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Experimental indications of high-recycling and the role of pressure and power dissipation for detachment at W7-X

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New experimental evidence based on spectroscopy, see Fig. 1, and other edge diagnostics indicate the existence of a high-recycling regime in W7-X. The high-recycling regime has not been accessible in the predecessor W7-AS and was predicted by modeling [1] for W7-X. The island divertor stellarator W7-X has also demonstrated stable, detached, high density divertor plasmas with good particle and power exhaust conditions, such that steady-state operation with particle removal by the pumps and sufficient power dissipation have been achieved [2,3,4,5]. Experimental measurements show also high divertor densities, complete heat flux detachment from the target, high neutral compression and beneficial impurity transport with indications of divertor retention of low-Z impurities [6] and benign core impurity transport [7]. This is a very important finding with respect to future power plants as the ability to exhaust the fusion power compatible with the limits of the plasma facing components is a paramount requirement for such a device. Therefore, the W7-X program develops and investigates exhaust scenario based on a detached divertor plasma.\\
Two approaches of achieving heat flux detached divertor targets have been followed in the OP1.2b campaign. First, density ramp experiments using a feedback controlled gas puff system [2,3]. Second, impurity seeding of N and Ne were used to increase the radiated power and achieve detachment at lower plasma densities [5]. We focus here mainly on density ramp experiments.
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Fig. 2 shows the timetrace of a density ramp discharge that leads to completely heat flux detached targets after 3.0s. Consistent with the modeling expectations [8], above a threshold of $n_{e,tar} \lg n_{e,up}$, the radiation increases strongly with a small density increment and the radiation front detaches from the target and moves toward the X-point. The movement of the radiation front is indicated by the movement of the N$f_{rad} > 50\%$-line (399.5 nm) radiation and the high density region in the divertor shown in Fig. 3.b and 3.a, respectively.

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Currently, the exact localization of the radiation front with bolometry is not conclusively possible with respect to its position around and along the separatrix, but upstream profile diagnostics show a significant reduction of the electron temperature from about 150 eV to 50 eV around the separatrix up to 3.4 cm inside the nominal separatrix position. Keeping in mind the large uncertainties in the latter, this is still indicative of increased power losses in the very edge of the confined region and could be comparable to the very localized radiation features in X-point radiation regimes in tokamaks [9]. As N^+ pre-dominantly radiates at temperatures of $^+$, its location can be taken as a reference for the ionization front. This implies that the ionization front lifts off the target concomittent with the radiation front during the detachment transition. Fig. 2.c shows that at the same time a drop in neutral compression(black line) by about 50 % with only marginally reduced divertor neutral pressures is observed in experiment. Stark broadening of Balmer lines is used to assess the electron density in the divertor, see Fig. 1. High densities on the order of $^+$ with $T_e = 3\,\mathrm{eV}$ indicate the existance of a high recycling regime in W7-X experiments. Line ratio analysis of the Balmer lines ($10^{20} m^{-3}$) shows that the divertor plasma in W7-X detachment conditions is still ionization dominated. The absence of strong recombination and the low neutral pressures of order 0.1 Pa in the experiments thus imply that the perpendicular transport is an important if not the dominant pressure loss channel in W7-X.
As a consequence, the dominant detachment physics in W7-X seems to be different to the traditional picture in tokamaks: In tokamaks large pressure losses and particle flux reduction across wide parts of the target are

not easily obtained [9,10]. Pressure conservation naturally leads to the onset of a high recycling regime with lowering divertor temperatures. The high divertor densities then enable large power losses from impurity radiation. In contrast, the long connection length of island divertor stellarators, such as W7-AS and W7-X, provides large pressure losses from the main particle flow channel via perpendicular transport. The pressure losses can actually suppress the high recycling regime altogether, as observed in W7-AS [9], or limit the achievable divertor densities. In combination with the increased importance of perpendicular energy transport in the Scrape-Off Layer this prohibits large dissipated power fractions in the divertor by radiation [8]. As a consequence, a particular focus of tokamak detachment studies is the pressure loss, whereas in W7-X to characterize the available Scrape-Off Layer and divertor power losses and to achieve high divertor densities have a higher priority. The latter will be addressed in this contribution. The experimental data will be used to validate EMC3-Eirene modeling and the physics processes that lead to the radiation movement, the high recycling regime and the neutral pressure build up in the divertor will be analyzed.

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