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High density operation at JET by pellet refuelling*

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Abstract
Several approaches are used at JET to achieve operation at high density with good energy confinement. One of them is the injection of solid fuel pellets to realize efficient particle refuelling by deposition deep inside the plasma column. The new pellet launch system capable of launching from the torus magnetic high field side was investigated for its capability to fulfil this task in conventional ELMy H-mode discharges. Optimized pellet scenarios were developed for plasma configurations with $I_P = 2.5$ MA, $B_t = 2.4$ T, averaged triangularity $\langle\delta\rangle \approx 0.34$ and mainly neutral beam heating at a level of approximately 17 MW. The accessible operational range was extended by the pellet tool with respect to gas puff refuelling. For example, H-mode conditions could be maintained at densities beyond the Greenwald level. Plasma energy confinement was observed to become density independent at high densities. When avoiding confinement deterioration due to pellet triggered MHD activity or parasitic pellet born gas in appropriate pulse schedules, enhanced particle inventory with more peaked density profiles was achieved while maintaining the plasma

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[12] See appendix of the paper by Pamela J Overview of recent JET results *Proc. IAEA Conf. on Fusion Energy (Sorrento, 2000).*

pressure profile. First attempts indicate that pellet advantages can be combined with the benefits achieved by higher triangularity. Very high particle refuelling efficiencies were found for pellets injected into 'ITER-like' discharges with an upper triangularity $\langle\delta^{u}\rangle$ of 0.53.

1. Introduction

The demonstration of long pulse operation of tokamak plasmas at a high density level while maintaining a good energy confinement is crucial for ITER-FEAT. Approaching density values envisaged as operational parameters for ITER-FEAT [1] by means of gas puffing, standard ELMy H-mode scenarios show a sudden drastic confinement degradation [2]. Pellet injection allowing more efficient refuelling by deeper particle deposition is known to extend the operational area accessible by gas puff refuelling only. For this reason, investigations of pellet particle refuelling have been conducted at JET. Experiments concentrated on the developement of optimized refuelling scenarios, starting with conventional, well established ELMy H-mode scenarios. Since this discharge type chosen has been used frequently before, a broad and reliable database for comparison of pellet refuelling with similar experiments applying ordinary gas puff is available. Based on these reference discharges, pellet sequences were optimized for long pulse fuelling to high densities in the vicinity of the Greenwald density while maintaining the plasma energy to a maximum extent and keeping the impurity level low. Further, first attempts were undertaken to combine pellet advantages with the positive effects achieved by increased triangularity. For all experiments, the new pellet injection system using in-vessel guiding tubes was employed, allowing pellet launch both from the torus low field side (LFS) and high field side (HFS).

2. Experimental setup

JET was operated during this campaign using the Mark II gas box divertor with central septum. Lower single null plasma configurations applied during the pellet sequence optimization typically had elongations $\kappa \approx 1.7$, volume $V_{\mathrm{P}} \approx 80\,\mathrm{m}^3$ and an edge safety factor $q_{95} \approx 3.2$ with a toroidal magnetic field $B_{\mathrm{t}} = 2.4\,\mathrm{T}$ and plasma current $I_{\mathrm{P}} = 2.5\,\mathrm{MA}$, or $B_{\mathrm{t}} = 2.7\,\mathrm{T}$ and $I_{\mathrm{P}} = 2.8\,\mathrm{MA}$. D-shaped equilibria were run with averaged triangularity $\langle\delta\rangle \approx 0.34$ (upper triangularity $\delta^{u} \approx 0.38$, lower triangularity $\delta^{l} \approx 0.30$) as standard vertical (V) target version with the separatrix strike zone on the vertical divertor target plates or in a slightly modified 'corner' (C) version, where the outer strike zone was fitted next to the pumping slit in the corner of the divertor plates. For auxiliary plasma heating, mainly NBI (D^0 injection) was used. Further increase of P_{heat} beyond the maximum available NBI power of about 17 MW took place in a few shots by additional ion cyclotron resonance heating (ICRH). Experiments were performed in Deuterium plasmas, for cases with ICRH minority heating a few per cent of hydrogen were added.

For the investigations of pellet injection into 'ITER-like' discharges, the configuration with upper triangularity $\delta^{u} \approx 0.53$, lower triangularity $\delta^{l} \approx 0.43$, $I_{\mathrm{P}} = 2.5\,\mathrm{MA}$, $B_{\mathrm{t}} = 2.7\,\mathrm{T}$, $q_{95} \approx 2.85$ was chosen with 16 MW NBI.

The JET pellet injection system [3] is capable of delivering nominal $(4\,\mathrm{mm})^3$ cubic D pellets (containing 3×10^{21} D atoms) at a maximum repetition rate of 10 Hz. Pellet size, velocity and repetition rate are restricted by injector settings and thus fixed within one plasma discharge. However, single pellets can be omitted to reduce the repetition rate to a fraction of the preselected value. Pellets were launched at a speed of $160\,\mathrm{m\,s^{-1}}$ into the plasma from

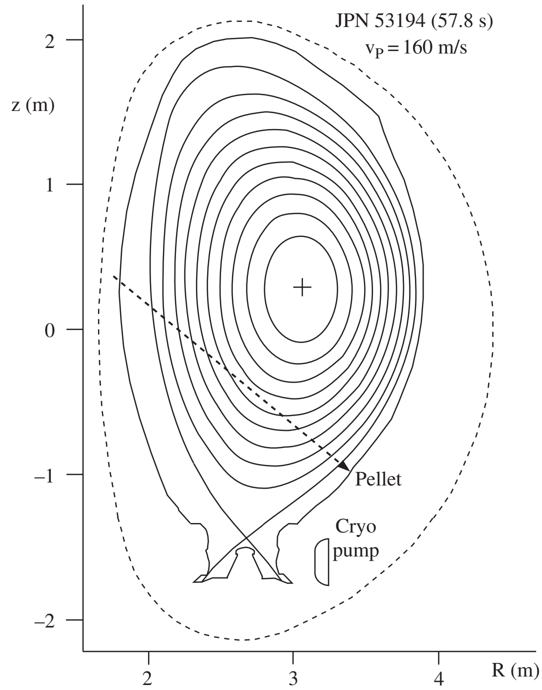

Figure 1. Poloidal cross section of JET with Mark II gas box divertor and central septum; magnetic structure of used lower single null plasma configuration with $I_P = 2.5$ MA, $B_t = 2.4$ T, $q_{95} = 3.2$, $\langle\delta\rangle \approx 0.34$ and strike zone deep in divertor throat for efficient pumping. Used designated pellet injection path from the HFS (maximum launch speed $v_P = 160\,\mathrm{m\,s^{-1}}$).

the magnetic HFS along a designated trajectory tilted by 44° to the horizontal plane with a tangency radius at about a normalized minor radius of $\rho \sim 0.6$–0.7.

A schematic poloidal cross section of JET including the magnetic flux tube pattern of the applied configuration is given in figure 1. The designated pellet injection path is also included.

3. Optimization strategy

The intention of our investigations was to obtain densities in the vicinity of the Greenwald density $\bar{n}_e^{Gw}$ while still keeping the confined energy high. Using available equipment, the objective was to improve performance by developing target plasma discharges fully compatible with pellet refuelling and optimize adapted pellet sequences. During this optimization process it turned out that special attention had to be payed to three critical issues,

- prompt particle losses from the plasma forming a parasitic pellet born gas puff up to the amount of the pellet particle flux, finally causing increase of neutral gas pressure and edge density
- trigger of central MHD activity by the pellet, and
- ELM bursts following pellet injection,

as each one of these pellet related effects can cause severe energy losses and must therefore be avoided or minimized.

Excessive increase of the edge density could be avoided by restricting the maximum pellet rate to 6 Hz. This prevented an increase of the neutral gas pressure in the main chamber beyond a level of 2×10^{-3} Pa found critical for the onset of confinement degradation.

Like many high performance operational modes pellet refuelling scenarios also suffer from magnetohydrodynamic (MHD) mode activity, and especially neoclassical tearing modes (NTM) on resonant flux surfaces become a major obstacle for reaching high performance. Pellets driving up density accordingly reduce temperature. Reduction of the ion temperature causes a shrinking poloidal ion gyro radius $\rho^*_{\mathrm{p,i}}$, reducing the critical pressure $\beta_{\mathrm{p}}^{\mathrm{onset}}$ for the triggering of an NTM by a sufficiently large perturbation [4]. Thus, if previous pellets have driven down the plasma temperature too far, strong local perturbations on resonant surfaces introduced by a further pellet can trigger an NTM. In order to improve this situation, it was necessary to keep the temperature above a critical level. Our prime choice was to increase the heating power by using combined NBI and ICRH heating. Reduction of MHD activity was achieved when approaching the maximum heating power of about 18 MW available in these experiments but discharges still stayed close to the critical onset level of the modes.

Another way attempted to avoid NTMs at the available power level was to reduce the normalized plasma pressure β_{N} by increasing B_{t}. Indeed, discharges at elevated B_{t} seemed to be less prone to core MHD activity. However, these discharges were hampered by a transition from the type-I to the type-III ELM regime and associated with a strong reduction of the plasma energy content [5]. This is due to the unfavourable scaling of the power threshold for type-III ELMs with B_{t} and the reduced energy confinement of type-III ELMy H-mode phases compared to type-I ELMy scenarios [6]. With the available heating power, the threshold to maintain type-I ELMs cannot be surpassed any longer once density increase and edge temperature reduction by the pellets set in. This makes operation at increased B_{t} unfavourable.

Mitigation of the confinement losses imposed by pellet induced ELM activity was achieved by adapting the pellet fuelling cycle. Interrupting the pellet string allows a recovery of the plasma energy content while the particle inventory still remains elevated. The optimized pellet sequence consists of an initial density build up phase at a high repetition rate followed by a density sustainment phase with the pellet rate clipped to a significantly lower value.

In the discharges with the 'ITER-like' configuration, short trains of typically three pellets at 2.5 Hz repetition rate were launched once the discharge evolution had settled in the heating flattop phase.

4. Long pulse fuelling to densities at Greenwald level avoiding persistent confinement degradation

Applying the refuelling scenario optimized in the way described before, successful density increase was achieved, transiently even beyond the Greenwald level. During the recovery phases after each pellet in the final sequence, the plasma energy approaches values achieved in an unfuelled comparison discharge. This is shown in figure 2 where the temporal evolutions of essential plasma parameters are displayed. For the example shown, a power of about 1 MW ICRH was added to about 17 MW NBI for a total of 18 MW heating power. The initial 6 Hz pellet sequence causes the expected energy drop due to enhanced ELM activity. To allow full energy recovery, an extra pellet was eliminated before entering the 3 Hz sequence. The early injection sequence composed of the initial 6 Hz phase and the following pellet pause transformed initial target plasma conditions to a higher density level, while maintaining plasma energy content before the final pellet sequence at a clipped repetition rate starts. Colder, more dense plasmas are better suitable for deep pellet penetration and particle deposition, hence improved refuelling performance is achieved. With this reduced repetition rate, the transient energy drop initiated by each pellet can be almost fully recovered before the next pellet arrives in the plasma. Nevertheless, successive injection gradually drives up the density further until finally the required density level is achieved. The discharge approaches its high density and

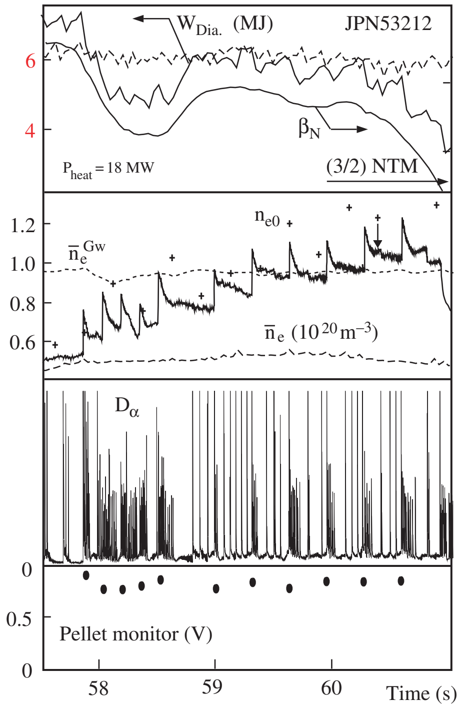

Figure 2. Optimized pellet refuelling for high performance high density operation. $\bar{n}_e > \bar{n}_e^{Gw}$ is achieved at the energy content of an unfuelled reference discharge (- - - -) as energy recovers after the initial pellet sequence. Diamagnetic plasma energy and normalized pressure: first box; line averaged (——) and Greenwald density as well as central density (++): second box; D_α radiation signal from the outer divertor region monitoring ELMs: third box; microwave pellet mass dectector signal: fourth box.

energy phase through refuelling cycles that show pellet driven density increases followed by short phases of strong particle and energy losses turning into confinement recovery phases before the next pellet initiates the next density stepup. At last, $\bar{n}_e > \bar{n}_e^{Gw}$ is reached with about 6.1 MJ plasma energy content and β_N still above 1.85, corresponding to a H97 scaling factor of about 0.86. Finally, the high performance phase is terminated by a growing (3/2) NTM, triggered already by the pellet injected at about 60.0 s. A power scan showed a decrease in core MHD activity with increasing heating power with the maximum available heating power just marginally sufficient for this kind of operation.

Compared to a reference discharge with slightly less heating power (16 MW NBI) and no pellets, the same energy content is confined in the plasma but at about twice the particle inventory. With pellets the rather stiff relation between edge and core density is broken up, which is usually found in scenarios where density ramp up is done by gas puff refuelling. At the expense of slightly more heating power with respect to the reference discharge, a more peaked density and an accordingly flattened temperature profile is achieved while the pressure profiles are virtually identical. The slightly reduced energy confinement in the pellet discharge is due to remaining ELM losses but is at least partly also caused by a less favourable NBI power deposition profiles for the high density profile [7]. Significant reduction of the plasma impurity content is achieved during the high density phase, Z_{eff} dropping from about 2.0 to 1.5.

Analysis of the safety factor and the current density profiles applying the EFIT equilibrium solver shows that there is no substantial modification by the pellets. This is because pressure and resistivity profiles remain essentially unchanged. Although pellet induced density increase reduces the temperature, its effect on the resistivity is compensated by the simultaneous reduction of Z_{eff}.

To allow an assessment of achieved performance in the various pellet refuelling approaches, a comparison between the best performed discharges without and with gas puff refuelling in the same plasma configuration and with according heating powers was done. We choose to compare with data from the JET steady state database [8] and plot the Greenwald fraction of the density versus the energy confinement time with respect to the ELMy H-mode scaling [9]:

$$\tau_{\mathrm{E}} = H97 \times \tau_{\mathrm{E}}^{H97} \qquad \text{with } \tau_{\mathrm{E}}^{H97} = 0.029 I_{\mathrm{P}}^{0.9} B_{\mathrm{t}}^{0.2} P_{\mathrm{heat}}^{-0.66} A^{0.2} R_0^{2.03} n^{0.4} \epsilon^{0.19} \kappa^{0.92} \tag{1}$$

(with A the atomic mass and ϵ the inverse aspect ratio, units are MA, T, MW, amu, m and $10^{20}\ \mathrm{m}^{-3}$).

Figure 3 shows database values obtained in experiments both with the current gas box (open circles) as well as with the previous MKII divertor (open squares) plotted together with the pellet data, the unfuelled reference discharges (filledsquares) were also included. Obviously, the reference data points agree very well with the database set and the pellet refuelling can significantly enhance the accessible operational area in the used plasma configuration. The drastic confinement degradation for gas puff refuelled discharges at $f^{\mathrm{Gw}} = 0.85$ is clearly visible, inhibiting H-mode operation at the Greenwald density. On the other hand, this goal can be quite easily achieved when using pellets as can also be seen in figure 2. From figure 3 it becomes also clear that the H97 scaling describes the attainable plasma energy confinement level rather well up to about $f^{\mathrm{Gw}} \approx 0.7$ but shows a growing discrepancy when $\bar{n}_{\mathrm{e}}$ is increased further. Indicated already by data from gas puff scans, this evolution becomes obvious in the pellet experiments. It seems that the confinement scaling changes from $\sim \bar{n}_{\mathrm{e}}^{0.4}$ valid for low and moderate densities to a more $\sim \bar{n}_{\mathrm{e}}^{0}$ like behaviour in the high density range. The evolution of a pellet discharge in this f^{Gw}–$H97$ diagram occurs, as already mentioned, in fuelling cycles with maximum values expanding almost along an isoenergetic contour. The short phase of strong energy and particle losses following pellet injection drives discharge parameters somewhat

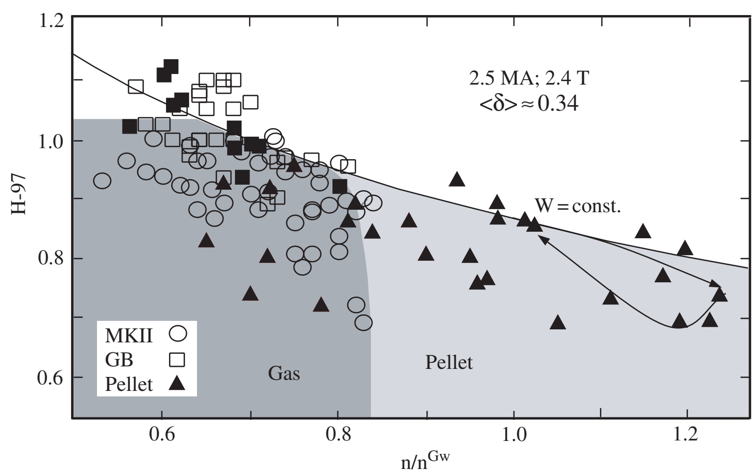

Figure 3. Extension of accessible operational area for 2.5 MA/2.4 T HT plasma configuration by pellet refuelling visualized in a f^{Gw}–$H97$ plot. Values from JET data base for MKII (○) and current gas box (□) as well as from reference shots (■) included. Pellet refuelling (▲) allows high density operation at elevated confinement level.

away from this boundary line but the discharge then recovers to maximum performance. The amplitude of the fuelling cycle with the used performance parameters is visualized by the spread of the data.

5. Refuelling in discharges at highest triangularity

Applying extreme plasma shaping, i.e. using very high triangularity, improvement of the operational parameters was achieved. Especially, the density level where onset of confinement degradation with gas puffing was faced [5] could be improved significantly.

A first test was set up by choosing a high triangularity plasma configuration showing sufficient robustness and replaced gas puffing by moderate pellet injection. The comparison to a reference discharge with a constant gas puffing rate of $2 \times 10^{22}\,s^{-1}$ and a discharge incorporating a short pellet sequence at 2.5 Hz without gas puffing is shown in figure 4. While the gas bleeding discharge shows only a slow density ramp up, pellets induce strong enhancement of the particle inventory. This indicates a much higher refuelling efficiency for pellet refuelling compared to gas puffing, especially if one also takes into account the reduced particle influx (2.5 Hz pellet rate is equivalent to an average particle flux of $0.4 \times 10^{22}\,s^{-1}$, only 1/5 of the gas puff rate applied in the reference discharge).

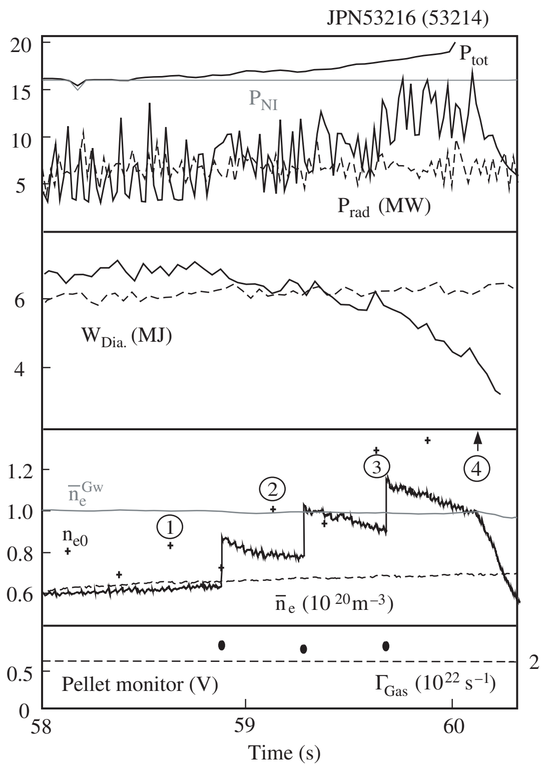

Figure 4. Pellet refuelling (——) in a discharge with extreme triangularity compared to gas puff reference shot (- - - -). Short sequence of pellets (three pellets at 2.5 Hz, equivalent to $0.4 \times 10^{22}\,s^{-1}$ averaged particle flux) initiates strong density ramp up, whereas steady state gas puffing at $2 \times 10^{22}\,s^{-1}$ only induces moderate enhancement. Strong density peaking and according temperature reduction (see figure 5, according times indicated) finally causes a core collapse due to Bremsstrahlung losses terminating the high performance phase.

The post-pellet density decay shows only a very small fast component, the major part of the pellet induced density decays on a slow timescale. Furthermore, typical values for the slow decay time obtained in the extreme triangularity configuration are much longer than those achieved using the conventional plasma shape. For example, for the second pellet shown in figure 4 $\tau_{slow} \approx 1.7$ s is obtained, whereas values typically below 0.5 s occur in the previously described refuelling experiments. It was concluded that the plasma retains pellet deposited particles extremely well. A particle loss rate of less than 0.2×10^{22} s^{-1} can be estimated from the density decay. Applied rates, already reduced to about the minimum value found reasonable in all previous experiments, thus turned out to be still too high. Therefore, density ramp up and according temperature reduction take place too fast. Creating of a cold, dense core plasma results in a strong increase of radiative losses by Bremsstrahlung, finally causing an abrupt loss of confinement terminating the high performance phase of the discharge. Density and temperature profile evolution of the pellet fuelled discharge presented in figure 4 are shown in figure 5, with profiles at corresponding times indicated.

High pellet particle retention times obviously allow further reduction of pellet particle fluxes in future experiments. This reduction to a level not achieved before for successful density ramp up might also help to reduce convective losses and thus maintain high confinement. Further investigations on pellet fuelling of extremely shaped plasmas are planned with reduced size pellets, aiming at a gradual density build up applying smaller density steps.

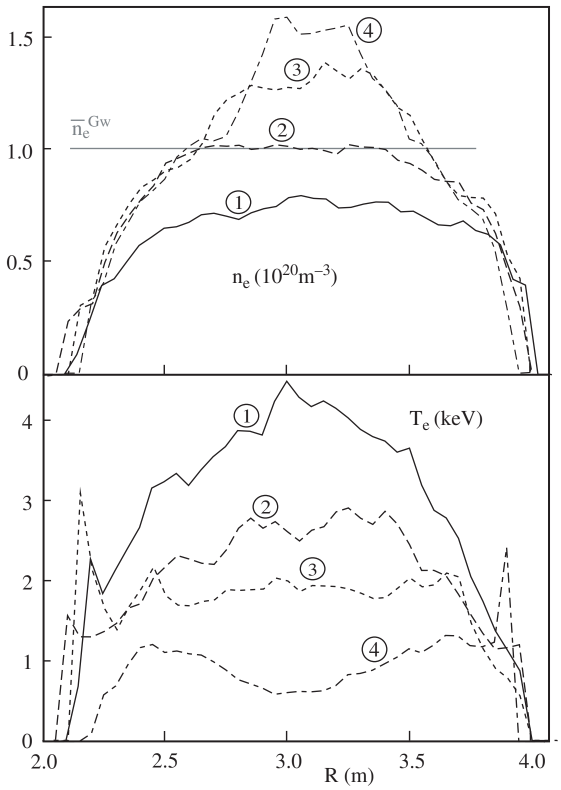

Figure 5. Density and temperature profile evolution of the pellet fuelled discharge presented in figure 4 (corresponding times in figures 4 and 5 indicated).

6. Outlook for further improvements

Experiments performed during this study demonstrated the potential of pellet injection to improve operational capabilities of a large tokamak. However, there still seems to exist headroom for further enhancement of the pellet tool. The essential goal to improve pellet refuelling performance is a further reduction of pellet imposed disadvantages, i.e. mainly post injection losses. Therefore, the request is to aim at realizing deeper pellet penetration into the plasma. As deeper penetration results in deeper deposition and hence in a reduction of particle and energy losses in the fast density decay phase [10], pellet penetration appears to be the key for improvements of the pellet tool.

Investigation of pellet penetration in the experiments performed showed that pellets penetrate almost to the tangency point of the designated trajectory. As the useful pellet velocity component perpendicular to the flux surfaces therefore almost vanishes, penetration potential is missed. A technical assessment has been performed in order to find out alternative injection scenarios capable of achieving deeper penetration and eventually allowing higher launch velocities. There is a possibility of pellet launch through a guiding tube installed mainly outside the vessel. The tube enters the vessel only in its final part through a port located at the inner top of the vacuum vessel, allowing for a significant increase of bent radii all along the tube. Therefore, improved launch velocities can be expected with this launch scenario. To make best use of the higher pellet speed, the injection part will be directed closer towards the plasma centre to allow deeper penetration. Experiments performed recently at ASDEX Upgrade [11] showed that doping pellets with small amounts of about 1% nitrogen can harden the ice. This allows for further enhanced launch speeds in a given injection scheme without causing deleterious effects on the plasma performance. At ASDEX Upgrade, HFS pellet launch velocities up to $600\,\mathrm{m\,s^{-1}}$ with an outside the vessel guiding tube and up to $900\,\mathrm{m\,s^{-1}}$ with additional doping were achieved. As the JET injector is built similar to the ASDEX Upgrade pellet system, a significant improvement of currently available launch speeds of $160\,\mathrm{m\,s^{-1}}$ maximum seems therefore quite feasible. Also, first engineering steps are underway to prepare for tritium pellet injection. Intended for the use in the foreseen tritium campaign of JET-EP, pellets could serve as an efficient tritium refuelling method and allow minimization of the tritium inventory necessary to employ for certain tasks.

7. Summary and conclusions

In the investigation presented here, it was demonstrated that pellet injection is suitable for long pulse fuelling to high densities in the vicinity of the Greenwald density while keeping the ELMy H-mode. To achieve this goal a series of possible degradation mechanisms must be avoided. This is essential to avoid excessive edge density increase by parasitic pellet born gas, the triggering of core MHD events, in particular, NTMs triggered by pellets when the plasma is cooled too strongly, and persisting energy losses by pellet induced ELM losses. The boundary conditions were met by using appropriate plasma configurations with sufficient heating power, experiments however showed that maximum available heating powers were only marginal. Future plans to extend heating power capabilities at JET, e.g. in the framework of the enhancement project (JET-EP), could improve this situation.

Benefits of pellet refuelling and extreme plasma shaping were found suitable for combined use. Very long pellet particle retention times and high fuelling efficiency was found for pellets injected in discharges with extreme triangularities. Even further reduction of particle rates seems feasible, allowing the efficient use of fuel.

Further optimization of the injection set up is underway, aiming at higher launch speed and more central particle deposition. Thus, a further performance improvement by reducing post-pellet induced convective energy losses is expected.

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