Behaviour of Upstream Separatrix Density in JET H-mode Plasmas

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ABSTRACT

The variation of $n_e^\text{Sep} / \bar{n}_e$ in JET H-modes is described. The upstream separatrix density, $n_e^\text{Sep}$, was determined using total pressure balance, in conjunction with ‘onion-skin’ modelling and reciprocating Langmuir probe measurements. It was found that the ratio $n_e^\text{Sep} / \bar{n}_e$ was strongly influenced by ELM frequency increasing, proportional to the rate of particle loss to the SOL from ELMs, towards the pedestal density and then saturating. The initial $n_e^\text{Sep} / \bar{n}_e$ ratio and rate of increase was different for horizontal and vertical target configurations with the latter having an initial $n_e^\text{Sep} / \bar{n}_e$ ratio of 0.12. Related information on the behaviour of the density SOL width and the variation of $n_e^\text{Sep} / \bar{n}_e$ with confinement are also presented.

1. INTRODUCTION

Information on the behaviour of the upstream separatrix density, $n_e^\text{Sep}$, is important because it strongly influences conditions at the divertor target. For example, with 9-10MW of power into the scrape-off layer (SOL), it was found that $n_e^\text{tgt} \propto (n_e^\text{Sep})^{1.6}$ under high recycling or conduction limited regimes. It has also been postulated that $n_e^\text{Sep}$ may play a role in the loss of confinement in H-modes [1,2]. To allow comparison with other tokamaks and to the required ITER conditions the ratio $n_e^\text{Sep} / \bar{n}_e$ is presented. In L-mode a $n_e^\text{Sep} / \bar{n}_e$ ratio of approximately one-third is generally assumed as reported elsewhere [3-5]. In H-mode the situation is further complicated by the formation of the pedestal and the presence of ELMs. There is also the difficulty in locating with sufficient accuracy the separatrix position owing to the smaller SOL width. The present ITER design considers a fixed $n_e^\text{Sep} / \bar{n}_e$ consistent with the reported findings for L-mode which is found not to be the case for JET H-mode plasmas.

The variation in $n_e^\text{Sep}$ between ELMs for fuelling scans in horizontal and vertical target configurations using the JET MkIIA and MkIIAP divertor is presented here. Following this introduction a description of the method for determining the separatrix position using total pressure balance is given. The behaviour of the separatrix density, which was found to be strongly influenced by ELM frequency and different for horizontal and vertical target configurations, is then given. Note that separatrix values given here are for between ELMs at the outer midplane. Finally, related information on the behaviour of the density SOL width and the variation of $n_e^\text{Sep} / \bar{n}_e$ with confinement are presented.

2. DETERMINATION OF UPSTREAM SEPARATRIX POSITION

The determination of the upstream separatrix from magnetic equilibrium reconstruction is difficult because it has an uncertainty of 1cm which is comparable to the SOL width. The approach taken at JET is to use total pressure balance, in conjunction with ‘onion-skin’ modelling (OSM) [6] and upstream reciprocating Langmuir probe measurements, in the following manner:
(i) Separatrix at target defined as peak in $T_e^{Tgt}$ and/or $J_{sat}^{Tgt}$.

(ii) $T_i^{Tgt} = T_e^{Tgt}$ assumed, consistent with equipartition criteria [7].

(iii) Upstream total pressure calculated using OSM $n_e^{Up}$, $T_e^{Up}$ and $T_i^{Up}$ and found to be

$$n_e^{Up} (T_i^{Up} + T_e^{Up}) \approx 2 n_e^{Tgt} (T_i^{Tgt} + T_e^{Tgt}) = 4 n_e^{Tgt} T_e^{Tgt}$$  \hspace{1cm} (1)

(iv) Reciprocating probe total pressure profile, calculated using measured $T_e^{Up}$ and OSM $T_i^{Up}/T_e^{Up}$ ratio, shifted to match OSM.

OSM has its boundary conditions specified at the target from Langmuir probe measurements which give the initial 2D variation, Fig. 1. The conservation equations are solved in 1D along each flux tube using NIMBUS, which is a neutral hydrogenic Monte Carlo code [8], to provide the hydrogenic ionisation and power terms. Within the OSM it is possible to adjust the $T_i^{Tgt}/T_e^{Tgt}$ ratio to account in some way for the poor power balance observed in these H-modes as observed elsewhere [9]. The target probes calculated at most 1.5 MW to the target (using $T_i^{Tgt} = T_e^{Tgt}$) with approximately 6 MW expected from global parameters. Adjusting $T_i^{Tgt}$ to obtain power balance required $T_i^{Tgt}/T_e^{Tgt}$ ratios of up to twenty and was inconsistent with equipartition [7]. Using $T_i^{Tgt}/T_e^{Tgt} > 1$ would increase the $n_e^{Sep}/n_e$ ratios presented here by ~0.1.

An example of the upstream total pressure profile obtained from the OSM and reciprocating probe data is shown in Fig. 2(a). The scatter in the experimental data arises from fluctuations [10] and because the reciprocating probe could not, in this instance, distinguish between individual ELMs. Other measurements using a triple Langmuir probe array were able to distinguish between individual ELMs. The corresponding upstream density profiles are shown in Fig. 2(b). Note the steeper gradient of the pressure profile within 5mm of the separatrix which then broadens to become comparable to the density scrape-off width. This is a consequence of the temperature profile, which has a steep gradient up to 5mm from the separatrix and then flattens, whilst the density profile is observed to have a constant scrape-off width.

Reciprocating probe measurements can also be used to determine separatrix densities for detached divertor conditions where the OSM is invalid. Analysis of attached cases give the absolute position of the separatrix, assuming this does not change for the same magnetic
equilibrium during detachment, the location of the reciprocating probe measurement relative to this can be determined and, if required, its profile extrapolated to the separatrix.

3. GENERAL BEHAVIOUR AND CONDITIONS AT TARGET DURING H-MODE FUELLING SCAN

Separatrix densities between ELMs at the outer midplane were determined for a series of H-mode fuelling scans performed:

- at fixed field and current, (2.3 T/2.3 MA, 2.5 T/2.5 MA and 3 T/3 MA)
- with 12 MW NBI heating,
- with unplugged (MkIIA) and plugged (MkIIAP) divertor,
- on horizontal (H/SFE) and vertical (V/SFE) target,
- with low (LT) and high (HT) triangularity (LT have $\Delta \leq 0.2$, HT have $\Delta \geq 0.3$).

With increasing $D_2$-fueling rate, $n_e$ and the confinement factor, $H97$, reach a limit and then decrease with further fueling whilst the ELM frequency continues to increase [11]. The H/SFE/LT configuration attains a peak $n_e$ of typically $7.3 \times 10^{19} \text{m}^{-3}$ which is 78% of the Greenwald density limit for both MkIIA and MkIIAP whilst its HT equivalent attains a peak $n_e$ of typically $9.1 \times 10^{19} \text{m}^{-3}$, 94% of the Greenwald density limit. In comparison the V/SFE/LT configuration attains a peak $n_e$ of typically $7.6 \times 10^{19} \text{m}^{-3}$, 77% of the Greenwald density limit, and a peak $n_e$ of typically $8.3 \times 10^{19} \text{m}^{-3}$, 80% of the Greenwald density limit, for the HT case.

Comparison of the horizontal/vertical target parameters given in Table 1 shows a higher electron temperature for the inner horizontal target than for the vertical, with comparable ion-flux, whilst on the outer target, the electron temperature decreases at a lower rate for the
(a) HORIZONTAL TARGET CONFIGURATION : MkIIAP/H/SFE/LT

<table>
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<th>OUTER</th>
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(b) VERTICAL TARGET CONFIGURATION : MkIIAP/V/SFE/LT

<table>
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<th>OUTER</th>
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<td>Peak Ion-Flux (A/cm²)</td>
</tr>
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Table 1: Comparison of target parameters between horizontal and vertical target configurations.

horizontal target which also has a higher ion-flux. The equivalent unplugged MkIIA sequence of Table 1 had decreased inner and outer electron temperatures (up to a factor of two) with similar inner ion-fluxes and lower outer ion-fluxes. The main differences with H/SFE/HT configurations are lower inner ion-flux (up to factor of two) and slightly lower outer electron temperature, with similar changes to LT in going from MkIIa to MkIIAP except for the outer ion-flux which is up to 1.5x higher in MkIIa. Main differences for the V/SFE/HT configuration are an initially higher outer electron temperature for MkIIA which then decreases at higher fuelling rates as for LT, Table 1, and converges to the MkIIAP values. The outer ion-flux is also higher for MkIIA/V/SFE/HT.

4. BEHAVIOUR OF N_E^SEP WITH ELM FREQUENCY

It was found that n_e^Sep varied most strongly with ELM frequency, Fig. 3, and, because of the relation between ELM frequency and triangularity [12], for the same target configuration a difference in the rate of increase in n_e^Sep/ n_e is observed for LT and HT. No difference exists between the unplugged (MkIIA) and plugged (MkIIAP) divertor, for the same configuration and triangularity. The only major change that was observed in going from MkIIa to MkIIAP was a
~35% decrease in the midplane pressure [1] with no significant change in confinement, $n_e$ or divertor pressure. Figure 3(b) also shows that the vertical target has both a lower $n_e/\bar{n}_e$ and $n_e^{\text{Sep}}/\bar{n}_e$ ratio. The lowest $n_e^{\text{Sep}}/\bar{n}_e$ ratio is 0.12 for the V/SFE/HT configuration.

For all cases, $n_e^{\text{Sep}}$ is seen to increase towards the pedestal density and saturate at a rate dependent on triangularity and target configuration. This results in $n_e^{\text{Sep}}/\bar{n}_e$ ratios of up to 0.72, Fig. 3(a), which has also been found on DIIID [13] and ASDEX-U [14]. In addition the DIIID results had $n_e^{\text{Sep}}/\bar{n}_e$ ratios as low as 0.15 and found that it increased with upstream electron pressure, speculating that this dependence is related to ELM activity. If the two-point model [15] were used to calculate the upstream parameters then the $n_e^{\text{Sep}}/\bar{n}_e$ ratios quoted here would be reduced by up to a factor of two. The main difference of the more refined OSM from the two-point model is the inclusion of parallel ion heat convection and radiation in the edge. Consistent with most modelling, it calculates $n_e^{\text{Sep}}$ accurate to within a factor of two. Whilst the reciprocating probe measurements verify the OSM calculations, the scatter in the data in these ELMy H-modes is often of the same magnitude. As mentioned before, determination of the separatrix from magnetic equilibrium reconstruction is not sufficiently accurate in H-modes and would lead to even higher errors in $n_e^{\text{Sep}}$. The fact that $n_e^{\text{Sep}}$ values presented here do not exceed the pedestal values gives some confidence in the data and perhaps represents its upper limit. It is important to emphasise, however, that it does not alter the trends described here and shown in Figs. 3 and 4.

The correlation of $n_e^{\text{Sep}}$ with ELM frequency, $f_{\text{ELM}}$, shown in Fig. 3 led to the hypothesis that the increase in $n_e^{\text{Sep}}$ was proportional to rate of particle loss to the SOL from ELMs, i.e. $\propto f_{\text{ELM}} \Delta n_e^{\text{Edge}}$. Generally the characteristics of LT pulses are high $f_{\text{ELM}}$ with a lower drop in edge pedestal density per ELM, $\Delta n_e^{\text{Edge}}$, whilst HT pulses are characterised by low $f_{\text{ELM}}$ and higher
$\Delta n_e^{\text{Edge}}$. Figure 4 illustrates the increase in $n_e^{\text{Sep}}$ as a function of $f_{\text{ELM}} \times \Delta n_e^{\text{Edge}}$, which, for a given target configuration, unites both the LT and HT data in support of this hypothesis. The difference in target configuration remains, however, which is reflected by the difference in target parameters, Table 1.

The saturated $n_e^{\text{Sep}}$ for H/SFE data at $f_{\text{ELM}} \times \Delta n_e^{\text{Edge}} > 550 \times 10^{18}$ m$^{-2}$/s were obtained from reciprocating measurements only, using the method described in Section 2, as detachment at the target had occurred at these higher ($\Phi > 2.8 \times 10^{22}$ elec/s) fuelling rates. Comparable data for V/SFE were not available as the vertical target more readily detaches, Table 1, and because there were no reciprocating measurements in these pulses.

5. BEHAVIOUR OF SOL WIDTH

As well as a variation in $n_e^{\text{Sep}}$, changes to the density SOL width were observed. The between ELMs, density SOL width mapped in flux space to the outer midplane, $\lambda_{n_e}$, was found to be slightly smaller for the vertical target configuration with LT ($\lambda_{n_e} = 0.3$ midplane cm for MkIIAP/V/SFE/LT with no fuelling) than for the equivalent horizontal case ($\lambda_{n_e} = 0.44$ midplane cm) in these H-mode pulses. Typical flux expansions from the target and from the reciprocating system to the outer midplane were $\geq 10$ and $\sim 2.5$ respectively so that these small values could be resolved from the data.

With HT no significant difference was found between the horizontal and vertical target, Fig. 5. Code simulations [16] predict a thinner SOL width for a vertical target as a result of differences in the recycling pattern which has been observed in L-mode [17] with
Although this is not a direct one-to-one comparison as they were at different stages of detachment. These data show that the difference is not so large in H-mode under more comparable main plasma conditions. A broadening of the SOL width as the target conditions approach detachment does occur, consistent with previous observations [18], with $\lambda_{ne} = 0.55$ midplane cm for MkIIAP/H/SFE/LT at a fuelling rate, $\Phi$, of $2.2 \times 10^{22}$ elec/s.

No difference was seen, Fig. 5, for both LT and HT in the upstream profiles for the horizontal target between unplugged (MkIIA) and plugged (MkIIAP). In contrast there was a significant decrease in the upstream density for the V/SFE/HT configuration in going from MkIIA to MkIIAP which is a consequence of the electron temperature and ion-flux being lower in the MkIIAP case as described in Section 3.

6. VARIATION WITH CONFINEMENT FACTOR, H97

The confinement factor, H97, (corrected for fast ions) has been found to be related to ELM frequency, $f_{ELM}$, by [19]

$$H97 = 1.23 - 0.57 f_{ELM} \tau \{1 - \exp[-1/(f_{ELM} \tau)]\}$$

where $\tau = 0.034$ s has been determined from the experimental data and is representative of the time taken for the confined plasma to reheat the edge pedestal following an ELM. It has been postulated [1] that it is $n_{e}^{Sep}$ rather than an increased main chamber neutral pressure which produces the confinement degradation observed in these H-modes, because confinement quality was better correlated with divertor neutral pressure and with $n_{e}^{Sep}$ than with midplane neutral pressure. The hypothesis being that in steady-state the exhaust rate must be equal to the fuelling rate and $n_{e}^{Sep}$, which is strongly related to $n_{e}^{Tr} (\propto (n_{e}^{Sep})^{1.6})$ and thus the exhaust rate, will adjust in such a way so as to achieve this balance.

Figure 6 shows how H97 (corrected for fast ions) varies with $n_{e}^{Sep}/\overline{n}_{e}$. The highest confinement is obtained for the smallest $n_{e}^{Sep}/\overline{n}_{e}$ and steadily decreases until $n_{e}^{Sep}$ attains the pedestal value at $H97 \approx 0.8$. As shown in Fig. 4, an increased exhaust rate results from increasing $f_{ELM}$ brought about, in these H-modes, by increased gas fuelling. This is accompanied by an increase in $n_{e}^{Sep}$ and consequent increase in $n_{e}^{Tr}$ eventually leading to detachment which, recent
modelling [20] would suggest, sets a limit on the maximum achievable $n_e^{\text{Sep}}$. Whether this then produces the observed loss of confinement or is just a reaction to the loss of confinement is still under investigation. Further comments on the density limit in H-modes can be found in [2].

7. CONCLUDING REMARKS

Total pressure balance, in conjunction with OSM and upstream reciprocating probe measurements, has been used to determine $n_e^{\text{Sep}}$ in H-mode plasmas over a variety of conditions. It was observed to increase towards the pedestal density $\propto f_{\text{ELM}} \Delta n_e^{\text{Edge}}$ and saturate with the rate of increase being lower for the vertical target configuration. Whilst the value of $n_e^{\text{Sep}}$ may be accurate up to within a factor of two, consistent with most modelling and due to the scatter in the experimental measurements, it is important to emphasise that its behaviour with, for example, $f_{\text{ELM}}$ remains the same.

The preferred ITER target configuration closest to these JET data is the V/SFE/HT which has $n_e^{\text{Sep}}/n_e$ ratios ranging from 0.12 with $f_{\text{ELM}} = 5$ Hz to 0.45 for $f_{\text{ELM}} = 17$ Hz. A pragmatic approach to the calculation of $f_{\text{ELM}}$ for ITER, based on observations from several tokamaks [21], gives a value of 1-2 Hz which, from these results, implies a low $n_e^{\text{Sep}}/n_e$ ratio between ELMs making $n_e^{\text{Tgt}}$ low and likely to be in the attached regime. Further studies to establish a suitable scaling to larger machine size of $f_{\text{ELM}}$ are required, however, and there are other mechanisms, e.g. use of RF heating to produce smaller, more frequent ELMs, which could be used. Studies of how $n_e^{\text{Sep}}/n_e$ scales between current tokamaks are also required, though the similarity between JET, DIII-D [13] and ASDEX-U [14] results would suggest that it is invariant to machine size.

Further studies of JET data will include determination of $n_e^{\text{Sep}}$ over a wider range of plasma current and toroidal field, to test the model of [20], and in lower density, higher $f_{\text{ELM}}$, RF heated H-mode fuelling scans.

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