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A new plasma condensation phenomenon in the W7-AS island divertor

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Abstract

In the W7-AS stellerator with island divertor very high densities can be achieved in the high-density H-mode. As a consequence, the plasma in the divertor detaches as previously shown by the reduction of the particle flux at some strike point positions and an upward movement of the ionisation front. Our spectroscopic measurements prove the simultaneous formation of a high-density (8×10^{20} m^{-3}), low temperature (0.2 eV) region at the detachment transition in the divertor on top. This plasma is strongly recombining, as a result a strong up/down pressure asymmetry develops. Since flux amplification at the strike points was not found in the island divertor, we suppose that a nonlinear thermal condensation instability leads to the observed high-density region.

Keywords: Plasma-wall-interaction; Stellerator; Divertor; Detachment; Recombination; Hydrogen emission

1. Introduction

The divertor experiment in W7-AS has been designed for the $\iota = 5/9$ island configuration. The main result was the discovery of a new regime with neutral beam heating which can be maintained over many energy confinement times for the first time. Very high line-averaged densities were achieved up to 3.5×10^{20} m^{-3}. Since there are many similarities to the H-mode in W7-AS it is called high-density H-mode (HDH-mode) [1].

At very high density the divertor plasma detaches. The particle flux is reduced at some strike line positions [2]. Spectroscopic measurements show a movement of the emission zone of the carbon CII ion away from the target [2]. Since the CII ion emits at 4–6 eV [3] this means a corresponding movement of the ionisation front, i.e. the plasma is detached from the target plate. In the following we will show that the temperature in some divertor regions is still lower after the detachment transition. From a spatial and spectral investigation of the hydrogen emission we will identify a recombining plasma zone in the divertor. Finally we discuss the possible nature of the detachment transition.

2. Divertor diagnostics

The divertor modules are arranged on top and at bottom of the five elliptical planes. Each module is 0.7 m long. Fig. 1 shows how the upper target plate and baffles intersect the magnetic islands in the elliptical plane. Two islands are cut by the target tile.

Most of the divertor diagnostics is concentrated at the targets in module 1 and 2. Both oppositely arranged modules are equipped with flush-mounted Langmuir probes. The neutral pressure is measured by ionisation manometers [4]. The module at bottom is observed by a sophisticated CCD camera system operating with different interference filters. Two of the CCD cameras serve for observation of the hydrogen emission lines of H_α and H_γ. A third camera measures the CII emission at 658 nm. The CCD cameras are absolutely calibrated by means of an integrating sphere. The upper module is

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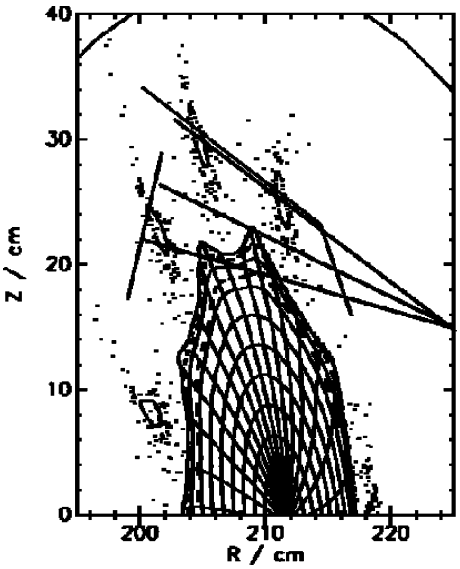

Fig. 1. Flux surfaces of the magnetic vacuum field for the discharge #54990 and the divertor structures (target and baffles) on top. The spatial range of the divertor spectrometer is shown and a special line-of-sight at 22.4 mm for which data is presented in the following.

observed by a single H_α camera. For some shots the upper target was also observed in the light of H_γ and CII by a change of the filters.

A spectrometer is mounted in the upper divertor module with lines-of-sight nearly parallel to the target plate (see Fig. 1). The divertor region was imaged through a narrow slit in the outer baffle to a spectrometer, using two mirrors positioned into the vacuum vessel, via an UV-achromat. The spectrometer is of low resolution ($f = 190$ mm). With a 300-grooves/mm grating, it covers a wavelength range of about 100 nm on the back-illuminated CCD chip.

Fig. 2 shows as an example an H_α photo of the upper target to make clear the observation geometry. Target tile 12 is nearest to the plasma (watershed). Langmuir probe arrays are located in target tiles 5 and 13. The divertor spectrometer samples data at target tile 9. Three strike lines appear in the light of H_α. Comparing these with the magnetic configuration in Fig. 1 we identify the inner strike line as the outer fan of the inner island. The middle and outer strike lines correspond to the inner and the outer fan of the outer island, respectively. The inner fan of the inner island is very weak and located at the inner baffle.

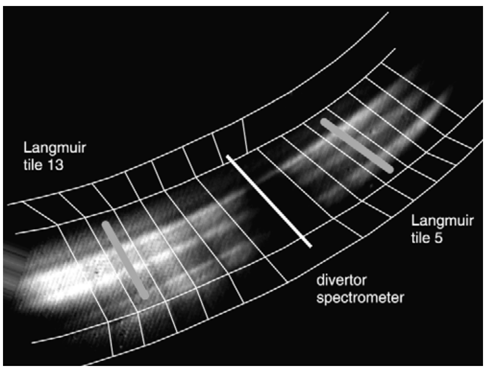

Fig. 2. H_α strike line pattern of the divertor on top (attached shot #54454).

3. Hydrogen emission

A hydrogen plasma is ionising when the electron temperature exceeds 2 eV. Then recombination rates are small compared to ionisation rates, i.e. there is net ionisation. For ionising plasma conditions the H_α emission in front of a confining wall can be interpreted in terms of a hydrogen atom influx Γ from this surface. It holds $\Gamma = S/XB \cdot I$, where I is the H_α or H_γ intensity (irradiance in $\mathrm{W\,cm^{-2}}$), and S/XB is the atomic physics factor of the corresponding electron transition (S is the ionisation rate, X is the excitation rate and B is the branching ratio). In Fig. 2 the divertor plasma is ionising and the H_α pattern represents the particle flux.

When the temperature sinks below 2 eV the plasma is no longer ionising. At 1.3 eV recombination rates become comparable to ionisation rates; below this net recombination occurs. This transition is accompanied by a sudden intensity increase of the hydrogen Balmer lines with high quantum numbers. It can be detected by monitoring the line ratio of two Balmer lines with high and low quantum number, e.g. H_α and H_γ. Fig. 3 shows the line ratio H_α/H_γ as a function of the electron temperature for densities of $n_e = n_i = 4 \times 10^{19}$ m^{-3}. It was evaluated using the Johnson–Hinnov model [5]. This ratio takes on two characteristic values: in an ionising

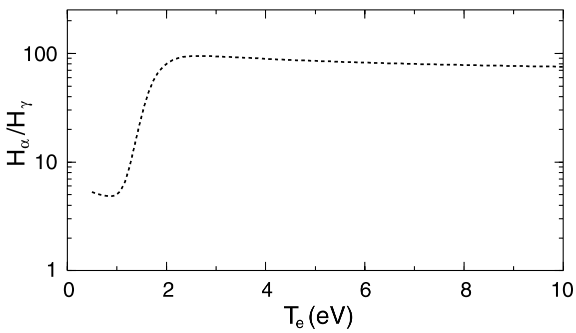

Fig. 3. Line ratio H_α to H_γ as a function of the electron temperature. It was calculated for $n_e = n_i = 4 \times 10^{19}$ m^{-3} using the collisional-radiative model from Johnson and Hinnov. The transition from net ionisation to net recombination occurs between 1 and 2 eV.

plasma it is about 85, in a recombining plasma it is about 5. Only during the transition from net ionisation to net recombination, i.e. between 1 an 2 eV, there is a substantial change of the ratio. Using the line ratio method, a recombining plasma can be identified and recombining regions can be distinguished from ionising ones.

4. Detachment in the island divertor

Normal confinement is characterized by a relatively low edge density. The separatrix density scales like $n_{es} \propto n_e^{0.45}$. The edge density saturates and high densities necessary for detachment cannot be obtained. In the HDH-mode line-averaged-densities up to $n_e = 3.5 \times 10^{20}$ m^{-3} were achieved. Furthermore, the density profiles are broader compared to the normal confinement regime leading to much higher separatrix densities. Above 2×10^{20} m^{-3} the separatrix density saturates at a value of 6×10^{19} m^{-3} up to the onset of detachment [4].

Consider a detached discharge in hydrogen (#54490) with a negative magnetic field of −2.5 T and an enhanced plasma radius of 13.6 cm. Control coils were activated. Fig. 4 shows time traces of the energy content, the density derived from the bremsstrahlungs signal, heating power of the neutral beams and total radiated power. Fig. 5 shows the evolution of the divertor pressure in the upper and lower module. Initially the pressure linearly rises with the ramp-up of the density. In this phase the pressure is up/down symmetric. At 250 ms the plasma detaches. Now the divertor pressure becomes

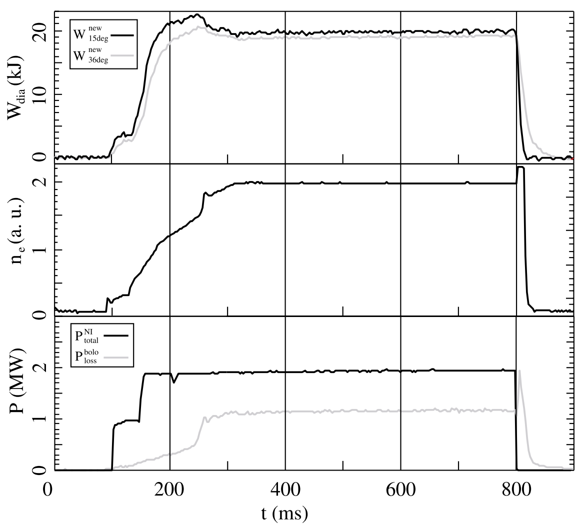

Fig. 4. Signal traces of discharge #54490: Energy content, density derived from bremsstrahlung, radiated power and power of neutral beam heating. At 250 ms the divertor plasma detaches.

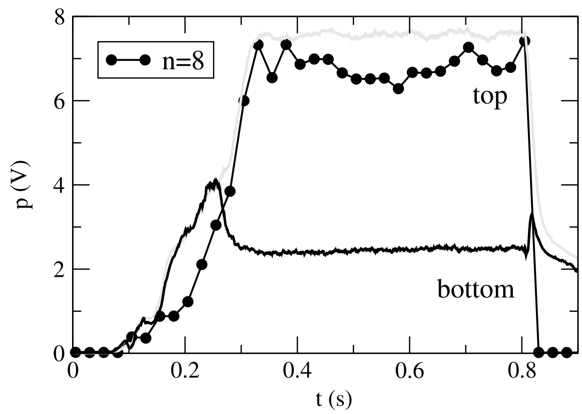

Fig. 5. Temporal behaviour of the neutral pressure in the upper (grey line) and lower divertor module (black line). The thin line with the symbols shows the intensity of the hydrogen Balmer line $n = 8$ (in arb. units) sampled in the upper divertor with the divertor spectrometer at $\Delta L = 22.4$ mm.

asymmetric; it goes up in the upper divertor module while it decreases in the lower module. Simultaneously, the ion saturation current of some Langmuir probes in target tile 13 is significantly reduced. Fig. 4 shows that the discharge is not strongly influenced by the detachement transition. The main effect is an increase of the radiated power so that the energy content is slightly reduced.

5. Volume recombination

Fig. 5 shows the temporal evolution of the Balmer line $n = 8$. It increases already slightly before detachment transition due to the density ramp-up, but at the transition it is proportional to the pressure. This behaviour suggests that the pressure increase is caused by an enhanced recombination rate in the plasma volume. Fig. 6 shows the hydrogen spectrum in the detached state at 375 ms. The Balmer series up to $n = 12$ is distinctly pronounced. From the Balmer series the plasma parameters can be determined for the region from which the Balmer lines are emitted. The density can be estimated from the Stark broadening of the lines. From the Inglis–Teller relation we obtain about 1.5×10^{21} m^{-3}. Due to the bad resolution of the instrument this value is certainly to large. Calculated Stark widths for $n = 6, \ldots, 12$ can be found in [6]. The measured half width of the Balmer line $n = 8$ is 1.2 nm. The resolution of the spectrometer is 0.5 nm. Estimating the lower limit of the line width to 0.7 nm, we obtain a density of about 8×10^{20} m^{-3}. The temperature can be estimated from a Boltzmann plot and the decay of the continuum. We obtain temperature between 0.1 and 0.2 eV. For such low temperatures and high densities the three-body

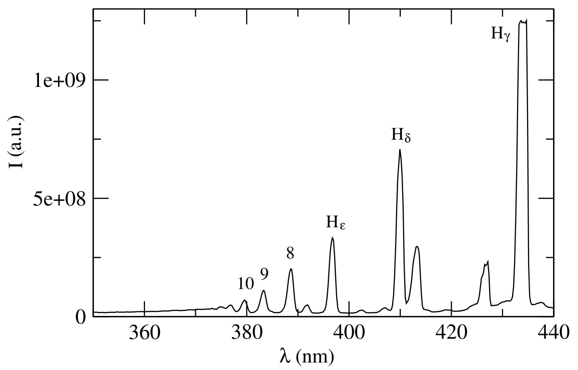

Fig. 6. Hydrogen spectrum sampled with the divertor spectrometer in the detached phase of discharge #54490 at 375 ms. The Balmer series up to $n = 12$ appears. Data is for the line-of-sight at $\Delta L = 22.4$ mm.

recombination exceeds the ionisation by orders of magnitude, i.e we have net recombination in the divertor volume.

The location of the recombination zones in the poloidal direction can be estimated from the CCD camera observing the upper target. Fig. 7 shows the profiles of the H_α and H_γ lines along the target tiles 5 and 13 in which the Langmuir probes are mounted (see Fig. 2). The data was sampled during a series of discharges like #54490. The profiles from the target tile 5 are clearly different indicating a change of the line ratio along the target tile 5. H_α has its maximum at the strike point as determined by the H_α profile from the attached shot #54454. H_γ peaks more inboard in the center of the recombination zone. Since H_γ for the upper target plate was not absolutely calibrated the line ratio for the outer part (including the strike line) was set to 80. Such a value is expected for an ionising plasma. At smaller radii it decreases by a factor of 3. We conclude that the region where H_γ peaks is recombining while the strike line itself and the region at larger radii is ionising. At target tile 13 the H_γ profile is much broader than at tile 5. H_α and H_γ peak in between the strike lines. Furthermore, the line ratio at the strike lines is about the same as in the recombing region at tile 5. All this together suggests, that at tile 13 the recombination zone is broader and that it comprises the strike line region.

These findings are in line with a characterization of detachment by the Langmuir probes for which the saturation currents at the strike line positions were used [2]. According to this detachment occurs at target tile 13 while the inner strike line at tile 5 remains attached. With the results obtained from the analysis of the line ratio we conclude that at tile 13 the plasma detachment is due to volume recombination. At tile 5, however, there is also a recombining region. In contrast to tile 13 it is small and well separated from the strike line region.

6. Summary and conclusion

We have shown that at the detachment transition a high density, low temperature plasma zone forms in the island divertor of W7-AS. Temperatures in the order of 0.2 eV and densities in the order of 8×10^{20} m^{-3} were estimated from the Balmer lines of hydrogen. Hence, the density is one order of magnitude above the separatrix density. The high-density zone corresponds roughly to the inner island (see Fig. 1). At target tile 5 this zone is smaller and separated from the strike line. At tile 13 it is

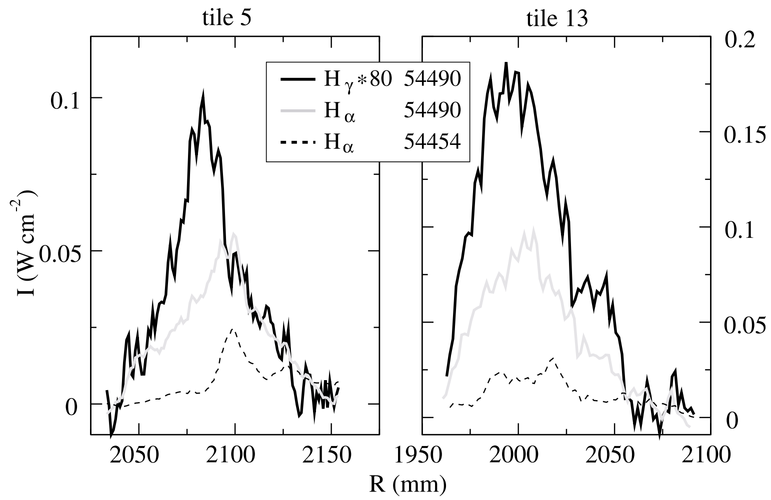

Fig. 7. Radial profiles of the H_α and H_γ (multiplied by a factor of 80) line from the upper divertor plasma. The left figure shows data from tile 5 and the right figure data from tile 13. Data from the attached shot #54454 is also shown for the determination of the strike points positions (see Fig. 2).

much larger and affects the strike line region. This correlates with the reduction of the particle flux to the target tile 13 as observed by the Langmuir probes. The formation of the recombination zone on top causes the up/down asymmetry of the pressure; the asymmetry can be used as a convenient indicator for detachment.

The existence of the high-density region in the divertor strongly suggests the action of a nonlinear process like a thermal instability, i.e. the plasma in a divertor island is unstable in a certain temperature range.

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