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Volume recombination and detachment during H-mode discharges in ASDEX Upgrade and JET

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Introduction Detachment of the divertor plasma will be one of the key methods by which the target plate heat and particle fluxes in a future reactor will be reduced [1]. Recent studies have shown that volume recombination is the driving mechanism for plasma detachment [2,3,4,5]. However, this regime has to be obtained under reactor relevant conditions such as during ELMy H-modes with acceptable core plasma confinement. In the first part of this paper, we present new highly time resolved spectroscopic and probe measurements during high density ELMy H-modes in ASDEX Upgrade which allow us to characterize the volume recombination between and during ELM events. Approaching the density limit strong volume recombination is observed in both inner and outer strike points between (but not during) ELM events. It appears that strong detachment can be sustained before reaching the density limit. The comparison of these results with similar ELMy H-modes in JET shows different behaviour in that detachment is only achieved at the inner strike point between ELMs but not at the outer indicating a larger in-out asymmetry. Possible explanations for the different behaviour are proposed.

Diagnostic and measurements In the ASDEX Upgrade divertor arrays of lines of sight viewing poloidally across the strike point are available (Fig.1). In the outer divertor, there are two systems in two different toroidal positions, while only one is present in the inner divertor.

The lines of sight are coupled via optical fibers to two photomultiplier systems with interference filters, permitting the measurement of the D_α and D_γ radiation with a time resolution of 100 μs. Initially the D_α and D_γ radiation were measured only in the outer divertor using the two similar system. A beam splitter was later used for simultaneous emission measurements in both the outer and the inner divertor. At low density and high temperature the atomic levels 3 and 5 of deuterium are populated by excitation. At lower temperature and higher density the n = 5 level starts to be populated by recombination. Therefore the ratio of the $5 \rightarrow 2$ (D_γ) and $3 \rightarrow 2$ (D_α) line emissivities can be used as a recombination indicator.

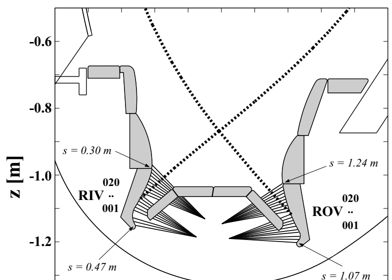

Figure 1: *Poloidal section of the ASDEX Upgrade divertor with the spectroscopic lines of sight.*

The first discharge analysed (# 12195) is an H-mode NBI heated density ramp CD_4 fuelled (Fig.2). The main plasma parameters are: I_p = 1 MA, q_{95} = 4.2, P_{NBI} = 5 MW. The density ramp starts at 1.5 s with n/n_{GW} = 0.4 (density normalized to the Greenwald density). At this time the measured photon ratio D_γ/D_α is about constant at 0.02-0.03. The density measured from the Langmuir probes is $1\text{-}3 \cdot 10^{19}$ m^{-3}. At this density the expected D_γ/D_α photon ratio for excitation only is 0.010-0.015. Presumably due to the inte-

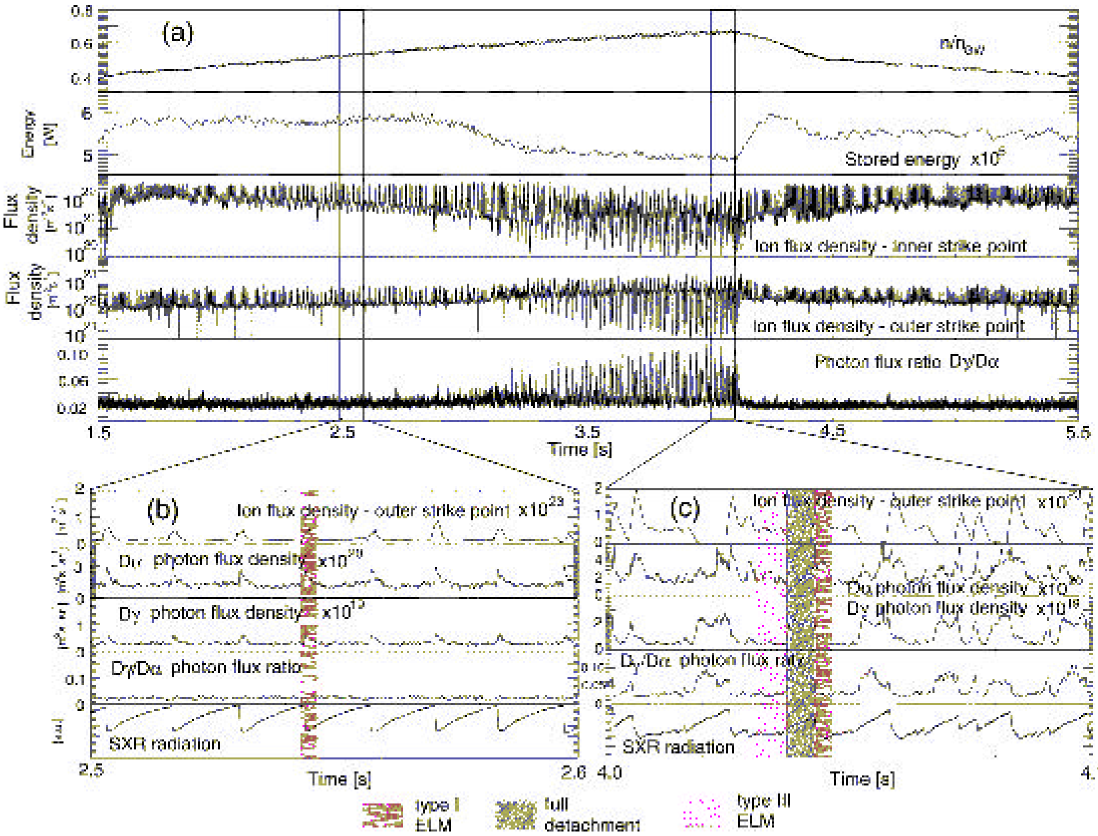

Figure 2: *Time traces of n/n$_{GW}$, stored energy, ion flux at the inner and outer strike point (SP) and photon ratio D$_\alpha$/D$_\gamma$. In (b) and (c) are the zoomed only for the outer divertor: ion flux at the SP, D$_\alpha$ and D$_\gamma$ photon fluxes, their ratio D$_\gamma$/D$_\alpha$ and SXR radiation.*

gration of the signal across the separatrix, a fraction of the radiation originates from the colder region where a contribution from recombination is present. At 3.1 s (n/n$_{GW}$ $= 0.55$) volume recombination and detachment begin as indicated by the drop in the ion flux minima and by the increase to 0.1 of the maxima in the photon ratio D$_\gamma$/D$_\alpha$. The average power density on the target calculated by thermography drops from 1.3 MW/m^2 before recombination to 0.6 MW m^{-2} during recombination, increasing again after to 1.5 MW m^{-2}. During the detached phase the peak power density drops from the initial 10 MW m^{-2} to 5 MW m^{-2}. At the beginning of the recombining phase the plasma energy contents decreases, together with the appearance of type III ELMs. After the gas puff stops (4.1 s) the plasma reattaches and conditions similar to before detachment are reached again.

As an ELM indicator which is unaffected by the divertor conditions, soft x-ray (SXR) emission from the plasma edge is used. The SXR intensity increases between ELMs, dropping strongly during type I ELMs and weakly for type III ELMs. During the initial phase there are only type I ELMs (Fig.2b). Later during the discharge, full detachment and strong recombination are evident between ELMs (Fig2c). The occurrence of type I ELMs causes the reattachment of the plasma and subsequently the plasma stays attached as long as type III ELMs are present, detaching again between ELMs. It is interesting to note that during the low density phases the maxima in the emission for D$_\alpha$ and D$_\gamma$ are synchronous with the ELMs, as seen from the strong SXR radiation drop, and with the ion flux peaks at the target (Fig.2b) while in the high density phase of the discharge the maxima in the $D\gamma$ radiation are anticorrelated with ion flux (Fig.2c). During detachment the drop in the ion flux is explained by means of a recombination sink. Fig.3

shows the three different time intervals during the discharge: at low density before recombinatin set in (a), at medium density during weak recombination (b) and at high density during strong recombination (c).

In the first phase the ion flux and the D_γ are correlated indicating that the D_γ radiation is mainly due to excitation. In the second phase both periods of correlation (excitation radiation) and anticorrelation (recombination radiation) between the ion flux and D_γ are observed.

In the third phase most of the D_γ radiation is due to recombination. To calculate the recombination flux, we can utilise the effective recombination events per photon [6](calculated as 50 for $n_e = 2{\cdot}10^{20}\,\mathrm{m}^{-3}$, $T_e = 0.8$ eV). During full detachment the recombination sink gives rise to most of the ion flux drop, as shown in Fig.3c. It seems that momentum loss through ion-neutral collisions does not play a strong role in the obtained divertor detachment. Similar qualitative results for recombination are obtained for the other discharges analysed, but due to impurity redeposition on the optical elements inside the vessel the interpretation of the spectroscopic measurement is more difficult .

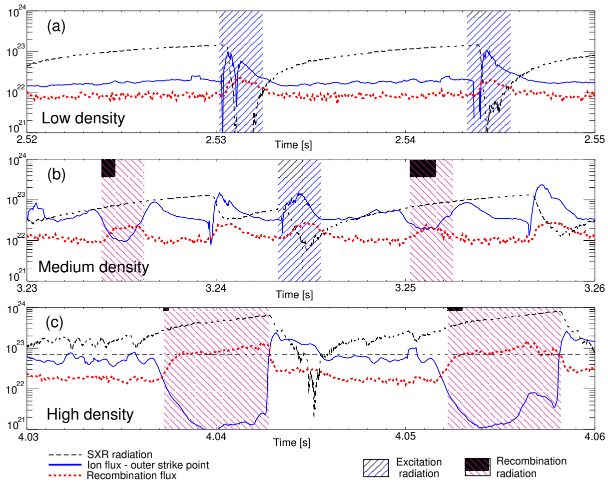

Figure 3: *SXR radiation, ion flux and recombination events (D_γ photon flux times 50) at the outer divertor. (a) low density (b) medium density (c) high density.*

Comparison between ASDEX Upgrade and JET In order to improve our understanding of the relationship between detachment and the behaviour of ELMy H-mode discharges, we have attempted the first direct comparison between ASDEX Upgrade and JET results.

While the arrays of target Langmuir probes between the two experiments are similar, the routine spectroscopic measurements of the $D\gamma/D\alpha$ ratio are in JET at a relatively slow time resolution compared to ASDEX Upgrade (AUG) and are integrated over the inner and outer strike zones. We have therefore concentrated upon the comparison of probe measurements of the ion fluxes which indicate the onset of detachment. We have compared two series of ELMy H-mode discharges which have very similar upper triangularity

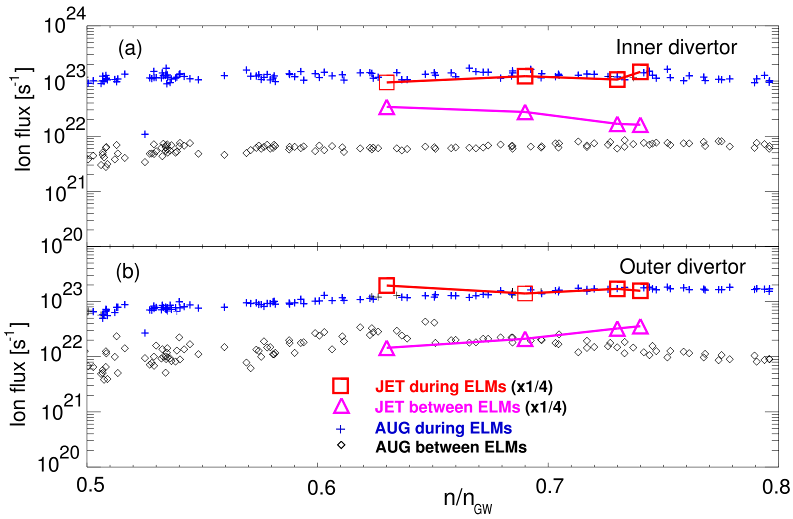

Figure 4: *Ion fluxes during and between ELMs in the inner (a) and in the outer (b) divertor as funtion of the density normalized to Greenwald (n/n_{GW}) for ASDEX Upgrade and stationary JET discharges.*

of 0.27 (JET) and 0.26 (AUG) but different lower triangularity of 0.24 (JET) and 0.04 (AUG). Fig.4 shows the inner and outer ion fluxes both during and between ELMs for both experiments as a function of the fraction of the Greenwald density. In both experiments the NBI heating power was chosen to be a similar factor above the H-L transition threshold, being 12 MW in JET and 5 MW in ASDEX Upgrade. The triangularity of the JET case is slightly higher with an average of 0.25 compared to 0.15 in ASDEX Upgrade. In the case of the ASDEX Upgrade experiments the density scan is carried out in one discharge while for JET stationary discharges were done, resulting in one measured point per discharge. One should note that normalisation factors have been applied to Fig.4 in order to compare the two datasets with a factor of 1/4 applied to the JET dataset. One can clearly see from Fig.4 that in the inner divertor the ratio of fluxes between and during ELMs is much higher in ASDEX Upgrade which corresponds to an early onset of detachment. This is confirmed by electron temperature measurements which show at 0.63 n/n_{GW} at the inner divertor $\sim$5 eV (AUG) and $\sim$10 eV (JET) while for the outer divertor $\sim$8 eV (AUG) and $\sim$23 eV (JET). In both experiments, the ELMs are seen to "burn through" the detachment at both divertors. It is also evident from Fig.4 that the outer divertor of JET does not show any sign of detachment up to $n/n_{GW} >$ 0.75 of Greenwald where the density begins to saturate. In contrast, outer divertor detachment occurs in ASDEX Upgrade at $n/n_{GW} >$ 0.65.

Discussion and conclusion Novel highly time resolved measurements of recombination in ASDEX Upgrade have confirmed that detachment is associated with volume recombination. Approaching $n/n_{GW} = 0.55$ the outer divertor detached between ELMs. However, the type I ELMs were seen to burn through the recombining region even when the plasma is completely detached. The type III ELMs which are often observed following a type I ELM are seen to keep to plasma attached. Recovery of full detachment is only seen after the type III ELMs cease and the plasma reverts to an ELM-free phase. The analysis of the recombination sink using simple estimates shows that the drop in ion flux to the divertor can be accounted for completely.

Initial comparison of ELMy H-mode experiments in JET and AUG shows that at similar n/n_{GW} the JET divertor is both less detached and more asymmetric than in AUG. In JET partial detachment is seen at the inner divertor with no signs of detachment at the outer divertor up to n/n_{GW}=0.75. In contrast, detachment is observed at both the inner and outer divertor of AUG and can be sustained before the density limit. These results are consistent with the observation that the radiation losses at the outer divertor of AUG are enhanced with respect to JET and were speculated to be associated with higher density at the outer divertor of AUG [7]. While further detailed studies are required, it nevertheless appears that the detachment behaviour in the two experiments is markedly different and may challenge analytical theory [8] which relates detachment to the density limit.

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