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1. INTRODUCTION.

The performance of the hybrid H-mode regime has been extensively investigated in JET experiments up to $\beta_N = 3$, toroidal field $B_t = 1.7T$, with type I ELMs edge conditions. The optimized external current drive sources and stability properties in the plasma core provide a good prospect of achieving a high fusion gain at reduced plasma current for durations up to 2000s in ITER [1]. One of the remaining issues is the problem of erosion of the divertor target plates associated with the type I ELM regime. A possible solution could be to operate with a plasma edge in the type III ELM regime (reduced heat loads) obtained with impurity seeding [2]. In this paper we report on experiments that have recently been performed on JET to investigate the feasibility of an integrated hybrid type III ELM regime with nitrogen seeding.

2. DESCRIPTION OF THE HYBRID TYPE III ELM SCENARIO.

2.1. EXPERIMENTAL SCENARIO

The target plasma is a hybrid H-mode with type I ELMs (T_{ped}~1000eV), $I_p = 1.7MA$, q_{95}~3.2 in which NBI injection is feedback controlled to ~18-20MW to achieve $\beta_N = 2.6$. A high triangularity magnetic configuration ($\delta = 0.44$) is used with MkII-HD divertor (with horizontal septum replacement plates). Nitrogen is injected into the private-flux zone of the divertor (from the horizontal target plate located on the high field side – GIM11). Nitrogen is chosen because it radiates at low plasma temperature, mainly in the divertor and pedestal region. Lower hybrid heating is used during the plasma current ramp up (during ~3s) to delay the penetration of the plasma current density towards the plasma core with the aim of broadening the q profile when the main heating is applied. This is followed by an intermediate $\beta_N = 2$ phase (during ~3s) for stabilization of the q-profile close to 1 in order to stabilize the MHD. The β_N request is then increased during 4 seconds ($\beta_N = 2.6$ has been obtained with high deuterium fuelling and $n_e \sim 0.95 \cdot n_{Gr}$). During this phase, a pre-set injection of deuterium is applied in the bottom of the divertor (on the low field side – GIM9). Nitrogen injection is applied during the first three seconds of the $\beta_N = 2.6$ plateau.

2.2. HYBRID TYPE I AND III ELM SCENARIOS

The transition from type I to a stationary type III ELM regime has been obtained with radiative feedback control on the bolometric signals. The maximum radiated power fraction achieved with deuterium fuelling alone is P^{rad}/P^{tot}~35%. Using deuterium plus nitrogen fuelling enables to increase the radiative fraction up to 50%. This value is obtained by using the baseline of the bolometer signals, which represents the level of radiation *in between* ELMs. The type III ELM regime, characterized by the ELM frequency and amplitude, is achieved when f^{rad}>40%. Fig.1 shows the hybrid type III ELM regime compared to the reference hybrid scenario with high D-fuelling.

A strong gas puff ($\Phi_D = 5\times10^{22}$ e/s and $\Phi_D = \sim7\times10^{22}$ e/s) is required to cool the pedestal and reach the type III ELM regime. This phase is followed by a moderate and decreasing impurity fuelling ($\Phi_N \sim 3\times10^{22}$ e/s) to maintain the regime stationarity. The total radiated power fraction achieved with the type III ELM regime is ~ 50% with β_N = 2.6 (P_{NBI} ~ 20-22MW) and a thermal confinement factor of $H98^*$(y,2)~0.83. The MHD activity is characteristic of that observed in standard hybrid scenario (no strong MHD and reduced sawtooth activity). Note that n=1 sawtooth precursors are present during the seeding phase, which means q_{min} is equal to or smaller than 1. A net reduction of the heat load on the divertor tiles that are normally subject to high heat flux is observed in the hybrid type III ELM regime as discussed next.

3. PLASMA MODIFICATION WITH D AND N FUELLING:

The reference hybrid scenario with low D-fuelling (Pulse No: 68505: Φ_D=0.6 · 10^{22} e/s) shows a pedestal ion temperature of ~1000eV (measured at the top of the pedestal with the edge CXRS diagnostic). Such plasma conditions are associated to type I ELM behavior with high erosion rates. Increasing deuterium fuelling (Pulse No: 68515: F_D=5 · 10^{22} e/s) reduces the pedestal temperature below 800eV. The radiated fraction does not increase significantly (maximum f^{rad} reached with D-fuelling is 35%) and the type III ELMs regime is not attained. Adding N-seeding allows to increase simultaneously the radiated fraction up to 50%, while cooling the pedestal ion temperature below 700eV, thus leading to the type III ELM regime. The heat load reduction associated with the type III ELM regime is presented in Fig.2. The surface temperature as measured with the wide-angle thermographic viewing system [3] shows a net amplitude reduction during the N-seeding phase. The averaged surface temperature remains stable on the outer target plate where the heat flux is expected to be maximum. During ELMs, the surface temperature variation DT_{ELM} is almost completely mitigated on the upper dump plate and outer limiter and partially reduced on the outer target plate region. Simultaneously, the bulk temperature is completely stabilized on the outer target plate where the heat flux is normally higher. The modification of the radiation behavior due to nitrogen seeding is illustrated in Fig.2 (e) and (f).

4. HYBRID TYPE III ELM PERFORMANCE:

The hybrid type III ELM scenario using N-seeding has been successfully developed in JET with I_p = 1.7MA, q_{95} ~3.2, n_e~0.95 · n_{Gr}, β_N ~ 2.6. The plasma performance of this scenario is described by the global energy confinement factor $H98_{(y,2)}$ presented in Fig.3 as a function of the radiated fraction for a series of hybrid discharges with D-fuelling and a mixture of D+N fuelling. The contribution of fast particles has been subtracted in order to identify the thermal part of the confinement. With pure deuterium fuelling, the standard H-mode behaviour is observed: at low-D fuelling (Pulse No: 68505) the hybrid discharges fulfil the ITER confinement requirements when high-D fuelling is accompanied by a net reduction of the global confinement: ~10% losses with Φ_D = 5 · 10^{22} e/s (Pulse No: 68515) and ~20% losses with Φ_D = 9 · 10^{22} e/s (#68739) without significant increase of the radiated fraction. N-seeding does not modify significantly the global energy confinement but enables to reach higher radiated fraction. The degradation of global confinement associated with the type III ELM regime is about 10% compared to the reference hybrid high D-fuelling discharge (#68515), which uses the same D-fuelling: $\Phi_D = 5 \cdot 10^{22}$ e/s. The integrated hybrid type III ELM scenario shows good edge plasma conditions (reduced heat loads and erosion) with moderate MHD activity (q_{min} close to unity). Although this scenario does not fulfill the ITER requirements ($H98_{(y,2)}{}^{*}$~0.83), it is optimized for current drive sources due to high b_N operation and offers good prospects of achieving stable long discharges in ITER.

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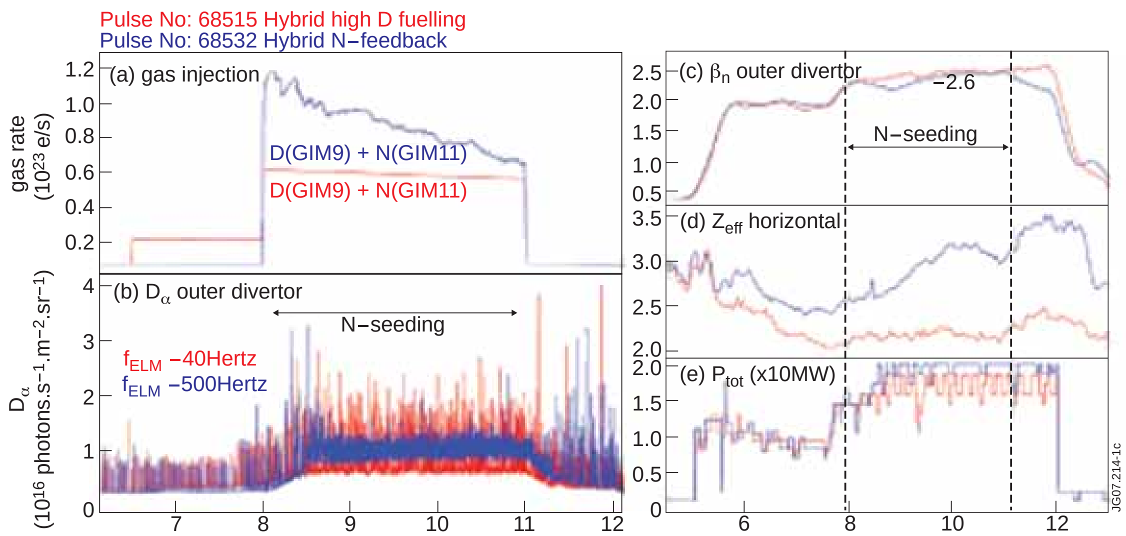

Figure 1: (a) Gas fuelling. (b) D_α signal in the outer divertor. (c) β_N. (d) Z_{eff} from visible spectroscopy (horizontal channel). (e) Neutral beam power for the reference type I and type III ELM regimes.

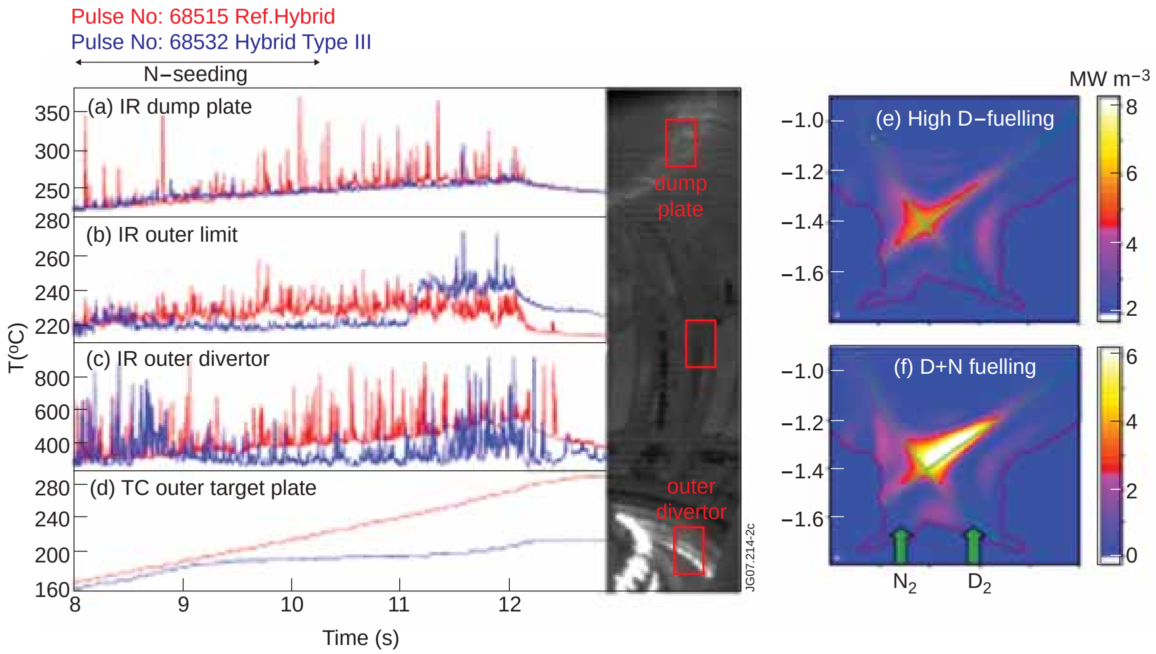

Figure 2: Maximum surface temperature in the dump plate (a), the outer limiter (b) and the outer divertor region (c). Bulk temperature into the horizontal target plate on the low-field side - below the outer strike point (d). Tomographic reconstructions of P^{rad} in the divertor: (e) reference hybrid scenario; (f) hybrid type III ELM scenario with N-seeding.

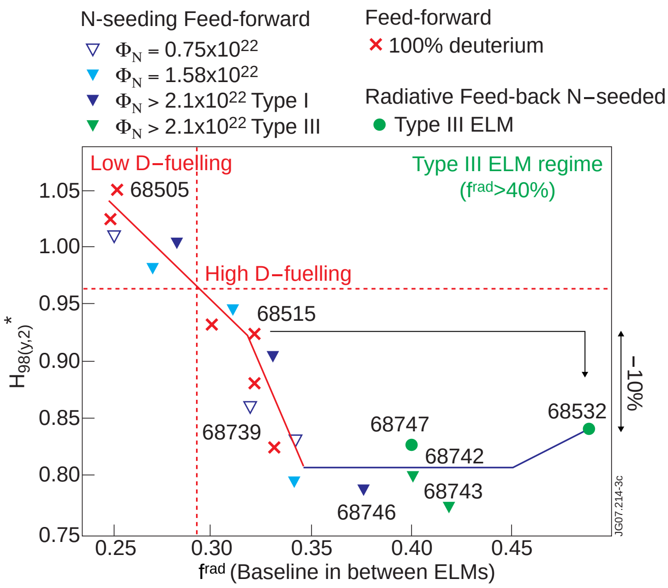

Figure 3: Thermal confinement enhancement factor $H98_{(y,2)}$ versus the radiated fraction measured in between ELMs for a series of pulses with D-fuelling only (red) and D+N fuelling (blue and green are associated with type I and III ELM regime respectively).