stellarator news

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LHD construction status — Supporting structure and cryostat

The superconducting coils in the Large Helical Device (LHD) are supported by a torus-shaped structure called the “supporting structure for the electromagnetic forces.” The major radius and minor radius of this structure are 3.9 m and 1.85 m, respectively. It is made of 100-mm-thick type 316 stainless steel in which the carbon and nitrogen content was controlled to increase strength at low temperature. The weight of this structure after assembly is about 400 tons. This structure will be cooled down to liquid helium temperature. The total mass that will be cooled is 850 tons including the magnets. This structure has been assembled in the LHD hall because transportation in its

Fig. 1. The lower and upper parts of the supporting structure for the electromagnetic forces. The structure covered with a green sheet (left side) is the completed lower half of the supporting structure. The upper half (at right) is being prepared for welding. It is inverted for the welding work.

final form is impossible. The 20 sections, built by the manufacturer, are 36° fan-shaped pieces, assembled into upper and lower hemispheres. Figure 1 shows the lower part of the supporting structure, covered with a green sheet (at left at the final location of LHD) and the upper part (at right) which is inverted for welding. The lower part was completed in FY 1994 and the upper part in FY 1996. During the process of welding the ten sections of each half, the average deformation was less than 4 mm, which allowed us to achieve the required overall accuracy of 5 mm. The deformation during the welding of the upper supporting structure showed a good symmetrical correlation with the lower one. After the completion of the lower and upper parts, they were welded together at the equator, holding the helical coils in the torus shell. Figure 2 shows a picture of the upper structure being moved to its final position. After the supporting structure was assembled, shell arms that are attached to the coil covers of the helical coils were connected to the inside of the supporting structure by welding, and the upper and lower halves of the supporting structure were also connected by welding.

In parallel with assembly of the coils and supporting structure, assembly of a cryostat vessel for the cryogenic structures has been started. The cryostat vessel for LHD is a 13-m-diam torus with a bell-shaped poloidal cross section. This vessel consists of four parts: a base plate, an outer wall cylinder, an inner wall cylinder, and an upper cover. Except for the inner wall cylinder, each part was divided into ten sections for transportation from the manufacturer to the site. Figure 3 shows the outer and inner wall cylinders and Fig. 4 shows the upper cover. The vessel is made of type 304 stainless steel with a thickness of 150 mm for the base plate and 50 mm for the side wall and the upper cover. Two important design requirements of the LHD cryostat vessel are to incorporate a sufficient number of access ports and to maintain the cryogenic vacuum conditions. This cryostat vessel has 98 ports for plasma diagnostics, vacuum exhaust, current leads, safety valves, helium coolant plumbing, etc. High accuracy is required for these ports to ensure high diagnostic precision. Our target accuracy for these port sections is < 5 mm.

Following the assembly of the supporting structure and the helical coils, a number of tasks will go on simultaneously to the end of this year: (1) removing the winding core for the helical coils, (2) assembling the plasma vacuum vessel, (3) installing the poloidal coils, (4) connecting the wall cylinder and the upper cover of the cryostat vessel to the base plate, and (5) constructing many other peripheral devices.

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Fig. 2. Completion of the supporting structure. The lower part is in place with the helical coils positioned on it. The upper half is being moved into position.

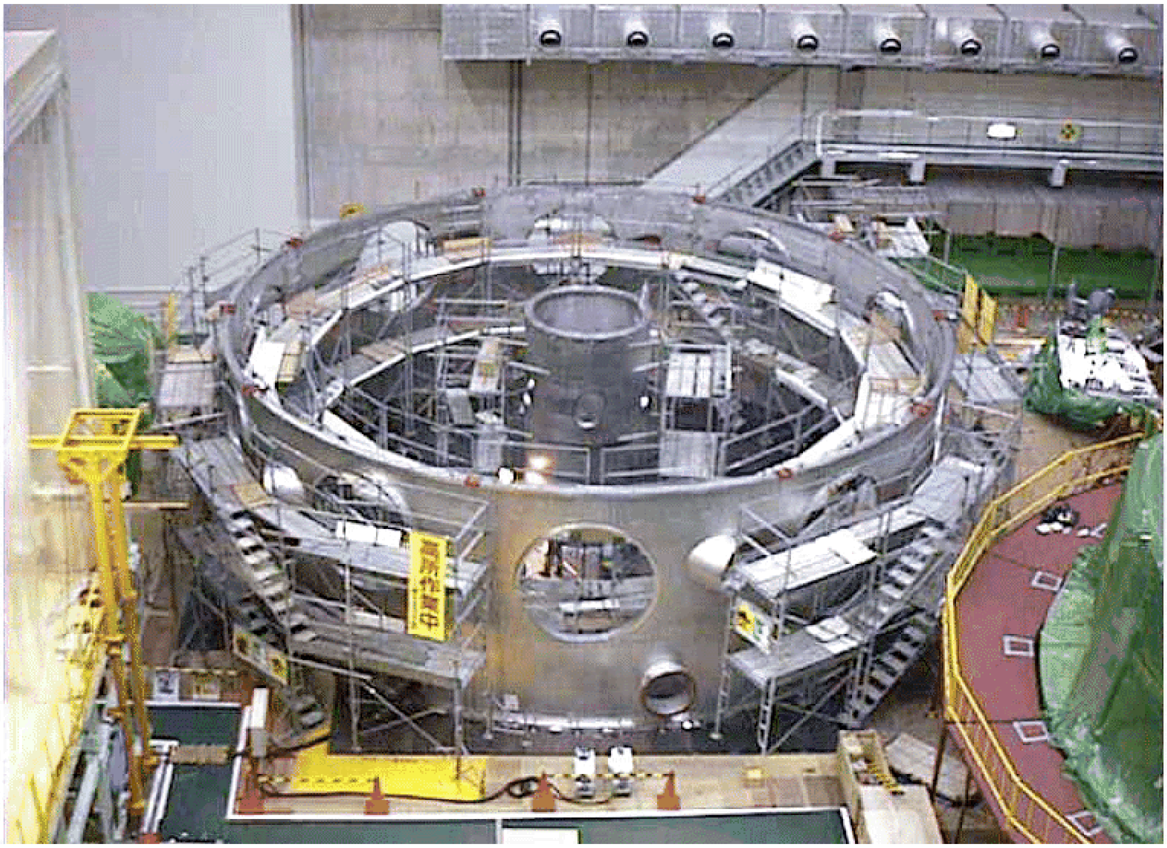

Fig. 3. The outer and inner wall cylinders of the cryostat vessel.

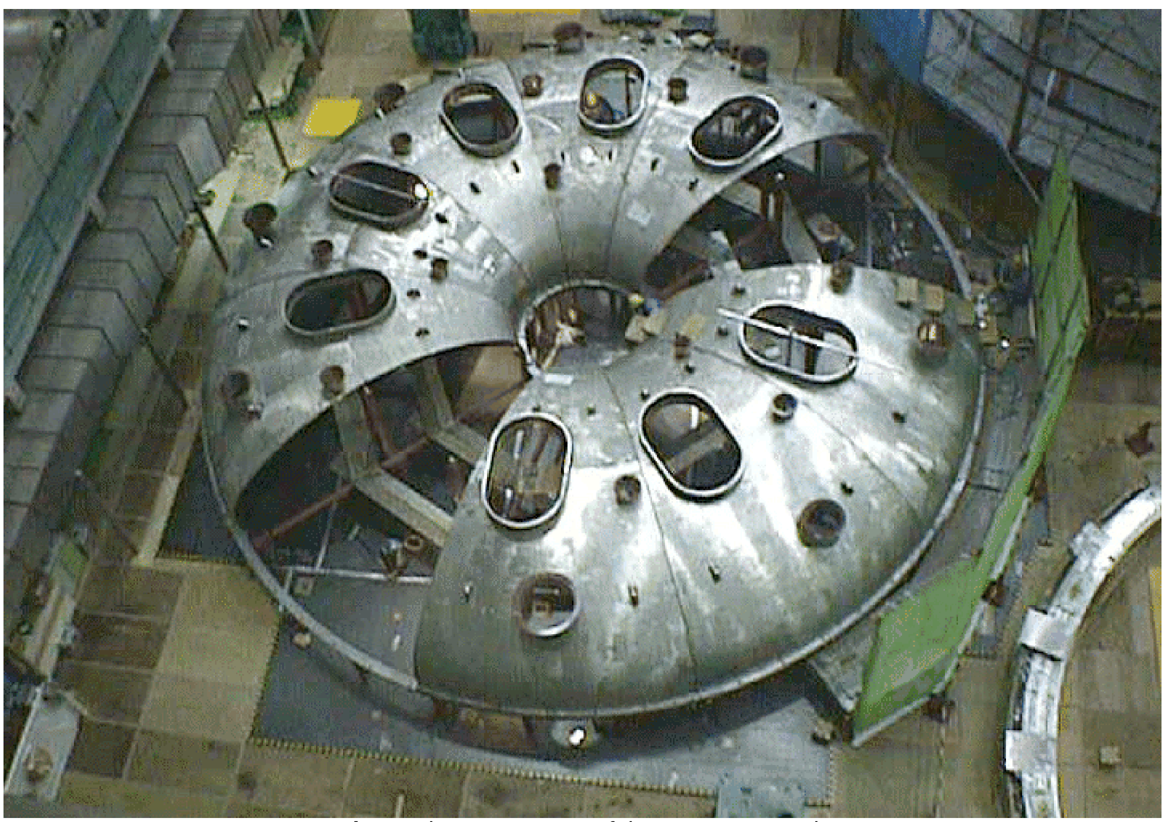

Fig. 4. The upper cover of the cryostat vessel.

Engineering studies for the W7-X divertor

The advanced stellarator Wendelstein 7-X (W7-X) is under construction at the Greifswald branch of IPP Garching, Germany. The mission of this experiment is to demonstrate (without the use of tritium, however) the relevance of stellarators to the development of a future, economically feasible, fusion power plant. European associations have been invited to contribute to W7-X.

The steady-state magnetic field of W7-X is produced by superconducting coils in a modular arrangement (see Fig. 1) within a common cryostat, with an appropriate support structure around the plasma vessel. The basic magnetic topology is produced by 50 nonplanar coils. A set of 20 planar coils gives sufficient flexibility of the field configurations. Systems to provide stationary electron resonance cyclotron heating at 10 MW and pulsed ion cyclotron resonance heating and neutral beam injection (4–20 MW) are being prepared, as are the necessary operation and control systems.

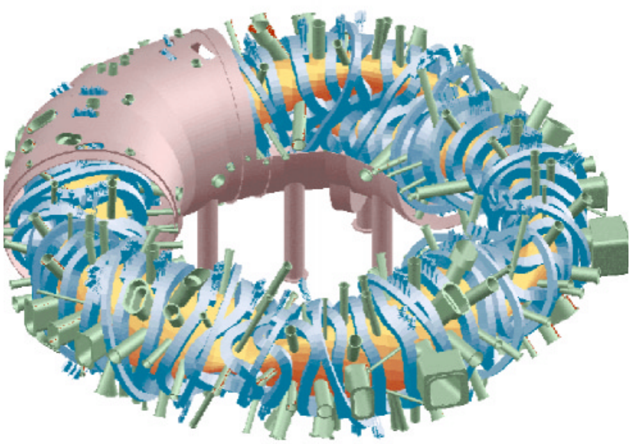

Fig. 1. Modular coils of W7-X with outer and inner vacuum vessel and diagnostic ports of the cryostat. Major radius = 5.5 m, average plasma radius = 0.5 m, 5 field periods.

The present work of W7-X engineering is focused on various R&D activities: the manufacture of a full-size nonplanar, non-circular superconducting coil, the development of an advanced conductor, the manufacture of a section of the cryostat, and the development of the W7-X divertor. The development program for the superconducting coils of W7-X was summarized in *Stellarator News* #42, and a general overview on the engineering of W7-X was given in *Stellarator News* #39. Engineering studies for the W7-X divertor are discussed in more detail here, highlighting two aspects: the small influence of a finite-beta plasma on the magnetic topology, and the thermal behavior of prototype target elements at high heat loads.

The five-fold symmetry of the magnetic configuration of the device is produced by two modular sets of superconducting coils. A combination of 5 different nonplanar coil shapes produces the “standard configuration” of W7-X (edge rotational transform $\iota_a = 1$), as illustrated in Fig. 2; different currents in these coils, together with currents in planar coils with 2 different shapes, introduce a wide range of useful magnetic field topologies. Consequently a modular divertor has been developed for W7-X, comprising 10 divertor units, 2 units per field period. To achieve effective particle and energy exhaust for a wide range of magnetic parameters of W7-X, an open divertor structure was chosen as a first approach.

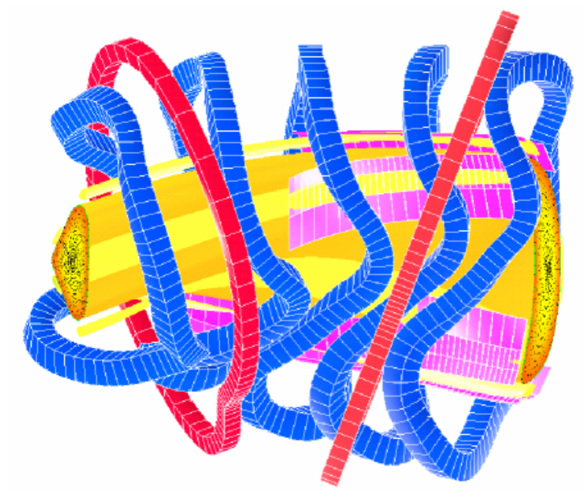

Fig. 2. Modular coils of W7-X and contours of divertor and baffle plates, shown for half of a field period.

The optimization of the divertor geometry is based on field line tracing for the vacuum configurations and simulation of perpendicular transport by “field line diffusion” (Monte Carlo code) to calculate the power deposition on the targets [1], whereas the pumping efficiency is estimated by means of the EIRENE code, taking into account reasonable boundary parameters. The intersection angles of the flux bundles on the targets are typically 1–3°. Local power densities of up to 8 MW/m^2 at the target plates are obtained in a wide range of magnetic parameters, considering as a “worst case” a low-density plasma at high temperature. With neutrals and impurities taken into account, it is possible to achieve significant unloading of the target plates at moderate separatrix densities in two-dimensional (2-D) studies using the B2/EIRENE codes [2].

In order to optimize the divertor geometry for finite beta and to improve scrape-off layer (SOL) studies, a detailed knowledge of the corresponding magnetic field structure is necessary. For this purpose, magnetic fields are calculated for equilibria with a $\langle\beta\rangle \le 5\%$ and edge rotational transform ι_a = 5/6, 5/5, and 5/4. We use a system of numerical codes that allows us to calculate vacuum magnetic fields and trace field lines (GOURDON code) to determine free-boundary equilibria (NEMEC code [3], which assumes nested flux surfaces) and to obtain the topology of the magnetic fields of these equilibria in the edge region (MFBE code [4]). A slight decrease of the rotational transform with increasing beta is seen near the magnetic axis.

During optimization of the divertor topology in 1996 it was found that a local enlargement of the vacuum vessel is necessary to intercept the energy and particle outflow by target plates arranged in the vicinity of the bean-shaped plasma cross section. As a consequence, two of the modular coils (designated 4 and 5) and also the auxiliary coils were locally enlarged in the radial direction. These small modifications of the coil shapes could be made without significant change of other magnetic parameters (e.g., the plasma radius and the shear, the magnetic well, and the low-harmonic Fourier components of the magnetic field). Figure 3 compares the vacuum fields (top) with the corresponding topologies at $\langle\beta\rangle$ = 4% (bottom) for the three typical values of ι_a of the W7-X coil configuration and confirms that the properties expected for optimized Helias configurations are maintained, namely small outward shift of the plasma column and almost stationary positions of the X- and O-points of the finite-size edge islands.

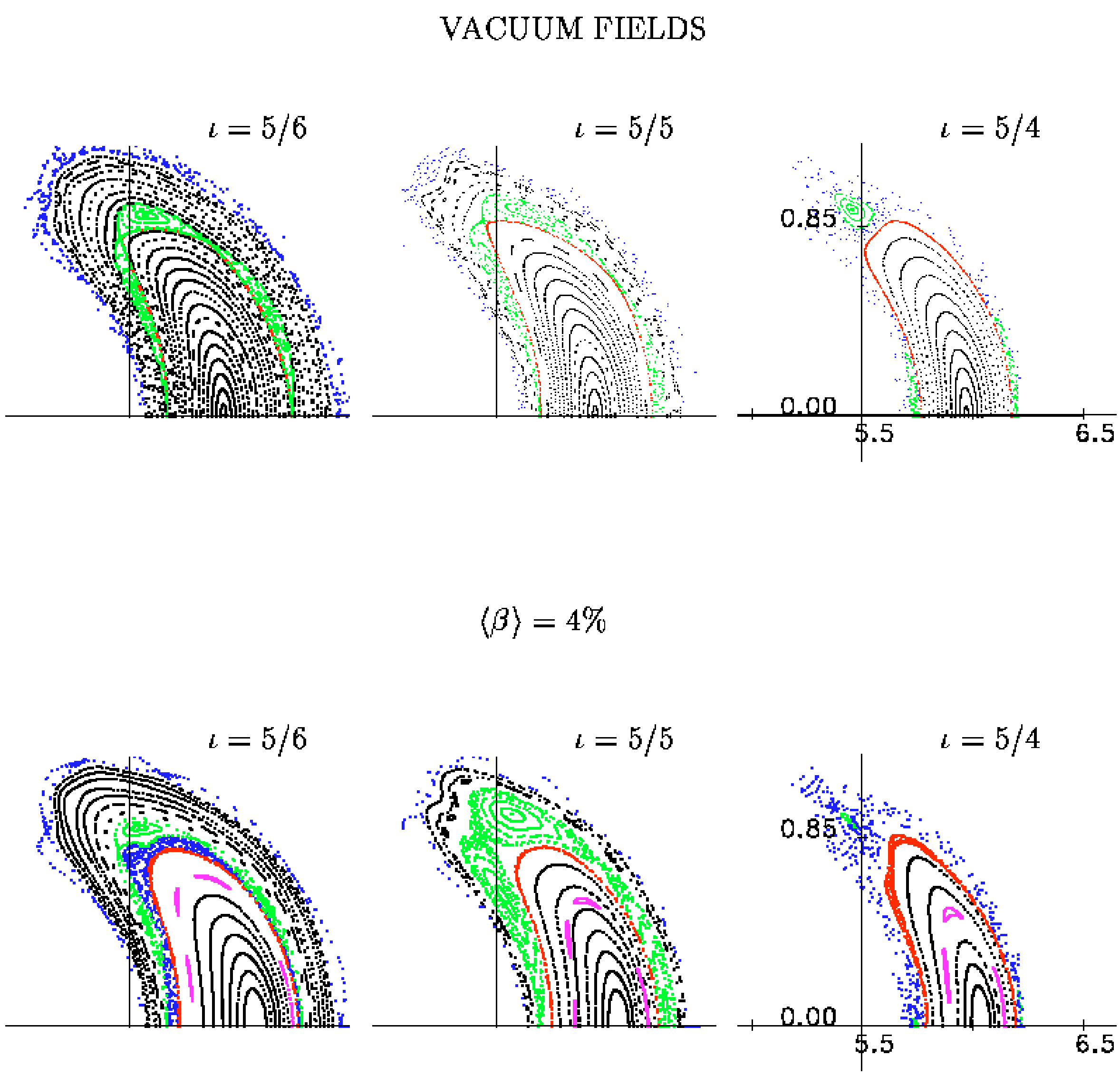

Fig. 3. Comparison of vacuum fields (top) and finite-beta configurations (bottom) for the bean-shaped plasma cross section of W7-X. Detailed determination of the divertor target and baffle plates is being performed for these configurations.

An almost complete description and three-dimensional (3-D) CAD studies of the main divertor components have been derived; these integrate

⇒ target plates and baffles (Fig. 4), including modularized water-cooling circuits and feedthroughs of the vessel,
⇒ control coils with DC currents for fine-tuning of the edge configuration and/or AC currents for sweeping to reduce peak heat loads at the target plates,
⇒ operational diagnostics (thermography), and
⇒ the pumping system, consisting of turbomolecular pumps.

Cryopumps are under development.

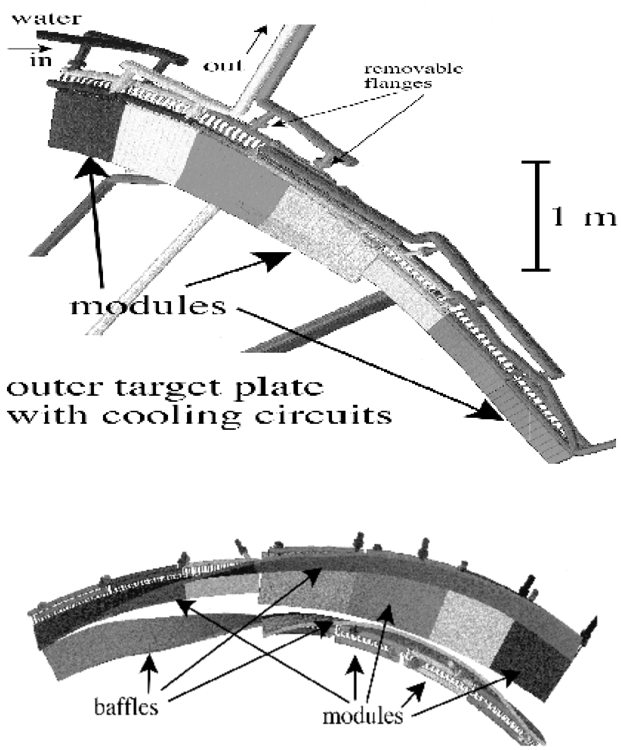

Fig. 4. CAD drawing of the outer target plate of one divertor unit. Target elements are combined into modules. The lower part shows the two target plates and baffles of one divertor unit as seen from the magnetic axis. Note the gap for pumping.

An R&D program has been started for the target element as the most critical component of the divertor, especially with respect to the thermal behavior at high heat loads. For the prototype target plates, the favorable fin design was selected for the cooling channels. The internal fin structure maximizes heat transfer at minimum water flow rate and pressure drop. The material combination TZM/CFC was chosen to integrate the brazing technique as developed for application by the NET/ITER team. Prototype target elements were successfully manufactured by Plansee AG and Ansaldo Ricerche.

Thermal power load tests using the JUDITH electron beam facility of the Forschungszentrum Jülich (H. Bolt et al.) showed that the measured temperatures agree very well with results of 3-D finite-element modeling. Stationary thermal conditions are reached after approximately 8 s. Two elements were cycled up to 5000 times with a power load of 10 MW/m^2, leading to average surface temperatures of about 1000°C without indications of deterioration of the thermal contact between TZM and CFC. One example is illustrated in Fig. 5.

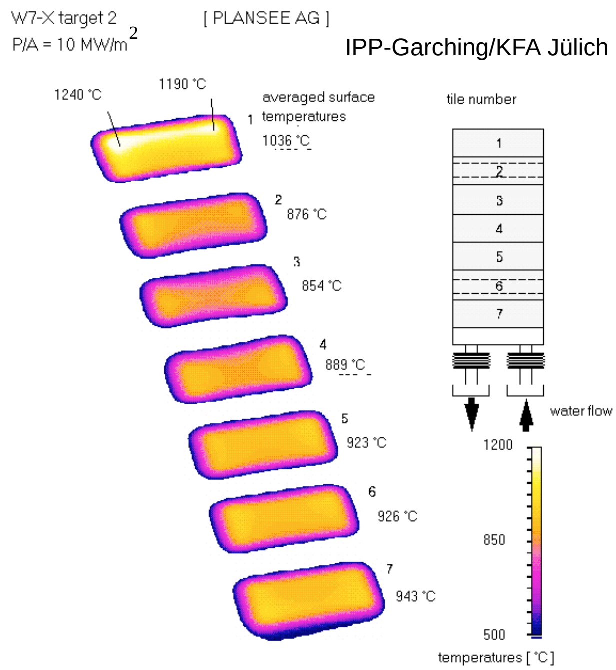

Fig. 5. Infrared images and surface temperatures obtained for a power load of 10 MW/m^2 in the electron beam facility JUDITH (Forschungszentrum Jülich); prototype target element #2, manufactured for W7-X by Plansee AG.

In conclusion: A divertor system capable of stationary operation with a heating power of 10 MW has been developed for the advanced stellarator W7-X. The edge topology of W7-X is characterized by an inherent divertor where the last closed magnetic surface of the confinement region is defined either by the inner separatrix of islands (intersected by target plates) or by an ergodized boundary with remnants of islands. Detailed numerical calculations demonstrate the small influence of a finite-beta plasma on the magnetic topology. With neutrals and impurities taken into account, it is possible to achieve significant unloading of the target plates, which are already at moderate separatrix densities as determined in 2-D studies.

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