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High-density H-mode operation achieved using efficient plasma refueling by inboard pellet launch

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Abstract

A systematic study was performed on high-density H-mode operation in the tokamaks ASDEX Upgrade and JET using inboard pellet launch refueling. The pellet particle flux was found to correlate with the achieved density enhancement. After injection of each pellet the decay of the density enhancement starts on a fast time scale until about half of the pellet inventory is expelled, slowing down significantly as the base density is approached. Whereas the overall slow decay happens in the particle confinement time, its first phase results from a sequence of ELMs following each injection. Loss of particles in an ELM sequence is accompanied by a loss of energy, causing a reduction of the plasma energy. Full plasma energy recovery after an ELM sequence occurs faster than the slow density decay, allowing transient operation at high densities maintaining full confinement. However, confinement degradation by inappropriate discharge scenarios must be avoided. Pellet-induced ELM bursts result in a particle flux from the plasma recycling at the wall, adding up with gas fluxes from other sources. Insufficient pumping can then lead to a neutral gas pressure increase causing confinement degradation. Also, excessive temperature reduction by pellets close to rational surfaces can create conditions likely to catalyze the growth of neoclassical tearing modes (NTMs) at high β_N, which may then be triggered by a succeeding pellet.

Keywords: Fuelling; Pellet; ELM; H-mode; ASDEX-Upgrade

1. Introduction

Operating a tokamak safely in the vicinity or even beyond the empirical gas puff density limit while maintaining the high confinement (H)-mode offers significant advantages for a future fusion reactor. H-mode operation at high densities can help to reduce the required reactor size. In H-mode plasma discharges, confinement and density limitations are dominated mainly by edge parameters [1]. Increasing the density is accompanied by an edge density rise because the core profiles remain flat. As the increase of edge density has been found to correlate with a decrease of energy confinement, depositing particles mainly in the plasma edge, e.g., by gas puffing, cannot achieve a density increase without confinement degradation. This stiff relation between edge density and $\overline{n_e}$ has to be broken off by a fueling method allowing for particle deposition deep inside the core plasma, improving the discharge performance by creating more peaked density profiles. Injection of pellets produced from frozen hydrogen isotopes is currently the most developed fueling method meeting these criteria [2]. In numerous studies [3] the method has been demonstrated to open access to operational regimes not reachable by gas puffing. However, high fueling efficiency is needed as otherwise the beneficial effects are spoiled by the increase of neutral pressure from fuel losses. Moreover, in a future fusion reactor high fueling efficiency is essential to keep throughputs and therefore inventories of the

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hazardous tritium fuel component at a minimum [4]. Conventional injection from the torus outside unveils a strong efficiency degradation with increasing plasma temperature. In hot plasmas, the pellet ablated material is subject to a fast curvature drift shifting the deposition profile towards the magnetic low field side [5,6] and causing strong particle losses. Moreover, during H-mode phases ELMs are triggered by the pellets and further rapid particle losses take place [7]. As shown first on ASDEX Upgrade [8] and meanwhile confirmed by several other tokamaks, the curvature drift acts favorably in the case of inboard pellet injection, maintaining high efficiency also for hot H-mode plasmas. Further experiments aimed at increasing density without confinement degradation using inside pellet launch are needed to establish a common physics base of high-density tokamak operation and are regarded as an area of crucial research [9]. As a first step, systematic studies were performed at ASDEX Upgrade and JET to establish scenarios for persistent density increase whilst avoiding degradation of particle and energy confinement.

2. Experimental

Both the ASDEX Upgrade and JET pellet injection systems are based on a centrifuge accelerator [10], recently modified to enable inboard launch by adapting the centrifuge to a guiding tube installed inside the torus vessel leading to the inboard side. In addition, the ASDEX Upgrade injector was adjusted for high repetition rates and particle fluxes in the inboard launch scenario [11]. It is now capable of firing pellets with a speed of 240 m/s at a repetition rate of up to 60 Hz. This yields a maximum nominal pellet particle flux $\Phi = 2.6 \times 10^{22}$/s for the biggest available pellet size (cubic $1.9 \times 1.9 \times 2.0$ mm^3). Approximately 60% of this is lost during acceleration and in the bent guiding tube resulting in a particle flux into the plasma of about 10^{22}/s, which is consistent with the maximum pellet-induced plasma particle enhancement found. The inventory of the storage cryostat was sufficient to deliver pellet sequences of 2 s duration at maximum rate. Pellets were injected towards the plasma center under 44° to the horizontal plane. The delay between the pellet request and arrival at the separatrix was about 80 ms with a 0–17 ms jitter.

For JET refueling experiments, cubic (4 mm)^3 pellets usually were injected also under 44° to the horizontal plane but tangentially to a flux surface with $\rho \approx 0.7$. To compare fueling behavior of inboard and outboard launches, pellets were also injected from the torus outside on the horizontal midplane aiming toward the plasma center. Switching from inboard to outboard launch could be realized from pellet to pellet. A maximum pellet velocity of 180 m/s and repetition rates of up to 10 Hz were applied, the system response time was about 90 ms. Pellets were delivered for the full plasma discharge duration due to the continuous extrusion capability [12].

During pellet experiments, both tokamaks were operated in lower single null configuration, at ASDEX Upgrade with standard low triangularity (averaged $\delta < 0.2$) configuration, at JET with an upper δ of 0.25 (referred to as LT configuration) or 0.38 (HT configuration). 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 density controlled pellet injection was performed in some discharges.

3. Results

Our investigations concentrated on injecting cryogenic deuterium pellets into deuterium discharges, at ASDEX Upgrade with $I_P = 0.8$ MA, $B_t \approx -2.0$ T, $q_{95} \approx 4$ and at JET mainly with $I_P = 2.5$ MA, $B_t \approx -2.4$ T, $q_{95} \approx 3$.

3.1. Density enhancement

At ASDEX Upgrade a detailed investigation was performed on the relation between the applied pellet particle flux Φ and the achieved density enhancement Δ beyond the base value $\overline{n_e^b}$ achieved in a reference shot without pellets. As a result, pellet injection acted purely additively to the plasma density as $\overline{n_e^b}$ could be varied, for example by gas or impurity puffing or by cryopumping without a significant influence on the relation between Δ and Φ. This relation still holds for requested densities $\overline{n_e^r} = \overline{n_e^b} + \Delta$ well-beyond the Greenwald density $\overline{n_e^{Gw}}[10^{20}\ \mathrm{m}^{-3}] = I_P[\mathrm{MA}]/\pi a_0^2[\mathrm{m}]$ [13] (a_0 horizontal plasma radius). Fig. 1 displays the Φ–Δ diagram for the performed discharges, illustrating the correlation.

Data for this plot were taken from steady-state discharges controlled to one fixed density value (open squares), as well as from shots with a slow density ramp up (triangles, every data point represents one pellet sequence).

The required pellet particle fluxes to achieve a given Δ, and, moreover, the temporal evolution of density control sequences can be explained by a simple model for the plasma particle content taking into account density evolution after pellet injection and the injection system response time. Results of this simulation are also given in Fig. 1. The density decay after pellet injection at $t = t_0$ can be described rather well by the expression:

$$\overline{n_e}(t) = \overline{n_e^b}(t_0) + \mathrm{A}\exp\{-(t - t_0)/10\ \mathrm{ms}\} + (\Delta - A)\exp\{-(t - t_0)/120\ \mathrm{ms}\}$$

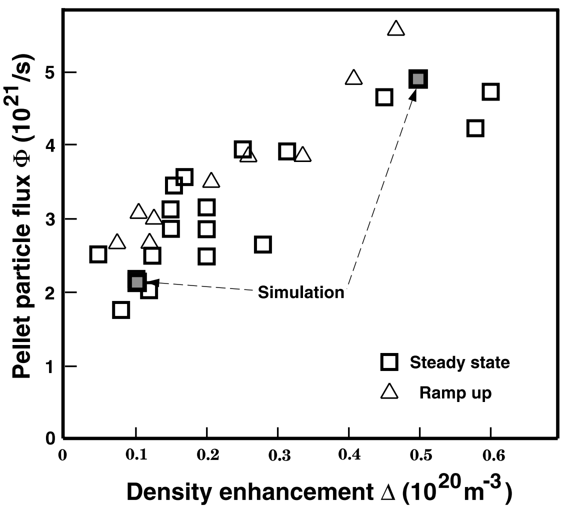

Fig. 1. Applied pellet particle flux Φ versus pellet-induced density surplus Δ. Data were taken from ASDEX Upgrade steady-state discharges (open squares) and from discharges with slow density ramp up. Results from a simple particle content modelling are shown as well.

with the amplitude, A, reaching typically about half the density increment caused by the last injected pellet (about 10^{19} m^{-3}). When pellet injection was terminated, the discharge returned to the density established in an equivalent discharge without pellet injection. The density decay in the final slow phase, occurring most probably with the particle confinement time, occurs rather smoothly. Immediately after the pellet, the density evolution can be well described by an exponential decay with the fast time scale.

Measurements at higher temporal resolution revealed that density loss occurs in steps correlated with strong ELM activity. After pellet injection, $\overline{n_e}$ stayed almost constant for about 4 ms. Then, a rapid density decrease occurred, expelling typically 6×10^{19} particles within 2–3 ms. This short phase with strong particle flux (typically 3×10^{22}/s) from the plasma was followed again by a quiescent phase until the next rapid density decay. Typically, on the injection of a pellet three to five strong ELMs were recorded before the ELM intensity abated to its initial amplitude and the transition to the slow decay phase took place.

In JET, a similar behavior was found. Higher pellet particle fluxes achieved by increasing the repetition rate lead to higher final densities without any significant influence of conditions in different target discharges. However, higher pellet fueling efficiencies achieved by switching from outboard to inboard injection resulted in a higher final density. During H-mode phases, the same ELM behavior was observed as on ASDEX Upgrade. A sequence of ELMs was triggered by each pellet, with each of the pellet-induced ELMs stronger than a usual 'background' ELM. Duration of this sequence of rapid particle losses in JET was about 100 ms, containing about five strong ELMs.

3.2. Energy confinement

Pellet refueling showed a remarkably improved plasma energy confinement compared to gas puffing for the same discharge parameters. Stable quasi-steady-state H-mode operation beyond the Greenwald density was achieved and maintained during the whole pellet sequence. Still, a tendency of some reduction in energy confinement with rising $\overline{n_e}$ was detected. Present in each single discharge, the confinement degradation was attributed to at least one of the four following reasons:
(a) Degradation of W_{MHD} of the target plasma by unfavorable performance of the discharge, e.g. too strong gas or impurity puffing;
(b) Increase of neutral gas pressure and hence edge density through insufficient pumping caused by a parasitic pellet born gas puff;
(c) Triggering of neoclassical tearing modes (NTMs) by the pellets;
(d) Bursts of several strong ELMs expelling particles and energy following pellet injection.
Whereas the first problem occurred accidentally and was not related to pellet injection, the latter three were induced by pellets and have to be considered in more detail.

3.2.1. Edge density induced degradation

Energy confinement degradation related to increasing edge density was observed in ASDEX Upgrade when only turbomolecular pumps were used. The degree of degradation was found to be identical for pellet and gas puff refueling at the same edge density in identical target plasmas. Thus, the pellet-induced particle flux from plasma recycling at the wall had the same deleterious effect on the confinement as external gas puffing [14]. Applying the cryopump to prevent a strong neutral gas pressure rise in the divertor region during pellet phases eliminated the increase in edge density and hence circumvented pellet-related confinement degradation.

3.2.2. NTM induced degradation

NTMs with (3/2) and (2/1) structure have been observed in previous experiments on ASDEX Upgrade at high energy content in the plasma [15], resulting in a significant reduction of the plasma energy content. Such NTMs were found to be triggered also by pellets, even if the global energy content and hence β were already somewhat reduced by pellet refueling. A typical discharge with pellet-triggered NTMs in ASDEX Upgrade evolved as follows: the pellets started to reduce the plasma temperature and especially the ion temperature and hence the poloidal ion gyro radius $\rho^*_{p,i}$ at the resonant surface. According to the ion polarization current model this reduces the achievable β_p^{onset} before an NTM may get triggered by a large enough perturbation, as $\beta_p^{onset} \sim \rho_{p,i}^*$ holds [16]. One of the subsequent pellets after this cooling process then triggers the (3/2) NTM on the $q = 3/2$ surface. The exact mechanism of the trigger of the mode is not yet fully understood and is a subject for further investigation [17]. With increasing amplitude of this mode, a strong decay of the confinement was first observed. One of the next pellets eventually triggered a (2/1) NTM at the $q = 2$ rational surface, causing an even stronger drop in the energy confinement. This (2/1) NTM typically locked to the vacuum vessel and caused a final confinement drop drawing the discharge sometimes back to the L-mode.

The onset conditions for pellet triggered (3/2) NTM were found to lie on the same scaling for the maximum achievable local critical β^c derived using sawteeth provided seed islands. The above-mentioned scaling [16] is equivalent to $\beta_N^{onset} * I_p \sim 1.1\sqrt{T_i}$ at the $q = 3/2$ surface and could be used for choosing plasma conditions less vulnerable towards NTMs. By this way, the NTM onset in pellet refueled discharges was prohibited to a large extent.

3.2.3. ELM burst induced degradation

Whereas the mechanisms causing energy confinement degradation listed above under (a)–(c) ((b) and (c) are discussed in Sections 3.2.1 and 3.2.2., respectively) could be prevented by appropriate means, some remaining loss of confinement correlated with the bursts of several strong ELMs following the pellet injection in H-mode phases could not be avoided, either in ASDEX Upgrade or in JET discharges. Having been often disguised by the stronger effects on the confinement by the other degradation mechanisms, this effect occurs after each pellet is injected into a H-mode plasma and causes the currently still observed operational limitations at both ASDEX Upgrade and JET.

Obviously, pellet-induced ELM bursts expel both particles and energy, as illustrated in Fig. 2 where the time traces of $\overline{n_e}$ and the plasma MHD energy W_{MHD} are given. W_{MHD} is obtained by function parametrization of the ASDEX Upgrade equilibrium using numerous diagnostic signals (uncertainty for the data shown below 4%) [18]. The sequence plotted consists of six single pellets injected in a phase with 5 MW heating power applied, driving $\overline{n_e}$ far beyond the Greenwald density (dashed line) while maintaining H-mode signature (as indicated e.g. by continuing ELMs). After the pellet sequence, the density surplus Δ decayed as described by the equation given above. Correlated with the start of the pellet sequence, a decay of the plasma energy by $\Delta W \approx 50$ kJ set in. Once this level was reached, no further degradation took place despite further pellets arriving in the plasma. About 20 ms after the last pellet,

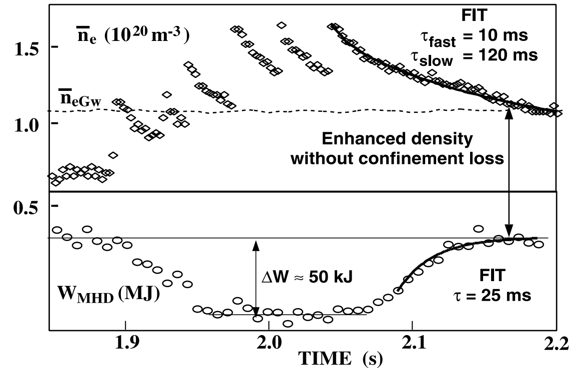

Fig. 2. Evolution of plasma density and energy during and after a pellet sequence in ASDEX Upgrade. Fit results for the phase after the sequence are also given, where finally steady-state performance at enhanced density without confinement loss is achieved transiently.

the burst of strong ELMs ended as indicated by the change over from the fast to the slow-density decay phase, and the plasma energy recovered to the initial value. The pellet-induced ELM bursts cause a loss power P_{ELM} which adds transiently to the steady state background loss power $P_{heat} = P_{loss} = W_0/\tau_E$. Assuming an unchanged energy confinement time τ_E, this temporary loss can be estimated as:

$$P_{ELM} = P_{heat}\Delta W/W_0 \approx 5 \text{ MW} \times 50 \text{ kJ}/500 \text{ kJ} = 0.5 \text{ MW}.$$

During this phase with the additional losses present, an averaged particle outflux from the plasma of 2×10^{21}/s is observed, mainly due to fast pellet losses by the ELM bursts. Profiles taken by the Thomson scattering system timed with respect to pellet injection showed the location of pellet particle deposition in this phase taking place about 15 cm inside the separatrix where $T_e = 800$ eV. Assuming $T_i \approx T_e$ since density and hence collisionality are sufficiently high, these particles, first thermalized and then partially lost during the ELM could yield a convective loss power of $3\Phi_{loss}k_BT \approx 0.77$ MW. Thus, one can assume that the observed pellet-induced ELM bursts cause both the observed particle and the energy losses, as this interpretation matches well with the observed slowing down of the density decay and the recovery of plasma energy, once the bursts come to an end.

As the ELM burst losses are of transient nature and the time scale for plasma energy recovery after the pellet sequence (25 ms) is significantly shorter than the particle confinement time (120 ms), transient operation at enhanced density with no confinement loss with respect to the initial conditions can be achieved. As shown in Fig. 2, about 130 ms after the last injected pellet of the sequence, the plasma energy has fully recovered to the initial level while there is still a significant fraction of the pellet-induced density surplus present, keeping the density even beyond the Greenwald level. Thus, for a short period enhanced operation is achieved. Further improvement could thus be envisaged by optimizing the injected pellet sequences, eventually by starting a further density increase with the next pellet sequence at the time the plasma energy has just recovered since the previous sequence.

3.3. Operational parameters already achieved at ASDEX Upgrade and JET

First steps to optimize pellet refueling by careful tailoring of the injection sequences have already been taken at ASDEX Upgrade and at JET. Achieved discharge parameters for both tokamaks are visualized in the $\overline{n_e} - W_{MHD}$ diagrams shown in Fig. 3. The boundaries in this operational diagram reached by continuous pellet injection (filled symbols) matched the degradation expected due to the ELM burst losses (assuming $P_{heat} - P_{ELM} = W_0 - \Delta W/\tau_E$, solid curve) in the absence of further pellet-induced loss mechanisms quite well. Data sets achieved for both tokamaks look rather similar when the axes are scaled accordingly. In these plots the intersection of the degradation curve with the Greenwald density was chosen as fixed-point. To illustrate the significant improvement already achieved by continuous pellet injection with respect to gas refueling, the trajectory of an according discharge with gas puff-

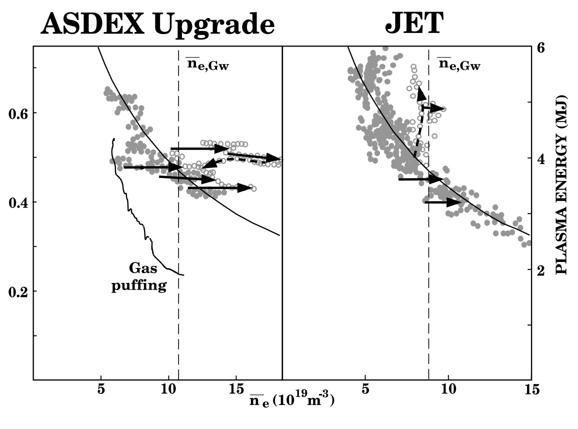

Fig. 3. Operational $\overline{n_e} - W_{MHD}$ diagrams achieved for ASDEX Upgrade ($I_P = 0.8$ MA, $B_t \approx -2.0$ T, P_{NI} 5–10 MW) and JET ($I_P = 2.5$ MA, $B_t - 2.4$ T, P_{NI}11–17 MW). Solid dots represent the data achieved for continuous pellet injected, open circle transient enhanced operation. Solid arrows indicate pellets, dashed arrows the temporal discharge evolution. The solid curve is obtained assuming energy loss by thermalized pellet particles in ELM bursts assuming $P_{ELM} \sim \Phi_{loss}$. The according Greenwald densities and a typical evolution for a gas puffed discharge are given also.

induced density enhancement is given in the ASDEX Upgrade diagram. Parameters achieved in transient operation by interrupted pellet sequences are shown by the open symbols in Fig. 3. Here, the pellet sequences were restarted at the optimum operational point during the recovery phase after a pellet train. Whereas in ASDEX Upgrade the density increase of several pellets (indicated by arrows) could be cumulated before P_{ELM} losses again caused a reduction of W_{MHD}, at JET further improvement in the current set-up can only be realized with the first pellet. This is due to the rapid pellet repetition rate of the ASDEX Upgrade injector, which allows several pellets to be launched until W_{MHD} approaches its new, reduced equilibrium, whereas the JET injector repetition rate is about equal to this time.

3.4. Profile effects

The improvement of discharge performance by replacing gas puffing with pellet injection is mainly due to profile effects. Whereas the global parameters are improved by pellet refueling, e.g. as shown in Fig. 3, the edge parameters stay unchanged. Analyzing their confinement degradation versus e.g. separatrix density or edge pedestal pressure, no difference is found with respect to the fueling technique. However, pellet injection allows for deeper particle deposition than gas puffing, thus, breaking the stiff relation between core and edge density observed with gas puffing. At comparable edge densities stronger peaked density profiles achieved with pellets allow more particle inventory, exceeding in this way the Greenwald density. In pellet refueled discharges operational limits are, as in conventional H-mode plasmas, mainly imposed by the edge parameters. This gives the potential for improved operation with respect to plasma energy due to the peaked density profile, as illustrated in Fig. 4. There, a simple schematic sketch of the evolution for the (electron) density, temperature and pressure profiles is modeled for both gas and pellet-induced density ramp up. Typical idealized initial density and temperature profiles are assumed like those found at the starting point of the gas fueled trajectory in Fig. 3. In the same way idealized final profiles for gas refueled discharges at maximum H-mode density just before dropping back into L-mode and for the pellet shot at a requested density near the Greenwald density were taken. During gas puff refueling, the increase of the pedestal density leads to a more box-shaped profile towards high densities [19]. The final temperature and pressure profiles were calculated using two typical experimental observations. Firstly, the pedestal pressure remained constant during gas injection due to an according adiabatic pedestal temperature drop. Secondly, the temperature reduction was global due to the observed profile stiffness [1]. The occurring reduction of the pressure profile inside the pedestal, which means a

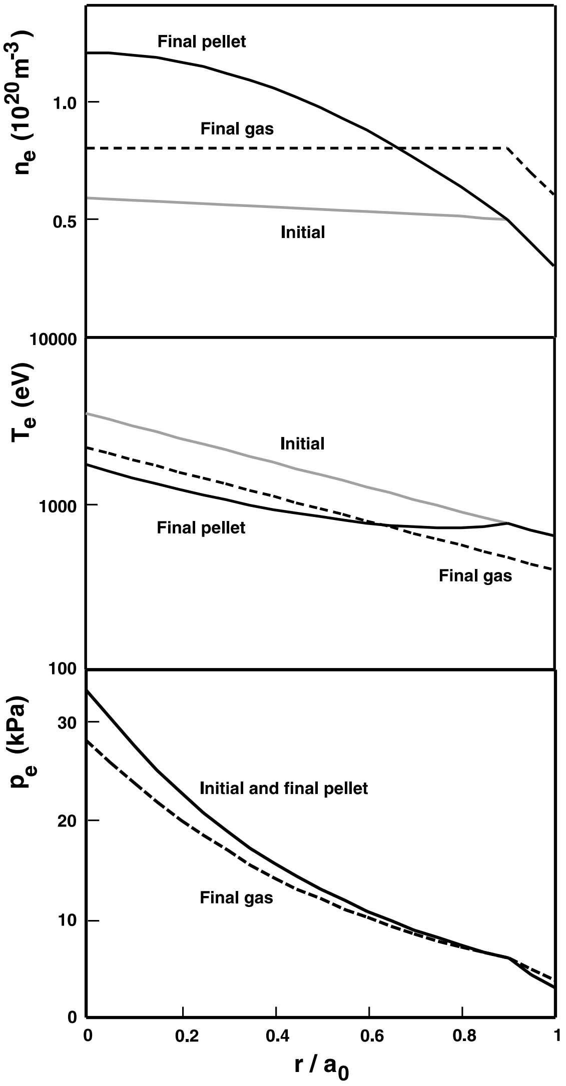

Fig. 4. Density, temperature and pressure profile evolution from the initial (solid grey) to the final state in the case of gas puff (dashed) in pellet (solid black) refueling.

plasma energy loss, is only a profile effect. At still higher densities, however, energy losses increase when the edge temperature drops below a critical value and the H-mode transport barrier starts to vanish [1]. Pellet injection ideally (no pellet-induced losses or transiently enhanced phases) does not increase the edge density but significantly enhances the core density by extending the edge gradient zone deeper into the plasma, leading to a peaked density profile. Since the plasma energy content is not altered strongly during the density ramp up, the pressure profile remains essentially unchanged. Therefore, after the ELM bursts the initial temperature can be maintained at the edge but is modified in the core and, notably, the profile stiffness must disappear. This conclusion agrees well with the experimental observation in the high-density phase at the end of the ELM burst. The observed loss of temperature profile stiffness there implies that the ratio $T/(\mathrm{d}T/\mathrm{d}r)$ is limited by a critical value rather than remaining constant.

4. Discussion

Inboard pellet injection has demonstrated the potential for a strong density build-up and control beyond the Greenwald density without losing the H-mode. Pellet refueling considerably extends the operational space with respect to confinement by uncoupling edge density and core density, which creates peaked density profiles. This is mainly due to profile effects, as density peaking avoids central pressure losses due to stiff temperature profiles. Moreover, the temperature profile stiffness could not even be sustained due to the strong core density increase. The observed reduction of the ratio $T/(\mathrm{d}T/\mathrm{d}r)$ may indicate that at higher densities the critical gradient is not reached due to the reduced heating power per particle. Avoiding energy degradation by e.g. insufficient pumping or triggering of NTMs, the occurrence of strong pellet-induced ELM bursts under H-mode conditions turned out to form an unavoidable remaining loss channel. The corresponding energy degradation was found to show the same characteristics for continuous pellet refueling in both, ASDEX Upgrade and JET, due to the observed linear relation between pellet flux and the induced density enhancement. Making use of the particle confinement time being longer than the energy recovery time required after a pellet sequence, transient operation even beyond this boundary was achieved.

Regarding the results of the present studies at ASDEX Upgrade and JET several options for further performance improvement seem feasible. The first option is full optimization of pellet sequencing, aimed at establishing a pellet fuel cycle avoiding persistent plasma cooling and confinement loss. This will be envisaged mainly at JET, especially by technical attempts to improve pellet repetition rates. Secondly, mitigating of pellet-induced ELM bursts should reduce particle and energy losses, resulting in less reduction of confinement. Modeling pellet injection into ELMy H-mode discharges [7] predicts increasing delay and hence reduction of pressure losses caused by pellet-induced ELMs with increasing pellet penetration. Aiming at higher pellet speeds to yield deeper pellet particle deposition, the injection system at ASDEX Upgrade will be upgraded again.

Whereas these steps are taken to minimize ELM burst losses in order to approach an almost ‘adiabatic’ density increase, further improvement beyond this aim might be possible if this temperature stiffness can be restored in the case of very peaked density profiles.

Provided operational limits currently faced are due to stiff temperature profiles with the ratio $T/(\mathrm{d}T/\mathrm{d}r)$ limited by a critical value e.g. by ITG modes, the reduction observed for $T/(\mathrm{d}T/\mathrm{d}r)$ in the plasma core during high-density pellet operation may indicate that there is still some headroom for further pressure rise in the center by additional central heating. Probably, this will bring local parameters at rational surfaces with low m,n numbers close to onset conditions for NTM, which could then be triggered by further pellets. However, active control of these NTMs by current drive inside the magnetic islands is a technique which already proved its feasibility [20].

In summary, pellet refueling already achieves significant advantages in tokamak operation compared to gas refueling, especially in the high-density H-mode regime. However, from the current experience it seems there is still the potential for further improvement.

References

[1] W. Suttrop et al., Plasma Phys. Contr. Fus. 39 (1997) 2051.
[2] K. Thomassen et al., Fus. Tech. 34 (1998) 86.
[3] S.L. Milora, W.A. Houlberg, L.L. Lengyel, V. Mertens, Nucl. Fus. 35 (1995) 657.
[4] M.J. Gouge et al., Fus. Technol. 1644–1650 (1995) 28.
[5] J. deKloe et al., Phys. Rev. Lett. 82 (1999) 2685.
[6] H.W. Müller et al., Phys. Rev. Lett. 83 (1999) 2199.
[7] P.T. Lang et al., Nucl. Fus. 36 (1996) 1531.
[8] P.T. Lang et al., Phys. Rev. Lett. 79 (1997) 1487.
[9] ITER Physics Basis Editors et al., Nucl. Fus. 39 (1999) 2137.
[10] C. Andelfinger et al., Rev. Sci. Instrum. 64 (1993) 983.
[11] P.T. Lang, P. Cierpka, Rev. Sci. Instrum. 69 (1998) 2806.
[12] M.J. Watson et al., Improvement, commissioning and operation of the JET pellet centrifuge', in: 18th SOFE, Albuquerque, October 1999, proceedings to be published.
[13] M. Greenwald et al., Nucl. Fus. 28 (1988) 2199.
[14] V. Mertens et al., in: Proceedings of the International Congress Plasma Physics and 25th EPS Conference Control Fusion and Plasma Physics Prague, 1998, p. 523.
[15] M. Maraschek, S. Günter, H. Zohm, ASDEX Upgrade Team, Plasma Phys. Contr. Fus. 41 (1999) L1.
[16] S. Günter, A. Gude, M. Maraschek, H. Zohm, ASDEX Upgrade Team, Nucl. Fus. 38 (1998) 1431.
[17] M. Maraschek, Private communication.
[18] P.J. McCarthy, F.C. Morabito, Int. J. Appl. Electron. Mech. 9 (1997) 1.
[19] W. Suttrop, V. Mertens, H. Murmann, J. Neuhauser, J. Schweinzer, ASDEX Upgrade Team, J. Nucl. Mater. 266–269 (1999) 118.
[20] H. Zohm et al., Nucl. Fus. 39 (1999) 577.