First observation of a stable highly-radiative divertor regime at stellarator W7-X

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1. Introduction. Shortly after the first successful operation with five inboard limiters, the stellarator Wendelstein 7-X (W7-X) [1] was upgraded by installing ten up/down-symmetrically-paired inertially cooled test divertor units (TDUs). This enabled the conduction of first divertor experiments at W7-X late last year which significantly differ in their radiation behavior of impurities in comparison with the previous limiter plasmas [2]. First, the region of intensive radiation emission, which was typically located several cm inside the last closed flux surface (LCFS) of the limiter configuration, shifts outwards towards the separatrix of the divertor configuration or even into the Scrape-Off-Layer (SOL), depending on the radiation strength. Secondly, for certain plasma scenarios the radiated-power fraction is significantly increased without serious degradation of energy confinement. We report here the results obtained during the first divertor operational phase at W7-X. A stable highly-radiative divertor (SHRD) regime has been discovered, in which radiated power loss approached 95% of the heating power and 'complete' plasma detachment from the divertor targets is confirmed by the IR-cameras of the thermographic diagnostic.

2. Experiment description. W7-X is a midsize stellarator ($R_0 = 5.5$ m, $a \sim 0.5$ m). The plasma facing components (PFC) consist of the graphite-covered TDUs and wall protections as well as stainless-metal wall. Turbomolecular pumps allow control of the machine vacuum. He Glow- and ECR-heated He-discharges are used for machine conditioning. Boronisation has not yet been performed for this operation phase. Intrinsic impurities are mainly low-Z elements, such as carbon and oxygen [3, 4]. The experiments described here were carried out in 'standard' magnetic configuration ($B_0 = 2.5$ T) with a 5/5 island chain at the edge. Island dimension is around 8 cm radially. Plasma is generated using X2-mode electron cyclotron resonance heating (ECRH).

The experimental results reported here are based on the following diagnostics: a two-camera bolometer system installed at a triangular cross-section (with a spatial resolution of 3-4 cm) for measuring the plasma radiation [5]. The total radiated power loss, P_{rad}, is a linear extrapolation of the radiation in the viewing volume to the whole plasma volume ignoring the toroidal variations. The line-integrated signals are used for P_{rad} calculations in order to avoid the uncertainties from deconvolution procedures. An interferometer is used for measuring the line-averaged plasma density, the magnetic diagnostic for measuring the plasma stored energy, ECE (electron cyclotron emission) radiometers for electron temperature measurements, target plate thermography for heat loads measurements, and spectroscopic diagnostics, such as HEXOS (a high-efficiency XUV overview spectrometer) [3] and filterscopes [4], for monitoring impurity ion radiations.

3. **The SHRD-regime with 'complete' plasma detachment** Fig. 1 shows the diagnostic waveforms of the hydrogen discharge #20171109.045 with gas-puffs before and shortly after starting ECRH (3 MW). High-speed frozen hydrogen pellets are injected at 30 Hz from both the low- and high-field side at 1.7s (lasting 0.4 s). The line-averaged density $<n_e>$ is 2.0 10^{19} m^{-3} and the radiation fraction, $f_{rad} = P_{rad}/P_{ECRH}$, is 0.7 before injection. The injected pellets penetrate into the core region causing rapid increments of the plasma density. The plasma temperature is reduced as indicated by the ECE signals. Density profiles measured by Thomson scattering are initially flat, but become centrally peaked (see Fig. 2). The plasma stored energy W_P increases reaching a maximum at a time point after pellet injection. Then the density falls

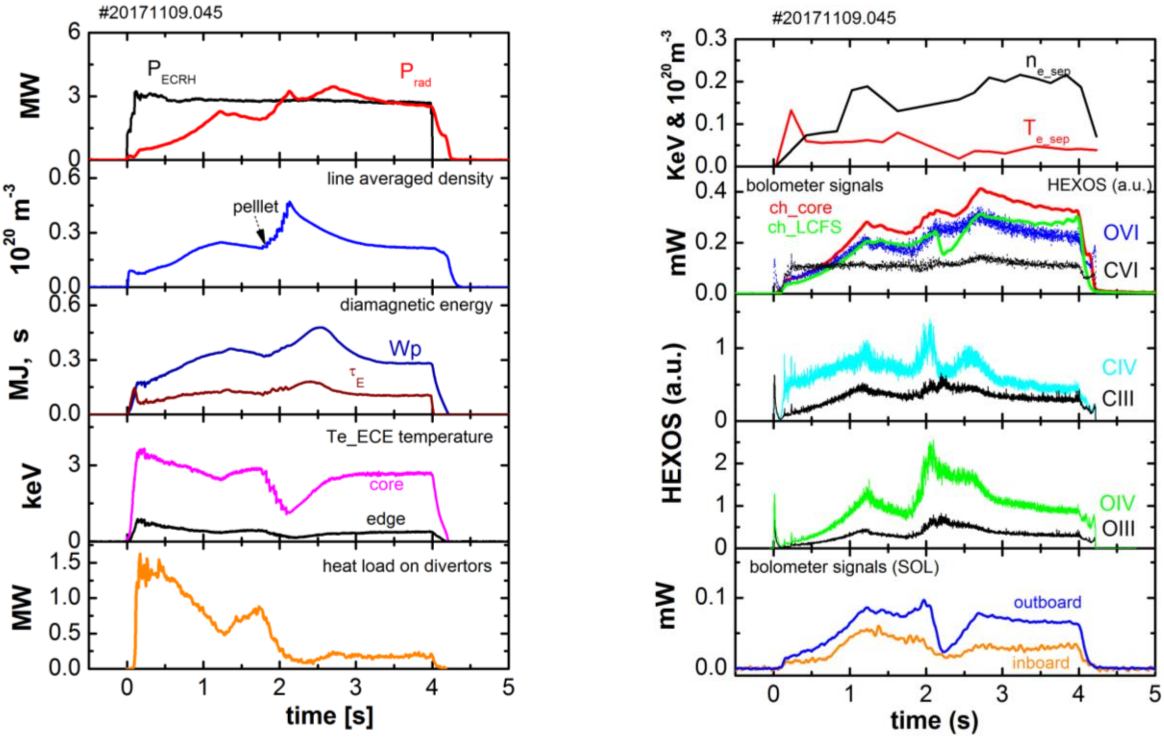

Fig.1 (Left) Time traces of global plasma parameters for H-discharge (#20171109.045) with pellet injection at 1.7s showing the establishment of a SHRD regime (f_{rad} ~ 0.95) with 'complete' plasma detachment (total heat load on to divertor targets reduces by a factor of ~10) after injection (3 s) till to program end. (Right) The edge plasma parameters, T_{e_sep} and n_{e_sep}, impurity carbon and oxygen spectral line intensities, and selected bolometer signals for channels viewing through core and separatrix (ch_LCFS) as well as island chain radiation at SOL. The enhancement of emission from the oxygen ions with high ionization stages (OVI) in the SHRD-regime relative to that at the reference time point correlates with increments of the bolometer signals (ch_core, ch_LCFS) as well as $P_{rad.}$

returning to the original value in 0.9 s. Also other plasma parameters, such as T_e, W_p and P_{rad} approach a constant value. From 3 s on, the radiation fraction reaches 0.95 of 3MW ECR-heating power, displaying a stable highly-dissipative plasma regime. Consistent with the bolometer measurements the IR-cameras monitoring the divertor targets reveal a reduced heat load on all ten divertor units by a factor of more than 10. The remaining small fraction might be assigned to contributions from photons and CX-neutrals comparable to a noise equivalent level of 0.4 MW/m^2 (Fig. 1 left). The plasma maintains in this ‘complete’ detached phase until the end of the discharge.

3.1 Bulk plasma characteristic and confinement Fig.1 (left) depicts the evolution of the global confinement time, $\tau_E = W_p/(P_{ECRH} - dW_p/dt)$ using the diamagnetic energy W_p and the heating power P_{ECRH}. We get $\tau_E = 0.1$s in the SHRD plateau, which is very close to that before pellet injection for the same density (this is the reference time point for further discussions). Further analysis is performed by collecting the confinement time in other H-discharges under the same magnetic configuration and heating power; the τ_E at this SHRD-regime follows the ISS04 scaling law, $\tau_E \propto \langle n_e \rangle^{0.54}$ closely and less performance degradation is observed. The density/temperature profiles before and after injections are shown in Fig.2 (top, middle), indicating flattened $\langle n_e \rangle$-profiles. Pellet induced peaked profiles (2.4 s) is also demonstrated. The T_e-profiles are generally centrally peaked; during pellet injection $T_e(0)$ decreases below 4 keV, and in the SHRD-regime (3s) a little lower than at reference time point. A 2D radiation intensity distribution in the SHRD-regime obtained using Minerva Bayesian tomographic reconstruction [6] of the bolometer measurements is shown in Fig. 2 (Low). It clearly reveals that intensive radiation comes from the separatrix vicinity and some strong radiation from the main plasma edge region. A poloidal asymmetry is visible but the mechanism driving it is still unclear.

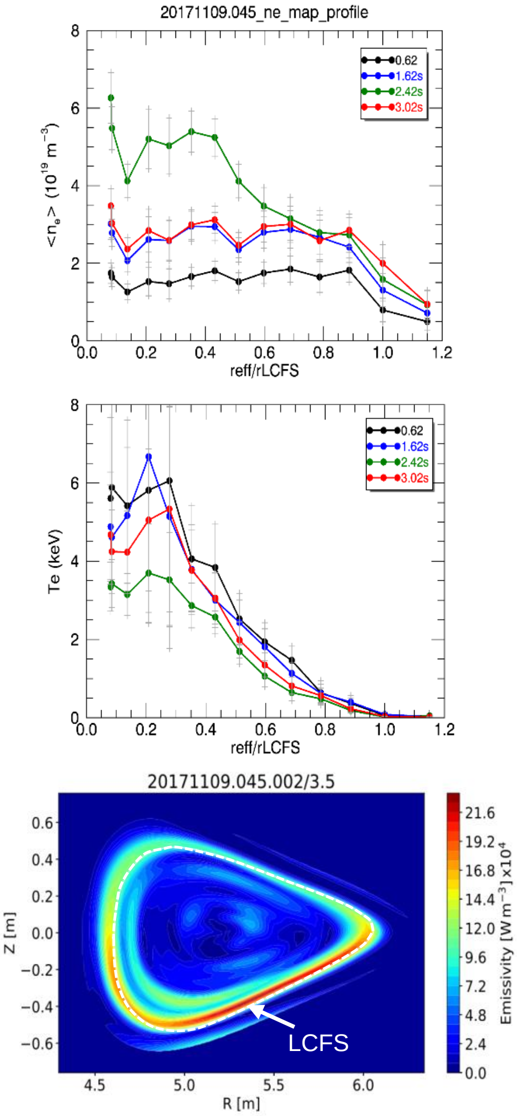

Fig. 2 (Top & middle) density and temperature profiles measured by Thomson scattering before, during and after pellet injections. (Bottom) 2D radiation distribution obtained by Minerva Bayesian tomographic reconstruction based on bolometer measurements (3.5s).

3.2 Impurity contributions to SHRD-regime Fig. 1 (right) shows the edge parameters. Conditions for reaching SHRD-regime are a separatrix temperature $T_{e,sep}$ of ~50 eV (lower than at reference time point) with uncertainty around factor 2 and density $n_{e,sep}$ reaches 2 10^{19}m^{-3} (higher that at reference time point). The bolometer channels viewing the island chain radiation at SOL remain constant. However, they have a weaker chord-brightness than that at the reference time point. It is consistent with the spectral line intensities from the impurity ions at lower ionization stages, such as CIII-IV (OIII-IV changes less), which radiate at the low-temperature SOL. In contrast, the emission of the higher ionization stages, such as OVI, increases after pellet injection and CVI remains almost unchanged (Fig. 1 left). This implies that the enhancement of P_{rad} in the SHRD-regime is attributed to the radiation from oxygen ions at higher ionization stages, such as OVI. Z_{eff} is ~2.5 before pellet injection and with slight increment at the SHRD-regime. Simulations with 1D-impurity transport code STRAHL [7] using a transport coefficient $D = 0.5\ m^2/s$ show that OVI and CVI are indeed present at Te~50-100 eV in the vicinity of the separatrix. 3D simulations using EMC3-EIRENE [8] show that radiation zone shifts inward to higher-T_e range or close to X-points in the island chain for high-density and high-radiation regime and with reduced toroidal variations. These findings are qualitatively consistent with the bolometer observations. They support the numerical algorithm for calculating P_{rad}, especially at SHRD-regime.

4. Discussions and remarks In addition to the discharge shown above, plasma detachments have been observed also in discharges without pellet injections: in some with prefilled hydrogen, SHRD-regime is obtained even shortly after plasma built-up, which can be maintained stably. They have usually very flat density profiles with $n_{e,sep} \geq 2.0\ 10^{19} m^{-3}$ depending on the heating power. In a discharge with divertor hydrogen-puffing, complete detachment can be maintained as long as 3 s. These all demonstrate that W7-X, due to its special island chain structure in the magnetic topology, has the potential to attain a highly dissipative divertor regime, via intensive edge-localized radiation either from the intrinsic impurities, such as carbon and oxygen, or seeded light impurities, such as N_2. Attaining an operation mode as SHRD-regime, with a significant reduction of the heat flux onto the divertor target plates without degrading core plasma performance, is desirable as a divertor operation mode. Such an operational mode is necessary for stationary discharges in a future fusion power plant. It is expected that the density threshold for the SHRD-regime will increase as a result of a reduction of the oxygen content after boronisation of the first wall.

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