The new ASDEX Upgrade upper divertor for special alternative configurations: design and FEM calculations

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ASDEX Upgrade (AUG) is the experimental tokamak based in Germany that since many years, 1991, explores technical solutions to address physic aspects. This time, the aim is to prove that alternative divertor configurations (X-divertor or Snowflake divertor) can mitigate the power exhaust problem, in a machine with high heating power like AUG. To realize the required magnetic configurations [2], two poloidal field coils are required in the divertor region. The upgrade in AUG will be carried out in the upper divertor and the following components will be newly designed and installed in the next years: cryopump, inner and outer divertors and finally two divertor coils [4]. In the design phase, many challenges were faced: 1) Manufacturing and qualification of a conductor able to safely operate the coils [6]; 2) Implementation of the new components in a tight room, maintaining the plasma volume and the present plasma configurations; 3) Implementation of the divertor coils close to the strike line.

The design has reached a certain level of maturity and a prototyping phase has been started. The installation of the component is planned for 2022 and at that time AUG will be the first tokamak having in-situ winded coils.

The components design is based on the experience gained in years of AUG operation, which allowed for the building up of an extensive database to get the input parameters for the FEM analyses.

Induced and halo currents interacting with the static toroidal field are the main source of loads in the structure. Different electromagnetic models were prepared to address the problem together with their corresponding mechanical models. The design has been iteratively changing according to the results of the FEM analyses. The paper will present the design of the upper divertor components and the analyses carried out to verify their mechanical integrity.

Keywords: ASDEX Upgrade, In-vessel coil, Snow-flake divertor

1. Introduction

The power exhaust problem in the fusion reactor is one of the critical aspects that has to be addressed (better say solved) by the mid-size tokamaks steering the design of the next fusion reactor (DEMO). The solution proposed in ASDEX Upgrade (AUG) foresees the installation of two coils in the region of the null point in the upper divertor (Fig. 1). Here the aims are the flaring the magnetic field, expansion of the poloidal flux tube and increasing the reconnection length in order to reduce the heat flux in the divertor target [1].

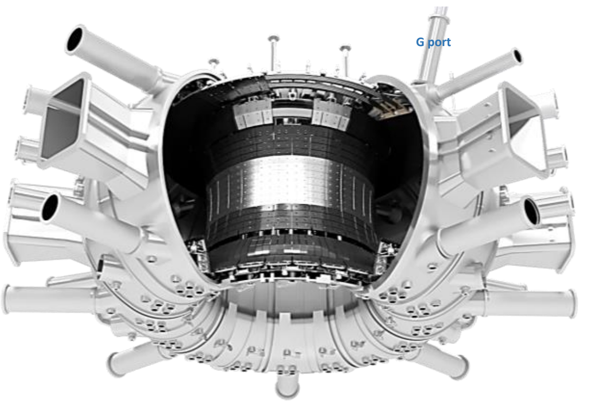

Fig. 1 Overview AUG: the upgrade will be done on the upper part of the vacuum chamber. The oblique port (G port) where the coils are routed out is indicated.

With the installation of the two in vessel coils, AUG will address physic problems, while the technological implications for a futuristic nuclear fusion reactor need to be studied elsewhere. AUG operates with plasma pulse length up to 10 s and with a dwell time of 20 minutes, during which the in-vessel components are passively cooled. For AUG maximum values for plasma heating and Psep/R are respectively 110 MJ and about 2.5 MW/m.

Taking advantage of the installation of the two coils, the whole upper divertor will be upgraded namely with cryopump, inner divertor and outer divertor that will act as casing of the in-vessel coils. The main components are highlighted in Fig. 2. The paper describes the design of the components (Par.2) and in the following chapters is reported an overview of the calculations carried out for the dimensioning of the components.

2. Design overview: coils and upper divertor structures

The main component that drives the design of the upper divertor is the couple of coils placed close to the plasma strike line. To guarantee the novel/advanced divertor configurations reported here [2] the coils are fed up 52 kA pro coil, operating in counter current, allowing both polarities. Between the two coils, a small difference in term of current is allowed, but the force imbalance has to be withstood by the AUG vacuum vessel (VV), or better to say, the rods where the VV is hanging on [3]. In a first stage, different conductor type where considered [4], but to fulfil the safety requirement, avoiding short circuit

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between adjacent windings, the conductor needs to have a protection jacket.

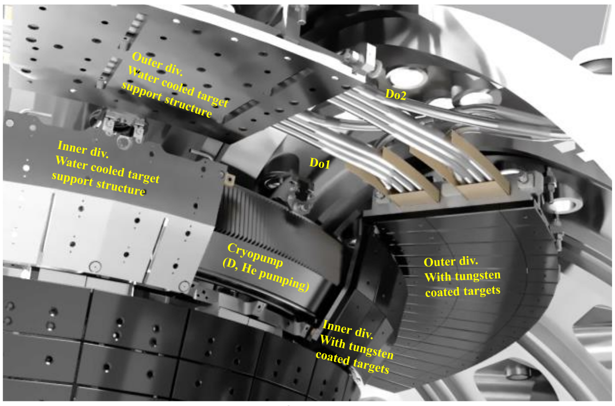

Fig. 2. Main components of the upper divertor that will be installed in the next years in AUG.

The selected conductor consists of a seamless hollow OF copper (ID=8mm; OD=18mm) with extruded Tefzel HT 2183 and a stainless steel jacket, that will provide protection from in-windings arcs and vacuum tightness. The conductor is passively water cooled. It has been electrically qualified and further details are available here [6]. The induced voltage during a plasma disruption and the temperature rise of the copper during the operation defined the conductor's size and the number of the coil windings. According to the AUG database, the maximum expected dB/dt during a disruption will be about 100 T/s, inducing a voltage in coil's winding of about 1kV/turn. The electrical strength of the insulation can largely cover the required electrical strength with its 2.5 mm thickness (70 kV/mm). The coils are concentric and each of them made of four windings. They will be winded in the vacuum vessel (VV) and routed out through an oblique port without joints. Of course, this solution strongly relies on the feasibility to bend the entire coil inside the VV, facing the space limitations inside a fully equipped tokamak operating since 30 years. During the coil operation, the copper temperature rise will be limited up to 60°C, in order to limit the thermal stresses on the conductor itself.

The coil windings are fully embedded in the supporting structure of the outer divertor, which consists in a stiff toroidal ring made of sector wise modules bolted together through electrical insulated flanges, in order to maintain the electrical scheme of the AUG VV and guarantee the plasma breakdown [5]. Each module has a steel casing having two slots to allocate the coils, a cooled plate bolted on the bottom, which act also as protecting cover of the coils. Graphite tiles coated with tungsten [4] are clamped on the cooling plates the. The module is bolted into the VV sector by means of four supports.

The inner divertor design is driven by room requirements since it is squeezed between the new cryopump and outer divertor. It is sector wise structured and each module has a main plate weakly cooled on which the graphite tiles are bolted in. The plate rests on the bottom on a ring connected to the VV, which it is also supporting the cryopump module, and on the top to the nearby vertical port of the VV. Details on the new cryopump of the upper divertor are here available [7]. Both the divertors have to withstand electromagnetic forces during a disruption event: namely induced current and halo currents flowing through the component before reaching the VV. The estimation of both is based on the measurements available in the AUG database.

The coils are not affected by disruptions since the power supply delivering the unbalanced current is connected to an 'intelligent crow bar' that will open the circuit allowing an over voltage rather than an over current [8]. Nevertheless, the coils have to withstand the electromagnetic forces rising up during their operation. These forces, having the coils the current flowing in opposite side are cancelling out, except for the small unbalanced current component. These forces and moment are taken up by the AUG VV. Within the windings these forces are not severe, but they strongly increase as soon as the coil current crosses the toroidal field where the coils feedthrough are routed out inside the G port. During the operation, the thermal expansion of the conductor is causing secondary stress on the coils. To reduce their impact the coils are left almost free to move inside the slots of their casing: small sliding supporting elements in torlon will permit the sliding.

3. Inner and outer upper divertors

3.1 Induced currents

To evaluate the induced current in the divertors an octant finite element electromagnetic model of AUG has been setup with the commercial code ANSYS. The model consists of the AUG magnet system, VV and the upper divertor. The plasma current and its position are prescribed according to the data available in the AUG database. The worst vertical displacement event in term of dB/dt was selected as reference case [3]. The electromagnetic model is shown in Fig. 3.

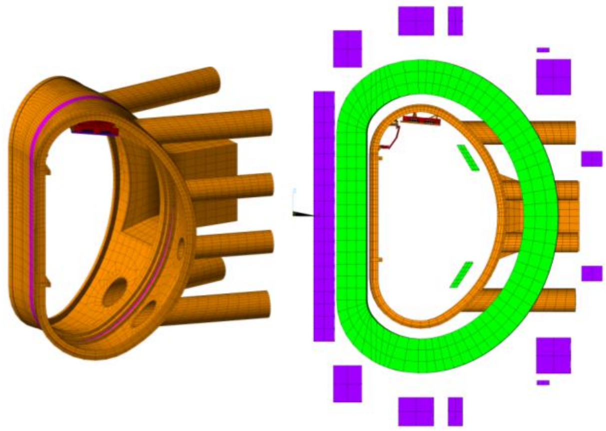

Fig. 3 FEM electromagnetic of AUG: the magnet system, VV and main components of the upper divertor are modelled.

The calculated electromagnetic forces are transferred node by node to the structural model of the upper divertors. In Fig. 4 and Fig. 5 the structural model and the stress distribution respectively for the outer and inner divertor are illustrated. As reported, the stresses are well below the limits.

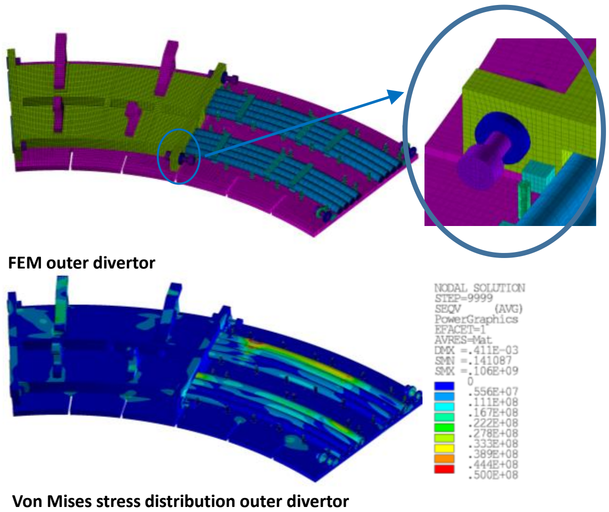

Fig. 4 Top: FEM outer divertor. Bottom: Von Mises [Pa] stress distribution on the outer divertor (without preload stresses caused by the connecting bolts) during a disruption.

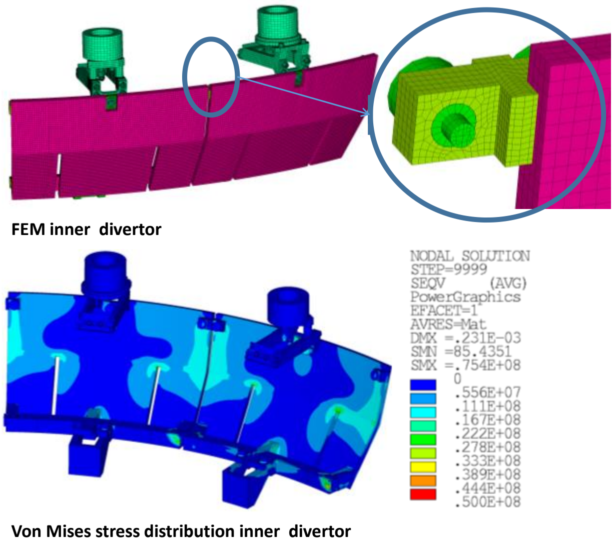

Fig. 5 Top: FEM inner divertor. Bottom: Von Mises [Pa] stress distribution on the inner divertor (without preload stresses caused by the connecting bolts).

3.2 Halo currents

The evaluation of the halo currents is based on database build up in 30 years of operation of AUG, assuming that their distribution is not effected by the new divertor configuration. The maximum halo current is assumed to be the 40% of the plasma current that means 25 kA per module assuming 1 MA plasma current. In Fig. 6 the halo current versus the plasma current measured in the last campaign is reported. The measured halo current are applied in electrical model of the divertor (upper and lower) and the calculated current path is superimposed to the static magnetic field, for the evaluation of the electromagnetic forces to be applied in the mechanical models. The inner divertor required some iteration to get a design that withstands the halo forces. In fact, in the present design the inner divertor has been connected to a port of the VV in order to provide some stability in the vertical axis.

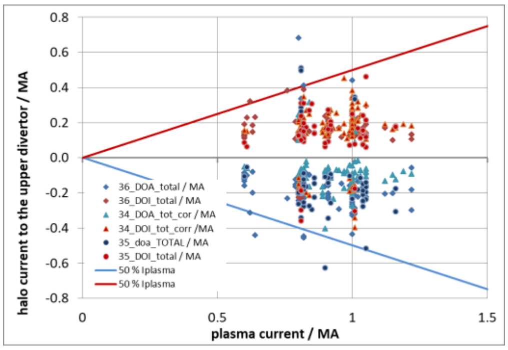

Fig. 6. Halo current [MA] as function of the plasma current in the last campaigns of AUG.

In Fig. 7 are reported the deformation and Von Mises stress distribution for the inner divertor.

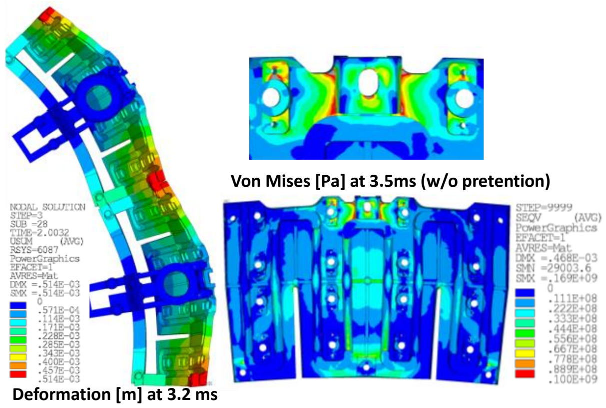

Fig. 7. Inner divertor: deformation [m] on the left and von Mises stress [Pa] on the right (without preload stress).

On the contrary, the outer divertor design has been always robust against halo current.

4. Divertor coils

4.1 Static electromagnetic (EM) forces

An ad hoc model including the full coil model has been built to evaluate the electromagnetic forces acting in particular on the feedthrough of the coils, where the current path is crossing the toroidal magnetic field. Fig. 8 illustrates the model including the AUG magnet system and the two divertor coils and on the right side, the calculated forces per unit length acting along the outermost coils as function of the conductor position. As expected, the forces in the feedthrough are quite high. To stand the forces in this position, the feedings line of the coils will be bundle together before to be inserted in the VV port, to compensate the forces acting on the conductors.

The stresses in the corresponding mechanical model are quite low inside the port, but significant bending stress are calculated in the unsupported part of the coils, as can be seen in Fig. 9.

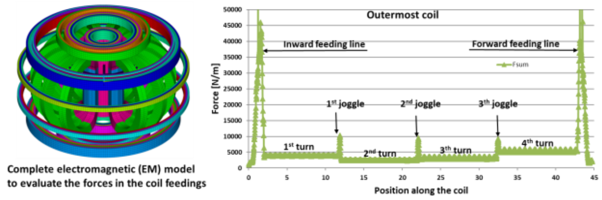

Fig. 8. On the left side: AUG electromagnetic model to evaluate the forces acting along the conductor. On the right hand side the force per unit length versus the conductor position is reported for the outermost coil.

The linearization of the stresses clearly indicates a bending that required some additional sliding support of the coil to the casing.

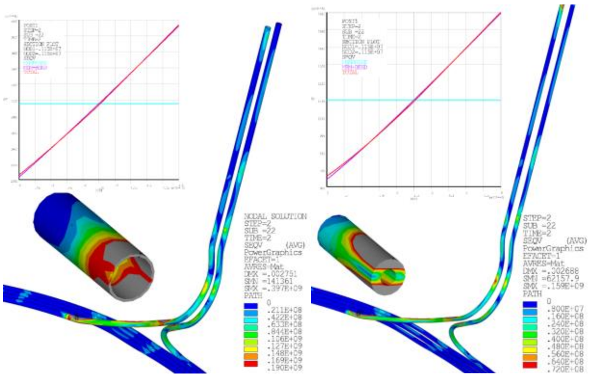

Fig. 9. Von Mises [Pa] stress distribution for the outermost coil: on the left hand side stress refer to the stainless steel jacket of the conductor. On the right hand side, it refers to the copper hollow conductor. The linearization of the stresses shown a clear bending of the components. Allowable stresses for the copper and stainless steel are respectively, 66 MPa and 192 MPa.

4.2 Thermal model

During the operation of the tokamak the coils are heated up due to the joule heating. Per design, the temperature rise of the copper is limited to 60°C. The conductor is mainly cooled down in the dwell time with a water flow rate of 0.3 kg/s, which correspond to 6m/s. Hydraulic tests have shown that no erosion of the inner surface of the copper is induced by the flow rate. The 3D model of the coils with cooling elements (Fluid116 with heat transfer coefficient as function of the temperature) is illustrated Fig. 10. The corresponding mechanical model shows some high stress in the feedthrough region that requires still some optimization in the distribution of the supporting elements.

5. Discussion and conclusions

The design of the new upper divertor with its integrated coils is now in final design phase. Some modification in the coils layout is expected as feedback of the prototyping and/or the finalization of the bending procedure inside the AUG vacuum vessel. In addition, the coil feedthrough need some iteration to overcome the stress concentrations seen during the coils operation.

On a first attempt, the effect of the baking up to 150 °C on the coils has been simulated and no problems are highlighted.

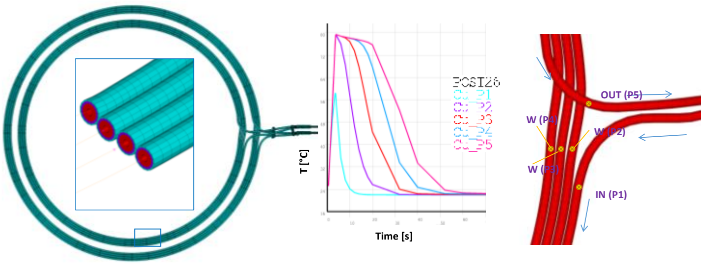

Fig. 10. Thermal model of the coil on the left hand and on the right the temperature distribution of the temperature in different copper locations.

The FEM analyses, together with the qualification of the conductor [6], have shown the feasibility of the project. The prototyping of the main components already started and the manufacturing of the conductor is ongoing. The installation of the component should start in the 2022 and it would take more than a year. For that time, AUG will be the first tokamak having in-situ winded coils and will provide return of experience to ITER that also plans to install in-situ winded coils.

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