Fuel Retention in Discharges with Impurity Seeding after Strong Be Evaporation in JET

S. Brezinsek 1), T. Loarer 2), K. Krieger 3), S. Jachmich 4), M. Tsalas 5), I. Coffey 6),
T. Eich 3), W. Fundamenski 6), C. Giroud 6), S. Grünhagen 6), A. Huber 1), U. Kruezi 1),
S. Knipe 6), G.P. Maddison 6), K. McCormick 3), A.G. Meigs 6), Ph. Morgan 6),
V. Philipps 1), G. Sergienko 1), R. Stagg 6), M.F. Stamp 6), and JET EFDA Contributors*

JET-EFDA, Culham Science Centre, Abingdon, OX14 3DB, UK
1) Forschungszentrum Jülich, Institute of Energy Research - Plasma Physics
EURATOM Association 52425 Jülich, Germany
2) CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France
3) Max-Planck-Institut für Plasmaphysik, EURATOM-IPP, D-85748 Garching, Germany
4) Association Euratom-Etat Belge, ERM-KMS, Brussels, Belgium
5) Association EURATOM-Hellenic Republic, NCSR "Demokritos", Attica, Greece
6) EURATOM/CCFE Fusion Association, Culham Science Centre, Abingdon, Oxon,
OX14 3DB, UK

E-mail contact of main author: s.brezinsek@fz-juelich.de

Abstract. Preparatory experiments for the ILW were carried out to simulate the massive Be first wall by a thin Be layer, induced by evaporation of 2.0g Be, and to study its impact on fuel retention and divertor radiation with reduced C content and N seeding. Residual gas analysis reveals a reduction of hydrocarbons by one order of magnitude and of O by a factor 5 in the partial pressure owing to the evaporation. The evolution of wall conditions and the increase of C radiation with constant N radiation have been studied in a series of ELMy H-mode plasmas (2.7T, 2.5MA, P=16MW) whereas a non-seeded reference discharge was executed prior to the evaporation to document the initial wall fluxes. The Be flux at the midplane, measured in-situ by spectroscopy, increased by a factor 20 whereas the C flux decreased by ~50% in the limiter phase of the first discharge. Erosion of the Be layer and partial coverage with C takes place quickly. To make best use of the protective Be layer, only the first 4 discharges were employed for a gas balance analysis of the D and N inventory. The major fraction of the recovered gas is D which leads to a retention rate of $1.94\times10^{21}\mathrm{Ds}^{-1}$ - comparable to rates with C walls under similar plasma conditions. But the Be evaporation provides a non-saturated surface with respect to D and short term retention is not negligible in the balance; the measured retention rate is overestimating retention with respect to steady-state conditions. Moreover, C was only moderately reduced and continuous co-deposition with eroded Be and C occurs. 3.0% of the gas recovered is N; representing a legacy equivalent to 30% of injected N. The lower C content leads only to a minor reduction in divertor radiation as the reference phase prior to seeding indicates. N adds to the radiation of D and remaining C and the N content rises due to the legacy effect. Also C radiation increases with exposures time, and both contributors causing an increase of the radiation fraction in divertor from 50% to 70%. The radiation pattern suggests that N dominates the increase in the first discharges.

1. Introduction

ITER will operate in the non-active phase with plasma-facing components (PFCs) made of Be for the main chamber, carbon-fibre composite (CFC) for the divertor target plates, and W for the divertor baffle and dome area. The divertor foreseen for the activated operational phase will be made purely of W. The replacement of CFC by W is governed by the need to remain within the safety limit for the in-vessel tritium inventory, and thus, to minimise the tritium retention which is in carbon-dominated machines determined by co-deposition in layers in remote and partially inaccessible areas. A drawback of the exchange is the loss of intrinsic C

---

[*] See the Appendix of F. Romanelli et al., paper OV/1-3, this conference

radiation in the divertor and the need of extrinsic impurity seeding to achieve a radiating divertor and detached plasma operation which is necessary for divertor integrity. In the ITER-Like Wall (ILW) experiment at JET [1], replacement of PFCs made of CFC by massive Be in the main chamber and W in the divertor will be done, providing an ideal test bed for ITER.

Preparatory experiments for the ILW were conducted with the current PFCs made of CFC aiming on the one hand on reference plasmas to document the fuel retention and the material migration to remote areas, and on the other hand to develop wall-compatible plasma scenarios with respect to power handling and material erosion [2]. In particular impurity seeding has been identified to be mandatory to assure integrity of the PCFs made of W by sufficient divertor radiation. Plasma scenarios with nitrogen and neon seeding were developed [3] providing compatibility with the envisaged engineering limits for the PFCs, in particular for the outer target plate [4] and will allow repetition of the discharges with the ILW. However, the total divertor radiation in these experiments represents not solely radiation from the seeding species but always a combination of seeding species and carbon whereas the contribution from the seeding species to the total radiation has been varied extensively [5].

Here, we report on a specific ILW preparatory experiment which was carried out to simulate the massive Be first wall by a thin Be layer, induced by a massive Be evaporation, and to study its impact on fuel retention and divertor radiation with transiently reduced C content. Additionally, impurity seeding with N was applied in order to compensate for the transient loss in C radiation, thus, the experiment is to a certain extend complementary to [5], providing constant extrinsic impurity radiation with increasing C radiation due to re-erosion of the protective Be layer. Though a massive Be evaporation [6] provides only a transient and inhomogeneous coverage of the first wall, it can still be seen as a first small step on the way from a CFC to a Be first wall, providing an outlook on what can be expected from the ILW.

Characterisation of the Be evaporation and quantification of the achieved C suppression is described in section 2. The evolution of the wall conditions and the increase of C radiation in time with constant N injection rate have been studied in a series of comparable plasmas in fixed magnetic configurations. The target scenario in standard type I ELMy H-mode was developed in [3] to be compatible with ILW engineering limits. The D_2 fuelling and N_2 seeding rate have been chosen deliberately to achieve electron temperatures (T_e) at the outer target plate which will inhibit physical sputtering and minimise W erosion in the ILW divertor. The plasma conditions in the core and at the outer target for both parts of the experiment, gas balance analysis and study of the nitrogen contribution to the divertor radiation, are presented in section 3. Section 4 deals with the gas balance study with the active gas handling system (AGHS) at JET [7] providing a detailed balance of the injected and retained fuel and impurity gas. Moreover, the characterisation of the nitrogen legacy and the impact of N on C erosion with variation of the seeding location are discussed. The variation in the total impurity radiation and radiation distribution with increasing plasma exposure time are discussed in section 5. Finally, conclusions are drawn with respect to the ILW in section 6.

2. Be evaporation

Four Be evaporator heads were inserted near the vessel midplane and operated at temperatures between 920° and 960°C in vacuum for a cumulated duration of 8 hours. In total about 2.0g of Be was evaporated from the four point-like sources equally distributed in toroidal direction. This corresponds to an equivalent Be deposit of about 12nm layer thickness on the first wall though toroidally and poloidally inhomogeneous distributed. The layer thickness was extrapolated from a time-resolved deposition measurement during a Be evaporation at a different head temperatures, recorded in-situ by a QMB positioned on the outer divertor apron. Simulation of the poloidal distribution of Be deposited on the first wall and subsequent erosion by plasma impact under different plasma conditions is presented in detail in [8].

A reference discharge prior to the Be evaporation discussed here was executed to document the initial influx levels of impurities such as oxygen, hydrocarbons and carbon with optical spectroscopy. Prior to the evaporation a residual gas analysis RGA was performed and the gas composition in the vacuum vessel determined. The RGA reference spectrum is depicted in fig. 1a) and shows apart from the dominant deuterium mass substantial contributions of $C(H,D)_x$, $C_2(H,D)_y$ and $C_3(H,D)_z$ group, remaining the cracking pattern of deuterated water as well as contributions from oxygen and carbon mono- and dioxide. A RGA scan recorded after execution of the Be evaporation just prior to the first plasma is depicted in fig. 1a, too.

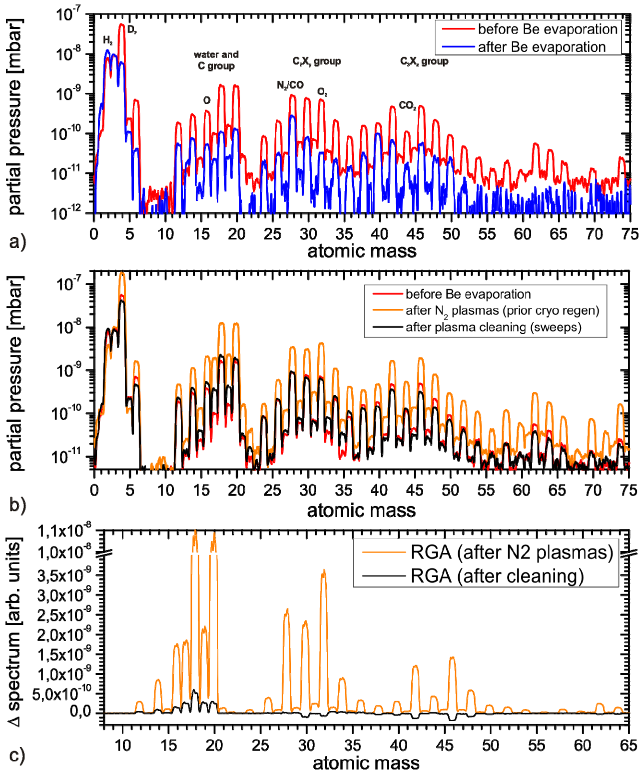

FIG. 1(a) RGA spectrum prior and post Be evaporation. Strong reduction of hydrocarbons, water, and oxygen can be detected after the evaporation. (b) Comparison of spectra taken after a reference discharge, after four consecutive plasma discharges with nitrogen seeding and after a cleaning discharge without seeding but with strike-point sweeping. (c) Corresponding difference spectra.

A substantial reduction of all groups of deuterated hydrocarbon by about one order of magnitude in the partial pressure after applying the evaporation is detectable revealing a significant coverage of the CFC and carbon layer surfaces with Be. Moreover, the gettering of oxygen can additionally be observed by a further reduction of the corresponding masses 32 and 16, partially masked by hydrocarbons, of about a factor 5. Less reduced is mass 40 representing mainly Ar which remains almost unaffected in the residual gas in the vessel.

The Be erosion flux measured by optical spectroscopy of BeII at 436.0nm at the midplane was increased by a factor 20 whereas the corresponding C flux, measured by CII at 426.7nm, decreased only by ~50% in the limiter phase of the first discharge with respect to the reference discharge. However, erosion of the Be layer and partial deposition by C occurs on a short timescale, and in the first 4 discharges (~120 plasma seconds), which have been used for the gas balance study, already the Be flux in the limiter phase is decreased and lays only about a factor 5 above the initial value; the C erosion flux increases in the same time to about 60% of the reference. The decay of the Be flux in time is stronger than in previous experiments with Be evaporation in L-mode plasmas without limiter phase and larger wall clearance [6].

3. Plasma scenario and outer target plasma conditions

The chosen target scenario for the experiment was a standard fuelled ELMy H-mode (2.7T, 2.5MA, q_{95}~3.5, P_{in} =16MW, δ~0.4, f_{gw}~0.95, ΔW_{ELM}~ 100kJ) which has been developed in [3]. The D_2 injection (Γ_{D2}=1.85x10^{22}e/s) and N_2 injection rate (Γ_{N2}=3.55x10^{22}e/s) into the divertor were chosen deliberately to achieve peak T_e at the outer strike point below 10eV which will minimise the W sputtering in the divertor of the ILW by all remaining impurities (C, N, O etc.). In fact the fuelling rate was even slightly raised with respect to the reference value to achieve the requested high recycling/partial detachment regime at the outer target in order to compensate for expected changes in the wall recycling. Fig. 2 shows time traces for D_α, the N_2 seeding rate with injection into the outer scrape-off layer (SOL), the density normalised to the Greenwald density as well as the total input power, the radiated power and the confinement factor. A short phase prior to the seeding has been used to follow up the N content in the wall from discharge to discharge.

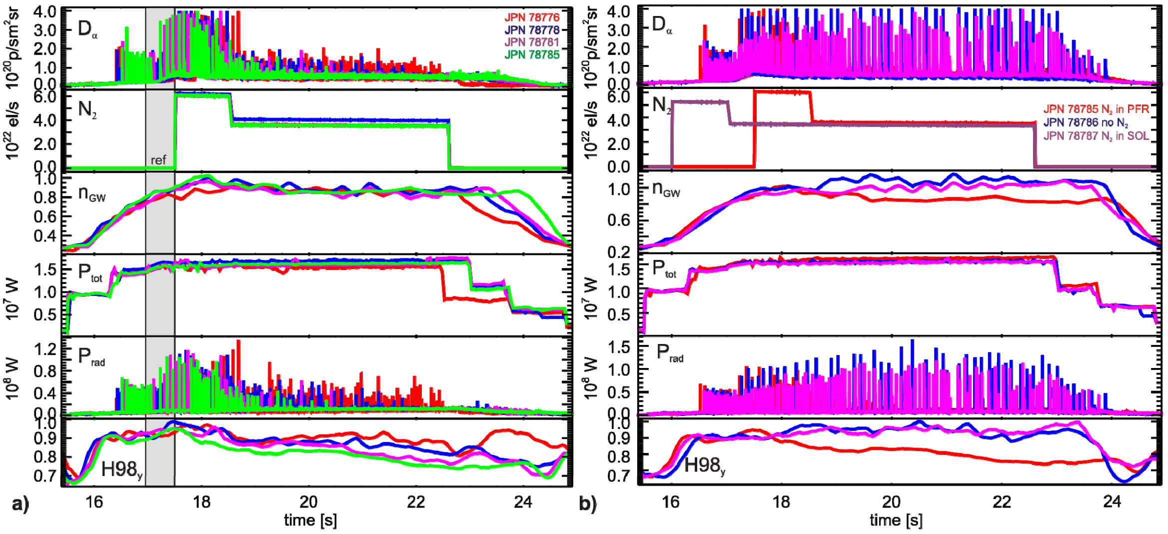

FIG. 2. Time traces of characteristic plasma properties. (a) The first four discharges used for the gas balance analysis. Nitrogen tends to build up a legacy in vessel which leads finally to degradation of the confinement in time at constant N injection rate. (b) Comparison of three discharges with N_2 injection into the SOL and injection into the PFR as well as a reference discharge without seeding.

The first four discharges, used for the gas balance, are depicted in the left hand side of fig. 2a). Though the waveform and the strength of the seeding injection is kept constant, the nitrogen inventory increases in time and lead to a transition from type I ELMy H-mode to type III ELMy H-mode with degradation of the confinement in the last discharge from initially H98y=0.92 to 0.83 at t=20s; the non-seeded but fuelled reference reached H98y=0.95. The initial nitrogen recycling flux at the beginning of the first discharge would represent a good compromise with respect to acceptable target conditions and confinement, however, real-time control on the seeding species N, which would be required to maintain the nitrogen recycling level, was not yet been developed but will be in place with the ILW.

The target conditions have been analysed with the aid of a set of Langmuir probes embedded in the outer target plate. The applied combination of seeding and fuelling leads to detachment at the outer target associated to peak electron temperature values in-between ELMs below 10eV in the first four discharges as required from the scenario. Fig. 3 shows the n_e- and T_e-profiles for the last of the first four discharges in comparison with a non-seeded reference which has been executed as fifth discharge directly after the gas balance experiment under otherwise identical plasma scenario. The density and temperature profiles were recorded during a small strike-point sweep at the end of the discharge flattop (t~21-22s). For comparison also profiles for the subsequent discharge with N_2 injection into the outer SOL (#JPN 78787) instead of the private-flux region (PFR) (JPN#78785) is plotted. The corresponding core parameters are shown in fig. 2b). N_2 seeding into the SOL is not inducing type III ELMy H-mode as the seeding into the PFR does under otherwise comparable injection rates. Moreover, the confinement remains unaffected with the seeding into the PFR which can be seen in comparison with the non-seeded reference discharge (JPN #78786), however, the comparison is to a certain extended affected by the nitrogen legacy.

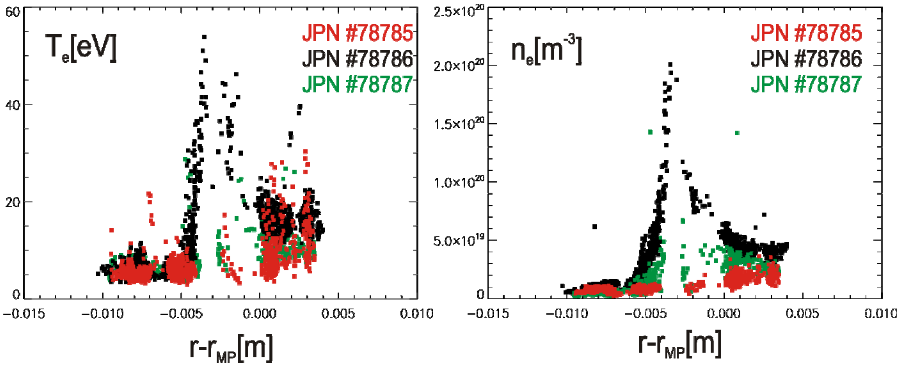

FIG. 3 T_e- and n_e-profile at the outer target in discharges with N_2 seeding into the outer SOL (#78785), into the PFR (#78787) and without active seeding recorded between the other two cases (#78786).

Both discharges with active seeding in either PFR or SOL are partially detached at the outer strike-point with T_e <10eV whereas the discharge without active seeding, but remaining and declining N legacy is reaching a peak T_e ~50eV at the strike point – a typical value for attached plasmas at the outer target of JET. The peak electron density in the non-seeded reference case reaches $2x10^{20}m^{-3}$ and drops in the detached cases to $4x10^{19}m^{-3}$ (seeding into SOL) and $2x10^{19}m^{-3}$ (seeding into PFR) reflecting a roll over in the ion flux to the target. The flatten profiles in both seeded cases show the extension of the detachment at the outer target plate into the SOL, thereby the seeding into the PFR seems to be more pronounced with a higher degree of detachment.

4. Gas balance analysis and nitrogen legacy

In order to have the major benefit of the carbon reduction and to make use of the protective Be layer, only the first four successful plasma discharges have been used to perform a gas balance analysis of the fuel and the nitrogen inventory with the aid of the AGHS. Though the very first discharge after the Be evaporation was successfully performed, a number of subsequent discharges had no successful breakdown which is likely related to the purity of the plasma and the fuel uptake of fresh Be wall. However, the unsuccessful breakdowns are assumed not to influence the gas balance analysis which has been performed in the following way: a cryogenic pump regeneration before and after the four successful discharges has been applied in order to recover the injected gas from only this experiment and analyse it according its composition. The method and precision of the system is described in detail in [7]. The total amount of injected gas is equivalent to 20.6barl D_2 and 2.5barl N_2 whereas 17.3barl have been recovered after 30 minutes. The major fraction of the recovered gas is deuterium (~95%) which leads to a retention rate of $1.94x10^{21}Ds^{-1}$ related to the accumulated time in divertor configuration of 96s. The retention rate is comparable to retention rates in experiments in pure carbon environment with similar magnetic configuration but at lower electron density [7]. But the measured retention rate in this experiment is overestimated in comparison with the pure carbon references due to the fact that the Be evaporation provides a non-saturated Be-wall surface with respect to deuterium and represents therefore not a steady-state result but includes the short term retention till wall saturation takes place. Indeed the requested gas amount to achieve a similar density in the limiter phase as in CFC is slightly higher in the first pulse after the Be evaporation (7.5×10^{21}D), but equals in the subsequent discharges slowly to the reference value with PFCs made of CFC. After the initial restart phase comparative studies with the ILW will start with saturated Be walls and will not be affected by this transient effect.

However, the basic mechanism for the relative high fuel retention observed in this experiment is still the co-deposition of deuterium in layers. This is in line with the measured high Be influx from the main chamber into the inner divertor leg which is a net deposition zone for both Be and C. Therefore, the co-deposition occurs to a large extend with freshly eroded Be from the main chamber wall which migrates to the divertor by SOL flows and finally deposits. Secondly, C was in this experiment only moderately reduced by the inhomogenous coverage with Be owing to only four evaporator heads and co-deposition with both Be and C takes place. The fraction of co-deposition due to C increases in time when the C source grows due to re-erosion of the protecting Be layer. With the ILW and PFCs made of bulk Be and thick Be coatings these transient effects observed here, wall loading and re-appearance of C, will not happen. Co-deposition of fuel with Be will remain as dominant mechanism for the fuel retention, though we assume that a final transport in remote areas will be reduced with respect to C due to the absence of chemical sputtering for Be and therefore less steps of re-erosion and deposition will occur. Moreover, laboratory experiments [9] suggest less tritium content in Be layers and recovery at lower surface temperatures than for C layers.

In addition to the balance in fuel, also the first gas balance in injected, recovered and retained nitrogen has been performed in JET. About 3.0% of the total gas recovered consists of the seeding and non-recycling impurity N_2. The recovered amount is equivalent to 30% of the injected N_2. The observation is in line with the so-called legacy effect of N which has been observed earlier in JET. Potential explanation for these long last in the vessel is surface dilution of the PFC material by nitrogen leading either to N-containing layers or even to nitride formation as revealed recently for comparable plasmas by spectroscopy in the JET divertor [10]. A similar effect has also been observed in W PFCs in the full W ASDEX-Upgrade [11].

Apart from the gas balance analysis of fuel and seeding gas, the nitrogen legacy has been observed in this experiment in-situ during plasma discharges by optical spectroscopy and by RGA spectra. Fig. 1b) shows three comparative RGA spectra before the Be evaporation, after the N injection of the first four discharges and, finally, after execution of a conditioning discharge with extensive strike-point sweeping aiming in a release of incorporated nitrogen in the vessel. The corresponding difference spectra with respect to the initial RGA reference spectrum before the Be evaporation are depicted in 1c). The conditioning discharge is similar to the reference discharge apart from the fact that higher hydrocarbons are still below the initial value and methane is significantly increased. Thus, the impact of the Be evaporation on the coverage of the CFC and carbon layers is almost gone after one day of operation. The second spectra in 1c) provides also indications for remaining nitrogen and nitrogen derivates in the residual gas prior to the cryogenic pump regeneration, but detailed analysis is necessary to fully deconvolute the cracking pattern.

Divertor spectroscopy confirms the nitrogen legacy by prolonged appearance of a nitrogen source over several discharges without active seeding – measured in-situ by NII lines. Fig. 4a) shows the evolution of CII (427.6nm), NII (438.0nm) and BeII (436.0nm) on a discharge to discharge base, whereas the reference values from the reference discharge are indicated without nitrogen seeding is indicated. The operation with detached outer divertor target leads to a moderate C and Be erosion which drastically increase when the active seeding is stopped. The spectra were taken with a direct imaging spectrometer system observing the outer target plate, technical detail are described in [10].

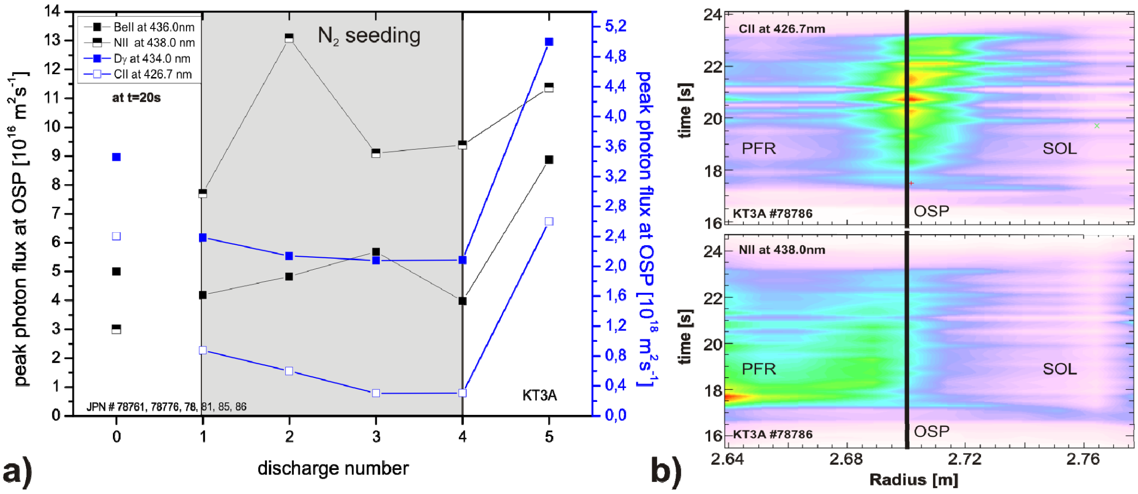

FIG. 4. (a) Discharge-to-discharge evolution of CII (426.7nm), NII(438.0nm) and BeII (436.0nm) at t=18s. The reference values from the discharge before Be evaporation (JPN#78761) is indicated. (b) Temporal evolution of the NII and CII emission in the first discharge without active nitrogen seeding.

Fig. 4b) shows the spatially resolved time evolution of CII (426.7nm) and NII (438.0nm) recorded in the first discharge without nitrogen seeding, directly after the gas balance was performed. Though interfered by ELMs a clear increase of the CII photon flux with decreasing NII photon flux can be observed. NII reduces to about half of the initial value in the discharge without any significant change in the local T_e confirmed by Langmuir probes, The later fact allows the conclusion that the N source is also dropping to half the initial value. Also the increase in CII emission is related to an increase of the C source owing to the re-erosion of the nitrogen-containing layer. In parallel the appearance of CN, observed also previously as CN B-X in JET [10], reflects the sputtering of a nitrogen-containing layer in the SOL. The time evolution of the BII emission at 436nm is comparable with the CII emission, indicating that still some Be is on the outer target deposited. However, the nitrogen spectroscopy on NII in the divertor indicated a typical nitrogen legacy of max. 20% which cannot account for the missing amount of nitrogen measured by AGHS.

5. Divertor radiation

The reduction of carbon after the Be evaporation shall have an impact on the radiation in the divertor. However, the radiation in the reference experimental phase prior to the first nitrogen injection decreased only moderate. Radiation of N adds to the radiation of D and remaining C in the divertor as it can be seen in fig. 5a)-c) which shows the increase in the radiated fraction in the first discharge after the Be evaporation from f_{rad}=30% prior to the seeding, to f_{rad}=40% starting with the seeding, and with constant seeding rate into the PFR to f_{rad}=50% at the end of the plasma flattop. The bolometric reconstruction in the divertor provides also information about the radiation pattern in between ELMs and reveals that N, which is injected into the PFR, is mainly radiating close to the x-point whereas C radiates also along the separatrix – as observed elsewhere [11]. In the subsequent discharges the nitrogen content in the divertor increases due to the legacy effect. Also the carbon radiation starts to increase from discharge to discharge, and both contributors causing an increase of the radiation fraction from initially 50% at the end of the first pulse to 60% at the end of the fourth pulse (fig. 5(d)) and finally 70% at the end of experiment. It is not directly possible to draw firm conclusions about to say which one of the two contributors causes the increase, but the radiation pattern in fig. 5 indicates that the rise in radiation is due to the N increase in time in the first four discharges.

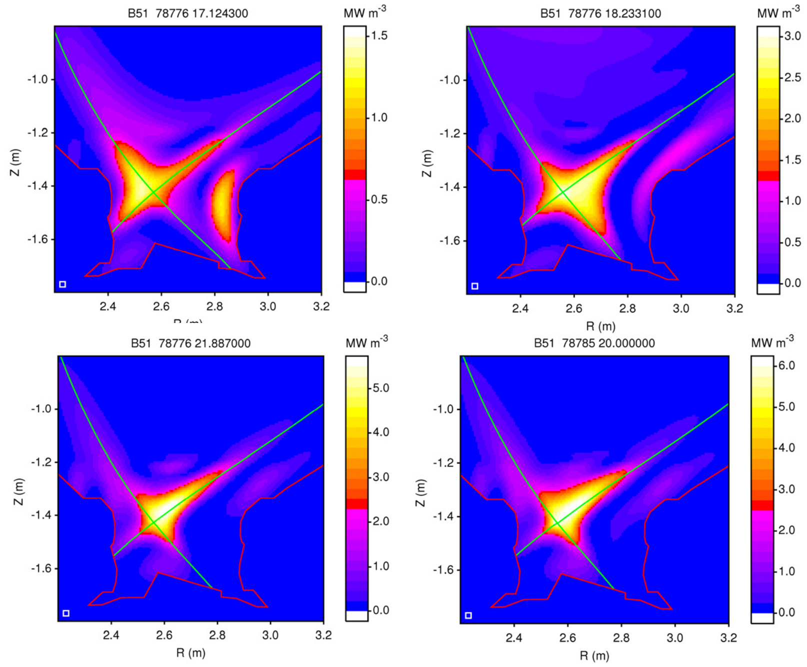

FIG. 5. Divertor radiation in the first discharge after the Be evaporation: (a) prior to N_2 injection (f_{rad}=30%), (b) with start of N_2 injection (f_{rad}=40%), and (c) with 2.5s of N_2 injection (f_{rad}=50%). (d) The radiation in the fourth discharge f_{rad} increases to 60% though the N_2 injection is constant. The radiation pattern shows the major increase at the x-point region indicating N as driver for the rise in radiation.

6. Summary and conclusion

The transient phase with reduced C radiation after a massive Be evaporation was applied to mimic the ILW and to perform a gas balance analysis of the injected fuel. Plasmas with detached outer-strike point on the load-bearing plate, which will be with ILW made by bulk W, were executed with N seeding in order to reduce the power load and to cool down the divertor plasma below 10eV and ensure low sputtering in-between ELMs. The plasma performance is modestly reduced but fully compatible with the ILW engineering requirements whereas substantial nitrogen legacy has been quantified by the gas balance analysis. This gas balance was performed in the first four discharges after the evaporation providing a similar fuel retention rate in comparison with comparable plasmas in the CFC environment but without seeding. A reduction of deuterium retention rate as expected from the ILW could not be observed and two reasons have been identified: the short term retention is included as the wall is non-saturated with respect to D and, secondly, the Be coverage is incomplete and causes a fast reappearance of C in the plasma and subsequent co-deposition of fuel by Be and C.

Acknowledgements

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

References

[1] G.F. Matthews et al., Phys. Scripta T138 (2009) 014030
[2] S. Brezinsek et al., accepted for publication Journal Nuclear Materials
[3] G.P. Maddison et al., accepted for publication Journal Nuclear Materials
[4] V. Riccardo et al., Phys. Scr. T138 (2009) 014033
[5] C. Giroud et al., this conference
[6] K. Krieger et al., J. Nucl. Mater. 390-391 (2009) 110
[7] T. Loarer et al., J. Nucl. Mater. 390-391 (2009) 20
[8] K. Krieger et al., this conference
[9] G. de Temmerman et al. , Nucl. Fusion 49 042002
[10] S. Brezinsek et al. submitted to J. Nucl. Mater.
[11] A. Kallenbach et al. submitted to J. Nucl. Mater.