Pedestal confinement in hybrid versus baseline plasmas in JET

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**See the Appendix of F. Romanelli et al., Proceedings of the 22nd IAEA Fusion Energy Conference 2008, Geneva, Switzerland*

The hybrid confinement regime has been extensively explored in the 2008-2009 JET campaigns, obtaining confinement factors up to $H_{IPB98(y,2)}$~1.4 and normalised pressure β_N~3 in both low and high triangularity configurations. A comparison of pedestal and core confinement has been recently carried out in ASDEX Upgrade and DIII-D [1]. The present paper examines the contribution of the pedestal to the total confinement in the hybrid regime in JET. The pedestal parameters are measured using the new High Resolution Thomson Scattering (HRTS) data (measuring electron temperature T_e and density n_e) combined with Charge Exchange data (measuring the ion temperature T_i, the effective charge Z_{eff}). Ion density is estimated from n_e and Z_{eff} assuming carbon as main impurity: $n_i=n_e(7-Z_{eff})/6$. To investigate the origin of the better confinement in the hybrids, a comparison with baseline H-mode scenarios is made. In total, four different scenarios are studied, see table 1 for details.

scenario	δ	Ip (MA)	P_{NET} (MW)	Bt (T)	q95	β_N	H98
Baseline low trian.	~0.28	1.0-2.5	5-20	1.1-2.8	2.8-3.5	1.4-1.9	0.8-1.1
Baseline high trian.	0.4-0.45	1.0-2.5	5-20	2.1-2.8	3.4-3.8	1.6-2.1	0.7-1.1
Hybrid low trian.	~0.23	1.7-2.0	5-20	2.0-2.4	3.7-4.5	1.3-2.7	1.0-1.6
Hybrid high trian.	0.35-0.4	1.3-2.0	5-20	1.7-2.4	3.5-4.5	1.8-2.5	1.0-1.3

Table 1. Parameter range of the four analyzed scenarios

The discharges and the corresponding analyzed time intervals are selected with the following criteria: only Type I ELMy shots, constant power for a few confinement time, constant $H_{IPB98}(y,2)$, no neo-classical tearing modes (NTMs) and good quality kinetic profiles. In the following, pedestal parameters are calculated by fitting experimental data with a modified *tangent hyperbolic* function; core data are calculated at $\rho_{tor}=0.3$.

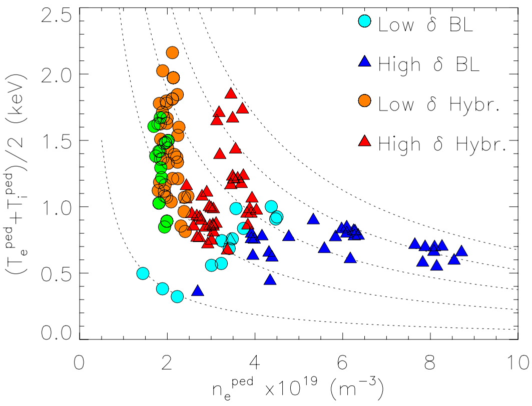

Figure 1. Pedestal temperature versus electron pedestal density. Dashed lines represent constant pressure curves. The green dots are low δ hybrids plasma with density control in which only the input power is varied. These colour and symbol codes are used throughout the paper.

Pedestal characteristics

The correlation between the pedestal temperature and the pedestal electron density, figure 1, is useful to describe the four groups of shots.

- The baseline low δ shots are part of a current scan study. High current shots are characterized by high pressure.

- The baseline high δ shots are part of current scan and fuelling experiments. The pedestal pressure increases with increasing current. At fixed current the pedestal density is increased by gas fuelling while the pedestal temperature is decreased. As a result the pedestal pressure is kept fixed and the data follows approximately a constant pressure curve.
- For the hybrid low δ a large variation in the pedestal temperature is present, while the density is approximately constant. This behaviour is due to (i) variation of the heating power, (ii) current profile optimisation by variation of heating timing and current waveforms (iii) variation of the fuelling schemes that were employed in NTM avoidance schemes [2,3].
- The hybrid high δ are characterized by current scan and gas fuelling. In this regime the pedestal pressure is not maintained at increased fuelling levels [4].

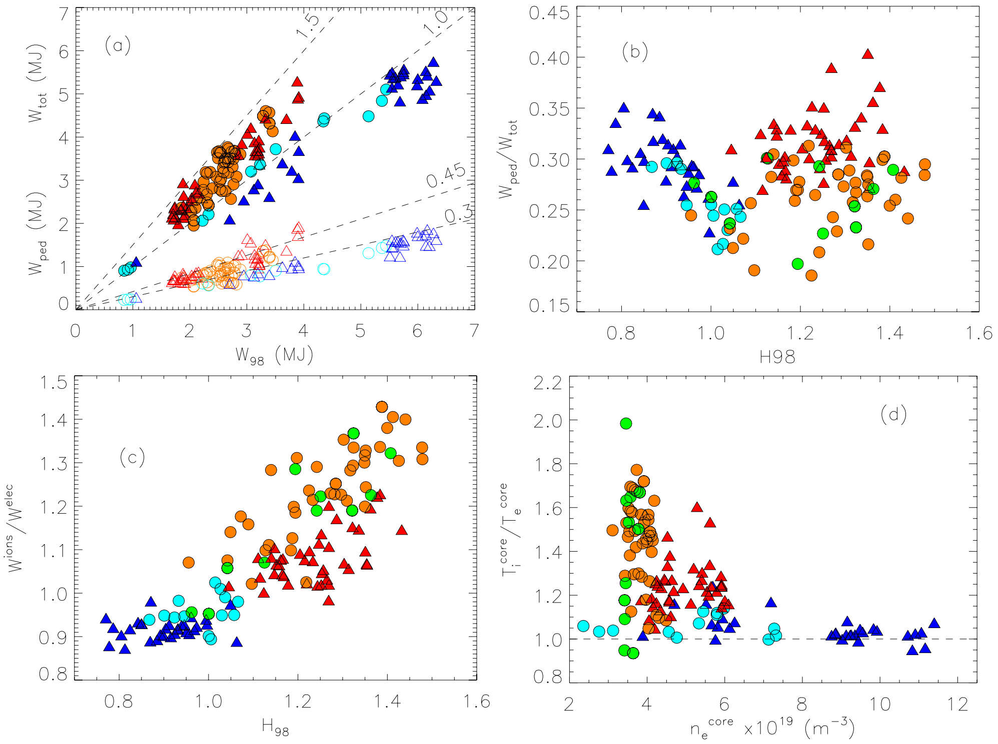

Figure 2. (a) Total energy (full symbols) and pedestal energy (open symbols) versus W98. The dashed lines are arbitrary lines to highlight the separation between hybrids and baseline plasmas and the numbers correspond to the slopes. (b) Pedestal energy normalized to total energy versus H98. (c) Ratio of ions energy and electron energy versus H98. (d) Ratio of Ti over Te in the core versus the core density.

Confinement

Figure 2(a) shows the dependence of the pedestal (W_{ped}) and total (W_{tot}) stored energy calculated from kinetic profiles compared to stored energy according the IPB98(y,2) scaling W_{98}, defined as:

$$W_{tot} = W^{elec}+W^{ions} = \frac{3}{2}k_B\int_0^1\left[n_e(\psi)T_e(\psi)+n_i(\psi)T_i(\psi)\right]\frac{dV}{d\psi}dV,$$

$$W_{ped} = \frac{3}{2}k_B\left[n_e(r_{ped})T_e(r_{ped})+n_i(r_{ped})T_i(r_{ped})\right]\cdot V_{tot} \quad \textit{and} \quad W_{98}=\tau_E^{98(y,2)}\cdot P_{NET} \quad (P_{net} \textit{ is the net input power})$$

For the hybrid plasmas W_{tot} rises well above W_{98} by up to 50% compared to the baseline plasmas, as expected from the improved confinement factor H_{98} in these plasmas. In this study, H_{98} is calculated from the kinetic profiles as $H_{98}=W^{tot}/(P_{net}\tau_E^{98})$. Moreover, also the pedestal energy for the hybrid plasma is approximately 50% higher than baseline W_{ped} (see the slope of the dashed lines in figure 2(a)). The relative contribution of the pedestal to the total energy content versus H_{98} is shown in figure 2(b). A weak negative trend is present for the baselines. For the hybrids, the large scatter does not allow any conclusive claim, but the results seem to suggest the opposite (positive) trend for the high δ regime. A clear separation is visible between the low and high triangularity discharges, independent of the regime (hybrid or baseline). The edge MHD stability for the peeling and the ballooning modes improves with triangularity [5] which allows for steeper pressure gradients and higher pedestal pressure for the high δ discharges. An analysis is ongoing on the correlation of the core confinement with triangularity.

To further investigate the origin of the improved confinement, the role of electrons and ions has been studied separately by calculating the total stored energy for the two species, W^{elec} and W^{ions} respectively. Figure 2(c) shows the ratio between of W^{ions} and W^{elec} versus H_{98}. This ratio, being $W^{ions}/W^{elec}>1$ for the hybrids, seems to show that the hybrid increased performances are driven more by the ions. Note that at the same H98 the ion contribution to the total energy is higher for the low δ hybrids than for the high δ. For the baseline plasmas the opposite relation holds, $W^{ions}/W^{elec}<1$, as for these $n_i < n_e$ and $T_i \approx T_e$.

In figure 2(d) the ratio between core T_i and core T_e is shown versus the electron density. While for the hybrid scenarios $1<T_i^{core}/T_e^{core}<2$, for the baseline scenarios $T_i^{core}/T_e^{core} \approx 1$ for the entire density range of density. For the hybrid plasmas a decoupling of T_i and T_e occurs at high input power. In figures 2(b) and (c) the green dots represent a power scan in the low δ hybrid plasmas from $P_{net} \approx 8$MW to ≈ 20MW. When P_{net} is increased H_{98} raises as does T_i/T_e. So far improved hybrid confinement at higher density and $T_i=T_e$ has not been achieved on JET [3].

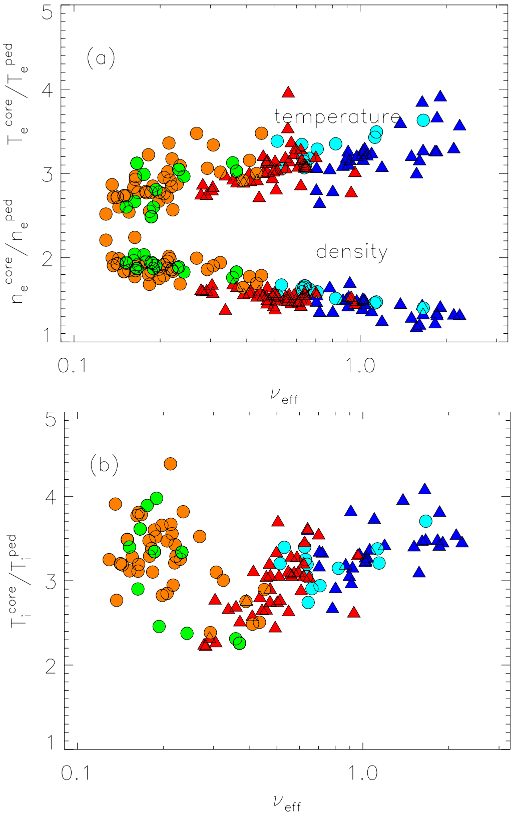

Figure 3. (a) Profile peaking for electron temperature and electron density versus collisionality. (b) Profile peaking of ion temperature versus collisionality.

Edge vs core confinement; kinetic profile peaking.

The relative contributions from the pedestal vs core plasma are now further discussed. The relative role of the edge vs core confinement is discussed in [6-8] for various devices, where the density peakedness is found to decrease with $\nu_{eff}=10^{-14}Z_{eff}\langle n_e\rangle/\langle T_e\rangle^2$. In these studies no clear experimental trend of temperature peakedness was found. Figures 3(a) and 3(b) show the profile peakedness for n_e, T_e from the HRTS system and T_i from Charge exchange for the database in this paper. Like in previous results, a clear variation of the density peaking is found with $\nu_{eff.}$, see Figure 4(a) for an example of the profiles. For the first time, this study also shows that the peaking of the electron temperature increases slightly with ν_{eff} (see Figure 4(b) for an example of T_e profiles at low and high collisionality).

This positive correlation is even more marked for the ion temperature profile at $\nu_{eff}>0.25$, figure 3(b), corresponding to the baseline and high δ hybrid plasmas, where ions and electrons are strongly coupled through equi-partition. As a result, the pressure profile peaking barely depends on collisionality, see figure 4(c). This observation is supportive of theories where the pressure profile, rather than the temperature profile, is stiff [9]. Since, for a given average pressure $\langle p\rangle$, fusion power scales as $p_0^2/\langle p^2\rangle$, this also shows that the potential benefits of density peaking for fusion performance, as described in [8], may be mitigated by temperature flattening. For $\nu_{eff}<0.25$ however, corresponding to the low δ hybrids with the highest T_i/T_e and highest H_{98}, the trend of the T_i peakedness is broken. In this regime the electrons and ions are decoupled; the source of the enhanced ion temperature peaking in this regime is studied in [10]. No strong ion ITB is seen in these plasmas, but the ion temperature is indeed steeper for the high T_i peaking shots, see Figure 4(d).

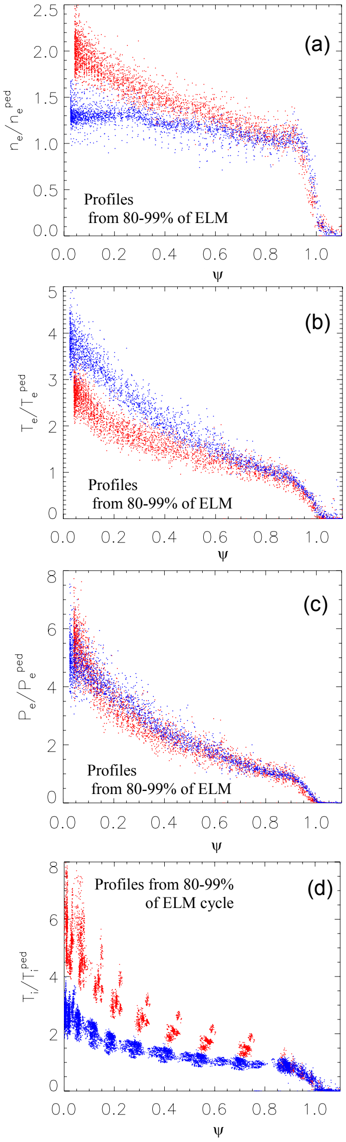

Figure 4. Profiles normalized to the pedestal height for (a) electron density (b) electron temperature and (c) electron pressure, for $\nu_{eff}<0.15$ (red) and $\nu_{eff}>1.9$ (blue). (d) Normalized Ti profiles for low δ hybrids with $T_i^{core}/T_i^{ped}>3.8$ (red) and $T_i^{core}/T_i^{ped}<2.6$ (blue).

Conclusions

- Hybrids and baseline plasmas cover different parameter space both at the pedestal and in the core (low n_e, high T_e).
- Confinement improvement is strongly coupled to high T_i/T_e ratio.
- Improved confinement at $T_i=T_e$ has not yet been achieved.
- Strong T_i peaking has been observed for the low δ hybrid plasmas as well as a lower (but still high) peaking for the high δ hybrids.
- The transition between hybrids and baseline plasmas is smooth in every parameter studied in this paper. Both core and edge confinements are improved. For low δ hybrids the increased T_i peaking is correlated with the enhanced confinement. For the high δ hybrids the improved pedestal confinement might be more relevant, fig 2(a).
- A negative correlation between n_e peaking and collisionality is observed while a positive correlation is present for T_e. A positive trend is present also for T_i at $\nu_{eff}>0.25$, while for lower collisionality (corresponding to low δ hybrids) a negative trend is observed.
- For the shots considered in the present database, the fuelling does not produce a significant density increase in the low δ hybrids. The high δ hybrids offer a route to increased density. The upcoming input power enhancements on JET will provide a tool to investigate whether the confinement degradation due to fuelling can be overcome in these plasmas.

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