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Power loads in the limiter phase of Wendelstein 7-X

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Wendelstein 7-X (W7-X), an advanced stellarator with five-fold symmetry, started its first plasma operation phase (OP 1.1) in December 2015. Electron cyclotron resonance heating (ECRH) power between 4 MW (1 sec) to 0.6 MW (6 sec) was used. The plasma duration was restricted administratively to a 4 MJ energy limit. The wall was protected in the initial campaign of W7-X with 5 uncooled fine grain graphite limiters installed on the inboard side of the plasma vessel [1]. In this paper the first results of the power load onto these limiters are presented.

The surface temperature on the limiters is investigated with two infrared (IR) cameras: a microbolometric camera (8-14 μm , spatial resolution of order of 5 mm) and a high resolution IR camera (3-5 μm , spatial resolution of order of 1 mm). The microbolometric camera observes the left side of the limiter in module 5 from the top (Fig. 1(b)) and the high resolution IR camera observes five of the nine tiles above the midplane of limiter 3. With a framerate up to 50 Hz, the microbolometer camera can resolve a half limiter with a time resolution of 20msec, while the high resolution camera can run with a framerate up to 400 Hz (for a cropped image) to measure fast temperature changes during short events. The heat flux density is evaluated with the THEODOR (THERmal Energy Onto DivertOR) code [4] from evolution of the surface temperature data by solving a linear heat diffusion equation for a bulk of tile (2D) [5]. The code takes a 1D profile of the surface temperature and the thickness of the material as input.

The magnetic field configuration for the initial campaign has been chosen to avoid stochastic regions and large magnetic islands at the plasma boundary. This assures that the limiters efficiently intercept $> 99\%$ of the convective plasma heat load at the plasma edge. (For 4 MW of ECR heating each limiter is expected to absorb 400 kJ at heat fluxes of up to 10 MWm^{-2} [2]). Simulations [3] indicate that the scrape-off layer consists of magnetic field lines with limiter-to-limiter connection lengths of the order of a few tens of meters. Three separate helical magnetic flux bundles of different connection length of 36 m, 43 m and 79 m form a 3-D structure of magnetic footprints on the limiter surface (Fig. 1(a)). This results in heterogenous power deposition patterns over the limiter surface. In particular, two heat stripes are predicted and seen by the IR cameras, running the length of the limiter, whenever the plasma contacts the limiter (Fig. 1(b)).

For plasmas that don't contact the limiter (for example high density cold collapsing plasmas), no heat stripes are seen. As predicted by EMC3-Eirene modeling the maximum is located in the region of the flux tube with a connection length of 79 m [3] (Fig. 1(a)).

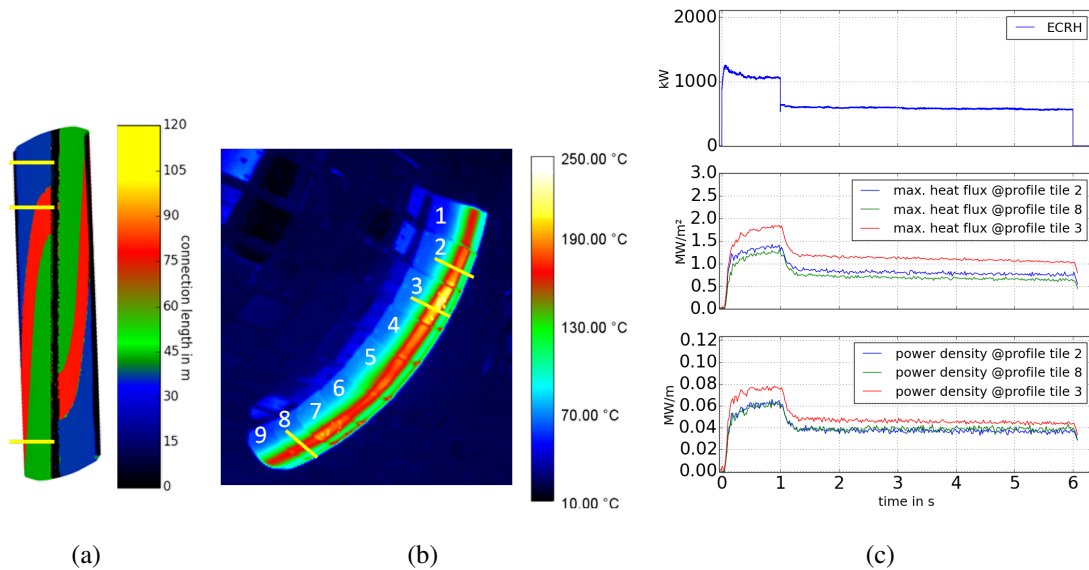


Figure 1: (a) Modeled connection length footprint on the limiter (b) view of the microbolometric camera. Three slices (yellow lines) are used to evaluate limiter power fluxes (c) timetrace of a 6 s discharge, top: ECRH power, middle: max heat flux density for three different profiles, bottom: line integrated power density for different tiles

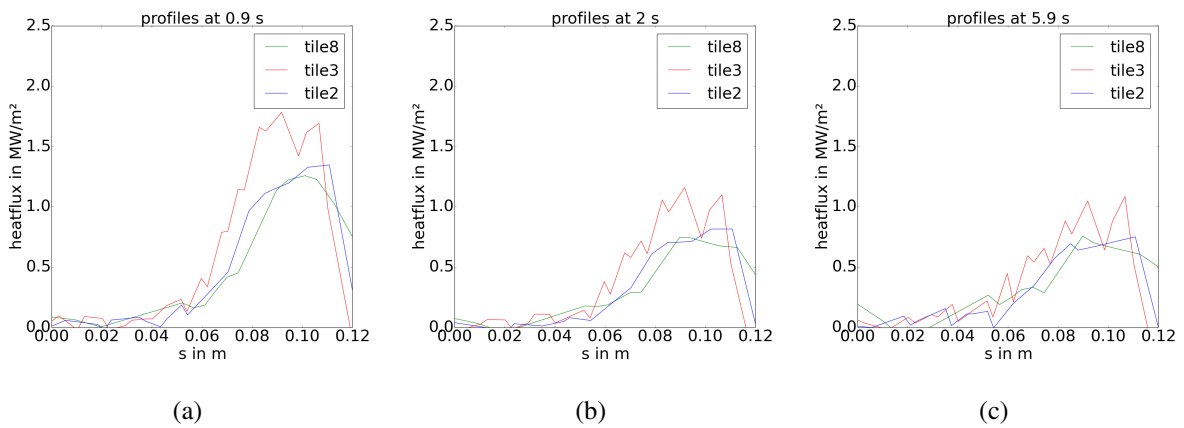


Figure 2: the 3 different profiles on tile 2,3 and 8 for: (a) 0.9 s, (b) 2s , (c) 5.9 s

For a first evaluation three different profiles are taken (yellow slices in Fig. 1(b) and Fig. 3). They are chosen to investigate the local power through 3 different connection length flux tubes. These profiles are evaluated for a 6 sec low power, high energy discharge. The discharge starts with 1 MW ECRH for 1 sec with a step down to 600 kW ECRH for the next 5 sec (Fig. 1(c)). The maximum temperature increase in this shot is found on tile 3 (Fig. 1(b)), where the

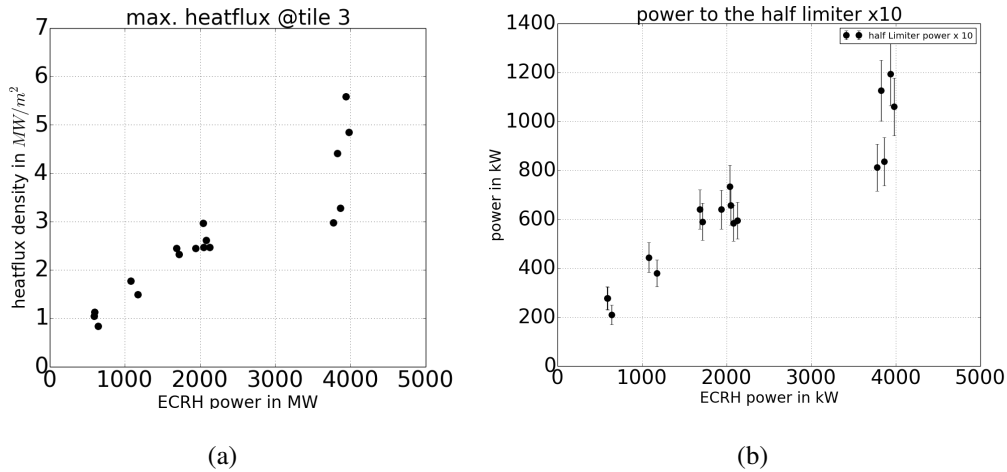


Figure 3: heat flux density over time t and surface position s for different connection length: (a) 36 m (b) 43 m (c) 79 m

79 m long flux tube strikes the limiter. This results also in a higher maximum heat flux density measured in the profile taken on tile 3 (Fig. 1(c)). The time evolution of the heat flux density on all three tiles follow the time behavior of the ECRH with a slight delay of about 40 to 60 msec. This initial delay can be explained by the plasma growing during the start up. At first the maximum heat flux density rises up to $1.8 MW/m^2$ on tile 3 (Fig. 1(c), 2(a)). The profiles on the other two tiles show at the same time a similar behavior but a 30% lower maximum heat flux density (Fig. 1(c), 2(b), 2(c)). The profile width is nearly the same for all three profiles (Fig. 2(a)) during the first second, which ends also in same line integrated power density for the two tiles with the shorter connection lengths. When the heating power is reduced the heat flux density on all tiles decreases with again a delay of 40-60 msec. While the ECRH power decreases about 40% in less than 1 ms, the heat flux density shows a decay of about 40% on a much longer timescale of ~ 240 ms. This longer decay time is related to the plasma energy confinement time. Over the 5 sec the heat flux density shows a slight decay over time to $1 MW/m^2$ for the profile on tile 3 and down to $0.6 MW/m^2$ for the other two profiles. The reason for this is not fully clear at the moment. The three different profiles with the different connection length show a very similar time behavior and profile width but different maximum values. This ends up in 30% lower maximum heat flux and also integrated power density for the two profiles in the region of the flux tubes with shorter connection length. These results shows that the connection lengths have an impact onto the heat flux density on the limiter in Wendelstein 7-X.

Looking at shots with different ECRH power profiles and line integrated densities allows us to observe the maximum heat flux density on tile 3 as a function of ECRH power (Fig. 3(a)). The scaling shows a linear characteristic. The two outliers near 4 MW ECRH power (Fig. 3(a))

are from discharges with a heavy gas puff (a high line integrated density ($> 3 * 10^{19} m^{-2}$)). The maximum heat flux goes up to $5.6 MW/m^2$ for 4 MW ECRH power. This maximum is below the estimated maximum of $10 MW/m^2$ for the designed graphite limiter. This lower heat flux density is not inconsistent with higher fraction of radiated energy.

By taking several profiles on the limiter (every 5 mm) and integrating over all, we can estimate the deposited power onto the limiter. To make statements about the total power fraction the calculated power on the half limiter is multiplied by 10 under the assumption of the five fold stellarator symmetry (Fig. 3(b)). This shows a similar scaling to the previous maximum heat flux density estimate, with the same two outliers for high line integrated densities. At the low ECR heating power of 600 kW, the fraction of deposited power goes up to 50%. For high heating powers up to 4 MW the fraction of limiter deposited power drops to $\sim 30\%$. The cleanest shots were usually the first few discharges of the day (following helium glow discharge cleaning). Later in the day, deteriorating wall conditions would actually prevent the achievement of long discharges. So for now, we can not completely untangle the energy balance[6] differences between high ECRH power (short discharges) and long pulse (low power) ones.

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