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Divertor Development for Wendelstein 7-X

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Abstract

A divertor concept for stationary operation with a power deposition of up to 10 MW has been developed for the HELIAS type Wendelstein 7-X. In respect of the extended parameter range an "open divertor" was chosen as a first approach. The 3D interacting surface was shaped according to results of boundary modelling. Ten divertor units were designed which include the target plates, baffle plates, control coils and additional cryo panels. Compact prototype high heat load elements were successfully tested using an electron beam facility with a power load up to 12 MW/m^2.

Keywords:

HELIAS, boundary structure, effects of finite $<\beta>$, divertor concept, modelling, deposition pattern depending on parameters of operation, engineering of target elements

1. Introduction

The standard magnetic configuration [1] of W7-X (R=5.5 m, a=0.55 m, B=3 T, 5 periods) is generated by a set of 50 poloidally closed, non-planar coils, being arranged in five equal sectors. The shape of the coils is determined by the chosen magnetic configuration, which was optimised on the basis of criteria for equilibrium, stability and confinement. Additional 20 planar coils, four per period arranged under specified particular angles with respect of the equatorial plane, provide flexibility for the variation of the magnetic parameters (Fig. 1). An attribute of the selected magnetic configuration is an inherent divertor.

2. Divertor in W7-X

The cross-section of the magnetic surfaces in W7-X changes periodically as one proceeds in toroidal direction, with poloidal symmetry planes showing either a bean-shaped or a triangular shaped contour. A "helical edge" which connects the bottom and the top of indented cross-sections for 1/5 of the toroidal circumference characterises the shape of the magnetic surfaces. Along these edges the helical curvature dominates the toroidal one. Due to the resonances of sideband Fourier components of the radial B spectrum with the local values of the rotational transform and the low shear situation of the W7-X configuration natural islands are generated. The LCMS is either defined by the inner separatrix of a natural island chain which is intersected by target plates or by an ergodised outer layer with remnants of O- and X-points of related islands. Unlike in tokamak divertors the X-lines in island divertors are helical, with the pitch depending on the resonant rotational transform of the island chain. For the standard magnetic configuration ($\iota=1=5/5$ at the boundary) five toroidally closed helical X-lines are present. In the case of extended islands the positioning of divertor elements along the helical edge allows to concentrate the plasma flow on target plates and to uncouple the plasma core completely from the wall.

An "open divertor" system [2] was chosen in a first approach to achieve effective power and particle

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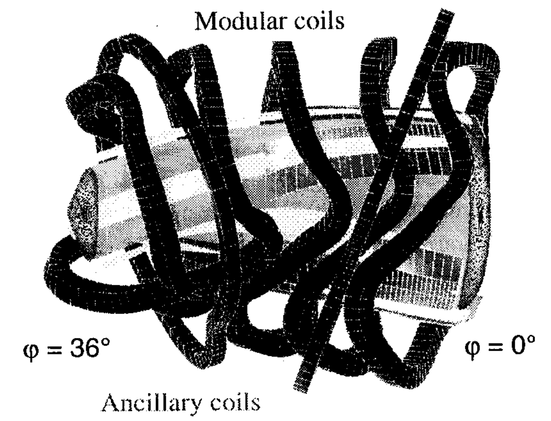

Fig. 1 W7-X coil system. One half period (φ = 36° to 0°), including 5 modular coils and 2 ancillary coils, of 5 periods of the total device is shown. The LCMS, the 5/5 islands for $\iota = 1$ at the boundary and the target places of the divertor units are added.

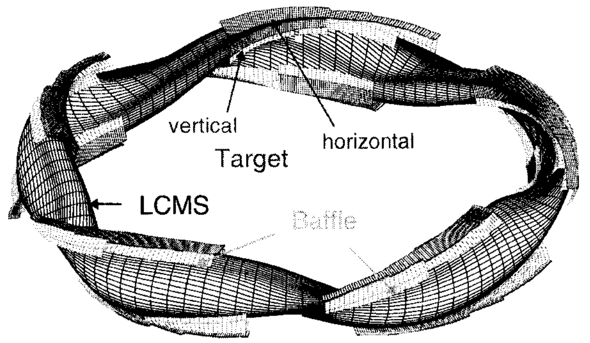

Fig. 2 W7-X divertor. 10 divertor units (two units per period) including target and baffle areas are arranged inside the vessel and outside the LCMS at the boundary.

exhaust in the wide envisaged magnetic parameter range (Fig. 2).

3. Divertor Modelling

Because of lack of an elaborated 3D code, presently, almost deduced and calibrated from tokamak data banks several methods have been applied to define the specifications and shape the geometry of W7-X divertor components. Such tools are also very valuable for parameter studies, but need particular input assumptions and have to be executed in combination and iterations. For the design of the W7-X divertor the following informations were used:

- The results of 3D ray tracing of the vacuum configuration, also including finite $<\beta>$ equilibrium cases at the boundary [3] are used to define the interacting divertor surface pattern. In combination with simulation of perp. transport (a typical transport coefficient is 1 m^2/s, values up to 10 m^2/s were investigated) by Monte-Carlo code the power load was estimated.
- The multi-fluid code B2 [4] was adapted to describe the SOL parameters. Since B2 is a 2D code the geometry of the boundary was averaged (distances) and integrated (areas and volumes) in the toroidal direction. Significant unloading of the target plates is predicted by radiation losses of C impurities [5]. A high recycling mode seems possible for relatively low separatrix densities above 2×10^{19} m^{-3}.
- Simplified 3D SOL models were evaluated to get information about the temperature and density distribution. For this, the 3D flux topology was combined with 1D fluid models. This method has benefits from the ordering of the open flux bundles outside the separatrix region where only field lines with a long connection length approach close to the LCMS and get significant loading from the confinement area by perpendicular transport [6]. The 1D treatment of the bundles of different length and power and particle flows delivers the plasma parameters along the field lines. Finally, the superposition in 3D geometry let approximate the 3D temperature and density profiles.
- The position of the pumping gap and the geometry of the baffle plates was optimised on the basis of 3D neutral particle studies by means of the EIRENE code [7]. The concentration of the neutral particles close to the target plates and the improvement of the pumping efficiency were intend

First attempts to analyse the complex boundary physics of W7-AS, the precedent device of W7-X, using the 3D plasma transport EMC3 (Edge Monte Carlo 3D) have been started with promising results[8].

4. Properties of the "Open Divertor" Concept of W7-X

The topology of the boundary is dependent on the magnetic and plasma parameters of the experiment. For the detailed study a new code, MFBE [3], has been developed and applied in combination with NEMEC. Comparisons of the magnetic field structures of finite β equilibria with the vacuum magnetic field confirm a small outward shift of the plasma column, slight decrease of the rotational transform, and almost stationary positions of the X- and O-points of the natural islands. The LCMS of finite β equilibria lies always inside the LCMS of the vacuum field. These results are the basic requirements that a target and baffle configuration

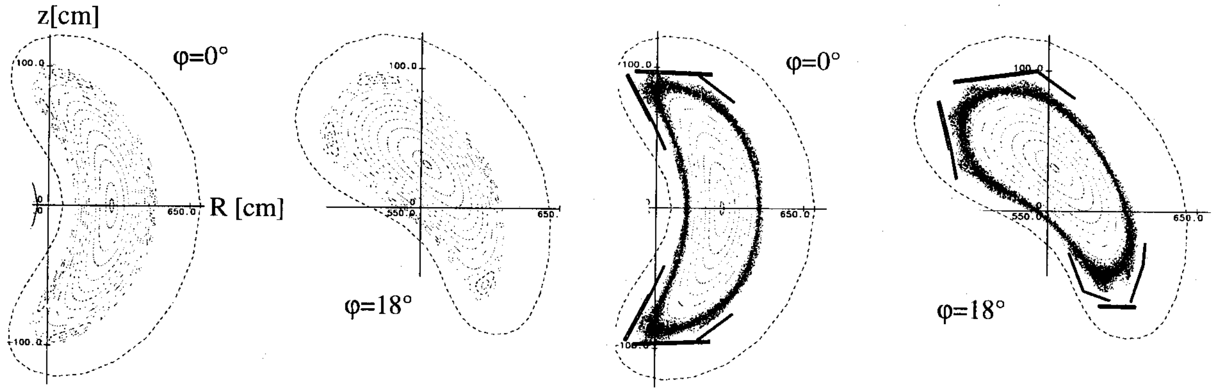

Fig. 3 Poloidal cross-sections of W7-X at toroidal angles $\varphi = 0°$ and 18°. The Poincare plots are shown for the standard case: the vacuum configuration with the 5 islands ($\iota = 5/5$ at the boundary) on the left side, the result of diffusion simulation ($D = 1$ m^2/s) together with the target and baffle plates on the right side. The broken line represents the inner vessel contour.

will become operational without geometrical adjustment depending on the experimental parameters. As an example, for the standard case (equal current to all modular coils) with a rotational transform of $\iota = 5/5 = 1$ the magnetic field structure is shown for the vacuum case on Fig. 3 at particular cross-sections. Additionally, the interaction with the chosen target and baffle is described: Field lines starting close to the LCMS are followed until hitting the target area. Perpendicular transport has been simulated by "field line diffusion" ($D = 1$ m^2/s) on the basis of the Monte-Carlo method. The interaction pattern for various magnetic parameters and $<\beta> = 0$ and 4 % on the target plates are presented in Fig. 4. The typical wetted area is 2 m^2. To concentrate the power flux on the targets for all operational parameters the 3D target surface has to be shaped as a compromise and must be extended to an area of 22 m^2. For a power flow of 10 MW across the LCMS the power deposition patterns and the angles of incidence were calculated. With an resulting angle of incidence of $1-3°$ a power load of 8 MW/m^2 and a particle flux of 10^{23} m^{-2}s^{-1} were obtained in the worst case.

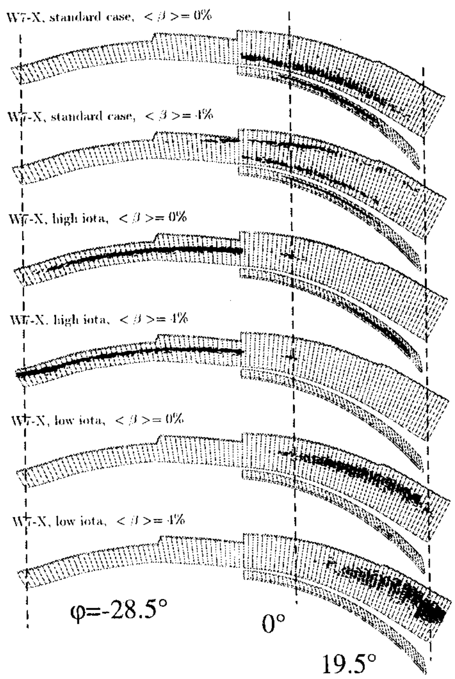

Fig. 4 Intersection pattern on the target area of one divertor unit. The variation of the deposition depending on the rotational transform for $<\beta> = 0$ and 4% has been calculated ($D = 2$ m^2/s). The two target plates are approximated combining standard target elements with a width of 5 cm and a length of 27 to 57 cm.

In the W7-X device control coils (one saddle coil per divertor unit, protected by the baffle plates) will be provided which, primarily, should be used for compensation of field errors. The magnetic parameters of the boundary, the extension of the islands and ergodisation can be influenced and thus the distance of the LCMS from the target surface. In combination with the control coils a large variety of boundary parameters becomes experimentally accessible. Further, by application of AC currents up to 20 Hz the deposition pattern at the targets can be shifted significantly and thus broadened with the result of reduced local power load.

5. Engineering of the W7-X divertor

An almost complete description and design of the main divertor components has been worked out for stationary operation [9]:

- target plates and baffles, including water cooling circuits, feed troughs on the vessel
- control coils
- pumping system, consisting of TM pumps.

Whereas for the additional cryo panels inside the vessel and the wall protection only principal solutions are available, so far. In respect of the geometrical restrictions of the W7-X vessel (the typical distance between vessel and LCMS in the divertor region is 30–50 cm and between target surface and LCMS 10 cm) the design of the components and the arrangement must be very compact. To avoid problems with high Z impurities during long-pulse operation, Carbon was selected for all plasma facing surfaces. Target plates and baffles will be baked out at 350°C. The wall protection has to be designed for conditioning at 150°C, a limit related to the maximum operational temperature of the inner SS cryostat.

The most critical component is the target area. Therefore, a R&D programme has been started to examine several cooling concepts and material combinations (CFC tiles linked to TZM, CuCrZr, Glidcop). Recently, such prototypes were successfully tested with a power load up to 12 MW/m^2. The following criteria are used for the design of the high heat flux components:

- Maximum heat load 10 MW/m^2 during stationary operation.
- For easy maintenance and repair, to provide flexibility for the experimental programme and diagnostics the optimised 3D target surfaces are approximated by 2D target elements with the dimensions: width 5 cm, length 27–57 cm.
- Arrangement of a set of 10–15 elements and water manifolds as modules for prefabrication and testing outside the vessel. The target area of one divertor unit being divided in two parts for effective pumping will be formed by 14 individual modules. Finally (Fig. 5), 144 elements have to be combined for one divertor unit. By standardisation the number of different types could be reduced to 5. The flat elements are mounted on the supporting framework of the modules approximating the calculated 3D surface. Finally, the surface is smoothed by 3D machining to eliminate steps.

Depending on the progress of the physical understanding and control of the boundary during the experiments modifications of the divertor system (vented targets, "closed divertor", change of material etc.) are expected. The design of the components, the supporting and alignment structure of the target and baffle plates, the cooling circuits and the interfaces of the vessel must be flexible for future needs.

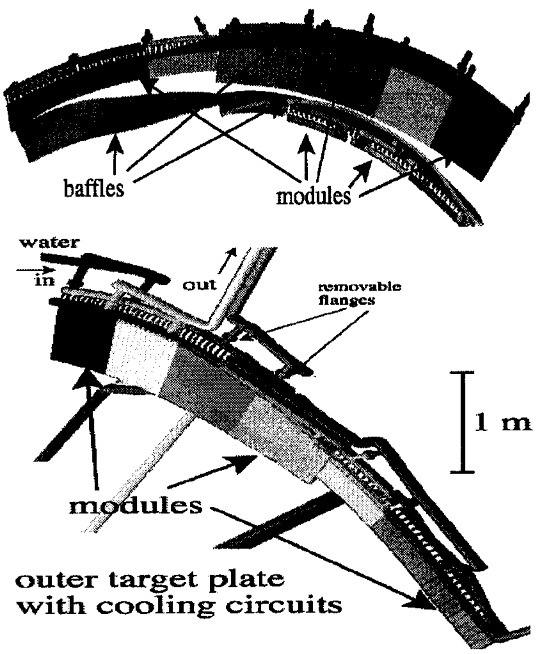

Fig. 5 Target area of one divertor unit.
The upper part shows the two target plates and baffles as seen from the magnetic axis. Note the gap for pumping. The lower part describes the outer plate: 10-15 standard target elements are combined to modules (marked with different grey intensity). The interfaces to the cooling circuits can be identified.

6. Conclusions

Principal solutions for critical components and some details of a divertor system for the HELIAS configuration W7-X have been worked out. The properties of the magnetic configuration allows to select a divertor geometry without needs of adjustment dependent of the particular plasma parameters and $<\beta>$. The adaptation on a wide operation range of the magnetic parameters requests an "open divertor". Additionally, experimental flexibility is provided by means of control coils. The further optimisation of the divertor will be a major goal of the activities in W7-X. A "closed divertor" may be tested in a second step in W7-X and could become a solution for a HELIAS reactor [10].

The development and experimental verification of 3D boundary codes is urgently necessary. For this purpose, the new LHD device with many similar parameters will play an important role. Depending on the progress of understanding and modelling of the boundary plasma some changes of the geometry and specifications have to be expected until the start of the experiment, planned on 2005.

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