*36th EPS Conference on Plasma Phys. Sofia, June 29 - July 3, 2009 ECA Vol.**33E**, P-1.156 (2009)*

SOL and divertor investigations in Nitrogen seeded discharges

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Introduction

During the recent years all plasma facing components in ASDEX Upgrade originally made from carbon were covered by tungsten. After the first boronisation the intrinsic radiation dropped and the power loads to the divertor could exceed power limits for carbon tiles with thick tungsten coating [1]. Therefore, operation with high heating power required additional radiative cooling. This is achieved by feedback-controlled nitrogen (N_2) seeding [2]. N_2 seeding did not only result in an acceptable electron temperature T_e level in the divertor but the H-mode discharges also showed an improved energy confinement [3]. While the influence of the N_2 seeding on the radiation is discussed in [4] and changes of the core transport are shown in [5] this paper focusses on the effect on ELMs, the divertor plasma and transport to the first wall at the outer midplane.

Discharges and global behaviour

The investigations were performed in H-mode discharges with a plasma current $I_P = 1\,\mathrm{MA}$, magnetic field $B_t = -2.5\,\mathrm{T}$, a D gas puff of $\Phi_D = 5.8\times10^{21}\,\mathrm{s}^{-1}$ or $\Phi_D = 9.5\times10^{21}\,\mathrm{s}^{-1}$ resulting in a line averaged density of $\bar{n}_e \approx 8\times10^{19}\,\mathrm{m}^{-3}$. Only for the higher gas puff rate together with N_2 seeding the density reaches $\bar{n}_e \approx 9.5\times10^{19}\,\mathrm{m}^{-3}$. The N_2 injection was in the range of $0.5-2\times10^{21}\,\mathrm{s}^{-1}$ to keep the temperature in the divertor in all discharges at a nominal value of $3\,\mathrm{eV}$ [2]. The N concentration (low % range) in the plasma might vary from shot to shot. The discharges with low Φ_D had $P_{NBI} = 7.5\,\mathrm{MW}$ NBI heating the ones with high Φ_D had $P_{NBI} = 5.0\,\mathrm{MW}$, $1.5\,\mathrm{MW}$ ECRH were always applied. Figure 1 shows the global behaviour of the discharges. Multiple occurence of shot numbers in the figure correspond to different time intervals in the discharge. Seeded discharges show a higher total radiation P_{rad}, about 15 % increase for seeding in the main chamber, 40 % when the seeding is done in the private flux region (PFR). The best results concerning reduction of power load to the divertor and confinement are achieved when the N_2 is injected in the PFR. The improved confinement is shown in the bottom part of figure 1. The stored energy

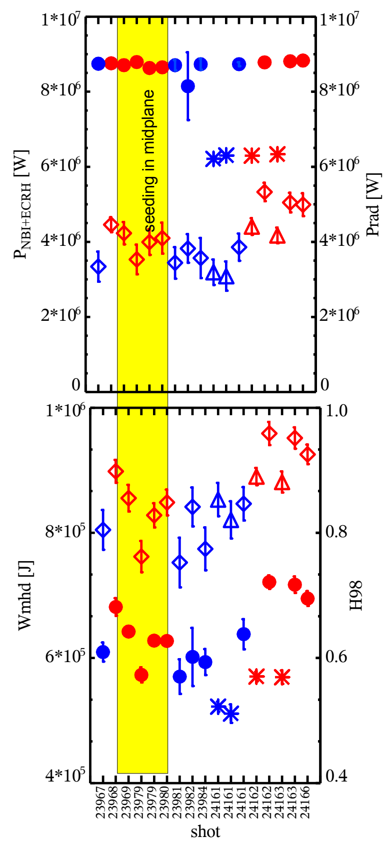

Figure 1: *Top: Heating power (circles and stars), radiated power (diamonds and triangles), bottom: energy content (circles and stars) and H-factor 98Py2 (diamonds and triangles). Stars and triangles correspond to discharges with $P_{NBI} = 5\,MW$, circles and diamonds to $P_{NBI} = 7.5\,MW$. Red indicates seeded, blue unseeded discharges.*

rises by 5% only for N_2 seeding from in the main chamber while PFR seeding causes a rise of 10%. The H-factor rises by 5 – 10% with the tendency of a larger increase with higher heating power. The increased stored energy is related to a rise in the pedestal pressure. Noticeable is the first investigated period of # 23979, although with N_2 seeding it shows the same confinement like comparable unseeded discharges. This is related to a low P_{rad} which is in the same range as for unseeded discharges. Obviously there is a direct relation of P_{rad} and the confinement improvement. For the applied gas fluxes there is the general trend for the seeded discharges that the H-factor increases with P_{rad}. The reason for the reduced P_{rad} during one period of # 23979 is not yet resolved. So far only a moderate memory effect due to N_2 seeding was seen which is not of importance for the discharge performance (see figure 1,3).

ELM activity

The ELMs are detected by the W influx into the divertor plasma [6]. This signal is mainly related to the temperature increase in the divertor during ELMs. The ELM duration determined from this signal corresponds very well to the time periods while filaments related to the ELM activity occur at the Langmuir tips of the filament probe [7] which is located in the outer midplane. The filaments are seen as strong peaks in the saturation current I_{sat} (see figure 2). N_2 seeding causes, independent of the seeding location, an increase in the ELM frequency f_{ELM} by 20 – 50% (see figure 3). The ELM duration in the divertor is strongly reduced from 3 to 2 ms when the N_2 is injected into the PFR. There is only a small reduction of the ELM duration ($\sim$ 10%) visible for N_2 seeding in the outer midplane. In discharge sequence # 23967-# 23984 the energy loss per ELM ΔW_{ELM} is clearly reduced when seeding N_2. For the sequence # 24161 - # 24166 ΔW_{ELM} is about independent of seeding. But the rise in W_{mhd} due to seeding was most pronounced in this discharge series (higher W_{mhd} tends to higher ΔW_{ELM}) and the losses in the unseeded discharge were already low. It is unlikely that the low energy loss per ELM in the unseeded discharges is due to a memory effect from the seeding in the previous discharge, because this is not seen for # 23981. There is the tendency that ΔW_{ELM} is larger when seeding in the midplane than for PFR seeded cases.

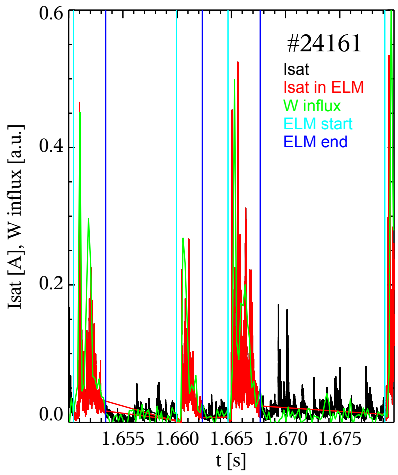

Figure 2: *ELM filaments in I_{sat} at the outer midplane compared to the W influx in the divertor. The cyan and blue bars indicate ELM start and end times as determined from the W influx.*

Divertor plasma

Figure 4 shows the time traces for the ion saturation current I_{sat}, the floating potential V_{fl}, n_e and T_e in the divertor measured by flush mounted Langmuir probes [8] in triple configuration after conditional averaging. The probe was located in about 2.5 cm distance outside the separatrix along the target tiles (corresponds to 6 mm in outer midplane). In red and green unseeded discharges are shown, in blue a discharge with seeding in the PFR and in cyan an example for seeding in the main chamber. I_{sat} during the ELM does not differ much when going from unseeded to seeded discharges despite the fact that the ELM event is much shorter when N_2 was injected into the PFR. In all cases there is a second maximum in I_{sat} about $4-5$ ms after the ELM peak. This I_{sat} rise is related to a density peak as observed before [9]. This density increase is reduced with N. The ELM related peak in V_{fl} is substantially smaller with seeding, especially when the injection was made into the PFR. This can be due to a reduced peak temperature or due to a broader profile. Seeding in the PFR also leads to a clear reduction of the T_e peak (from ~ 40 to ~ 30 eV), while seeding in the main chamber does not significantly influence the peak temperature, but the temporal width of the T_e peak is narrower. Just before the ELM rise the behaviour long time after an ELM can be seen. Without seeding there is a low density, high temperature ($T_e = 15-20$ eV) divertor plasma in front of the probe, while N_2 seeding keeps $T_e \approx 7$ eV at densities which are about a factor of two higher than without seeding. This power flux reduction in between ELMs was the original goal of the N_2 seeding and is independent of the seeding location.

Filaments and fluctuations in the SOL

Langmuir probes just in front of the outer limiter were used to investigate the ion saturation current I_{sat}. This quantity gives a hint on the radial transport in the SOL to the first wall. Figure 5 shows the average I_{sat} for 3 Langmuir tips in unseeded and seeded discharges with $P_{NBI} = 5$ MW, seeding in the PFR. In ELMs and in between ELMs there is a strong reduction of I_{sat} by $30-50$ % . Remarkable is that # 24161a has a rather high f_{ELM} between a typical f_{ELM} of seeded and unseeded discharges, but shows about the same I_{sat} distribution function as the later period with lower f_{ELM}. Therefore we conclude that the reduction of I_{sat} in front of the limiter is not only related to the f_{ELM} increase with seeding. Looking into the probability distribution function (PDF) of I_{sat} for an individual probe tip shown on the left in figure 6 it is obvious that in unseeded discharges there are more large events although similar I_{sat} peak values can still occur in seeded discharges. This is of importance since they are related to big filaments carrying a rather high energy which might be able to harm the first wall in future fusion devices. This higher fraction of large events can also be seen in inter ELM and ELM intervals (figure 6, right hand side) while as expected the probability of large events rises during ELM activity. As for the divertor measurements a reduced ELM duration is seen with seeding reducing the number of big filaments per ELM. In inter ELM periods even moderate large filaments might vanish completely with seeding (cyan curve). Normalizing $I_{sat} - \mathrm{mean}(I_{sat})$ with the standard deviation all discharges show

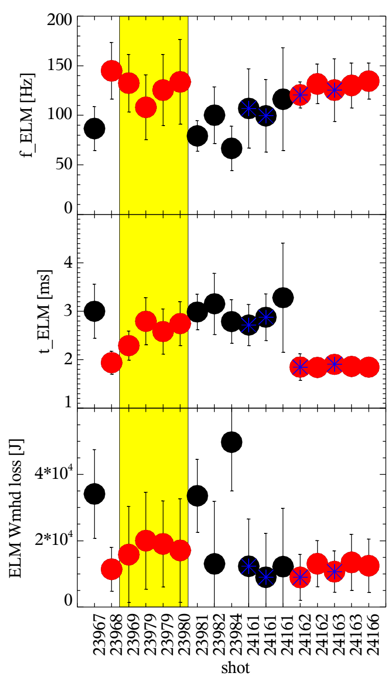

Figure 3: *From top to bottom: ELM frequency, ELM duration, energy loss per ELM for the discharges in figure 1. Red corresponds to seeded, black to unseeded cases. Blue stars mark $P_{NBI} = 5$ MW. The yellow background indicates seeding in the midplane.*

the same distribution. From this observation it can be concluded that the transport mechanism stays unchanged. N_2 injection just reduces the strength of the transport not the mechanism. In black the Gaussian distribution function is shown. The comparison indicates a strongly filamentory transport in front of the outer limiter as expected.

Summary

Discharges with and without N_2 seeding were compared. N_2 seeding causes an increase in the ELM frequency and improves the energy confinement. Discharges with N_2 seeding show low energy losses per ELM and seeding into the PFR decreases significantly the ELM duration and the peak electron temperature in the divertor during an ELM. Seeding keeps the divertor plasma in between ELMs at higher density and lower temperature. The rate of big filaments leaving the pedestal zone and reaching the outer limiters is reduced when the discharge is seeded.

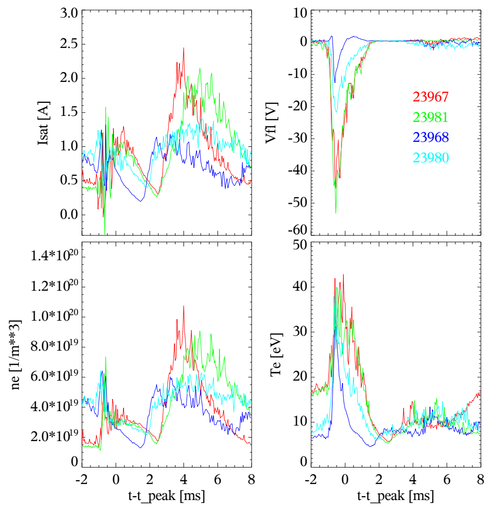

Figure 4: *Time traces of I_{sat}, V_{fl}, n_e and T_e for a Langmuir probe in the divertor about 2.5 cm outside the separatrix.*

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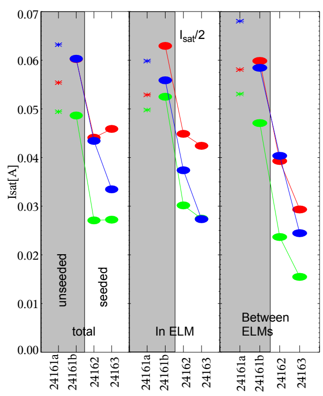

Figure 5: *Mean I_{sat} for 3 filament probe tips in seeded (white background) and unseeded discharges. From left to right: total average, average during ELMs and average in between ELMs.*

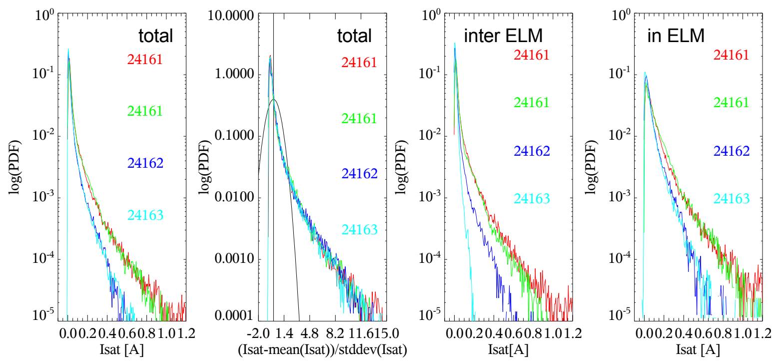

Figure 6: *From left to right: PDF of I_{sat} at filament probe, normalized PDF, PDF of I_{sat} in between and in ELMs. All PDFs are shown for unseeded (red and green) and seeded (blue and cyan) cases.*