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Pellet refuelling of particle loss due to ELM mitigation with RMPs in the ASDEX Upgrade tokamak at low collisionality

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The complete refuelling of the plasma density loss (pump-out) caused by mitigation of edge localised modes (ELMs) is demonstrated on the ASDEX Upgrade tokamak. The plasma is refuelled by injection of frozen deuterium pellets and ELMs are mitigated by external resonant magnetic perturbations (RMPs). In this experiment relevant dimensionless parameters, such as relative pellet size, relative RMP amplitude and pedestal collisionality are kept at the ITER like values. Refuelling of density pump out of the size of $\Delta n/n \sim 30\%$ requires a factor of two increase of nominal fuelling rate. Energy confinement and pedestal temperatures are not restored to pre-RMP values by pellet refuelling.

Keywords: plasma density, pellet fuelling, ELM control

(Some figures may appear in colour only in the online journal)

1. Introduction

The operation of tokamak fusion reactors is based on plasmas in the high confinement regime, the *H*-mode. However the *H*-mode is typically accompanied by edge localised modes (ELMs) which are not compatible with the long term divertor operation and therefore ELM control has to be applied. One of the ELM control techniques is the application of resonant magnetic perturbations (RMPs) produced by an external set of magnetic coils [1–4] and such a system is considered on ITER [5].

The application of RMPs in tokamaks has, however, unwanted side effects. It is often observed that when ELMs are mitigated the plasma density is significantly reduced which is dubbed as a 'density pump-out' effect. This happens if RMPs increase inter-ELM transport or the increase of ELM frequency $f_{\rm ELM}$ by RMPs is not matched by sufficient reduction of particle loss per ELM $\delta N_{\rm ELM}$ and thus the related particle loss $\Phi_{\rm ELM} = f_{\rm ELM} \delta N_{\rm ELM}$ increases. Density pump-out is however not necessarily generic. It can be avoided by adjusting the plasma position as demonstrated in Tore-Supra [6] or by flipping the phase of the n = 3 RMP field as shown in DIII-D [7]. In ASDEX Upgrade the density even increased during RMP ELM mitigation at high collisionality [8].

In ITER, the plasma density should be carefully adjusted during all phases of plasma evolution as it is the density through which the fusion power is controlled [9]. During the H-mode phase the density control by gas fuelling is likely to be inadequate [10] and fuelling by frozen deuterium-tritium pellets launched from the high field side of the plasma is part



⁴See www.euro-fusionscipub.org/mst1.



Figure 1. Temporal evolution of plasma parameters with ELM mitigation by RMPs and pellet fuelling. (*a*) Line integrated density (bottom trace), pellet ablation radiation monitor (top trace, inverted), (*b*) divertor strike point current, (*c*) energy confinement times, (*d*) time averaged electron and ion pedestal temperatures are calculated as: $T_{e,ped} = \langle T_e(\rho \approx 0.94) \rangle_{\Delta t=0.3 \text{ s}}$, $T_{i,ped} = \langle T_i(\rho = 0.93) \rangle_{\Delta t=0.1 \text{ s}}$, (*e*) RMP current, (*f*) NBI and ECRH power.

of the ITER design [11]. As a consequence, ELM control by RMPs and pellet fuelling should be tested simultaneously as a part of integrated scenario development.

Simultaneous pellet fuelling and ELM control by RMPs has been attempted on a number of machines. In DIII-D, the plasma with ELMs suppressed by RMPs has been refuelled by pellets but at a cost of return to ELMy *H*-mode [12] although there are cases when pellets do not trigger ELMs [1]. On JET, pellets have been used to refuel plasmas with RMPs though at relatively low plasma currents and using low field side pellets [4]. In ASDEX Upgrade, compatibility of pellet fuelling with ELM suppression by RMPs has been demonstrated although at high plasma collisionality and deeper pellet deposition [13]. On Mega Amp Spherical Tokamak (MAST), plasmas with RMPs have been refuelled by high field side pellets with moderate effect on ELM mitigation but gas fuelling was significant and $\delta N_{\text{ELM}} \sim 3\%$ of the plasma particle content, i.e. ~6 times larger than the ITER target [14, 15].

The present experiment was performed on ASDEX Upgrade and was designed specifically to demonstrate simultaneous density and ELM control under conditions envisaged in ITER during the density ramp and flat top *H*-mode phases [9]. The plasma pedestal collisionality, relative RMP amplitude and the ratio of pellet-to-plasma particle content are set close to the values expected in ITER i.e. $\nu_{*i,ped} = 0.19$, $b_{res}^{r} = 0.52 \times 10^{-3}$ and $N_{pel}/N_{plasma} = 7\%$ respectively (for definitions and details see the sections 2 and 3 below). We decided that the parameter to restore after application of ELM control is the plasma density as this will be the control situation during the density ramp and flat top phases in ITER. Another possibility would be to restore the plasma temperature but this would not mimic the ITER situation where during the density ramp up phase full auxiliary power is necessary and during the flat top phase fusion power will dominate.

2. Experimental setup

The experiment was conducted on the ASDEX Upgrade tokamak. The plasma has a single null divertor, with radius of the geometric axis $R_{\text{geo}} = 1.62 \,\text{m}$, minor radius a = 0.482 m, plasma current $I_p = 0.82 \text{ MA}$, toroidal field $B_{\rm T}(R = 1.65 \,{\rm m}) = 1.83 \,{\rm T}$ and safety factor $q_{95} = 3.8$. Fresh boronisation is applied to obtain low density and consequently low plasma collisionality. To improve reliability of the discharge small gas fuelling is applied with constant rate of $\Phi_{gas} = 0.5 \times 10^{21}$ at s⁻¹. Traces of the plasma parameters are shown on figure 1. The plasma is heated mainly by neutral beams. In addition a smaller amount of electron cyclotron heating (ECRH) is added with 3rd harmonic resonance absorption on axis. There is some residual power absorbed at the 2nd harmonics layer located at the top of the pedestal $\rho_{\rm pol} = 0.85 - 0.90$ on the high field side ($\rho_{\rm pol} = \sqrt{\psi_{\rm N}}$ where $\psi_{\rm N}$ is the normalised poloidal magnetic flux). Simulation by the TORBEAM code [16] shows that this residual 2nd harmonic power increases during the shot due to the gradual decrease of electron temperature and at ~6.0s it reaches 0.45



Figure 2. Temporal zoom into divertor strike point current at times indicated by arrows on figure 1(*b*). (*a*) Before RMPs, (*b*) after RMPs and (*c*) during pellets. Vertical black markers show the timing of core Thomson scattering measurements ($\rho_{pol} \leq 1$).

MW. This is about 5% of total the heating power and thus the residual 2nd harmonic power absorbed at the pedestal top should not significantly affect the discharge scenario.

ELM mitigation is provided by the RMP field created by an array of 8 upper and 8 lower coils located at the low field side of the plasma. Coils are connected to create a perturbation with n = 2 toroidal mode number and with 90° spatial phase-shift between lower and upper array for magnetic field alignment. In our case the normalised resonant component of applied (vacuum) perturbed field at $\rho_{pol} = 0.95$ is $b_{res}^{r} = 0.43 \times 10^{-3}$. For more details on RMP amplitude and on this scenario in general see the reference [17]. For ITER, the values of b_{res}^{r} have been calculated in [18]. For n = 3 configuration, the normalised resonant component of applied perturbed field are normalised to the toroidal magnetic field on geometric axis [18]. This analysis shows that the amplitude of RMP field in Or ASDEX Upgrade experiment is close to that expected in ITER.

Switching on the ELM mitigation coils causes the change of ELM behaviour and consequent density drop (see figures 1(a), (b) and 2). In addition RMPs also cause the drop of ion pedestal temperature while the electron pedestal temperature remains relatively unaffected. These are typical features of ELM mitigation by RMPs at low collisionality and are discussed in detail in [17]. Note that the reference phase just before RMPs is not fully stationary because of unintended drop of ECRH power between 2.2s and 2.4s (see figure 1(f)). As a result there is a sudden increase of density followed by the change in energy content and consequent transient in energy confinement time.



Figure 3. Ablation traces for all pellets in figure 1. Each data point represents pellet position at one frame of visible light camera with 75 000 frames s⁻¹ and 6.5 μ s exposure time. Labels correspond to the surfaces $\rho_{pol} = \text{const.}$ The solid diagonal line represents the nominal pellet flight line given by geometry of flight tube.

After the density reached a new quasi-stationary phase with RMPs the plasma is refuelled by high field side (HFS) pellets. The geometry of the pellet injection is shown in figure 3. Deuterium pellets have a nominal size of $1.4 \times 1.4 \times 1.5$ mm. Allowing 30% loss in the flight line the pellet particle content is $N_{\rm pel} = 1.2 \times 10^{20}$ atoms. This gives within a factor of 2 the same pellet-to-plasma particle ratio as expected in ITER, i.e. $N_{\rm pel}/N_{\rm plasma} = 7\%$ [10]. Pellets are launched from the high field side with a velocity of 560 m s⁻¹. Locations of pellets are determined from fast camera images in visible light (figure 3) and they show that pellets are evaporated in the outer 20% of the minor radius ($\rho_{\rm pol}\,{>}\,0.8$). Due to the geometry of the pellet launch some redistribution of pellet material by ∇B -drift is expected but nevertheless our pellets partially mimic ITER-like shallow pellets with deposition at $\rho_{\rm pol} \sim 0.8 - 0.9$ [19–21]. The pellet frequency is increased in 3 steps as seen in figure 1(a). At the initial pellet rate $f_{pel} = 7.5$ Hz the density changes only marginally. By doubling the pellet rate to $f_{\rm pel} = 15\,{\rm Hz}$ the density increases and it is restored to pre-RMP values. Figure 4 shows the density profiles at 3 time points: t_1 -just before RMP application, t_2 -after RMPs just before pellet fuelling and t_3 -after pellet refuelling (see arrow markers in figure 1(b)). It is seen that after pellet refuelling the density profile is within $\sim 10\%$ the same as before application of RMP. The details of the timings of ELMs and Thomson scattering measurements near these 3 time points is given in detail in figures 2(a)-(c) by the upper vertical black lines. It appears that almost all Thomson measurements fall during the between-ELM periods, which supports the comparison of the three profiles in figure 4.



Figure 4. Density profiles before RMPs (red), during RMPs (green) and after pellet re-fuelling (blue). The times around which the profiles are taken are indicated by arrows in figure 1(*b*). For each time point the figure shows about four consecutive Thomson scattering profiles within the specified time intervals, without averaging.

This shot is a result of several calibration shots in which the pellet size, frequency, velocity and timing were varied to obtain the best match in refuelling. Naturally the number of available calibration shots is limited and therefore still better match is possible. Ultimately the density should be controlled by feedback system using real time changes of pellet frequency (and perhaps including control of RMP current). Such experiments are planned in future. It is interesting that our pellet size and frequency is close to that used in DIII-D experiment where plasma was fuelled by HFS pellets ($N_{pel} = 1.2 \times 10^{20}$ atoms, $f_{\rm pel} = 20 \, \text{Hz}$) but ELM mitigation was provided by pacing pellets [22]. In DIII-D case such fuelling pellets lead to a significant density increase. Higher efficiency of pellet fuelling in DIII-D case is consistent with the fact that pellet ELM pacing does not lead to pump out effect. The critical question about refuelling of the density pump out is the price to pay in terms of efficiency of ELM mitigation, efficiency of pellet fuelling and possible reduction in confinement. These three aspects are now discussed separately below.

3. Efficiency of ELM mitigation

ELMs are detected by current on the tile at the divertor strike point. This signal is shown on figure 1(*b*) and in details around time points t_1 , t_2 , t_3 on figure 2. Before the application of RMPs the ELM frequency is $f_{ELM}(t_1) = 210$ Hz and it is a mixture of large (type-I) ELMs and smaller ELMs. Whether the smaller ELMs are type-IV (often referred as the low collisionality branch of type III ELMs [23, 24] remains to be identified. When RMPs are applied the ELM frequency increases to $f_{\rm ELM}(t_2) = 570$ Hz. In this phase only small ELMs are present. The application of pellet refuelling leads to a decrease of ELM frequency to $f_{\rm ELM}(t_3) = 440$ Hz. Despite this decrease, the ELM frequency after refuelling is still 2 times higher compared to the phase before RMP (time point t_1).

The relative energy loss per ELM before RMPs for large type-I ELMs is $\delta W_{\rm ELM}/W(t_1) \approx 5\%$, as determined from equilibrium reconstruction (W is the stored plasma energy). After the application of RMPs the ELM loss is so small that it is not reliably measured by equilibrium reconstruction and we use the inverse of normalised ELM frequency $\delta W_{\text{ELM}}/W \sim (f_{\text{ELM}} \tau_{\text{E,th}})^{-1}$ as a proxy, where $\tau_{\text{E,th}}$ is the thermal energy confinement time calculated by TRANSP [29] (see figure 1(c)). Application of RMPs reduces the inverse of normalised ELM frequency from $(f_{\text{ELM}} \tau_{\text{E,th}})^{-1}(t_1) \approx 7.2\%$ to $(f_{\rm ELM} \tau_{\rm E,th})^{-1}(t_2) \approx 4.5\%$ (here $\tau_{\rm E,th}(t_1)$ is an average over ± 0.25 s). After refuelling by pellets inverse of normalised ELM frequency $(f_{\text{ELM}} \tau_{\text{E,th}})^{-1}$ increases to $(f_{\text{ELM}} \tau_{\text{E,th}})^{-1} (t_3) \approx 5.0\%$. Therefore refuelling of density pump out preserves ELM mitigation but at compromised level, with $(f_{\rm ELM} \tau_{\rm E,th})^{-1}$ about 5 times larger than the ITER target $(f_{\text{ELM}} \tau_{\text{E,th}})^{-1} \sim 1\%$ [10]. It has to be noticed that using the inverse of the normalized ELM frequency as a proxy for the normalized ELM energy loss makes the implied assumption that the energy loss rate by ELMs is the same as the long time average energy loss rate. For that reason, and since it is the peak power density on the target that really determines ELM induced erosion, we have also inspected the infrared camera data which show the peak power density at divertor due to ELMs, q_{peak} . We found that these data display the similar trend as inferred from inverse ELM frequency: Application of RMPs reduces q_{peak} approximately twofold from $q_{\text{peak}}(t_1) \sim 8 \,\text{MW}\,\text{m}^{-2}$ to $q_{\text{peak}}(t_2) \sim 4 \text{ MW m}^{-2}$. The subsequent pellet refuelling does not change the power density and within the data scatter $q_{\text{peak}}(t_2) \sim q_{\text{peak}}(t_3) \sim 4 \,\text{MW}\,\text{m}^{-2}.$

Density pump out raises the question whether the ELM mitigation is not simply the result of change of density and RMPs act only as a density control tool. Broadly speaking our data show that the ELM frequency is not a simple function of pedestal density as this is almost the same before RMPs and after refuelling by pellets, $n_{e,ped}[t_1, t_3] = [2.9, 2.6] \times 10^{19} m^{-3}$, while the ELM frequency differs by a factor of two f_{ELM} [t_1, t_3] = [210, 440] Hz. In addition if f_{FLM} would be a simple function of density one would expect that the modulation by pellets will cause the synchronous modulation of ELM frequency and this is not observed as seen in figures 2(b) and (c). The data also do not support simple dependence of $f_{\rm ELM}$ with ion collisionality: Between t_1 and t_3 the ion collisionality increases as $\nu_{\text{si,ped}}[t_1, t_3] = [0.089, 0.21]$ suggesting f_{ELM} is increasing with increasing $\nu_{*i,ped}$, however this trend is not supported by time point t_2 were $\nu_{*i,ped}[t_2] = 0.10$, $f_{ELM}[t_2] = 570$ Hz, suggesting f_{ELM} decreases with $\nu_{*i,\text{ped}}$ between t_2 and t_3 . Here, $\nu_{\rm *i,ped} = 4.9 \times 10^{-19} q R_{\rm geo} n_{\rm i,ped} (m^{-3}) Z^4 \ln \Lambda_{ii} / (T_{\rm i,ped}^2 (eV) \varepsilon^{3/2})$



Figure 5. Detail of pellet deposition cycle. (*a*) Core and edge interferometer signals, (*b*) divertor current signal representing ELMs, (*c*) density profiles from Thomson scattering at times indicated by vertical lines in panel (*a*) in corresponding colours and line style.

[25], $\ln \Lambda_{ii} \approx 17$, $\varepsilon = a/R_{geo}$, $n_{e,ped} [t_2] = 1.69 \times 10^{19} m^{-3}$, $T_{i,ped}[t_1, t_2, t_3] = [1735, 1264, 1085] eV$, safety factor q = 3.3, ion charge Z = 1.5, $n_{i,ped} = n_{e,ped}/Z$. The fact that RMPs affect the ion and not the electron pedestal temperatures might indicate that it is the ion collisionality that might be relevant. Nevertheless the values of electron-ion collisionalities are similar $\nu_{*ei,ped}[t_1, t_2, t_3] = [0.18, 0.11, 0.25]$.

Finally note that even in the phase with full pellet refuelling (t_3) the ion collisionality is similar to that expected in ITER: $\nu_{*i,ped} = 0.19$ ($T_{i,ped} = 4 \text{ keV}$, $n_{e,ped} = 8 \times 10^{19} \text{m}^{-3}$). This means that pellet fuelling in ASDEX Upgrade is compatible with the low collisionality regime relevant to ITER operation.

4. Fuelling rate

The density pump out indicates that RMPs increase particle loss. The size of this additional loss channel can be estimated from the time derivative of the electron particle content at the time of RMP initiation: $\Phi_{\text{RMP}} = dN_e/dt|_{t=2.63s} \approx$ $d(n_e\ell)/dt|_{t=2.63s} V/2a \approx 1.0 \times 10^{21} at s^{-1}$. Here $(n_e\ell)$ is the horizontal line integrated density, $V = 12.1 \text{ m}^3$ is the plasma volume and *a* is the horizontal plasma radius. After the transient phase lasting about 0.3 s the plasma density equilibrates to about 60% of its pre RMP value. This decrease is approximately proportional over the whole plasma cross section from the pedestal to the core as seen in figure 4.

The above estimate for Φ_{RMP} is comparable to nominal fuelling rates: The pellet frequency at which the initial density is completely restored is $f_{\text{pel}} = 15 \text{ Hz}$ giving the fuelling rate of $\Phi_{\text{pel}} = N_{\text{pel}}f_{\text{pel}} = 1.9 \times 10^{21} \text{ at s}^{-1}$. The nominal gas valve flow rate is $\Phi_{\text{gas}} = 0.5 \times 10^{21} \text{ at s}^{-1}$ and the fuelling rate of neutral beams is $\Phi_{\text{NBI}} = 0.88 \times 10^{21} \text{ at s}^{-1}$, both approximately constant in time. Combining these values the ratio of nominal fuelling rates before and after refuelling is: $\Phi(t_3)/\Phi(t_2) = 1 + \Phi_{\text{pel}}/(\Phi_{\text{gas}} + \Phi_{\text{NBI}}) = 2.4$. In other words the cost for refuelling of RMP pump out, of the size of 30%, is the increase of nominal fuelling rate by a factor of 2.4.

The fact that nominal fuelling ratio $\Phi(t_3)/\Phi(t_2)$ is larger than the ratio of electron particle contents after and before refuelling, $N_{\rm e}(t_3)/N_{\rm e}(t_2)$, is the combination of two effects. Firstly, the nominal gas valve flow rate Φ_{gas} is not equal nor proportional to the gas fuelling rate as the neutral pressure around the plasma is linked to recycling and can vary in time. (In our case the neutral gas density in the divertor roughly doubles, $(3.5 \rightarrow 6.2) \times 10^{19}$ at m⁻³, during the pellet refuelling phase $4 \rightarrow 6s$.) The second effect is that the global particle confinement time $\tau_{\rm p} = N_{\rm e}/\Phi$ for phase with pellet fuelling is different from the phase with gas and beam fuelling. This is because these three fuelling methods deposit particles at different plasma radii and local particle transport is different in corresponding parts of the plasma. In addition, for pellets the link between the global particle confinement time and the local particle transport is more complex because of the transient character of post-pellet particle losses. For a single pellet, at the fully refuelled phase, the whole pellet cycle is shown in figure 5. It is seen from the signals of line integrated densities that the post-pellet losses involve two phases: fast loss lasting ~10 ms followed by slow density decay up to the next pellet. These two timescales are now discussed separately below.

4.1. Fast time scale particle loss

Figure 5(*a*) shows that the line integrated density covering the edge zone with $\rho_{\text{pol}} > 0.85$ decays with a characteristic time constant of $\tau_{\text{pellet}} = 8.8 \text{ ms}$. Thomson scattering density profiles taken at times which are bracketing this phase (red and blue symbols in figures 5(*a*) and (*c*) show that 6.8% of total plasma particles is lost during this time interval (the corresponding change in the core line integrated density is 2.8%). The time constant τ_{pellet} is referred to as the pellet retention time. When normalised to the global energy confinement time τ_{E} (see figure 1(*c*)) the ratio is $\tau_{\text{pellet}}/\tau_{\text{E}} = 0.19$. This value is similar to that measured in MAST with RMP ELM mitigation and shallow pellet deposition, $\tau_{\text{pellet}}/\tau_{\text{E}} = 0.17$ [15]. The nominal pellet diameter in MAST was 1.3 mm, similar to that in ASDEX Upgrade.

From figure 5(a) it is also seen that this density decay is not continuous but occurs in steps which are well correlated with ELMs. There are about 3-4 ELMs responsible for the whole density loss during the τ_{pellet} timescale. Comparing the density profiles immediately after the pellet evaporation and 8 ms after the pellet one can see that during this time interval a large fraction of the pellet material in the zone $\rho_{\rm pol}\,{>}\,0.77$ is lost. It is also obvious that the character of the particle loss is not diffusive as the loss occurs also in the zone with initially inverted density gradient ($dn_e/d\rho_{pol} > 0$). This observation is similar to that in MAST where it was interpreted as being due to the existence of sizeable eddy structure during the ELM [15]. This structure was observed by beam emission spectroscopy which showed perturbation of plasma density up to ten percent and spanning from the edge up to $\rho_{\rm pol} \sim 0.7$. If the associated electrostatic potential has the amplitude of the order of Boltzmann value then the $E \times B$ drift might explain the observed particle loss.

Comparing ELMs before and after the pellet one can see that ELMs are not significantly affected by pellets, at least as monitored by the divertor tile current (see figures 5 and 2(c)). This situation would be favourable in ITER where one of the concerns is that the pellet can trigger one or a burst of several ELMs that will result in prompt particle loss. Nevertheless this weak pellet-ELM interaction on ASDEX Upgrade is quite surprising given the large change in density gradient inside the separatrix due to the pellet, but could indicate that pedestal stability and strength of edge transport barrier is controlled mainly by pressure, and simultaneously the pellet deposition is close to adiabatic. In comparison in MAST RMP experiment, the post-pellet ELMs are about 1.5 times larger compared to pre-pellet ELMs [15]. The variability of ELM response to pellet on different devices is not understood. The situation is complicated by the fact that conventional 2D peeling-ballooning stability analysis seems not to explain the ELMs behaviour with RMPs and pellets as shown in figure 7 and section 5 below.

Between post pellet ELMs, during RMPs (figure 5, at ~6.36 s), the edge interferometer signal is approximately constant. This is in contrast with the phase before application of RMPs (around time point t_1) when the density typically increases between large ELMs. This indicates that even immediately after the pellet, when the density gradient inside the separatrix is large, the status of the edge transport barrier is different compared to the pre RMP phase. Such a conclusion is supported by a measurement of the radial electric field (though time averaged) showing clear difference between pre RMP and pellet refuelled phases (see next section and figure 6). The above is also in line with our previous conclusion that RMPs are directly responsible for ELM control rather than the density itself.

The density profile immediately after the pellet is hollow (figure 5) raising a question of the intensity of inward particle transport. In the zone $\rho_{pol} = 0.45 - 0.65$, 8 ms after the pellet, the density is slightly higher than the density immediately after the pellet perhaps hinting the existence of inward particle



Figure 6. Radial electric field E_r measured by boron 5 spectral line for different times of shot #31132: red before RMPs, green during RMPs and blue after pellet refuelling.

flux. However the analysis of this important process would require temporarily resolved profile data (or box car analysis) which is outside the scope of this paper. Post pellet plasmas with hollow density profiles were analysed in MAST in references [26, 27]. It was found that an inverted density gradient can unfavourably suppress micro-instabilities reducing the core fuelling rate, however, this depends on the actual values of the temperature gradients after the pellet. For completeness we note that the fast redistribution of density can be caused also by sawteeth which are present during the pellet refuelled phase. In our case, however, sawteeth are not correlated with pellets and thus not responsible for fast redistribution of plasma particles after the pellets.

4.2. Slow time scale particle loss

About 10 ms after the pellet the line integrated densities decay with the time constant much longer than the edge pellet retention time (figure 5). During this phase the density decreases in the outer part of the plasma $\rho_{\rm pol} > 0.45$ while in the core remains constant so that the profiles become gradually more peaked. Comparison of profiles at the beginning and the end of the pellet cycle shows good agreement confirming that the plasma is in a quasi-stationary phase. The fact that a quasistationary density is sustained with the pellet frequency much smaller than the inverse of the edge pellet retention time $1/\tau_{\text{pellet}}$ is a consequence of deeper pellet deposition. A fast camera data presented in figure 3 show that pellet ablation and ionisation occurs up to the normalised radius of $\rho_{\rm nol} > 0.86$. However the pellet particles are deposited much deeper up to $\rho_{\text{pol}} \sim 0.45$ as seen in figure 5(c). This difference can be attributed to ∇B drift of pellet material due to the high field side injection geometry. Such low pellet frequency would be favourable for ITER fuelling but the extrapolation from our data is not straightforward as the predicted pellet deposition is shallower in ITER meaning a shorter decay phase. Note that the separation between fast and slow decay phases is not sharp as the density profile evolves from hollow to peaked.

During the whole pellet cycle the density gradient scale length just inside the separatrix is comparable to the ion banana full width $\Delta r_b/a = 0.16$. This suggests that finite ion Larmor radius effects could be an important part of the mechanism of particle loss in these low collisionality pellet fuelled plasmas. The significance of this effect in ITER is however not obvious because the normalised ion Larmor radius is 6 times smaller in ITER compared to the present ASDEX Upgrade plasma.

The profile analysis shown in this section is done for a single pellet. As usual in pellet fuelling studies the particular pellet is selected according to its good coverage by Thomson scattering pulses (unless event triggered system, such as in MAST, is used [15]). We have, however, inspected all pellets and available profile data and they are consistent with the effects discussed in this section. The features such as the hollow density profile immediately after the pellet, the role of ELMs in pellet retention, including their non-diffusive nature, and relative independence of pellets and mitigated ELMs are all common. In addition these characteristics are similar to those reported in similar experiments in MAST [14, 15, 26] indicating that these observations are generic.

5. Energy confinement and pedestal

Application of RMPs is reducing the energy confinement time by ~ 30% (between t_1 and t_2 in figure 1(c)). This is the case for both the total value $\tau_{E,tot}$ (including fast ions) and thermal value $\tau_{E,th}$, where both quantities are calculated by TRANSP code [28]. During the refuelling phase by pellets (between t_2 and t_3) the energy confinement increases only by ~13%, clearly not restoring to the pre RMP value. In addition this increase is even less than predicted by IPB98(y, 2) scaling, $\tau_{E,th} \propto n_e^{0.41}$ [29], according to which $\tau_{E,th}$ should increase by 16–20%. Finite beam shine through does not affect these conclusions as it is included in calculation of $\tau_{E,th}$ by TRANSP, and its variation is small (shine through reaches its maximum of 0.85 MW at 3.1 s and monotonically decreases to 0.3 MW at 6.0 s).

The aforementioned global confinement broadly correlates with the behaviour at the pedestal. The application of RMPs reduces the pedestal ion temperature by 37% (figure 1(*d*)). Simultaneously the radial electric field at the pedestal becomes less negative by ~50% (figure 6). In contrast the electron pedestal temperature is not affected by the application of RMPs (see figure 1(*d*)). During the pellet refuelling phase, both electron and ion pedestal temperatures are modestly reduced, by 16% and 19% for ions and electrons resp. This change is somewhat lower than the increase of pedestal density during refuelling. The modest change in temperatures during refuelling is echoed by the fact that the radial electric field is unchanged within the error bars (figure 6). The details on how the radial electric and its error bars are evaluated are described in [30]. Here we only note that radial profile alignment procedure is



Figure 7. Ideal MHD stability analysis of pedestal for 3 times of the shot 31132: before RMP (2.20s), during RMP (3.9s) and during pellet fuelling (5.965 s). Open symbols are for averaged over ELMs, full symbols are for the end of an ELM cycle. max α and max $\langle j_{ll} \rangle$ represent the maximum of corresponding quantities over the pedestal.

applied to the charge exchange recombination spectroscopy data assuming that the electron temperature at the separatrix is approximately 100 eV and that the maximum gradients of ion and electron temperatures coincide [30]. Also note that resolving the radial electric field at the separatrix is rather difficult due to the low signal to noise ratio, since the fractional abundance of the impurities is low. Sweeping the plasma allows to increase the density of the radial grid points but such a method was not applied in this discharge.

The stability of the pedestal during the three different phases was also tested against ideal MHD (peeling-ballooning) modes. Electron and ion temperature and electron density profiles were fitted in a window 3 ms before a type-I ELM for the pre-RMP phase and averaged over ELMs during the RMP and pellet fuelled phases. Reference equilibria with these kinetic constraints were then produced using the CLISTE code [31, 32] and used as input to produce a grid of synthetic equilibria in $\langle j_{l'} \rangle - \alpha$ space [33]. The peak normalised pressure gradient at pedestal max α was varied by factors of 0.8-1.4 around the reference point, while the peak poloidally averaged pedestal current density $\max \langle j_{l'} \rangle$ was varied between 0.5 and 1.7 times the experimental value. The stability of each of these synthetic equilibria was calculated using the MISHKA code [34] for a range of toroidal mode numbers between n = 1 - 70. Figure 7 shows the calculated ideal stability boundary and experimental points. Before RMP phase, the experimental point lies on the stability boundary, as expected. However, no stability boundary could be found in the range scanned during either the RMP or the RMP with pellets phases, i.e. all scanned points are ideal-MHD stable. For the phase with RMP and pellets we also analysed the time slice at the end of an ELM cycle (figure 7, full blue symbol). The data point is also found inside the stable region, close to the ELM averaged case, which is a consequence of small ELM size in this phase. This all indicates that either conventional 2D or ideal MHD analysis is not appropriate in describing dominant instability during RMP and pellet phases and further theoretical development is necessary to produce reduced models for inherently 3D situations. Such analysis of MAST data can be found in [35].

6. Discussion

In this section we would like to make two comments on simultaneous ELM and density control.

Firstly, the correlation of density pump out and drop of ion temperature suggests that the particle and heat fluxes are connected. In analogy with the link between the plasma particle and heat transport in the plasma core [36] one can calculate the dimensionless ratio of the particle, $\Gamma_{\rm e}$, and heat flux, Q, such as $\Gamma_{\rm e}T/Q$, with T being the plasma temperature. Applying this parameter to the pedestal top at the time of fully refuelled plasmas (time interval t_3 on figure 1) we find that the value linked to ion pedestal temperature is $\Gamma_e T_{i,ped}/Q \sim \Phi(t_3)T_{i,ped}(t_3)/P_{aux} = 0.05$, where P_{aux} is the heating power. The numerical value of this parameter is controlled by the physics of transport mechanism. For example in case of convective ELMs, $\Delta N_{e,ELM}/N_{ped} = \Delta W_{ELM}/W_{ped}$, this ratio is $\Gamma_e T_e/Q \sim 0.33 \alpha_0 \sim 0.066$, where $\alpha_0 \sim 0.2$ is the fraction of heat flux transported by ELMs [10]. Therefore this parameter provides a useful constraint for the plasma pedestal temperature, in particular it shows that, for a given power and character of pedestal transport, the pedestal temperature is inversely proportional to the fuelling flux. This illustrates the challenge of simultaneous ELM and density control when ELM mitigation at constant density results in increased fuelling which in turn leads to the reduction of pedestal temperature.

Secondly, the evolution of density inside the separatrix over the whole pellet cycle (see figure 5) illustrates another interplay between pellet fuelling and ELM control by RMPs. On the one hand the fuelling pellet is increasing the density gradient in $\rho_{\rm pol}$ > 0.9 while after the pellet this density gradient is reduced. This gradual reduction of density gradient between pellets results from the fact that the density inside the separatrix is not in equilibrium and particle loss due to RMPs is larger than NBI and gas fuelling. This is different from the situations with gas fuelled plasmas where statements about the effect of RMPs on edge density gradient can be made, e.g. small decrease [37] or no effect [17]. In ITER the effect of gas fuelling will be even smaller and therefore the evolution of density profiles between pellets will be mainly controlled by RMPs. From the control point of view we will be left with a task how to balance pellets and RMPs so that the density and ELMs are simultaneously acceptable over the whole pellet cycle.

7. Conclusions

Complete refuelling of density pump out due to ELM mitigation by RMPs is demonstrated by pellets under conditions of ITER-like relative RMPs amplitude, pellet size and plasma collisionality. It is shown that:

• ELM mitigation is preserved by pellet refuelling. ELM frequency with pellets and RMPs is higher by a factor

of 2 compared to non-RMP non-pellet reference (for normalised ELM frequency $f_{\text{ELM}} \tau_{\text{E,th}}$ this factor is 1.5).

- The frequency of ELMs mitigated by RMPs is unlikely a simple function of density or collisionality and data indicate that RMPs are directly involved in ELM control.
- Refuelling of density pump out of the size of 30% requires an increase of the nominal fuelling rate at least by a factor of two.
- Immediately after the pellet the plasma density decays on a fast time scale and during this phase the loss is dominated by ELMs, with a clear non diffusive character. The related normalised pellet retention time is similar to that in MAST.
- Pellets do not trigger bursts of ELMs.
- Energy confinement and pedestal temperatures are not restored to pre-RMP values by pellet refuelling. Conventional $\langle j_{ll} \rangle \alpha$ analysis does not explain the ELM behaviour during RMP and pellet phases.

These data provide a good starting point for future integrated density and ELM control experiments. We need to clarify why even at ITER-like collisionality, fuelling and amplitude of RMP field, the normalised ELM size is still larger than the ITER target. Also shallower pellet deposition should be tried to approach the ITER situation even closer. Inability of pellet refuelling to restore the energy confinement is another issue. It is possible that the situation discussed in this paper is the result of dominant ion heating and experiments to clarify this would be valuable.

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