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COMPARISON OF PUMPING LIMITER, DOUBLE-NULL AND SINGLE-NULL DIVERTOR CONDITIONS FOR THE ASDEX UPGRADE TOROIDAL FIELD MAGNET

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Abstract - ASDEX Upgrade (AU) is a tokamak experiment with external poloidal field coils. It will be provided with divertors of single-null (SN) and double-null (DN) configurations. Additionally, a pumping limiter (L) is envisaged. The design principle of the toroidal field (TF) magnet for AU is described and the stressing of the supported TF coils compared for the three operation modes. Special consideration is given to the SN divertor as a favourite option for AU as well as for INTOR and NET.

The local poloidal field (PF) required for the production of the SN stagnation point is significantly larger in comparison with limiter tokamaks such as JET, though the total sum of PF currents differs only little. The support of the lateral forces produced in the toroidal field (TF) coils by the PF thus requires a very rigid structure in order to protect the TF coils from being overstressed by shearing and bending. The mechanical effects of the SN loading have been little discussed up to now. They are difficult to understand because of the lack of symmetry of the PF currents with respect to the torus plane.

Fig. 1 - Plan view of the toroidal field magnet for AU
1. BASIC DESIGN FEATURES

The toroidal magnet comprises 16 water-cooled TF coils and the turn-over structure (TOS), which houses the outer parallel flanked part of the coils (Fig. 1). The TOS contains 8 large casings, which are split in the torus plane by flanges. To provide force locking in toroidal direction, two small casings, located symmetrically above and below the torus plane, link adjacent large casings. Due to the missing vertical connection of the small casings each large casing has to take up in the torus plane the shear forces resulting from the lateral loading of two coils. The small casings provide ample space for 8 large horizontal access ports. The dimensions available of these openings are laterally the full gap width of adjacent coils (>600 mm) and vertically 960 mm. Each large casing contains two access ports directly above and below the torus plane flange with a 330 by 330 mm² clear opening. The remaining openings for access to the plasma and the recesses for the coil watermanifolds are shown in Fig. 1. Due to lack of space the position of adjacent watermanifolds alternates with respect to the torus plane. The double pancake copper coils are constant tension D-shaped (Fig. 2). Their bore opening is 2.96 m vertically and 1.9 m horizontally. The magnet is designed to produce a maximum TF of \( B_0 = 4 \) T on the plasma axis with a radius of \( R_0 = 1.65 \) m.

The centering force (CF) exerted by the TF is supported via a vault, which is formed by the 16 tapered inner coil legs. Mismatch due to manufacturing tolerances will be compensated by means of epoxy-filled steel bladders. The resulting vault compression stress acting over the lateral coil surfaces CFSA of Fig. 2 provides force locking also with respect to shearing. At a friction coefficient of 0.39, typical for insulation on steel, a shear force as large as the CF per coil (15.7 MN at \( B_0 = 4 \) T) could be transferred between adjacent coils. Hence the vaulted inner coil legs act mechanically like a closed cylinder with cross-section CFSA. The lateral forces exerted on a TF coil outside the TOS can thus immediately be counteracted in the vault by horizontal and vertical shear forces. This is of prime interest for the DN and SN loading distributions. The remaining lateral PF forces are transferred via the areas TOSA of Fig. 2 into the TOS and also counteracted there by shearing forces. Shear sleeves and dowels are thus required on the casing joints. Figure 2 also shows the auxiliary fixtures for assembling and adjusting the coils. The steel bracing tapes will be removed after assembly of the complete toroidal magnet.

2. ELECTROMAGNETIC PF FORCES

The electromagnetic forces exerted on a TF coil due to the interaction of coil current and external PF are proportional to the product of the TF on the plasma axis (\( B_0 \)) and the plasma current (\( I_p \)). The three configurations DN, L and SN are thus always compared at the same product \( I_p \times B_0 \).
Starting from the L configuration, the quadrupole PF component of the diver-
tor configurations has to be increased significantly in order to shift the 
stagnation point(s) towards the plas-
ma boundary. Additionally a hexapole 
PF component is required to readjust 
the right height-to-width ratio of the 
plasma column (triangularity). Both 
PF components are quickly decaying 
from the PF coils, arranged outside 
the TF coils, towards the plasma. 
Consequently these divertor-specific 
field components increase considerab-
ly the lateral magnetic load in the 
winding of the TF coils, as demonstra-
ted in Figs. 3 and 4.

The L force distribution, familiar 
from JET, is compared in Fig. 3 with 
that of the DN case. Both configura-
tions show odd symmetry with respect 
to the torus plane (z = 0).

In Fig. 4 the SN force distribution 
is shown. Thereby the stagnation point 
was assumed above the torus plane. 
The SN loading resembles near the 
stagnation point the DN distribution, 
however, with a reduced hexapole PF 
component. Below the torus plane it 
resembles the L case. Hence the SN 
force distribution does not show 
simple z = 0 symmetry. The main 
problem of the divertor force distribu-
tions are the increased forces outside 
the TOS, i.e. in the region between 
the apex of the coils and the vault. 
There the maxima of DN and L differ 
by more than a factor of three and 
those of SN and L by a factor of two.

The dominant actions of the PF forces 
on a coil can immediately be derived 
from Figs. 3 and 4. For DN and L the 
et forces of upper and lower coil 
half rotate due to the odd z = 0 sym-
metry the complete coil around the 
X axis. The quadrupole forces twist 
the coil around a vertical axis. The 
opposite twists of upper and lower half 
of a coil compensate each other. 
Hence the coil could balance this 
mode elastically without the assistance 
of the TOS or the vault. In the SN 
case this compensation exists no longer, hence the total coil is rota-
ted around a vertical axis. This displacement mode shows even symmetry 
to z = 0. Of course, the modes of odd z = 0 symmetry are also present.

The even and the odd SN modes can be separated by decomposing the cur-
rent distribution as shown in Fig. 5. The SNA current distribution 
produces a magnetic flux which in the torus plane is directed horizon-
tally. This flux distribution causes the displacement modes of even
**3. THE FINITE-ELEMENT (FE) MODEL**

The stress analysis was performed with the FE model shown in Figs. 6 and 7. This model represents the main force transfer properties between coils and TOS as well as via the flange connection joints of the TOS casings. However, simplifications were met with respect to the TOS recesses. Only the large and small port near the torus plane, the largest recesses of the TOS, were accurately represented. The alternation of the watermanifold recesses was neglected for the sake of higher order structural symmetry in lateral direction.

Hence 16 watermanifold recesses instead of the actual 8, were assumed above the torus plane. To compensate for the resulting reduction in stiffness, the adjacent circular port openings of Fig. 1 were neglected. Also the vertical openings are not considered at present. In this case the FE model needs only to comprise the sector shown in Fig. 1, i.e. one coil and the adjacent halves of a large and a small casing.

The coil is represented up to the vault by 30 beam sections. Alternatively three dimensional (3D) elements could have been taken. However, the internal bending ($M_b$) and twisting ($M_t$) moments as well as the shear forces ($Q$) provided by beam elements are directly related to the external (lateral) forces. Consequently beam elements are much better suited for the interpretation of results than the involved stress distributions provided by 3D elements.
However, at a later stage 3D elements will be applied for more detailed investigations of local effects. In this case the insulation components will also be meshed as detailed as possible (computer capacity). In the vault region the coil is represented by plate elements like the TOS. Truss elements (hinged bars) connect coil and TOS laterally at cross-sections which are stiffened by bulk heads (Fig. 7). With a few iterations all trusses which showed tension forces could be eliminated, thus only compressional forces were transferred into the TOS after the last iteration. The number of casing joints of the FE model agrees with reality. However, the correct circumferential position could not be realized for each of the 12 joints. The FE model represents the joints by beam elements in order to transfer shear and tension forces between the two casings.

Each coil consists of 24 insulated turns which are bonded by epoxy resin (vacuum impregnation). Consequently the beam twisting and bending stiffness of the total coil cross-section were inserted and the constants of elasticity averaged over turn copper and insulation. For the plates of the TOS the elasticity modulus of steel ($E = 200$ GPa) was inserted.

Boundary conditions are required where the structure of Fig. 1 is cut by the symmetry planes of the FE model, i.e. within the vault and the TOS. These boundary conditions are described by means of translational and rotational displacement constraints, which follow from the symmetry conditions of the corresponding loading. For a plane of odd symmetry the inplane displacements and consequently the out-of-plane rotation are blocked. For a plane of even symmetry the out-of-plane displacement and the inplane rotations are blocked. The symmetry relations of the torus plane are given in Fig. 5. The lateral planes throughout show odd force symmetry. The natural boundary conditions suppress all possible rigid body motions of the FE model. Only in the SNA case a rigid body rotation around the torus axis remains unstrained. In this case the stiffness matrix of the FE model cannot be inverted. However, this rotation is not excited by the external forces. Consequently it can be eliminated by blocking on the TOS one-translational degree of freedom in and normal to a lateral plane of symmetry. Thereby the stress distribution will not at all be affected.

4. STRESS ANALYSIS OF THE TF COILS

For the SN case the most important results are shown in Figs. 8 to 11 as a function of the cross-section numbers (CSN) of Fig. 7. The plots cover the upper part of a coil up to the vault, i.e. the region which was represented by bars. The SNA and SNB components are plotted separately. Consequently the results for the lower part of the coil can also be extracted from the plots. The corresponding results for the DN and L loading show qualitatively the same distributions like the SNB loading, the quantitative differences follow from Table 1.

The lateral displacements are plotted in Fig. 8. In the region supported by the TOS the SNB and near the vault the SNA loading dominate the displacement pattern. The shear forces ($Q$) of Fig. 9 are strongly
influenced by the concentrated force transfer into the TOS via trusses. The supporting influence of the TOS tip (CSN 18, 19) on the coil is obvious. For the upper half of the structure altogether 20% of the total forces transferred into the TOS and 30% of the coil forces of the unsupported part of the coil are taken up by the TOS tip. The distribution of the bending moments (Mb), shown in Fig. 10, is dominated by the SNB loading. The maximum of Mb outside the TOS coincides in location with that of the force distribution.

Due to the increasing reduction of the coil cross-section towards the vault the bending stress shows its maximum (18 MPa) on CSN 31 of the lower half of the coil. The bending stresses on the watermanifold are comparatively small (7 MPa). Near the TOS tip, at CSN 17, the zero points of SN loading, displacement and bending moment coincide rather well. There a hinge can thus be assumed on the coil. The TOS tip is too near to this location in order to balance a marked part of the moment formed by the external loading around this hinge. Most of this moment has thus to be taken up by the vault. The odd SNB loading is counteracted there (CSN 31) mainly by the shear force of Fig. 9, which entails a vertical
frictional shear stress within the vault. The even SNA loading is mainly counteracted on CSN 31 by the twisting moment \( (Mt) \), shown in Fig. 11.

The moment \( Mt \) entails a horizontal frictional shear stress within the vault. Outside the vault it could most effectively be taken up by a closed casing around the coil, e.g. a welded steel casing (thermal problems) or an epoxy casing with crossing KEFLAR fibres wound around the coil under an angle of 45 degrees. However, the vault current density of the coil winding is fixed by the required adiabatic pulse duration of the magnet and the addition of a casing would thus increase considerably the total tokamak system. Consequently, the TF coils of AU dispense with a casing in and near the vault region.

In the bare coil cross-section twisting moments show a very inhomogeneous distribution of shear stresses. Additionally the winding insulation, also stressed by the twisting shear, can only take up small shear stresses of about 35 MPa at the highest operational temperature of 70° C. The twisting moments thus limit at the design shear of 20 MPa the SN operation of AU to \( Ip \times Bo \leq 4.5 \) MAT. In this case, at the maximum plasma current of 1.6 MA \( (q = 2.2) \), a friction coefficient of 0.15 is sufficient for the equilibrium of the vault.

In Table 1 the three configurations DN, SN and L are compared at \( Ip \times Bo = 3.9 \) MAT with respect to the maximum bending stress and twisting shear on the vault (CSN 31) as well as the maximum displacement. The DN case shows the largest bending stresses, the SN case the largest twisting shear. With respect to these values the corresponding stresses of the L case are more than a factor of three smaller.

5. CONCLUSIONS

The mechanical problems for the TF magnet of a tokamak with a reactor-relevant axisymmetric divertor are decidedly aggravated. However, the combination of frictional vault support and TOS, as chosen for AU, effectively supports the large lateral SN or DN divertor forces produced by external PF coils.

For INTOR or NET conditions the larger aspect ratio will reduce the mechanical problems. In case of a welded-in superconducting winding, the coil casing takes up most effectively the SN twisting shear. Additionally, due to the low operational temperature, much larger shear stresses are allowable for the coil winding. Consequently the force problems of the TF magnet should be solvable for a toroidal divertor of a fusion reactor.

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