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** See annex of F. Romanelli et al, "Overview of JET Results",*
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## ABSTRACT

The initial conditioning cycle of JET ILW is analysed and compared with restart and operation in 2008 with a carbon dominated wall. Comparable water and oxygen decay times are observed during bake-out in both cases. Despite a $2\times10^{-3}$ mbar·l/s leak rate during plasma operation, lower O levels are measured with the ILW. However, no wall conditioning has been necessary after plasma restart, which dramatically contrasts with 2008. Higher O levels measured after nights or week-ends, BeO layers being formed and re-eroded, do not impact plasma operation and performance with the ILW. First results on isotopic wall changeover by GDC on the ILW six months of the first $D_2$ campaign evidence a reservoir of about $3.10^{22}$ atoms, i.e. ten time lower than in carbon PFCs. A study in JET of the glow discharge current distribution for different ratios of the ionization mean free paths to the vessel dimensions seems to indicate sufficient toroidal and poloidal homogeneity in ITER.

## INTRODUCTION

Wall conditioning of tokamaks is a common tool to influence fuel - and impurity recycling and to improve plasma performance and reproducibility [1]. In this respect, wall conditioning techniques must meet requirements specific to the material of the Plasma-Facing Components (PFCs). Of particular interest is the change in the wall conditioning effectiveness from fusion devices with carbon-dominated PFCs, where most experienced has been gained, to full metallic walls which will be present in ITER and DEMO reactor [2-5]. Given the new wall material mix [6] and recognizing that scale size plays an important role in glow discharge uniformity, the study of wall conditioning in the largest existing tokamak JET, with its new ITER-Like Wall, is of particular importance for ITER, which will also have a beryllium first wall and a tungsten divertor during nuclear operations.

In this paper, we present an analysis of the wall conditioning of JET with ILW. The initial conditioning cycle of the ILW after its installation in 2010/11 is discussed in a first part. A comparison is made with previous restarts and operation with a carbon-dominated wall. Vacuum vessel bake-out at 200°C and 320°C and about 200 hours deuterium Glow Discharge Conditioning (D2-GDC) before first plasma operation with ILW are analysed. The follow-up of wall conditions after the first plasma, by means of optical emission spectroscopy and mass spectrometry, and the impact of impurity level on plasma operation and performance during the first months of the campaign with the ILW, are presented in the second part. The question of the residual carbon content and fluxes during plasma operation is presented in [7]. A third part reports the results of the first isotopic wall change over experiment from D to H by GDC on the ILW. A study of the poloidal and toroidal glow discharge wall current distribution as a function of the electrode number, glow current and deuterium pressure is finally presented and the results are extrapolated to ITER, where the originally planned GDC system is being currently relocated, from the lower lateral ports to outer midplane and upper lateral ports, using an electrode design concept similar to that employed at JET [8].

## 1. ANALYSIS OF THE INITIAL JET CONDITIONING CYCLE WITH ILW AND COMPARISON WITH 2008 RESTART IN JET-CFC.

The vacuum vessel temperature and the torus pressure, measured by a Penning gauge, during the initial conditioning cycle of the JET vacuum vessel are shown on Figure 1. Nearly one month has been necessary between the initial evacuation of the vacuum chamber (18th of May 2011) and the first bake-out (15th of June), during which a first three days long bake-out at 200°C was performed, before venting the tokamak for air leak investigation. It was pumped-down again on the 6th of July, the vacuum vessel leak rate having been reduced down to $2\times10^{-3}$3 mbar.l/s. Before bake-out, water, oxygen, carbon monoxide and dioxide are the main species in the residual gas. The vessel was then maintained at 320°C for almost one month, during which the divertor cryopumps were cooled down and maintained at liquid nitrogen temperature and deuterium glow discharges with a cumulated duration of 215 hours were performed. The vacuum vessel was finally cooled down at 200°C on the 12th of August, for the restart of plasma operation which took place with the first plasma twelve days later. Be evaporation [1] has been neither applied before the first plasma, although it was required in all conditioning cycles with carbon walls, nor during the whole first campaign with ILW.

Figure 2 shows the RGA signals of water and hydrogen from the beginning of the second bake-out, compared with those measured during the restart of 2008 with carbon dominated PFCs, after a short intervention without exchange of major PFCs. At 200°C, water, which dominates outgassing, is released with a characteristic e-fold decay time about 15 hours in both cases. After one day, hydrogen outgassing saturates with the ILW, whereas no peak is seen in 2008, where the vessel was cooled down after only two days at this temperature. In both cases, desorption of hydrogen and carbon containing species, like $CO_2$ and CO, becomes more pronounced as the vacuum vessel temperature is increased. Since the vessel temperature is directly brought from 200°C to 320°C in the 2011 restart, hydrogen peaks more rapidly with the ILW than with the carbon wall, but water outgassing is somewhat faster, with a characteristic e-fold decay time about 2-3 days for the Be first wall, compared to 4 days in the 2008 restart with carbon dominated PFCs. At the end of the bake-out, residual pressure was widely dominated by hydrogen. A total amount of 70g of water and 20g of oxygen, estimated by mass spectrometry and considering a vessel pumping speed about 6 m3/s, was pumped out during the bake-out. Divertor cryopumps could be cooled down to liquid nitrogen temperature after nearly 300 hours at 320°C, the water partial pressure being below $10^{-7}$ mbar, thus preventing water condensation on cryopanels, and $D_2$-GDC were performed. Figure 3 illustrates the effect of a $D_2$-GDC applied to the JET ILW on the residual gas. The signals of all masses are reduced by a factor 2 to 10, in particular carbon (12), hydrogenated (18) and deuterated water (20), oxygen (32) and carbon dioxide (44), but the nitrogen (28, 14) and argon (40) levels are clearly constant, evidencing the air leak mentioned above. On Figure 4 are shown the partial pressures of water, carbon monoxide and dioxide, along the D2 glow discharges which were conducted in the first conditioning cycle of JET ILW. Both the water and carbon monoxide signals are reduced by one order of magnitude throughout the 150 hours GDC at 320°C. However, once the vessel is cooled down to 200°C, thermal desorption of impurities from the PFCs is less effective and condensation increases at the PFCs. Further conditioning by $D_2$-GDC was hence needed as it can be seen on Figure 4. In total, 30g hydrogen, 140g water, 50g CO and 15g $CO_2$ were removed by the 215 hours GDC.

## 2. MONITORING OF IMPURITY CONTENT

It must be firstly stressed here that, following the initial conditioning cycle, the first plasma in JET with ITER-like Wall reached a plasma current of 1MA at the first attempt and lasted 15sec., with a radiative power fraction $F_{rad} = P_{rad}/POhm$ as low as 40%. A comparison of the achieved plasma currents in both the 2008 restart and the restart with the ILW is shown on Figure 5. Whereas it took about 45 shots in 2008, a 2MA target current could be reached after 5 shots only in the restart with the ILW, Frad staying below 30% afterwards (right axis on Figure 5). Moreover, no non-sustained breakdowns could be attributed to conditioning issues [6,9], and this despite the presence of the above-mentioned air leak. In contrast, $D_2$ and He-GDC as well as beryllium evaporation were always needed in restarts with carbon walls to reach target plasma currents.

Levels of impurities in the residual gas in JET vacuum vessel, such as oxygen, water, or carbon dioxide, were monitored by mass spectrometry throughout the experimental campaign with ILW and compared with the restart in 2008. Figure 6 shows the partial pressures of impurities one our before the first plasma pulse of the day. The water level is clearly lower with ILW than in 2008, as well as oxygen, which is not measurable after 1000 plasma shots, despite the air ingress which can be seen on the constant $N_2$ (m/e = 28) MS signal. Carbon containing species (m/e = 12, 44) are only present at beginning of ILW campaign, whereas they remain at a high level throughout operation in 2008. Similar are the in-situ spectral observations of during plasma operation and in the analysis of the plasma exhaust by AGHS [7].

The temporal evolution of the oxygen level in the plasma was monitored by optical emission spectroscopy throughout the experimental campaign. The results are shown on Figure 7, where the intensity of the OV line after X point formation, measured by VUV spectroscopy on a vertical line of sight , and normalized to the density, is plotted as a function of the number of plasma shots for both restarts. Thanks to the getter capabilities of beryllium, the oxygen level remains lower than in previous restarts with carbon walls, despite the air leak rate, which typically forms one BeO monolayer on the first wall in less than a day. This leads to saturation effects and enhanced O and C content while operating after nights or week-ends [7], without impacting low power plasma operation and performance. The red dashed lines represent the GDCs that were necessary to reduce the fuel and impurity content in both restarts. The fact that, after the initial conditioning cycle of JET ILW and despite the air ingress, there has been no further need for any conditioning by $D_2$-GDC is a dramatic change with respect to previous restarts with carbon dominated PFCs and very relevant information for the conditioning of ITER.

## 3.ISOTOPE EXCHANGE

Isotopic exchange by GDC is an option to mitigate the tritium inventory build-up on ITER [10, 11]. The efficiency of the technique on a tokamak with the relevant material mix has been assessed for the first time using H2-GDC on the ILW after six months of the first deuterium campaign. For this the ILW was preloaded by a 30 min $D_2$-GDC ($p = 3\times10^{-3}$ mbar, I = 15 A, U = 500 Volts) and at t~0, the gas injection was switched to $H_2$, keeping pressure and voltage constant. After nearly one and a half hour, the gas injection was switched back to $D_2$.

As in carbon, the analysis of partial pressures, calculated by mass spectrometry, shows that the wall isotopes are mainly released in the form of HD, which pressure decreases as the wall isotopic ratio evolves. The temporal evolution of the fluxes of retained and outpumped species (H or D), calculated from the gas balance between injected and pumped particles, is plotted on Figure 8. The accessible reservoir for isotopic exchange, i.e. the amount of wall D atoms that can be replaced by H atoms, is about $3\times10^{22}$ in the one and a half hour H2-GDC, which is lower by a factor 10 with respect to previously reported values in JET with carbon PFCs [11]. It should be noted here that this value is comparable to the dynamic retention at the end of Be limiter discharges in JET ILW [12]. H retention proceeds at a similar rate, as it can be seen on Figure 8, despite the large fluctuations in the calculations due to a large signal to noise ratio on the gas injection signals.

## 4. POLOIDAL AND TOROIDAL GLOW DISCHARGE WALL CURRENT DISTRIBUTION

The poloidal GD wall current distribution in JET is studied as a function of the glow current, deuterium pressure, and location of anodes. The originally planned GDC system in ITER is being currently relocated. However, the foreseen anode locations (outer midplane and upper lateral ports) and the envisioned range of glow pressures in ITER may not ensure adequate coverage of the PFCs. Indeed, scale size plays an important role due to the ratio of mean-free path for neutral ionization, which can be long (1-2m) in the low pressure glow plasma, to the typical dimensions between the anode and the first wall. Experiments on JET, using the new wall Langmuir probe capability with the ILW, provide a direct way to assess the expected glow current distribution at ITER first wall. The four glow discharge anodes, toroidally distributed in octants 2, 4, 6 and 8, were switched on and off sequentially, and the homogeneity was assessed from the ion saturation current Isat at the Langmuir probes arrays in the inner and outer limiter of octant 8. The distance from the anodes 2 and 6 to the probes is approximately 6 m, which is comparable to ITER poloidal dimensions. The distribution of the ion saturation current normalized to the total GDC current is plotted on Figure 9 as a function of poloidal coordinates. The plot corresponds to various anode configurations at a fixed pressure of $3\times10^{-3}$ mbar. Operating two toroidally opposed anodes provides good uniformity within the studied pressure range, whereas switching only one anode on introduces a strong inhomogeneity: the ion fluxes to the inner wall are 3-4 times higher than the fluxes to the outer limiter. The ion flux distribution is strongly influenced by the pressure, as it can be observed on Figure 10. Increasing the pressure from $3\times10^{-3}$ mbar to $2\times10^{-2}$ mbar while only the anode located in octant 2 is activated shifts locally the glow discharge towards the outer wall, but the homogeneity remains unchanged below $3\times10^{-3}$ mbar. The discharge is poloidally homogeneous if all anodes are active, which, extrapolated to the ITER case, tends to indicate that 4 anodes may provide sufficient toroidal and poloidal homogeneity.

## CONCLUSION

The restart of operation of JET with the ITER-Like Wall after its installation in 2010/11 is analyzed and compared with the 2008 restart with a carbon dominated wall. Comparable decay times are observed for both hydrogen and water during vacuum vessel bake-out at 200°C and 320°C of both 2008 and 2011 conditioning cycles. About 200 hours $D_2$-GDC applied to the ILW are found to remove a significant amount of water and carbon oxides. A 1MA plasma is obtained at the first attempt in the ILW, higher plasma current targets being rapidly reached without any need for GDC or Be evaporation, with a radiative power fraction below 30%. This contrasts with restart in JET CFC, where further wall conditioning was always necessary to raise the plasma current at restart. Level of impurities such as oxygen, water or carbon, monitored either by optical emission spectroscopy or mass spectrometry throughout the experimental campaign with ILW, are much lower than in 2008. Despite a vacuum vessel leak rate about $2\times10^{-3}$ mbar·l/s, O is gettered at the Be wall and lower levels are measured during plasma with the ILW. Higher levels measured after nights or week-ends, BeO layers being formed and re-eroded, do not impact plasma operation and performance during the restart with the ILW, and neither GDC nor Be evaporation were necessary for operation.. The efficiency of $H_2$-GDC for isotopic exchange has been assessed using H2-GDC on the ILW after six months of the first deuterium campaign. The ILW reservoir accessible for isotopic exchange by GDC compares well to the dynamic retention in Be limiter discharges. It is about $3\times10^{22}$, i.e. one order of magnitude than in carbon PFCs. The study of the JET glow discharge as a function of the electrode number, glow current and pressure seems to indicate that the envisioned GDC system for ITER will provide sufficient toroidal and poloidal homogeneity.

## ACKNOWLEDGEMENTS

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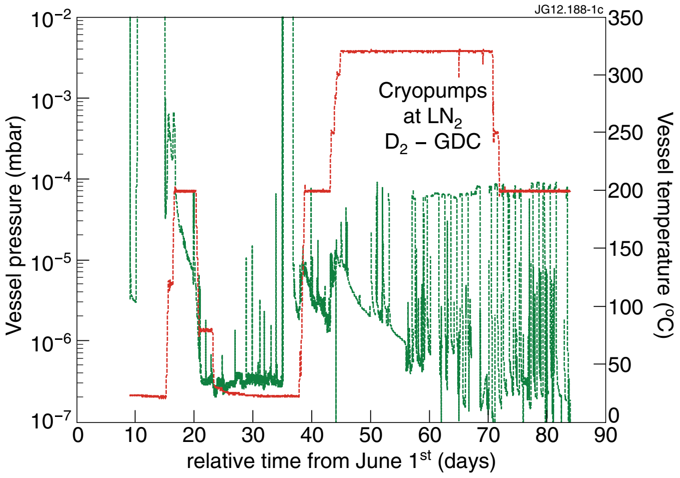

*Figure 1: Penning pressure (green) vacuum vessel temperature (red) of the initial conditioning cycle of JET with ILW.*

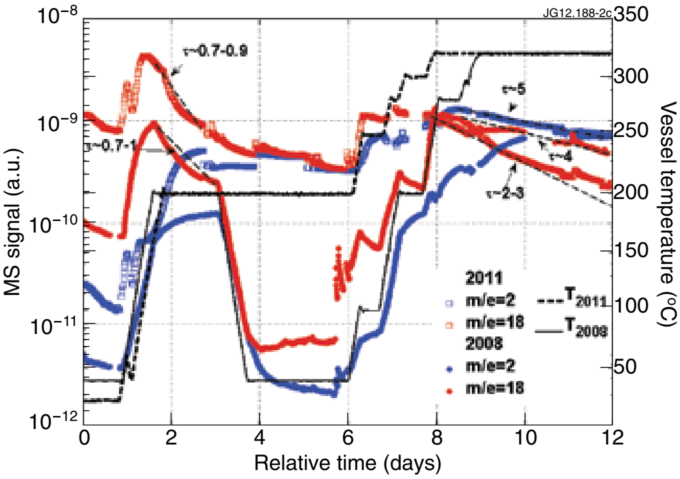

*Figure 2: Water (red) and hydrogen (blue) partial pressure signals and vessel temperature (black) of the initial conditioning cycle of JET with ILW (open symbols and dashed line) and the 2008 restart (full symbols and line).*

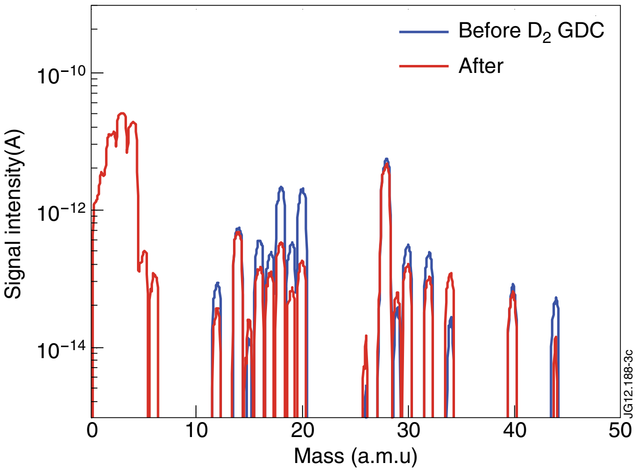

*Figure 3: Mass spectrum before (blue) and after (red) D2-GDC in JET with ILW.*

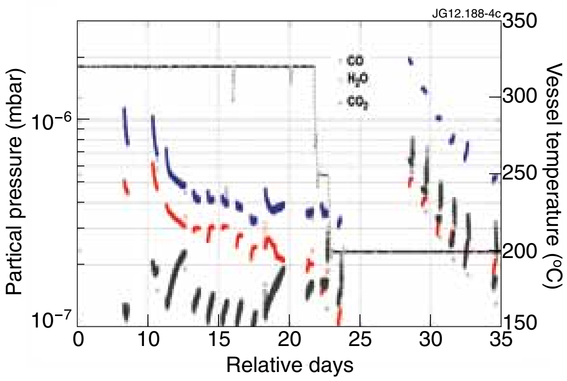

*Figure 4: Partial pressure in the $D_2$-glow discharges of JET ($p=3.10^{-3}$ mbar, U=500 Volts, I=15A) of the initial conditioning cycle.*

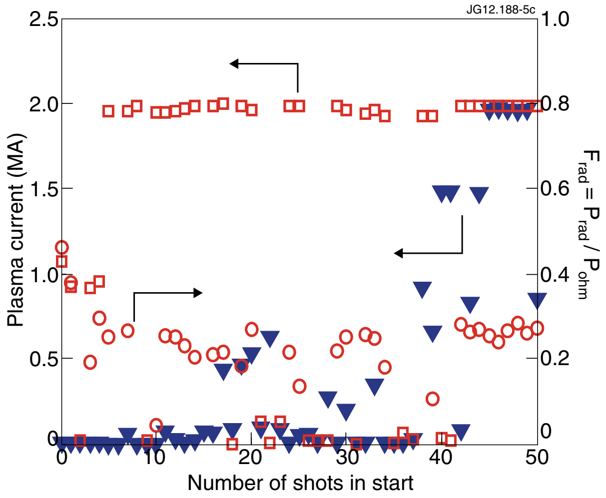

*Figure 5: Left axis: maximum plasma current versus number of shots in the 2008 (blue triangles) and 2011 restarts (red squares). Right axis: radiative power fraction in the restart with ILW.*

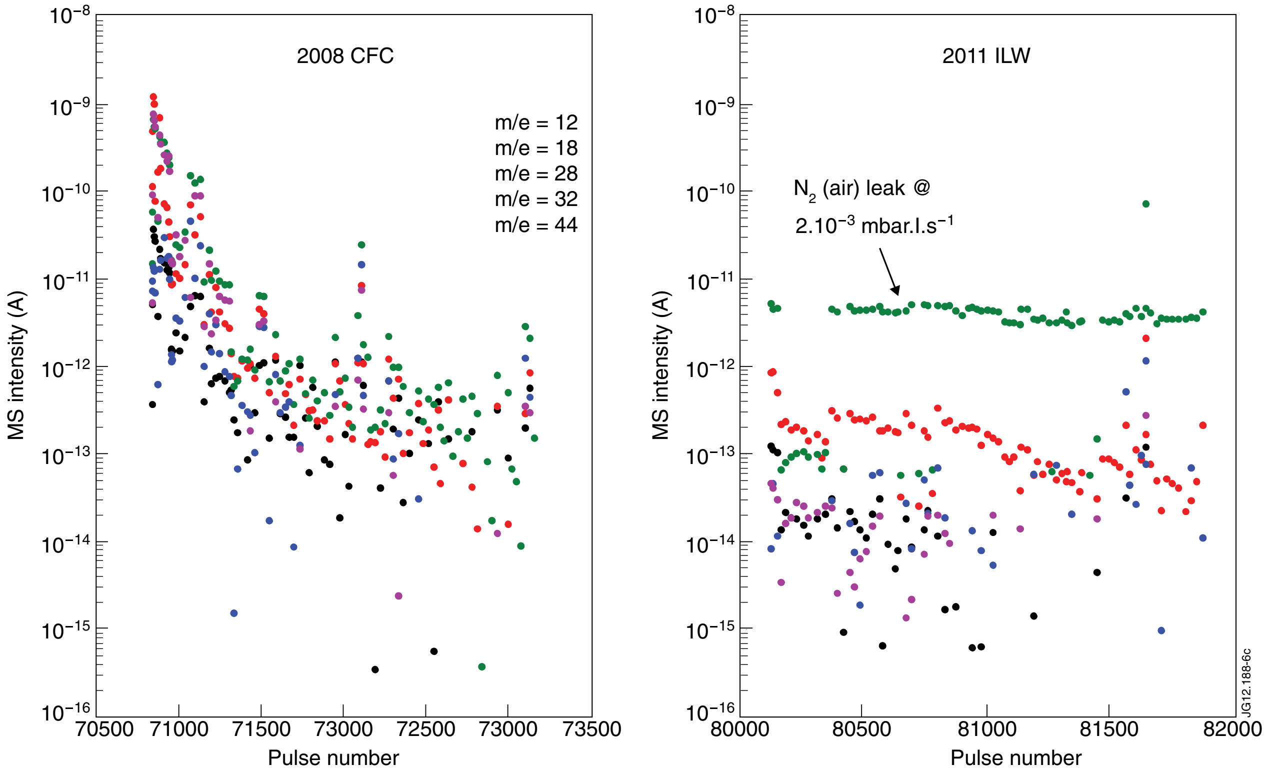

*Figure 6: Residual level of gas impurities recorded one hour before the first plasma pulse of the day for the 2008 restart( left) and for the restart with ILW (right).*

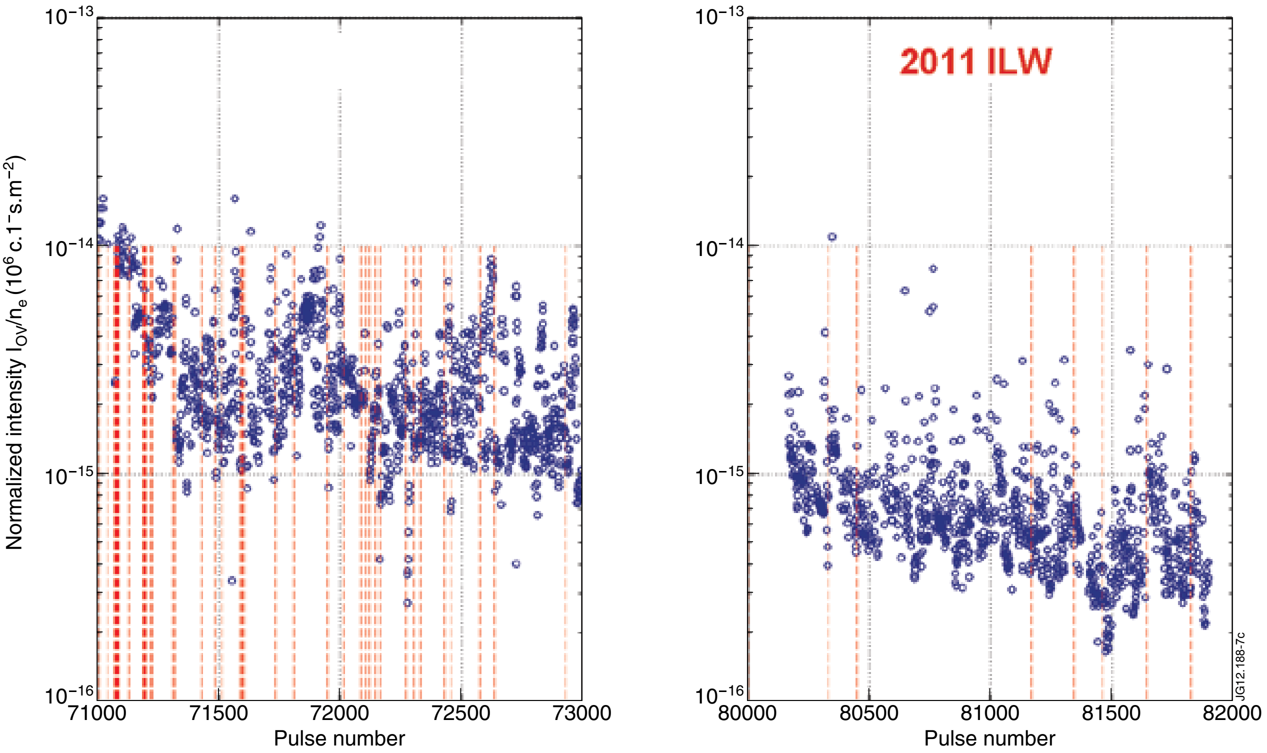

*Figure 7: Normalized OV line intensity in plasmas and frequency of GDCs for the 2008 restart( left) and for the restart with ILW (right).*

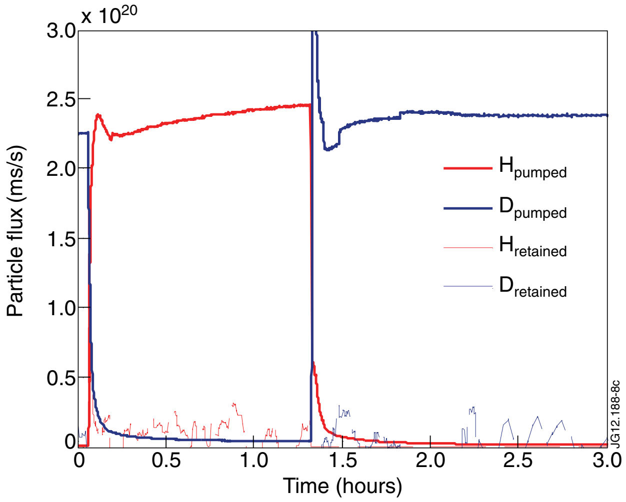

*Figure 8: Temporal evolution of the exhausted (full lines) and retained (dashed) hydrogen (red) and deuterium (blue) fluxes during change-over GDC ($p=3.10^{-3}$ mbar, U=500 Volts)*

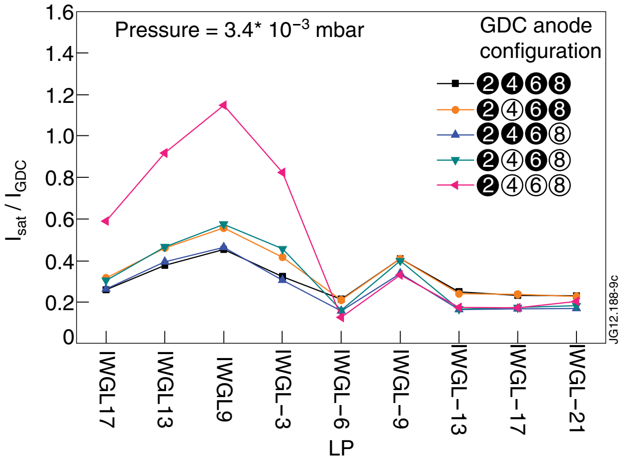

*Figure 9: Poloidal distribution of the ion saturation current normalized to the total GDC current as a function of the number of active anodes and their location.*

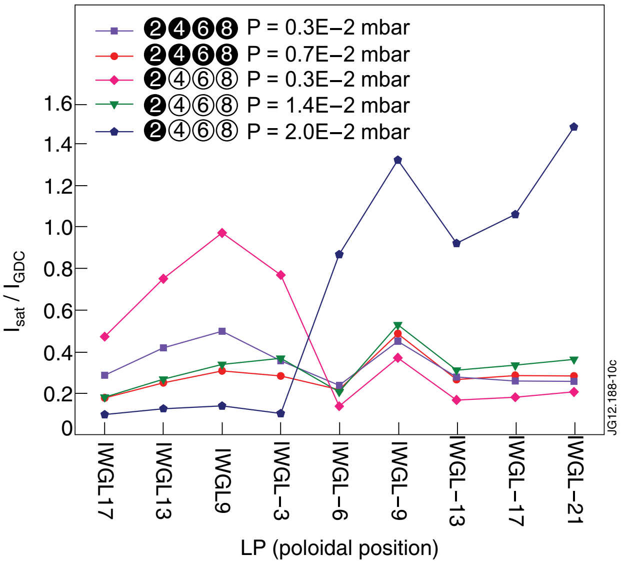

*Figure 10: Influence of the GDC pressure on the poloidal distribution of the ion saturation current.*