

First operation with the JET International Thermonuclear Experimental Reactor-like walla)

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First operation with the JET International Thermonuclear Experimental Reactor-like wall^{a)}

R. Neu,^{1,2,b)} G. Arnoux,³ M. Beurskens,³ V. Bobkov,² S. Brezinsek,⁴ J. Bucalossi,⁵ G. Calabro,⁶ C. Challis,³ J. W. Coenen,⁴ E. de la Luna,⁷ P. C. de Vries,⁸ R. Dux,² L. Frassinetti,⁹ C. Giroud,³ M. Groth,¹⁰ J. Hobirk,² E. Joffrin,⁵ P. Lang,² M. Lehnen,⁴ E. Lerche,¹¹ T. Loarer,⁵ P. Lomas,³ G. Maddison,³ C. Maggi,² G. Matthews,³ S. Marsen,¹² M.-L. Mayoral,³ A. Meigs,³ Ph. Mertens,⁴ I. Nunes,¹³ V. Philipps,⁴ T. Pütterich,² F. Rimini,³ M. Sertoli,² B. Sieglin,² A. C. C. Sips,¹⁴ D. van Eester,¹¹ G. van Rooij,⁸ and JET-EFDA Contributors^{c)}

JET-EFDA, Culham Science Centre, OX14 3DB Abingdon, United Kingdom

¹EFDA-CSU, Boltzmannstr. 2, 85748 Garching, Germany

²Max-Planck-Institut für Plasmaphysik, Euratom Association, Boltzmannstr. 2, 85748 Garching, Germany

³Euratom/CCFE Fusion Association, Culham Science Centre, Abingdon OX14 3DB, United Kingdom

⁴IEK-4, Association EURATOM/Forschungszentrum Jülich GmbH, Jülich 52425, Germany

⁵IRFM-CEA, Centre de Cadarache, 13108 Saint-Paul-lez-Durance, France

⁶Associazione EURATOM-ENEA sulla Fusione, CNR ENEA Frascati, 00044 Frascati, Italy

⁷Laboratorio Nacional de Fusion, Asociacion EURATOM CIEMAT, Madrid, Spain

⁸Association EURATOM/DIFFER, Rijnhuizen, P.O. Box 1207, 3430BE Nieuwegein, The Netherlands

⁹Association EURATOM-VR, Division of Plasma Physics, KTH, Stockholm, Sweden

¹⁰Association Euratom-Tekes, Aalto University, FI-00076 Aalto, Finland

¹¹Association EURATOM-Etat Belge, ERM-KMS, Brussels, Belgium

¹²Max-Planck-Institut für Plasmaphysik, Euratom Association, Wendelsteinstr. 1, 17491 Greifswald, Germany

¹³Institute of Plasmas and Nuclear Fusion, Association EURATOM-IST, Lisbon, Portugal

¹⁴EFDA-CSU, Culham Science Centre, OX14 3DB Abingdon, United Kingdom

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To consolidate International Thermonuclear Experimental Reactor (ITER) design choices and prepare for its operation, Joint European Torus (JET) has implemented ITER's plasma facing materials, namely, Be for the main wall and W in the divertor. In addition, protection systems, diagnostics, and the vertical stability control were upgraded and the heating capability of the neutral beams was increased to over 30 MW. First results confirm the expected benefits and the limitations of all metal plasma facing components (PFCs) but also yield understanding of operational issues directly relating to ITER. H-retention is lower by at least a factor of 10 in all operational scenarios compared to that with C PFCs. The lower C content (\approx factor 10) has led to much lower radiation during the plasma burn-through phase eliminating breakdown failures. Similarly, the intrinsic radiation observed during disruptions is very low, leading to high power loads and to a slow current quench. Massive gas injection using a D₂/Ar mixture restores levels of radiation and vessel forces similar to those of mitigated disruptions with the C wall. Dedicated L-H transition experiments indicate a 30% power threshold reduction, a distinct minimum density, and a pronounced shape dependence. The L-mode density limit was found to be up to 30% higher than for C allowing stable detached divertor operation over a larger density range. Stable H-modes as well as the hybrid scenario could be re-established only when using gas puff levels of a few 10^{21} es⁻¹. On average, the confinement is lower with the new PFCs, but nevertheless, H factors up to 1 (H-Mode) and 1.3 (at $\beta_N \approx 3$, hybrids) have been achieved with W concentrations well below the maximum acceptable level. [<http://dx.doi.org/10.1063/1.4804411>]

I. INTRODUCTION

Plasma wall interaction (PWI) research and development has become a priority for the international fusion community because of the huge extrapolation necessary in terms of particle fluence and transient power loads when progressing to next step devices such as International Thermonuclear Experimental Reactor (ITER) or DEMO. In response, the

ITER-like wall (ILW) project was initiated at Joint European Torus (JET)^{1,2} using beryllium (Be) as first wall and tungsten (W) as divertor armor material, mimicking the ITER choice materials for plasma facing components (PFCs) during its active phase.³ The experiments at JET with its ILW (JET-ILW) started in summer 2011, providing the unique opportunity to address specific issues related to the parallel use of Be and W for PFCs with plasma parameters closest to those of ITER. Amongst these are the investigation of fuel retention compared to a carbon device, the test of ITER relevant conditioning procedures, mixed materials effects, W erosion and transport in ITER relevant scenarios (baseline and

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^{b)}Invited speaker. Electronic mail: Rudolf.Neu@efda.org

^{c)}See the Appendix of F. Romanelli *et al.*, Proceedings of the 24th IAEA Fusion Energy Conference 2012, San Diego, USA.

advanced), the effect of Edge Localized Modes (ELMs) and ELM mitigation methods as well as the behavior of melt layers under steady state and transient heat loads.

In order to keep the implementation of the ILW manageable, the impact of the change in materials on JET operational limits and on the existing support structures had to be minimized. In the main chamber this was achieved by using bulk beryllium on Inconel carriers for the limiters and with tungsten coated Carbon Fibre reinforced Carbon (CFC)⁴ in some higher heat flux recessed areas, for example, the neutral beam shine through areas, and beryllium coated Inconel elsewhere.⁵ The divertor consists of W-coated CFC tiles⁶ and a single toroidally continuous belt of bulk tungsten at the outer strike point⁷ (see Fig. 1). Besides this obvious reconstruction a large amount of smaller items had to be changed/optimized,⁸ for example, the upper dump plate now consists of bulk Be ribs with Be coated Inconel plates between, rather than a continuous sheet of tiles. The anticipated operating limits with the ILW are fundamentally driven by the relatively low melting point of beryllium (1629 K), the limited robustness of tungsten coatings to slow and fast thermal cycles and the thermal capabilities of the support structures for the bulk tungsten tile.⁹

The protection of the ILW was an integral part of the project from very early on. In order to achieve PFC temperature measurements in real time, a comprehensive set of bi-color pyrometers (8) and monochrome video cameras (7) with adjustable filters and thermo-couples was installed. These measurements were used to establish a map for the energy deposition at all relevant PFCs in order to allow a fast reaction of the discharge control preventing their overload.¹⁰

II. OPERATIONAL EXPERIENCE WITH THE JET ITER-LIKE WALL

A. Plasma breakdown

The ITER-like wall was found to have a profound impact on plasma breakdown.¹¹ As expected, the avalanche phase was unaffected and seems to be dominated by the pre-fill pressure and its composition, but the burn-through phase strongly depends on the plasma facing material. The recycling or out-gassing properties and the levels of main

impurities such as carbon changed significantly with the introduction of the ITER-like wall, affecting the density and radiation in the burn-through phase. The highest radiation levels during the burn-through phase were obtained at the start of the ILW operation, when the carbon levels were still higher, but also during and after the use of N as extrinsic impurity in experiments for radiative cooling. The lower radiation efficiency of beryllium in comparison to carbon in combination with the fact the peak radiation is at lower temperature, allows for a faster burn-through. For the carbon wall, out-gassing and impurity release were responsible for a large part of the electron density build up during the burn-through phase. In contrast, this component was almost absent with the ITER-like wall and the density was determined by the amount of pre-fill gas making it more reproducible and successful plasma burn-through could be achieved with higher pre-fill pressures and higher densities. The higher dynamic retention with the ITER-like wall made it, however, more difficult to sustain the neutral and plasma density which in turn may have complicated low voltage breakdown (mode B) for which the Townsend avalanche criteria¹¹ allow only a limited pre-fill pressures range. Independently, the changes in breakdown with the ITER-like wall did not lead to a substantial reduction in flux-consumption.

The plasma burn-through including plasma-surface interaction effects has been self-consistently modeled.¹² The simulations show that with a carbon wall chemical sputtering allows the carbon content to build up during the formation of the plasma, dominating the radiation. In contrast the model shows that physical sputtering of beryllium does not raise radiation levels much above those obtained with pure deuterium plasmas, similar to that seen experimentally.

As a consequence of this very beneficial behavior of the plasma break down, no overnight glow discharges and no Be evaporation were necessary in contrast to the experience with carbon walls. Note that there were only two Be-evaporations in the first year of operation in order to investigate their influence on the impurity production by ion cyclotron resonance heating (ICRH).

B. Impurity sources and content

Monitoring pulses were introduced to the routine plasma operations of JET-ILW¹³ and typically performed once a week, in order to allow tracking the evolution of the machine performance and intrinsic impurities throughout the 2011/2012 campaigns. After the initial restart of JET-ILW about 300 JET Pulses (2000 s) of divertor operation were required to establish a steady state divertor impurity composition. During this period the carbon signal (C II, 515 nm) at the outer strike point decreases by a factor of three, whereas the Be intensity (Be I, 457 nm) increases by a factor of two. At the inner strike point, a similar increase of the Be intensity is found, whereas the C II intensity slowly increases after an initial drop by about 20%. This different behavior can be explained with the assumption that the outer strike point area is typically erosion dominated, whereas the inner one represents a deposition zone as shown by WALLDYN simulations in Ref. 14. Throughout the further campaigns only a

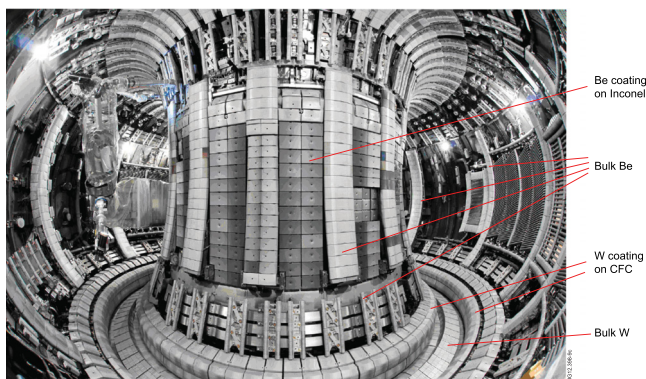


FIG. 1. View into the JET torus with its new ITER-like wall. The main wall tiles are bulk-Be or Be coated Inconel and W-coated CFC tiles (NBI shine through areas and restraint rings). The divertor is composed of bulk W tiles for the horizontal target and W-coated CFC tiles for the rest.

moderate increase ($\leq 20\%$) of the carbon influx from the inner divertor was found. This observation is attributed to the fact that although the monitoring pulses were performed always identical, the energy input into the plasma discharges in between the monitoring discharges was continuously rising throughout the campaigns probably mobilizing residual carbon. These carbon sources are not known in detail, but similar to the findings in ASDEX Upgrade (AUG), it is assumed that they originate from C layers at the vessel walls deposited during earlier campaigns and from side and back surfaces of the W coated CFC tiles. In this context, it has to be noted that no macroscopic failure of the W coatings was detected by regular video inspections of the vessel interior so far as well as in a first assessment after the surfaces during the ongoing vent. Fig. 2 shows a compilation of Z_{eff} values and normalized main chamber carbon influxes (CIII/n_e^2) for all discharges throughout the ILW campaigns as well as from the previous campaigns with the MkII HD CFC divertor (further denoted as “JET-C”). Carbon drops by a factor of about 20 and at the same time the averaged Z_{eff} drops from 1.96 to 1.21.¹⁵ Assuming C as the main intrinsic impurity in JET-C and Be in JET-ILW, respectively, an averaged carbon concentration of $\approx 3\%$ and an averaged beryllium concentration of 2% can be deduced, in line with typical concentrations deduced from charge exchange spectroscopy (CXS). The CXS also shows C concentrations in the ILW well below 0.5%. As with the C influx from the divertor, the C

influx in the main chamber shows a clear increase towards the end of the first year of operation. This increase is strongly correlated with the increased energy throughput stated above and shows a very similar correlation with power as in JET-C, albeit at a factor of 10 lower levels.¹⁵ Due to the strong gettering effect of Be, oxygen is strongly suppressed and despite an evident vacuum leak, its level at the beginning of the JET-ILW campaigns is as low as in JET-C after months of operation and many Be evaporations.

Passive spectroscopy was used for the characterization of the erosion at the solid Be limiters using the inverse photon efficiency (the so called S/XB -value).¹⁶ In order to calculate an “effective” erosion yield the peak Be particle flux densities were normalized to the saturation current measured by Langmuir probes mounted on the reciprocating probe evaluated at the same radial position. The value is called “effective” since this yield includes also the sputtering by impurity ions and the effect of self-sputtering. It is equivalent to the gross erosion yield, whereas the net erosion yield also takes into account the (prompt) re-deposition of the target material. Effective yields of up to 10% were observed for a wide range of plasma parameters in a series of limiter discharges specifically performed for an erosion study.¹⁷

The W erosion in the JET outer divertor was evaluated as a function of the divertor electron temperature in L-mode and H-Mode discharges again by means of visible spectroscopy.¹⁸ The W influx was deduced from a transition at 400.9 nm in neutral tungsten (W I) and the temperature dependent S/XB -value was taken from a recent compilation of theoretical and experimental data from different devices. These values range from $S/XB = 8$ at $T_e = 10$ eV to 28 at $T_e = 30$ eV and 50 at $T_e = 80$ eV.

In the investigated L-Mode discharges (1 MW of neutral beam injection (NBI) heating), the effective erosion yield increases monotonically with divertor temperature up to $\approx 5 \times 10^{-4}$ at $T_e = 45$ eV and for the lowest value of $T_e \approx 7$ eV achieved in a density scan, a steep decrease of the effective erosion yield below 10^{-6} is found, revealing the threshold behavior expected for W sputtering dominated by Be^{2+} ions. Indeed, there is good agreement of effective erosion yields with calculated sputter yields assuming a 0.5% Be fraction in the divertor plasma, which is consistent with spectroscopic measurements of the Be influx.¹⁸ It has to be noted, however, that at low line averaged plasma densities ($n_e \leq 2 \times 10^{19} \text{ m}^{-3}$) and ICRH power up to 3 MW, effective erosion yields $> 10^{-3}$ are measured at divertor temperatures above 50 eV, pointing to a higher fraction of impinging Be ions.

In H-Mode discharges, a large difference between inter- and intra-ELM W sputtering is observed. In a discharge heated with 13 MW of NBI, with $n_e = 7.5 \times 10^{19} \text{ m}^{-3}$ and 10 Hz ELMs, a W influx of $6.3 \times 10^{18} \text{ W-atoms s}^{-1}$ and an effective inter-ELM sputter yield of 4×10^{-5} was found, thus being similar to the L-mode sputter yields given above. The intra-ELM sputtering measurement for this case gave a W source of $4.7 \times 10^{18} \text{ W-atoms/ELM}$. Given the 10 Hz ELM frequency, this means that intra-ELM sputtering dominated by a factor of 8 over the inter-ELM sputtering similar to observations in AUG.¹⁹

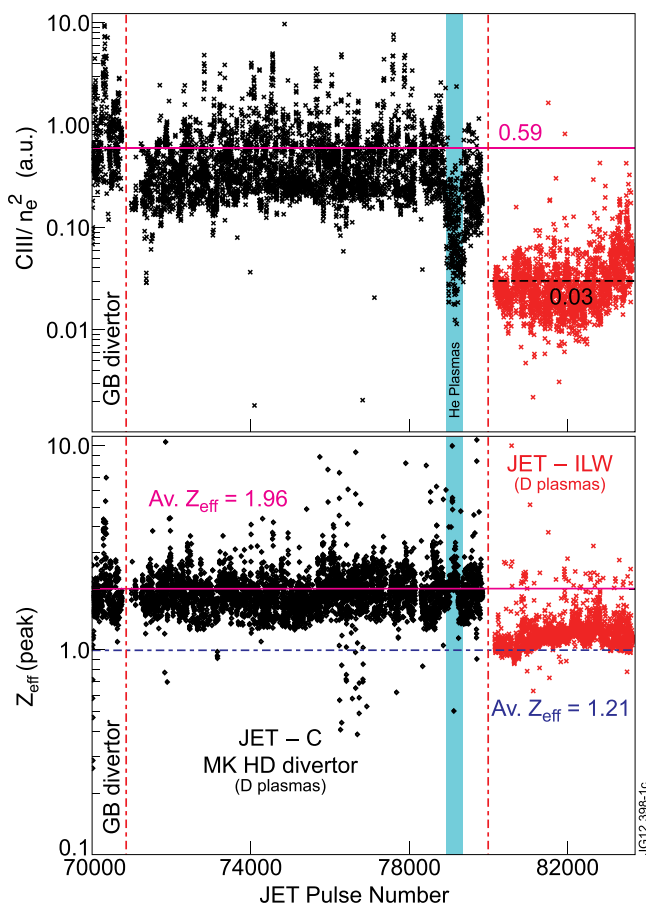


FIG. 2. Reduction of carbon influx and Z_{eff} after the transition from carbon PFCs to Be and W PFCs.

Nitrogen seeding has been used for reducing power and energy loads on divertor targets by radiative cooling (see Sec. III E). As long as the cooling is not efficient enough an increase of the W influx is expected with the increased N influx. This effect was investigated in L-mode discharges with 1.1 MW heating power from NBI and N₂ seeding rates $4 \times 10^{21} - 1 \times 10^{22} \text{ es}^{-1}$. A maximum effective erosion yield is observed around a divertor temperature of $T_e = 20 \text{ eV}$, i.e., here the effect of plasma cooling started to dominate and nitrogen seeding had a net beneficial effect on the W erosion when the divertor temperature decreased below 15 eV.

In Fig. 3, the impact of equal amounts of auxiliary heating (3.5 MW) applied by either ICRH or by NBI is presented, while ensuring the density is the same (central line integrated density $\approx 6 - 7 \times 10^{19} \text{ m}^{-2}$).²⁰ The strong increase of the central electron temperature during ICRH and the much larger effect on T_e compared to NBI heating is due to the strongly localized power deposition of the ICRH. The calculated power deposition profiles for electron and ion heating show that for NBI the power density of the ions is larger (factor 1.5) than to the electrons inside $\rho < 0.5$ and the overall deposition profile is very flat over the whole plasma radius. For ICRH, the deposition profile is strongly peaked within $\rho < 0.5$ with more than 3 times larger power density for the electron heating than for the ions at $\rho \approx 0.15$. The radiation level during ICRH is larger by a factor of 3 and most radiation originates from the main chamber while the radiation for beam heating is mainly concentrated in the divertor region (Fig. 3(d)). The W concentration in the plasma was evaluated from Vacuum Ultra-Violet (VUV) spectroscopy.²¹ Several spectral features, namely the so-called “W quasicontinuum” originating from the ionization stages

W²⁷⁺ to W³⁵⁺ and single spectral lines from W³⁹⁺ to W⁴⁵⁺ could be identified. Using the measured electron temperature profiles and the resulting W ionization equilibrium, the emissions from these distinctly different ionization states can be used to extract information on the W concentration profile. As can be seen from (Fig. 3(c)), the W concentration strongly increases during ICRH. The total radiation originating from W can be calculated from these concentrations by using the radiation loss parameter (see Ref. 22). A large part of the increased radiation during ICRH can thereby explained by the increased W concentration. The ratio between the edge and core W concentrations measured by spectroscopy suggests that the W density profile is hollow, pointing to the beneficial effect of central ICRH with respect to the suppression of W accumulation as already observed in AUG²³ and in JET for Ni.²⁴ This observation is corroborated by tomographic reconstruction of bolometric measurements which show an off-axis peaked radiation pattern. However, the strong increase of the W content was unexpected because the antenna limiters are completely made out of Be. Moreover no significant increase of the W source in the divertor, neither at the strike point region nor at the baffle at the divertor entrance was observed, leaving the source yet to be identified.²⁵ In principle, a change in the (edge) transport could also lead to a higher W concentration, but this seems to be unlikely because copper, which is detected as a trace impurity, does not increase during ICRH. In order to shed more light on potential sources, two beryllium evaporations were performed towards the end of the campaign. This resulted in a reduction by almost a factor of 2 of the total radiation during ICRH, which lasted for more than 10 discharges. Since the W divertor sources recovered much faster after the Be evaporations than the high Z content of the main plasma, one can conclude the additional W (and Ni) sources during ICRH must not be located in areas with large particle fluxes. Indeed, tungsten surfaces exist in recessed areas in the main chamber at the high field side as well as at the low field side,⁸ but the detailed mechanism how the plasma can reach this areas during ICRH has still to be assessed.

C. Disruption behavior

The ITER-like Wall had a significant impact on disruption physics at JET.²⁶ The strong reduction of the C concentration seen from the very first ILW discharges had two direct consequences. First, the onset of the disruptive “density-limit,” the MARFE development, occurs at lower divertor temperatures, well below the optimum temperature for C radiation, and thus it is possible to achieve higher line-averaged plasma densities.²⁷ Second, lower radiation and hence higher temperatures are observed during unmitigated ILW disruptions as can be seen in Fig. 4. This lengthened the current quench phase, increasing the impulse by the electromagnetic disruption force on the vessel. Moreover, a larger fraction of the total energy being conducted to the Be wall which is vulnerable to melting.²⁶ Because of the larger vessel forces and heat loads, active mitigation by massive gas injection (MGI) became a necessity for ILW operations.

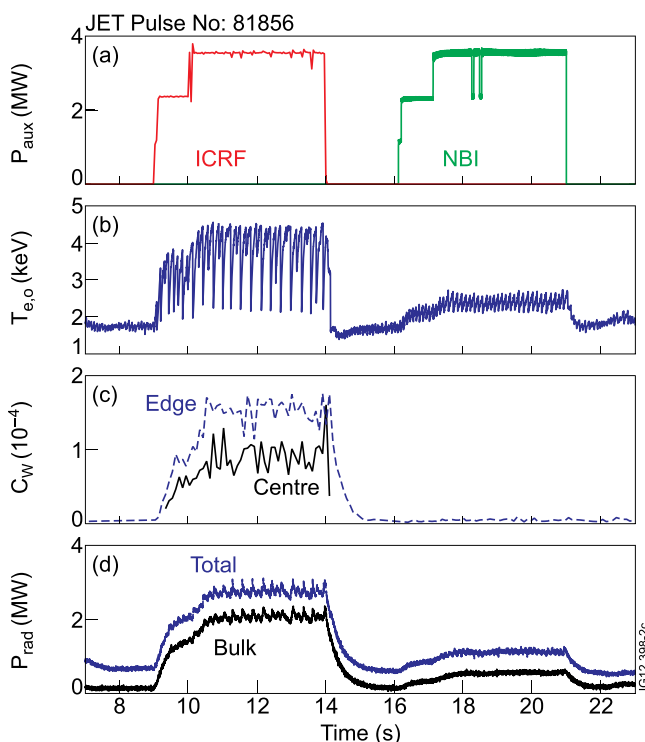


FIG. 3. Behaviour of W content and bulk radiation in the L-Mode discharge 81856 ($B_t = 2.55 \text{ T}$, $I_p = 2.5 \text{ MA}$).

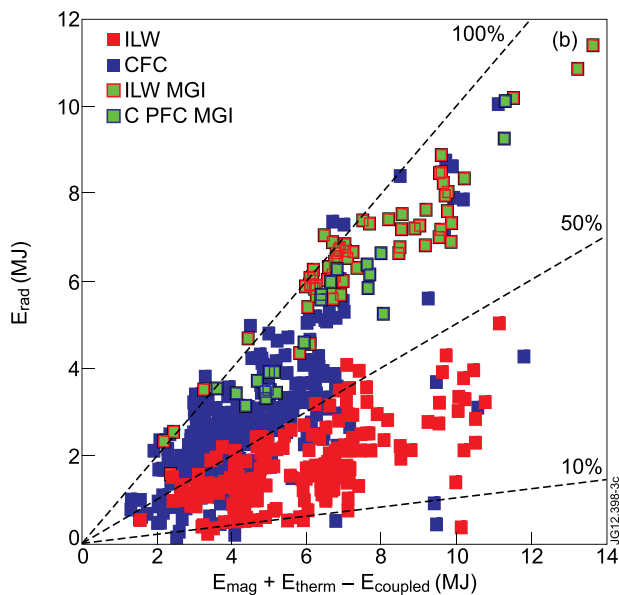


FIG. 4. Radiated energy during the current quench of (un-)mitigated disruption in JET-C and JET-ILW versus the available thermal and magnetic energy (the energy coupled back into the toroidal conductors is subtracted).

For the first time it has been applied as an active protection system at JET.

In Fig. 4 it can be seen that MGI is capable of increasing the radiation fraction close to 100%, thus significantly reducing the fraction of energy conducted to the PFCs and reducing the current quench duration. On the positive side, the longer current quench rates, and thus lower toroidal electric fields have made it more difficult to generate runaway electron beams.²⁸ Disruptions with the ILW, unmitigated and even those mitigated by MGI, were found to have a negligible impact on the following discharge. So far no cases have been found where the plasma formation failed because of deconditioning due to disruptions.

D. Fuel retention

Global gas balance experiments have been performed throughout the first campaigns starting with Ohmic plasmas in the initial phase of divertor operation and finishing with NBI heated H-mode plasmas at the last day of operation. The short term retention, studied *in-situ* by investigating the gas puff levels and neutral pressures, increases in the limiter plasma phase with the Be first wall. However, the outgassing after the discharge over compensates this transient retention.²⁹ The long term retention, i.e., the number of retained deuterium ions in the first wall components per second, has been deduced taking into account the amount of injected D through the gas injection systems and, if applicable, the neutral beam injection, and the number of actively pumped neutrals by the applied pumping systems. The pumped gas is collected by the JET active gas handling system (AGHS), quantified by calibrated pressure measurements, and analyzed for its components by gas chromatography.^{30,31} All experiments were carried out in series of comparable repetitive discharges. A minimum of 9 and a maximum of 34 consecutive discharges were performed, until the number of

injected particles reached approximately the analysis limit of the AGHS. By this procedure, the plasma exposure was maximized and the impact of history effects minimized. The retention rates were obtained by dividing the number of injected particles by the integrated plasma time in divertor configuration reflecting the plasma time with the main ion flux interaction with the divertor PFCs. In order to compare with previously performed reference discharges in JET-C,³² the discharges with the ILW were adapted in input power, magnetic configuration and fuelling rate to match edge plasma conditions, i.e., the density and deuterium ion flux, of CFC references as closely as possible. Apart from the material comparison, the fuelling rate ($1 \times 10^{21} \text{ D s}^{-1}$ to $1 \cdot 10^{23} \text{ D s}^{-1}$), also the auxiliary heating ($P_{aux} = 0$ to 12.0 MW), as well as the ion flux to the divertor ($\Gamma_{ion} = 2 \times 10^{22} \text{ m}^2 \text{ s}^{-1}$ to $2 \times 10^{23} \text{ m}^2 \text{ s}^{-1}$) were varied. All JET-ILW experiments showed low retention rates covering a range of $2\text{--}16 \times 10^{19} \text{ D s}^{-1}$ applying the same analysis as in JET-C and showed high purity of the recovered gas of more than 99.0% D. In L-Mode as well as in H-Mode a reduction of the retention by at least a factor of 10 is deduced which confirms qualitatively the predicted reduction of fuel retention in ITER with Be first wall and W divertor compared with a hypothetical full carbon ITER described in comprehensive studies.³³ The most likely mechanism for the remaining fuel retention in the JET-ILW experiments is co-deposition of fuel in Be-layers which is in line with the measured high Be influx from the main chamber into the inner divertor leg whose plasma-facing surfaces are a net deposition zone. Studies at the linear device PISCES on the fuel content in Be layers showed a ten times lower D content than C layers at 200°C (Ref. 33) which are consistent with the observed reduction. Co-deposition with W is not of importance and implantation is the main mechanism for the retention in W as experiments in AUG confirmed,³⁴ but the W retention plays a negligible role in comparison with the Be co-deposition. Long-term outgassing also observed in JET-C, but being of minor importance due to the higher absolute retention,³⁵ has also been observed in JET-ILW for about 100 h after plasma pulses with the deuterium pressure decaying as $\sim t^{-0.8}$ (Ref. 29) which will lead to a further substantial reduction of the fuel content in the metallic PFCs. Therefore, it is expected that the post mortem analysis of Be and W components will show a significant lower long term fuel content as deduced from the gas balances. The tiles will be retrieved from the vessel during the current vent end of 2012.

III. H-MODE PHYSICS IN AN ALL-METAL ENVIRONMENT

A. L-H power threshold

Dedicated experiments have been carried out to investigate the L-H power threshold in JET-ILW, with I_p/B_t and plasma shape matched to those within JET-C.³⁶ The plasma density was varied from discharge to discharge and slow input power ramps (ICRH or NBI), typically 1 MW/s , were used to measure P_{thr} . In JET-C, at $B_t = 1.8 \text{ T}$, $I_p = 1.7 \text{ MA}$, the threshold power P_{thr} defined as heating power reduced

by dW/dt was found to be consistent with the multi machine scaling law $P_{thr,08}$.³⁷ Conversely, in density scans with the ILW both P_{thr} and $P_{sep} = P_{thr} - P_{rad,bulk}$ (the bulk radiated power) increase below a minimum density, $n_{e,min} \approx 2.2 \times 10^{19} \text{ m}^{-3}$ thus recovering the low density behavior observed with MkII-GB divertor (C wall) as well as in the all metal devices Alcator C-Mod³⁸ and AUG.³⁹ At plasma densities above $n_{e,min}$, P_{thr} is reduced by $\approx 30\%$ and P_{sep} by $\approx 40\%$ in JET-ILW compared to JET-C. A similar reduction of the H-mode threshold has been found in AUG comparing operation with carbon PFCs to that with tungsten PFCs.⁴⁰ The strong influence of the wall change from C to Be/W on P_{thr} and P_{sep} is also observed at 3.0 T/2.75 MA and $n_{e,min}$ increased roughly linearly with B_t , being unfavorable for ITER, which needs to access the H-mode at high magnetic field ($B_t = 5.4 \text{ T}$). At a given edge density, the L-H transition occurs at a lower edge electron temperature, $T_{e,edge}$ with the ILW. In NBI heated discharges, where the ion temperature $T_{i,edge}$ can be measured by edge charge exchange spectroscopy, $T_{i,edge}$ and $T_{e,edge}$ are found to be strongly coupled over the explored density range.

B. Baseline H-mode scenario

In order to allow the reliable and safe operation in high power H-Modes special emphasis was dedicated to the H-Mode scenario development. The main elements were the establishment of a stable current ramp up phase, the avoidance of large ELMs at the entry of the H-mode phase, the optimization of confinement in the flat-top phase, and finally the safe exit from H-Mode and discharge landing — always staying within the material limits given by the metallic wall.⁴¹ Stable Type I ELM sawteething H-modes have been achieved for 4 to 5 s (duration of main heating phase) in low and high δ plasmas, initially at 2.0 MA/2.1 T and then at 2.5 MA/2.7 T with $q_{95} = 3.5$ and above 20 MW of auxiliary

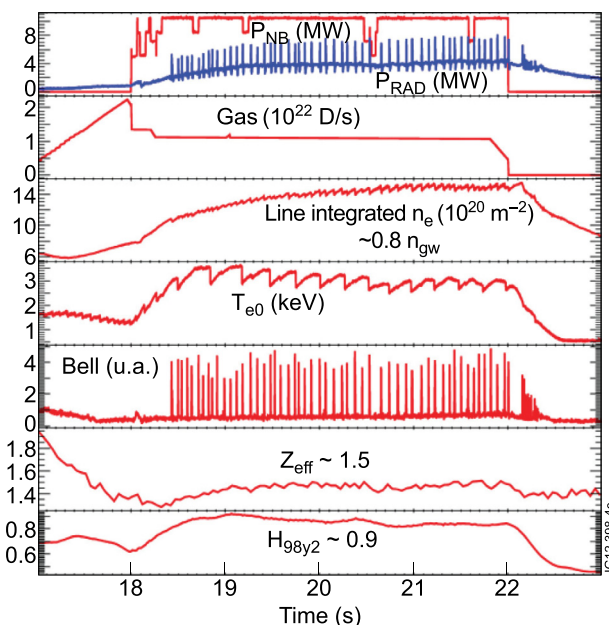


FIG. 5. Stable H-mode discharge (#82122) in JET-ILW with $I_p = 2.0 \text{ MA}$, $B_t = 2.1 \text{ T}$.⁶⁶

power (see Fig. 5). It became clear that deuterium had to be puffed at a significant rate (above 10^{22} D s^{-1}) in the divertor during the main heating phase to achieve stable conditions with respect to central radiation peaking as already shown in AUG.⁴⁰ By increasing the puff rate the ELM frequency increased and a minimum ELM frequency of typically 10 Hz or more was necessary to prevent excessive core plasma radiation arising from W and Ni, which could lead to a back transition to L-mode as the power crossing the separatrix decreases. In this situation, the sawtooth activity did not seem to prevent radiation peaking and even vanished as the temperature became hollow (see Sec. III D). In general, no disruption occurred if the auxiliary heating was maintained, whereas switching off the NBI power in such a case could lead to disruption by a radiation collapse event. The increase of the NBI power combined with strong deuterium gas puffing rate (above 10^{22} D s^{-1}) opened up the operating space by increasing central transport and the ELM frequency and therefore flushing out tungsten from the bulk plasma (see also Sec. III D), as seen in AUG.^{42,43} Since both the increase of the loss power (power crossing the separatrix) and the gas puffing contribute to expel tungsten by increasing the ELM frequency, it was also found that the minimum gas puffing rate decreases with the loss power. However, the high gas puffing rate also deteriorated the confinement of the H-mode (see Fig. 6). At high triangularity ($\delta \approx 0.4$), the H-mode scenario shows a normalized confinement degradation of 10% to 30% with gas puffing which was not observed with the C-wall at a similar level of gas fuelling.⁴⁴ For the lowest fuelling cases, the confinement factor $H_{98(y,2)}$ sometimes approached 1 indicating that $H = 1$ access is possible at $I_p \leq 2.5 \text{ MA}$ (without strong central heating). In an attempt to increase the ELM frequency without increasing the gas

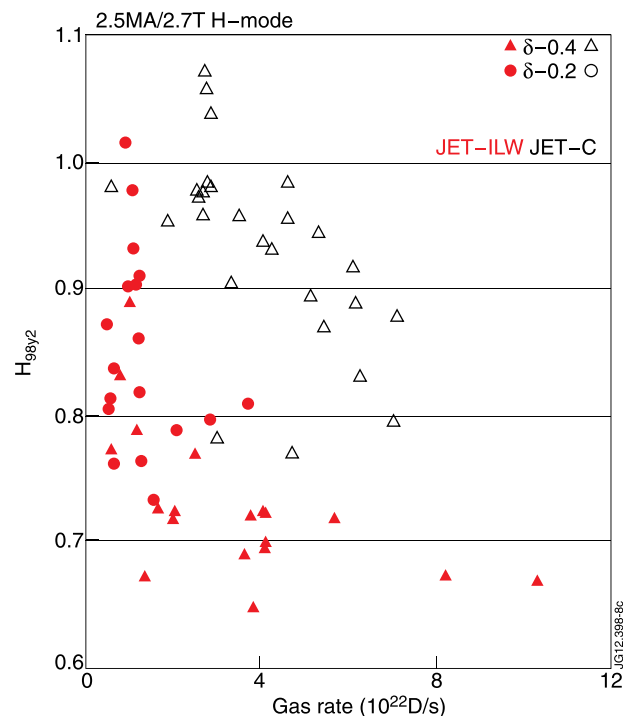


FIG. 6. Confinement factor $H_{98(y,2)}$ in $I_p = 2.5 \text{ MA}$, $B_t = 2.7 \text{ T}$ low- δ (circles) and high- δ discharges versus the gas puffing rate in JET-C (black) and JET-ILW (red, filled).

puffing rate or the heating power, ELM magnetic triggering by fast vertical plasma movements (“vertical kicks”) has been used. The vertical kicks are produced by applying periodically rapid voltage spikes to the coils producing the radial magnetic field. Although the ELM frequency could indeed be controlled at about 30 Hz and the gas rate could be reduced down to $5 \times 10^{21} \text{ Ds}^{-1}$,⁴⁵ the H-factor has not yet been restored to values closer at 1, hinting to another necessary ingredient responsible for the reduced confinement.

Part of the scenario development in JET-ILW was also devoted to the adaptation of the H-mode termination and discharge landing. Because with the ILW the W could accumulate and radiate from the plasma core, switching off the power at termination often resulted in a radiative collapse. This may be explained by the longer residence time of heavy impurities in the plasma than that of light impurities. The use of electron heating (typically $\approx 2 \text{ MW}$ of ICRH) in the landing phase was successful in avoiding disruptions. In this phase, the electron temperature could be increased up to 6 or 7 keV and helped in preventing the radiation collapse.

On the basis of the initial low triangularity ($\delta = 0.2$) H-mode development at 2.5 MA/2.7 T ($q_{95} = 3.5$), the baseline operational domain was extended up to 3.5 MA/3.2 T ($q_{95} \approx 3$). The large gas injection was intentionally used again to stabilize the discharge keeping the ELM frequency above $\approx 10\text{--}20 \text{ Hz}$. Strike point sweeping of about $\pm 6 \text{ cm}$ was successfully applied on the bulk tungsten tile to keep the surface temperature at the tile below 1200°C . Using this cautious approach, plasmas were successfully developed at $\beta_N \approx 1.4$ with 25 MW of NBI power for more than 5 s duration and a Z_{eff} of 1.2–1.3. ICRH power was also coupled successfully up to a level of 3.5 MW during the flattop. An elevation of the core temperature and larger sawtooth activity were clearly observed in the ICRH phase, but there was no clear evidence yet that it had a beneficial effect on the high Z impurity core concentration. In comparison to the C-wall high current scan with the same triangularity, the confinement is consistently lower by 20% to 30% at same the plasma current, q_{95} and shape. Attempts to recover the confinement by lowering the gas injection down to a rate of $2 \times 10^{22} \text{ Ds}^{-1}$ and increasing the heating power to provide $P_{\text{loss}}/P_{\text{th}}$ well above 2 while keeping the ELM frequency above 10 Hz, have not succeeded in recovering more than 10% of the confinement. As a result, the ρ^* and ν^* are still higher by typically 50% and 30%, respectively, than with the C-wall.

C. Hybrid H-mode scenario

The hybrid scenario has also been developed using as references the work carried out in JET-C.⁴⁶ This scenario is traditionally characterized by its access to high normalized pressure ($\beta_N > 2.5$) and no or infrequent sawteeth activity due to its “broad” q -profile shape. The latter is achieved in JET by using the current overshoot technique which helps keeping the central target q value (q_0) close to unity and maximizes the amount of current density at mid-radius. As already found in the baseline scenario, more gas had to be injected in the early phase of the discharge compared to the

experiments in JET-C to achieve the same plasma density although the X-point is already formed after 1.4 s. Too low gas injection resulted in the creation of a run-away electron population and an increased tungsten level. With increased gas injection, the early q profile at the X-point formation was 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 C-wall. Using this I_p overshoot technique, the hybrid scenario has been developed at low δ ($\delta \approx 0.2 - 0.3$) and high δ ($\delta \sim 0.4$) for $q_{95} \approx 4$ at 1.4–1.7 MA/2.0 T and 1.7–2.0 MA/2.3 T.⁴¹ In all discharges, the outer strike point was located on the horizontal divertor bulk tungsten tile (with the C-wall the plasma configuration had a more outward strike point position closer to the pumping louvers). In these attempts, the hybrid scenario could be reproduced showing for about 2 to 3 s similar global performance ($H_{98(y,2)} = 1.1 - 1.3$ with $\beta_N \approx 3$) as achieved in the C-wall at both high and low triangularity, however for the low triangularity at higher density and lower temperature. For both triangularities moderate gas fuelling ($\approx 5 \times 10^{21} \text{ Ds}^{-1}$) was required to keep the discharge stable with regard to core radiation. The hybrid scenario with the ILW had in general similar $m = 1$, $n = 1$ fishbone activity as with the C-wall. However, unlike the experiments in JET-C, continuous $m = 1$, $n = 1$ modes sometimes developed leading to a significant reduction of confinement.⁴⁷ Similarly, the $m = 3/n = 2$ and $m = 4/n = 3$ MHD activities were also observed, leading to a slow decrease of central electron temperature and an enhanced radiation from the plasma core. This is in contrast to observations with the C-wall where such events could be recovered from and did not terminate the discharge in radiative collapse.

The difference in performance between the hybrid and the baseline H-modes is quite obvious but the reasons for this are not yet understood, even though part of the improved performance can be attributed to better core confinement (see Sec. III F). A possible explanation could be that higher confinement is preferably achieved at higher β -values or at an operation further above the L-H threshold (2–3.5 instead of 1.5–2.0 used in the baseline scenario) as there are also hints for this from AUG.⁴⁸ Additionally, the hybrid H-mode scenarios are not run with the same I_p , B_t , and q_{95} as the baseline scenarios and heating deposition and the radiation profiles may be different in these two scenarios.

D. W accumulation

In discharges where too much W enters the plasma core, W accumulation can develop, strongly impacting on the core plasma parameters and the confinement. Fig. 7 shows an H-mode discharge with an ELM-frequency of 10–15 Hz, exhibiting the typical behavior of slow W accumulation. From $t = 9.0 \text{ s}$ onwards, the deuterium gas puff is lowered to $5 \times 10^{21} \text{ s}^{-1}$. Up to $t = 11.5 \text{ s}$ the diamagnetic energy (W_{dia}) does not considerably change, while the radiated power in the main chamber (P_{rad}) continuously increases. Similarly, the core electron temperature (T_e) as measured by electron cyclotron emission (ECE) decreases, while the edge values stay constant (Fig. 7(b)). During the same period, the

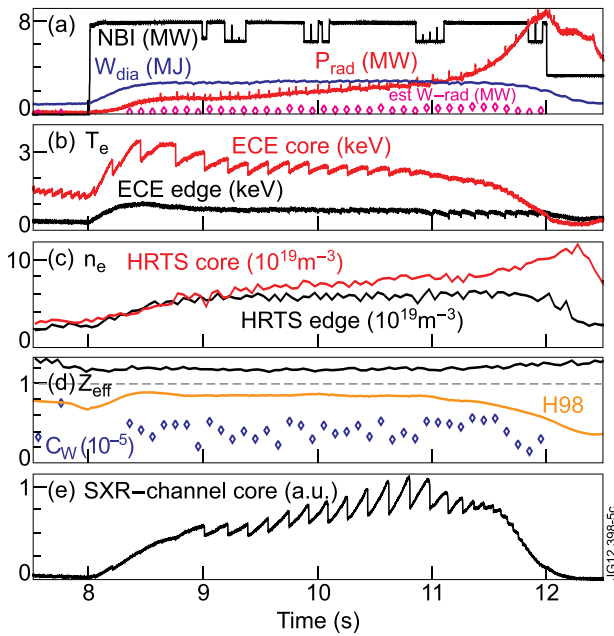


FIG. 7. Evolution of W-accumulation in a $I_p = 2.0$ MA, $B_t = 2.1$ T H-Mode discharge (#81913).

electron density (n_e) (Fig. 7(c)), as measured by Thomson scattering, keeps rising in the plasma core and the edge values stay constant, which implies that the density starts peaking. After $t = 11.5$ s, the core T_e collapses drastically and a steep increase of P_{rad} is observed affecting W_{dia} and correspondingly the H -factor (Fig. 7(d)). As the line averaged $Z_{eff} \approx 1.2$ does not strongly change during the rise of the radiation, medium to high-Z elements must be causing it. However, the W-concentration (c_W) as measured by the spectrometer stays constant throughout. In order to estimate the radiated power due to W, the W-concentration, which is locally measured at a certain radial range, is assumed to apply for the full plasma volume — this estimate is depicted in Fig. 7(a) and labeled *est. W-rad*. The W-radiation seems to be negligible during all phases of the discharge, and thus seems to indicate that W may not be responsible for the rise of the main chamber radiation. However, the spectrometer line of sight is vertical and may be missing parts of the W emissions because of poloidal asymmetries that arise from centrifugal forces. Additionally, the measured W spectral lines in the VUV spectral range yield information from a limited radial region only.²¹ This interpretation is confirmed by Soft X-Ray (SXR) emission profiles revealing poloidal asymmetries, which can be described as a consequence of centrifugal forces acting on strongly rotating W ions⁴⁹ as described earlier in the case of nickel by Wesson.⁵⁰ The asymmetries show up most clearly just outside of the sawtooth inversion radius. Since strong contributions to the SXR signal from other intrinsic impurities can be excluded by auxiliary spectroscopic measurements, the SXR emissions allow for the calculation of the local W-concentrations using an ionization equilibrium neglecting transport. The latter assumption has been shown to be reasonable for W in the core (see Ref. 51) and from the W-concentration the total, local radiated power densities can be derived using the W cooling factor.²² In principle a similar (more direct)

evaluation of the W density and radiation profiles could be performed using radiation profiles measured by bolometry. However, it turned out that the bolometer measurements can be dominated by divertor and edge radiation, making the deconvolution of the core radiation less precise and more prone to artifacts. The deduced strong localized radiation peaking is very characteristic of so-called central impurity accumulation. In Refs. 52 and 53, it was found that impurity accumulation occurs when turbulent transport in the plasma core is weak, and the neoclassical transport becomes important. The cleaning effect of large turbulent core transport is not only based on diffusive effects but also supported by a turbulent outward pinch for the impurities requiring steep temperature gradients.^{54,55} The radiation/heating balance in the core of the presented discharge #81913 (Fig. 7) reveals radiative cooling of similar size as the local heating power thereby decreasing the core T_e and flattening the T_e gradients leading to a feedback loop of decreasing transport and increasing radiation.⁴⁹

This investigation of the local power balance seems to be the key for understanding the accumulation process and the application of mitigation methods. Applying a sufficiently large gas puff ($\geq 10^{22} \text{ s}^{-1}$) decreases the edge temperatures, and thereby the W source and the W penetration. Furthermore, the increase of ELM frequency efficiently expels W from the pedestal region.⁴³ Altogether this leads to a reduction of the W density at the pedestal top, which sets the boundary condition for the core W density. Keeping this level low allows maintaining large enough anomalous transport in the core to suppress the self-amplification of the central accumulation. On the other hand increasing the local heating power in the center (see for example, Refs. 24, 56, and 57) makes the core less vulnerable even at higher impurity/radiation levels.

E. Radiative cooling

With the change to the JET-ILW, a strong reduction of the C divertor radiation was expected (and eventually also found). In order to prepare for this situation, specifically in the presence of the enhanced NBI heating power, an elaborate program on radiative cooling using either N_2 or Ne was conducted in JET-C.^{58,59} Typical for these discharges was a moderate degradation of the confinement (see Fig. 8) with increasing impurity injection. The transition from the type-I to the type-III ELM regime turned out to be the limitation in achieving a large ratio of divertor/X-point radiation over main plasma radiation with an H -factor close to 1.

Similar discharges were repeated in JET-ILW with practically identical shape (2.5 MA/2.7 T) with the aim to characterize the differences between JET-C and JET-ILW.⁶⁰ As described above, the W contamination in the main plasma made operation at low fuelling difficult and high- δ ELMy H-mode at 2.5 MA is restricted to fuelling levels higher than $0.9 \times 10^{22} \text{ Ds}^{-1}$ in contrast to the lowest fuelling of $\approx 0.3 \times 10^{22} \text{ Ds}^{-1}$ in JET-C related studies. Generally, the unseeded discharges in the ILW show a lower radiation fraction and a lower Z_{eff} compared to their JET-C counterpart, when staying above the minimum fuelling level. The measurements

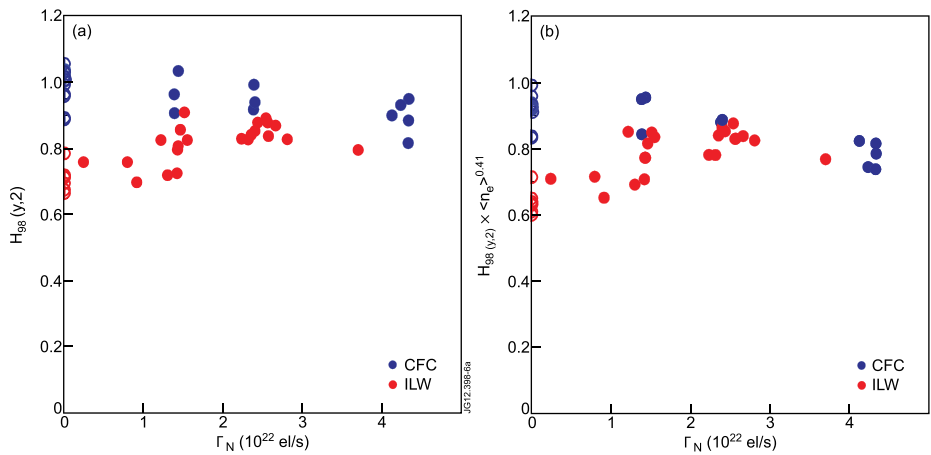


FIG. 8. Normalized confinement versus N_2 -seeding rate: (a) compared with the $H_{98}(y,2)$ scaling and (b) with the density dependence removed from the H98 scaling.

confirm that as nitrogen is injected in the plasma, the divertor behavior similar to the JET-C N_2 -seeded discharges is recovered. In fact, partial divertor detachment is obtained at the N_2 seeding rate of $\approx 2.5\text{--}3.7 \times 10^{22} \text{ es}^{-1}$ and with fuelling rate from 0.8 and $2.9 \times 10^{22} \text{ Ds}^{-1}$ and the electron temperature is then reduced to $\approx 5 \text{ eV}$. Different to JET-C, type-I ELMy plasmas exist in JET-ILW below the critical electron temperature deduced for type-III ELMs in JET-C at high density. In addition to increasing the radiative power and reducing the inter ELM power load, nitrogen seeding has been found to improve plasma energy confinement in high- δ ELMy H-modes by raising the pedestal density and temperature. This leads to H-factors only slightly below their JET-C counterparts as seen in Fig. 8(a). A very good match is found if the density dependence is removed from the IPB98(y,2) H-factor scaling, as shown in Fig. 8(b), since n_e of seeded discharges tends to be higher in JET-ILW than JET-C for the same seeding level. The best N_2 -seeded pulse in JET-ILW yielded $n_e/n_{GW} \approx 1$ with $Z_{eff} \approx 1.5$.

This is the first time in JET that injection of impurities lead to an increase in global energy confinement. It is important to note that the increase in confinement stems from the pedestal and not from an improved energy and particle confinement in the core plasma, since density and temperature peaking remained unaffected. A similar correlation between nitrogen seeding rate and stored energy has already been observed in AUG and is reported to be linked to a positive correlation between H-factor and Z_{eff} (Ref. 48), which is not (yet) found with the JET-ILW.

The JET-ILW results strongly suggest that the carbon impurities played a role in the performance of the high-shape plasma scenario in JET-C. In JET-ILW plasmas the divertor radiative power and the pedestal confinement increase up to values similar to those in the deuterium fuelled JET-C counterparts, as the nitrogen seeding rate is increased. Once the maximum pedestal pressure has been achieved with nitrogen seeding, a further raise in seeding level leads to a decrease in density and a weaker decrease in temperature, very similar to the behavior of plasmas in JET-C with N_2 -seeding. These observations indicate that C level and associated radiation may have been a hidden parameter in the JET-C confinement behavior in high-shape fuelled discharges, and that the injection of N_2 partially recovers this effect. A direct consequence

of the increased edge stability resulting in higher confinement and lower ELM frequency is the tendency for an unstationary behavior similar to that shown for the unseeded case in the Fig. 7. It is, however, important to note that high- δ ELMy H-modes were not stationary in JET-C either. In fact, ICRH was added to neutral-beam heating as an integral part of the scenario for control of density peaking and sawteeth.^{61,62} In the JET-ILW discharge, first test with ICRH heating in this scenario did not show any benefit so far, probably due to the lower available power and the additionally induced W source (see Sec. II B).

Although the confinement improvement was found to be very robust in high δ discharges it could not be reproduced in low- δ configurations. The range of Z_{eff} values covered with the low- δ configuration was from 1.2 to 1.5 and thereby covering the important part of the range covered with high- δ plasmas (1.1–1.8). The reason for this different behavior is not clear, but it reflects to some extent the differences in confinement behavior already observed in D-puffed discharges in JET-C. In course of this investigations on low- δ discharges, vertical target configurations were also tested, whereas in almost all other investigations the outer strike point was positioned on the horizontal bulk W target (“tile 5”). In terms of divertor geometry this configuration is much closer to the ITER configuration. Interestingly the W contamination in the main plasma was much reduced and the operational window seemed to extend to very low fuelling close to levels used in JET-C. Due to the limited amount of discharge time this beneficial behavior could not be investigated in detail but it will be a top priority for the upcoming campaign in 2013.

F. Confinement studies

A JET-ILW scenario confinement database has been constructed with over 400 baseline H-mode (Type I ELMs) and hybrid plasmas.⁶³ This database has been compared with a similar one which was established in JET-C.⁶⁴ In JET-C, baseline ELMy H-mode plasmas achieved good normalized confinement with $H_{98}(y,2) \approx 1$ in un-fuelled plasmas. High triangularity baseline plasmas could be fuelled up to the Greenwald density without significant confinement loss, whereas gas-fuelled low triangularity plasmas showed a

degraded confinement. In the case of the high- δ discharges, the maintained high confinement was attributed to the fact that the gas puff did not degrade the pedestal pressure, but rather decreased the ELM frequency, obviously compensating the increased edge transport. In JET-ILW increased fuelling was required to avoid W contamination (see above). Although there is insufficient overlap in high gas fuelling levels for the JET-C and JET-ILW experiments, the data trend suggests that the low triangularity plasmas show a similar degradation of $H_{98(y,2)}$ with fuelling level in JET-ILW compared to JET-C. However, the confinement in JET-ILW high triangularity baseline plasmas is reduced by 10%-30% over the entire fuelling range (see also Fig. 6). In contrast to the situation in JET-C, the ELM frequency did not drop at higher puffing levels, but rather increased. It has to be noted that the degraded confinement in the high triangularity pulses is not due to an increase in plasma radiation. In the absence of carbon as a radiator, the divertor radiation is reduced in JET-ILW compared to JET-C, and in absence of strong W contamination, the core radiation in JET-ILW is similar or even lower than in JET-C.

The global normalized confinement of the hybrid plasmas in JET-ILW was comparable to that in JET-C for both low and high triangularity hybrid plasmas. In JET-C the achievable confinement was best at low or zero gas fuelling, where $H_{98(y,2)} \leq 1.4$ was achieved for both low and high triangularity. In JET-ILW zero gas puffing was not achievable due to the need to mitigate W accumulation. However, since the heating power in the hybrid scenario was rather high (≈ 20 MW) and the plasma current was rather low ($I_p \leq 2$ MA) to achieve high β , lower gas puffing levels than in the baseline scenarios could be used, revealing similar confinement as the JET-C experiments at similar fuelling levels.

The main reason for the confinement reduction in plasmas in JET-ILW is the reduction in pedestal pressure, which sets the boundary condition for the core. In the hybrid plasmas, where also some loss of pedestal confinement was observed, it was compensated by a steepening of the core profiles, and as a consequence the global confinement approached that achieved in JET-C (see above). In the absence of ion temperature measurements $T_i = T_e$ is assumed. This is justified by the relatively high plasma densities in baseline JET-ILW plasmas, such that the ion-electron heat exchange time is low compared to the energy confinement time — but this needs to be verified with actual T_i measurements when available. Obviously, the role of plasmas shaping and particular the triangularity in setting the edge stability has reduced in JET-ILW — at least for the investigated plasma configurations. The high triangularity plasmas are more strongly affected by the change in wall material than the low triangularity plasmas, since they obviously lost their distinct behavior concerning the pedestal stability and ELM behavior. Therefore, it seems that the change in the edge impurity composition has a stronger effect on the edge stability when the triangularity is increased. An increased Z_{eff} in the pedestal region leads to ion dilution and affects the edge current distribution. Replacing carbon with nitrogen as a divertor impurity can indeed affect the pedestal

confinement indicating the importance of the role of the impurity composition (see Sec. III E) specifically in high triangularity plasmas, which were degraded more strongly with the ILW. The role of edge impurities on the pedestal stability remains to be studied, but the absence of C as an edge impurity seems to be a good candidate to explain the observed differences in JET-C and JET-ILW. Furthermore, the core profile stiffness can be affected by the core rotation and/or rotation gradients,⁶⁵ which may have changed due to the different energy mix of the NBI particles. However, no rotation profiles are available yet and a detailed study of core profile stiffness will be conducted as soon as measurements are available.

IV. SUMMARY AND CONCLUSIONS

With first operation with the ITER-like wall in JET many results achieved in Alcator C-Mod and ASDEX Upgrade could be confirmed, but also new aspects due to the ITER-like material mix were observed. The first result achieved was the documentation of the strongly facilitated conditioning, allowing the device to be run throughout the campaign without glow discharge or any other surface conditioning. This is reflected also in the very reliable breakdown over a much larger density range compared with C PFCs. The reason for this very beneficial behavior can be found in the very low C and O content documented by spectroscopic and Z_{eff} measurements and low levels of retained gas which make control of the initial density much easier with ILW. The absence of C as a radiator is also found during unmitigated disruptions, leading to a low fraction of radiated energy during the thermal quench. Consequently, rather high plasma temperatures prevail after the thermal quench resulting a very slow current decay, large reaction forces on the vessel and rather high localized power loads. The use of massive gas injection strongly increases the radiated energy as well as reducing the reaction forces in both cases to levels observed in mitigated disruptions in JET-C. The D retention is reduced by at least a factor of 10 in all investigated scenarios, which is consistent with earlier estimations. The absolute amount of the retained D is being deduced in post mortem investigations of tiles recently retrieved from JET at the end of 2012. Comprehensive investigations have shown a significantly lower L-H threshold than in JET-C as well as distinct minimum density below which the threshold rises again, different to results in JET-C but similar to earlier results in JET with the MK II - gasbox divertor configuration as well as from Alcator C-mod and ASDEX Upgrade. ICRH has proven a similar heating efficiency as NBI in L-Mode discharges however an increased level of W and Ni is observed during ICRH despite the higher central temperatures reached. The sources for this increase have not been identified yet but the temporal behavior of the recovery of the impurity level after a Be evaporation hints of the fact that remote areas not directly exposed to large plasma fluxes strongly contribute to the impurity source. This observation is particularly important because it suggests that in ITER the ICRH induced W source will not play a dominant role since the whole main chamber is covered by Be. In addition, the

distinctively different behavior to the ASDEX Upgrade, where the antenna limiter itself was identified as the main source, provides useful information for antenna optimization. As expected, the operational space in H-Mode was reduced compared to the operation of JET-C. Most importantly, no H-Mode discharges could be performed with zero gas-puffing. Although this denies access to low density edge conditions, it provides a focus on operation schemes accessible with gas-puffing which will be also a prerequisite for ITER and DEMO. The counter measures developed earlier in ASDEX Upgrade for the prevention of W accumulation were mostly confirmed although a significant reduction of the central W concentration in H-Mode through the application of ICRH has not been achieved. The most striking effect with the JET-ILW was the lower pedestal confinement observed in comparable discharges. There is no evidence that this is caused by W radiation. On the contrary the discharges showing a good (pedestal) confinement tend to have a higher W concentration and W bulk radiation, due to improved particle confinement than similar discharges with lower confinement. At the moment there is no theory or modeling based explanation for this degradation. An important experimental observation comes from nitrogen seeding experiments which allow to recover most of the confinement in high δ discharges by leading to increased pedestal temperatures. Since nitrogen radiates at similar temperatures to carbon it may play the role of a surrogate for the missing C in the plasma edge.

In its first year of operation, the JET ITER-like Wall experiment has achieved important results for the operation of ITER. Although not all of the results provide a positive scaling towards ITER, none of them is seen as a show stopper. Some of the surprising results may even give rise to new theoretical insight in confinement physics. As part of the stepwise approach foreseen from the very beginning of the ILW the next campaigns will concentrate on the expansion and exploration of the full operational range of JET, allowing more than 30 MW of auxiliary heating power.

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