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Effect of triangularity variation on edge operational boundaries in ASDEX Upgrade

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Introduction

Recent modifications of in vessel components of ASDEX Upgrade allow variation of the plasma shape. Plasma shaping, especially increased triangularity δ and elongation κ, is expected to improve stability and may lead to favourable tokamak H-mode performance improvement. On the other hand, peak power losses during type-I Edge Localized Modes (ELMs) are critical and must be assessed for any reactor-relevant operation regime.

Separate papers on this conference report the effects of plasma shape (triangularity) variation in ASDEX Upgrade on transport [1] and the density limit [2]. Here, we compare measurements of H-mode edge operational boundaries. Three principal shapes are studied, a "low"-triangular shape ($\delta_l = 0.3$, $\delta_u = 0.0$) and two shapes with "medium" ($\delta_l = 0.41$, $\delta_u = 0.2$) and "high" ($\delta_l = 0.42$, $\delta_u = 0.3$) triangularity. All plasmas were in elongated ($\kappa = 1.7$) single-null geometry, with ion grad-B drift towards the X-point. Most discharges are neutral beam heated; ICRF heating did not lead to different edge parameter behaviour. All medium and high-δ and most low-δ discharges have been performed with the ASDEX Upgrade Divertor II [3], which allows good baffling for the low-δ shape. Compared to divertor I, the neutral deuterium compression ratio in divertor II is increased from 30...50 to 100...200. Figure 1 shows the divertor neutral gas flux vs. main chamber neutral gas flux for Divertor I (low δ) and Divertor II (low, medium and high δ). With medium and high triangularity, the outer strike point cannot remain in the well baffled region of the current divertor II, but is moved to the top of the private flux region baffle. Consequently, the neutral compression ratio is somewhat reduced and lies in between the divertor I and divertor II low-δ values.

The most striking difference between low and high triangularity shapes is that not only a better degree of confinement is obtained at higher δ, but also the confinement degradation with

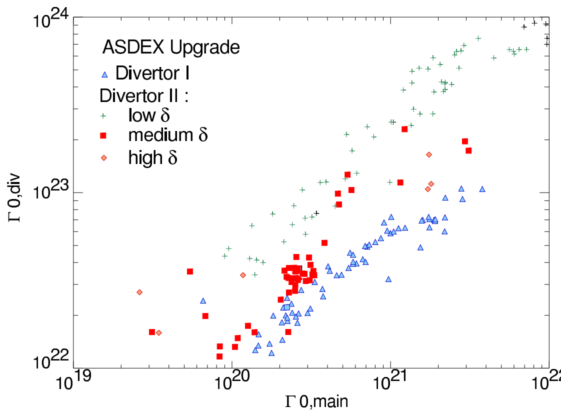

Figure 1: Divertor neutral gas flux vs. main chamber neutral gas flux for low, (Divertors I and II) medium and high triangularity (Divertor II only)

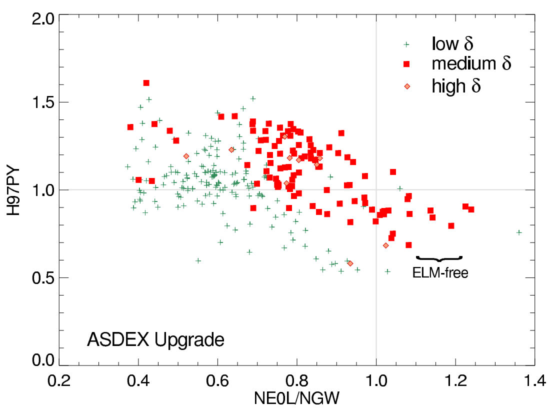

Figure 2: Confinement measured against the H97P(y) scaling vs. line-averaged density, normalized to Greenwald density, for low, medium and high triangularity

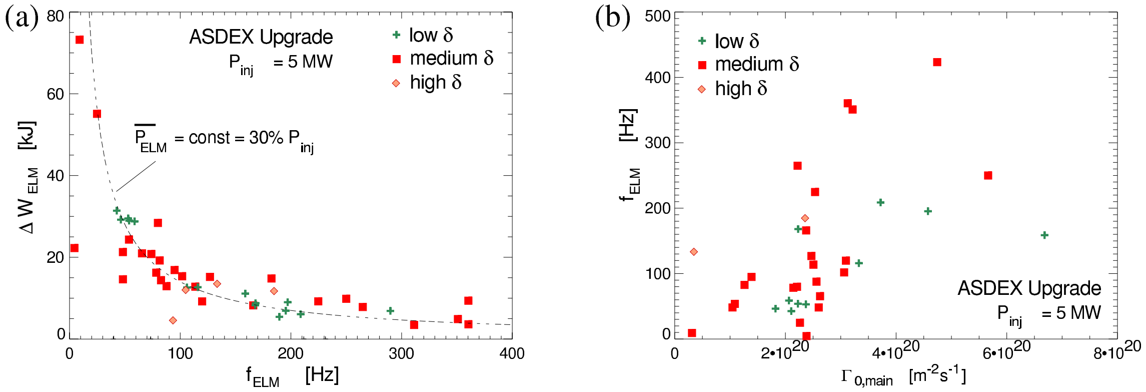

Figure 3: Type I ELM behaviour for plasma shapes with varying triangularity δ: (a) Energy loss vs. frequency (b) frequency vs. main chamber neutral flux

increasing density sets in at higher densities compared to the case of low δ, as illustrated in Fig. 2, which shows the thermal stored energy relative to the ITER H97P(y) ELMy H-mode confinement scaling [4] vs. line-averaged density, normalized to the Greenwald density limit scaling n_{GW} [5]. Similar results have been previously obtained in JET [6].

Behaviour of Edge Localized Modes

The behaviour of ELMs is found to change with varying triangularity. If the heating power is kept slightly above the H-mode threshold power, long ELM-free phases are found at medium and high triangularity, during which the density rises continuously, and peaked profiles develop with line averaged density ranging up to 40 % above the Greenwald density limit scaling. Simultaneously, Z_{eff} and the radiated power rise continuously without saturation even after several energy confinement times. These ELM-free phases are typically terminated by a sequence of few very large ELMs, which expel up to 10 % of stored energy from the plasma. In the low-δ plasma shape, ELM-free phases with a duration in excess of 50 ms generally do not occur.

For low and medium δ, the former both with Divertor I and Divertor II the ELM frequency and ELM energy and particle losses have been evaluated for type I ELMy phases within a range of parameters. It is found that for any given heating power the ELM energy loss is inverse proportional to the ELM frequency, so that the average power loss during ELMs is a constant, and does in particular not depend on plasma shape (see Fig. 3 a). The data base contains also a large heating power variation for low δ discharges which shows that the average ELM loss power is a roughly constant fraction of heating power (around 30 %). Except for giant ELMs, ELM energy loss is in the same range for all shapes. Notably, the ELM energy loss is significantly below and the ELM frequency above the JET/DIII-D scaling (for $\delta \approx 0.3$) derived from the ITER ELM database [7]. The ELM frequency and size sensitively reacts to the main chamber neutral gas flux (Fig. 3 b), a parameter not contained in the JET/DIII-D ELM scalings.

Edge parameters and Edge-Core Relation

Edge parameter measurements have been performed for both low and medium triangularity discharges, using Thomson scattering diagnostics for T_e and Li-beam and DCN laser interferometric measurements for n_e in the pedestal region. At medium and high triangularity with particularly high density at the edge and in the scrape-off layer, much of the Li-beam intensity is absorbed outside the separatrix, leaving insufficient light intensity for density measurements

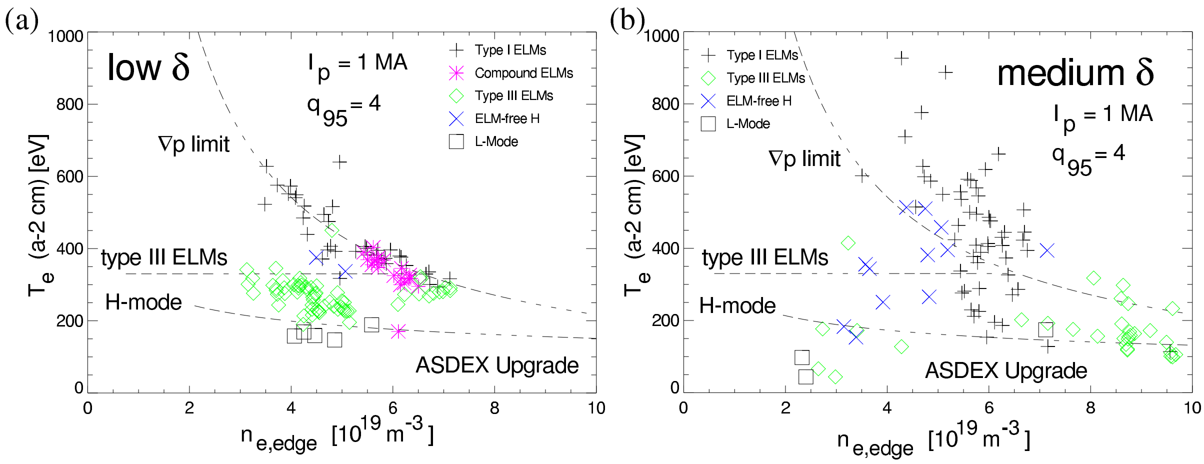

Figure 4: Edge operational diagrams $T_e(a-2\text{ cm})$ vs. $n_{\text{e,edge}}$ at low (a) and at medium triangularity (b), dashed lines indicate operational boundaries at low δ (see text)

in the pedestal region. As an estimate of $n_e(a-2\text{ cm})$, an effective edge density $n_{\text{e,edge}}$ is constructed from the line-integrated density $\overline{n}_{\text{e,edge}}$ of a peripheral interferometer chord, tangential at $\rho_p = 75$ % (on top of the density pedestal), divided by the ratio $\overline{n}_{\text{e,edge}}/n_e(a-2\text{ cm})$. It is found that the ratio $\overline{n}_{\text{e,edge}}/n_e(a-2\text{ cm})$ is a constant for each shape (1.3 for low, 1.2 for medium and high δ) so that the line average remains a good measure of the pedestal density. The edge pressure $p_{\text{e,edge}}$ is approximated by multiplication of $n_{\text{e,edge}}$ with T_e from Thomson scattering taken at a scattering volume near midplane centered at $r = a-2$ cm ($\rho_p^2 = 95$ % poloidal flux). A much more detailed edge profile analysis is reported in Ref. [8] for discharges where dedicated high resolution edge measurements have been made. Figure 4 shows T_e (a-2 cm) vs. $\overline{n}_{\text{e,edge}}$. From comparison of Fig. 4 (a) with figure 12 of Ref. [9] one sees that major operational boundaries, edge pressure limit, H-mode threshold and type III ELM boundary (indicated by dashed lines) are accurately represented. Figure 4 (b) shows that at elevated triangularity the pedestal pressure during type I ELMy H-mode can be increased by about 50 % over that at low δ. With increasing density, this gain of pressure gradient seems to vanish, and a large scatter of the measurement is obtained at $\overline{n}_{\text{e,edge}} = 6\times10^{19}$ m^{-3} and above. Type III ELMy H-mode is generally obtained at higher edge densities or at very low edge density with heating power just above the H-mode threshold. In contrast to low δ cases, a large region of ELM-free discharges is now found at medium δ for edge temperatures in between those of type III and type I ELMy discharges. The type III ELM boundary and the H-mode threshold for medium δ appears somewhat ambiguous but at the present time not enough measurements have been made to clarify possible shape dependences.

It has been found earlier (see, e.g. Ref. [9]) that a relation between edge and core parameters exist which can be expressed as a correlation of edge (pedestal) pressure and stored energy. Using the effective edge pressure $p_{\text{e,edge}}$ as defined above and the total MHD stored energy W_{MHD}, this relation is shown in Fig. 5 for low (Fig. 5 a) and medium (Fig. 5 b) triangularity. One can see that within some scatter this relation holds independent of plasma shape, with the same average ratio of W_{MHD} and $p_{\text{e,edge}}$. The confinement improvement obtained with more shaped plasmas is linked to a higher edge pressure.

It should be noted, however, that for the given experimental arrangements of vertical field coils in ASDEX Upgrade, the plasma shape cannot be maintained independently of poloidal beta (β_p). In particular, at low β_p in L-mode or H-mode with degraded confinement, the elevated triangularity shape cannot be precisely obtained so that a correlation between triangularity and

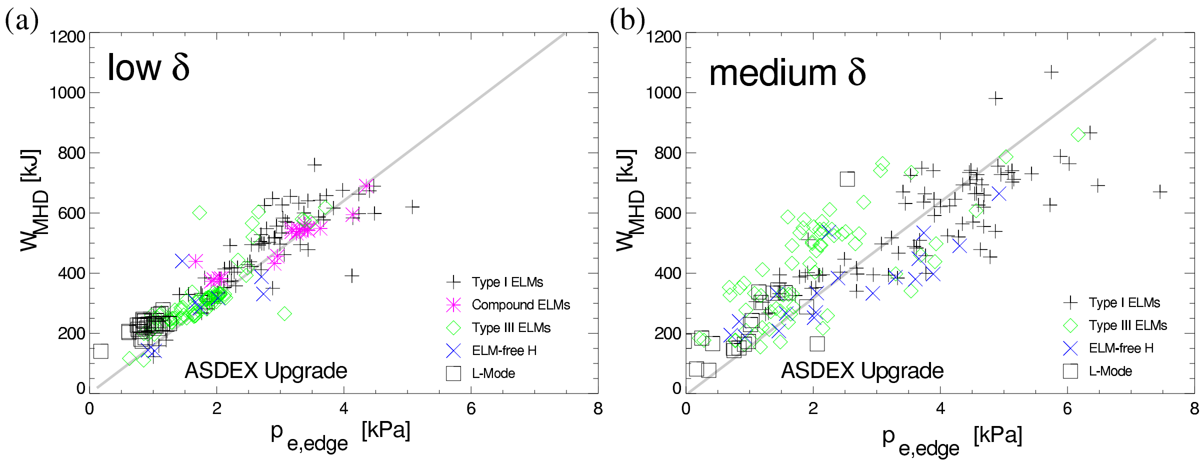

Figure 5: at low (a, $\bar{\delta} = 0.2$) and at medium triangularity (b, $\bar{\delta} = 0.3$) for $I_p = 0.6 \ldots 1.2$ MA; all discharges without impurity injection

both pedestal pressure and stored energy exists. It is thus difficult to assess whether the observed pedestal pressure variation at elevated δ is a cause or consequence of confinement changes.

Summary and Conclusion

In agreement with previous observations on JET [6] plasmas with increased triangularity display improved type I ELMy H-mode confinement which can be maintained at higher densities compared with low triangular shapes. In contrast to other observations, in particular the JET/DIII-D ELM scaling [7], this does not necessarily imply larger type I ELM losses. However the strongest impact on ELM behaviour arises from the main chamber neutral flux, and any increase of the neutral influx seems to have direct impact on confinement. This may be an indirect effect due to an increased scrape-off layer density [10]. The previously established relation between edge (pedestal) pressure and core confinement (stored energy) [9] is found to hold independently of plasma shape. In contrast to the low-δ case, a variation of pedestal pressure (and accordingly of stored energy) is observed at fixed plasma current and magnetic field which is correlated to changes in triangularity induced by β_p dependent control limitations. Because of the linkage between δ and β_p, the precise causality chain is not obvious. It is possible that direct effects on confinement may cause a pedestal pressure variation or, alternatively, edge phenoma like changing wall recycling may alter the pedestal pressure and thereby confinement.

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