EFDA–JET–CP(12)02/43

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** See annex of F. Romanelli et al, "Overview of JET Results",*
(23rd IAEA Fusion Energy Conference, Daejon, Republic of Korea (2010)).

Preprint of Paper to be submitted for publication in Proceedings of the
20th International Conference on Plasma Surface Interactions , Eurogress, Aachen, Germany
21st May 2012 - 25th May 2012

ABSTRACT
The residual carbon content and carbon edge flux in JET have been assessed by three independent diagnostic techniques after start of plasma operation with the ITER-Like Wall (ILW) with beryllium first wall and tungsten divertor: (i) in-situ measurements with optical spectroscopy on low ionisation stages of carbon, (ii) charge-exchange recombination spectroscopy as soon as neutral-beam heating was available, and (iii) residual gas composition analysis in dedicated global gas balance experiments. Direct comparison experiments in Lmode discharges were carried out between references from the previously installed material configuration with plasma-facing components made of carbon-fibre composite (JET-CFC) and the JET-ILW. The temporal evolution of the C divertor flux since installation of the ILW has been studied in the ohmic phase of dedicated monitoring discharges which have been executed regularly throughout the experimental exploitation so far (60000 plasma seconds). The C divertor flux behaviour in the divertor can be divided in three phases: initial fast drop, moderate reduction phase, and a long lasting phase with almost constant C flux. The Be flux in both divertor legs mirrors the behaviour of C. All experiments and diagnostic techniques demonstrate a strong reduction in C fluxes and C content of more than one order of magnitude with respect to JET-CFC which is in line with the reduction in long-term fuel retention due to co-deposition. There is no evidence of an increase in residual carbon in time, thus no indication that a damage of the thin tungsten coatings on CFC substrate in the divertor occurred.

1. INTRODUCTION
The ITER-Like Wall (ILW) with Plasma-Facing Components (PFCs) made of beryllium in the main chamber and tungsten in the divertor [1] was successfully installed in 2010/11. Since then, successful plasma operation starting in ohmic conditions and leading to H-mode discharges with stepwise increase of input power up to $P_{aux} = 25MW$ has been executed [2]. A key issue of the JET ILW experiment is, apart from the demonstration of full plasma compatibility with the W divertor, the reduction of the long term fuel retention with respect to the previous conditions with all PFCs made of Carbon-Fibre Composite (CFC). The codeposition of fuel with carbon has been identified previously as the predominant mechanism responsible for the long term retention [3] and has been found in particular in remote areas in the divertor caused by stepwise transport of C [4,5]. The replacement of the first wall from JET with carbon walls (JET-CFC) to the full metallic JET (JET-ILW) was performed in one shutdown extracting the carbon-based plasma-facing components. Apart from the outer-target plate which is made of bulk W lamellae, a substantial amount of CFC-based armor is still used in the divertor, coated typically by 20μm of W at the plasma-facing side [6] providing a potential reservoir of C in the vessel. Moreover, no active cleaning of plasmarecessed areas, made in particular of inconel, took place during the vessel opening.

With respect to carbon, the questions of interest are: (i) to which extent are the C fluxes and concentrations reduced, and (ii) where is the remaining C deposited and mixed with Be. The latter is eroded at massive Be limiters and migrates to the divertor [7]. But only the combined use of in-situ methods and ex-situ post mortem analysis will give the complete answer. The temporal evolution of C fluxes, concentrations and distribution with operational time and increasing input power is of vital importance to interpret ILW experiments. Here, we concentrate on in-situ methods and compare the different C-related quantities with references obtained in dedicated reference discharges prior to the first wall exchange [8]. Three independent techniques have been applied to study in-situ the residual carbon in JET-ILW starting from the first plasma after installation till currently about 60000s of plasma operation with ILW have been executed: (a) photon fluxes by emission spectroscopy in a statistical approach, in reference plasmas, and in newly introduced monitor discharges, (b) concentrations by charge exchange, and (c) concentrations in the gas exhaust collected in gas balance discharges and analysed by the active gas handling system. The major part of experimental analysis relies on optical spectroscopy, but substantial confirmation of the major reduction of C in JET-ILW is given by the other two complementary methods. Overall, all three techniques showed a strong reduction in residual C and are in line with the reduction in long term fuel retention by at least one order of magnitude [9].

2. EXPERIMENTAL RESULTS AND DISCUSSION

- The residual C flux in the plasma edge layer has been studied by emission spectroscopy of low ionisation stages of carbon, i.e. CII and CIII lines in the VUV-VIS range in the main chamber and divertor. To reveal general trends, we first present the shot-to-shot evolution over a long period, covering the phase form the last major opening of JET-CFC since installation of the MKII HD divertor and the first 2500 pulses of JET-ILW. Figure 1(a) shows the photon flux of the CII line (97.1μm) emitting in the scrape-off layer in the main chamber (midplane) shortly after X-point formation. The C flux is normalised to the line averaged density to allow a more appropriate discharge-to-discharge comparison in different magnetic configurations and confinement modes. A drop of the residual carbon edge flux of more than one order of magnitude - on average a factor 20 - is measurable. Also, a decay in the C base level is detectable in the starting phase of ILW operation which shows that a certain plasma fluence is required before an equilibrium is reached [7]. With use of auxiliary-heating in these pure deuterium plasmas, more spreading around an almost constant value starts to appear. It is remarkable, that the C levels of the JET-ILW are only slightly below the levels in the last He campaign in JET-CFC, where only physical sputtering of C by He takes place as no chemical sputtering of C by He does not occur. In figure 1(b) is the variation in Z_{eff} for the same set of plasma discharges depicted. A comparable sharp drop with introduction of the ILW as in the C edge fluxes is also detectable in Z_{eff} which reduces in average from 1.9 to 1.2 with change of the main wall material. This underlines that the C core content is reduced in the same way as the edge flux and confirms that the main plasma impurity and contributor to Z_{eff} changed from carbon to beryllium. The oxygen content is in general low due to the good gettering properties of Be, and the O levels are about one order of magnitude lower in comparison with previous restarts despite an existing air leak [10].

- Apart from this statistical approach, further insight in the changes of the low Z-impurity composition can be obtained from detailed comparison of reference discharge pairs performed before [8] and after installation of the ILW. For this purpose, predominantly L-mode discharges have been executed in order to have best as possible spectroscopic diagnosis and plasma characterisation required for edge modelling - of which details can be found in [11]. Figure 2(a) shows the magnetic configuration of the comparison discharges in JET-ILW and JET-CFC in low triangularity $\delta = 0.2$ at $I_p = 2.5MA$, $B_t = 2.5T$ with additional heating $P_{aux} = 1.8MW$ by neutral beam injection. To match the edge density and temperature as best as possible several density steps have been introduced. Figure 2(b) shows the Brightness of CII at 426.7nm at the outer W target plate for the different density plateaus. The different steps correspond to the low recycling, the high recycling regime, and, in the case of the JET-ILW at highest densities, to semi-detached divertor conditions. The reduction of the CII Brightness at the target plate in the full ionising, high recycling regime is about a factor 20, thus comparable to the average value in the statistical observations in the main chamber emission of CIII. This numbers are in-line with active spectroscopy by chargeexchange recombination observing the CV I line at 529nm [12] which reveal a reduction of the core C concentration from 0.50% to about 0.05% for the medium plasma density phase ($< n_e >= 2.2\times10^{19}$ m^{-2}) with the divertor in the high recycling regime. The C concentration drops below the detection limit of the diagnostic system for higher densities.
- A comparable finding, though with a less pronounced reduction in C, has been obtained in series of L-mode discharges in high triangularity magnetic configuration ($I_p = 2.0MW$, MA, $B_t = 2.4T$, $\delta = 0.4$) which have been executed in the early phase of ILW exploitation and used for gas balance studies. These about 25 identical discharges with moderate radio frequency of 0.8 – 1.5MW have matching references taken in the last JET-CFC campaigns which allow good statistics. In figure 3a are two emission spectra depicted which have been taken at the outer divertor target plate in the spectral range between 424.0nm and 438.0nm covering lines of the main impurities Be, C, CD, Ar and $D\gamma$ as deuterium reference line representing the recycling flux, or equivalent, the impinging ion flux. The reduction of both, the CII emission at 426.7nm and the CD A – X emission with the band head at 431.0nm by a factor 7 and 10, respectively, is clearly visible. In the JET-CFC case, the outer divertor at the near scrape-off layer is a clear net-erosion zone and the CII emission reflects the sum of chemically and physically sputtered C whereas the CD A – C band is a representative of chemical sputtering only [13]. In the case of the bulk W divertor, the CII emissions is predominately caused by the recycling of residual C ions in the plasma at the target plate. The remaining appearance of hydrocarbon radicals indicates a minor contribution from a potential thin and transient layer on top of the W surface. Comparable observations have been made under similar ionising conditions with $T_e > 30eV$ in TEXTOR in the erosion zone of W test limiters, where only a drop of 30% of the CD A – x emission had been detected in comparison to a graphite limiter under identical experimental conditions. The massive reduction by one order of magnitude of CD in the case of JET-ILW with respect to JETCFC indicate that

this sensitive contribution of the transient layer to the total C emission is negligible with respect to C recycling. The mostly intact W surface is confirmed by the measurable W sputtering at the outer target plate, which can be explained for comparable plasma conditions by an impinging flux of 1.5% Be ions [14]. In fact the spectrum in fig. 3a) reveals the Be flux in form of BeII emission at 436.0nm in case of JET-ILW whereas the same line was below the detection limit in the case of normal JET-CFC operation where Be was introduced for conditioning purpose by Be evaporations. Only in reversed field operation one could detect the line in the outer divertor leg due to higher flux of Be from the main chamber. ArII can be attributed to a reservoir of Ar in the W-coatings induced by the production process [6].

Apart from optical spectroscopy the gas composition of the recovered gas has been analysed by gas chromatography in particular concerning hydrogen isotopes and volatile carboncontaining species in both the JET-ILW and JET-CFC discharges. The fraction of residual methane decays almost exponential and varies between 0.60% (first gas collection) and 0.15% (L-mode experiments) which is in all gas balances significantly lower than the fractions measured in JET-CFC which varied between 0.80% and 1.60% depending on the wall conditions. In the case of JET-ILW, the decay is dominated by the reduction of the C content in the plasma with time, which was highest in the first divertor plasmas and reaches a base level in latter experiments, which is likely be determined by the presence of the air leak. Remaining excursions in the methane fraction indicate the sensitivity concerning wall conditions. It should be noted that the discussed discharge comparison in high triangularity was performed in the early phase of ILW exploitation where the base level has not been reached, marked in fig.3b), whereas the previously discussed low triangularity comparison was performed in the phase where the base level was already reached.

- To document the temporal evolution and the impact of wall conditions on the residual C content, dedicated monitoring pulses have been introduced. The same magnetic shape in low triangularity as depicted in fig. 2a has been applied in these pulses at I_p = 2.0MW and B_t = 2.0T which are identical to the first divertor plasmas executed with the ILW [7]. The monitoring pulse has been extended in time and available input power, and apart from the initial limiter and ohmic divertor phase of 4s duration, also L-mode and H-mode phase have been added; each phase of 4s includes a sweep of the strike points for plasma characterisation. Here, we focus only on the ohmic part which is available for all about 100 pulses executed so far. The plasma conditions at the outer-strike point have been measured by a set of Langmuir probes embedded in the target plate and amounts to T_e = 40 and $n_e = 7.5\times10^{18}\ m^{-3}$. Figure 4a shows the time evolution of the flux ratio $\frac{\phi(CII)}{\phi(D_\gamma)}$ (top) and $\frac{\phi(BeII)}{\phi(D_\gamma)}$ (bottom) averaged over typically 1.5s in the ohmic phase for all available monitoring discharges in the outer divertor starting with the first diverted plasma of the ILW. The normalisation to D_γ shall compensate any changes in the transmission of the first quartz window of fibre-coupled spectroscopic system due to local deposition. The integral line-of-sight covers the whole radial extension of the outer divertor plate. The temporal behaviour of the C and Be flux ratios is almost mirrored and three phases can be distinguished. The first 2000 plasma seconds reflect the initial, transient phase which shows a steep decrease in the C edge flux by a factor 3 and increase of the Be edge flux by a factor 2. It reflects the conditioning of the device with the new plasma-facing materials, however, initial conditioning in the main chamber was already done in the preceding limiter plasmas required for commissioning of the control systems. The second phase shows a moderate decrease of C and increase of Be and corresponds to the phase when subsequentially the heating systems have been brought in operation and different magnetic configuration where executed before the monitoring discharge have been executed. The third phase starts around discharge JET Pulse No: 81300 and both the C and Be fluxes in the divertor are almost constant. Figure b) shows the corresponding flux ratios in the inner divertor leg observed by an comparable integral view of the inner divertor which is slightly colder and denser, but still fully in the ionising regime. The temporal behaviour of the flux ratios can as in the case of the outer divertor be divided into three phases, whereas the Be flux in the last phase seems to decrease slightly. Both the inner divertor and the outer divertor show no signature of a systematic fourth phase with increased C levels which would indicate that we would have a substantial damage of the W-coatings on CFC or reached substantial carbidisation as reported in laboratory experiments [6].

The arrows in figure 4a) and b) shall guide the eye, but they well reflect the base levels of Be and C fluxes which corresponds to discharges executed during a normal operational day. Excursions to higher C or lower Be fluxes are mainly due to conditioning effects after breaks, thus, caused by the air leak and i.e. formation of BeO, or non-normal plasma operation in the preceding discharges. This impact can be also seen during the first phase which is shown enlarged in figure 4c) for the outer divertor and two different ionisation stages for carbon. The flux ratios of $\frac{\phi(\mathrm{CII})}{\phi(D_\gamma)}$ with CII at 515nm and $\frac{\phi(\mathrm{BeII})}{\phi(D_\gamma)}$ with CII at 465nm show the same temporal behaviour with a clear decay of the base levels, but increased levels after breaks of more than 9h, thus overnight or over the weekend. Typically, three to four subsequent discharges are required to reach the same base level which is then stable as it can be proven in the case of a gas balance, where the last 34 of the 37 consecutive identical discharges executed in one day show a constant flux ratio. These three to four discharges to reach steady-state conditions are also required in the later phase of operation as it can be seen in fig.4a) and b) at the right-hand side. Here four monitoring discharges where executed in a row and demonstrate an almost vertical drop in C and increase of Be till the base level is reached. This confirms that in particular in phases 2 and phases 3 the variation is dominated by the changes in wall conditions and not by a global increase of C or decrease of Be levels.

3. SUMMARY AND CONCLUSION

Three techniques have been applied to study and quantify the residual carbon content in the first operational phase of the ITER-Like Wall in JET: (i) In-situ measurements with optical spectroscopy in an either purely statistical approach counting every diverted plasma as well as in a set of dedicated comparison pulses between JET-ILW and JET-CFC. The averaged drop of the C edge flux in the main chamber from the statistical approach is about a factor 20 and is in good agreement to the reduction in C fluxes in the divertor measured on reference L-mode plasmas in low triangularity performed after several months of ILW plasma operation. A less pronounced reduction of about a factor 7 in CII emission at the outer target plate has been recorded in the earlier phase ILW exploitation. (ii) With introduction of NBI power, active charge-exchange has been applied to measure the C core concentration in L-mode plasmas. Initial results in the high recycling divertor regime showed strong reduction of the C concentration by one order of magnitude down to 0.05% which is close to the detection limit of the system. (iii) Independent information about the C content is obtained from gas balance measurements with cryogenic pump regeneration and gas chromatic analysis of the recovered gas. The level of hydrocarbons in decays in time starting from 0.60% in the first collection and reaching a base level about 0.15% which is almost one order of magnitude lower than in JET-CFC.

Overall, all three techniques showed a strong reduction in the C fluxes and C content of more than one order of magnitude and are in line with the reduction in long term fuel retention by one order of magnitude which is presented in a separate paper [9]. The long term temporal evolution of the C flux in the divertor has been investigated with the aid of comparable monitoring discharges and three phases have been identified during the first year of ILW operation: initial fast drop (ohmic campaign), moderate reduction (L-mode campaign), and the current phase of almost constant C flux (all different plasma conditions). The Be flux in both divertor legs mirrors the behaviour of C. Substantial variation of the base levels in both C and Be have been detected after periods (> 9h) of non-operational time.

The question of the origin of the C in the full metallic JET-ILW remains: No active cleaning of the vessel walls took place before installation of the new wall components which led to an initial inventory of C in the device [2]. The complex conditioning procedure with baking and deuterium glow discharges reduced, as reported in [10], this initial carbon content, however, still residual C is present at the first wall before first tokamak plasma operation took place. The initial source reduced with plasma operational time resulting in the observed first phases with C flux decay measured by spectroscopy and residual gas composition analysis. In parallel, the Be flux increased due to erosion at the Be limiters and subsequent local re-deposition as well as transport into the divertor and co-deposition on W. Moreover, air leaks contributed via CO2 to the C source which is particularly pronounced after longer periods without plasma operation where the gettering properties of the active Be surfaces are already saturated by the formation of BeO.

Secondly, installation of the new plasma-facing components provides a potential source of C in the vessel. On the one hand, C is an impurity in the percentage range (max. 6%) in the W-coating [6] which might explain the slight deviation of the mirrored behaviour of C and Be in the inner divertor made completely of W-coated CFC. On the other hand, the CFC base structure of the plasma-facing components provides a potential source of C as e.g. the backside are not coated. The sum of these sources defines the currently constant low base level of C edge flux and C concentration in the plasma of less then 0.1%. There is currently no indication that a significant damage of the thin W coating has occurred or that W coating has been transformed to WC with plasma and heat exposure. Future monitoring discharges will reveal when the W-coatings lifetime is consumed leading to release of a substantial amount of C to the plasma.

ACKNOWLEDGEMENTS

This work, supported by the European Communities under the contract of Association between EURATOM/FZJ, was carried out within the framework of EFDA. The views and opinions expressed herein do not necessarily reflect those of the European Commission

REFERENCES

[1]. V. Philipps et al., Fusion Engineering and Design **85** (2010) 1581
[2]. G.F. Matthews et al., this conference
[3]. G.F. Matthews et al., Journal of Nuclear Materials **337-339** (2005) 1
[4]. S. Brezinsek et al., Journal of Nuclear Materials **337-339** (2005) 1058
[5]. A. Kirschner et al., Journal of Nuclear Materials **337-339** (2005) 17
[6]. C. Ruset et al., Fusion Engineering and Design **84** (2009) 1662
[7]. K. Krieger et al., this conference
[8]. S. Brezinsek et al., Journal of Nuclear Materials **415** (2011) S936
[9]. T. Loarer et al., this conference
[10]. D. Doaui et al., this conference
[11]. M. Groth et al., this conference
[12]. M. von Hellermann et al. Plasma Physics and Controlled Fusion, **37** (1995) 7194
[13]. S. Brezinsek et al., Physica Scripta **T145** (2011) 014016
[14]. G. van Rooij et al., this conference

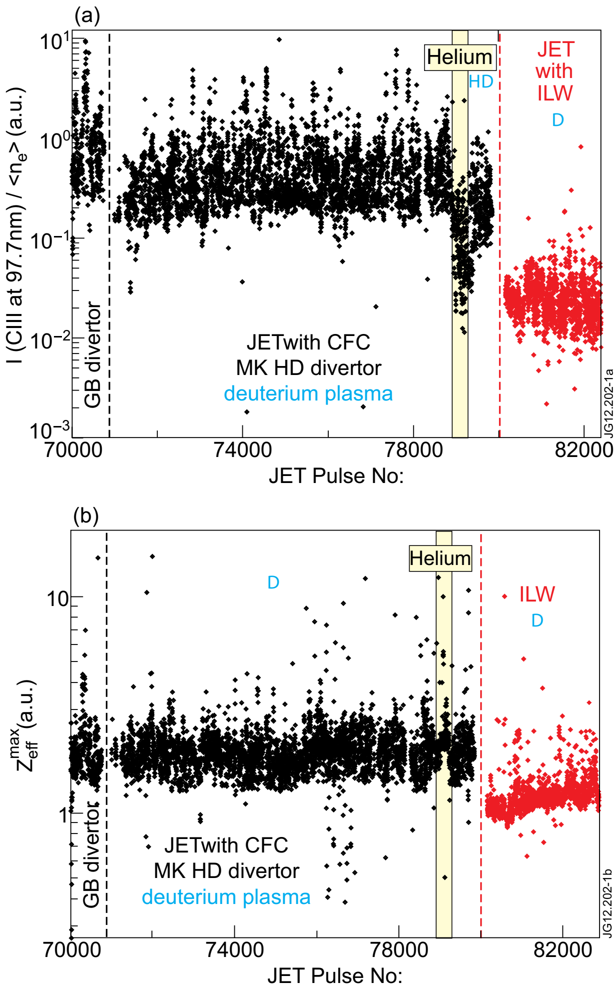

Figure 1: a) Long term evolution of C^{2+} in the plasma edge layer in the main chamber. The JET operation with CFC walls and MKII HD divertor is performed in the pulse range JET Pulse No: 71000–80000 followed by plasma operation with ILW from JET Pulse No: 80300 on. The CIII emission at 97.7nm is normalised to the line averaged density, recorded with an edge channel of the interferometer, and time averaged over 0.5s after the X-point formation. b) The evolution of Z_{eff} for the time period and integral used for CIII confirms the exchange of the main plasma impurity from C to Be with introduction of the ILW.

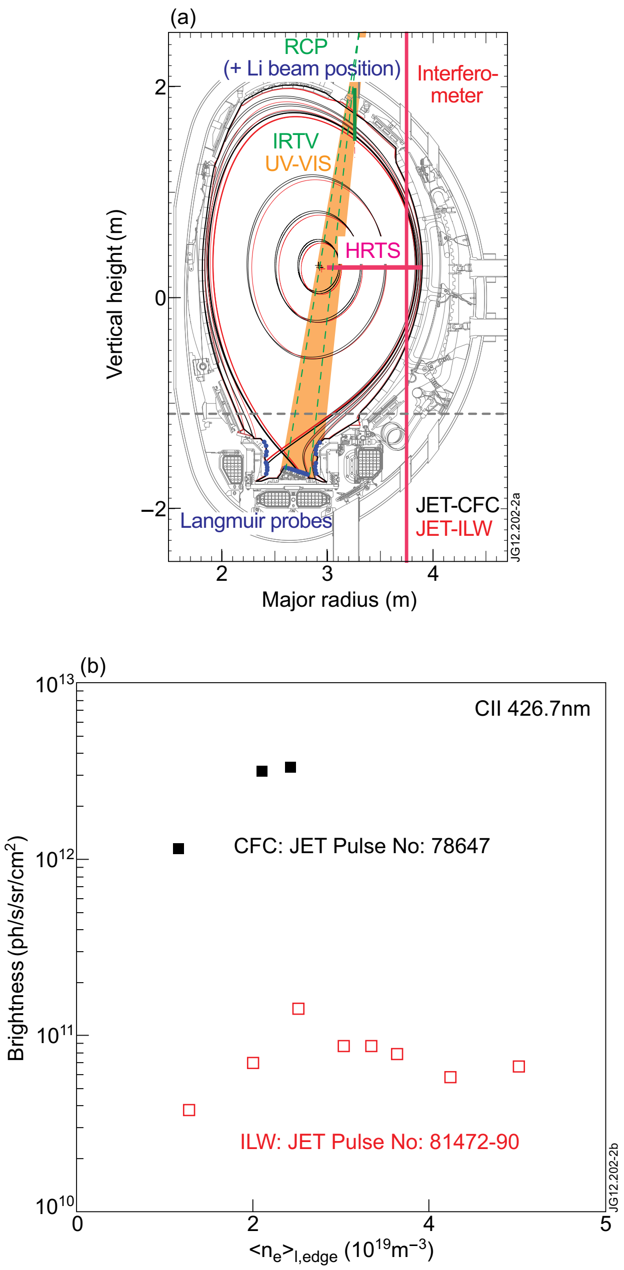

Figure 2: a) The low triangular magnetic configuration used in the comparative, matching L-mode plasmas in JET-CFC and JET-ILW with several density steps at I_P = 2.5MAand B_t= 2.5T as well as in the monitoring pulse introduced in JET with start of ILW operation. The position and the lines-of-sight of spectroscopic systems used for the comparison are marked; the direct imaging divertor spectroscopy has been employed to compare the outer divertor carbon influx measurements. b) The integral CII brightness at the outer divertor target plate made of carbon-fibre composite (JET-CFC) and massive tungsten (JET-ILW) in the set of comparative L-mode plasmas after approximately 5 months of ILW operation.

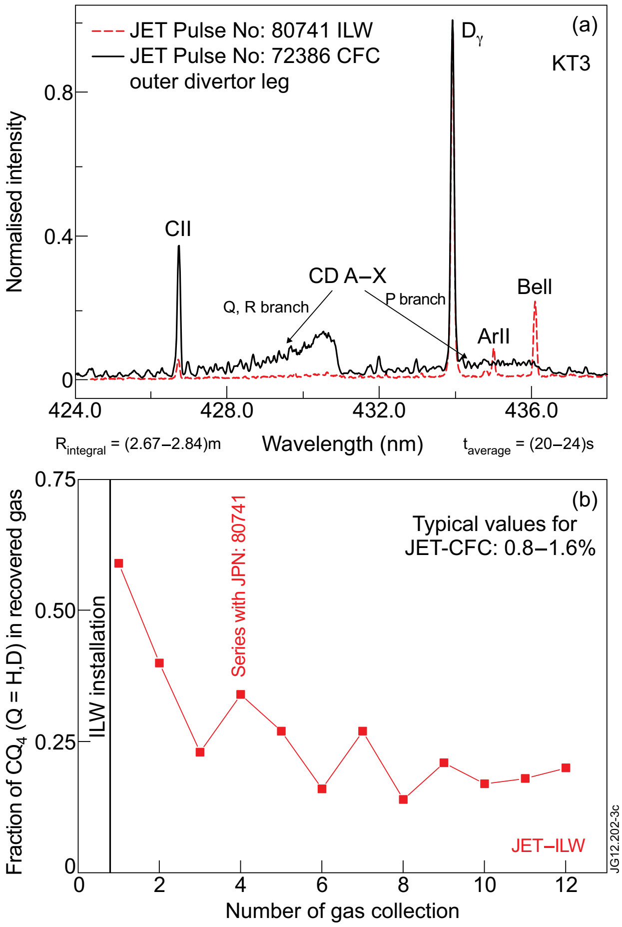

Figure 3: a) Emission spectrum in the spectral range between 424nm and 438nm at the outer target plate in two L-mode comparison pulses (Ip = 2.0MW, Bt = 2.4T) in high triangularity with moderate auxiliary power by radio frequency heating (0.5 – 1.5MW). The CII emission at 426.7nm and the he CD (A –X band) emission dropped by more than a factor 7, respectively 10, in the early ILW operational phase with respect to JET-CFC. b) Residual methane fraction in the collected gas from a series gas balance experiments with composition analysis by gas chromatography.

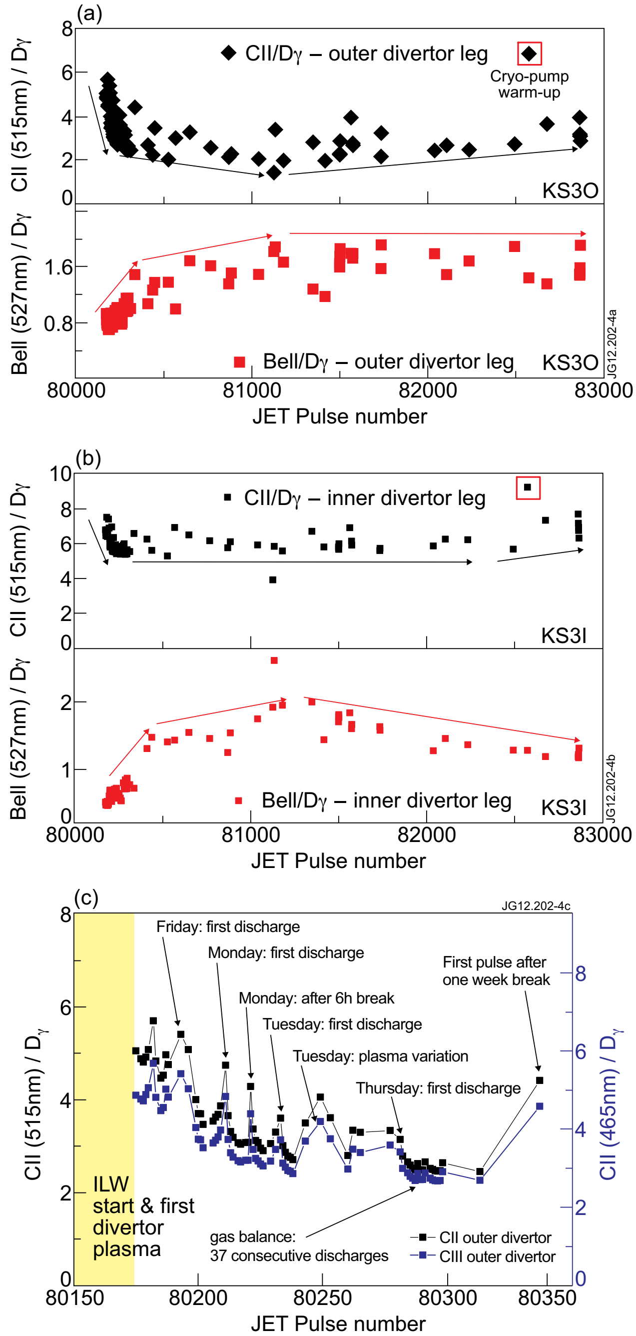

Figure 4: Be and C fluxes in the divertor during the ohmic phase of the monitoring pulses.The temporal evolution of the flux ratios CII to Dγ, respectively Be II to Dγ, in the outer (a) and inner divertor (b) is mirrored under the fully ionising plasma conditions at both legs. The lower envelope for C and the upper for Be represent the long term behaviour whereas transient excursions are related to changes in wall conditions. c) The decay of CII intensity at 426.7nm and CIII intensity at 465.0nm during the first campaign is overlaid by transient excursions after breaks in operation and, thus, impact of the air leak.