Optimisation of pellet scenarios for long pulse fueling to high densities at JET

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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 refueling by deeper particle deposition is known to extend the operational area accessible by gas puff refueling only. For this reason, investigations of pellet particle refueling have been conducted at JET. Experiments concentrated on the developement of optimised refueling 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 refueling with similar refueling experiments applying ordinary gas puff refueling is available.

2. Experimental set up

JET was operated during this campaign using the Mark II gas box divertor with central septum. Lower single null plasma configurations applied in this study typically had elongations $\kappa \approx 1.7$, volumes $V_P \approx 80\,\mathrm{m}^3$ and an edge safety factor $q_{95} \approx 3.2$ with a toroidal magnetic field $B_t = 2.4\,\mathrm{T}$ and plasma current $I_P = 2.5\,\mathrm{MA}$, or $B_t = 2.7\,\mathrm{T}$ and $I_P = 2.8\,\mathrm{MA}$. D-shaped equilibria were run with averaged triangularity $< \delta >\approx 0.34$ (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 deep into the pump throat towards 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, to achieve better coupling of the ICRH a few % of hydrogen were added when needed.

The JET pellet injection system is capable of delivering nominal (4 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 m/s into the plasma from the magnetic high field side along a designated trajectory tilted by 44° to the horizontal plane with a tangency radius at about a normalized minor radius of $\rho \sim 0.6 - 0.7$.

3. Optimisation strategy

The intention of our investigations was to find a way for using pellet refueling for obtaining densities in the vicinity of the Greenwald density $\bar{n}_e^{Gw}$ while still keeping the confined energy high. Using available instrumentation and features, the objective was to improve performance by developing target plasma discharges fully compatible with pellet refueling and optimise adapted pellet sequences. During this optimisation process it turned out that special attention had to be payed to three critical issues

- prompt particle losses causing increase of neutral gas pressure and edge density
- trigger of mode activity by the pellet
- 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 6Hz. This prevented an increase of the neutral gas pressure in the main chamber beyond a level of $2 \times 10^{-3} Pa$ found critical for the onset of confinement degradation.

Like many high performance operational modes also pellet refueling scenarious suffer from magnetohydrodynamic (MHD) mode activity and especially neoclassical tearing modes (NTM) on resonant flux surfaces becoming 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 $\rho_{p,i}^*$, reducing the critical pressure β_p^{onset} for the triggering of a NTM by a sufficiently large perturbation [3]. 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 a 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 [2]. The reason for this behaviour might be the unfavourable scaling of the power threshold for type-III ELMs with B_t. With the available heating power, obviously 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 establishing a pellet fueling cycle. Interrupting the pellet string allows a recovery of the plasma energy content while the particle inventory still remains elevated. The optimised pellet sequence developed 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.

4. Results

Applying the refueling szenario optimised in the way described, successful density increase beyond $\bar{n}_e^{Gw}$ was indeed achieved without significant persistent loss of plasma energy content. This is shown in the figure 1, where the temporal evolution of essential plasma parameters energy, normalized pressure, line averaged and central density obtained in such a sequence are displayed as well as the D_α radiation signal from the outer divertor region for ELM monitoring and the microwave pellet mass dectector signal. For the example shown, a power of about 1 MW ICRH was delivered adding up with about 17 MW NBI to 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 skipped before entering the 2 Hz sequence.

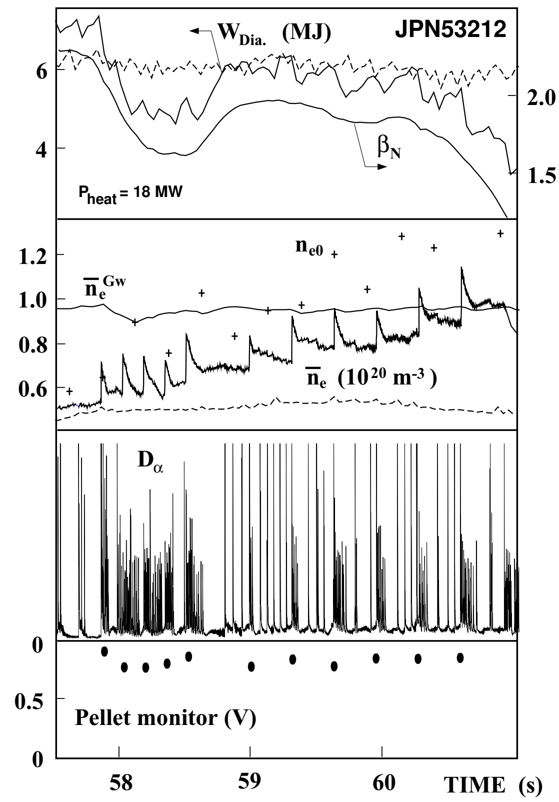

Figure 1: *Optimised pellet refueling for high performance high density operation. Energy recovery after initial pellet sequence, reduced pellet rate establishes refueling cycles with gradually increasing density. Finally, $\bar{n}_e > \bar{n}_e^{Gw}$ is achieved at energy content of unfueled reference discharge (dashed lines, P_{heat} = 16 MW).*

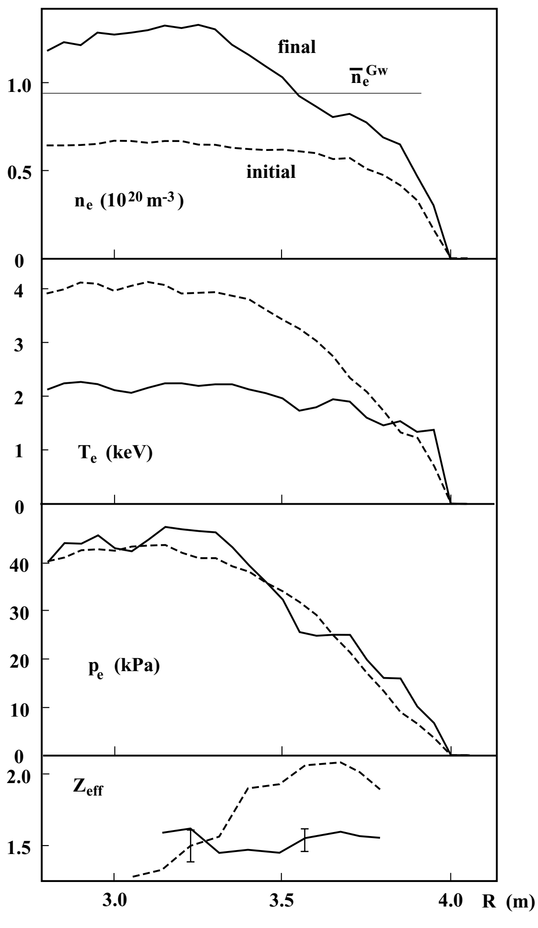

Figure 2: *Density, temperature, pressure and Z_{eff} profiles present in the high density phase at about 60.1 s during (solid) and initial profiles (dashed).*

Thus, before the final pellet sequence at reduced repetition rate starts, initial target plasma conditions were already transformed to a higher density level better suited for

deep pellet particle penetration and deposition, hence improved refueling performance was achieved. With this reduced repetition rate, the transient energy drop initiated by every pellet can be almost fully recovered before the next pellet arrives in the plasma. Nevertheless, successive injection gradually drives up the density further until eventually the required density level is achieved. The discharge approaches its final parameters through refueling cycles that show that the pellet driven density increases followed by short phases of strong particle and energy losses which turn into confinement recovery phases before the next pellet initiates the next density step up. At last, $\bar{n}_e > \bar{n}_e^{Gw}$ is reached with about 6 MJ plasma energy content and β_N still above 1.8 due to a H97 scaling factor of about 0.82. Finally, the high performance phase is terminated by a pellet triggered (3/2) NTM, indicating that the available heating power was just marginally sufficient for this kind of operation.
Compared to an unfueled reference discharge with slightly less heating power (16 MW NBI), the same enery content is confined in the plasma but at about twice the particle inventory and a much more peaked density profile. This profile shaping by the pellets is visualized in figure 2, where density, temperature and pressure profiles are compared. Solid lines showing profiles from the high density phase in the pellet refueling experiment, dashed lines from the reference discharge (averaged over 10 profiles from steady state phase). With pellets edge and core densities are uncoupled unlike those found with density ramp up by gas puff refueling. At the expense of slightly more heating power with respect to the reference discharge, a more peaked 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 might also be referred to a less favourable NBI power deposition profiles for the high density profile. Significant reduction of the plasma impurity content is achieved. This can be seen from Z_{eff} profiles also given in figure 2, obtained for the phase just before pellet injection and during the high density phase.

5. Summary and discussion

In the investigation presented it is shown that pellets can significantly enhance the operational headroom by achieving high density and good confinement simultaneously . Improvements are due to the capability to break the stiff relation between edge and core density present in gas puffed discharges. Particle deposition by pellets can lead to peaked density profiles and high central density while keeping edge profiles almost unchanged. The suitability of pellet injection for long pulse fueling to high densities in the vicinity of the Greenwald density is demonstrated. It is planned to adapt such optimised pellet sequences for applications e.g. in discharges with strong shaping using very high triangularity, internal transport barriers or in the radiative improved mode.

References

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† see appendix of the paper by J. Pamela "Overview of recent JET results", Proceedings of the IAEA conference on Fusion Energy, Sorrento 2000.