Optical Study of Divertor Detachment in W7-AS

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Abstract. The W7-AS stellerator was equipped with ten divertor modules to investigate the island divertor concept. First results of a new regime with good confinement properties and a detached divertor plasma were reported recently. In this paper we evaluate the hydrogen emission from the detached divertor plasma. Simultaneous 2D measurement of H_α and H_γ emission allows the evaluation of the regions with volume recombination and an estimation of the plasma temperature. Results are compared to the findings of thermography and Langmuir probes.

1. Introduction

The island divertor experiment in W7-AS has been put into operation recently. It is based on the intrinsic magnetic island configuration at $\iota = 5/9$. First attempts were made to study the divertor plasma over a wide range of densities. 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. In the following it will be called Improved High Density Confinement (IHDC).

Different diagnostics was applied to study the behaviour of the divertor plasma. CCD cameras were used to observe the divertor targets in the light of H_α and H_γ. The hydrogen emission will be used to characterize the divertor plasma for different conditions according to the electron temperature: $T_e > 5eV$ (attached), $T_e < 5eV$ (detached) and $T_e < 1.3eV$ (volume recombination).

The following Sec. 2 describes shortly the divertor geometry and the diagnostics used for the investigation of the plasma. In Sec. 3 the hydrogen emission for different plasma conditions is discussed. The typical change of the hydrogen emission is shown for the transition of an ionising to a recombining plasma is given. In Sec. 4 the attached divertor plasma of the normal confinement regime is characterized and in Sec. 5 the strongly detached state in the new IHDC regime is described. Finally, the results are summarized in Sec. 6.

2. Experimental

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 target plates and the baffles intersect the magnetic islands. Most of the divertor diagnostics is concentrated in one ellipical plane. Both oppositely arranged modules are equipped with flush-mounted Langmuir probes. The module at bottom is observed by a 2D infrared camera and different

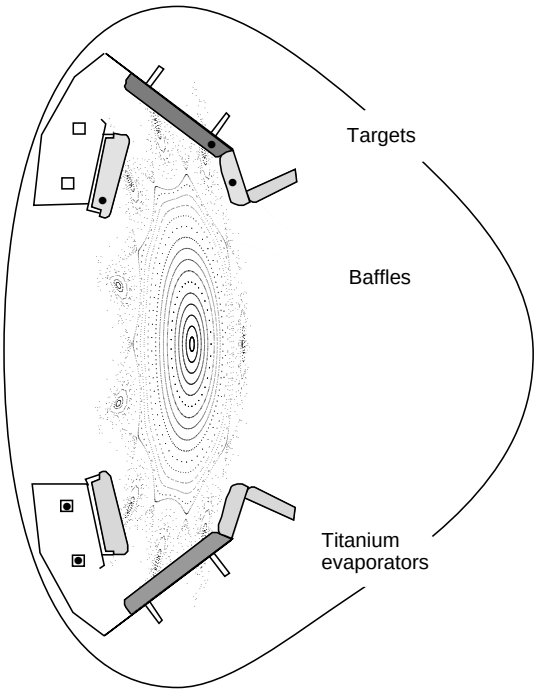

Figure 1. Elliptical plasma cross section with the vacuum magnetic field for $\iota = 5/9$ and the two divertor modules on top and at bottom.

2D CCD cameras operating in the visible spectral range. Two of the CCD cameras serve for observation of the hydrogen emission. They are equipped with interference filters for H_α and H_γ. The CCD cameras are absolutely calibrated by means of an integrating sphere.

Fig. 2 shows as an example an H_α photo of the lower target to make clear the observation geometry. It shows two strike lines corresponding to the intersected magnetic islands. The inner stripe splits sometimes into two closely neighboured lines. Target tile 12 is nearest to the plasma (watershed). Langmuir probe arrays are located in target tiles 5 and 13. In Fig. 2 two regions are defined; region 'D' means detached and region 'A' means attached. Region D detaches rather uniformly while in region A the strike lines remain attached.

3. Evaluation of the Hydrogen Emission

3.1. Calculated hydrogen emission

For ionising plasma conditions the H_α emission in front of a confining wall can be interpreted in terms of a hydrogen atom influx from this surface. A hydrogen plasma is ionising when the electron temperature exceeds 2eV. Then recombination rates are small compared to ionisation rates, i.e. there is net ionisation. In such a plasma the hydrogen influx is given by the simple relation

$$\Gamma = S/XB \cdot I$$

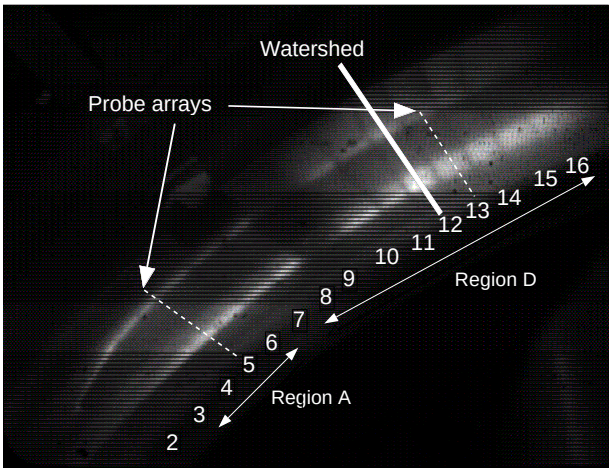

Figure 2. View of the divertor target at bottom in the light H_α. Target tiles are numerated. Tile 12 is closest to the plasma (watershed). There are two strike line corresponding to the intersected magnetic islands. Regions 'A' and 'D' behave differently in the detachment process.

where I is the H_α intensity (irradiance in Wcm^{-2}), and S/XB is the atomic physics factor. S is the ionization rate, and X is the excitation rate. B takes the branching of the transition into account. In general, the dependence of this factor on the plasma parameters must be considered. Fig. 3 shows S/XB for H_α over T_e calculated using the ADAS programme package. The parameter is the electron density. For T_e above 10 eV S/XB is nearly constant. Above a density of $2 * 10^{19} m^{-3}$ it depends almost linearly on electron density. Only when the plasma density is below $1 * 10^{19} m^{-3}$ and the temperature exceeds 10eV, a constant factor of 10 can be used. Otherwise the variation of S/XB must be taken into account.

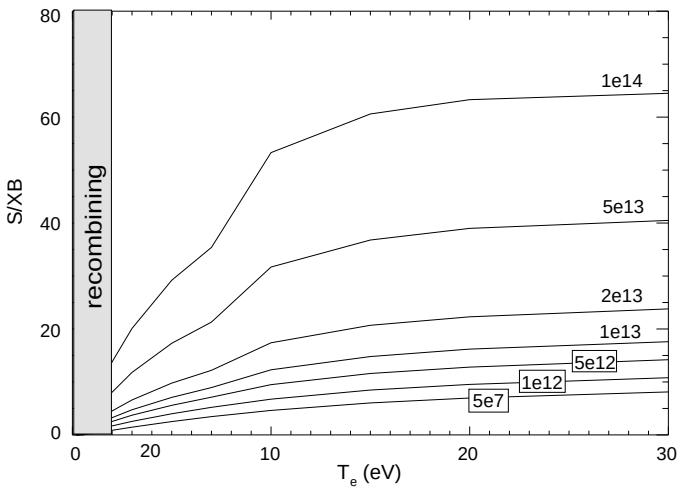

Figure 3. Atomic physics factor S/XB for H_α in dependence on electron temperature. Parameter is the electron density. Below 2 eV the plasma is recombining and the factor cannot be applied to obtain the atomic influx.

Fig. 3 shows that below 10 eV S/XB decreases monotonically. At constant hydrogen influx, a decrease of the temperature in the divertor plasma below 10 eV would result into an increase of the H_α emission (temperature effect). There is, however, still another process connected with an increase in the H_α emission. When the temperature sinks below 2 eV the plasma is no longer ionising. Now recombination rates become comparable to ionisation rates; even net recombination may occur. This transition is accompanied by a sudden increase of the intensities of the hydrogen Balmer lines (recombination effect). Both effects can be separated when the ratio of two Balmer lines is monitored. Fig. 4 shows the line ratio H_α/H_γ as a function of the electron temperature for $n_e = n_i = 4 \cdot 10^{19} m^{-3}$. It was evaluated using the Johnson-Hinnov model. This ratio takes on two characteristic values: in an ionising 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.

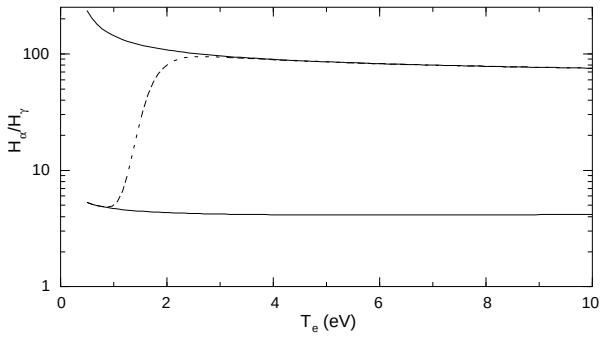

Figure 4. Line ratio H_α to H_γ as a function of the electron temperature (dashed line). It was calculated for $n_e = n_i = 4 \cdot 10^{19} m^{-3}$ using the collisional-radiative model from Johnson and Hinnov. Line ratios are also shown for the cases recombination and ionisation alone (solid lines). The transition from net ionisation to net recombination occurs between 1 and 2 eV.

3.2. H_α emission during the transition from an ionising to a recombining plasma

In the following we consider the local hydrogen emission during density ramp-up and compare it to the plasma parameters at this point. Fig. 5 shows the emission of H_α and H_γ at the position of probe #5 in the target tile 5 of a divertor module at bottom. The plasma parameters obtained from the probe (n_e, T_e and I_{sat}) are also shown. In the first phase of the discharge (up to 0.5 s) the H_α emission is proportional to the ion saturation current I_{sat}. The electron density is about $4 \cdot 10^{18} m^{-3}$ and the temperature about 15 eV. Note, that probe 5 is located between the strike zones. Plasma parameters are therefore considerably lower than in the strike point region. Since the plasma is ionising, the H_α emission current is proportional to the neutral influx.

After 0.45 s the saturation current decreases (detachment). Initially the H_α emission follows but after 0.5 s it even slightly increases while the current continues to decrease. During this phase the H_γ emission increases and the line ratio H_α/H_γ changes from 85 to 20. The H_α or H_γ emission cannot simply interpreted in terms of a

particle influx since the temperature of the divertor plasma is below 10 eV. Now either a temperature dependent factor S/XB has to be applied, or the flux approximation is even invalid since the plasma is recombining. The probe shows only a slight reduction of T_e to 10eV in contradiction to the drastic change of the line ratio. We conclude that temperature measurement by the Langmuir probe saturates at $T_e = 10eV$. The change of the line ratio indicates volume recombination and thus T_e below 2 eV.

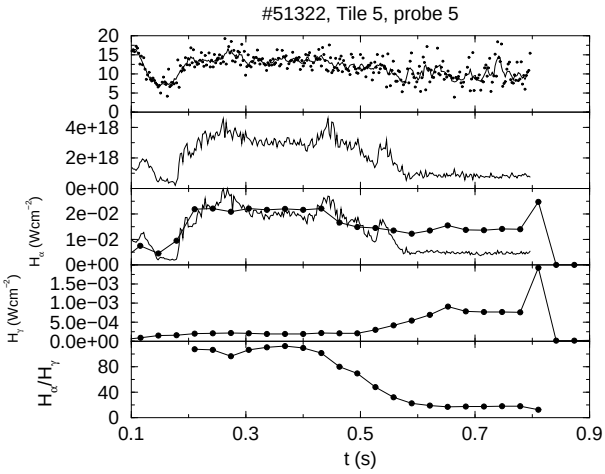

Figure 5. Local hydrogen emission and plasma parameters in the divertor during density ramp-up. Data are taken from discharge #51322 for probe 5 in tile 5 at bottom. The following traces are shown: (a) electron temperature, (b) electron density, (c) ion saturation current and H_α emission, (d) H_γ emission and (e) line ratio H_α to H_γ. The line ratio shows that up to 0.5 s the divertor plasma (at this local position) is ionising and from 0.6 s it is recombining.

Note, that the decrease of the line ratio from a value of 85 to 20 cannot simply used to estimate T_E as suggested by inspection of Fig. 4. The line-of-sight passes possibly an ionising zone located in front of the recombining plasma. A decrease of the line ratio can therefore also be interpreted as an increase of the length of the recombining region. To decide this question another geometry of the line-of-sight is necessary so that it passes the recombination zone alone.

4. Normal Confinement: Attached Divertor Plasma

Normal confinement is characterized by a relatively low edge density. The separatrix density scales like $n_{es} \propto n_e^{0.45}$. Due to this detached divertor plasmas cannot be obtained; plasma remains attached (high electron density and temperature). Consider an ECRH discharge (#51295) in which the line-averaged-density ramps over $0.15 - 1.1 \cdot 10^{20} m^{-3}$. Working gas is hydrogen, toroidal magnetic field $B_t = 2.5T$, ECRH power $P_{ecrh} = 1MW$. For separatrix densities above $1 \cdot 10^{19} m^{-3}$ the particle flux (and thus the H_α emission) in the divertor saturates.

We consider the divertor plasma in the saturated phase. Fig. 6 shows the spatial profiles of the H_α and H_γ emission for target tile 5 at bottom. The line ratio H_α to H_γ is also shown. It is about 100 in the range of the divertor target. We conclude that the whole divertor plasma is ionising and H_α can be interpreted in terms of a

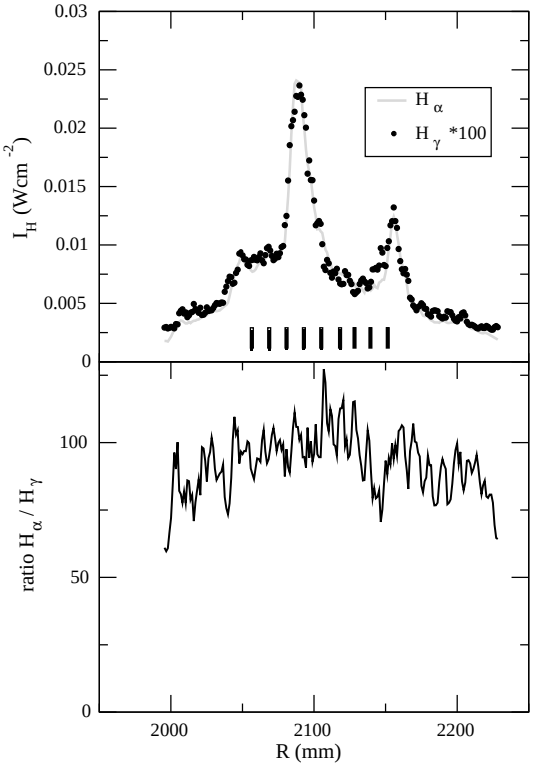

Figure 6. Spatial profile of the Hydrogen emission (H_α and H_γ, on top) and the line ratio H_α to H_γ. The plasma is attached (#51295, t=0.5 s). Data is given for target tile 5. The position of the probes in this tile is indicated. The whole plasma above the target tile is ionising.

particle influx.

Fig. 7 shows profiles of the plasma parameters at the location of tile 5. Electron density and temperature was measured by Langmuir probes. The particle flux was calculated from H_α. The variation of S/XB along the profile according to the measured density and temperature was taken into account. Finally, the power deposition was obtained from IR thermography. The particle fluxes and the power depositon profiles are asymmetric. Main interaction occurs at the inner strike line. Peak electron density is about $1 \cdot 10^{19} m^{-3}$, i.e. it is approximately equal to the separatrix density. There is no flux amplication as observed in a tokamak divertor. Peak temperatures are about 55 eV. Power deposition is given by

$$P = \delta \cdot \Gamma \cdot T_e$$

where δ is the sheath transmission factor. With $\delta = 8$ and a maximum particle flux of $\Gamma = 2 \cdot 10^{18} cm^{-2} s^{-1}$ we obtain a power flux of $1.4 MW m^{-2}$ which is in good agreement with the measured value (see Fig. 7).

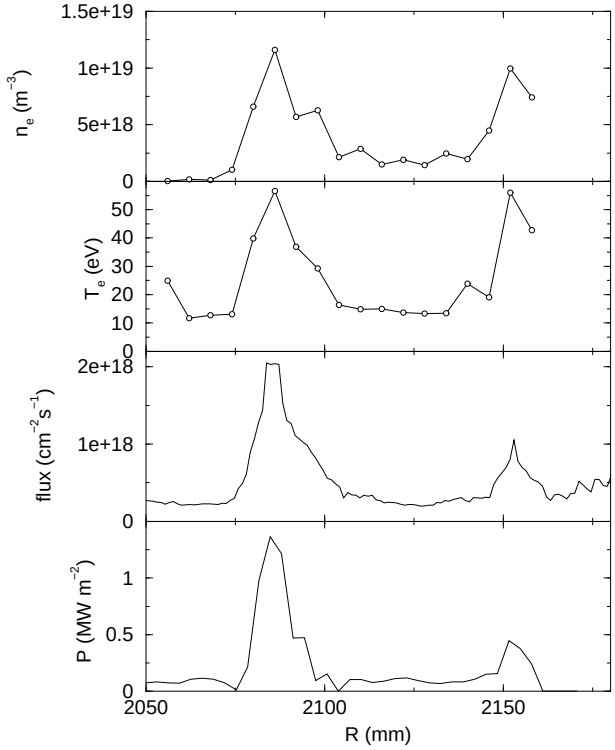

Figure 7. Divertor strike points in shot #51295: Density and temperature (Langmuir probes), particle flux (H_α) and power deposition (IR thermography). Data is shown for target tile 5.

5. Improved High Density Confinement: Detached Divertor Plasma

In the following section we study the case of strong divertor detachment. Strong detachment was obtained in the new IHDC regime. In this regime the energy confinement increases with density and flattens at very high densities. Line-averaged-densities up to $n_e = 3 \cdot 10^{20} m^{-3}$ were obtained. It is further characterized by broader density profiles leading to higher separatrix densities compared to the normal confinement regime. At the highest separatrix densities the divertor plasma is driven into the state of volume recombination. The recombination and temperature effect do not allow the interpretation of the hydrogen emission in terms of a flux. Instead the recombining region can be identified and the temperature can be estimated.

Consider a discharge (#51322) which is first established under attached divertor plasma conditions and driven by gas puffing in a strongly detached state. The magnetic configuration is the same as for discharge #51295 discussed in the previous section. For this state Fig. 8 shows the hydrogen emission H_α and H_γ) along the target tiles 5 and 13, respectively. The positions of the Langmuir probes are indicated by the small boxes. Since the probes cover almost the whole tile the boxes show it's approximate length. The line ratio H_α to H_γ which is also shown in Fig. 8, changes along the radius. This is different to the high density case with normal confinement. A high line ratio indicates the ionising plasma zone while a low value is characteristic for the

recombining plasma region.

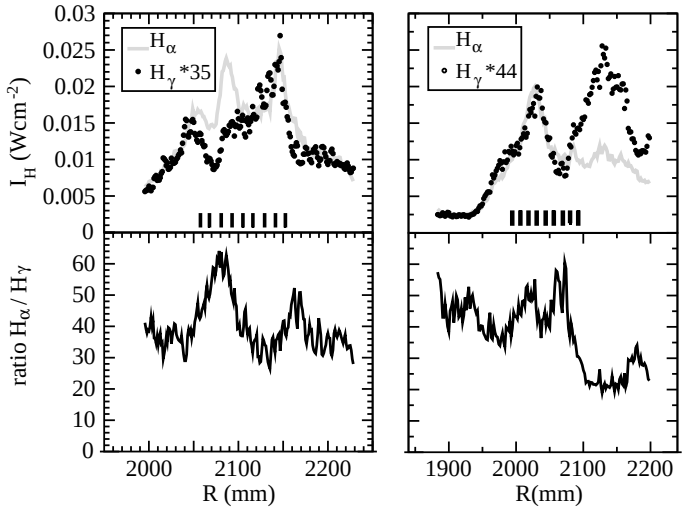

Figure 8. Spatial profile of the hydrogen emission (H_α and H_γ) and the line ratio. The plasma is strongly detached (#51322, t=0.716 s). Data is given for target tile 5 (at left) and 13 (at right). The positions of the probes in these tiles are indicated. The whole plasma above tile 13 is ionising while a region outside is recombining. At tile 5 the recombining region is located between the strike lines.

At both tile positions, there are recombining regions. However, they are located at different positions in respect to the target plate. Above target tile 5 there are two maxima of the line ratio corresponding to the location of the strike point. The line ratio reaches 60 and 50, respectively. Inbetween the strike lines the ratio decreases down to 30. We interprete this range as a recombining one while the strike lines seems to be ionising.

At target tile 13 the line ratio is about 50 over the whole target. Outside the target strong H_γ emission is observed leading to a ratio as low as 20. The target plasma over the whole tile 13 is ionising while the recombining region is located outside the divertor target.

Fig. 9 shows the power deposition in the detached state as measured by the IR-thermography. The power deposition is significantly reduced all over the target. Only at tile 5 (and 4-1) there is still a substantial power deposition. At the other tiles the power deposition is near the detection limit of the system. Fig. 9 shows also schematically the location of the recombination zone. Consider now target tile 13. The plasma over the whole target is ionising, i.e. the temperature is above 2 eV. On the other hand, the plasma is detached as indicated by the reduced power deposition,i.e. the temperature may be well below 10 eV (at this value the Langmuir probes saturate, see Sec. 3.2).

Since the plasma over the whole target tile 13 is ionising, in principle the neutral flux can be derived from the H_α signal. For electron temperatures below 15 eV there is, however, a strong dependence of S/XB on temperature (see Fig. 3). From a comparison of the particle flux obtained by the Langmuir probe and the H_α signal we may obtain an estimation of the electron temperature. Consider probe 4 of target tile 13 at which the maximum of the hydrogen emission is observed (see Fig. 8).

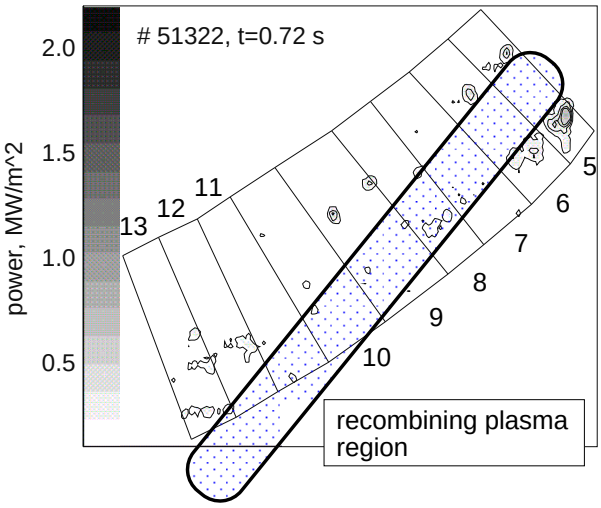

Figure 9. Thermal load of the divertor target at 0.72 s in discharge #51322 measured by the infrared camera. The location of the recombination zone is shown schematically. Outside this zone the plasma is ionising.

Fig. 10 shows the traces of H_α emission at the probe position and the ion saturation current scaled to H_α. The electron temperature obtained by the probe is also shown. It decreases continuously due to the density ramp-up. Up to 0.45 s the saturation current and the H_α emission are proportional to each other because S/XB does not depend on temperature above 15eV. Now the density is about $1 * 10^{19} m^{-3}$. After this time H_α deviates since temperature falls below 15 eV. Note that the temperature from Langmuir saturates again at 10 eV. The difference between saturation current and H_α reaches a factor of 7.5 at 0.7 s. From Fig. 3 we get S/XB(15eV)= 15. Then we would need S/XB=2 at 0.7 s to explain the discrepancy by the temperature effect. This value of S/XB corresponds to a temperature of 2 eV.

6. Summary

We have characterized the divertor plasma for two regimes with the same magnetic configuration: (a) normal confinement (attached plasma) and (b) improved high-density confinement (detached plasma). We observe two strike lines corresponding to the intersected islands. For the attached plasma typical maximum values of the inner strike line, which carries most of particles and energy, are: $T_e = 55\,eV$, $\Gamma = 2 \cdot 10^{18} cm^{-2} s^{-1}$ and $P = 1.4\,MW m^{-2}$. These values are compatible when assuming a reasonable value of 8 for the sheath transmission factor.

In the detached plasma the power flux is strongly reduced since the temperature and the particle flux is much lower compared to the attached case. Temperature in the strike line is estimated to about 2 eV. Since Langmuir probes saturate at 10 eV we used two spectroscopic techniques to obtain this result (line ratio H_α to H_γ and the temperature dependence of S/XB of H_α). Reduction of the particle flux is detected by the probes.

Moreover, in the the strongly detached state we observe a region in which net recombination occurs in the plasma volume. For net recombination T_e must be below

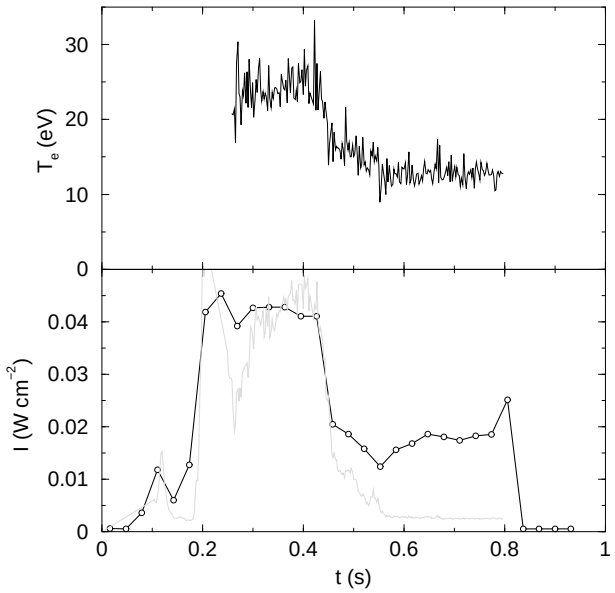

Figure 10. Traces of T_e (on top) and H_α and saturation current (at bottom) for probe 4 in target tile 13. Due to the density ramp-up the temperature decreases. Up to 0.45 s the H_α emission and the saturation current of the probe are proportional to the particle flux. After 0.45 s the temperature decreases below 15 eV and S/XB depends now on temperature. Since probe temperatures saturate at 10eV this effect will be used to estimate the temperature.

1.3 eV. However, this zone does not follow the strike lines at the target plate.