The Importance of the Ion ∇B Drift Direction for the Divertor Plasma at JET

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Introduction: Due to a lower power threshold for the H-mode, single null X-point discharges in JET as well as in other divertor Tokamaks are normally operated with the ion grad B drift pointing towards the divertor target (normal ion grad B drift direction). In such discharges a strong asymmetry in conducted power (up to 1 : 3) between the two divertor branches is commonly observed in JET and elsewhere [1,2]. This asymmetry is a well known problem for the power exhaust in a next step machine. However, its consequences for the plasma parameters in the divertor and so for its performance have in general been insufficiently emphasised so far. In this paper we demonstrate that optimum divertor plasma parameters are achieved when a single null divertor is operated with the ion grad B drift pointing away from the target (reversed ion grad B drift direction).

Experiments: During the 91/92 experimental campaign, extensive power and density scans ($\bar{n}_e$~ 2.5 to $6\mathrm{x}10^{19}\mathrm{m}^{-3}$, P_{IN} = 3 to 12 MW) were performed in single null X-point discharges with normal ion grad B drift direction on both the Beryllium and the Carbon targets. Regrettably no such systematic data were obtained with reversed ion grad B drift direction. In the latter case only three different types of single null X-point discharges, namely hot ion H-mode discharges ($\bar{n}_e$ ~ 2 to $3\mathrm{x}10^{19}\mathrm{m}^{-3}$, P_{IN} = 15 MW, C- and Be-target), radiative divertor discharges ($\bar{n}_e$ ~ 6 to $7\mathrm{x}10^{19}\mathrm{m}^{-3}$, P_{IN} = 10 and 22 MW, Be-target) and a few medium density H-mode discharges ($\bar{n}_e$ ~ $4\mathrm{x}10^{19}\mathrm{m}^{-3}$, P_{IN} = 12 MW, Be-target) are available in the JET data base. Due to the detachment of both strike zones in radiative divertor discharges, the plasma parameters in front of the target could not be measured, which excludes these discharges from a systematic comparison. In hot ion H-mode discharges, the strong temporal variation of the power conducted into the scrape off layer / divertor (dW/dt, C-bloom), which has a significant effect on the divertor plasma, complicates the data interpretation. The medium density H-mode discharges were performed late in the experimental campaign. The Be target was already slightly damaged and only a few of the target Langmuir probes were operational. Despite of the consequently bigger error bars, their qualitative behaviour was similar to that seen in hot ion H-mode discharges which is discussed below. This very restricted data set for the reversed ion grad B drift direction therefore does not allow direct comparison of similar discharges (same density, same heating power, similar power into the SOL) with opposite ion grad B drift directions. However, due to the significantly different behaviour of the divertor plasma when operating with reversed ion grad B drift compared to normal ion grad B drift, conclusions can nevertheless be drawn. All the data discussed in this paper were obtained during H-modes due to the larger amount of data available. The L-mode behaviour is very similar.

The plasma parameters (electron density-, D^+-flux, and Te- profiles) in the divertor are measured by Langmuir probes embedded in the target tiles applying the same evaluation method as in [3]. In addition spatially resolved Hα measurements (CCD) are available for the C-target. Combining these Hα data with the Te profiles from the Langmuir probes yields neutral deuterium influx profiles. While quantitatively the Hα based D-flux deviates in some cases up to a factor of two from the D^+-flux obtained by Langmuir probes, the qualitative behaviour (in-out asymmetry) is very similar (Fig. 1). Due to the fact that the spatially resolved

Hα measurements are not available for all discharges with reversed ion grad B drift direction, the conclusions drawn in this paper are partly based on Langmuir probe data only.

Results and discussion: Fig. 1 shows the Te and the D^+-flux profiles on the C-target during the ELM free H-mode phase of two low density ($\bar{n}_e \sim 3\times10^{19}m^{-3}$) discharges: i.) a 12 MW NBI heated discharge with normal ion grad B drift direction (Fig. 1a, 1b); ii.) a 15 MW NBI heated hot ion H-mode discharge (V-H-mode) with reversed ion grad B drift direction (Fig. 1c, 1d).

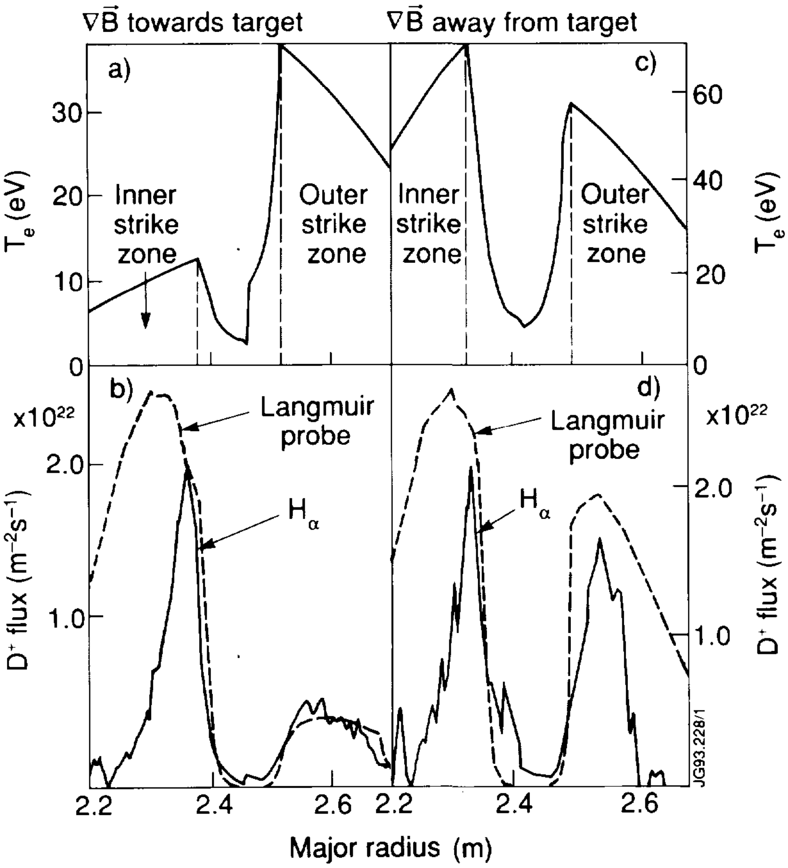

Fig. 1: Te and D^+-flux profiles on the C-target for a 12 MW NBI heated ELM free H-mode discharge with normal ion grad B drift direction (a,b) and a 15 MW NBI heated hot ion H-mode discharge with reversed ion grad B drift direction (c,d). The pronounced asymmetry between the strike zones in case of normal ion grad B drift in contrast to reversed ion grad B drift can be seen.

In the case with normal ion grad B drift direction (Fig. 1a, 1b) a relatively high Te (~40 eV) and a low D^+-flux (~$5\times10^{21}m^{-2}s^{-1}$) can be observed at the outer strike zone, while the inner strike zone displays low Te (~10 eV) and a relatively high D^+-flux (~$2\times10^{22}m^{-2}s^{-1}$). This behaviour indicates that already at low mid plane density two different divertor regimes (low recycling, high recycling) start to develop at the two strike zones. The hot ion H-mode discharge with reversed ion grad B drift direction (Fig. 1c, 1d) has a more symmetrical distribution of Te (~60 eV) and the D^+-flux (~$2\times10^{22}m^{-2}s^{-1}$) between the two divertor divertor legs. In this case both divertor branches are in the same divertor regime. The difference in the absolute values of the divertor plasma parameters and in particular of Te between these two discharges can be explained by their different heating power and confinement regimes. The behaviour of the divertor plasma parameters shown in Fig. 1 is not only representative for the whole duration of these two discharges but also for the effect of the ion grad B drift on the divertor plasma in general. Fig. 2 shows the separatrix density at the inner and outer strike zone (from Langmuir probes) plotted versus the line averaged density in the main plasma for both ion grad B drift directions and many discharges.

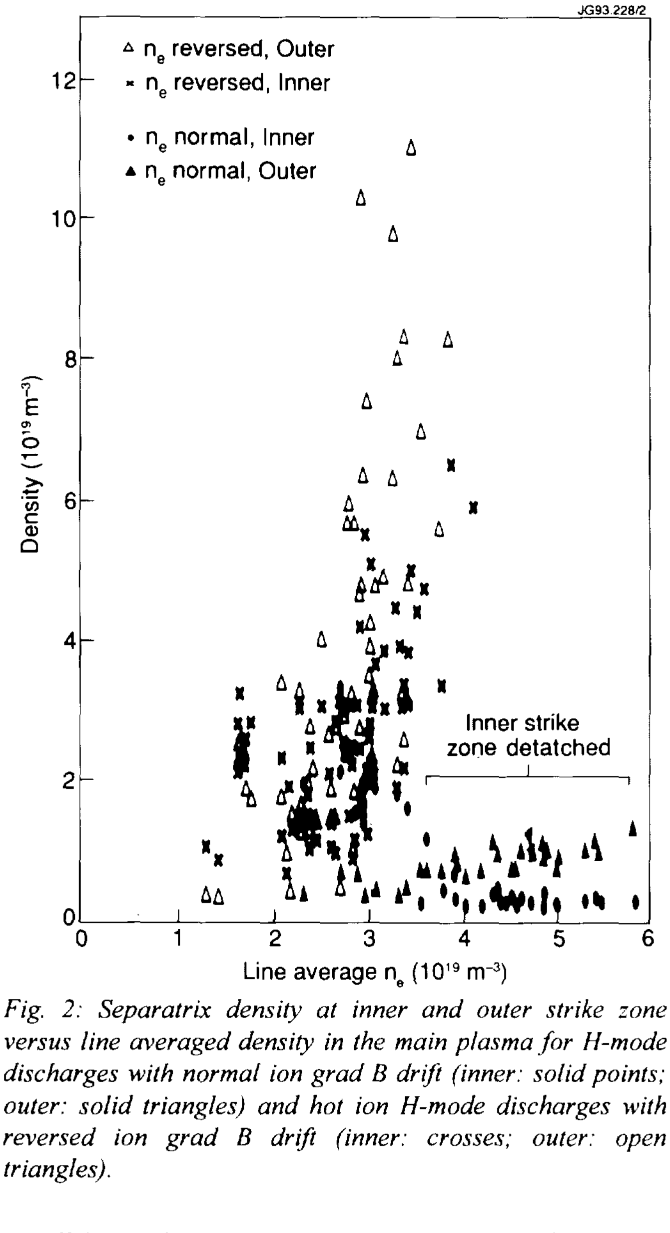

Fig. 2: Separatrix density at inner and outer strike zone versus line averaged density in the main plasma for H-mode discharges with normal ion grad B drift (inner: solid points; outer: solid triangles) and hot ion H-mode discharges with reversed ion grad B drift (inner: crosses; outer: open triangles).

In the case of 12 MW NBI heated ELM free H-mode discharges with normal ion grad B drift direction (solid symbols) the inner strike zone density (solid points) starts by a factor of 2 higher than the outer strike zone density (solid triangles) and detaches when the main plasma density is increased (high recycling regime -> gas target). The outer strike zone density on the other hand remains relatively low (low recycling regime) over the whole density range. When the main plasma density is increased to the point where the outer strike zone should enter the high recycling regime, the inner strike zone is starved of power, detaches and ultimately a density limit disruption (Marfe) occurs. During the 91/92 campaign, it was therefore not possible to achieve a high recycling outer divertor strike zone with normal ion grad B drift direction, even for high mid plane densities. As already discussed above, hot ion H-mode discharges with reversed ion grad B drift direction (Fig. 2: open symbols) display more symmetrical plasma parameters in the two divertor channels. In this case both divertor branches are in the same regime for a wide range of densities, allowing the achievement of high recycling conditions simultaneously at the inner (Fig. 2: crosses) and outer divertor leg (Fig. 2: open triangles). Due to the high radiation losses during C-blooms and the consequent reduction in the power conducted into the divertor late in the heating phase of these discharges, very high divertor densities are achieved at moderate main plasma densities (Fig. 2: open symbols).

The above described behaviour of the divertor plasma can be qualitatively understood by a simple one dimensional analytical model for the scrape off plasma such as the two point model [4,5]. In this simple model the divertor regime is mainly determined by the density at the mid plane separatrix and by the power flux into the divertor channel. When solving the equations of this model, the dependence of the divertor density n_d and temperature T_d on the mid plane scrape off layer density n_s and on the power flux parallel to the field lines $q_{//}$ is approximately

$$n_d \approx \frac{n_s^3 L_{//}^{\frac{6}{7}}}{q_{//}^{\frac{8}{7}}} \quad , \quad T_d \approx \frac{q_{//}^{\frac{10}{7}}}{n_s^2 L_{//}^{\frac{4}{7}}} \qquad (1)$$

Therefore for fixed n_s, but different powers $q_{//}$ conducted into each divertor branch at a given connection length $L_{//}$, the corresponding divertor densities n_d and temperatures T_d will be different. In addition, different dependencies on the scrape off layer density n_s will occur, resulting in increasingly divergent n_d and T_d between the divertor legs with growing n_s. In the Single Null X-point discharges described above, with normal ion grad B drift direction (Fig. 2, solid symbols) the behaviour of the plasma parameters in the two divertor branches is therefore qualitatively in line with expectations from the 2 point model for a strong asymmetry in conducted power between the two divertor branches. In discharges with reversed ion grad B drift direction (open symbols), the measured plasma parameters in the two divertor legs suggest a more even distribution of conducted power. In this case the two divertor legs are expected to display similar plasma parameters over a wide range of densities and powers conducted into the divertor, as seen in the experiment (Fig. 2). This allows for a given SOL power, higher main plasma densities to be achieved before divertor detachment occurs, and makes it possible to obtain a low temperature high density plasma in both inner and outer divertors simultaneously. When assessing the power loading of the Be divertor target from tile temperature measurements (by a CCD camera through a 844.5 nm filter) during discharges with reversed ion grad B drift direction the picture is not so clear anymore. These data show a pronounced effect of the ion grad B drift direction at low mid plane density, which seems to vanish at high densities. From the bigger outer surface of the main plasma one would always expect a higher power loading at the outer divertor strike zone. This geometric effect seems to be counteracted by a force which depends on the direction of B as well as on the density (collisionality). The density dependence can be inferred by comparing hot ion H-mode discharges with radiative divertor discharges [6], representing the two extreme ends in the scanned density (collisionality) range. While the hot ion H-mode discharges show clearly a stronger heating at the inner strike zone, the radiative divertor discharges display burn through and consequent target tile heating predominantly at the outer strike zone. Grad Te x B and grad Ti x B forces, which would vanish if Te = Ti and which would be strong if Te << Ti, are suggested as an explanation of the observed effects [7].

In addition to the importance of the ion grad B drift direction described above, the X-point to target distance (connection length, divertor volume) also has some influence on the divertor in-out asymmetry. During an X-point to target distance scan ($\Delta x = 8, 16, 25$ cm) with normal ion grad B drift, a reduced asymmetry in the densities and temperatures measured at the two strike zones was observed at the maximum Δx [3].

Conclusions: The achievement of a high density low temperature divertor plasma (high recycling regime) is essential for good impurity retention as well as for low target power load and low target erosion (impurity production). In a next step machine stable divertor regimes beyond the high recycling regime (radiative divertor, gas target) have to be obtained in order to solve the power exhaust problem. Such a divertor can only work if the same divertor regime is obtained simultaneously in both strike zones over a wide parameter range. In order to achieve this, the conducted power to outer and inner strike zone has to be approximately equal. The only way found so far in JET which accomplishes this is to have the ion grad B drift pointing away from the divertor target.

Literature:

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