First scenario development with the JET new ITER-like wall

E. Joffrin\textsuperscript{1}, M. Baruzzo\textsuperscript{2}, M. Beurskens\textsuperscript{3}, C. Bourdelle\textsuperscript{1}, S. Brezinsek\textsuperscript{1}, J. Bucalossi\textsuperscript{1}, P. Buratti\textsuperscript{5}, G. Calabro\textsuperscript{5}, C.D. Challis\textsuperscript{1}, M. Clever\textsuperscript{4}, M. Coenen\textsuperscript{4}, E. Delabie\textsuperscript{6}, R. Dux\textsuperscript{7}, P. E. de la Luna\textsuperscript{8}, P. de Vries\textsuperscript{9}, J. Flanagan\textsuperscript{3}, L. Frassinetti\textsuperscript{10}, D. Frigione\textsuperscript{5}, C. Giroud\textsuperscript{3}, M. Groth\textsuperscript{11}, N. Hawkes\textsuperscript{3}, J. Hobirk\textsuperscript{7}, M. Lehnen\textsuperscript{1}, G. Maddison\textsuperscript{3}, J. Mailloux\textsuperscript{1}, C. F. Maggi\textsuperscript{7}, G. Matthews\textsuperscript{3}, M. Mayoral\textsuperscript{12}, A. Meigs\textsuperscript{3}, R. Neu\textsuperscript{7}, I. Nunes\textsuperscript{13}, T. Puetterich\textsuperscript{7}, F. Rimini\textsuperscript{3}, M. Sertoli\textsuperscript{7}, B. Sieglin\textsuperscript{7}, J. van Rooij\textsuperscript{9}, I. Voitsekhovitch\textsuperscript{3} and JET-EFDA Contributors

JET-EFDA, Culham Science Centre, Abingdon, OX14 3DB, UK
\textsuperscript{1} IRFM-CEA, Centre de Cadarache, 13108 Saint-Paul-lez-Durance, France
\textsuperscript{2} Consorzio RFX, Corso Stati Uniti 4, 35127 Padova, Italy
\textsuperscript{3} Euratom/CCFE Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK
\textsuperscript{4} Association EURATOM/Forschungszentrum Jülich GmbH, 52425 Jülich, Germany
\textsuperscript{5} Associazione EURATOM-ENEA sulla Fusione, C.R. Frascati, Frascati, Italy
\textsuperscript{6} École Royale Militaire, Avenue de renaissance, 1000 Brussels, Belgium
\textsuperscript{7} Max-Planck-Institut für Plasmaphysik, Euratom Association, 85748, Garching, Germany
\textsuperscript{8} Laboratorio Nacional de Fusion, Asociacion EURATOM-CIEMAT, Madrid, Spain
\textsuperscript{9} Association EURATOM/DIFFER, Rijnhuizen, PO Box 1207, 3430BE Nieuwegein, The Netherlands
\textsuperscript{10} Division of Fusion Plasma Physics, Association EURATOM-VR, KTH, SE-10044 Stockholm, Sweden
\textsuperscript{11} Association Euratom-Tekes, VTT, PO Box 1000, 20440 VTT, Finland
\textsuperscript{12} EFDA-CSU, 85748 Garching bei München, Germany
\textsuperscript{13} Instituto Superior Tecnico, 1049-001 Lisboa, Portugal
\textsuperscript{14} JET-EFDA-CSU, Culham Science Site, Abingdon, Oxon OX14 3DB, UK

E-mail: emmanuel.joffrin@jet.efda.org

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Abstract

In the recent JET experimental campaigns with the new ITER-like wall (JET-ILW), major progress has been achieved in the characterization and operation of the H-mode regime in metallic environments: (i) plasma breakdown has been achieved at the first attempt and X-point L-mode operation recovered in a few days of operation; (ii) stationary and stable type-I ELMy H-modes with $\betaN \sim 1.4$ have been achieved in low and high triangularity ITER-like shape plasmas and are showing that their operational domain at $H = 1$ is significantly reduced with the JET-ILW mainly because of the need to inject a large amount of gas (above $10^{22}$ D$^{-1}$) to control core radiation; (iii) in contrast, the hybrid H-mode scenario has reached an $H$ factor of 1.2–1.3 at $\betaN$ of 3 for 2–3 s; and, (iv) in comparison to carbon equivalent discharges, total radiation is similar but the edge radiation is lower and $Z_{eff}$ of the order of 1.3–1.4. Strong core radiation peaking is observed in H-mode discharges at a low gas fuelling rate (i.e. below $0.5 \times 10^{22}$ D s$^{-1}$) and low ELM frequency (typically less than 10 Hz), even when the tungsten influx from the divertor is constant. High-Z impurity transport from the plasma edge to the core appears to be the dominant factor to explain these observations. This paper reviews the major physics and operational achievements and challenges that an ITER-like wall configuration has to face to produce stable plasma scenarios with maximized performance.

Keywords: JET, ITER-like wall, scenario

(Some figures may appear in colour only in the online journal)
1. Introduction

The transition to all metal plasma-facing components (PFCs) is an essential step on the path to reactor scale fusion devices because they minimize hydrogen fuel retention in PFCs [1]. In this context, the JET ITER-like wall (JET-ILW), with PFCs made of beryllium in the main chamber and tungsten in the diverter, was installed successfully in 2010/11 [2] to validate the first wall material mix for ITER. Consequently, demonstrating the compatibility with the new JET-ILW of typical ITER scenarios (such as the baseline or the advanced inductive H-modes (so-called ‘hybrid’) scenarios developed previously in a carbon environment) has been one of the main lines of the research of the 2011–2012 JET experimental campaign.

Stable H-mode baseline plasmas ($q_{95} \sim 3$, $\beta_N \sim 1.4$) have been achieved in JET for about 5 s, up to a current of 3.5 MA with a confinement factor $H_{98.2}$ in the range of 0.7–0.9. Hybrid H-modes have reached $\beta_N$ above 3 at $I_p = 2$ MA ($q_{95} \sim 4$, $\beta_N \sim 3$), with $H_{98.2}$ factor exceeding 1.2 for 2 s. Although operational issues (such as the limited steady-state heat load or the changes in plasma impurity composition) were foreseen, the landscape of the scenario of the operational domain has changed significantly and is consistent with the observation on other metallic devices, such as ASDEX Upgrade [3] or C-MOD [4, 5]. The most important result is that the access to $H \sim 1 \text{ confinement is in general much more restricted than with the carbon wall for the baseline H-mode scenario in both low ($\delta = 0.2$) and high shape ($\delta = 0.4$) mainly because of the need to control core radiation, which was achieved by significant gas puffing rate. However, even with some gas puffing ($\sim 5 \times 10^{21} \text{ s}^{-1}$), an $H$ factor close to 1.3 can be reached in the advanced inductive (hybrid) H-mode scenario in comparison with the JET-ILW.

This paper first presents an overview of the scenario performance with the JET-ILW and then details the developments of the H-mode at high plasma current ($I_p = 3.5$ MA) and at high normalized pressure ($\beta_N \sim 3$), referred to as the advanced inductive (hybrid) scenario [6]. Plasma contamination, tungsten influx and core transport, the role of the ELMs, and radiation patterns are important elements to be addressed and compared with the carbon wall in our discussion. In developing a fully integrated scenario, the main building blocks making a complete discharge, from formation to current decay, have also been studied experimentally. Current ramp-up and -down phases, H-mode termination, and techniques for reducing the impact of disruption are also presented.

2. An overview of the H-mode development in JET with the JET-ILW

In JET with the JET-ILW, all of the existing carbon-fibre composite (CFC) in direct contact with the plasma has been replaced with bulk beryllium as the predominant main chamber material and with tungsten surfaces in the diverter [2]. The diverter consists of thin (30 $\mu$m) W-coated CFC tiles and a single toroidally continuous belt of four-fold bulk tungsten tiles at the outer strike point, where the heat flux is expected to be the strongest [7]. The anticipated operating limits with the JET-ILW are most fundamentally driven by the relatively low melting point of beryllium (1356 °C), the limited robustness of tungsten coatings to slow and fast thermal cycles (operating temperature limited to 1200 °C), and the thermal capabilities of the support structures for the bulk tungsten tile limiting the energy dumped into the tile to typically 60 MJ per stack. The protection of the JET-ILW was an integral part project from very early on and the surface temperature on the tiles (in particular the bulk tungsten tile used in general for the outer strike point of the magnetic configuration) has been systematically monitored during the step-wise increase of the power.

With the JET-C wall, multiple conditioning cycles based on glow discharge cleaning (GDC) in deuterium and beryllium evaporation were required and the first breakthroughs were not sustained for very long, showing a high level of total radiation. In contrast, with the JET-ILW, reliable breakdown conditions with pre-magnetization of the primary current have been recovered in JET in the first discharge and even optimized to voltage of the order of that expected in ITER ($\sim 0.25$ V m) [8]. This was achieved despite the fact that no specific conditioning of the wall had been applied prior to first plasma, with the exception of wall baking up to 320 °C for 4 weeks [9]. In contrast, a series of identical limiter and X-point ohmic discharges have been carried out to establish the wall properties in constant plasma conditions [10]. The first experiments have also shown that a larger amount of gas (by, typically, a factor of 2–4) is required with the JET-ILW in the limiter phase to develop the discharge in the early phase of the current ramp-up phase so as to avoid either core impurity accumulation [11] or discharges sustained by slide-away electrons.

After this first step, stable type-I ELMy sawtoothing H-mode regimes have been achieved routinely in low and high triangular shaped magnetic configuration at 2.0 MA/2.1 T and then at 2.5 MA 2.7 T, with $q_{95} = 3.3$ and neutral beam injection of typically 15 MW of input power for 4–5 s (figure 1). In all experiments, the outer strike point was located onto the bulk tungsten tile away from the outer pumping louvre by about 8–12 cm. Although metallic impurity events have been observed during this initial development phase [12], in the course of further operations their frequency decreased steadily as the heating power was increased. This suggests either a conditioning effect of wetted surfaces by the plasma (metallic dust coming from the installation of the components) or a redistribution of the dust (consisting of W, Ni, Cr, Fe) in places of the vessel not receiving significant direct power flux. In these discharges, $Z_{eff}$ is also substantially lower with the JET-ILW and a reduction from typically ~2 in the JET-C to ~1.3 in the W-wall is generally achieved, corresponding to a reduction of carbon content by a factor of 20 [1]. Consequently, the dilution is also significantly less in these discharges than in the JET-C (typically 0.9–0.95 instead of 0.8), which is favourable for fusion born neutron production.

In this early phase of the H-mode operation [13] it became clear that a significant amount of deuterium (rate above $10^{22}$ D s$^{-1}$) had to be puffed continuously during the main heating phase in order to achieve stable conditions in the H-mode phase and to prevent central radiation peaking, as already experienced in the ASDEX Upgrade [14]. When lowering the gas fuelling rate, an increase of the bulk plasma radiation is observed from bolometry reconstruction, which is
often correlated with a collapse of the central temperature and the loss of sawteeth (figure 2). In addition, this behaviour is often correlated with an increase of the tungsten concentration in the plasma core, as inferred from visible spectroscopy and soft x-ray emission. As the core radiation increases, the ELM frequency decreases, and the ELM-free phases increase in duration, this can eventually lead to a back-transition to L-mode as the power across the separatrix \( P_{\text{NET}} \) decreases. Here, \( P_{\text{NET}} \) is defined as \( P_{\text{NET}} = P_{\text{IN}} - dW/dt - P_{\text{RAD, BULK}} \). (The last term is the total radiated power inside the last closed flux surface and \( P_{\text{IN}} \) the total input power.) In these conditions, disruption by radiative collapse is less likely to occur if \( P_{\text{IN}} \) is maintained, provided that heat deposition is located in the plasma centre (using ICRH for example) where the impurity and radiation peaking tend to occur, possibly by neoclassical transport, as observed in ASDEX Upgrade [15].

In JET, gas injection had been previously used to increase the ELM frequency in the carbon wall [16]. The increase of power in the H-mode regime also leads to an increase of the type-I ELM frequency. The increase of the NBI power combined with a strong deuterium gas puffing rate (in general above \( 10^{22} \text{ D s}^{-1} \)) have both helped us to operate a stable H-mode regime in JET with the JET-ILW by increasing the ELM frequency, as can be observed on figure 3. By scanning down the gas injection with the JET-ILW, a minimum ELM frequency of typically 10 Hz was found to be necessary to prevent excessive core plasma radiation peaking. The role of the ELM on core radiation control has also been observed in ASDEX Upgrade and the property they have to flush out tungsten is evidenced [3]. A similar effect seems to be at play in the H-mode operation with the JET-ILW. However, it should be pointed out here that intra-ELM sputtering for 10 Hz ELM was found to dominate inter-ELM sputtering by almost one order of magnitude [17]. The increase of ELM frequency with the power could, therefore, compete with a possibly stronger ELM-induced tungsten sputtering source.

In an attempt to open up the space for \( H = 1 \), and to minimize the gas fuelling rate, vertical kicks [18] have been applied to control the ELMs at a given frequency larger than the natural frequency. Although the ELM frequency could indeed be controlled at about 20 Hz and the gas rate minimized down to \( 5 \times 10^{21} \text{ D s}^{-1} \) (see figure 3), the confinement factor could not be restored to values \( H \sim 1 \). More experiments are required to optimize the use of the kick technique (also including the use of pellet pacing [19]) to demonstrate the benefit of ELM pacing in the control of the core radiation. However, these preliminary experiments suggest that ELM control has become a key element in the achievement of stable H-mode discharge in a metallic environment.

As expected, the use of gas injection can degrade the confinement of the H-mode (see figures 4(a) and (b)). At high triangularity (\( \delta \sim 0.4 \)) the H-mode scenario shows a confinement degradation with gas puffing, which was generally not observed with JET-C [16]. Equivalent discharges with the same magnetic configuration at high triangularity 2.5 MA/2.7 T, using the same power and similar gas puffing rate (\( (3-4) \times 10^{22} \text{ s}^{-1} \)), show significantly lowered confinement with the JET-ILW (\( H_{\text{H98y2}} \sim 0.7 \)) compared to JET-C (\( H_{\text{H98y2}} \sim 1 \)). Although the underlying reason for this difference at high triangularity is not fully understood yet, it is most likely to be linked with the change of wall material. This also indicates that the gas injection itself is not the only cause of the reduced confinement factor. In addition, in the low triangularity shape (\( \delta \sim 0.2 \)) a minimum gas injection is now required, in contrast to the operation with JET-C. Figure 4(b) shows the behaviour of \( P_{\text{RAD, BULK}}/n_i^2 \) (representative of the impurity concentration in the discharge since \( P_{\text{RAD, BULK}} \) scales as \( n_i n_e \), and only weakly on \( T_e \), like \( T_e^{3/2} \) typically) as function of the gas injection amplitude. Above \( 2 \times 10^{22} \text{ D s}^{-1} \), the level of core radiation is equivalent to that with the carbon wall but this level increases by a factor 5 to 6 when the gas is lowered. In the lowest fuelling cases, the bulk radiation is generally higher than in equivalent pulses in the JET-C and the confinement factor \( H \) sometimes approaches 1, indicating that the \( H = 1 \) access operating space is strongly reduced with the JET-ILW (figure 4(a)).

The discharge shown in figure 2 suggests that impurity peaking is occurring in the plasma core of the discharge, thus enhancing the core radiation [20]. In the ASDEX Upgrade, these events have been related to the strong neoclassical transport of high-Z impurities in the plasma core [14]. To understand the relative importance of the source and the tungsten transport in the H-mode discharges, radiation peaking has been examined for H-mode discharges in relation with the tungsten source inferred from spectroscopy (photon flux of the 400.8 nm W i line) that is integrated over the whole bulk tungsten divertor tile. This has been done by selecting a dataset of pulse run at same \( I_p, B_T \) (2.5 MA, 2.7 T), plasma shape (therefore, identical \( \lambda_q \) according to the recent multi-machine scaling [21]) and same \( P_{\text{NET}} \) range (from 12 to 14 MW); that is, the same power flowing in the scrape-off layer (SOL). The spectroscopic data have been averaged over 1 s and, therefore,
Figure 2. (a) Example of radiation increase observed in an H-mode with 2.0 MA/2.2 T ($q_{95} = 3.3$) in JET with the JET-ILW in the low shape magnetic configuration ($\delta = 0.2$). Note the decreasing ELM frequency as the radiation power is increasing, the collapse of the central temperature and the loss of sawteeth, indicating a change of the core current profile shape. The loss of confinement is following the temperature decay and a significant peaking of the soft x-ray profile, suggesting that high-Z impurities have been transported to the plasma core. At the end of the discharge, the radiative power exceeds the total input power and the density peaks dramatically. The dashed line indicates the time of the bolometry reconstruction shown in (b). (b) Bolometry reconstruction for pulse 81913 at 11.7 s shown in (a). Note the absence of any significant radiation in the outer diverter and the off-axis core radiation [16].

Figure 3. Net input power ($= P_{IN} - P_{RADBULK}$) versus the deuterium gas fuelling rate for both high triangularity pulses (triangles, $\delta = 0.4$) and low triangularity (circles, $\delta = 0.2$) type-I ELMy H-mode at 2.5 MA/2.7 T with the JET-ILW. The data are divided into three groups depending on their ELM frequency. Note that below $P_{NET} \sim 13$ MW, an ELM frequency above 20 Hz can be achieved. Above $\sim 9$ MW, an ELM frequency above 10 Hz can be achieved. The low frequency H-modes ($f_{ELM} < 10$ Hz) are very often showing a high level of core radiation. The two dots pointed by the arrows have been achieved with vertical kicks (see [14]) suggesting that kicks could give access to the operation of the H-mode at low gas fuelling rate.

over typically 20 to 30 ELMs and averaged over the bulk tungsten tile surface ($\sim 1$ m$^2$) weighted by the toroidal wetted fraction ($\sim 0.7$) to provide the total photon flux. Figure 5 shows that in the low triangularity shape the tungsten source averaged over ELM and inter-ELM phases decreases with the gas injection rate by typically a factor of 2 when the gas in quadrupled. Much less variation of the source is observed for the high triangularity discharge. This first analysis of the tungsten source indicates that the strong radiation peaking observed at low gas fuelling is not only caused by the influx of tungsten induced by hot ions hitting the targets but that impurity transport in the core of the discharge plays a key role in the behaviour of the H-mode discharge, particularly when the ELM frequency is not sufficiently high. Note that these discharges are not in a detached regime between ELMs; therefore, the temperature at the outer strike point is expected to be well above 10 eV.

The change of the wall composition is most likely at the origin of all the differences described above between the JET-C and JET-ILW. The absence of carbon as the main diverter radiator could lead to higher temperature in the JET-ILW diverter [22]. Bolometric reconstruction shows a strong reduction of the radiated power in the diverter outer region with the JET-ILW, by typically a factor of 3 (figures 6, (top and bottom)), in otherwise identical plasma conditions ($I_p$, $B_T$, $P_{IN}$) and for identical upstream and pedestal density, as inferred from the high-resolution Thomson scattering (HRTS) diagnostic. This could lead to higher conducted parallel power and, thus, different SOL temperature conditions. The neutral
Figure 4. (a). $H_{98y2}$ enhanced confinement factor (from the $H98y2$ scaling law) versus the gas rate for the same set of data as figure 3: blue with the JET-C and red with the JET-ILW. Circle (triangles) symbols are low (respectively high) triangularity magnetic configuration. Note that for the same plasma shape and same fuelling rate high triangularity plasma do not perform in the same way. With the JET-ILW, $H = 1$ could be reached only in a domain where the discharge is unstable with respect to core radiation (see figures 1 and 2). (b) $P_{\text{RADBULK}}/\langle n_e \rangle^2$ normalized to the volume average density squared versus the gas rate for two datasets of H-mode discharges with $I_p = 2.5$ MA and $B_T = 2.7$ T, blue with the JET-C and red with the JET-ILW. Circle (triangle) symbols are low (respectively high) triangularity magnetic configuration. Note that with the carbon wall, the $P_{\text{RADBULK}}/\langle n_e \rangle^2$ does not vary with the gas injection rate, whereas in the JET-ILW it increases strongly for gas fuelling rates typically below $2 \times 10^{22}$ es$^{-1}$.

Figure 5. Tungsten source integrated over the whole bulk tungsten tile and over 1 s as a function of the gas injection for fixed $P_{\text{NET}}$ power (using S/XB of 40). Note that, for the low triangularity (dots, dashed line) the tungsten source decreases with gas injection by typically a factor of 2 when the gas rate is increased by a factor of 4 (see the dashed line linear square fit to the dots). On the other hand, the tungsten source does not decrease significantly in the case of the high shape (triangles, solid line).

replacing the outer strike point location (for equivalent JET-C discharges, the outer strike point was located in the pumping louvre) leads to reduced pumping in the divertor area and may also contribute to this higher level of recycling flux. Also, it has to be noted that the deuterium gas puffing rate is still an order of magnitude below the recycling neutral flux but its impact on the confinement appears stronger [1]. The lower observed $Z_{\text{eff}}$ is another factor that could play a role in the edge transport barrier and pedestal stability, which would be consistent with the observation made by the first nitrogen seeding experiments with the JET-ILW [23], but also in C-MOD [24] and AUG [3], where the $H \sim 1$ could be recovered when injecting nitrogen gas which can radiate at the plasma edge.

3. Development of the H-mode baseline scenario at $I_p = 3.5$ MA

On the basis of the first H-mode regime developments at 2.5 MA/2.7 T ($q_{95} = 3.5$), a low shape ($\delta = 0.2$) baseline has been developed up to 3.5 MA/3.2 T ($q_{95} \sim 3$). This target provides an expansion of the operating domain to lower $\rho^*$ and $v^*$ and, thus, interesting data for the study of ELM heat load, particle peaking and confinement scaling as done with the JET-C [25] in view of the extrapolation to ITER. In addition, high-current operation has been the occasion to consolidate plasma operation techniques in a metallic wall environment and particularly in the development of active protections of the components, plasma and H–L transition landing and a controlled disruption using the mitigation valve [26].

As explained in the previous section, in contrast to the JET-C, an even larger gas injection rate (up to $6.0 \times 10^{22}$ es$^{-1}$) had to be used at higher plasma current to stabilize the discharge and keep the ELM frequency above $\sim 10–20$ Hz. In addition, strike point sweeping of about ±6 cm has been successfully
applied over the bulk tungsten tile to mitigate the surface temperature tile below 1200 °C and to spread the power over several stacks of this tile. Thanks to this, discharges have been successfully developed up to 3.5 MA and $\beta_N \sim 1.4$ with up to 26 MW of NBI power for more than 5 s duration and a $Z_{\text{eff}}$ of 1.2–1.3 (figure 7). A total of 3.5 MA has been reached in steps of 0.25 MA from 2.5 to 3.5 MA to carefully monitor the discharge behaviour at each step. About ten discharges have been achieved at 3 MA and three at 3.5 MA, thus, making a solid basis for further increase of the plasma current in future campaigns and detailed study of the physics properties such as the LH transition and heat or impurity transport.

In comparison to the high-current scan carried out in the JET-C with the same triangularity [25], the confinement is consistently lower by 20–30% at same plasma current, $q_{95}$ and shape (figure 8). This has been achieved despite in some cases injecting more than 50% of power than the power threshold $P_{\text{th}}$ from the scaling [27], which is equivalent to what had been done with the JET-C in similar conditions. Attempts to recover the confinement by lowering the gas injection and increasing $P_{\text{NBI}}/P_{\text{th}}$ well above two while keeping the ELM frequency above 10 Hz have not succeeded in recovering more than 10% of the confinement. In the carbon wall, only a low level of gas injection rate ($<1 \times 10^{22} \text{ s}^{-1}$) had been used, so a straight comparison with the Be/W wall is not possible. However, figure 9 indicates that, for these types of discharges, a correlation of the lost confinement with the gas injection in line with the equivalent discharges in the carbon wall. As a result, the $\rho^*$ range are typically higher by 50% and 30%, respectively, with respect to similar discharges with the JET-C.

In these discharges, ICRH power has also been coupled successfully up to a level of 3.5 MW. The resonance layer
The current ramp-down phase has been investigated along the same guidelines for ramps of $-0.14$ to $-0.5$ MA s$^{-1}$. Although $i_c$ increases from 0.9 to 1.2 in H-mode, the increase is limited as long as the discharge stays in H-mode. These results are in line with those obtained with the JET-C and, therefore, confirm that even for the fastest ramp-down it is possible to maintain plasma vertical position and avoid any significant flux consumption in the ramp-down of ITER. In general, no increase of the core radiation is observed in these experiments. The results are also giving confidence that the ramp-up/down of the baseline scenario can be integrated in the baseline scenario in JET and controlled within the poloidal field coil limits of ITER.

The H-mode termination and landing at high plasma current had also to be re-developed. Because the JET-ILW has changed the radiation distribution towards higher plasma core radiation, switching off the power at termination, as was done with the JET-C, often resulted in a radiative collapse and a disruption. This may be explained by the longer time of residence of heavy impurity in the plasma than light impurity. The use of electron heating up to 4 MW of ICRH in the landing phase has been instrumental in mastering the landing of the H–L transition by increasing the electron temperature to 5–7 keV and probably the anomalous particle diffusion processes. However, more dedicated experimental work is necessary to understand the physics associated with the back-transition and the external transport barrier collapse. The control of the H–L transition remains an important challenge for ITER operation.

With the JET-ILW, it is also observed that a lower fraction of the thermal and magnetic energy is radiated during the disruption [33]. This can potentially result in a higher fraction of the energy conducted to the PFCs and also an increase of the current quench duration. The latter enhances the impulse exerted by the disruption on the vessel and could result in high vertical excursions of the vessel. Extrapolation from intentional vertical displacement events at lower current showed that in the JET-ILW baseline scenario at $l_c = 3.5$ MA the absolute disruption force could exceed 600 tonnes, higher than what one would get with the JET-C. The experiments to qualify the efficiency of the massive gas injection (MGI) on disruption have shown that the MGI increases the radiation and, thus, reduces the heat loads and forces to the level of those observed in the JET-C [25]. Given these results, the MGI has been used routinely in closed loop above a plasma current of 2.5 MA. To trigger the MGI sensors based on the locked-mode signal and current quench, detectors (detecting $dl_i/dt$ or poloidal flux variations) [34] have been used. These triggers acted 67 times for current of 2.5 MA and above. However, these detectors sometimes act too late, in particular when the discharge is showing high core radiation, often leading to radiation collapse in the termination phase. To cover a broader range of disruption types, an engineering real time predictor has been designed [35] and tested in open loop during the high plasma current experiment. Based on a combination of classifier of seven characteristic temporal signals, this predictor showed that almost 90% of the disruptions could have been predicted 30 ms in advance of the disruption. As an example, this predictor could have acted and triggered the MGI on time in a 3.5 MA disruption (force: 320 T) that was induced by the ingress of a tungsten into the plasma. Finally, it should be
stressed that the use of the MGI has not significantly affected the breakdown of the next plasma with the JET-ILW or the performance in the subsequent discharges [8].

4. Development of the advanced inductive H-mode (hybrid) scenario up to $\beta_N \sim 3$

The hybrid scenario has also been developed using as references the work carried out with the JET-C [36]. This scenario is traditionally characterized by its access to high normalized pressure ($\beta_N > 2.5$) and no, or infrequent, sawtooth activity thanks to its ‘broad’ $q$ profile shape close to unity as the main heating power is applied. This is achieved in JET using the so-called current overshoot technique [37], which helps keep the central target $q$ value ($q_o$) close to unity and maximize the amount of current density at mid-radius, which has the effect of delaying the occurrence of neoclassical tearing modes before the current diffuses.

To achieve such ‘non-standard’ $q$ profiles, the impact of the metallic wall in the current on plasma current ramp-up has been first examined experimentally. After the plasma breakdown and an X-point formation 1.4 s later the plasma current is ramped up to its plateau in X-point (as planned for ITER). The comparison with the JET-C shows that more gas had to be injected in this phase to achieve the same plasma density. Too low a gas injection (equivalent to what was injected in the JET-C) resulted in the creation of a suprathermal electron population (up to 5 MeV as detected by $\gamma$-ray spectroscopy) and an increased tungsten level, which can lead sometimes to a hollow temperature profile in the ramp-up phase [11]. With increased gas injection, the early central $q$ profile at the X-point formation is much lower in the plasma core (typically 3 or 4 instead of 6 or 7 as measured by motional Stark effect (MSE)) than it was with the JET-C in similar conditions. This observation may have consequences for scenarios requiring early control of the target $q$ profile, such as the advanced tokamak scenario. The advanced inductive scenario is less affected by this first phase since the main heating phase is usually set up more than several resistive times after the X-point formation.

Using this plasma initial phase, the hybrid scenario has been developed at low shape ($\delta \sim 0.2$–0.3) and high shape ($\delta \sim 0.4$) for $q_{95} \sim 3.7$ at 1.7 MA/2.0 T and 2.0 MA/2.3 T, all using the $I_p$ overshoot technique. In these discharges, $\beta$ control by the neutral beam power has been used to set up the scenario target $\beta_N$ between 2.5 and 3. In all cases, the outer strike point was on the divertor bulk tungsten tile. This was, in general, not the case with the JET-C where the plasma configuration had a more outward strike point position closer to the pumping louvers of the divertor.

Despite the change in divertor geometry, it appeared that the hybrid scenario could reproduce for about 2–3 s (figure 10). A similar global performance ($H = 1.2$–1.3 with $\beta_N \sim 3$) was achieved in the JET-C at both high and low triangularity. For the low triangularity plasmas, a similar $H$ factor than in JET-C is achieved but at higher volume average density and lower volume average temperature, suggesting that kinetic profiles are different than with the JET-C (as we will discuss in section 5 of this paper). In both cases, a moderate gas fuelling rate ($\sim 5 \times 10^{21}$ D s$^{-1}$) is required to keep the discharge stable at 2 MA with regard to the increase of core radiation peaking. The high-frequency ELMs ($> 40$ Hz) and high (by more than a factor of 3) $P_{\text{NET}}$ power above the H-mode threshold may explain this. On the other hand, the quantity $P_{\text{RADBULK}}/(n_e)^2$ is in general higher with the JET-ILW by a factor of 2–3, even in the case of high $H$ factors. Exactly as for the baseline scenario (see the previous section), the core radiation is larger (by typically a factor of 3) and the divertor radiation smaller (more than $\times 2$) at similar electron density and temperature.

When achieved, the high performance ($H \sim 1.3, \beta_N \sim 3$) of the advanced inductive scenario with the JET-ILW often rolls over when MHD occurs in correlation with strong core radiation peaking. The MHD signature is similar to that of the JET-C, namely: $m = 1/n = 1$ continuous activity (with sometimes intermittent sawteeth) and 3/2 and 4/3 modes have been identified. The 4/3 mode is often accompanied by the (1, 1) mode. When a rational surface tears and an island forms (as evidenced by the phase inversion of the temperature oscillations observed on the electron cyclotron (ECE) radial channels) [38], its impact on the plasma performance is more profound and leads, generally, to core radiation peaking (as observed on the soft x-ray lines viewing the plasma core) and the loss of performance caused by high-$Z$ impurities (figure 11). This is in contrast with the JET-C, where such events led to moderate loss of confinement of typically 15% for a 3/2 mode and 5% for a 4/3 mode, the core radiation was much lower, and the discharge did not terminate in radiative collapse. From these observations, it seems on one hand that the MHD in the hybrid scenario changes dramatically the particle transport properties of the high-$Z$ impurities. On the other hand, the presence of impurities may also impact the mode stability. This
An example of the effect of tearing mode on the radiation in a typical hybrid discharge. The mode starts as a (1,1) that tears at 5.8 s and produces an $n=2$, $m=3$ island. As observed on both soft x-ray and bolometry signals, radiations are strongly peaking at this time indicating that impurities have moved towards the plasma core and performance rolls over dramatically from that point.

The complex interplay between MHD and impurity transport is not yet clear. Also, the difference between the $q$ profiles with the JET-C and with the W-wall cannot be identified within ±0.1 in $q$ from the MSE measurements. A further optimization of the $q$ target profile and its evolution might help in avoiding the occurrence of the mode and its consequences. Experimentally, a more stable operation could indeed be successfully achieved by setting up a lower $\beta_N$ target with the control scheme (2.7 instead of 3.0). The lower achieved normalized pressure does help in these cases avoiding the triggering of tearing modes but is also accompanied with a performance penalty ($H \sim 1.1–1.2$ instead of 1.3).

5. Scenario confinement properties with the JET-ILW

The poor confinement observed in the baseline scenario in general and the performance close to their JET-C target achieved by the advanced inductive scenario are quite unexpected. It is, therefore, interesting to review the differences between these two scenarios.

First of all, both scenarios are H-modes but they are operated at very different normalized pressure ($\beta_N = 1.4$ and $\beta_N = 3.0$ respectively). In the JET-ILW, the baseline and hybrid H-mode scenarios have not been run with the same $I_p$, $B_T$ and $q_{95}$ and may have, therefore, different transport properties. In addition, the scenarios have not been operated with the same magnetic configuration (but they have the same diverter geometry), which would allow a more accurate comparison of their core and pedestal confinement with the normalized pressure. The baseline scenario with the JET-ILW has been operated with a loss power significantly above the H-mode power threshold $P_{th}$ by a factor 1.5–2.0 and the hybrid scenario above the threshold, by typically a factor of 2.0–3.5, equivalent to the discharges run with the JET-C. It should be noted here that the power threshold from Martin’s scaling [27] has been mostly derived with data from carbon devices and do not account for the bulk radiation. In addition, LH threshold studies in JET [39] with the JET-ILW are also indicating that $P_{th}$ could be lower than with the JET-C [40].

The difference in confinement between the baseline and the hybrid scenarios will be examined next, looking at core and pedestal kinetic profiles data. This is done by making an extensive use of the HRTS diagnostic for $T_e$ and $n_e$ [41] using a large database (270 pulses) of H-modes baseline and hybrid at both high and low triangularity.

First, the pedestal temperature and density are inferred from a hyperbolic tangent fit of the HRTS measurements. In most of the pulses studied here, the core ion temperature and rotation could not be inferred from the charge exchange diagnostic in part because of the low signal-to-noise ratio resulting from the now low carbon concentration with the JET-ILW. However, edge/pedestal charge exchange data could be obtained and they show a very similar ion and electron temperature ($T_e \sim T_i$) in all scenarios. Therefore, at least for the pedestal, we can consider that the observations on electrons also hold for the ions. The pedestal temperatures and densities are compared in terms of $T_{ped}/I_p$ and $n_{ped}/n_{Greenwald}$, so that pulses of different currents and fields could be compared. In this way, the curved lines on figure 12 represent constant $\beta_p$ lines. From this figure, the pedestal temperature for the baseline scenario (both low and high shape) is significantly lower than for the hybrid scenario.
Figure 13. (a). Comparison of electron temperature and density profiles between JET-C (black) and JET-ILW (red) for the baseline H-mode scenario at high shape (right) and low shape (left) in identical conditions of input power and gas rate injection. For the high shape, the density profiles are almost identical but there exists a deficit in electron temperature. For the low shape, density is higher and the temperatures are significantly lower resulting in a lower electron pressure. (b) Comparison of electron temperature and density profiles between JET-C (black) and JET-ILW (red) for the hybrid H-mode scenario at high shape (right) and low shape (left) in identical conditions of input power. At low shape, the density is higher but the temperature is significantly lower resulting in an almost identical electron pressure consistent with a small difference observed on the global confinement.

lower (by typically 25–30% for an equivalent pedestal density), possibly because of the strong gas fuelling applied to these discharges in general. The hybrid scenario at low shape also shows low pedestal temperature but also a higher electron density. As a result, the pedestal electron pressure is typically the same and the data points lie on the same $\beta_p = \text{constant}$ line. On the same figure, the hybrid at a high shape has also a lower electron temperature with respect to the JET-C, whereas the density does not seem to compensate this loss completely and the electron pedestal pressure is lower by typically 10–20%. From these observations, it appears that the pedestal confinement is reduced in general for the JET-ILW plasma, except perhaps for the low shape hybrid H-mode scenario [41]. The different diverter geometry used between the JET-C (outer strike point located in the pumping throat) and JET-ILW (outer strike point away from the pumping throat by 10–15 cm) may contribute to the observed density and confinement difference.

Figures 13(a) and (b) illustrate the differences in electron temperature and density core profiles for both the baseline and the hybrid H-mode discharges (extracted from the data base used for figure 12) in similar conditions of plasma current, toroidal field strength, and input power. In all cases, the core density is stronger in the JET-ILW baseline and hybrid H-modes than in the JET-C equivalent discharges. Note that the pedestal confinement is reduced in general for the JET-ILW plasma, except perhaps for the low shape hybrid H-mode scenario [41]. The different divertor geometry used between the JET-C (outer strike point located in the pumping throat) and JET-ILW (outer strike point away from the pumping throat by 10–15 cm) may contribute to the observed density and confinement difference.

In all scenario cases, the absolute core temperature level is also lower in the JET-ILW, which is particularly apparent for the low shape discharges. Core transport is often characterized by the temperature and density gradient lengths $R/L_T$ and $R/L_n$. Because of the lack of ion temperature measurements, only partial conclusions can be drawn from the core profile analysis in the confinement zone ($0.4 < \rho < 0.7$). In particular, it is not possible to check how far these plasmas are from the critical gradients of ion temperature gradient (ITG) instability which was thought to be the dominant mode driving the turbulence [42] in the JET-C for both baseline and hybrid H-mode scenarios. For the low shape hybrid H-mode, the differences are so large between the JET-C and the JET-ILW in terms of $T_i/T_e$ and also $Z_{\text{eff}}$ that a complete transport analysis with the ion temperature measurements would be required to check this point thoroughly. The differences in the observed profile also imply that the collisionality for the low shape hybrid H-mode is typically 50% lower in the JET-C than in the JET-ILW. This observation may have important consequences in the particle (and impurity transport), as described in recent work [43] where it is claimed that particle transport increases with increasing collisionality.

From these observations, there is evidence that the change of wall material has changed both the pedestal and core kinetic profiles, and gradients mostly in low density (low shape plasmas) and, therefore, modified the transport properties of both the baseline and hybrid H-mode scenarios but possibly in different ways. At this point of the research, the lack of ion temperature data in the core does not allow a detailed transport analysis. In the case of discharges with thermal equilibration between ions and electrons, $T_i \sim T_e$ could
be assumed (for example, for high-current baseline scenario discharges). However, it is known that the ITG plays a significant role in impurity neoclassical transport [44] and that such an assumption could lead to incorrect conclusions on the transport differences between the JET-ILW and the JET-C.

6. Conclusions

The recent experiments at JET with the new JET-ILW have made significant progress in the scenario integration with a relevant wall for ITER. The operating domain for the scenarios is significantly different. In particular, the access to a confinement factor of $H = 1$ is seriously restricted. The requirement to control the transport of tungsten by the ELMs using gas injection has been shown to impact on the discharge confinement properties. In addition, the gas injection has had a significant impact on the W source in the H-mode regime. Although the W edge source and contamination in the core can be observed to vary with gas fuelling and $P_{NET}$, the evidence points towards the role played by the high-$Z$ impurity transport. The lower $Z_{eff}$ (~1.3) and lower radiation (and higher separatrix and target temperature) at the plasma edge in comparison to the carbon wall could also play a key role in the core and scrape-off layer transport. The observation that part of the stored energy in the baseline H-mode can be recovered using nitrogen injection [23] is a signature that the link between the SOL and the core confinement does exist. Despite these limitations, H-mode baseline discharges could be achieved to a plasma current of 3.5 MA using strong fuelling and this has helped to consolidate the operation of the H-mode regime, particularly with the integration of the disruption active control using the MGI installed on JET. At this point, it is not yet completely clear why the advanced inductive hybrid H-mode achieves $H$ factors close to those in the JET-C. The observations of the kinetic profiles indicate that both pedestal and core profiles in both low and high shape are significantly different, suggesting that the transport details across the plasma radius are also different than with the JET-C. The higher operating $q_{95}$ (~4) and the level of plasma current (less than 2 MA) so far used in this scenario could be beneficial. Therefore, future experiments that aim to develop the hybrid H-mode to a higher current and, therefore, higher thermal and particle confinement with a longer duration could behave in a different way. In addition, the MHD stability in these discharges has now become a key concern for the future because of its consequence on the impurity transport and energy confinement time. Continuous (1, 1) activity, for example, leads to radiation peaking and confinement degradation when it tears. This activity is much worse than with the carbon wall. For the future of the inductive advanced scenario (hybrid) in a metallic wall, this emphasizes the importance of $q$ profile control to prevent the triggering of tearing modes. This also suggests that the presence in the plasma of high-$Z$ impurities eroded from the diverter should be minimized even before (i.e. in the current ramp-up L-mode phase) the discharges enters into the burning phase.

The JET-ILW has also motivated the integration of key scenario elements, such as the use of the massive gas injection [26] for disruption mitigation, safe procedures for the landing of the H-mode and the study of the current ramp-up and -down flux consumption [29, 30]. The MGI has been instrumental in producing H-mode discharges at a current of up to 3.5 MA in JET with the JET-ILW. Although disruptions cannot yet be predicted with 100% confidence, the use of the MGI in a closed loop and the reduction of its reaction time (by bringing the MGI valve closer to the plasma in future campaigns) could minimize the disruption consequences to the minimum required for safe operation of the tokamak. Nevertheless, the triggering of the MGI must be used in the last resort after all other landing strategies have been exhausted. In the last campaign, safe landing procedures against core radiation collapse have also been developed using ICRH heating in the H to L transition, for example. The development of these elements and their integration in the plasma scenario remains an essential task for the preparation of the safe operation of the ITER scenario.

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