

Edge behaviour and divertor load in ASDEX Upgrade discharges with H-mode edge and improved core confinement

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Introduction

Future reactor grade fusion experiments like ITER must operate in an enhanced confinement regime like the H-mode discovered at ASDEX [1], in order to guarantee a sufficiently high fusion product at reasonable machine size. A further improvement in core plasma performance is possible by establishing an internal transport barrier (ITB) [2] inside the plasma edge region, e.g. by current profile tailoring using specific discharge ramp-up and heating scenarios. Further confinement improvements seem to be possible by appropriate plasma cross section shaping. For (quasi-)stationary operation such an improved confinement plasma must be combined with an edge scheme, which allows for safe power and particle exhaust, e.g. by an appropriate divertor. A specific problem in H-mode scenarios with good confinement is the appearance of edge localised modes (ELMs), which transport a large amount of plasma stored energy burst like to the divertor plates. Extrapolation from present machines to ITER show that the amount of energy transported by a single type-I ELM would exceed the energy level for melting and ablation of tungsten and carbon, respectively. In this paper, the elements of such an envisaged operation regime are analysed based on the experimental evidence collected up to now at ASDEX Upgrade.

Experiments

The fusion experiment ASDEX Upgrade is a medium size tokamak with improved shaping capability and with ITER like proportions. It is well equipped with edge and divertor diagnostics and various heating systems. The experiments under consideration are H-mode discharges of three types. (i) H-mode discharges with low and medium triangularity and type-I ELMs showing the typical degradation of confinement with increasing density. (ii) H-mode discharges with improved confinement established e.g. by current profile tailoring using specific discharge ramp-up and heating scenarios. This type of discharges requires a low triangularity where the strike point positions are in the divertor legs resulting in a high pumping efficiency of the cryopump. The improved confinement is lost with increasing edge density revealing the strong link between edge parameters and plasma performance. (iii) Discharges at high triangularity near to a double null configuration. This discharges show a good confinement also at Greenwald densities and a type-II ELM behaviour which is favourable for ITER due to the nearly continuous energy flux onto the divertor plates [3].

The variation of the essential parameters was: line averaged density: $4\text{-}12 \times 10^{19} \text{ m}^{-3}$; heating power: 2.5-15 MW; plasma current: 0.6-1.2 MA; averaged triangularity: 0.2-0.36; gas fuelling

in the midplane and the private flux region with hydrogen and hydrocarbons; edge pumping by an in-vessel cryopump.

Results and discussion

ELM behaviour and the edge profiles of electron temperature and density are affected by many parameters. As an example, Fig. 1 shows an H-mode discharge in ASDEX Upgrade. The H-mode with type-I ELMs is established at moderate density of $4 \times 10^{19} \text{ m}^{-3}$ and a neutral beam heating power of 2.5 MW. Later in the discharge, the heating power is further increased keeping the line averaged density constant. The ELM frequency did not change significantly as well as the energy confinement time. When the gas valve is opened to increase the density at 4.3 s, the ELM frequency increases despite the fact, that the heating power stays constant.

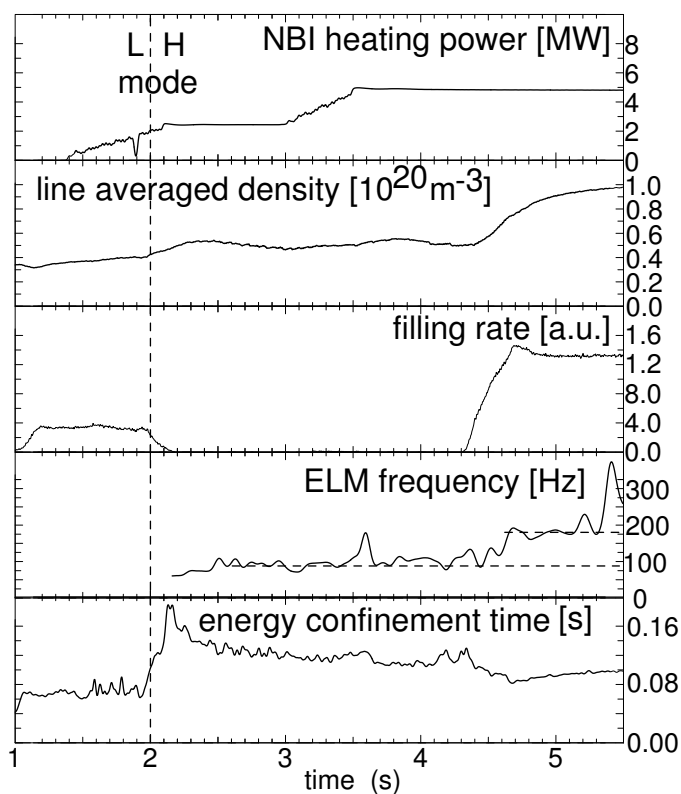


Figure 1 H-mode discharge with type-I ELMs.

This example reveals already that the frequency of type-I ELMs did not necessarily increase with NI heating power and is affected by other discharge parameters, such as density or gas fuelling, and plasma shape. It can be seen also in Fig.1 that in discharge phases, where the ELM frequency changes also the energy confinement time varies. This feature, observed in a large set of discharges gives the motivation to study the correlation between the ELM frequency and energy confinement time for a wide range of parameters (Fig. 2) including H-mode discharges with improved confinement.

We would expect, that the energy confinement time at a given frequency is higher for the improved confinement discharges because the ELMs are related only to the edge barrier and

the additional transport barrier leads to an independent increase of stored energy. All data points with improved confinement are located at the right hand side of the fit showing this tendency. That there is no clear separation between H-mode and H-mode with improved confinement comes from the fact that the confinement enhancement is located near to the plasma centre at $\rho_{pol} < 0.6$ resulting in a limited net increase of the plasma stored energy.

The low type-I ELM frequency at high triangularity (triangle pointing down) is caused by the appearance of small, but frequent type-II ELMs [3], which obviously enhance the cross field transport in between type-I ELMs, causing an increase of the time interval to the next large ELM. It should be mentioned, that the ELM frequency was inferred from target plate heat flux as measured by fast thermography. In contrast to divertor H_{α} , the small type-II ELMs are practically invisible on the heat flux as desired from the point of view of save power exhaust, while type-I ELMs are easily resolved. Of course, for the same reasons, the favourable discharges with type-II ELMs only do not appear at all in this graph.

From Fig. 2 a power law dependence for the relation between ELM frequency and confinement time is found: $f \sim \tau^{-\alpha}$, with $\alpha = 1.5$ for a fit through the ASDEX Upgrade data, and $\alpha=1.7$ if JET data from [4] are included.

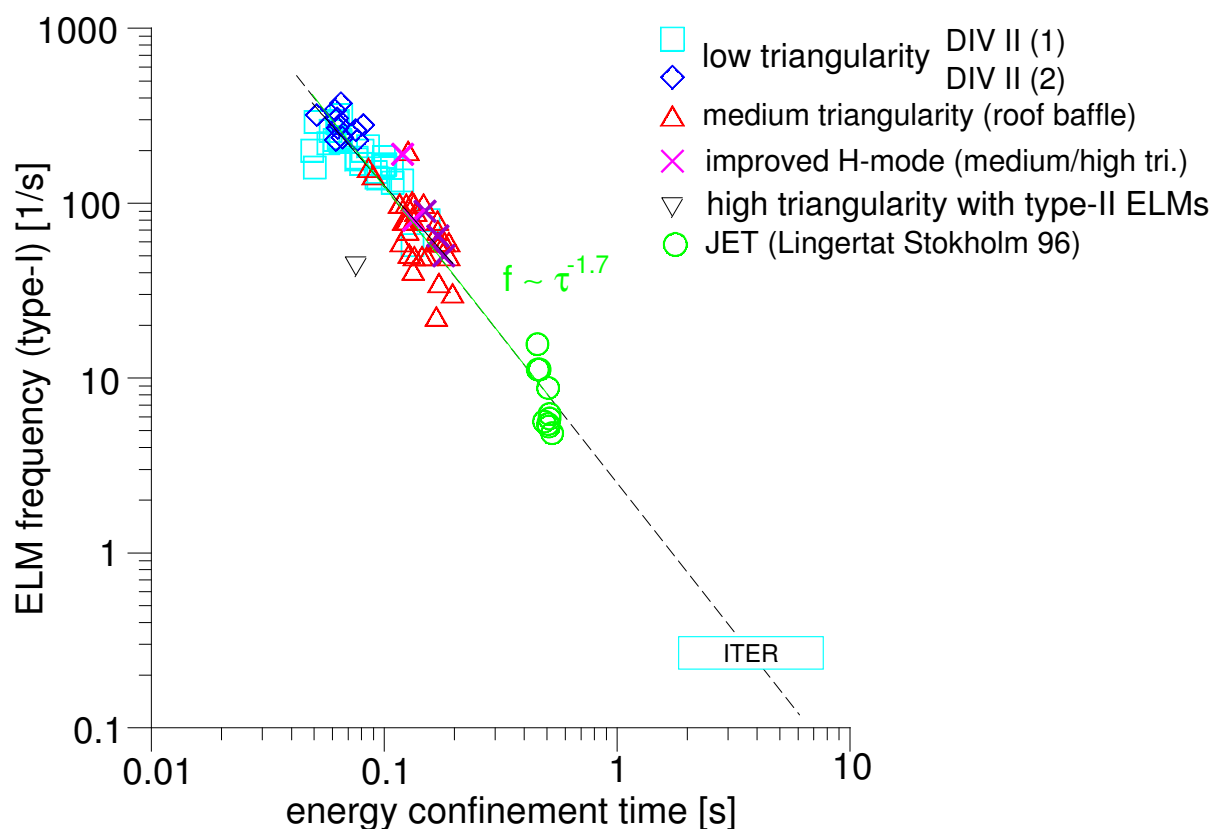


Figure 2 Correlation between type-I ELM frequency and energy confinement time.

Normally, the contribution of energy losses by ELMs, ΔW , is either expressed in fraction of plasma stored energy, $\Delta W/W$, or by the fraction of power transported by ELMs, $(\Delta W * f)/P_{heat}$. The values for ASDEX Upgrade are $\Delta W/W \approx 5\%$ and $(\Delta W * f)/P_{heat} \approx 30\%$ [5], respectively. Comparable values are reported also from other tokamaks: JET: $(\Delta W * f)/P_{heat} \approx 30\%$ [4]; DIII-D: $(\Delta W * f)/P_{heat} \approx 20\%$ [7]. The ELM transported power is considered to be constant [6] for individual machines and is assumed to be the same for ITER.

Substituting the ELM frequency by the confinement time reveals that the ELM transported energy should increase with the energy confinement as: $\Delta W/W \sim \tau^{0.1}$. Indeed, it was found at JET that the energy loss per ELM decreases with the frequency [8, Fig.17], i.e. increases with energy confinement.

The increase of the ELM transported energy with the energy confinement time aggravates the difficulty with type-I ELMs in ITER. The ELM frequency at an energy confinement time of 5 s will be about 0.2-0.4 Hz, resulting in a value for the energy per ELM of $\Delta W = 47$ MJ ($0.25 \times 75 / 0.4$ MW/Hz) which exceeds the tolerable value of 4 MJ by one order of magnitude.

Summary

It is shown that in low and medium density discharges the frequency of type-I ELMs and the energy confinement time are correlated.

The discharges with improved H-mode confinement fit into these dependencies due to the limited increase of the plasma stored energy.

The ELM transported power is constant for large and medium size tokamaks. This results in an increase of ELM transported energy with increasing energy confinement.

The shown correlation is based on data from ASDEX Upgrade. The added JET data supports the correlation found at ASDEX Upgrade.

The ELM database for ITER should be used to include data from different tokamaks to verify the ASDEX Upgrade result.

The existence of small frequent type-II ELMs reduces the contribution of type-I ELMs to the energy loss. H-mode discharges with type-II ELMs show a good energy confinement at high densities and mitigates the problem of intolerable high divertor load.

References

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