Influence of Plasma Edge Pressure Gradient Limits on H-mode Confinement in ASDEX Upgrade

W. Suttrop, M. Kaufmann, O. Kardaun, K. Lackner, F. Ryter,
H. Salzmann, J. Schweinzer, J. Stober, ASDEX Upgrade team,
Max-Planck-Institut für Plasmaphysik, EURATOM Association, D-85748 Garching

Abstract

Stiffness of core temperature profiles in H-modes of ASDEX Upgrade links global confinement to the edge pressure gradient in cases where the density profile remains unchanged. This is the case particularly in low radiation discharges with hot plasma edge, where electron density profiles are flat almost out to the plasma boundary. As a consequence, confinement scalings for discharges near and below the ideal ballooning limit differ. In particular, the favourable density dependence predicted by the ITER ELMy H-mode scalings is lost in type I ELMy H-mode. Density profiles show significant variation, e.g. spontaneous peaking during Completely Detached H-modes (CDH-modes), which may allow to combine good confinement with low edge temperatures and favourable type III ELMs.

Introduction

From core transport models involving critical gradients (e.g. [1]) one expects that above a certain heating power, core temperature profiles will become stiff, i.e. increased heat flux results merely in faint augmentation of grad T. As a consequence, boundary conditions at the plasma edge can determine the stored kinetic energy. In particular, any upper temperature or pressure limit at the plasma edge, e.g. the ideal ballooning limit, potentially defines a fundamental performance limit.

In a related paper [2], regime boundaries in edge parameter space (T_e^b, n_e^b) as identified on the ASDEX Upgrade tokamak (ideal ballooning limit, H-mode threshold, type III ELM boundary and density limit) are discussed. Here we concentrate on the effect of proximity to the ideal ballooning limit at the edge to global confinement scalings. We consider a data set of 798 time intervals in 131 H-mode discharges in deuterium performed during 1996 on ASDEX Upgrade with single-null divertor configuration and ion grad-B drift towards X point. Parameters are plasma current $I_p = 0.6\ldots1.2$ MA, toroidal field $B_t = 1.5\ldots3$ T, line averaged density $\overline{n}_e = 2.3\times10^{19}\ldots1.3\times10^{20}$ m^{-3}, and neutral deuterium beam heating power $P_{\rm NBI} = 2.5\ldots10$ MW.

Relation between edge and core confinement

On ASDEX Upgrade, stiffness of electron and ion temperature profiles is generally observed during neutral beam heated H-modes ($P_{heat} > 2.5$ MW). Fig. 1 a) shows that central T_e (taken at $\rho_p \approx 0.15$) and edge T_e (at $r = a - 2$ cm, both values measured by Thomson scattering) are nearly proportional for a variety of discharges near the ideal ballooning limit at the edge. A wide range of plasma parameters, particularly of $\overline{n_e}$, is covered by the data set (see above). The normalized electron pressure gradient $\alpha_e = 2\mu_0 R q_{95}^2/B_t^2\ p_e'$ during type I ELMy was found to be $\alpha_e = 1.6 \pm 20\%$ for the discharges in the data set. Also, type III ELMs can be obtained at the ideal ballooning limit in case of high edge density, if $T_e(r = a - 2\text{ cm})$ remains below 300 eV. Those cases adhere to the same edge-core relation. However, during L-mode and type III ELMy H-mode below the ballooning

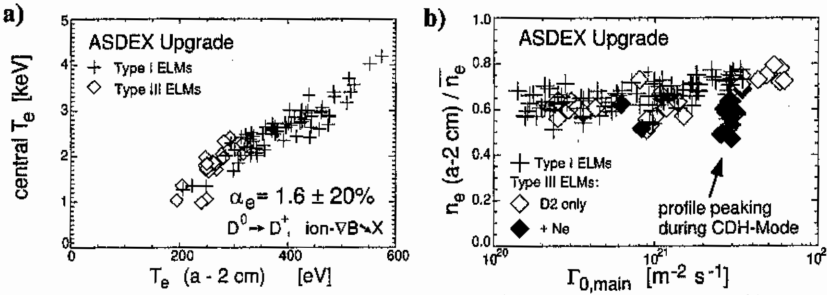

Figure 1: *Relation between plasma edge and core: (a) Electron temperature (discharges near the ideal ballooning limit at the edge), (b) relation between average and edge electron density for different levels of neutral gas flux.*

limit this relation between edge and core temperature breaks down, even at high P_{heat} (e.g. at high H-mode power threshold).

Density profiles in general do not show robust self-similarity. However, during type I ELMy H-mode the scrape-off layer and the plasma edge are hot ($T_e(r = a - 2 \text{ cm}) \geq 300$ eV) and the combination of low neutrals penetration depth and low beam fuelling in ASDEX Upgrade produces flat density profiles almost out to the separatrix. Fig 1 b) shows that the electron density n_e at $r = a - 2$ cm amounts to approximately $0.6 \times \overline{n_e}$ (line averaged density) over a wide range of neutral flux in the main chamber, a good shielding of the scrape-off layer and the plasma edge within 2 cm from the separatrix. Hence, self-similarity exists here. In contrast, neon puffed (CDH-mode [3]) discharges, show peaking of the central density attributed to an anomalous inward drift [4].

As a consequence of density and temperature profile similarity, one expects a relation between edge pressure and stored energy. Furthermore, as the edge radial gradient lengths are not varying much during H-mode, a relation between edge pressure gradient and core confinement is observed for cases near the ballooning limit (Fig. 2).

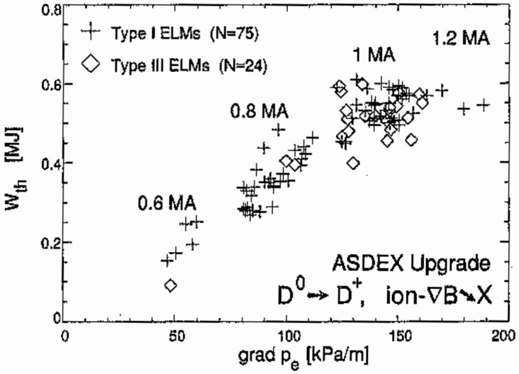

Figure 2: *Relation between thermal stored energy W_{th} and edge electron pressure gradient p'_e for discharges near the ideal ballooning limit at the edge (type I and type III ELMy H-mode).*

Stiffness of temperature profiles

Stiffness of core temperature profiles is usually very robust and not restricted to type I ELMy H-mode. An example is shown in Fig. 3, where in between two type I-ELMy H-mode phases, controlled neon gas puff has been used to radiate ≈ 85% of the input power at the edge. Complete Detached H-mode (CDH-mode) has been achieved. During the CDH-phase, central density peaking (Fig. 3 b) is observed. The NBI power is kept constant. The core temperature profile (T_e profiles are shown in Fig. 3 c) remains almost unchanged despite the strong density perturbation, resulting in an increase in stored energy even above the level during the initial type I ELMy phase. During the CDH phase, there is a two-fold departure from the edge-core relation described above for type I ELMy H-mode: The edge temperature drops due to forced impurity radiation, and at the same time confinement improves when the peaking of the density profile builds up.

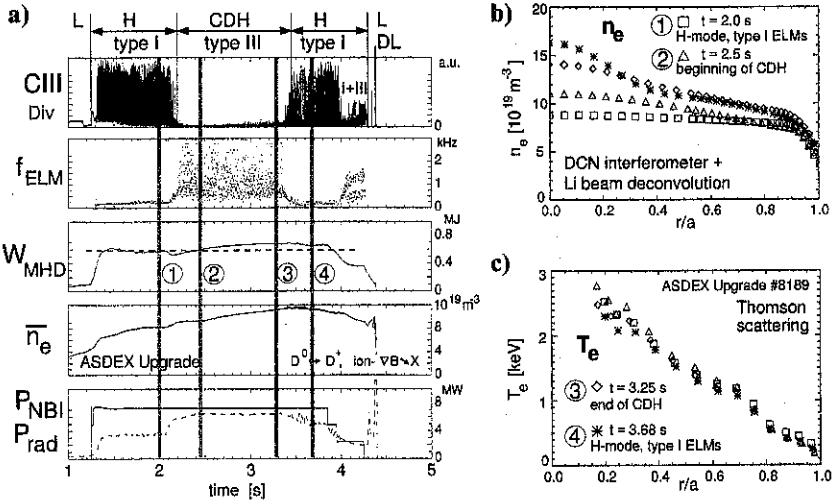

Figure 3: *Confinement improvement during a long CDH-phase (a) associated with central peaking of the density profile (b). The core electron temperature profile is stiff against the density change (c).*

Confinement at and below the ideal ballooning limit at the edge

Proportionality between stored energy and edge pressure gradient at the ballooning limit would imply that global confinement acquires the scaling of p'. This can be investigated by separate regression of p'_e and thermal stored energy $W_{\rm th}$ during type I ELMy H-mode (i.e. near the ideal ballooning limit) with respect to I_p, $\overline{n_e}$, B_t and P_{heat} (Fig. 4). The relations, found by ordinary least squares, are $p'_e(\text{edge}) = 158 \times 10^5 B_t^{-0.34\pm0.07} P_{\rm heat}^{0.20\pm0.03} \overline{n}_e^{-0.09\pm0.06} I_p^{1.9\pm0.13}$ (kPa/m) and $W_{\rm th} = 0.296 B_t^{-0.18\pm0.07} P_{\rm heat}^{0.40\pm0.03} \overline{n}_e^{-0.02\pm0.06} I_p^{1.38\pm0.12}$ (MJ). The units of I_p, $\overline{n_e}$, B_t and $P_{\rm heat}$ are MA, 10^{19} m^{-3}, T, and MW, respectively. Note that both p'_e(edge) and $W_{\rm th}$ do not depend on $\overline{n}_e$, in contrast to the favourable density dependence predicted e.g. by ITERH-92P(y) [5]. The I_p dependence of $W_{\rm th}$ is somewhat larger than in ITERH-92P(y) and also than for type III ELMy H-modes below the ideal ballooning limit in ASDEX Upgrade. However, it is smaller than that of p'_e. The latter effect, together with the retained $P_{\rm heat}$ dependence, appears as scatter of data points in Fig. 2 and indicates that p'(edge) may not be exactly the critical variable for confinement. It is speculated in [6] that the pressure or temperature at the edge pedestal top assumes this role. However, the edge pedestal width in ASDEX Upgrade shows little systematic variation, so that pressure gradient and pedestal pressure are almost proportional.

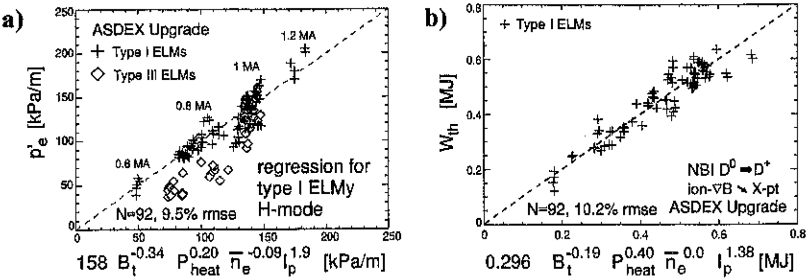

Figure 4: *Separate regression for type I ELMy H-mode discharges of (a) electron pressure gradient and (b) thermal stored energy.*

Analysis of type III ELMy discharges below the ideal ballooning limit yields a weaker scaling with I_p and more favourable B_t and n_e dependences while their confinement is below that of type I ELMy H-mode (with the exception of cases with strong density peaking) for the parameter range of ASDEX Upgrade encountered so far. Both scalings (near and far from the ballooning limit) match at high edge densities where, during type III ELMy H-modes, p'(edge) approaches the ideal ballooning limit.

Conclusion

A correlation between edge pressure gradient near the ideal ballooning limit and core confinement is found on ASDEX Upgrade which is based on robust temperature profile stiffness and flat density profiles during type I ELMy H-mode. A "near ballooning" confinement scaling results, which lacks the favourable density dependence of the ITER ELMy H-mode scalings but shows a somewhat stronger I_p dependence. A combination of good confinement and a sufficiently cold plasma edge, as to obtain divertor-compatible type III ELMs, seems possible by manipulation of the density profile. One successful scheme demonstrated on ASDEX Upgrade is the Completely Detached H-mode [3]. Another possibility would be central fuelling by deep pellet injection, where high fuelling efficiency can be achieved by injection from the high-field side [7].

References

[1] Kotschenreuther M *et al.* 1995 *Phys. Plasmas* **2** 2381

[2] Suttrop W *et al.* submitted to *Plasma Physics and Controlled Fusion*

[3] Gruber O *et al.* 1995 *Phys. Rev. Lett.* **74** 4217

[4] Becker G 1996 *Nuclear Fusion* **36** 1751

[5] H-mode Database Working Group 1992 Proc. 14th Int. Conf. IAEA Würzburg, Vol.3, p.251

[6] Janeschitz G *et al.* 1997 this conference

[7] Lang P *et al.* 1997 this conference