[b] ENEA

[a] ICAS

EUROfusion

MECHANICAL ANALYSIS OF THE TOROIDAL and POLOIDAL FIELD COILS FOR DEMOnstrating NUCLEAR FUSION REACTOR

[a]L. Giannini [b]L.Zoboli [a]A. Anemona [b]G. Tomassetti

ABSTRACT – The DEMO magnet system consists of 18 toroidal magnets (TFC), 6 poloidal magnets (PFC) and a central solenoid (CS). Operating currents and intense magnetic fields generate high stresses in these structures. In the pre-design phase in-depth mechanical analyses are needed so as to obtain a structurally and competitively solid power reactor for the future world energy demands. Separate ANSYS static structural analyses for the TF and PF are here presented. A topology optimised design for the intercoil supports is also given.

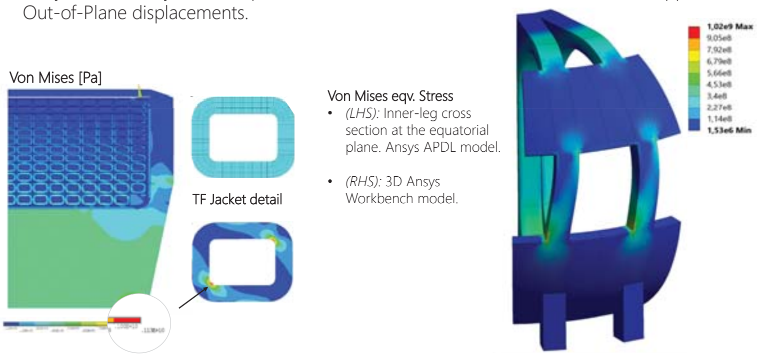
Magnet system:
1. Poloidal Field Coils
2. Toroidal Field Coils
3. Central Solenoid

TFC:

The D-shaped toroidal coils generate the toroidal magnetic field $\vec{B}_\varphi$ which is the primary confinement solution for the plasma. Each magnet is comprised of a winding pack (WP) and a steel casing. The ENEA WP2 design configuration consists of 202 superconducting cables, capable of carrying high currents ($i = 70.8\ \mathrm{kA/cable}$) when cooled below the critical temperature of $4.5\ \mathrm{K}$. At full operation (EOF scenario). The maximum toroidal field on the magnet is $\vec{B}_\varphi \simeq 12\ \mathrm{T}$.

Mechanical analysis (EOF scenario): B_x, B_y, B_z data obtained from a magneto-static analysis have been used to derive the Lorentz forces $\{\vec{F} = i\vec{L} \times \vec{B}\}$ in a MATLAB routine. Two analyses have been carried out: a fully-detailed, 2D GEN plane strain APDL model, and a 3D Static Structural Workbench model:

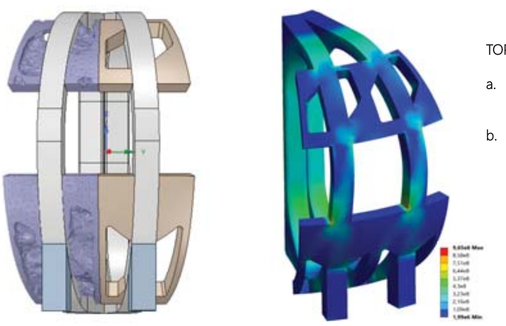
- The 2D model focuses on the equatorial TF inner leg; the loads have been applied in the WP at each S/C cable centroid, and magnet cool down effects have been included.
- The 3D model of the magnet features a homogenized WP, the load has been defined as body force density, and the presence of the Outer Intercoil Structures, which support the Out-of-Plane displacements.



Von Mises eqv. Stress
- *(LHS):* Inner-leg cross section at the equatorial plane. Ansys APDL model.
- *(RHS):* 3D Ansys Workbench model.

OPTIMISATION:

The out-of-plane component of the electromagnetic load exerts flexio-torsional strains and stresses in the TFC, causing the magnet to bend and twist. The Outer Intercoil Structures (OIS) act as supports for this load, inducing rigidity in the toroidal direction. Their optimum design problem has been tackled via a Topology Optimisation analysis, choosing a minimum compliance (maximum global stiffness) objective, and a 40% mass reduction as constraint. The engineered new shape of the OIS shows very good response to the magnet load in terms of stresses, indicating that it is possible to decrease their mass without undermining their structural requirement.

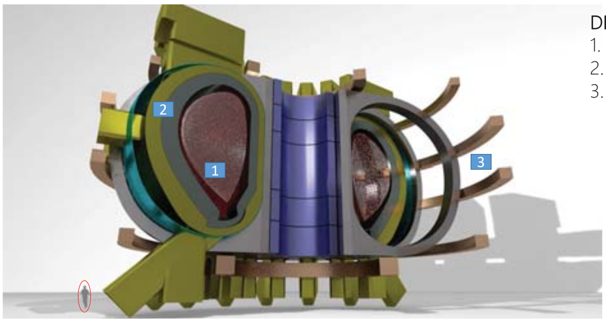


a b

TOPOLOGY OPTIMISATION:

a. Topology density and engineered design

b. Mechanical validation analysis

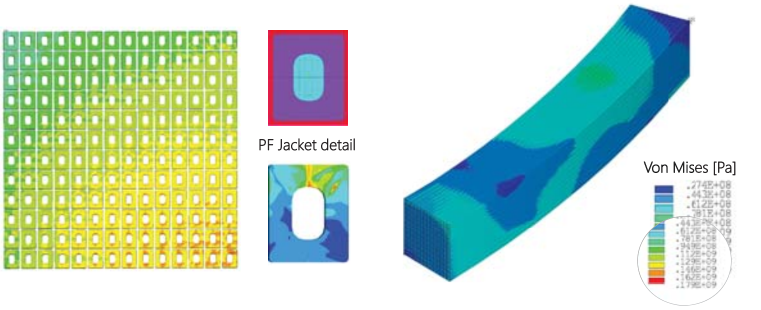


DEMO reactor:
1. Plasma
2. Vessel
3. Magnet system

PFC:

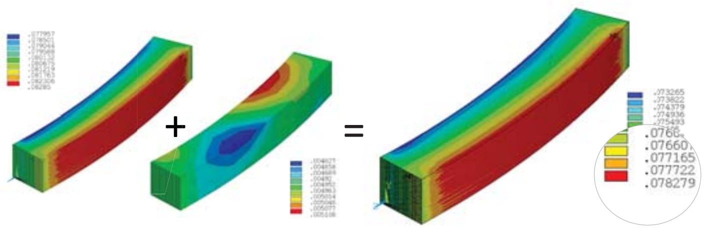
the circular poloidal coils surrounding the TFC system produce a vertical field $\vec{B}_z$ that ensures plasma equilibrium. These magnets are mechanically connected to the TFCs through flexible plates and sliding supports that allow radial shifting. This work focuses on the PF#4, the largest of the poloidal magnets, with a radius of 17 m and a section composed of 168 S/C wires. The magnetic field and the current are lower than the TF, and reach maximum values of respectively $\vec{B}_\varphi \simeq 5\ \mathrm{T},\ i = 55\ \mathrm{kA/cable}$.

Mechanical APDL analysis (EOF scenario):
Along the toroidal direction in correspondence of each TFC the magnetic field has a peak of intensity. There are 18 TF so the system can be easily studied in cyclic symmetry with a period of 20 degrees. Field values in each section, transformed into Lorentz forces, have been applied to superconducting cables. 168 application points and 40 interpolation sections are used in the considered repetition period of the load, with a maximum value $246\ MN/m^3$.



(LHS): full detailed cross section PFC analysis – *(RHS):* 20 degree 3D sector PF#4 model

The PF coils operate below the critical temperature for the Ni_3Sn superconductor, hence the effect of cool down on the structure is to be considered. Different thermal expansion coefficients between the jacket steel and epoxy filler induce potentially critical tensional states. Since the analysis remains within linear elasticity, nodal displacement solution can be summed by superposition of effects.



Cool Down (compression) + Lorentz Forces (traction) = Total max Displacement 7,8 cm

CONCLUSIONS:

- The TF innerleg 2D section analysis shows critical stress peaks (1.13 GPa) in the jacket corners. Parametric optimisation for the jacket thicknesses and curvature radii may alleviate this issue;
- The TF global 3D analysis is used as basis for a topology optimisation of the OIS between the magnets; an engineered optimum design is proposed;
- The PF coil tensional state is compliant with stress limits. However, the interaction between jacket and insulation must be thourougly characterised, as a failure on the insulation may lead to magnet collapse.