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# Operational boundaries of pellet fueled ELMy H-modes in ASDEX Upgrade and JET

P. T. Lang, O. Gruber, L. D. Horton, T. T. C. Jones*,
A. Lorenz, V. Mertens, ASDEX Upgrade and JET* Teams

*Max-Planck-Institut für Plasmaphysik, EURATOM Association*
*Boltzmannstr. 2, 85748 Garching, Germany*
** JET Joint Undertaking, Abingdon, U.K., OX14 3EA*

## 1. Introduction

The invention of cryogenic fuel pellet injection from the tokamak inboard [1] allowed for the first time efficient particle fueling in hot target plasmas. Prompt particle losses due to a fast diamagnetic curvature drift [2] of the deposited particles and immediate particle release due to ELMs during injection into H-mode phases can be strongly reduced by this novel technique. Thus, density ramp up beyond the Greenwald limit is achieved in ASDEX Upgrade and JET without losing typical H-mode features. The stiff relation between edge density and line averaged density $\bar{n}_e$ observed in a study of the H-mode gas-puff density limit at ASDEX Upgrade [3] can be broken off by injection of pellets allowing for particle deposition deep inside the core plasma. However, with increasing density some confinement degradation correlated to the occurence of pellet induced ELM bursts is still encountered. In this paper, a simple model is derived assuming the ELM bursts to form the major performance restriction.

## 2. Experimental set up and results

Both, the ASDEX Upgrade and JET pellet injection systems are based on a centrifuge accelerator [4], recently modified to enable inboard launch by adapting the centrifuge to a guiding tube installed inside the torus vessel leading to the inboard side. The ASDEX Upgrade injector was adjusted for high repetition rates and particle fluxes in the inboard launch scenario, the inventory sufficient to deliver pellet sequences of 2 s duration at maximum rate. Pellets were injected towards the plasma centre under $44^o$ to the horizontal plane. In JET refueling experiments, pellets available throughout the discharge were injected also under $44^o$ to the horizontal plane but tangentially to a flux surface with $\rho = 0.7$. Both tokamaks were operated in lower single null configuration, at ASDEX Upgrade with standard low triangularity (averaged $\delta < 0.2$), at JET with an upper $\delta$ of 0.25 or 0.38. Plasma heating was mainly applied via Neutral Beam Injection ($D^0$-injection), NBI, to an extent of up to 10 MW in ASDEX Upgrade and 17 MW in JET. Only preprogrammed pellet sequences were used on JET, on ASDEX Upgrade additionally on-line feedback controlled pellet injection was performed in some discharges.

A systematic study was performed to find a scenario for density control at a level well above the Greenwald limit whilst minimizing degradation of particle and energy confinement. Results from ASDEX Upgrade described in detail elsewhere [5] agree in their basic features with those found at JET. Pellet refueling showed a remarkably improved plasma energy confinement compared to gas puffing. Stable quasi-steady state H-mode operation beyond the Greenwald density was achieved. However, reduction of energy confinement was found in every discharge correlated with the presence of strong pellet induced ELM activity. The typical signature and effect of the pellet induced ELMs is shown on the example of the ASDEX Upgrade discharge #10533 in fig. 1. After pellet injection, $\bar{n}_e$ stayed almost constant for about 4 ms. Then, a rapid density decrease occured, expelling typically $6 \times 10^{19}$ particles within 2-3 ms. This short phase with strong particle flux (typically $3 \times 10^{22}$/s) from the plasma was followed again by a quiet phase until the next rapid density decay. The strong particle flux was correlated to the presence of strong ELM activity.

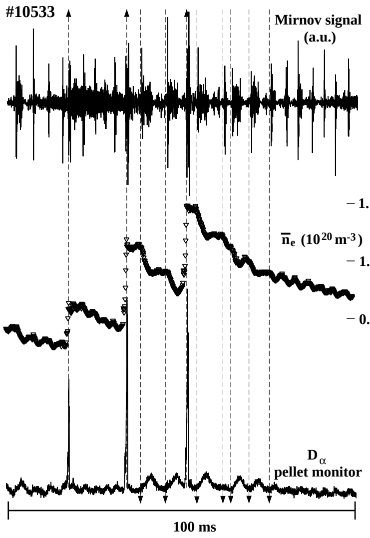

Figure 1: *Correlation between ELM activity and plasma density decay following pellet injection. Mirnov coil signal shows MHD activity, density from DCN-interferometer and pellet* $D_\alpha$*-monitor.*

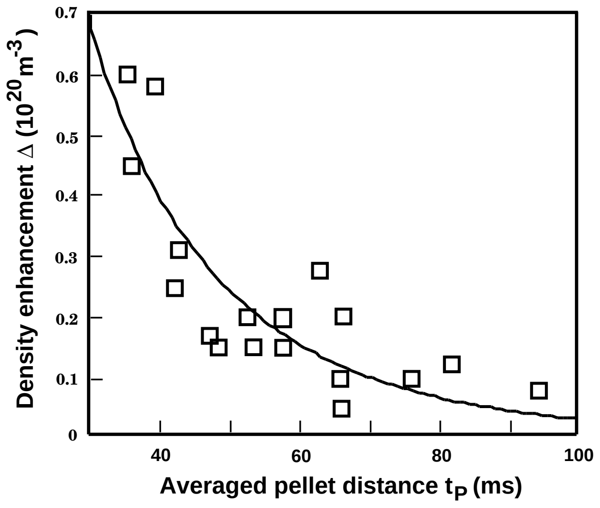

Figure 2: *Averaged temporal pellet distance versus pellet induced density enhancement* $\Delta$*. Data (squares) from 2 s steady state discharges. Solid curve is a least square fit by equ. 2* ($n_P = 1.74 \times 10^{19} m^{-3}$, $\tau_P = 24 ms$) *to the data.*

## 3. Performance limitations caused by pellet induced ELM activity

In the following, the possible restriction to the accessible tokamak operational area imposed by the pellet induced enhanced ELM activity will be analysed and compared to the observed behaviour. Assuming each single pellet causes an instant density increase $\bar{n}_P$ and the pellet induced density enhancement returns with a decay time $\tau_P$ towards the base density $\bar{n}_e^b$. Continuous pellet injection with temporal pellet distance $t_P$ causes a gradual density ramp up until stagnation at an enhancement level $\Delta$ is achieved. Each further pellet then causes an increase to a peak density $\bar{n}_e^b + \Delta + \bar{n}_P$ declining to $\bar{n}_e^b + \Delta$ just before the next pellet is injected, thus

$$(\Delta + \bar{n}_P)e^{-t_P/\tau_P} = \Delta \tag{1}$$

holds. The steady state density enhancement can be calculated as

$$\Delta = \frac{\bar{n}_P}{e^{t_P/\tau_P} - 1} \tag{2}$$

Data of an averaged pellet distance needed to achieve a requested density enhancement $\Delta$ in sequences of typically 2 s duration derived from the ASDEX Upgrade discharges are plotted as open squares in figure 2. To obtain according values for $n_P$ and $\tau_P$ for the further modelling, a least-square fit to the data was performed. The solid curve represents equ. (2) with $\bar{n}_P = 1.74 \times 10^{19}\ m^{-3}$ (yielding an effective pellet inventory $N_P \approx 2.1 \times 10^{20}$) and $\tau = 24\ ms$. With theses values, the required pellet particle flux

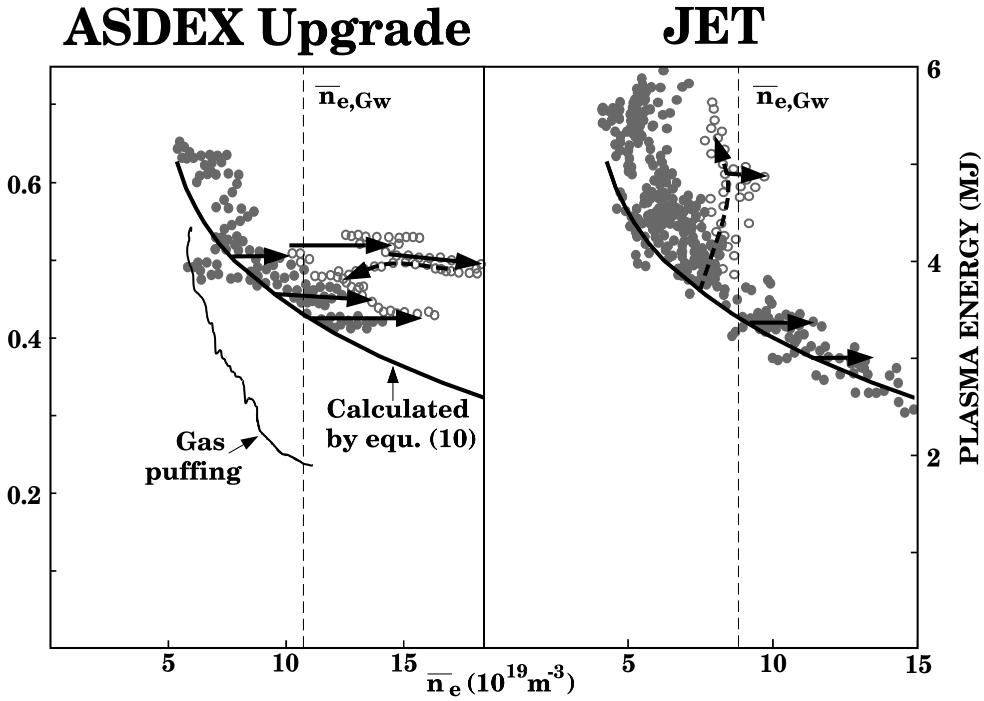

Figure 3: *Plasma energy versus line averaged density reached with steady state pellet injection (filled circles) and in transiently enhanced phases (open circles). Solid curves describes expected confinement reduction caused by ELM burst losses calculated according to equ. (10). Operational area limitation for gas puff refueling in ASDEX Upgrade also given for comparison.*

$$\Phi_P(\Delta) = \frac{N_P}{t_P} \tag{3}$$

for a given density enhancement can be calculated. Assuming particles of averaged temperature T lost in the ELM burst, the burst energy losses is

$$P_{loss} \sim \Phi_{loss}\ T \tag{4}$$

with $\Phi_{loss}$ the burst particle losses. As temperature profiles were found to be almost self similar under H-mode conditions [6], the loss power can be approximated as

$$P_{loss} = c\ \Phi_{loss}\ W \tag{5}$$

with W the plasma energy an c a proportionality factor. The equilibrium state before pellet injection set in is characterised by

$$P_h = \frac{W^0}{\tau_E^0} \tag{6}$$

with $P_h$ the heating power and $W^0$ and $\tau_E^0$ the pre-pellet plasma energy and energy confinement time. Once steady state conditions are established by pellet injection, a constant additional loss power imposed by ELM bursts changes (6) to

$$P_h - P_{loss} = \frac{W}{\tau_E} \tag{7}$$

Assuming an unchanged energy confinement time, combination of (6) and (7) yields

$$\frac{W}{P_h - P_{loss}} = \frac{W^0}{P_h} \tag{8}$$

and the steady state energy in the pellet phase can be calculated as

$$W = \frac{W^0}{1 + \frac{c\ \Phi_{loss}\ W_0}{P_h}} \tag{9}$$

As the particle losses are by far dominated by the ELM burst, $\Phi_{loss} = \Phi_P$ can be used in the steady state case. Thus, for a given $\Delta$ the according energy reduction due to (9) can be calculated using $\Phi_P$ obtained from (2) and (3).
In figure 3, data points achieved during steady state pellet injection both at ASDEX Upgrade and JET are given as filled circles. The limiting curve of the ASDEX Upgrade data is quite well reproduced by the relation

$$W = \frac{W^0}{1 + c'\ \Phi_P} \tag{10}$$

with $c' = 1.47 \times 10^{-22} s$. Assuming an averaged particle temperature $T = T_e = T_i$,

$$c' = \frac{3\ k_B\ T_0}{P_h} \tag{11}$$

gives $T_0 \approx 1.5\ keV$ for $P_h = 5\ MW$. This is in good agreement with the initial plasma temperature in the region of the main particle deposition. For the steady state JET data, the same curve obtained for ASDEX Upgrade fit to the data when taking into account the increased plasma volume and hence energy content of JET.

## 4. Discussion

The simple model derived in this paper describes quite well the baseline of the operational area achieved in ASDEX Upgrade with pellet refueling. Thus, the foremost loss mechanism is identified to be the rapid loss of thermalised particles in a burst of strong, long lasting ELMs occuring after pellet injection. Since these ELM burst losses obviously cause the operational boundary faced with, further performance improvement requires minimization these losses. The pellet surplus density decay was found to be $\tau_P = 24\ ms$ significantely shorter than the core particle confinement time ($\approx 120\ ms$ [5]). This indicates that there is still some headroom for further mitigation of pellet induced ELM bursts by deeper pellet penetration applying higher pellet launch speed. Moreover, as energy recovery takes place on a shorter time scale than the density decay, transient phases of improved confinement can be achieved. Such phases are represented by the open symbols in fig. 3. Further optimisation by creating a pellet fueling cycle with less ELM losses seems feasible. Appropriate experiments are in preparation.

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