FIRST DIVERTOR PHYSICS STUDIES IN WENDELSTEIN 7-X


1Max-Planck-Institut für Plasmaphysik, Greifswald, Germany
2University of Greifswald, Greifswald, Germany
3Australian National University, Canberra, Australia
4Forschungszentrum Jülich, Jülich, Germany
5University of Wisconsin, Madison, WI, USA
6Wigner Institute, Budapest, Hungary
7Princeton Plasma Physics Laboratory, Princeton, NJ, USA
8University of Cagliari, Italy
9Oak Ridge National Laboratory, Oak Ridge, TN, USA
10Los Alamos National Laboratory, Los Alamos, NM, USA
11National Institute for Fusion Science, Toki, Japan
12Auburn University, Auburn, AL, USA
13Laboratory for Plasma Physics, ERM/KMS Brussels, Belgium
14Department of Applied Physics, Ghent University, Belgium
15100 Impasse des Houllières, ZA Le Pontet, Meyreuil, France
16CEA, IRFM, Saint Paul-lez-Durance, France

Abstract

The Wendelstein 7-X (W7-X) optimized stellarator fusion experiment, which went into operation in 2015, has been operating since 2017 with an un-cooled but otherwise complete divertor. This allowed first divertor physics studies to be performed at pulse energies up to 80 MJ, as opposed to 4 MJ in the first operation phase, where five inboard limiters were installed instead of a divertor. This, and a number of other upgrades to the device capabilities allowed extension into regimes of higher plasma density, higher heating power, and significantly performance overall, eg. setting a new stellarator world record triple product. The paper focuses on the first physics studies of how the island divertor works. The results are overwhelmingly positive. The convective plasma heat loads arrive to a very high degree on the divertor plates, with only minor convective loads seen on other components, in particular baffle structures built in to aid neutral compression. The strike line shapes and locations change significantly from one magnetic configuration to another, in very much the same way that codes had predicted they would. Strike-line widths are as large as 10 cm, and the wetted area also large, which bodes well for future operation phases. The most notable result was the complete (in all 10 divertor units) heat-flux detachment obtained at high-density operation in hydrogen. This regime was stable and had good energy confinement times for several seconds.

1. INTRODUCTION
Wendelstein 7-X (W7-X) went successfully into operation in 2015 [1-4]. With a 30 cubic meter volume, a superconducting coil system operating at 2.5 T, and steady-state heating capability of up to 10 MW, it was built to demonstrate the benefits of optimized stellarators at parameters approaching those of a fusion power plant. Operation phase 1.2a (OP1.2a), which was performed in the second half of 2017, was the first operation phase with a full complement of plasma-facing components, including the full complement of 10 passively cooled fine-grain graphite divertor units, referred to collectively as the Test Divertor Unit (TDU). OP1.2a also featured an ECRH heating system with 10 gyrotrons, more than 30 diagnostic systems, and a pellet fueling system. The TDU has the same geometry as the water-cooled steady-state carbon-fiber-composite divertor that will be in operation in the early 2020’s. The upgrades enabled significant performance extensions and a comprehensive physics program [5], specifically the start of a divertor research program, results from which are reported here. The TDU implements the so-called island divertor concept, where intrinsic island chains at the plasma edge provide multiple x-points and the possibility to intersect the outflowing plasma in locations somewhat removed from the closed flux surfaces. This concept was used successfully on the predecessor experiment W7-AS [6].

2. ATTACHED DIVERTOR OPERATION AT LOWER DENSITIES

2.1. Divertor heat load patterns

At low to medium densities (n_e up to about 4*10^{19} m^{-3}), the plasmas were attached. More than 95% of the convective heat loads exiting the scrape-off layer (SOL) landed on the 10 divertor plates. The power load distribution on the divertor surface is determined by the intersection of the island chain forming the island divertor with the divertor target plates, and therefore the 3D strike-line geometry strongly depends on the chosen magnetic configuration. The measured strike-line geometry is in good agreement with numerical predictions. An example for the standard configuration is shown in Fig. 1. It shows the heat flux distribution measured on the surface of the lower divertor in module 2. On W7-X, the divertor surface temperatures are measured by 10 IR cameras (one for each divertor unit) detecting in the IR wavelength ranges of either 8-10 µm or 3-5 µm. The heat flux is then determined by solving a heat conduction equation for the bulk of the tile with the surface temperature time evolution as the input.

![Figure 1](image_url)  
*Figure 1 Heat flux density measured in one out of ten divertors of W7-X in so-called standard configuration. Two strike lines are visible on the horizontal (lower) and vertical (upper) target modules.*

The distribution of the heat flux within the strike line and its shape depends on several factors, e.g. field line connection length, plasma density and power entering the scrape-off layer. An example of the effects of plasma density on the strike line shape is shown in Figure...
2, where the peaking factor of the strike line is plotted against the plasma density. Additionally, the input power for each discharge is shown in the plot as the color of each dot. Increasing the density leads to smaller peaking factor, indicating that the power reaching the divertor is spread more uniformly on its surface. As W7-X aims to operate at very high densities ($n_e > 1 \times 10^{20} \text{ m}^{-3}$), this is a beneficial trend in terms of the safety of the plasma facing components. Interestingly, increasing the input power (and by that increasing the power entering into the SOL) also appears to result in a lower peaking factor. This suggests that increasing $P_{\text{SOL}}$ leads to enhancement of the perpendicular transport in the scrape-off layer. More details on divertor power loads are given in [7].

![Figure 2. Change of peaking factor with plasma density for the discharges with standard configuration.](image)

3. TESTS OF SCRAPER ELEMENTS

The scraper element [8] is designed to protect the edges of divertor components from overload in certain long-pulse OP2 scenarios where the magnetic topology changes due to ~40 kA of net toroidal current and ~3% plasma beta [9]. As these conditions are not directly accessible in OP1.2a, a set of magnetic configurations were developed to mimic this topology change using the W7-X coil set [10]. Experiments were performed in OP1.2a, without scraper elements installed, using a series of mimic configurations corresponding to five time points in the evolution of the OP2 scenario. The heat fluxes inferred from infrared cameras measurements [11] show good qualitative agreement with predictions from field line diffusion calculations from the DIV3D code [12], as shown in Fig. 3. These results indicate that the loading of the divertor edges is likely to occur as predicted by the OP2 scenario development simulations, suggesting that mitigation or avoidance is desirable, whether from scraper elements or another strategy such as ECCD or using the planar coil set to control the edge transform.
4. DETACHMENT

4.2. General observations

Detachment was observed in high-density hydrogen discharges. An example is shown in Fig. 4.

Fig. 4 Infrared camera data show a local heat flux reduction to the divertor target of about one order of magnitude during detachment. The detachment was stably maintained until the programmed end of the discharge. (Shot 20171109.045)
For the shown discharge, the transition to detachment occurred during a density ramp with the heating power held approximately constant around 2.7 MW, and detachment lasted until the programmed end of the discharge at \( t = 4 \) s.

As measured by Langmuir probes, electron temperatures at the divertor surface and the power flux to the divertor surface are strongly reduced, whereas the electron density level does not change significantly. In the example shown in Fig. 5, pellet injection increases the density after 2.2 s. A \( \text{H}_2 \) puff through a gas valve in the divertor at 2.7 s increases the density further and triggers the transition: The temperature measured by the Langmuir probes drops below \( \sim 15 \) eV, whereas the density only temporarily rises during pellet injection and gas puff, but afterwards assumes the same level as before the pellet injection (see fig. 6). We note that the Langmuir probes are located in a different divertor unit and also in a different of the five edge islands than the one directly fuelled by the gas puff.

![Fig. 5: Heating power and line density (lowest panel) and time evolution of power density \( q \), electron temperature \( T_e \) and electron density \( n_e \) across the lower divertor in module 5 during discharge 20171207.011. The heat flux (top panel) was calculated from the infrared observation of the divertor and is shown here for a position next to the Langmuir probe array. The positions of the 10 Langmuir probes are indicated by the red horizontal lines. The two middle panels show \( T_e \) and \( n_e \) as evaluated from the probe characteristics, swept at 500 Hz. Only probe no. 10 at a distance from the pumping gap of 0.15 m is at the edge of the strike line, and time traces calculated from this probe's signals are shown in fig. Langmuir-2.](image-url)
4.3. Neutral gas pressure and exhaust

Several pressure gauges of the ASDEX type have been installed in sub-divertor spaces and in midplane positions in order to characterize the exhaust capability and the neutral compression of the island divertor. Details can be found elsewhere [13].

Fig. 7 shows as an example the neutral pressure behavior in a discharge with divertor fueling (from 2-5 s). The line-integrated plasma density is relatively low, \(3 \times 10^{19} \text{ m}^{-2}\). The fueling pulses are clearly visible in the neutral pressure traces. The neutral pressure in the sub-divertor space varies between 3 and \(5 \times 10^{-5} \text{ mbar}\). The neutral compression, i.e. the ratio between sub-divertor and midplane pressure, varies between 6 and 8, which is relatively small compared to the theoretical prediction of 180 [14]. However, those calculations were done for the case of a higher electron density.

The effect of divertor fueling is stable detachment from 2 s onwards [13] in which the energy flux to the divertor targets is strongly reduced. A modest increase of the neutral pressure is seen during the period with stable detachment, possibly caused by the direct divertor gas inlet fueling.

![Figure 6: Time traces of electron temperature \(T_e\) and electron density \(n_e\) calculated from the characteristics of probe no. 10, closest to the strike line. Between 2.7 s and 3 s, the electron temperature measured by this probe drops from \(~50 \text{ eV}\) to below \(~15 \text{ eV}\), whereas the density resumes the same level as before the start of pellet injection.](image6.png)

![Figure 7: Neutral pressure traces of a discharge with divertor fueling (from 2-5s) that triggered stable detachment. Neutral compression, i.e. the ratio between the sub-divertor and midplane pressures, is shown in black.](image7.png)
5. PLASMA-WALL INTERACTIONS, WALL CONDITIONING AND IMPURITIES

5.4. Plasma-wall interactions and conditioning before boronization

The plasma-facing components in OP1.2a were fine-grain graphite for all components with significant heat loads, including the divertor, the baffles, and the heat shields, and stainless steel panels for recessed areas. These components were in general not water-cooled but would warm up adiabatically during a pulse, and a general slower increase of temperature during the run day was also observed, as one would expect. Before first operation in OP1.2a, a vacuum bakeout had been performed up to 150°C for more than one week, which eliminated most, but not all, of the water molecules trapped on the surfaces and in the bulk of the graphite. OP1.2a was performed without boronization, but extensive glow-discharge cleaning in hydrogen and helium was performed regularly between run days, and He discharges were used to help unload the walls from hydrogen during run days. While it took almost the entire OP1.1 campaign to get to reasonably low outgassing rates, the outgassing rate was below the best of OP1.1 after just two weeks of operation. Nonetheless, absorption and release of hydrogen from the walls made it difficult to control the plasma density in hydrogen discharges, possibly also complicated by the fact that the main gas inlet valves are located several meters away from the plasma edge, recessed in long ports. Control of the density in helium discharges was unproblematic.

5.5. Effects of boronization and spectroscopic observations of low-Z elements

In the OP1.2b phase, starting in July 2018, boronization was applied after the first few weeks of operation. This led to a strong reduction in oxygen outgassing, and operation at high density in hydrogen went from being very challenging to being routine, and pulse lengths in hydrogen could be strongly extended. Fig. 8 shows increases in stored energy, decreases in impurity concentrations, and decreases in radiative losses after boronization relative to before boronization. More details can be found in [15].

![Figure 8](image)

*Figure 8. Left: The diamagnetic energy and the plasma density both increased (at near-constant heating power) after boronization. Middle: The oxygen concentration dropped strongly after boronization. Right: As expected, the radiated power also dropped significantly after boronization.*

Visible divertor spectroscopy measured plasma and impurity lines during OP1.2, mainly in the divertor modules but also from the core plasma. Figure 9 shows an overview spectrum taken with an Echelle Esawin 3000 spectrometer during a hydrogen discharge, after
boronization. In both the core and divertor plasma, the Balmer lines are clearly visible. Among the impurity lines, carbon is the most intense, intrinsically being present in the edge plasma from the carbon target tiles. The C-III multiplet at 465 nm is particularly intense in both the divertor region and elsewhere in the plasma edge and is therefore also suitable for investigations with our ultra-high resolution spectrometer and Doppler coherence imaging diagnostics. Oxygen lines are present as well but much smaller.

![Visible spectra taken in W7-X from two different viewing ports: from AEA21 through the core plasma during discharge 20180905.16 and from AEF30 onto the lower divertor module 3 (in green) during the following discharge, 20180905.17.](image)

6. SUMMARY

First operation with an island divertor in W7-X was very successful. The heat loads generally appeared as expected, and for high-density hydrogen plasmas, stable heat-flux detachment was achieved under several conditions. The heat flux reduction was at least a factor of 10, and was characterized by a significant drop in target electron temperature and no large changes in the target densities, unlike typical tokamak-detachment cases. Likely related to this lack of density increase, the detachment observed in OP1.2a was characterized by only a modest neutral compression ratio, which may indicate that this detachment type is more akin to tokamak radiating-mantle discharges than tokamak detachment. In general, wall-conditioning improved significantly in OP1.2a over OP1.1. High-density operation was stably achieved in helium but was challenging in hydrogen throughout OP1.2a, but was achieved successfully after the first boronization in OP1.2b.

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REFERENCES

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