

# Toroidal Field Magnet and Poloidal Divertor Field Coil Systems Adapted to Reactor Requirements

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## Abstract

ASDEX Upgrade is a tokamak experiment with external poloidal field coils, that is now under construction at IPP Garching. It can produce elongated single-null (SN), double-null (DN) and limiter (L) configurations. The SN is the reference configuration with asymmetric load distributions in the poloidal field (PF) system and the toroidal field (TF) magnet. Plasma control and stabilization requires a rigid passive conductor close to the plasma. The design principles of the coils and support structure are described.

## 1. Introduction

ASDEX Upgrade has been designed in order to extend the favourable features found in ASDEX divertor discharges to poloidal divertor plasmas which are physically and technically compatible with reactor requirements. /1/

The poloidal divertor plasma configuration allows a large power flux to be transported from the plasma to the environmental material structure in such a way that sputtering, which is the main impurity source, is reduced to a minimum. The power lost from the plasma by thermal conduction and plasma flow is directed by the magnetic flux geometry to target plates specially prepared by active cooling and material selection. In ASDEX this configuration was achieved with relatively small multipole currents at the expense of putting the multipole coils close to the plasma inside the vacuum vessel, a solution not possible for reactors.

ASDEX Upgrade, now under construction, meets reactor requirements with regard to the plasma boundary and divertor as well as to the magnetic field coil system. In the following, the magnetic field coil system and support structure are described: the poloidal field system in Sec. 2, the toroidal field magnet in Sec. 3, and the passive structure, consisting of the passive stabilization coil and vacuum vessel, in Sec. 4. Section 5 describes the assembly concept.

## 2. Plasma Configuration and Poloidal Field (PF) System

The plasma equilibrium of a tokamak is maintained by the toroidal currents of external coils and the plasma current, all having rotational symmetry

to the main axis. The poloidal field pattern ( $B_r$ ,  $B_z$ ) of a single-null (SN) divertor configuration is shown in Fig. 1 together with the external coil currents. The plasma current is distributed over the area of closed field lines.

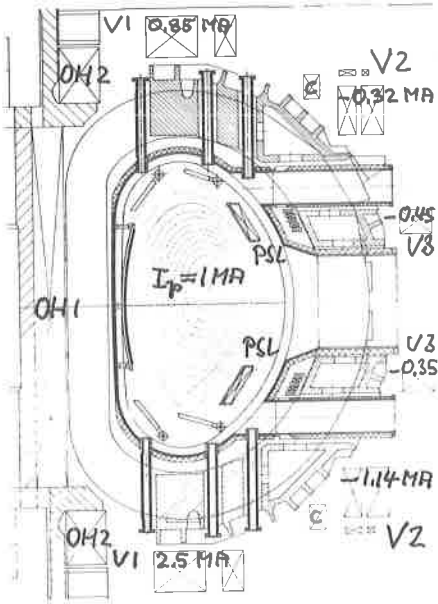


Fig.1: Poloidal field and PF coils

The separatrix separates the regions of closed and open poloidal field lines. It is marked by one and two null points for single (SN) and double-null (DN) configurations, respectively. In a reactor all poloidal field coils have to be placed outside the toroidal magnet to facilitate assembly and repair and to leave sufficient space inside the TF magnet for the blanket and shielding. This requirement was met in relative dimensions of ASDEX Upgrade.

During the INTOR conceptual study phase I, a SN divertor configuration was worked out /2/ with a total sum of multipole currents (absolute values) only 30 % larger than that of a comparable limiter (L) configuration. The main difference between the SN and L configurations is the absence of symmetry of currents and forces to the toroidal midplane.

The PF coil system /3/ is composed of the ohmic heating (OH) coils, the vertical field (V) coils and the control (C) coils. The OH coils serve for breakdown, plasma current build-up and control, the V coils for plasma equilibrium and shape control,

and the C coils for feedback stabilization of the plasma position and shape. A closed induction loop (PSC) close to the plasma and vacuum vessel eddy currents (Sec. 4) reduce the required response time of the C coils. Since the current programmes of OH, V and C coils change considerably during a discharge, the load distribution within the PF system also varies. The coil forces decompose into radial and vertical force components. The coils take up their radial forces by hoop tension. The vertical loads are supported by a stainless steel framework consisting of two spoke wheels, to which the upper and lower V coils are mounted (Fig. 2). The hubs of the spoke wheels are connected by a steel column which reduces the bending moments of the spoke-like beams and also supports the OH 2 coils, which attract each other. All forces of the PF coil system are balanced by the PF coil framework in such a way that the TF magnet is not loaded with these forces. Because of the space available there were no dimensioning problems with the PF support structure. Less space was available for the coil holders because the coils had to be placed as close as possible to the TF coils in order to reduce the PF coil

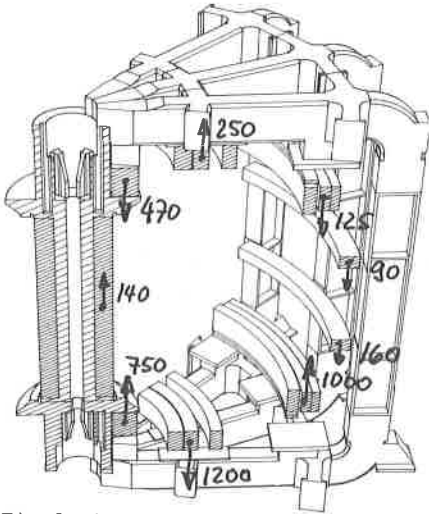


Fig. 2: Sector of PF coil support structure with loads in tons for  $I_p = 1.6$  MA.

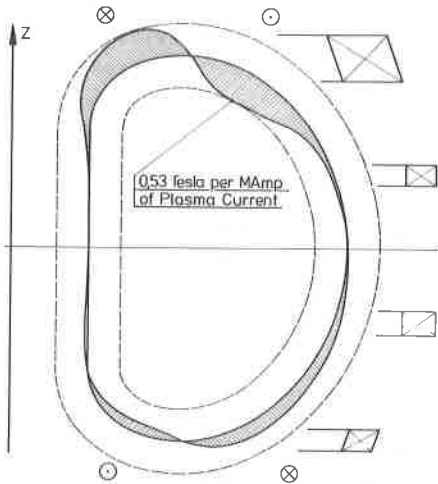


Fig. 3: TF coil lateral force load (SN) position in upper half, contrary to Fig. 1).

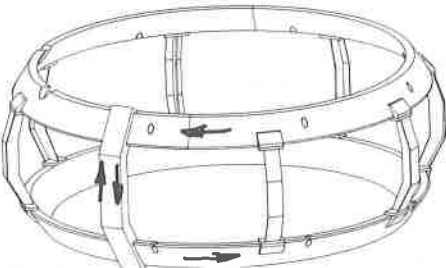


Fig. 4: Passive stabilizing loop.

currents. The vertical forces on the PF coils for SN 1.6 MA plasma are also given in Fig. 2 .

### 3. The TF Magnet

The toroidal field provides stability for the plasma and determines the attainable plasma pressure. Sixteen D-shaped coils form the ASDEX Upgrade TF magnet. The D is the appropriate shape for the axially symmetric forces. The wedge-shaped straight section of the D's forms a vault around the axis. The central ohmic heating coil is located in the bore formed by the vault. The symmetric TF forces produce mainly tension in the curved part of the D's. Other tokamaks have used the same principle.

However, the lateral forces on the TF coils produced by the SN poloidal field are larger than those produced in L configurations and not antisymmetric to the toroidal midplane [4]. Figure 3 shows a typical SN load distribution. The drilling and bending moments acting on the TF coils require a rigid overturning structure which forms a shell around the coils. It consists of 32 cast austenitic steel sector elements with many large penetrations for vacuum vessel ports. The vault cylinder in the inner part has to counteract the drilling moments of the single coils in addition to the central force support. The wedge surfaces of the single coils provide enough friction under the vault pressure force. Critical stresses are shearing stresses in the coil insulation. Their largest value appears where the coils leave the vault support. This critical shearing stress is roughly proportional to the product of the plasma current  $I_p$  and the toroidal field strength  $B_0$ . For ASDEX Upgrade SN operation the limiting value is  $I_p \cdot B_0 = 4.5$  MAT.

#### 4. Passive Conducting Structure and Plasma Control

The vacuum vessel consists of 8 rigid sectors with insulated flange connections. Resistive steel bellows bridging the insulation produce an all metal vacuum vessel from the plasma side. Fast plasma current changes induce eddy currents in the vessel whose distribution is determined by the rigid sector geometry /5/. Large forces on the vacuum vessel result in the case of plasma current disruptions. The typical R/L time constant of these eddy currents is 10 ms.

The elongated plasma is in radial direction stable but unstable for vertical displacements. A passive conductor loop close to the plasma (SN configuration) forming a one-loop saddle coil counteracts the plasma motion by induced current. It reduces the time constant required for active stabilization by the C coils to 100 ms. Figure 4 shows the passive control conductor. It is also seen in Fig. 1 in cross-section. Its size is determined by the acting forces (vertical 80 tons) and the large L/R time.

#### 5. Tokamak System Assembly

The vacuum vessel and its numerous ports require to start assembly in octants. Some ports can be welded in only after the adjacent TF coils are in place. Octants are connected to torus halves in a distance which allows to insert half loops of the passive and active stabilizing coils. The active coils just outside the vacuum vessel are auxiliary coils which allow plasma control with small power.

The lower spoke wheel with mounted PF coils is under the torus half in place already. The second torus half is moved on rails towards the first one and connected. Assembly of OH transformer coil, of the vertical PF support beams and the upper spoke wheel follow. The total weight of the system is about 700 tons, that of TF magnet and vacuum vessel 340 tons.

#### References

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