Long time-scale density peaking in JET

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Introduction. In ELMy H-mode, increasing the density generally results in a reduction of the energy confinement time to below the value predicted by the scaling law [1]. This confinement density limit has been attributed to the transition at the edge from type-I to type III ELMs. The collapse of the plasma edge from type-I to type-III ELMy regime can be avoided if the gas puffing rate is restricted. In such discharges the central density monotonically increases with a long time-scale and exceeds the Greenwald density limit (GDL) while type-I ELMs and good energy confinement are preserved [2, 3, 4]. During this process the pedestal density is clamped just below the GDL leading to a peaked density profile. Note that pedestal densities at the GDL has been recently achieved [5]. This paper reports on reproducing the scenario with density peaking on JET and identification of limiting factors.

Type-I ELMy H-mode above Greenwald density limit. Key ingredient of these experiments is the use gas fuelling rates below the values when degradation of edge transport barrier occurs (for this limit at higher current and power see [5], [6]). Secondly, the duration of the discharges has to be extended to allow for long time-scale evolution of density profile. We started with low field (B_T = 1T, I_p = 0.95MA) and low triangularity shape (δ = 0.26). With fuelling from outboard midplane of the main chamber at the rate of 2×10^{21} el/s and heating power P_{NBI} = 3MW the line averaged density was linearly increasing for 9s and reaching $\bar{n}/n_{Grw}\approx1.1$ (#50650, $n_{Grw}(10^{20}\text{m}^{-3})=I_p(\text{MA})/\pi a^2$). Low frequency (4Hz) type-I ELMs were preserved. The density at the top of the pedestal ($r/a\approx0.9$) is clamped at $n_{ped}\approx0.85\times n_{Grw}$ leading to a peaked density profile with central density of $n_0\approx1.4\times n_{ped}$. Similar results have been obtained at a medium triangularity (δ_L = 0.27, δ_U = 0.34), higher field B_T = 1.7T, I_p = 1.6MA and fuelling from outer divertor ring at the rate of of 2×10^{22} el/s. At P_{NBI} = 5.7 MW the densities of $\bar{n}/n_{Grw}\approx1.1$ have been reached with the timescale of 2-4s (#52458). Most of the studies, however, have been done at high triangularity (δ_L=0.4, δ_U=0.6) and higher field (B_T=2T, I_p=1.9MA). The gas was supplied from the outer divertor

*See annex of J. Pamela et al., "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).

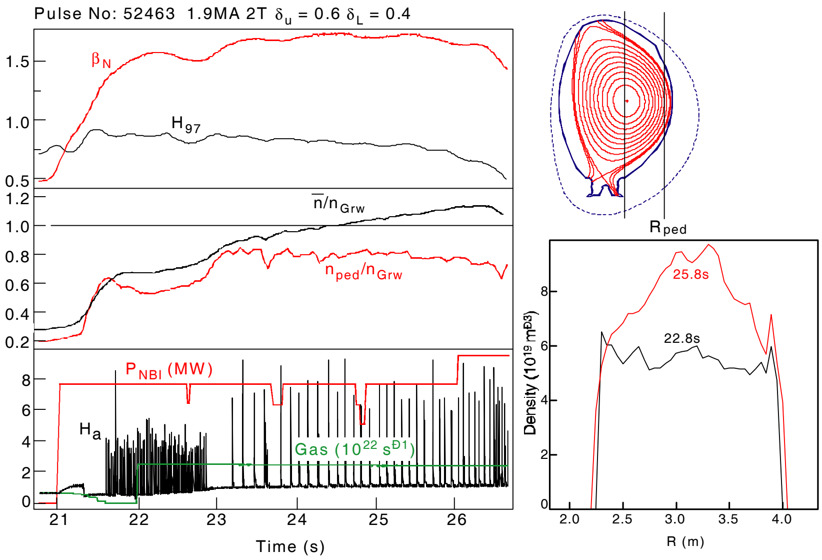

Figure 1. Discharge above the Greenwald density limit with type-I ELMs.

ring. An example of such plasma is shown in Fig. 1. The line-averaged density monotonically increases with a time scale of several seconds and exceeds the GDL by up to ~12%. The pedestal density is limited to about 80% of the GDL leading to a ratio of core to pedestal density of ~1.5. During this process type-I ELMs and good energy confinement are preserved. With the same shape this scenario has been reproduced even at higher field (B_T=2.7 T, I_p=2.5 MA) and power (P_{NBI} = 13.5MW). In this case (#52015) the gas puffing is from inner divertor ring at the rate of 1.5×10^{22} el/s. The line averaged density was increasing for 6s reaching $\bar{n}/n_{Grw}\approx1.0$ with highly peaked density profile $n_0\approx1.5\times n_{ped}$ while preserving low frequency (19Hz) type-I ELMs.

Power scan. The response of maximum achievable density on heating power was investigated at the same shape and gas puffing rate as in Fig. 1. The results are summarised in Fig. 2 showing the central density as a function of central electron temperature. For NBI power below 8MW the plasmas are transient. Central density increases linearly in time. Simultaneously the current density profile is broadening as indicated from the decrease of internal inductance and the rise of central safety factor and finally the sawteeth are lost. The loss of sawteeth results in an even larger increase of core density and at its maximum exceeding the GDL by 30-40%. The increase of the core density

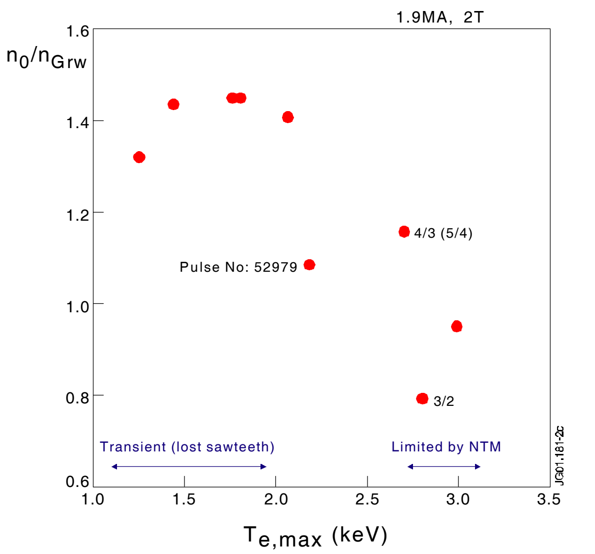

Figure 2. Dependence of central density on central electron temperature in power scans.

results in gradual reduction of core temperature and eventually the H-mode is terminated by the enhanced core radiation. At higher NBI power, 12-14 MW, the strong temperature reduction is avoided. At this power levels n_0 is limited by neoclassical tearing modes. Typically modes with high mode numbers *m/n*=4/3 (5/4) occur first. Already these modes are observed to stop the monotonic increase of n_0 resulting in quasi-stationary plasma. When large *m/n*=3/2 mode occur (7-10cm) the core density drops to the pedestal value leading to flat density profile.

With dominant ICRH heating (2nd harmonic, H-minority, B_T=1.7T, I_p=1.6MA) loss of sawteeth is avoided even at 8MW of total power. These plasmas have high core density, n_0/n_{Grw}≈1.1, and rather flat density profiles (high pedestal density). Global energy confinement is lower in these high density ICRH plasmas (H_{H98y2}=0.6).

Gas position scans. Variation of gas puff position so far showed the best results with fuelling from the inner ring on the divertor base, which correspond to puffing into the private region. Simultaneously the gas waveform has been optimised to moderate the size of the first ELM after the ELM-free phase which usually triggers a large *m/n*=3/2 neoclassical tearing mode. An example of such discharge is shown in Fig. 3. In this case the decrease of internal inductance is also evident, however, this trend slows towards the end of heating phase and sawteeth are preserved. The density profile reaches equilibrium leading to a quasi-stationary discharge with line averaged density $\bar{n}/n_{Grw}$=1.0 normalised energy confinement time of H_{H98y2}=0.96, β_N=2 and central density about 30% higher than the pedestal density.

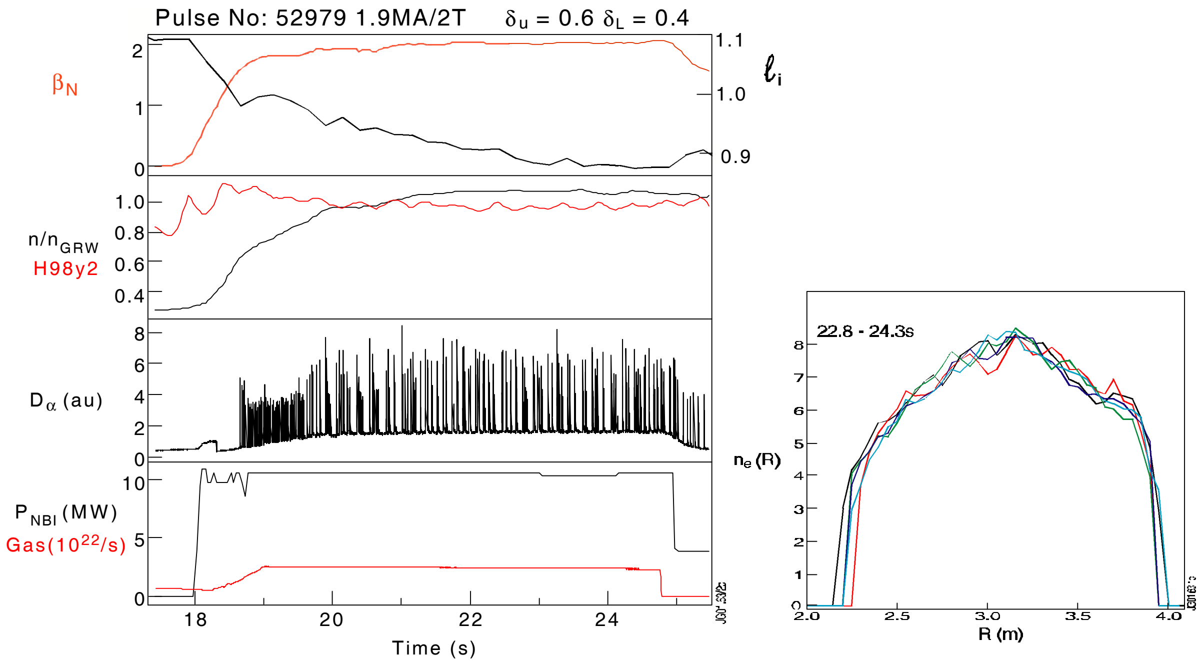

Figure 3. Quasi-stationary ELMy H-mode plasma at the Greenwald density limit.

Transport analysis. Analysis was done for quasi-stationary plasma shown in Fig. 3 using the JETTO code. At *t*=23s, *dn/dt*=0 so that the particle ion flux is outwards and equal to the NBI source. Inside the ρ=0.4 surface this source is $\Phi=2.6\times10^{20}s^{-1}$ which gives the flux density $\Gamma=\Phi/\Sigma=0.063m/s\times n_i$. At the same radius the Ware pinch velocity is V_W=0.046m/s (Fig. 4). This value is comparable to Γ/n_i and therefore the pinch and NBI fuelling play an equal role in density peaking if pinch velocity $V=V_W$ is assumed. At ρ=0.4 the density scale length $L_n=n_i/\nabla n_i$=2.4m giving the ion diffusion coefficient of $D=(\Gamma/n_i+|V_W|)\times L_n$ =0.28 m^2/s. At the same radius, the effective heat conductivity is $\chi_{eff}=1.2m^2/s$ so that the ratio $D\sim\chi_{eff}/4$ (see Fig. 4). Assuming an anomalous pinch, $V=10\times V_W$ results in particle diffusion coefficient of $D\sim\chi_{eff}$. This somewhat higher value perhaps indicating the upper limit for anomalous pinch, at quasi-stationary sawtoothing conditions. In this case, $V\gg\Gamma/n_i$, and the pinch would control the density peaking. Strong density peaking that occurs after the loss of sawteeth is well reproduced with the Weiland transport model [7].

The bootstrap current in these plasmas seems rather modest (I_{bs}/I_p~16%) in order to contribute to the observed broadening of current density profile.

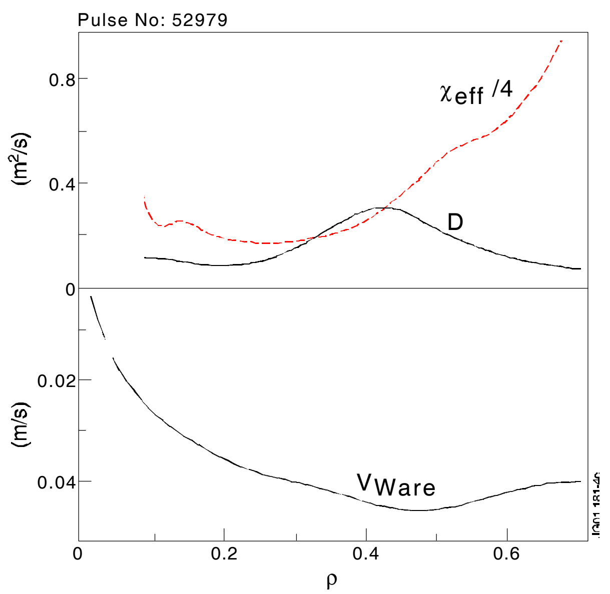

Figure 4. Ion particle diffusion coefficient D, ion thermal diffusivity χ_i and Ware pinch velocity V_W for #52979 @ 22.8 s (JETTO).

Conclusions. With reduced gas puffing and allowing for longer time scales the plasmas with central densities up to $1.4\times n_{Grw}$ can be achieved with low frequency type-I ELMs.
Significant density peaking is observed with NBI when large tearing modes are not present.
With gas puff optimisation the quasi-stationary discharge with $\bar{n}/n_{Grw}$=1.0, H_{H98y2}=0.96, β_N=2 and n_0/n_{ped}=1.3 is obtained. These plasmas are contributing to improvement of energy confinement scaling at high densities [8].

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