Effect of 'baseline' and 'hybrid' operational parameters on plasma confinement and stability in JET with a Be/W ITER-Like Wall

J. Mailloux[1] , M. Beurskens[1], I. Chapman[1], I. Nunes[2], B. Alper[1], M. Baruzzo[3], P. S. A. Belo[1], E. Belonohy[4], J. Bernardo[2], P. Buratti[5], C. D. Challis[1], E. de la Luna[6], L. Frassinetti[7], J. Garcia[8], C. Giroud[1], N. Hawkes[1], J. Hobirk[4] , E. Joffrin[8], D. Keeling[1], M. Lennholm[9], P. J. Lomas[1], T. Luce[10], P. Mantica[11], C. Marchetto[11], M. Maslov[1], G. Pucella[5], S. Saarelma[1], S. Sharapov[1], E. R. Solano[6], C. Sozzi[11], G. Szepesi[11], M. Tsalas[12] and JET EFDA contributors*

JET-EFDA Culham Science centre, Abingdon, [1]CCFE, Culham Science Centre, Abingdon, UK, [2]Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal, [3]ENEA, Consorzio RFX Padova, Italy, [4]Max-Planck-Institut für Plasmaphysik, D-85748 Garching, Germany, [5]ENEA, C.R. Frascati, Roma, Italy, [6]CIEMAT, Madrid, Spain, [7]VR, Fusion Plasma Physics, EES, KTH, SE-10044 Stockholm, Sweden, [8]CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France, [9]European Commission, B-1049 Brussels, Belgium, [10]General Atomics, P.O.Box 85608, San Diego, CA 92186-5608, California, USA, [11]IFP-CNR, via R. Cozzi 53, 20125 Milano, Italy, [12]FOM Institute DIFFER P.O. Box 1207 NL-3430 BE Nieuwegein, The Netherlands

**F. Romanelli et al, Fusion Energy 2012 (24th IAEA International Conference, San Diego, 2012)*

Database studies [1] on JET with the Carbon wall (JET-C) and JET-ILW suggest that the transition in confinement properties between the scenarios so-called ‘baseline’ (aiming at demonstrating/studying plasmas suitable for ITER baseline with q_{95}~3, $H_{98(y,2)}$~1, β_N~1.8) and ‘hybrid’ (for Q=5 long ITER pulse with q_{95}~4, but also possibly for Q=10, requiring $H_{98(y,2)} > 1$, $\beta_N \geq 2.5$) is of a continuous nature. The comparison gains relevance as in the first JET-ILW campaigns, ‘baseline’ plasmas showed a reduced confinement by ~20-30% (β_N~1.4, $H_{98(y,2)}$~0.7-0.8) compared to similar plasmas in JET-C [1,2] with possible impact on ITER's predicted performance of Q=10 with $H_{98(y,2)}$=1 assumed. In contrast, the ‘hybrid’ scenario performed equally well with β_N~3, $H_{98(y,2)}$~1.2 in both JET-C and JET-ILW. In order to understand whether the difference between scenarios is due to the different operational space, pedestal physics and/or turbulent transport in the core plasma, an experiment was conducted where the input power (hence β_N) and q_{95} were varied in ranges overlapping those typical of hybrid and baseline plasmas. Only low triangularity plasmas were used, and no N_2 seeding. To minimise the effect of neutrals on confinement (see e.g. [3]), the same low amount of D_2 was injected during the main heating. Note these experiments focused on reproducing the engineering parameters in both types of plasmas, to ensure valid comparisons, and not on optimising the plasma performance.

Effect of q_{95}: The q_{95} of baseline-like plasmas was varied from 3 to 4.5 (baseline to hybrid range) by reducing the plasma current (I_P), at same neutral beam power (Fig.1) and gas ~ 4×10^{21}e/s. The electron density (n_e) decreases with I_P, but the Greenwald fraction (f_{GLD}) is constant. The normalised confinement ($H_{98(y,2)}$) and total pressure (β_N) are unchanged with q_{95} (the fast particles content does increase as I_P & n_e are reduced). The ELM frequency (f_{ELM}) increases with q_{95}, which is desirable since high f_{ELM} helps to limit the impurity content in the core. Indeed, in this example, the plasma with lowest q_{95} shows large excursions of the total radiation from 49.8s, in contrast to the plasma with q_{95}=4.5 and highest f_{ELM}, even though the plasmas have the same edge T_e and T_i profiles. In this configuration, plasmas at q_{95}=3 needed higher gas to avoid high impurity content.

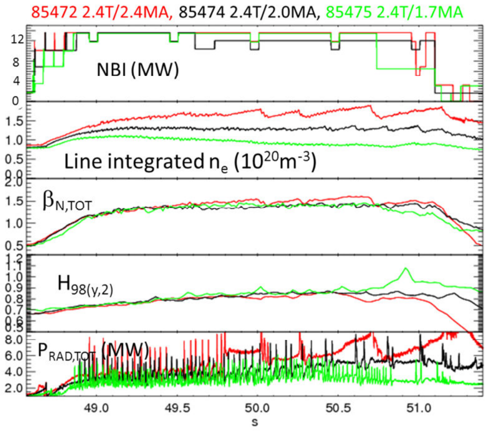

Figure 1. Comparison of baseline-like plasmas at q_{95} = 3 (red), 4 (black) and 4.5 (green)

Effect of the q-profile shape: 'Baseline-like' (i.e. with fully diffused q profile) and 'hybrid-like' (i.e. with tailored q-profile, with low magnetic shear in the core) plasmas have been compared at the same value of q_{95} and NBI power (and β_N). It was found that the confinement was similar when q_{95} and β_N were matched, independently of the core q-profile shape. Figure 2 shows an example at q_{95}=4, where a baseline-like plasma is compared to a hybrid-like plasma at the same power and gas during the main heating phase. The only difference between them is the q-profile at start of the high heating as confirmed by MSE data (Fig. 3) and by the location of MHD modes observed in these plasmas. Both plasmas reach the same β_N = 2.5 and $H_{98(y,2)}$=1.15 before the performance is degraded by MHD modes. The same β_N and $H_{98(y,2)}$ are found when comparing hybrid-like and baseline-like plasmas at q_{95}=3 (2T/2MA) at high power. At matched q_{95}, P_{ADD}, and gas, the n_e profiles and the electron and ion temperature (T_e, T_i) profiles are similar in baseline-like and hybrid-like plasmas, suggesting that the transport is similar despite the different q-profiles. Simulations with JETTO [4,5] with the quasi-linear transport code GLF23 [6] using the experimental q-profiles predict only small differences between the plasmas at matched q_{95} and high P_{NBI}, although the hybrid-like plasmas at both q_{95} show slightly higher core heat transport. Nonlinear gyrokinetic simulations are required for more

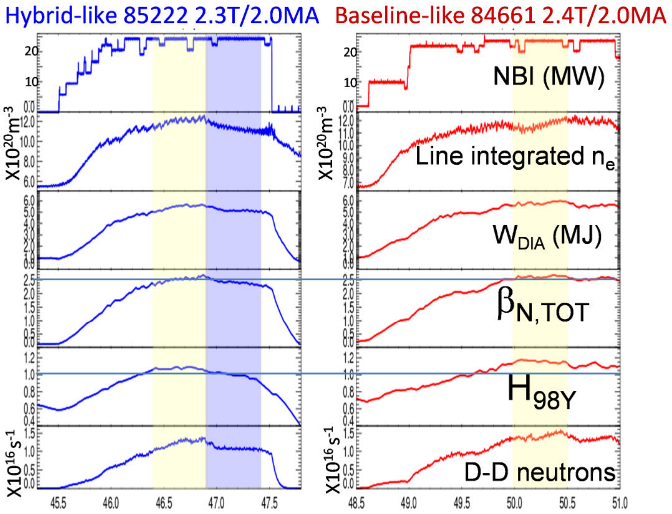

Fig. 2. Comparison of hybrid-like (blue) and baseline-like (red) plasmas at q_{95}=4 and high power. The yellow boxes show time for the detailed comparative analysis. The blue box shows when MHD modes (3/2, 4/3, 5/4) reducing the performance are observed

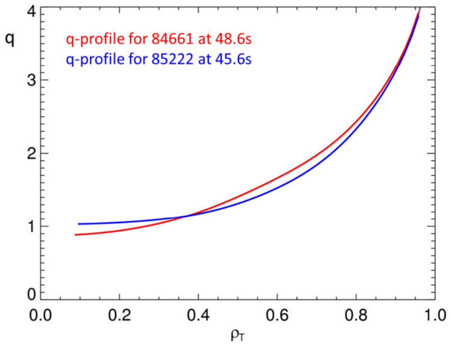

Figure 3. q-profiles at the start of the main heating for the plasmas in Fig.2

accurate predictions, also taking into account the fast ion pressure, which is higher in the plasmas at higher q_{95} and higher P_{NBI} according to TRANSP [7] interpretative analysis using the experimental profiles.

Effect of power: When they are performed at lower P_{NBI} (~14MW), both hybrid-like and baseline-like plasmas reach lower β_N (~1.4) and $H_{98(y,2)} \approx 0.85$. Figure 4 summarises the results with low and high power at q_{95}=4 and q_{95}=3, showing that the total thermal energy (W_{TH}) as a function of the power absorbed in the plasma (P_{IN}) behaves in a similar way in baseline-like and hybrid-like plasmas. Also, Fig.4 shows that they do not follow the curve predicted by the IPB98(y,2) scaling ($W_{TH} \propto P_{IN}^{0.31}$). Instead $W_{TH} \propto P_{IN}^{0.64}$ for the shots at q_{95}=4 and $W_{TH} \propto P_{IN}^{0.55}$ for q_{95}=3 ($\propto P_{IN}^{0.6}$ when averaging), indicating that these plasmas have a much weaker energy confinement degradation, $\tau_E \propto P_{IN}^{-0.4}$ instead of $P_{IN}^{-0.69}$ predicted by the IPB98(y,2) scaling [8]. This is consistent with the power degradation found in a dedicated, detailed, power scan in hybrid-like plasmas (with the same plasma shape as the dataset shown here), with all other engineering parameters kept the same. The pedestal pressure and core gradient increase with power, for both hybrid-like and baseline-like plasmas. This is due to T_e at the pedestal, but also to n_e in the core, as shown for example on Fig.5 for a baseline-like plasma at q_{95}=3. Indeed, although the overall n_e remains roughly the same, the n_e profile become more peaked as the power increases. This could be due to the lower collisionality and higher core fuelling obtained in the plasmas at higher power, in accordance with findings in several machines [9]. The pedestal stability was investigated with the codes ELITE and MISHKA [10]. For hybrid-like and baseline-like plasmas, the plasma is near the predicted stability boundary at high P_{ADD} (and $\beta_N \sim 2.5$), but within the stable region at low power ($\beta_N \sim$ 1.4-1.6), similarly to what is found in plasmas with high gas [11]. Finally, although it is expected that the q-profile affects stability to tearing modes, it is worth noting that in the limited dataset shown here ($\leq \beta_N = 2.5$), there is no evidence that the baseline-like plasmas are less stable than their hybrid-like counterparts.

Conclusion: The results shown here indicate that the differences in q_{95} and q-profile shape are not the main reason for the difference in $H_{98(y,2)}$ between baseline and hybrid plasmas in JET with ILW. However, a key parameter is the power. Because hybrid plasmas are performed with high additional power (to ensure high β_N) they benefit from the weaker power degradation of confinement (with respect to the IPB98(y,2) scaling) found in JET with ILW. In contrast, baseline plasmas use low power, just above the L-H power threshold based on the 2008 scaling [12], $P/P_{L-H,08}$ ~1.2, as expected in ITER (although it should be noted JET with ILW data does not fit this scaling as shown in [13]).

When the power is increased, baseline plasmas can reach higher $H_{98(y,2)}$ and β_N. As shown in [3], another important factor is the amount of neutrals present. Future work will include investigating the power degradation of confinement in plasmas with high gas.

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This work was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work was also part-funded by the RCUK Energy Programme under grant EP/I501045

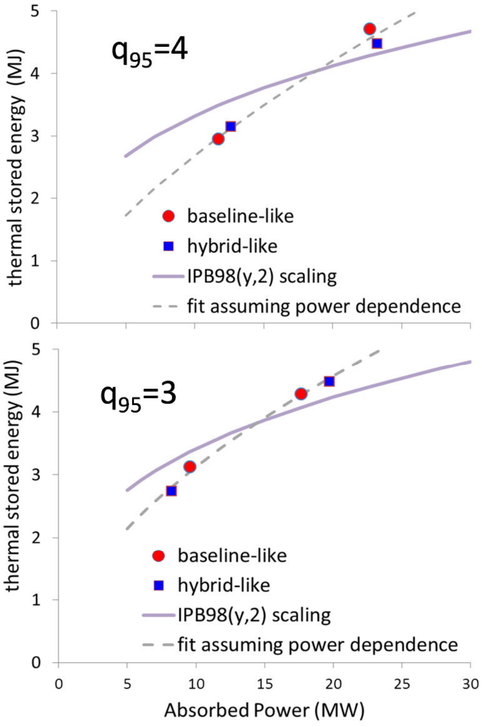

Fig. 4. W_{TH} vs P_{IN} for plasmas at q_{95}=4 and q_{95}=3 (data averaged over 0.4s) The solid curves are for $H_{98(y,2)}$=1and the dashed curves a fit to the data

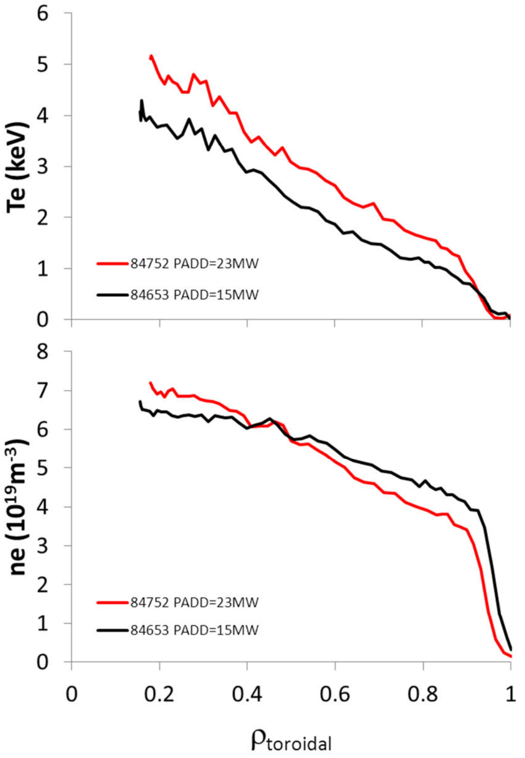

Fig. 5. a) Te profile and b) ne profiles for baseline-like plasmas at 2.4T/2.4MA, at low and high P_{ADD} (data averaged over 0.4s)