Effect of toroidal field ripple and toroidal rotation on H-mode performance and ELM characteristics in JET/JT-60U similarity experiments

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5 Appendix of M. L. Watkins, et al., Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu) IAEA (2006)

Abstract. The effect of the toroidal field (TF) ripple and edge toroidal rotation ($V_T$) on H-mode and pedestal performance as well as on ELM characteristics are investigated both in JET and JT-60U using matched plasma shape. In JT-60U, the amplitude of TF ripple ($\delta_r$) was reduced from \~1.2% to \~0.5% (averaged value at $B_{T} = 2.2$ T) after the installation of ferritic steel tiles (FSTs). In addition with FSTs, $\delta_r$ can also be varied by changing the toroidal magnetic field for a given separatrix position. In JET, the TF system can be configured to feed different currents to the odd and even coil sets out of 32 TF coils. In this operation mode, $\delta_r$ can actively be varied by selecting the appropriate differential current between each coil set. In both devices, it is observed that the edge $V_T$, which was in the same direction as the plasma current (co-$V_T$), reduced with increasing $\delta_r$. Even at the same $\delta_r$ of 0.5%, the achievable edge $V_T$ in JT-60U was still lower than that in JET due to higher neutral beam fast ion losses in JT-60U. A series of power and density scans performed at several $\delta_r$ indicated that plasmas with smaller ripple amplitude and/or larger co-$V_T$ are favourable to achieve higher $P_{ion}$ and $H_{95}$ factor in both devices. As for ELM characteristics, larger co-$V_T$ seems to increase the ELM energy loss together with the reduction of the ELM frequency.

1. Introduction
Inter-machine comparison is a very powerful tool to identify the physics mechanisms determining the plasma behavior, as well as a way to validate the assumptions behind the physics based scaling used for the prediction of the plasma parameters of ITER. Both in JET and JT-60U, inter-machine experiments have been performed to compare H-mode pedestal performance and ELM characteristics using matched plasma shape. In previous similarity experiments, the matching of pedestal dimensionless parameters in JT-60U were found to be difficult to scale to those in JET, and matched
dimensionless parameters could be obtained only with low heating power JET plasmas [1]. MHD stability analysis shows that the pedestal MHD stability of both tokamaks is similar and probably cannot explain the observed difference in ELMy H-mode performance [2], the toroidal field (TF) ripple and consequently different toroidal rotation profiles have been pointed out as major remaining differences between two devices, as shown in figure 1. Therefore, new similarity experiments focused on TF ripple and toroidal rotation profile have been performed in both devices.

Figure 1. Plasma configuration for similarity experiments together with ripple amplitude ($\delta$) in JT-60U (a) and JET (b). Here, $\delta$ is defined by $(B_{T,max} - B_{T,min})/(B_{T,max} + B_{T,min})$. The number of TF coils is 18 in JT-60U and 32 in JET.

The origin of the TF ripple is the finite number of TF coils. In JT-60U, 18 circular TF coils are used and therefore the contour plot of ripple amplitude ($\delta$) shows a circular shape, while JET is equipped with 32 D-shape coils resulting in very small $\delta$ with D-shaped contours, as shown in figure 1. For comparison, the number of TF coil in ITER is 18, which is the same number as in JT-60U, resulting in a ripple $\delta$ at the reference separatrix position of ~1.2% [3]. Nonetheless, fast ion (particle) confinement in ITER is extremely good, and fast ion losses are predicted to be negligible, at least for H-mode profiles and in absence of core MHD instabilities. Recent experiments in JT-60U show that $V_T$ is one of the key parameters to determine the pedestal performance and ELM characteristics [4, 5]. Thus, if $V_T$ is essential parameter in pedestal performance and ELM characteristics, $\delta$ itself is of minor importance for ITER plasmas. However, the heat load to the first wall due to the loss of $\alpha$-particles in reversed shear plasmas is expected to exceed the tolerable level. Therefore, to reduce the ripple loss power below 1% of $\alpha$-heating, the installation of ferritic steel plate has been planned in ITER [3]. Since the remaining $\delta$ near the mid-plane is expected to be ~0.5% in ITER with ferritic steel plates, both effects of TF ripple and $V_T$ on H-mode performance, and ELM characteristics are an important and belong to an urgent research area.

The paper is organized as follows. After the introduction, the experimental conditions for varying $\delta$ and the response of the plasma toroidal rotation at the pedestal ($V_T$) are described in section 2. The effects on the H-mode performance and pedestal due to changes in $\delta$ and the $V_T$ are described in section 3. The ELM characteristics, in particular ELM frequency dependence and ELM amplitude, are compared in section 4. Section 5 gives a the results of detailed comparison of the pedestal and H-mode
performance in terms of the effect of the injected torque in JET and the effect of local ripple amplitude near the X-point in JT-60U. Finally, a summary is given in section 6.

2. Experimental condition for ripple experiments

The method to vary \( \delta_t \) differed between JET and JT-60U. The TF ripple in JT-60U was reduced by using ferritic steel tiles (FSTs), which are optimized for ripple reduction at toroidal magnetic field \( (B_T) \) of \(<2 \) T [6]. Since the magnetic field produced by FSTs is saturated at 1.78 T for \( B_T \geq 0.6 \) T, \( \delta_t \) can be varied with \( B_T \) in JT-60U. In the previous similarity experiments, \( B_T = 3.2 \) T was used so as to match non-dimensional parameters between two devices at 1.08 MA and 1.8 MA. From the view point of the availability of edge diagnostics in JET and of the level of ripple reduction in JT-60U, two levels of \( B_T \), 2.2 T for the lowest \( \delta_t \) and 3.2 T for the direct comparison to the previous experiment, were selected at a fixed plasma current of 1.08 MA. Taking into account the constraints related to the matching of dimensionless plasma parameters as described in [1], plasma parameters of 1.14 MA / 2.0 T were chosen for the JET ripple experiment. In contrast, the TF system in JET can be configured to feed different currents to the odd and even set of coils out of 32 TF coils. In this operation mode, \( \delta_t \) can actively be varied by selecting the appropriate differential current between each set of coils. In this experiment, four levels of \( \delta_t \), 0.1%, 0.5%, 0.75% and 1%, were used. Beside different methods to vary \( \delta_t \), both devices also have a different NBI geometry and hence a different value of NB injected torque as well as a different dynamic range of fast ions losses, which is the source of effective counter torque due to the formation of an inward electric field [7] as well as a different value of NB injected torque. The specified experimental conditions in each device including the changes in \( V_T \) are described in this section.

2.1. Ripple experiments in JT-60U

The reduction of TF ripple using FSTs is shown in figure 2(a) and 2(b). Because of breaking of the 18-fold toroidal symmetry, the usual definition of ripple amplitude, \( \delta_t = (B_{T,max} - B_{T,min})/(B_{T,max} + B_{T,min}) \), is not valid in JT-60U after the installation of FSTs as shown in figure 2(b). Therefore, to compare ripple level with and without FSTs, we define a 'quasi' ripple well region as whether there is a local minimum of the magnetic field within \( \phi_s \Delta \phi < \phi < \phi_s + \Delta \phi \) at a given toroidal angle \( \phi_s \), where \( \Delta \phi \) is half of the period of the TF coil installation [6]. As can be seen in figure 2(a), the 'quasi' ripple well region becomes smaller with FSTs, even if evaluated at the P3 section where there is the maximum local ripple as shown in figure 2(b). Since there are no FSTs near the X-point (\( X_p \)), it is noted that a small level of local ripple (\( \delta_t \sim 0.24\% \)) remains in that region for this plasma configuration.

Figure 2(c) shows the geometry of NBIs in JT-60U. There are 4 tangential NBIs (two co-injection and two ctr-injection) with a tangency radius (\( R_t \)) of \( \sim 2.7 \) m and 7 perpendicular (perp) NBIs with \( R_t \sim 0.75 \) m. In addition to these positive-ion based NBIs (P-NBIs) with the acceleration voltage (\( V_{acc} \)) of \(<85 \) kV, there are two negative-ion based NBIs (N-NBIs) with \( V_{acc} \) of 350-370 kV. The reduction of fast ion losses from each P-NBI, which is evaluated using fully three-dimensional magnetic field orbit following Monte Carlo (F3D-OFMC) [8], are summarized in figure 2(d). In this figure, the loss power ratio is defined by \( (P_{CX} + P_{ripple} + P_{orbit})(P_{inj} - P_{shine}) \), where \( P_{CX} \), \( P_{ripple} \), \( P_{orbit} \), \( P_{inj} \) and \( P_{shine} \) are, respectively, the loss power due to charge exchange, the loss power through ripple trapped loss, the loss power due to unconfined orbits, the injected NBI power and the loss power due to shine through. It is noted that the fast ion losses for perp-NBIs with a slightly tilted injection angle to the plasma current (\( c_{oi} \)) are smaller than other perp-NBIs with a slight counter injection (ctr.) component. Therefore, to minimize fast ion losses, co-tangential NBIs and some \( c_{oi} \)-NBIs are mainly used in this experiment.

In the analysis for JT-60U plasmas, we used F3D-OFMC to evaluate the power deposition profile, the loss of fast ions, the shine through loss and the net torque injection. It is noted that F3D-OFMC only calculates the transfer of the torque from fast ions to bulk plasma by collisions.
2.2. Ripple experiments in JET

Since the operation with large $\delta_r$ has the potential to cause severe damage to in-vessel components, the local heat loads to in-vessel components were assessed by F3D-OFMC before the experiment. The analysis indicated that $\delta_r$ could be increased up to 1% in plasmas with 1.14 MA / 2.0 T, remaining within tolerable power density on all critical JET in-vessel components. Figure 3(a) shows the contour plot of $\delta_r$ with the current ratio of $I_{\text{odd}} / I_{\text{even}} = 0.52$, which produces $\delta_r = 1\%$ at the outer mid-plane. It is noted that the remaining local ripple near $X_p$ was $\delta_r < 0.1\%$ in the case of $\delta_r = 1\%$ at the outer mid-plane as shown in figure 3(a), while being $\delta_r \sim 0.24\%$ in JT-60U with $\delta_r \sim 0.5\%$ at the outer mid-plane with FSTs as shown in figure 2(a).

Figure 3(b) shows the geometry of the JET NBI system. There are 16 independent injectors located at two toroidal sections, octant 4 and 8. The $V_{\text{acc}}$ of these beams varies between 70 and 130 kV. Since there are two different groups of injectors with a different tangency radius; so-called 'tangential' beams with $R_T \sim 1.85$ m and so-called 'normal' beams with a smaller $R_T \sim 1.31$ m, the NB injected torque can be varied by changing the combination of NBIs. Nevertheless, the normal beam in JET is more...
Figure 3. (a) Contour plot of ripple amplitude with the current ratio of \(I_{\text{odd}} / I_{\text{even}} = 0.52\). (b) Port arrangement of NBI system in JET (top view). Tangential NBI (\(R_T \sim 1.85\) m) and normal NBI (\(R_T \sim 1.31\) m) are installed. Each system has 8 independent injectors.

tangential than perp-NBIs in JT-60U. Therefore, in higher heating power plasmas, the torque input from NBIs in JET was slightly higher than in JT-60U as described in next subsection.

In this paper, the power deposition profile, the loss of fast ions and the net torque injection for JET plasmas are evaluated with ASCOT [9] using the birth profile calculated by PENCIL [10, 11]. The shine through loss power is also given by PENCIL. Since a benchmark between F3D-OFMC and ASCOT indicated good agreement of the two codes, we could compare evaluated profiles with ASCOT and F3D-OFMC.

2.3. Changes in toroidal rotation by ripple amplitude and fast ion losses

Figure 4 compares the toroidal rotation frequency measured at the top of the \(T_i\) (ion temperature) pedestal between the two devices. The total torque injected by NBI was 5.5-8.5 Nm in JET except for plasmas with low heating power (\(P_{\text{NBI}} < 4\) MW), and in JT-60U, ~5.5 Nm without FSTs and 6-7.5 Nm with FSTs. It is noted that the injected torque in JET was proportional to the heating power, but that in JT-60U was varied only in a narrow range, because the number of tangential NBIs was fixed and the heating power was varied by changing the number of perp-NBIs (that provide very little input torque).

As a result, the toroidal rotation frequency in JT-60U plasmas varied mainly with the loss power of the fast ions as shown in figure 4(a). When the heating power was increased by adding perp-NBIs, the loss of fast ions also increased resulting in a larger ctr-rotation. Therefore, a wide variation in the rotation frequency was observed in plasmas with similar ripple amplitude (e.g. \(\delta r = 1.2\%\)) as shown in figure 4(c). After the installation of FSTs, fast ion losses were reduced as shown in figure 2(d). Plasmas with less ctr-rotation or co-rotation were obtained with similar NBI torque input, as reported in [12]. Nevertheless, higher fast ion loss power fractions than JET was observed.

In JET, the fast ions loss fraction did not vary much over the \(\delta r\) scan as shown in figure 4(a). Even in plasmas with \(\delta r = 1\%\), only 0.5 MW was lost from the injected power of 7.4 MW. Therefore, the toroidal rotation frequency in JET plasmas mainly related to the \(\delta r\) as shown in figure 4(c), which is consistent with other ripple experiments in JET [13]. For a similar level of torque input in both devices, the upper boundary of the achieved rotation frequency decreased with increasing \(\delta r\). But, the variation
of the rotation frequency at constant $\delta_1$ in JET was narrower than in JT-60U. The fact that there is a strong relation between $\delta_1$ and $V_T$ in JET plasmas implies that it will be difficult separating the influences of $\delta_1$ and $V_T$. It is also noted that there was only a few data with matched rotation frequency between the two devices as seen in figure 4(c) at $\delta_1 = 0.5\%$.

Figure 4. (a) Toroidal rotation frequency measured at the top of $T_i$ pedestal as a function of loss power of fast ions. (b) Magnification view of (a). (c) Toroidal rotation frequency as a function of ripple amplitude. Negative frequency means a direction of toroidal rotation counter to the plasma current. The total torque injected by NBI was 5.5-8.5 Nm in JET typically, and in JT-60U, ~5.5 Nm without FSTs and 6-7.5 Nm with FSTs (~9.5 Nm with N-NBI). Solid symbols show JET data and open symbols show JT-60U data.

3. H-mode and pedestal performance

Under the conditions described in section 2, a series of heating power and density scans was performed in both devices. For JT-60U, pedestal electron density ($n_{e,\text{ped}}$) and electron temperature ($T_{e,\text{ped}}$) were measured with a Thomson scattering system, while pedestal ion temperature ($T_{i,\text{ped}}$) was measured with charge-exchange recombination spectroscopy (CXRS). For JET, on the other hand, $n_{e,\text{ped}}$, $T_{e,\text{ped}}$ and $T_{i,\text{ped}}$ were measured with an edge chord of an FIR interferometer, electron cyclotron emission (ECE) radiometer and CXRS, respectively.

Figure 5 compares $n_{e,\text{ped}}$ and $T_{e,\text{ped}}$ in the ripple scan experiments. In JT-60U, the achievable electron pressure at the pedestal ($p_{e,\text{ped}}$) was similar both with and without FSTs (also high & low $B_T$ with FSTs) without gas puffing. A moderate gas puffing to increase the plasma density degraded $p_{e,\text{ped}}$ by ~20%, and in the latter phase of the discharge ELM characteristics changed at $n_{e,\text{ped}} = 2.4 \times 10^{19} \text{m}^{-3}$ from type I ELMs to type I+III ELMs. Therefore, it was still difficult to achieve high $n_{e,\text{ped}}$ in JT-60U plasmas even with FSTs, where the averaged $\delta_1$ was 0.5% at $B_T = 2.2 \text{ T}$. In the previous experiment without FSTs, an improvement of $p_{e,\text{ped}}$ was observed in plasmas with N-NBIs as indicated by open triangles in figure 5(a) [1]. When the same heating scenario using N-NBIs was applied to the plasma with FSTs at $B_T = 3.2 \text{ T}$, a higher $p_{e,\text{ped}}$ than in plasmas heated by only P-NBIs was achieved. The fact that higher $p_{e,\text{ped}}$ can be achieved both with and without FSTs indicated that there is unknown effect of the injection of N-NBI on the pedestal performance.
In JET, the achievable $p_e^{\text{ped}}$ was gradually degraded with increasing $\delta$ as shown in figure 5(b), although the reference data with no ripple ($\delta = 0.1\%$) are at lower $p_e^{\text{ped}}$ than the dataset obtained in the previous experiments reported in [1]. The exact reason for this difference between the two experimental campaigns has so far not been understood. Since one of the differences between JET and JT-60U is the achievable density, the response to gas puffing was also investigated in JET at $\delta = 0.1\%$ and $\delta = 0.75\%$. As indicated by dotted circles in figure 5(b), the $n_e^{\text{ped}}$ in plasmas at $\delta = 0.75\%$ could be increased to similar values as obtained at $\delta = 0.1\%$ by using the same amount of gas puffing. A small degradation of $p_e^{\text{ped}}$ was observed in JET plasmas with gas puffing. The degradation of $p_e^{\text{ped}}$ in JT-60U plasmas was larger than in JET, even with a smaller gas puffing rate. It is noted that the achieved density with ripple was always smaller than that without ripple under the same amount of gas puffing. In addition to this, when the density feedback control was applied, the required gas puffing rate was higher with ripple than without ripple. These observations indicate a density pump-out with ripple, which is consistent with other ripple experiments reported in [14].

![Figure 5. Comparison of pedestal density and temperature in ripple scan experiments in JT-60U (a) and in JET (b). Gray circles in (b) show dataset obtained in previous experiments reported in [1].](image-url)

In order to understand the effect of $\delta$ and $V_T$, the total pedestal pressure ($p_e^{\text{ped}} = n_e^{\text{ped}}T_e^{\text{ped}} + n_i^{\text{ped}}T_i^{\text{ped}}$) evaluated with a spatially constant $Z_{\text{eff}}$ and the thermal confinement enhancement factor are compared between two devices as functions of $\delta$ and $V_T$ in figure 6. Although the unselected dataset for JT-60U shows no clear trend in the achievable $p_e^{\text{ped}}$ between with and without FSTs (except for the plasmas heated by N-NBIs), the effect of heating power on $p_e^{\text{ped}}$ should be considered. When we compare only data with similar $P_{\text{NET}} = 6.3-7.3$ MW marked by solid symbols in figure 6, an improvement of $p_e^{\text{ped}}$ was observed in both figures 6(a) and (b). This kind of global behavior was also observed in the dedicated ripple experiment in JT-60U [4]. In JET, the achievable $p_e^{\text{ped}}$ gradually degraded with increasing $\delta$ and/or gradually improved with increasing $V_T$. The data selected by heating power also shows the same trend in both figures 6(a) and (b) due to the strong relation between $\delta$ and $V_T$ in JET plasmas. It is noted that the rate of change of $p_e^{\text{ped}}$ as a function of $V_T$ was similar between JET and JT-60U. The comparison at the same ripple and $V_T$ shows that the $H_{\text{II}}$ in JT-60U was smaller than in JET, while $p_e^{\text{ped}}$ was similar. This experimental result implies a different core transport.

The response of the $H_{\text{II}}$ factor was similar to that observed in $p_e^{\text{ped}}$ as shown in figure 6(c) and (d), where the upper limit of $H_{\text{II}}$ factor was gradually degraded with increasing $\delta$ and/or gradually improved with increasing $V_T$. In addition to this, the $H_{\text{II}}$ factor was degraded by $\sim 20\%$ with gas puffing,
which is usually observed in JET plasmas without large ripple. All these observations are consistent with other ripple experiment reported in [14].

![Figure 6](image.png)

**Figure 6.** Comparison of the total pedestal pressure \(p_{\text{ped}}\) as a function of \(\delta_t\) (a) and \(V_T\) (b). Comparison of the thermal confinement enhancement factor \((H_H)\) as a function of \(\delta_t\) (c) and \(V_T\) (d). Solid symbols show data selected by \(P_{\text{NET}} = 6.3-7.3\) MW.

In dedicated ripple experiments in JT-60U using two different plasma configurations [4], the effect of TF ripple on \(p_{\text{ped}}\) has been identified between plasmas with \(\delta_t \sim 2\%\) and \(\delta_t \sim 1\%\) using a large volume configuration (the separatrix of the configuration was close to the wall and \(V_P \sim 75\) m\(^3\)). No significant effect of TF ripple between plasmas with \(\delta_t \sim 0.4\%\) and \(\delta_t \sim 0.2\%\) was found with the small volume configuration (inward shifted plasma configuration with \(V_P \sim 52\) m\(^3\)), while the effect of \(V_T\) was clearly observed in both plasma configurations. The difference between plasmas with \(\delta_t \sim 0.1\%\) and \(\delta_t \sim 0.5\%\) was small as shown in figure 6(a) and (c). While in JET, degradation in \(p_{\text{ped}}\) and \(H_H\) factor was observed at \(\delta_t \sim 0.3\%\) [14]. To determine the acceptable level of \(\delta_t\), further investigation will be needed.

The effect of local ripple near \(X_p\) was also investigated in JT-60U, because ASCOT simulations that include the effect of ripple induced thermal ion losses indicates that the ripple near \(X_p\) might influence the plasma confinement [15]. This was investigated experimentally by shifting up the plasma position up vertically. The \(\delta_t\) near \(X_p\) was reduced from 0.24\% to 0.14\%, while ripple amplitude near outer mid-plane was almost unchanged. However, there was no clear difference in plasmas profiles \((n_e, T_e, T_i)\) both in the pedestal and the core. Therefore, the influence of local ripple near the \(X_p\) on H-mode pedestal performance seems to be small.
4. ELM characteristics

In JT-60U plasmas with FSTs, the ELM amplitude ($\Delta W_{\text{ELM}}$) increased by 50-150%, while the ELM frequency ($f_{\text{ELM}}$) decreased by only ~20%. Therefore, the ELM loss power, $P_{\text{ELM}} = f_{\text{ELM}} \times \Delta W_{\text{ELM}}$, increased by more than 30% for a given loss power through the separatrix ($P_{\text{sep}}$) as shown in figure 7(a). Higher $P_{\text{ELM}} / P_{\text{sep}}$ implies a reduction of inter-ELM transport, which is clearly observed in figure 7(b). This figure compares two discharges obtained from plasmas with similar $f_{\text{ELM}}$ and $P_{\text{sep}}$, one with and one without FSTs. Although both $\Delta W_{\text{ELM}}$ and pedestal stored energy ($W_{\text{ped}}$) were higher with FSTs, the normalized ELM energy loss ($\Delta W_{\text{ELM}} / W_{\text{ped}}$) still increased from <5% to 5-10% because of the larger change in $\Delta W_{\text{ELM}}$. The observed increase of a recovery rate of stored energy ($dW/dt$) by a factor of two can compensate approximately twice larger $\Delta W_{\text{ELM}}$. This plasma response is consistent with the observation that the increased $\Delta W_{\text{ELM}}$ at the same $f_{\text{ELM}}$ as found in plasmas without FSTs. The global behavior of ELM characteristics are compared in figure 7(c), where the normalized ELM frequency ($f_{\text{ELM}} / P_{\text{sep}}$) is plotted as a function of $V_T$. In contrast to pedestal and H-mode performance, a figure of $f_{\text{ELM}} / P_{\text{sep}}$ as a function of $\delta_r$ only shows a wide scatter. Moreover, the data obtained from JET/JT-60U similarity experiments shows the same trend as that from the dedicated ripple experiment with large volume configuration marked by squares. Therefore, the $V_T$ seems to be a leading parameter to change ELM characteristics, as reported in [4, 5]. The effect of $V_T$ was also found in a grassy ELM regime in JT-60U [16].

![Figure 7. Comparison of ELM characteristics in JT-60U. (a) ELM loss power ($P_{\text{ELM}}$) as a function of loss power through the separatrix ($P_{\text{sep}}$). (b) Comparison of the time evolution of plasma stored energy for the points indicated in (a). (c) Normalized ELM frequency as a function of $V_T$. Circles in (c) show data obtained from JET/JT-60U similarity experiments and squares in (c) show data obtained from dedicated ripple experiments with a large volume configuration. In these figures, only plasmas without gas puffing are plotted.](image)

In JET plasmas, the $f_{\text{ELM}}$ in reference data without ripple ($\delta_r = 0.1\%$) was slightly higher than that in the previous similarity experiments reported in [1] somehow. Nevertheless, global changes in the ELM characteristics similar to those reported for JT-60U have also been observed in the ripple scans as shown in figure 8. The vertical variation in figure 8(a) at $\delta_r = 0.1\%$ seems to be correlated by the different $V_T$ as shown in figure 8(b). Since this kind of ELM behavior was also found in a dedicated ripple experiment in JET using a typical JET plasma configuration, the effect of $V_T$ on ELM amplitude and frequency seems to be a common feature in two devices. The fact that the torque input is proportional to $P_{\text{sep}}$ can help to separate $\delta_r$ and $V_T$ in the comparison of normalized ELM frequency.

Because of the higher $f_{\text{ELM}}$ and lower $\Delta W_{\text{ELM}}$ the diamagnetic loop measurements, while operating with different currents in each JET TF coils set, could not detect the drop of the stored energy. Therefore, the fast drop of $T_{e,\text{ped}}$ ($\Delta T_{e,\text{ped}}$) measured with ECE radiometer is used as a representative of $\Delta W_{\text{ELM}}$. Figure 9 compares three discharges with different $\delta_r$ (0.1%, 0.5% and 1%), which are marked...
by (a), (b) and (c) respectively in figure 8(b). Lower heating power was applied to the plasma with larger $\delta$, resulting in smaller $P_{\text{sep}}$ at larger $\delta$. However, the $f_{\text{ELM}}$ increased with increasing $\delta$ ($V_T$). On the other hand, the drop in $T_{\text{e,ped}}$ decreased with decreasing $V_T$ (increasing $\delta$) together with the reduction of ELM averaged $T_{\text{e,ped}}$ corresponding to the reduction of $p_{\text{ped}}$ as shown in figure 5(b). Here, the normalized reduction of $T_{\text{e,ped}}$ ($\Delta T_{\text{e,ped}} / T_{\text{e,ped}}$) was 10.9%, 8.0% and 7.5% for figure 9(a), (b) and (c), respectively.

Figure 8. Normalized ELM frequency observed in JET plasmas as a function of $\delta$ (a) and $V_T$ (b). Labels in (b) show discharges plotted in figure 9. Only plasmas with $P_{\text{NET}} > 5$ MW are plotted.

Figure 9. Comparison of the time evolution of the divertor $D_\alpha$ signal and pedestal temperature during the ripple scan in JET. (a), (b) and (c) show plasmas with $\delta = 0.1\%$, 0.5% and 1%, respectively. The corresponding $V_T$ for each discharge is shown in figure 8.

5. Discussion
In the previous sections, the influence of the TF ripple and the toroidal rotation on the pedestal performance and ELM characteristics are described. In general, the pedestal performance affects the total plasma performance due to the well known stiffness of core profiles in the ELMy H-mode plasmas. In previous similarity experiments, on the other hand, it was found that core plasma profiles were different between JET and JT-60U even in cases where the pedestal value were very well matched between the two devices [1]. An apparent deviation from profile stiffness was also observed in JET plasmas, specifically when the toroidal rotation and torque input were varied by changing the combination of tangential and normal beams at a fixed TF ripple amplitude of $\delta = 0.5\%$, which is the same value as in JT-60U with FSTs.
Figure 10. Waveforms of two JET plasmas for the comparison of tangential and normal injection. (a) NBI heating power. $P_{\text{NET}} = 7.3$ MW in 60702 and 7.2 MW in 69703. (b) line-integrated electron density in the core and edge chord. (c) MHD energy evaluated with EFIT. (d) Divertor $D_\alpha$ signal. Thermal stored energy evaluated by JETTO with kinetic plasma profiles was 1.18 MJ for normal injection case and 1.24 MJ for tangential+normal injection case.

Figure 11. Comparison of plasma profiles in JET between two otherwise identical plasmas, one heated by only normal NBIs (69703, closed symbols) and by dominant tangential NBIs (69702, open symbols). (a) Power deposition profile evaluated with ASCOT. (b) Toroidal rotation frequency profile. (c) and (d) show ion and electron temperature profiles, respectively.
Figure 10 shows waveforms of two discharges, where only 6 normal beams are injected in 69703, while a combination of tangential (4 units) and normal (2 units) beams are used in 69702. A comparison of selected plasma parameters for the two discharges is shown in figure 10. As illustrated figure 10(b) and (d), averaged density and divertor $D_e$ signal were almost identical. The fast ion loss power was higher by $\sim 200$ kW for 69703, but this was almost compensated by slightly higher $P_{\text{NBI}}$ and $P_{\text{oh}}$, leading to almost identical power deposition profiles as shown in figure 11(a) (evaluated with JETTO [17] and ASCOT). Nevertheless, there is a clear difference in the plasma stored energy (both MHD and thermal) as shown in figure 10 (c).

A small, but obvious difference was observed in the temperature profiles as shown in figure 11 (c) and (d), in particular for $T_e$ profile. It is noted that the difference in the core profiles cannot be explained by the stiffness, because the pedestal parameters ($n_{\text{ped}}$, $T_{e\text{ped}}$ and $T_{i\text{ped}}$) are almost the same. The rotation profile was also different as shown in figure 11(b). However, the difference in the toroidal rotation at the top of pedestal was so small that no change in $p_{\text{ped}}$ is consistent with the result in figure 6. A similar response of the core plasma profiles has been observed in JT-60U after the installation of FSTs in plasmas with an internal transport barrier (ITB). When the plasma rotation was changed from ctr-rotation to co-rotation by changing the combination of tangential NBIs, the core electron transport gradually decreased while keeping the transport in peripheral region constant (outside ITB including the pedestal region) [18]. Since there is no transport model explaining an improved core confinement by such a small change in the plasma rotation so far, further analysis and experiments are required to obtain better understanding of the core transport properties, which is also important to obtain a reliable prediction of ITER plasma.

6. Summary

Dedicated ripple experiments were performed in JET and JT-60U using a matched plasma shape. After the installation of FSTs in JT-60U, $\delta r$ near the outer midplane was reduced to $\sim 0.5\%$ at $B_T=2.2$ T. In JET, on the other hand, $\delta r$ can be varied by selecting the appropriate differential current between odd and even set of coils out of 32 TF coils, providing in this case four levels of $\delta r = 0.1\%, 0.5\%, 0.75\%$ and 1%. Although the same level of ripple amplitude was successfully obtained in both devices, the $V_T$ in JET was still higher than that in JT-60U due to a different level of fast ion losses. Since a correlation between $\delta r$ and $V_T$ was found in JET plasmas, it is difficult to separate the two parameters, $\delta r$ and $V_T$, in JET experiments.

A series of power and density scans indicated that plasmas with lower $\delta r$ and/or larger co-$V_T$ are favorable to achieve higher $p_{\text{ped}}$ and $H_{\text{II}}$ factor in both devices. As for ELM characteristics, larger co-$V_T$ seems to increase the ELM energy loss together with the reduction of the ELM frequency. Sustaining a high $n_{\text{e ped}}$ was still difficult in JT-60U plasmas even with FSTs ($\delta r \sim 0.5\%$), while $n_{\text{e ped}}$ in JET plasmas at $\delta r = 0.75\%$ could be increased to similar value as at $\delta r = 0.1\%$ using the same amount of gas puffing. Therefore, there are still some differences between the two devices. In order to obtain a better prediction for ITER plasmas, further investigations into the effects of the TF ripple and the toroidal rotation are necessary, and determining the acceptable level of ripple amplitude in ITER is still difficult based on these experimental results in both devices. In addition to this, the development of a reliable model of momentum transport and of the source of effective torque at the plasma edge due to ripple losses is also important to predict ITER plasma performance and ELM characteristics.

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