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Analysis of the progress to detachment in the divertor of the MAST tokamak

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Abstract

Power handling and erosion of the divertor target plates are critical issues in the design of a next step fusion experimental reactor. Several steps can be taken to mitigate the effect of the plasma interaction with the divertor target, one of the most effective is plasma detachment. In MAST (Mega Ampere Spherical Tokamak) a series of experiments were conducted which aimed to achieve detachment for the first time on a spherical tokamak with rather open divertor geometry. This paper presents the results of these experiments, concentrating on a series of L-mode discharges, additionally heated with 750 kW of NB injection, for which the degree of detachment [Nucl. Fusion 38 (1998) 331] is calculated and discussed. Evidence for deuterium volume recombination in the lower outer divertor is shown and used to estimate with greater accuracy T_e (overestimated by the Langmuir probes for detached plasmas) in the divertor region.
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1. Introduction

If the results of power deposition and erosion on the divertor target plates of present day fusion experiments are scaled up to a next step fusion device such as ITER, the target lifetimes are shorter than desired [2,3]. A feasible solution to these problems is to operate in a detached divertor regime [4]. Detached divertor operation consists in transferring the plasma parallel momentum to the neutrals and then to the walls and to radiate the plasma energy by ionisation radiation and by two-body hydrogen recombination [5]. The combination of these two effects causes both the ion flux and temperature to decrease and a cushion of cold partially ionised and partially neutral gas to form between the plasma and the target plates.

In Mega Ampere Spherical Tokamak (MAST) such a beneficial regime has been explored and investigated for the first time in Spherical Tokamaks (STs) in Ohmic, L-mode and H-mode scenarios. MAST has a very open divertor configuration and its DND plasma is diverted on a section of the centre column in the inner strike points and onto 12 discrete ribs, each covered by three target plates, in the outer strike points [6]. Poloidal flux contours are shown in Fig. 1 for a typical MAST DND discharge. The plasma is additionally heated by 2 NB injection lines each capable of delivering up to 1500 kW of power.

This paper will concentrate on the results achieved in L-mode plasma heated with 750 kW of neutral beams and will only give a brief overview of the results of the experiments in Ohmic mode and H-mode.

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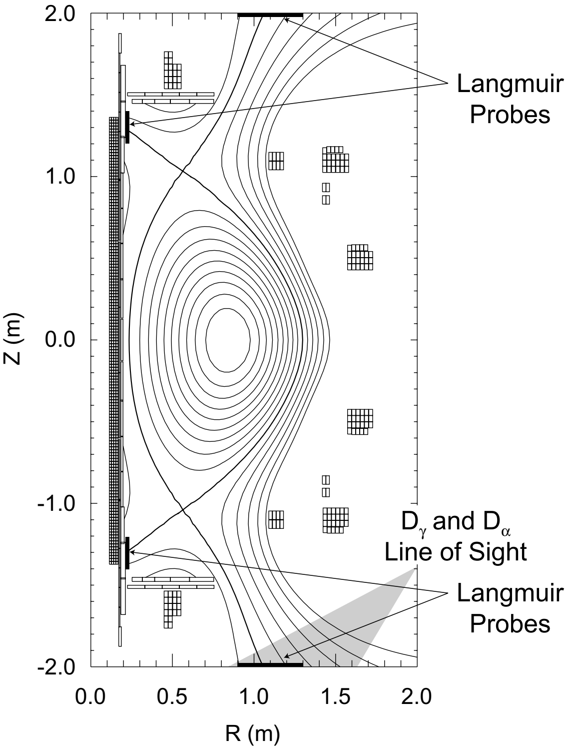

Fig. 1. Poloidal flux contours for a typical DND MAST discharge. In the figure the line of sight of the two spectrometers monitoring the D_α and D_γ light in the outer lower divertor and the locations of the target Langmuir probes are shown.

2. Diagnostics and experimental method

The divertors (upper and lower) are well equipped for target power loading studies, with 570 high spatial resolution, fast swept Langmuir probes embedded in the graphite centre column and divertor structures (see Fig. 1). They provide J_{sat} and T_e measurement with a spatial resolution of $\Delta z > 3.0$ mm in the inner strike points and $\Delta R > 10.0$ mm in the outer strike points and time resolution $\Delta t > 1.0$ ms. MAST is also equipped with several horizontal and vertical chords of visible D_α spectroscopy, and five chords bolometry covering the centre and lower part of the tokamak. For the detachment experiment, two dedicated spectrometers were monitoring both the D_α (656.1 nm) and the D_γ (434.1 nm) light emission integrated over the lower outer divertor region (see Fig. 1 for the spectrometers line of sight). The core plasma density is also monitored by an interferometer and by Thomson scattering. On some discharges the upstream T_e and n_e were measured by a mid-plane fast reciprocating probe with three Langmuir probes mounted on it [7] and an infrared camera measured the surface of divertor temperature at the outer lower divertor target plate.

Since the density operational space has been little characterised in MAST, part of the experiment was to investigate and characterise low and high recycling regimes as well as to attempt detachment experiments. In L-mode discharges, additionally heated with ~750 kW of neutral beam (NB) injection, the density was varied from 5.0×10^{18} to 3.0×10^{19} m^{-3} by deuterium gas injection from 10 piezo valves situated in the lower and upper divertor regions and at the mid-plane.

In this density range the ion saturation current density measured by the Langmuir probes at the target was found to first increase linearly with core density and then quadratically. When the J_{sat} started to increase quadratically, T_e was found to decrease as expected, indicating a transition from sheath limited (low recycling) to conduction limited (high recycling) regime in the SOL. J_{sat} varied from 0.7×10^3 A/m^2 (in low recycling regime) to 15×10^3 A/m^2 (in high recycling regime) while T_e was found to decrease from 60 eV down to 30–40 eV. Infrared camera measurements of the surface temperature at the lower outer strike points were found to be already below the detection limit ($\Delta T \sim 2$ K) in the high recycling regime. The temperature increase is small because the MAST solenoid fringing field causes the outer strike points to sweep a distance of 90 cm in 250 ms.

Once the fully attached L-mode plasma regimes were explored in MAST the density was increased until detachment of the strike points was obtained. At a density of 7.0×10^{19} m^{-3} the discharges were terminated by a MARFE forming in the main plasma.

Detachment was also explored and characterised in Ohmic discharges with similar density ramps and with the power increased it was attempted in H-mode discharges. In H-mode discharges detachment was attempted both by sole deuterium gas injection and also by Ne impurity seeding in the divertor.

3. Results

Fig. 2(a) shows the evolution of the discharge parameters in a typical L-mode detachment discharge with NB injection of 750 KW and 600 kA of plasma current. As the core density is increased in the X-point phase (after 90 ms) from 3 to 7×10^{19} m^{-3} the radiated power increases from 100 to 350 kW/m^2 and the divertor D_α increases by a factor of almost 3. The big spikes in the signal are due to sawtooth activity in the plasma. In Fig. 2(b) three ion saturation density profiles are shown for the upper inner strike points for three time slices selected to be as far as possible from the sawtooth crash. The ion saturation current density is plotted versus z position because, as already stated, the inner strike points lie on a portion of the centre column. In these plots the private flux region (PRF) lies on the right-hand side of the plots and the SOL on the left-hand side (see Fig. 1). As can be

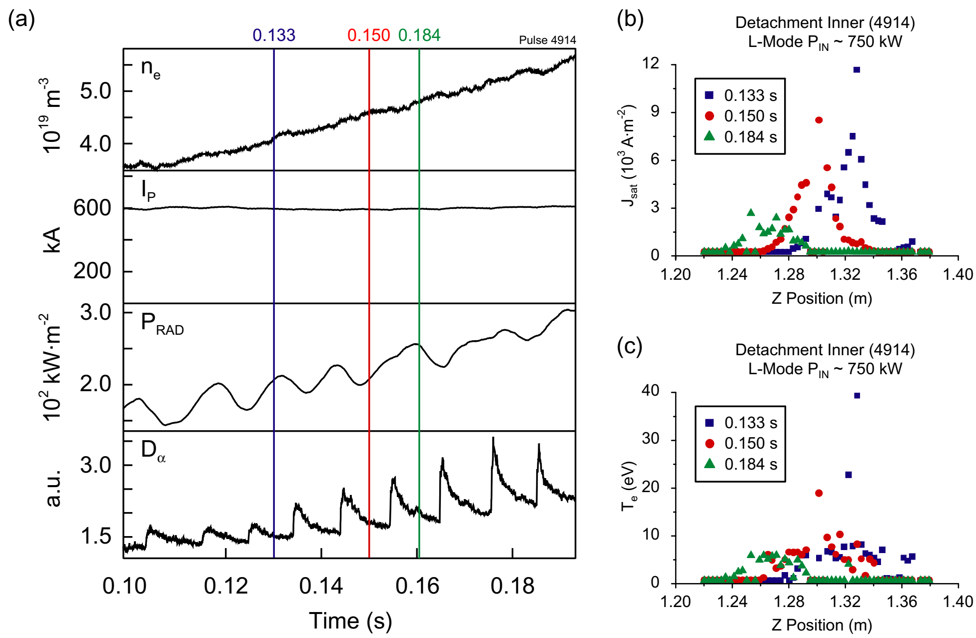

Fig. 2. Evolution of the MAST discharge parameters (a) and of the inner upper strike point J_{sat} (b) and T_e (c) at the onset of detachment for pulse 4914, a 750 kW NB heated discharge.

clearly seen in the figure at the core density of $\sim 4 \times 10^{19}$ m^{-3} the peak J_{sat} is 1.2×10^4 A/m^2 but as the density is increased further to 4.4 and then to 4.7×10^{19} m^{-3} the ion saturation current density drops first to 9×10^3 A/m^2 and then to below 3×10^3 A/m^2. Together with the drop of the peak value a flattening of the profile is also clearly noticeable. This is a sign of detachment starting from the strike point and moving out in deeper region of the SOL, this is consistent with what has been reported in the past [1].

In Fig. 2(c) it is possible to see profiles of electron temperature taken at the same time as the ion saturation current density ones. It is clear that together with a drop of J_{sat}, a decrease in T_e occurs. The data show a flat T_e profile at $\sim$6 eV. The value of the electron temperature measured by the probes is possibly overestimated by the effect of the non-Maxwellian electrons. In these experiments the peak J_{sat} at the outer strike points flattened to a value of $\sim 10^4$ A/m^2 but never dropped to very small values as the inner strike points did. The flattening of the profiles was also not so pronounced as for the inner strike points indicating a shallower detachment state. This is also in agreement with what has been reported in [1] and is due to the fact that more power flows to the outer strike points than to the inner ones. Infrared camera measurements showed the temperature increase in the outer strike points being below the noise level and a big component of signal coming from the bremsstrahlung radiation was observed. The peak power density at the inner strike points decreased from 25 kW/m^2 to <1 kW/m^2, while at the outer strike points the power density stopped increasing after reaching the value of 400 kW/m^2 at the onset of detachment. The power density profiles show also a typical flattening, indicating that detachment starts at the strike and then moves deeper in the SOL.

In experiments with a lesser amount of NB power injected, also the outer strike points show a deeper detachment, manifested with a drop of J_{sat} to less than 3.0×10^3 A/m^2 and a greater flattening of the J_{sat} and T_e profiles. The electron temperature is also found to drop to values $\sim$7 eV. Again the probes appear to overestimate the value of electron temperature for detached plasma. This can be confirmed by observing the behaviour of the D_γ over D_α ratio. This ratio, as already investigated in [8], remains very closely constant at low electron densities, it then decreases exponentially with increasing n_e until a very low $T_e \sim 1$ eV is reached and then sharply increases again. Corresponding to this drop of electron temperature is the onset of volume recombination between deuterium ions, phenomenon with extremely low cross-section at higher T_e.

Fig. 3 shows the evolution of the ratio of D_γ over D_α measured by two spectrometers in the outer lower divertor for an L-mode detachment discharge. As can be seen, the initially constant ratio falls sharply until, at a certain point ($\sim$220 ms), reverts and then sharply increases. This happens immediately after detachment

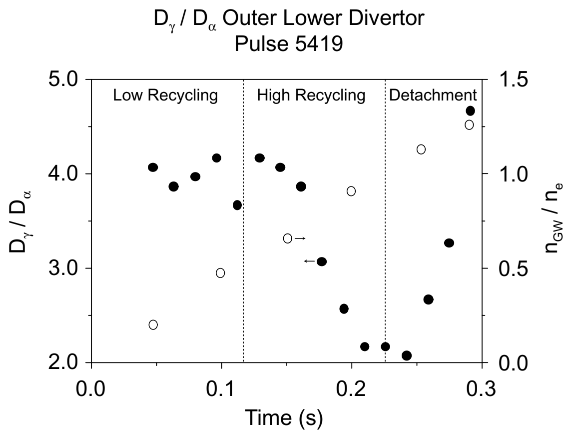

Fig. 3. Evolution of the D_γ over D_α and of the n_{GW} (Greenwald density) over n_e ratios for discharge 5419 as the outer lower strike point approaches detachment. In the figure the low and high recycling phases are also shown.

occurs at the divertor plates showing both evidence of volume recombination at the divertor and the overestimate of the temperature by the Langmuir probes.

Fig. 4 shows the peak J_{sat} plotted versus core density for the 750 kW NB heated L-mode discharges. In the figure the quadratic dependence $J_{sat} \propto n_e^2$ for the expected increase of ion saturation current density with the increase of core density is also plotted. The coefficient of the expression has been fitted to the data points for the high recycling regimes. From this figure it is possible to define the MAST degree of detachment (DOD) to be the ratio between the expected J_{sat} and the one measured at the target [1,9]. As can be seen at very low density the data lie above the curve. This is because below 2.5×10^{19} m^{-3} MAST is in a low recycling regime and therefore J_{sat} increases linearly with core density [9]; it then rolls over at around 3.5×10^{19} m^{-3} and decreases. It can be seen that the DOD is much higher for the inner strike points than the outer strike points. In the inner strike points a DOD of ~22 is obtained while in the outer ones the DOD only reaches ~6.

It is interesting to notice that, although the DOD is larger in the inner than in the outer strike points, the core density value at which detachment occurs is the same for all the four strike points. This is possibly due to the extreme STs' plasma geometry and the low toroidal field, which produce larger flux expansion and ion Larmor radii than ordinary tokamaks. The ultimate effect is that J_{sat} and T_e e-folding length are quite large (>10 cm) and therefore the plasma footprint and hence the power deposition is spread over a larger surface area.

It is worth mentioning that similar results and comparable DOD have been achieved in Ohmic discharges. As far as the additionally heated non-seeded H-mode discharges, detachment was only achieved in the inner strike points in the inter-ELM periods, but the strike points reattached at the ELMs. The DOD was also rather low <8. The density could not be increased without a density limit H–L transition. In the Ne impurity seeding attempts, the H-mode was lost almost immediately after the impurity was puffed into the divertor. A more comprehensive review of both the Ohmic and H-mode detachment experiments in MAST will however be the subject of a forthcoming publication.

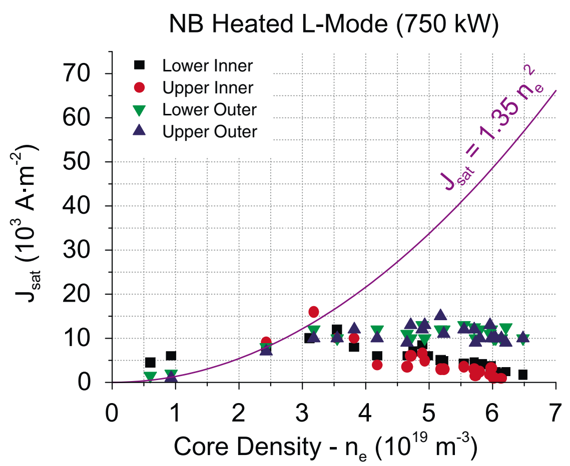

Fig. 4. Measured and extrapolated ion saturation current density (J_{sat}) for the inner and outer strike points of the NB heated L-mode discharges.

4. Summary and conclusions

Experiments aimed to characterise the MAST SOL were performed and the behaviour of the target J_{sat} has been studied for low and high recycling regimes.

For the first time on a ST experiments aiming to achieve detachment were performed in L-mode (750 kW NB injection), Ohmic mode and H-mode. Detachment was achieved in all regimes apart from during the ELMs of H-mode discharges. Evidence for extremely low target electron temperature and volume recombination has been found in the ratio of D_γ over D_α light from the outer divertor region.

DOD of 22 and 6 has been achieved in the inner and outer strike points respectively for NB heated L-mode discharges. All four strike points appeared to detach at the same value of core density, although the DOD was greater for the inner strike points than for the outer ones. In conventional aspect ratio tokamaks it is found that detachment occurs in the inner strike point at much lower core density than in the outer strike points. Moreover, detachment in the outer strike point is often spoiled by the onset of a MARFE and by a density limit disruption.

This relative ease in achieving detachment even in the outer strike points with the very open nature of the MAST divertor can be due to at least two reasons. The most important appears to be the fact that MAST can operate at quite high density relative to the Greenwald limit. The discharges presented in this paper reached a density 50% higher than the Greenwald density. MAST has also a larger power e-folding length at the outer target due to the effect of large ion Larmor orbits (low outboard toroidal field) which causes the power to spread over a larger area.

These encouraging results show that MAST behaves at least comparably to conventional tokamaks as far as techniques to ameliorate the power deposition and target erosion are concerned.

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