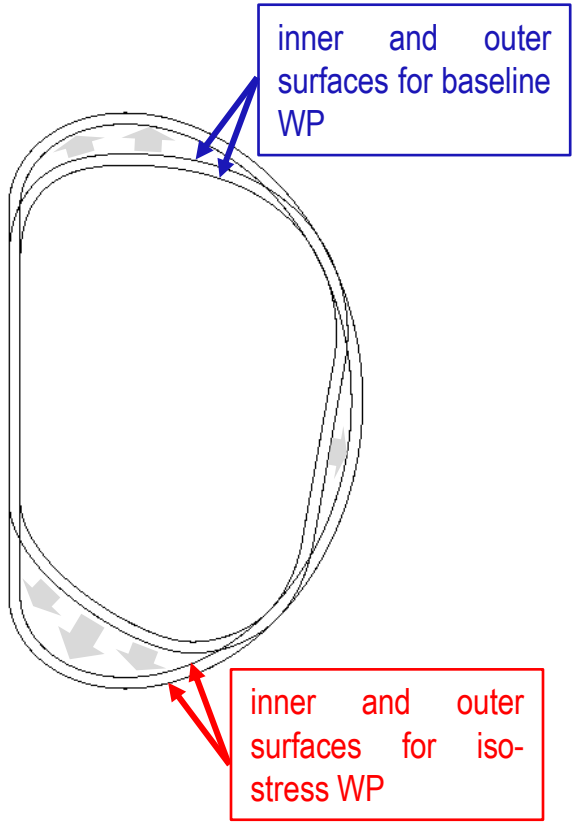
Optimisation Workflow: shape parameterisation

- WP inner and outer surfaces are considered for each pair baseline/iso-stress
- RBF Morph ACT Extension inside ANSYS Mechanical was used to perform shape parameterisation
- The displacement field shifting the first shape onto the second is applied to the whole TF structure (WP+casing+filler)



Optimisation Workflow: shape parameterisation

- A surface projection modifier was applied to each source-target pair
- The scaling of the defined displacement field determines the intermediate configurations in-between the initial shape and the iso-stress one (0 = baseline, 1 = iso-stress with steps of 0.1)



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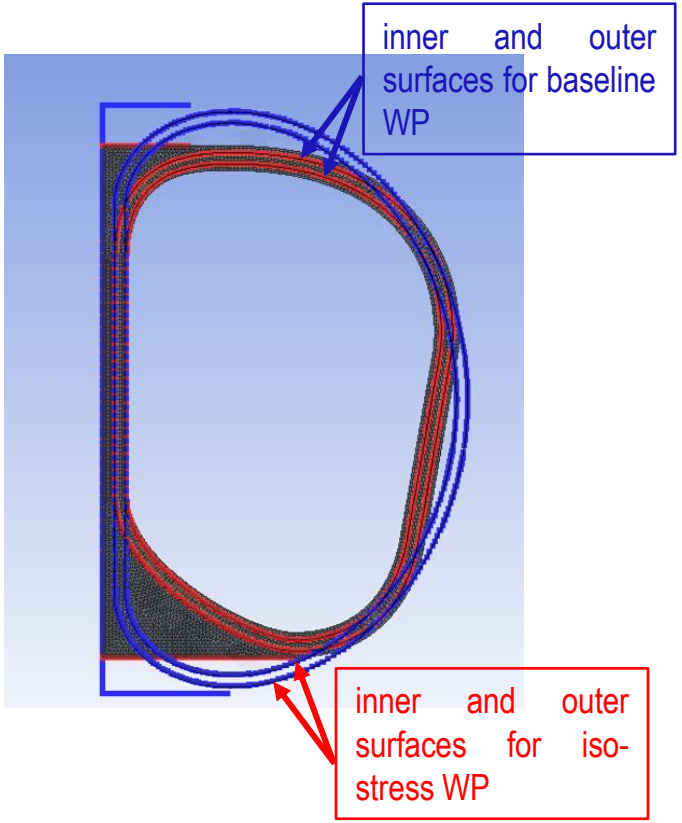
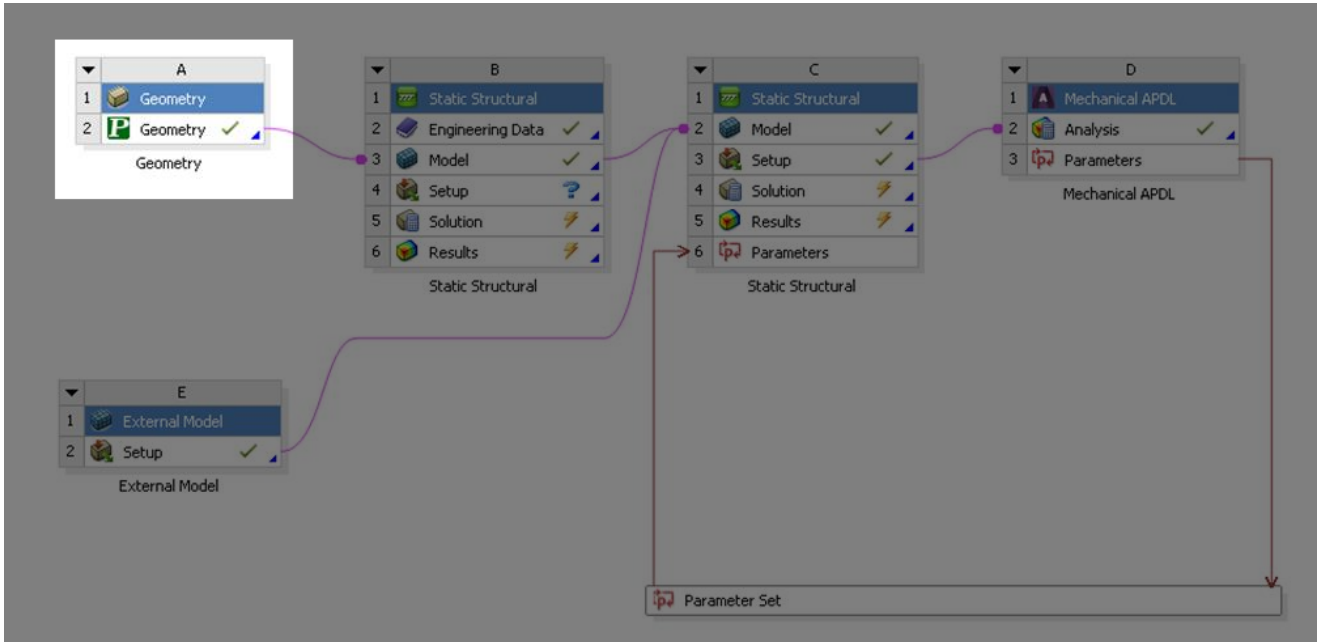


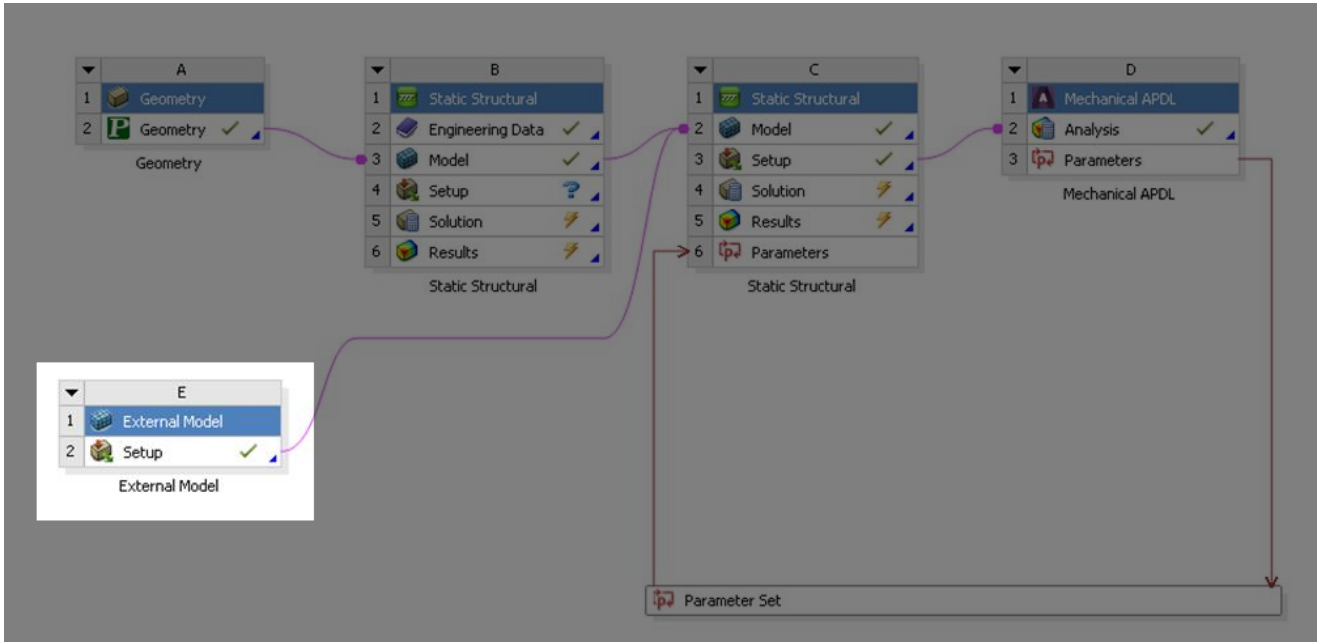
Optimisation Workflow

- Surface geometries are loaded from external CAD



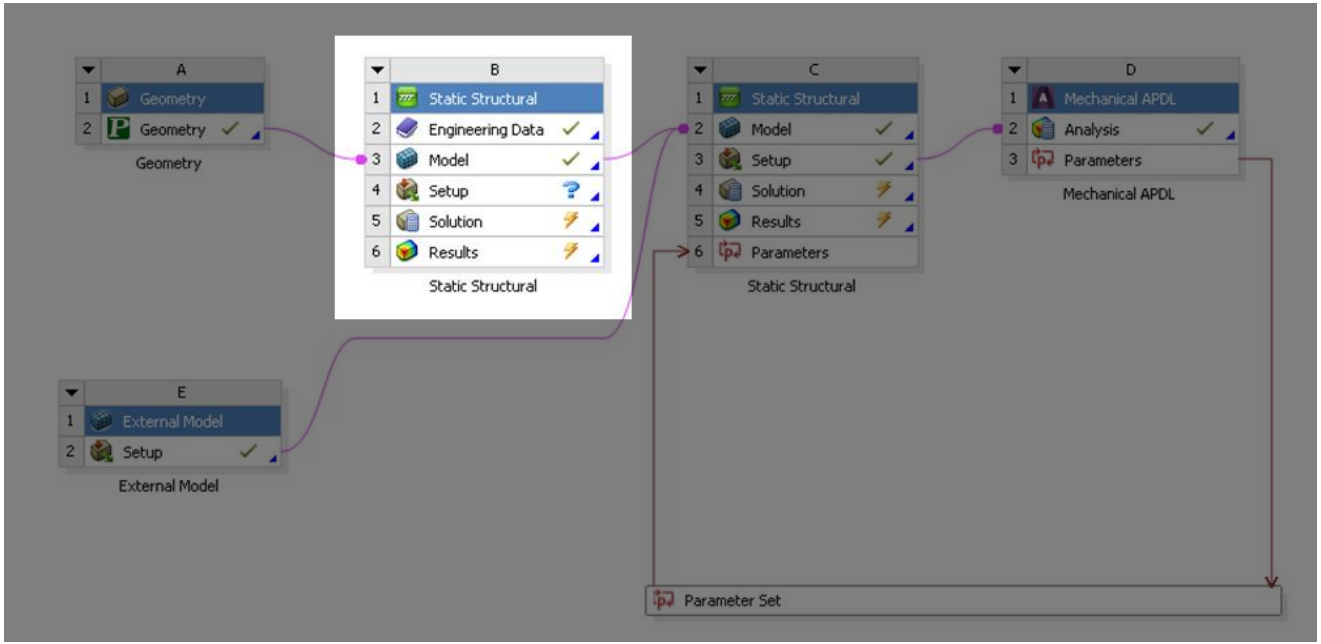
Optimisation Workflow

- Dead-mesh of the baseline model



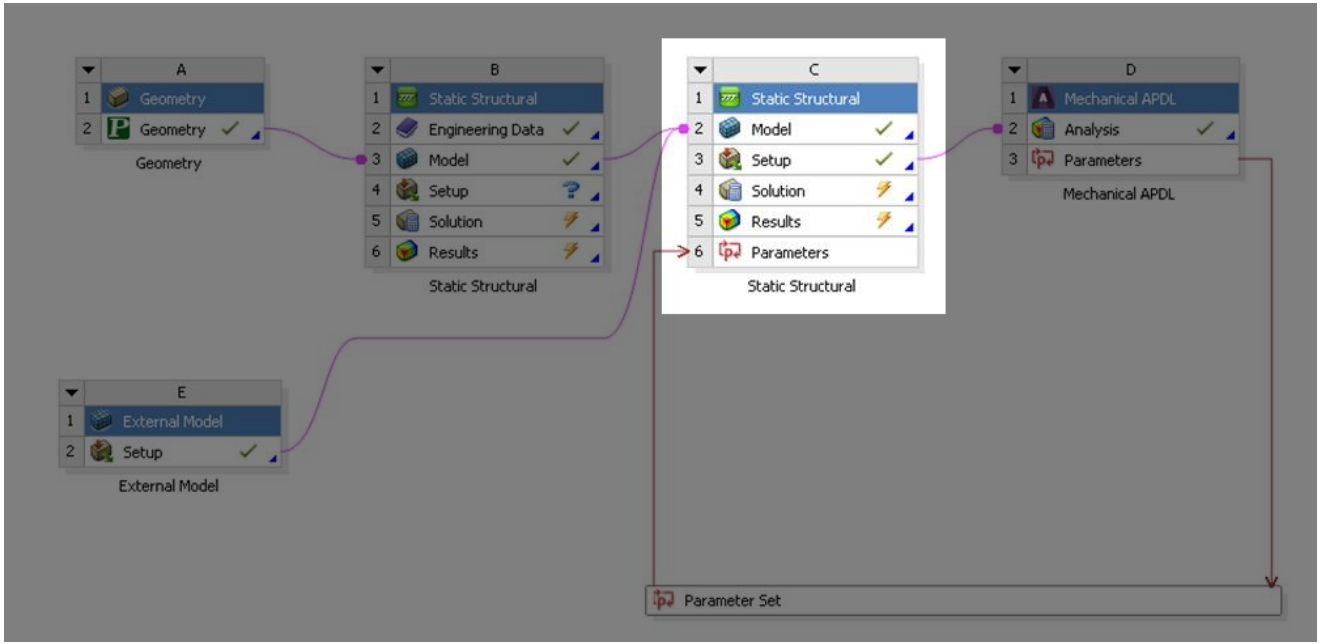
Optimisation Workflow

- Surfaces turned into ANSYS parametric geometries (meshed)



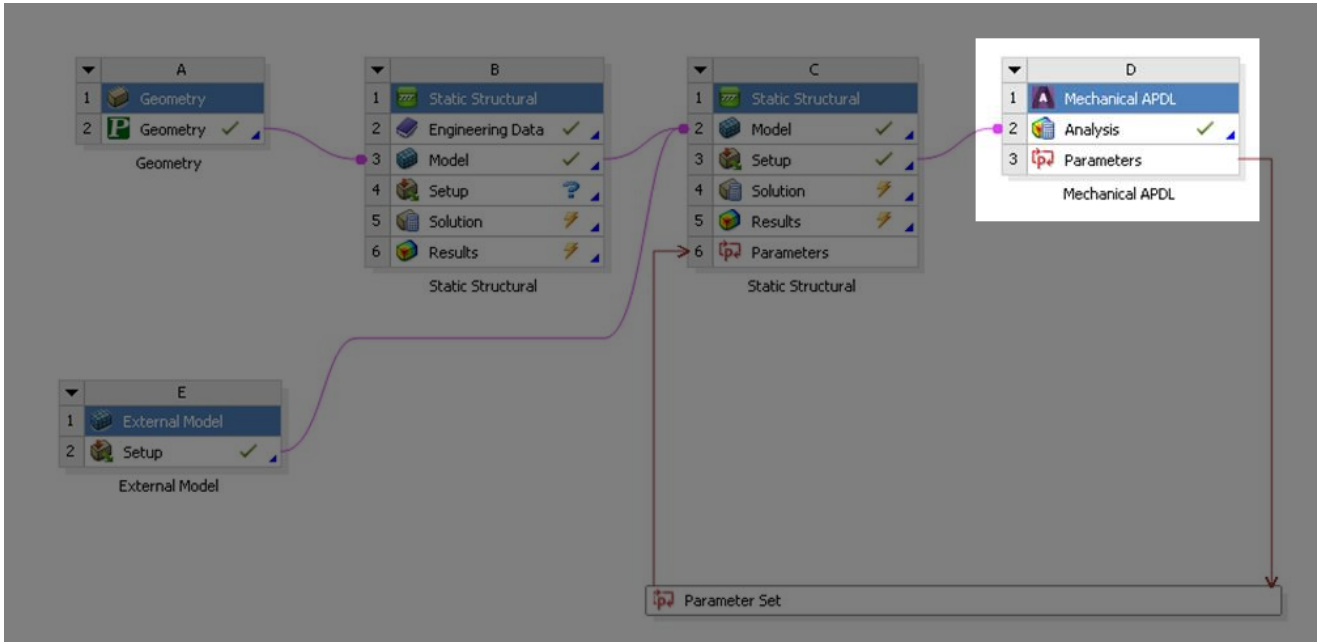
Optimisation Workflow

- RBFMorph modifies the model shape acting on nodal positions



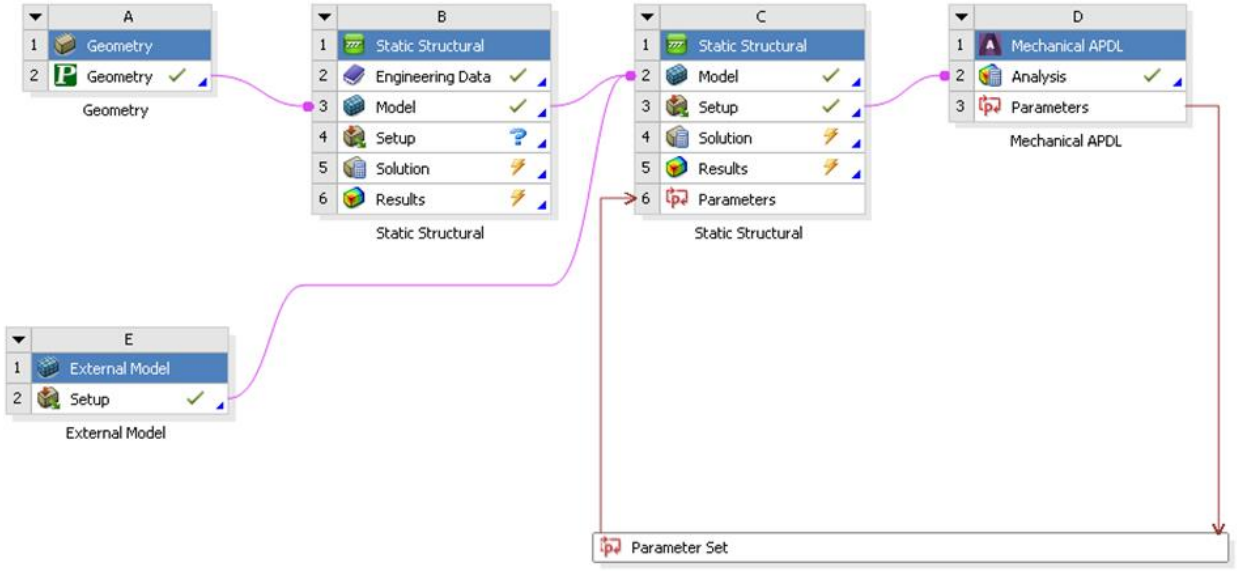
Optimisation Workflow

- Material assignment/orientation, EM analysis, structural analysis



Optimisation Workflow

- Optimisation is driven by DX, extracting stresses as output
- A DOE is calculated for each ADC configuration

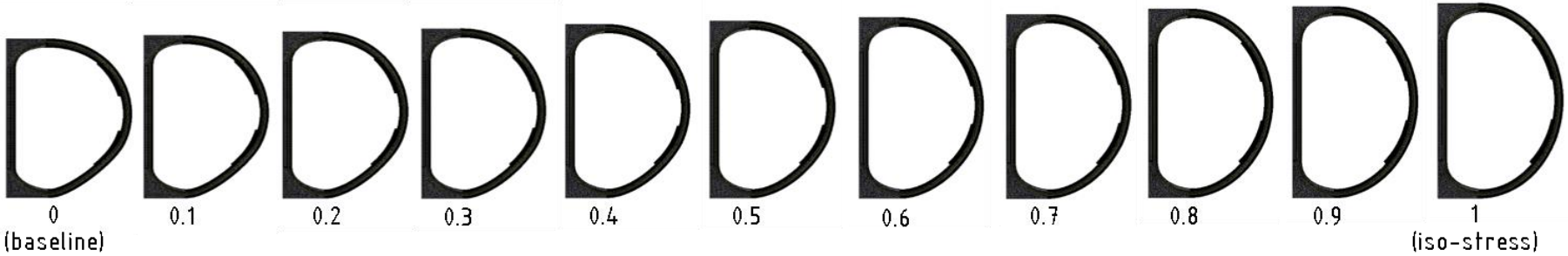


Optimisation Workflow: results

- Stress parameter σ_V introduced to evaluate optimisation, measuring the percentage of volume exceeding the chosen limit of 450 MPa of VM stress on casing
- Blending parameter between 0 (baseline) and 1 (iso-stress) is increased at intervals of 0.1
- Optimal shape for each ADC run is chosen to be the first with $\sigma_V \leq 1\%$
- Baseline σ_V values: 12%, 18%, 8%, 12%

Automatic workflow: SN results

- Evolution of the SN from the baseline to the iso-stress configuration



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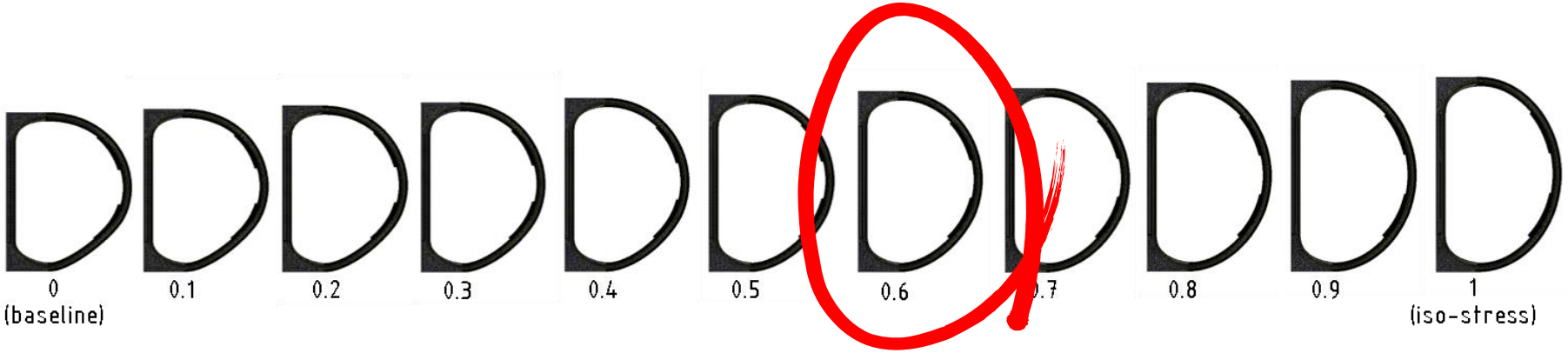
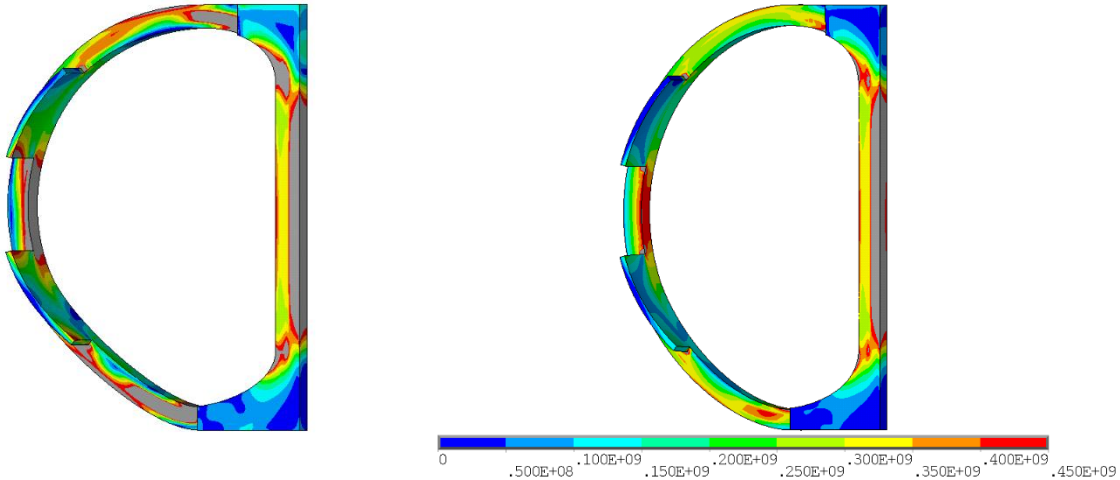


Automatic workflow: SN results

- Candidate shape with blending parameter 0.6
- Comparison with baseline and bending-free



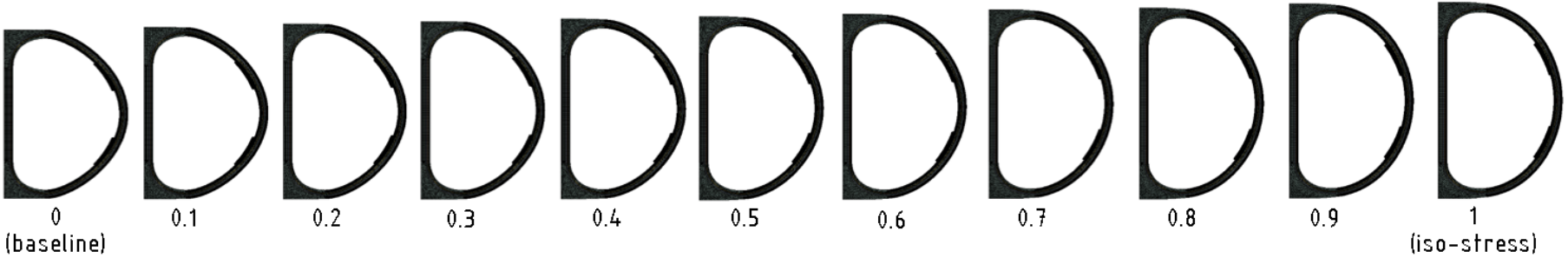
Baseline, H_{casing}=17.6 m

Candidate, H_{casing}=20.0 m

Bending-free, H_{casing}=21.6 m

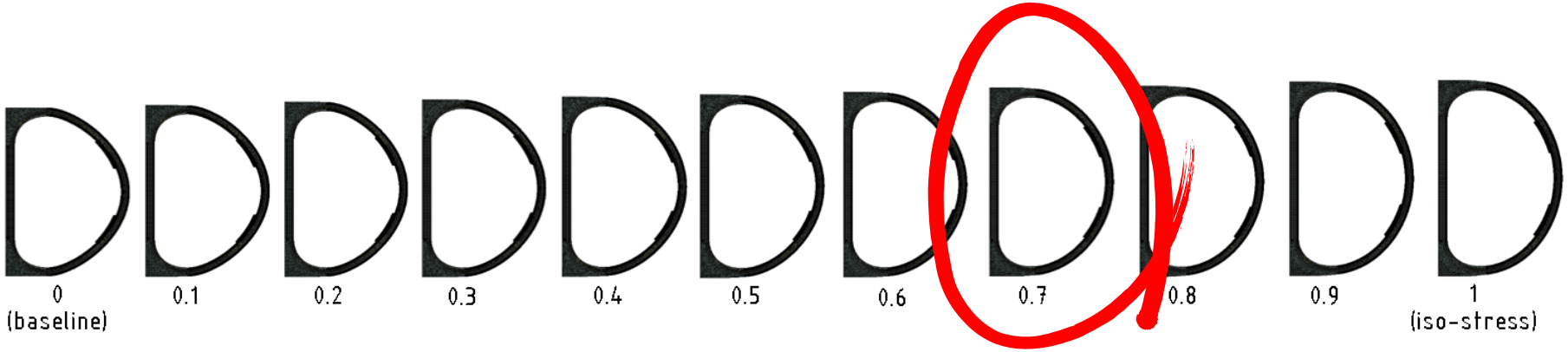
Automatic workflow: DN results

- Evolution of the DN from the baseline to the iso-stress configuration



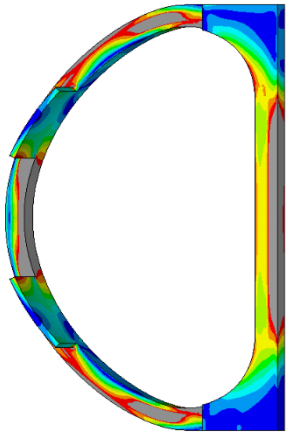
Automatic workflow: DN results

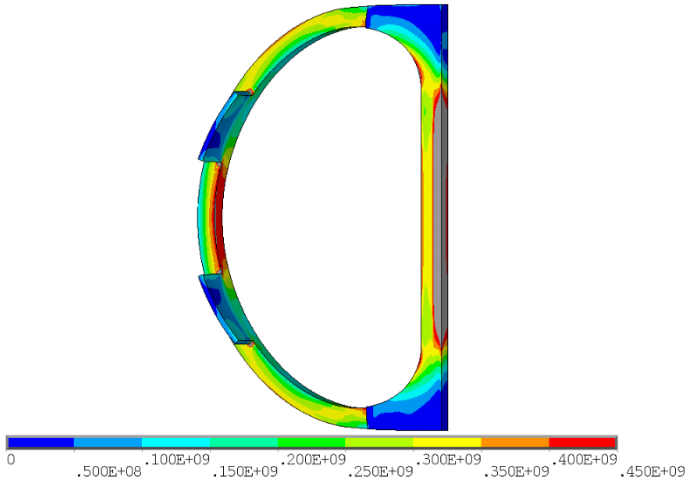
- Evolution of the DN from the baseline to the iso-stress configuration

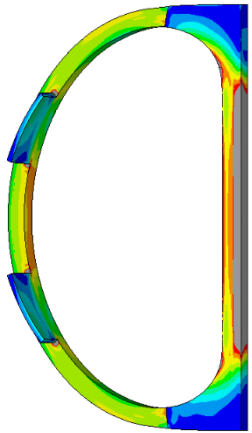


Automatic workflow: DN results

- Candidate shape with blending parameter 0.7
- Comparison with baseline and bending-free







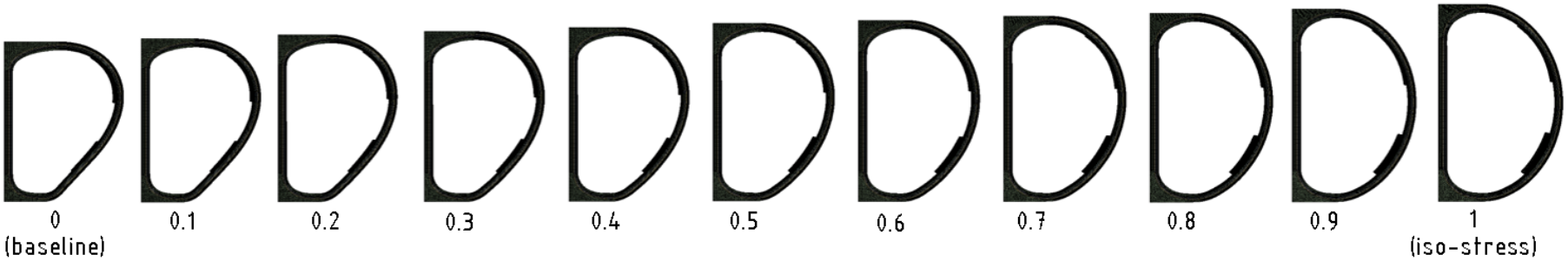
Baseline, H_{casing}=18.9 m

Candidate, H_{casing}=21.1 m

Bending-free, H_{casing}=22.0 m

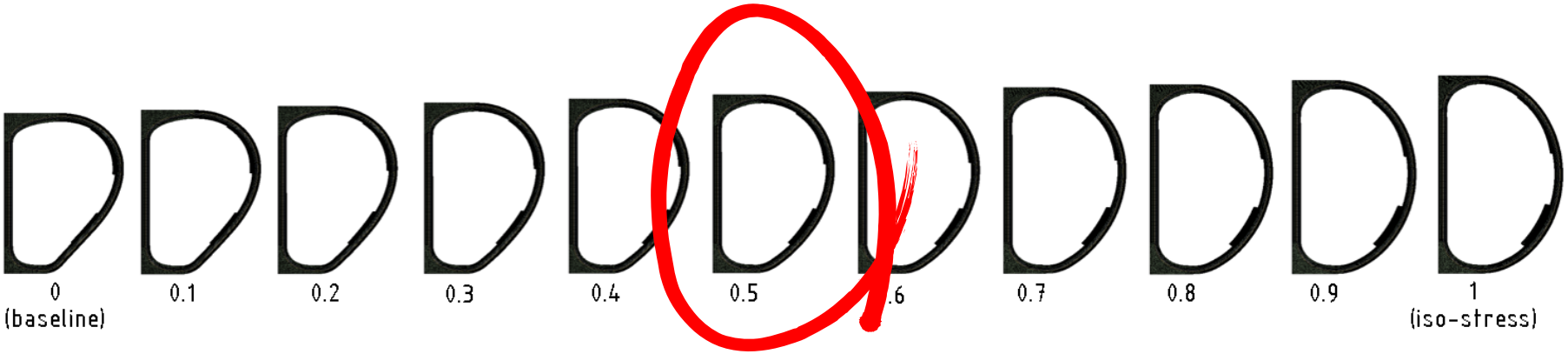
Automatic workflow: SF results

- Evolution of the SF from the baseline to the iso-stress configuration



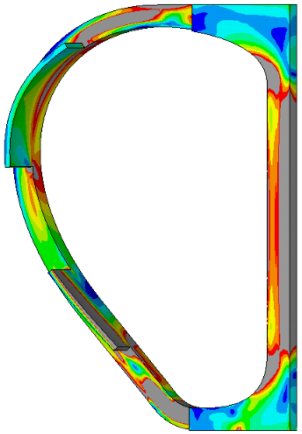
Automatic workflow: SF results

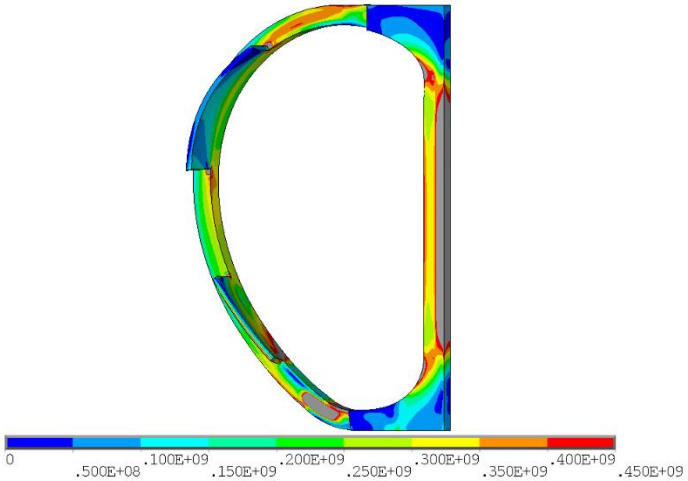
- Evolution of the SF from the baseline to the iso-stress configuration

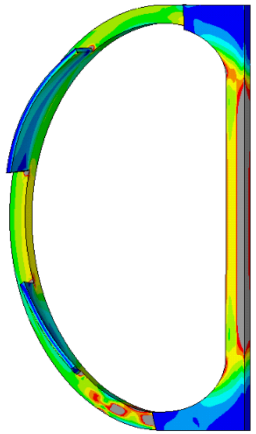


Automatic workflow: SF results

- Candidate shape with blending parameter 0.5
- Comparison with baseline and bending-free







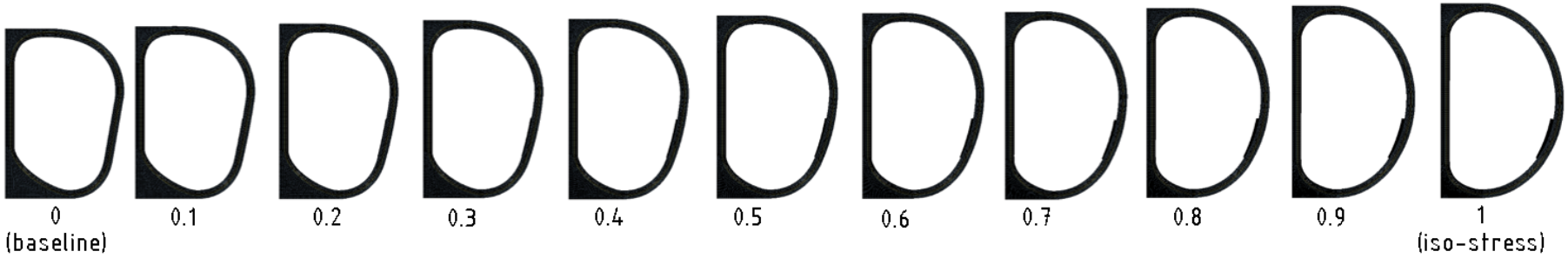
Baseline, H_{casing}=18.8 m

Candidate, H_{casing}=21.0 m

Bending-free, H_{casing}=23.2 m

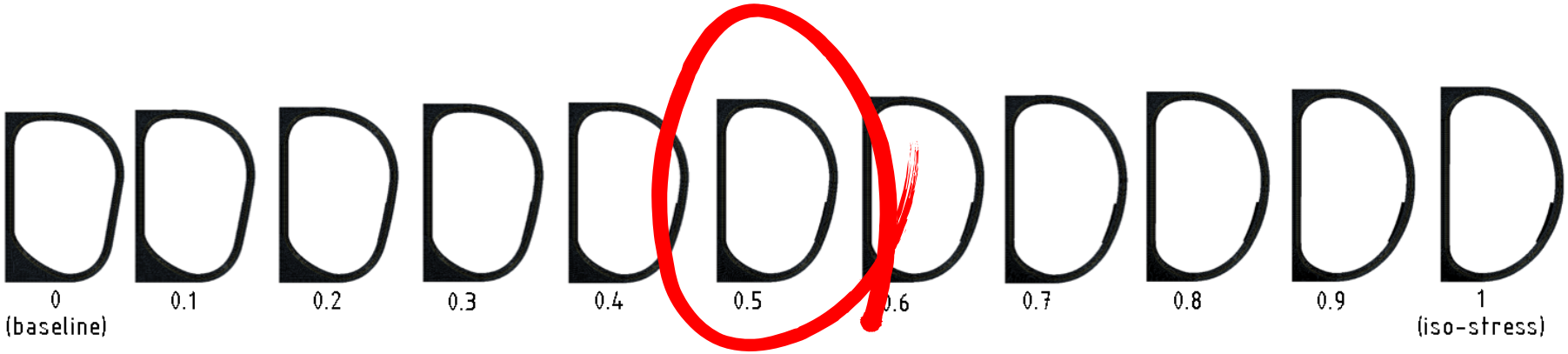
Automatic workflow: SX results

- Evolution of the SX from the baseline to the iso-stress configuration



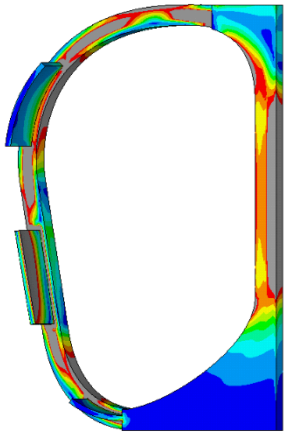
Automatic workflow: SX results

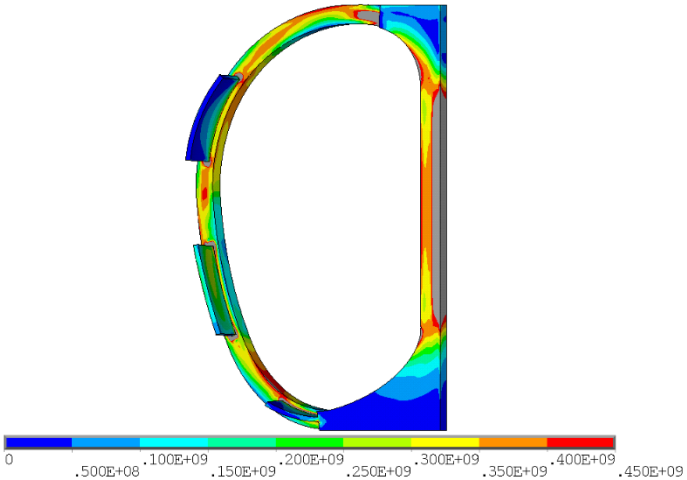
- Evolution of the SX from the baseline to the iso-stress configuration

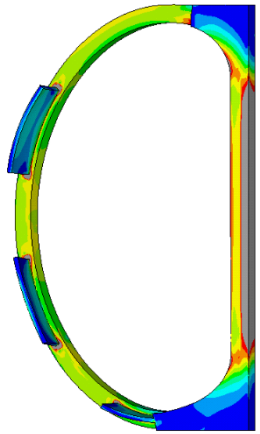


Automatic workflow: SX results

- Candidate shape with blending parameter 0.5
- Comparison with baseline and bending-free





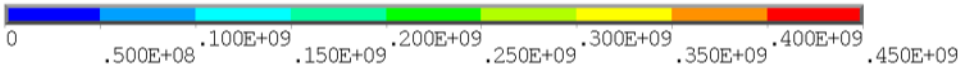


Baseline, H_{casing}=20.0 m

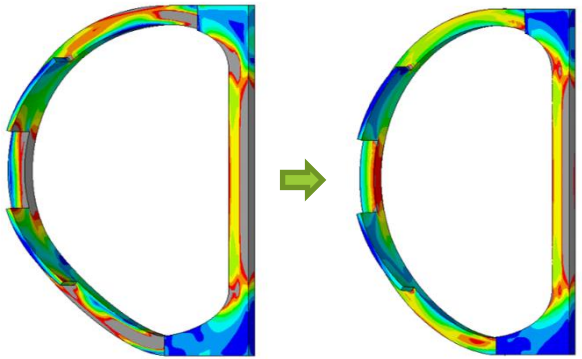
Candidate, H_{casing}=21.5 m

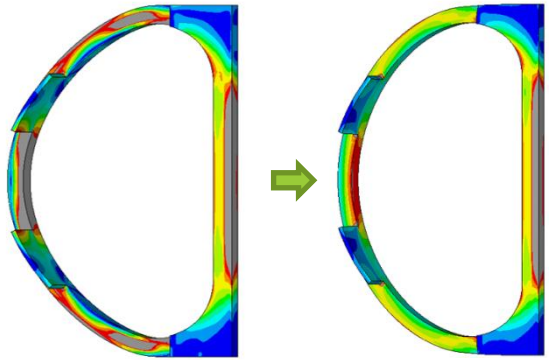
Bending-free, H_{casing}=23.0 m

Results



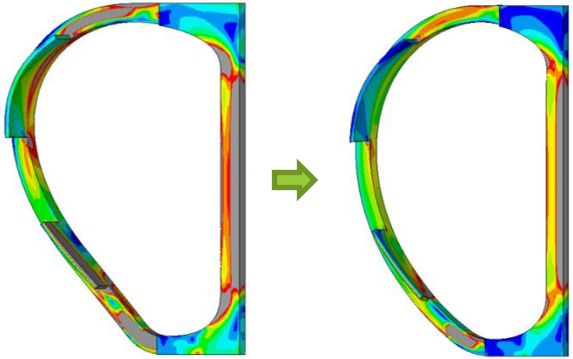
SN

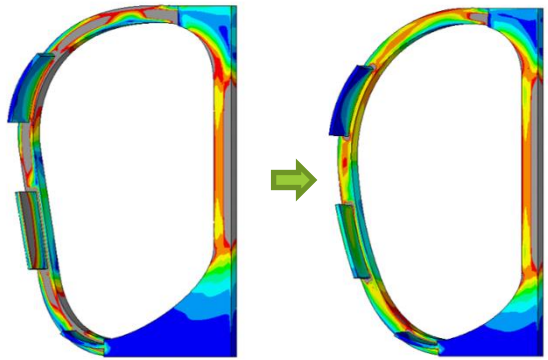




DN

SF





SX

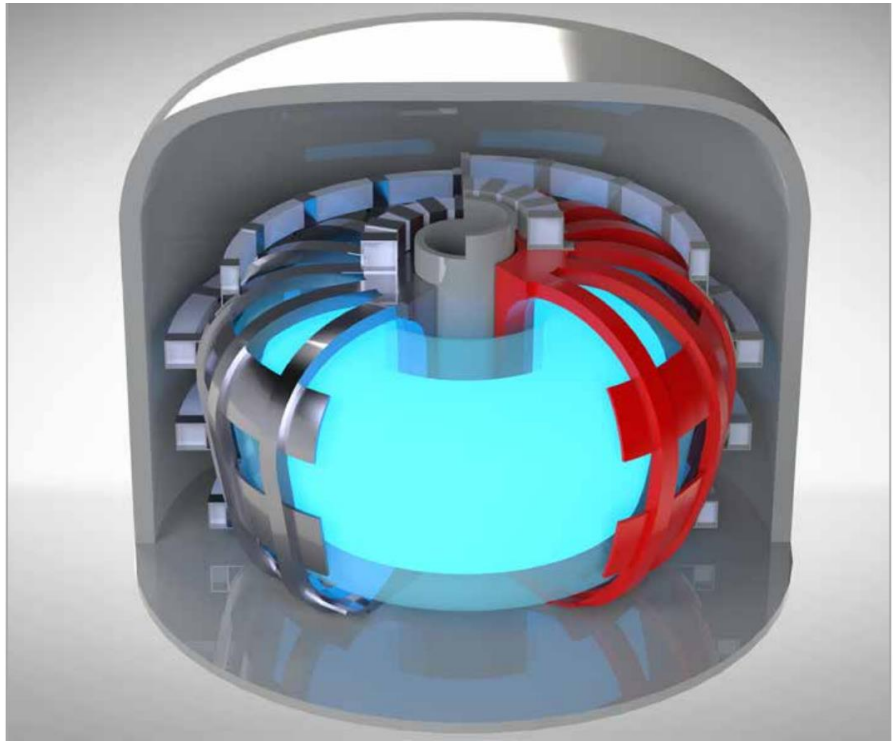
Conclusions

- The SN candidate, computed on the simplified model, was explored on the full model, obtaining a satisfactory result
- The TF coils of the DEMO ADCs were originally designed to generate a magnetic field with specific characteristics, but not to withstand the Lorentz forces from EM interactions
- An optimization procedure based on ANSYS Workbench, RBF Morph and ANSYS APDL was built to find a compromise between their original shape and an iso-stress profile
- Proposed workflow was able to successfully find the minimum shape modification for each ADC in order to reduce the stress level to below 450 MPa

Come visit us at RBF Morph booth!

I have heard that with fusion we can have our own stars

Have a look at the 3D printed prototype showing the effect of shape optimization



Visit the RBF Morph booth in the CAE Conference & Exhibition 2021