



Power loads to the limiters in the initial W7-X campaign

Wendelstein 7-X (W7-X) is an optimized superconducting stellarator with a helical magnetic axis. Its main objective is to demonstrate steady-state plasma operation at fusion-relevant plasma parameters and thereby verify that the stellarator is a viable fusion power-plant concept. The design of W7-X is based on an elaborate optimization procedure to overcome the shortcomings of traditional stellarators. As the machine is rather complex, during the design, development, and assembly important know-how in engineering and technology was acquired. The main construction phase of W7-X was completed in 2014. This was followed by the commissioning of the superconducting coils, which was successfully concluded with an assessment of a series of careful measurements of the magnetic field, not only confirming the basic magnetic field topology, but also demonstrating that potential error fields are within the correction capabilities of the W7-X trim coils [1]. After the operating permit was granted, first plasma operation started in December 2015 and lasted until March 2016. During integral commissioning of plasma start-up and operation, the plasma was heated using electron cyclotron resonance heating (ECRH), and an extensive set of completed plasma diagnostics allowed initial physics studies during the first operational campaign.

In the first operational phase, most of the graphite armor components and the island divertor were not installed. To protect metal parts (in particular the divertor frame structure) and to guarantee reasonable performance, a limiter configuration was used. Five graphite limiters, matching the five-fold symmetry of the plasma, were installed in symmetry planes at the inboard side of the vacuum vessel (see Fig. 1). The magnetic vacuum configuration of W7-X was chosen such that it has a smooth scrape-off layer (SOL), with no stochastic region and no large magnetic islands, such that the limiters efficiently intercept ~99% of the convective plasma heat load in the SOL. The typical connection length of magnetic field lines in the scrape-off layer was on the order of a few tens of meters, and obser-

vation revealed three separate helical magnetic flux bundles of different connection lengths. Therefore, separate heat flux channels were expected featuring localized peaks in the limiter power deposition patterns.

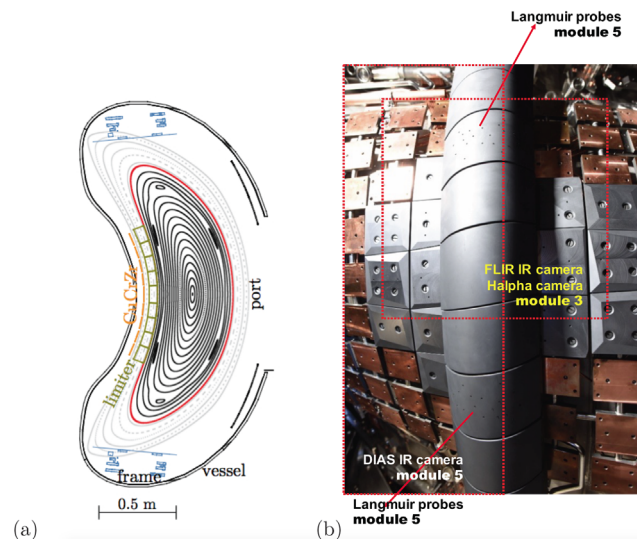


Fig. 1. (a) Magnetic flux surface calculated for the limiter configuration of W7-X during its initial campaign. (b) Graphite limiter on the inboard side of W7-X in module 5. Tips of Langmuir probes are visible above and below the midplane. The dashed rectangles indicate the camera views.

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In the initial campaign of Wendelstein 7-X, the machine was operated in a limiter configuration using up to 4 MW of ECRH power. Power loads to the limiters due to the 3-dimensional topology of the scrape-off layer were measured and calculated. 1

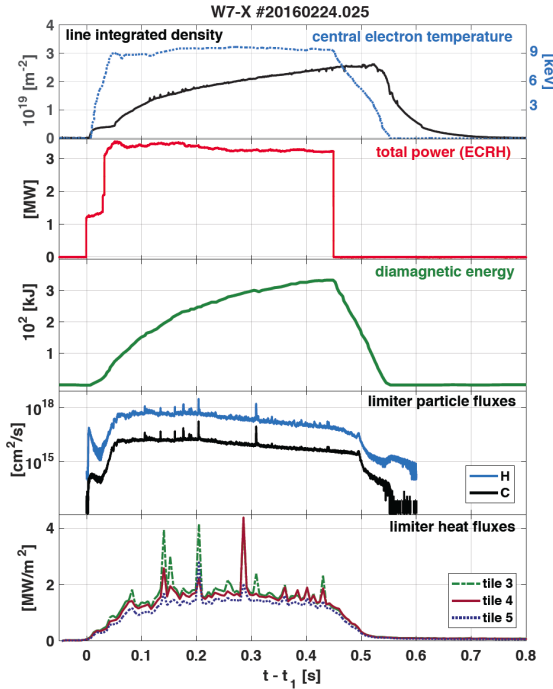


Fig. 2. Time traces for a typical hydrogen discharge during the initial campaign of W7-X. From top to bottom: electron temperature and density, total input power, diamagnetic energy, particle fluxes to the limiter, and at the bottom maximum heat flux density onto the 3 tiles indicated in Fig. 3(a).

Both in helium and hydrogen, plasma breakdown was easily achieved. However, the very first plasmas were small in diameter and highly radiating, and consequently the limiters initially received little deposited energy (only a few °C surface temperature increase). Then plasmas improved as we conditioned the walls with helium glow discharge cleaning (during periods without magnetic field), and with repetitive helium plasma discharges between main pulses. A typical discharge with an input energy of 3 MW and plasma duration of about 0.5 s is presented in Fig. 2. This led to a central electron temperature of $T_e \approx 9$ keV. As experience was gained with plasma vessel conditioning, discharge lengths could be extended gradually. Eventually, discharges lasted up to 6 s, reaching an injected energy of 4 MJ, which is twice the limit originally agreed upon for the limiter configuration [2]. At higher powers of 4 MW, central electron densities reached $3 \times 10^{19} \text{ m}^{-3}$, central electron temperatures reached 12 keV, and ion temperatures reached just above 2 keV [3]. Interestingly, as shown in bottom time trace of Fig. 2, the power loads to the limiter showed also transient events, which we attribute to anomalous transport in the SOL. Those transient events had mode-like structure with helical stripes on the limiter and a poloidal mode number

around 15. The transient power loads could exceed the steady-state values by more than a factor of 2. To our knowledge this is the first indication in a helical device that turbulent transport in the SOL plays a major role.

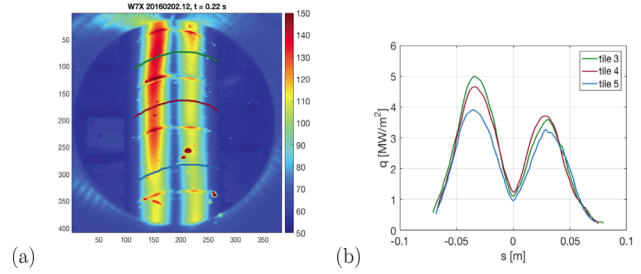


Fig. 3. (a) Infrared image of the limiter in module 3. Color scale denotes temperature. (b) Heat flux density profiles evaluated from the surface temperature at the locations indicated by colored lines in (a).

In the initial campaign important physics studies including the assessment of power balance and the heat load distribution over the inboard limiters could be studied. The surface temperature on the limiters was investigated using a set of infrared (IR) diagnostics: immersion tubes with near IR cameras with observation wavelength range between $0.8 \mu\text{m}$ and $1.0 \mu\text{m}$. Those cameras had rather poor spatial resolution and their dynamic range was also very limited (8 bit). Additionally we used high-resolution IR cameras: a microbolometric camera from DIAS ($8\text{--}14 \mu\text{m}$, spatial resolution of order 5 mm) and a mid-IR camera from FLIR ($3\text{--}5 \mu\text{m}$, spatial resolution of order 1 mm) [4]. The microbolometric camera observes the left side of the limiter in module 5 from the top (as indicated in Fig. 1), and the high-resolution IR camera observes five of the nine tiles above the midplane of limiter 3. With a frame rate of up to 50 Hz, the microbolometric camera can resolve a half limiter with a time resolution of 20 ms, while the high-resolution camera can run with a frame rate up to 400 Hz (for a cropped image) to measure fast temperature changes during transient events.

The power loads were calculated with the help of the well-known THEODOR (THERmal Energy Onto DivertOR) code developed at IPP Garching. Starting from the time evolution of the surface temperature data, the code calculated the heat flux density onto the surface by solving a linear heat diffusion equation for the bulk of tile (2D). The code takes a 1D profile of the surface temperature as input.

The results for helium plasmas at limiter 3 are presented in Fig. 3(b). At each side of the limiter we can observe two strike lines on the left and the right sides of the watershed. The plateau insert and a large part of the linear extensions at the edges are not loaded. The maximal loads are located in the areas where the angle between the surface and the field is about 20° .

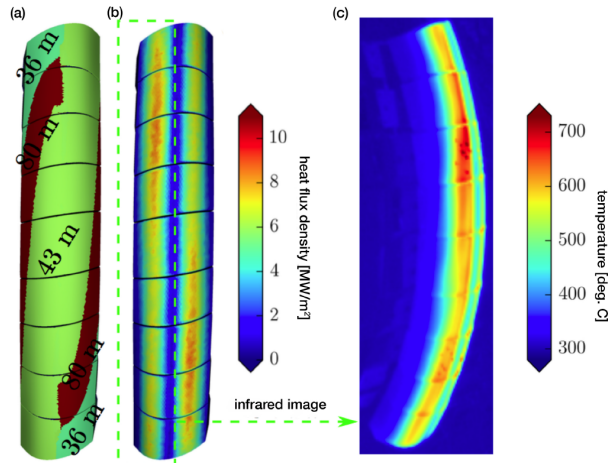


Fig. 4. (a) Simulated connection lengths and (b) heat flux density for the limiter during the initial campaign. (c) Temperature distribution on the limiter measured with the microbolometric IR camera in module 5 during a typical discharge. Only half of the limiter is visible.

On each limiter, three areas with different connection lengths are present. This is clearly visible in Fig. 4.

Field lines in the first area with connection length L_c about 39 m meet the same limiter after a single toroidal turn; in the second area with L_c about 43 m, they meet the next adjacent limiter (after 6/5 of a full turn); the third bundle with L_c about 80 m has field lines that make two full toroidal turns and an extra 1/5 of a turn, hitting the adjacent limiter. The heterogeneous distribution of the connection lengths in the scrape-off layer resulted in nonuniform heat flux densities. Figure 4(b) shows the heat flux densities simulated with Monte Carlo field line diffusion for the design parameters and ECRH power of 4 MW. In these numerical calculations, field lines from inside the last closed flux surface are traced with an additional perpendicular diffusion.

Two stellarator-symmetric strike lines are present on each limiter. The strike lines are not uniform vertically. Each strike line has three areas with the aforementioned different connection lengths and, as a consequence, with different incident power densities. The highest power density on the limiter is observed for the area with L_c about 80 m. The overall structure of the strike lines is confirmed experimentally with the infrared camera measurements of the limiter surface temperature as shown in Fig. 4(c). Also, the measurement shows the vertical variation of the temperature in the strike line. The highest temperatures, and therefore heat flux densities, appear in the region of long connection lengths with L_c about 80 m. These areas are mainly at tiles 3 and 4 on the left and tiles 6 and 7 on the right. In agreement with the stellarator symmetry, the left

and right strike lines are flip symmetric: the right one is the left one rotated by 180 degrees.

Using a rather limited set of tools we were able to characterize the heat fluxes on the poloidal limiters in W7-X during the first helium and hydrogen plasmas during OP1.1. A nonuniform distribution of power loads with two heating stripes on each limiter was observed. The measured patterns are consistent with modeling and can be understood in terms of longer flux bundles carrying more plasma heat flux. IR thermography and calorimetry using multiple IR camera systems, combined with slow thermocouples to account for toroidal asymmetries, allowed us to estimate that the limiters intercepted up to 60% of the total energy put into the vessel by the ECRH system for low-power (0.6 MW), long-pulse (6 s) shots, and a smaller fraction (~35%) for high-power (4 MW) short duration (1 s) discharges. More details may be found in upcoming papers [5, 6].

References

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