Effect of Variation in Equilibrium Shape on ELMing H–Mode Performance in DIII–D Diverted Plasmas* EX

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This paper describes experiments that have increased our understanding of the complex coupling of core plasma performance to plasma cross section and divertor plasma shape. A series of systematic shape variation experiments were done using ELMing H–mode plasmas in DIII–D. The response of core, pedestal, scrape-off-layer (SOL), and divertor plasma performance was examined versus *triangularity*, δ (Fig. 1), *up/down magnetic balance*, DR_{SEP} (Fig. 2), and secondary *divertor volume* as described in detail below. The data showed that high δ increases the energy in the H–mode pedestal (Fig. 1) and the global energy confinement of the core plasma. In addition, a nearly balanced double-null (DN) shape is effective for sharing the peak heat flux in the divertors (DR_{SEP} = 0.3 cm in Fig. 2). Finally, the presence of a second X–point in unbalanced DN shapes does not degrade the plasma performance if the secondary X–point is sufficiently far inside the vacuum vessel. These results indicate that for high δ operation an unbalanced DN shape has some advantages over a single-null shape for future high power tokamak operation.

The *δ variations* showed that in unpumped plasmas at low to moderate density, ($n_e/n_G \leq$ 0.7), the core and pedestal performance improve with δ (Fig. 1) [1]. The pressure at the top of the H–mode pedestal, p^{ped}, increased strongly with δ (Fig. 1) primarily due to an increase in the margin by which the edge pressure gradient exceeded the ideal ballooning mode first stability limit. A weak inverse dependence of the width of the H–mode transport barrier, Δ,

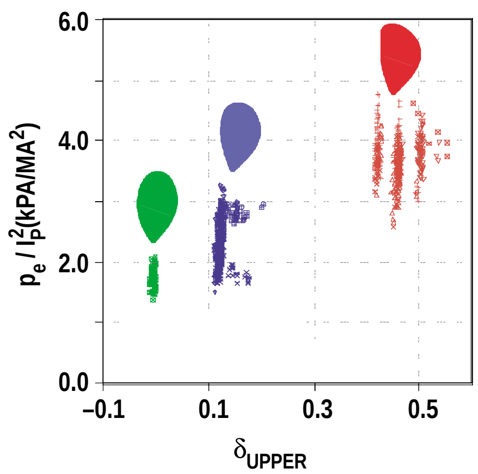

Fig. 1. Normalized pedestal pressure (averaged over Type I ELMs) increases with triangularity for moderate density unpumped plasmas.

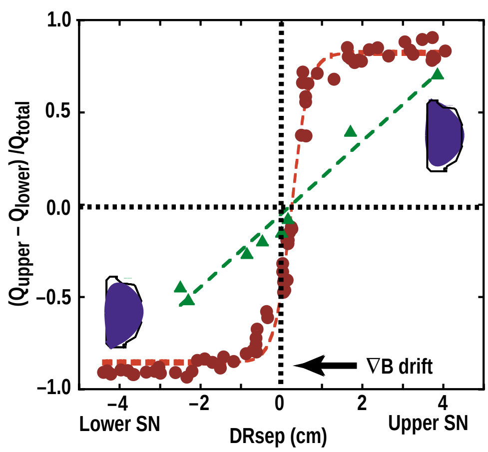

Fig. 2. Peak heat flux balance versus up/down magnetic balance showing sharp transition (circles) near DN shape (DR_{SEP} = 0) in attached plasmas, broad transition (triangles) at high density.

*This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48, DE-AC03-99ER54463 (GA), DE-AC04-94AL85000 (SNL), DE-AC05-96OR22465 (ORNL), and Grants DE-FG03-86ER53225 (UCLA), and DE-FG03-95ER54294 (UCSD).

on δ relative to a previously obtained scaling $\Delta \propto \left(\beta_p^{ped}\right)^{0.5}$ [2] was observed. However, the energy loss for Type I ELMs also increased with δ in proportion to the pedestal energy increase which could make divertor design more difficult. The normalized energy confinement, $H = \tau_E / \tau_E^{ITER89P}$, increased with δ as a result of an increase in the pedestal energy (Fig. 1).

At high density ($n_e/n_G \sim 1$), the performance *variation with δ* at fixed profiles was weak. Over a wide range of densities ($n_e/n_G < 0.7$) the pressure pedestal prior to an ELM was very nearly constant but depended on plasma shape. As density was increased, p^{ped} began to decrease in the range $0.6 < n_e^{ped}/n_G$ in both low and high δ discharges. Once the reduction in p^{ped} began it was observed to decay at a rate described by $\partial p^{ped}/\partial n \propto \eta^{-0.5}$, where η is the resistivity, independent of δ, and the p^{ped} at higher δ and higher T_e decayed more rapidly. This leads to the weak dependence of pedestal pressure on δ at high n_e/n_G. Both the change in pedestal pressure and the response of the density profile play a role in setting H. High density low δ discharges with divertor pumping showed density peaking leading to recovery of good confinement. SOL flow and the edge safety factor may also play a role in the density peaking; work continues in this area.

The *up/down magnetic balance* studies showed that the distribution of the heat flux to attached divertors can be predicted from knowledge of the flux surface geometry and midplane SOL power scale lengths [3]. For attached plasmas, the variation in heat flux sharing between divertors is large for small changes in DR_{SEP} near 0, i.e., near DN (Fig. 2). Here DR_{SEP} is the midplane radial distance between the upper and lower divertor separatrices. This sharp dependence however may actually be useful in feedback schemes to control DN shapes. This sensitivity is consistent with the measured midplane scrape-off width of the parallel divertor heat flux, λ_q. Furthermore, λ_q can be approximated to within a factor of two with a simple model using only the midplane scrape-off lengths of n_e and T_e. This suggests that divertor processes (e.g., recycling) are not dominating the physics. In detached plasmas, however, the heat flux sharing between divertors is much less sensitive to DR_{SEP} (Fig. 2) suggesting that divertor effects are playing a role.

Other effects of changes in *magnetic balance* can not be predicted from flux surface geometry alone. The peak heat flux in the outer divertor may exceed that of the inner divertor by tenfold in a balanced DN. The variation of the peak particle flux between attached divertors is less sensitive to changes in DR_{SEP} than in the heat flux case, suggesting that divertor processes are much more important here. As the balance is shifted slightly away from the ∇B drift direction heat flux sharing improves but the H-L back transition occurs at lower density.

For an unbalanced DN plasma, the divertor heat flux performance was not strongly degraded by reduction in the *secondary divertor volume* provided the secondary X–point was well inside the vessel. The secondary X–point maps at the midplane to a flux surface radially outboard of the primary. The performance sensitivity was examined by varying the secondary X–point height from the target plate while holding the primary X–point height fixed. The ion ∇B drift was in the direction of the primary divertor. The peak heat flux in the secondary divertor was nearly constant until the secondary X–point height was reduced below a threshhold value. At this point the peak heat flux increased a factor of 3. This indicates that the secondary divertor target was beginning to act like a heat flux limiter as flux surfaces, that were one SOL power scale length from the primary separatrix at the midplane, mapped to the target with negligible divertor leg length.

Core performance was affected as *secondary divertor volume* was reduced. The effective rate of rise of the core n_e at the L-H transition increased and the line averaged n_e at the H-L back transition decreased as the secondary X–point height decreased, presumably due to reduced screening of neutrals from the core by the smaller secondary divertor volume.

The quantitative understanding gained here provides valuable guidance as to the effect of shape variations on projected performance in future tokamaks. High core performance can be obtained with high δ plasma cross section. Favorable divertor performance can also be obtained at high δ in unbalanced DN divertors and the minimum divertor volume and magnetic balance requirements are predictable.

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