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ABSTRACT.

This paper covers the aspects of the long term evolution of impurities in the main plasma and divertor of the JET Tokamak with respect to the newly installed ITER-Like Wall(ILW). Three main aspects considered are, firstly, the changes related to the switch over from the carbon dominated JET-C(pre 2011) to the JET-ILW with beryllium as the main wall material and an all tungsten(W) divertor, secondly the evolution of impurity fluxes in the W divertor to monitor material migration and establishment of a steady state divertor surface composition, and thirdly the statistical analysis of irregular impurity events causing significant plasma contamination and radiation losses in the plasma core.

The main findings comprise of a drop in carbon emissions of a factor1 20 with respect to JET-C, immediate low oxygen content comparable to levels obtained previously after campaign long conditioning effects due to the beryllium main wall. Despite the attempts of reaching steady state divertor conditions after the initial 1600 plasma seconds the divertor is still evolving due to increasing heating power applied through out the campaign. The levels of carbon are evolving together with the beryllium levels. Spectroscopy is hinting at a change in the Mixed Material/ beryllium layer composition in the inner divertor. For the impurity events a steady number is observed despite the increase in machine flexibility and input power. Constant plasma operation alleviates part of the problem altogether.

1. INTRODUCTION

In ITER a beryllium(Be) first-wall and a tungsten(W) divertor allowing for high heat-fluxes in the areas close to and at the strike-point are currently foreseen. The recently installed ITER-Like Wall(ILW) [6] in JET(Fig. 1)represents test-bed to study the impurity evolution under ITER-Like plasma and material conditions. The replacement of the first-wall was performed by remote handling in one shutdown extracting all of the previously CFC (Carbon Fiber Composite)-based plasma-facing components. CFC at JET is currently used only as a substrate in the divertor, coated by typically 20m of W. Keep in mind those coatings still contain up to 8%(atomic) of carbon [1]. This could provide a potential reservoir of C in an addition to the mainly present Be and W. Plasmas including high power H-modes with auxiliary input powers of up to 25MW have been performed in the 2011 and 2012 JET program. The initial start-up campaign was, however, performed with a series of comparable Ohmic plasmas to study the evolution of the new wall during start of operation in divertor configuration [5]. Monitoring pulses [1] with constant conditions throughout the campaigns enable a follow-up on the wall and impurity evolution beyond dedicated experiments. This contribution will focus on the evolution of impurities, mainly carbon, beryllium and oxygen, during the performed monitoring pulses as well as their general behaviour during the 2007-2009 campaigns compared to the JET-ILW period. In addition implication for plasma operation due to spurious high-Z impurity events are described during the recent 2011-2012 campaign. A dedicated description of the initial plasma operation can be found in [5] while details of W erosion during the JET-ILW operation is described in [10, 2]. Issues connected to radio-frequency (ICRH) heating and connected core impurity accumulation are discussed in [7]

2. EXPERIMENTAL SETUP AND DIAGNOSTICS

Here, three different time series and several spectroscopic diagnostics were used. Firstly, averaged signals from the divertor phases of all pulses since 2007 are used to cover the major trends seen, especially with respect to the change over in wall materials from carbon to beryllium and tungsten. Here, variations of input power density or magnetic configuration and shroud small trends and variations. Secondly dedicated monitoring pulses introduced for the 2011/2012 campaign are used to investigate the evolution under identical plasma conditions throughout the campaigns. Both are discussed in section 3.1. Thirdly, identification of pulses with irregular radiation events. Each pulse showing a radiation spike has been put into a database to further study their behaviour and e.g. composition (Analysis cf. section 3.2).

2.1. DIAGNOSTICS

Local impurity line emission of eroded neutral atoms and subsequently singly charged ions was measured spectroscopically in the visible spectral range. Beryllium was detected using the BeI line at 457nm while for carbon in the divertor the CII line at 515nm was used. For lines of sight perpendicular to the viewed surface area, the intensity of these lines is approximately proportional to the gross erosion flux of the respective species. As the plasma parameters are kept constant during the cases describe the change in photon flux is a direct measure of changes to the impurity fluxes. Figure 1(a) shows a subset of the available lines-of-sight of the JET survey high-resolution spectrometers providing integral views of the outer and inner divertor regions respectively [5]. The VUV spectral range contains spectral lines from a wide range of elements and their various ionization states, making this range particularly valuable from the point of view of diagnosing high temperature plasmas- here the main plasma. Spectroscopic measurements reported below were performed using Princeton Instruments survey SPRED spectrometers [3, 11]. Using either routinely a 450g/mm holographic grating and measuring VUV spectra in the 10-110nm wavelength range with a horizontal line of sight into the plasma (Fig.1(a)) or a spectrometer with a 2105g/mm grating recording spectra in the wavelength range below 40nm looking nearly vertically down into the JET divertor. For both the VIS and UV Spectra usually the integral area defined by a given number of pixels on either side of the line centre is used as the intensity signal, these pixels also defining the background to be subtracted. However, to clearly identify W in the conned plasma a fit of the spectra is performed based on the method described in [8, 9].

2.2. METHODOLOGY

Monitoring pulses were introduced to the routine plasma operations of JET-ILW [1]. The monitoring scenario had to be compatible with operation at the beginning of the JET-ILW experiment. A plasma geometry(Fig. 1(a)) was chosen from a discharge scenario with a configuration specifically developed for JET-ILW operation in the previous experimental campaign. Figure 2 shows time traces of plasma parameters for a pulse in the later campaign. In the initial phase (JET Pulse No: 80170-80300) only an ohmic flattop phase was used adapting the pulse as subsequent plasma operation became available. This allows to follow the operational evolution through all stages for e.g. concentrating on the ohmic or L-mode phases as the physics questions requires. For the purpose of this paper the ohmic phase has been used as it is available throughout the complete campaign. The general trends observed in the change over from JET-C to JET-ILW have been characterized by analyzing a central phase of 1s in the flat-top of each discharge in divertor configuration. Here, mainly the UV spectroscopy, with lines-of sight through the conned plasma, together with general plasma parameters are used (Fig.4). The analysis concentrates on the main impurities, like C, Be and O. The analysis of impurity events utilizes the radiated power during a pulse as indicator of events changing the radiation level on a short timescale (ms). After compiling an extensive database each event was characterized with respect to the related UV emissions (W, Fe, Ni, ...) and a statistical analysis performed to characterize their evolution.

3. RESULTS

3.1. DIVERTOR EVOLUTION AND GENERAL IMPURITY DEVELOPMENT

Following the monitoring pulses it is clear that after the initial installation about 300 JET Pulses (2000s) of divertor operation were required to establish a steady state divertor composition [5]. Figure 3 is displaying the main low-Z impurities considered when studying the evolution of the divertor plasma, Be and C. The grey area depict the phase of constant plasmas in the beginning of the JET-ILW. In the course of the campaign a further evolution is however apparent.

Figure 3(a), (b) display the long term C and Be evolution measured during the constant ohmic phases of the monitoring pulses. An wide spread with a maximum increase of about 20% in the carbon levels is visible. While for both the inner and outer divertor an initial level of beryllium is established after 300-500 JET plasmas a change is obvious for the inner divertor emissions. While for the outer divertor, the composition between C and Be remains similar, the inner divertor displays a clear drop in beryllium emissions. This observation indicates that the balance between C and beryllium is changing. Keeping in mind that while the monitoring pulses have constant plasma conditions despite regular plasma operation evolving during the course of the JET-ILW operation towards higher power higher performance operation one can quite clearly observe the daily variations within the monitoring plasmas(for details see [1]). One particular case is represented by the red line. Here, an additional beryllium evaporation was performed to study its effect on main chamber impurities such as tungsten and nickel. The divertor is covered by beryllium with the Be emissions increasing as the carbon was reduced.

The presence of the beryllium coverage is particularly visible in the outer erosion dominated divertor as the beryllium is usual originating here from the Be contained in the arriving flux and not eroded locally.

We can conclude that while a relatively steady composition of the divertor is reached quite early in the campaign, evolution towards higher power operation is changing the material mix or layer composition especially in the deposition dominated inner divertor. We know beryllium is eroded from the main chamber wall depending on plasma density and input power causing high electron temperatures at the beryllium wall, new carbon sources however are not apparent.

One indicator of the impurity composition is the effective charge of the plasma observed from spectroscopy.

(1)

Higher auxiliary power and operation at low density caused a larger Be in flux due to increased main chamber erosion, while lower density also means less flux to the target hence less carbon. The evolution of main chamber impurities is deduced from UV emissions as depicted above. In equation 1 we assume one main impurity is dominating Z_{eff} and hence we can deduce the change in concentration from JET-C to JET-ILW, assuming C, Be being the main impurities respectively. Taking into account figure 4 we can also follow up the evolution of the impurity emissions, here C, O, as an indicator for the relative changes. Carbon drops by a factor 20, while oxygen is at least a factor of 10 lower compared to other restarts. For JET-C an average $Z_{eff} = 1.96$ is observed while this drops drastically for the JET-ILW to $Z_{eff} = 1.21$. Considering eq.(1) we conclude a concentration of carbon of 3% for the JET-C and beryllium of 2% for the ILW. This is consistent with previous CXRS observations of the carbon dominated JET [1], the JET-ILW is showing 2-3% Berylllium and 0.1-0.2% carbon. This means that two effects of the change over to the JET-ILW are obvious. Firstly, the carbon content was drastically reduced and secondly the beryllium first-wall allowing for a significant conditioning effect by bettering the remaining oxygen much better then in previous operational phases. In figure 4(b) a trend towards increased emissions in the later phases of the JET-ILW campaigns can be seen. This seems to be related to the increase in power and performance in the course of the JET-ILW operation. One has now to separate the potential increase of a carbon source from simple change in core plasma temperature and hence increased emissions. Taking the data on CIII emission an comparing this to the trend displayed we can deduce that the main change in the CIII emission is due to the increase of input power and not from the slight increase in C composition as displayed in Fig.3 where only 20% more carbon is visible in contrast to the factor of 10-15 observed here. In particular one can observed that the dependence on input power is the same for JET-C and JET-ILW. In conclusion no apparent strong arbon sources are evolving so far from potential damage of W-coated divertor surfaces. Figure 5(a) is showing PIN as well as the radiated Power in the course of the JET Pulse No: since 70000. The wide range of applied power is apparent as is the development since installation of the ILW. The overall input power is steadily increasing from ohmic plasmas to H-Modes.

3.2. IMPURITY EVENTS

In addition to the general long term impurity evolution also spurious impurity in fluxes from the first-wall and divertor were detected as irregular occurrences of additional radiation during all available plasma scenarios. The statistics presented here are with resect to events occurring during the flat-top main heating phase of the plasma. Additional events occurring during the ramp-up are not considered here. These events are probably small particles or dust occurring with a typically rise time of ms and sometimes lead to a long lasting increase(4s) in radiated power, potentially adding several 100kW up to a few MW to the steady state bulk radiated power level, typically 10-50% of the applied heating power. Data from the visible divertor spectroscopy shows only a few of the events, so far eluding definition of composition and origin of the source. These events can cause significant impact on plasma operation even though only a few have induced a disruption during the main heating phase. The frequency of these events is quite steady through out the JET-ILW campaign, hinting to a conditioning effect only appearing during constant plasma operation. Disruptions can however increase the number of events occurring in the subsequent 2-3 discharges apparently stirring up additional particles [4]. Performing different plasma scenarios, with distinct strike-point positions and input power variations an overall cleaning is not yet observed. The composition of these particles is determined from main chamber UV measurements from high-Z elements. Major contributions come from W and Ni/Fe/Cr, the latter grouped together since they should originate from Inconel or steel. The composition of more than 15% of the detected events could not be determined through UV measurements and could be caused by low-Z impurities e.g. The origin of the particles is thought to be either left over cuttings from in-vessel machining or abrasions from W-coatings due to installation. In addition melt damage on the beryllium limiters as well as the target Langmuirprobe tips from initial in vessel inspection was identified.

CONCLUSIONS

The carbon concentration has reduced by at least a factor of 10-20 compared to the CFC dominated JET-C. Carbon emissions despite their evolution with input power are not evolving drastically different from the JET-C. No apparent additional sources of carbon were observed, despite a slight increase in carbon in the divertor emissions - potentially from background carbon still remaining. Oxygen gettering by Be is quite beneficial as only low amounts of oxygen are observers. The divertor composition, especially the inner divertor material mix is still evolving despite the early campaign dominated transport towards a steady state divertor. Changes in plasma operation and especially heating power and density are likely to be the root cause for the observed behaviour. Dedicated effects relating to RF heating are observed with respect to High-Z core accumulation [7]. In contrast to the JET-C a large number of impurity events from W and nickel are observed impacting on plasma operation due to large tungsten radiation spikes. Constant plasma operation improves the situation, a long term conditioning is however not observed. In general a steady state with the JET-ILW is reached despite minor changes in divertor and main chamber emissons at the beginning of the campaign.

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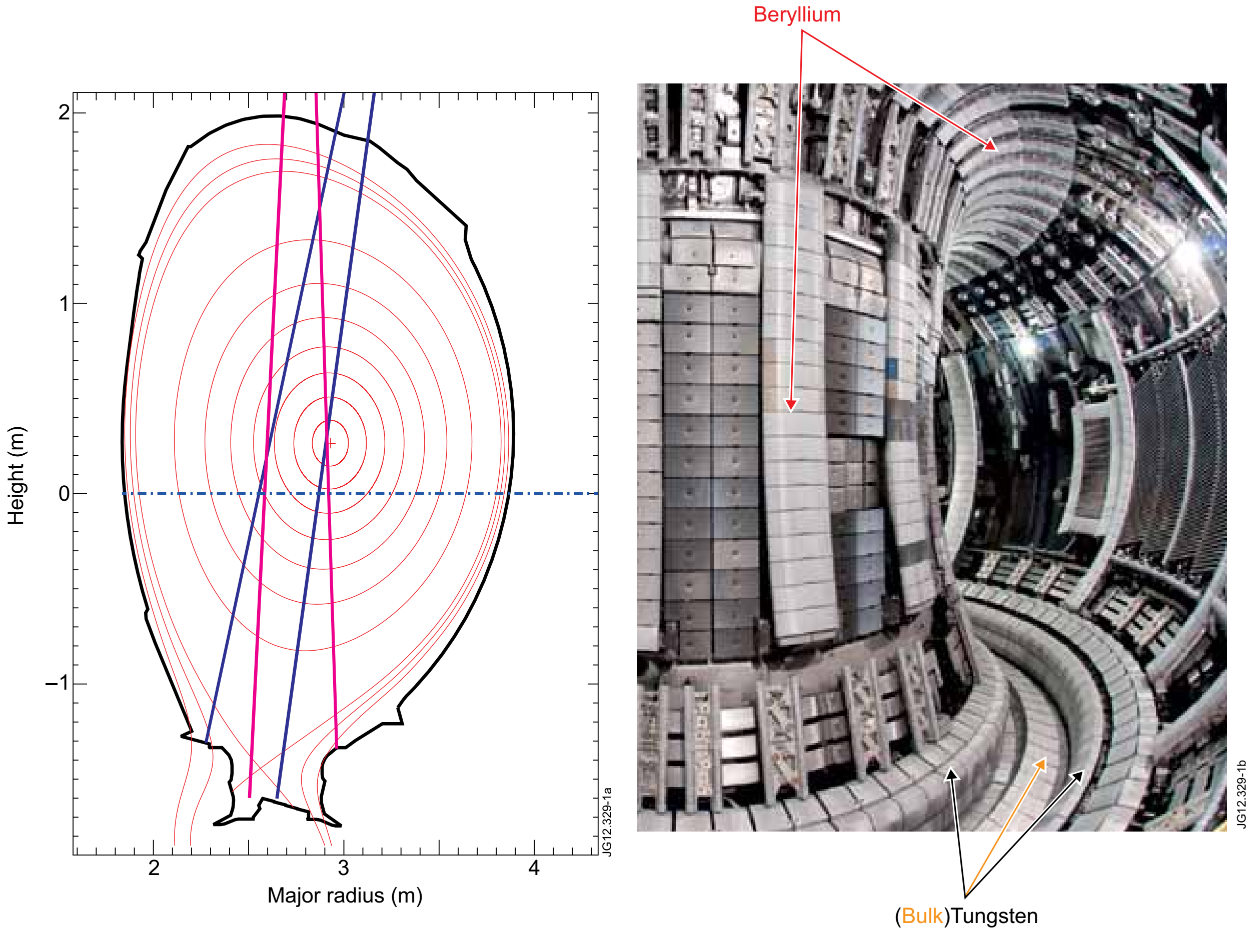


(a) Visible Divertor Spectroscopy(pink, blue) and Main Chamber UV(blue) lines-of-sight superimposed on JET inner wall and typical monitoring pulse plasma configuration

(b) The ILW of JET with beryllium first-wall and a tungsten divertor.

Figure 1: Diagnostic setup(a) and material mix of JET.

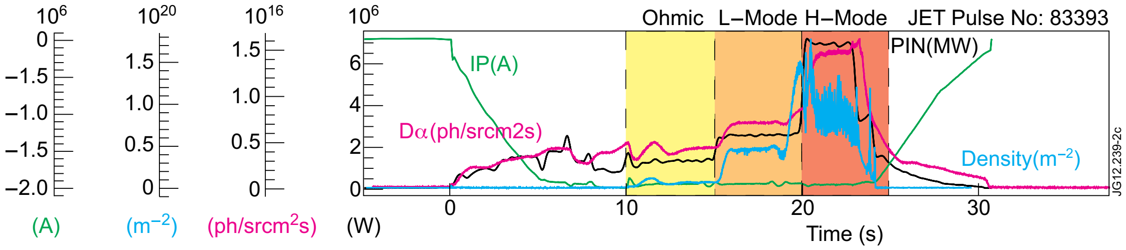


Figure 2: Typical timetrace for a monitoring pulse, here JET Pulse No: 83393.

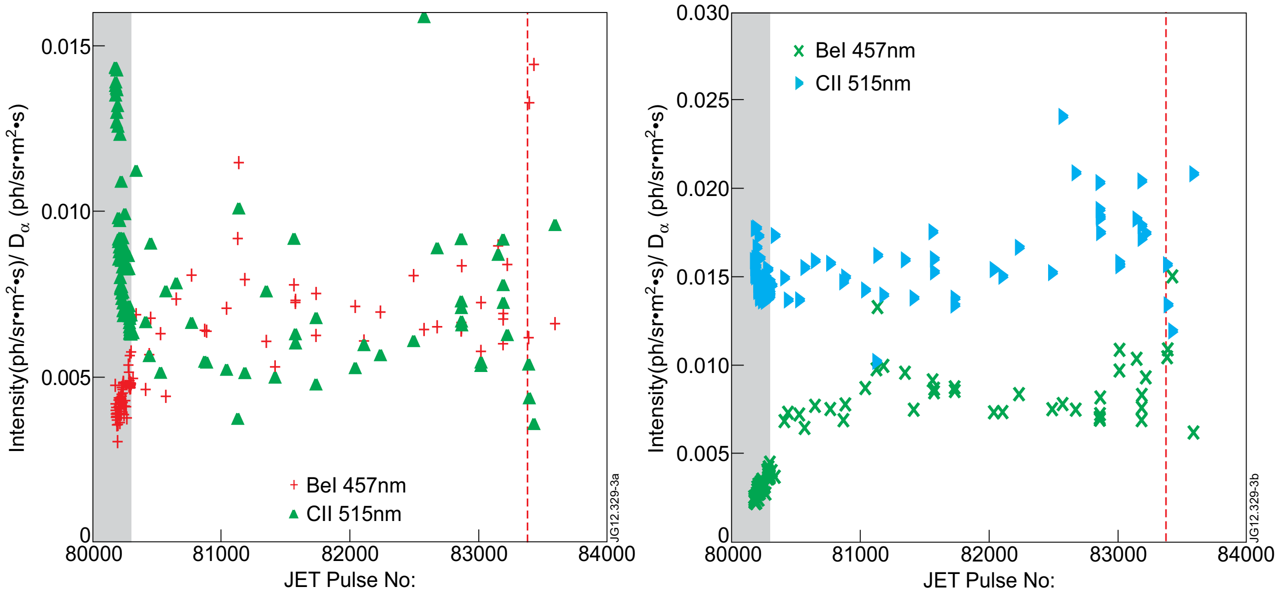


Figure 3: (a),(b) - CII(515nm) and BeI(457nm) Emissions normalized to D_α from monitoring pulses throughout the 2011/2012 JET campaign. The grey area depicts a period of initial constant ohmic plasmas. The red vertical line indicates a Be evaporation.

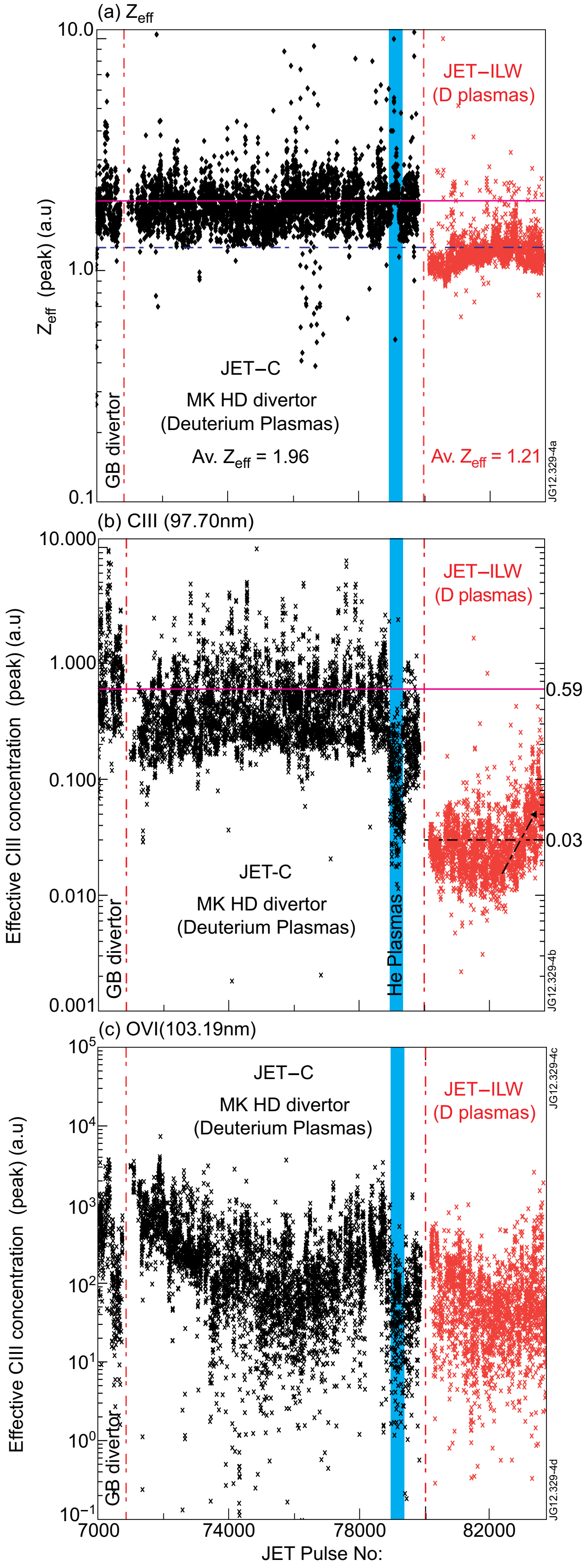


Figure 4: Evolution of main plasma UV emissions for C and O and Z_{eff} (JET Pulse No: 70000-83690).

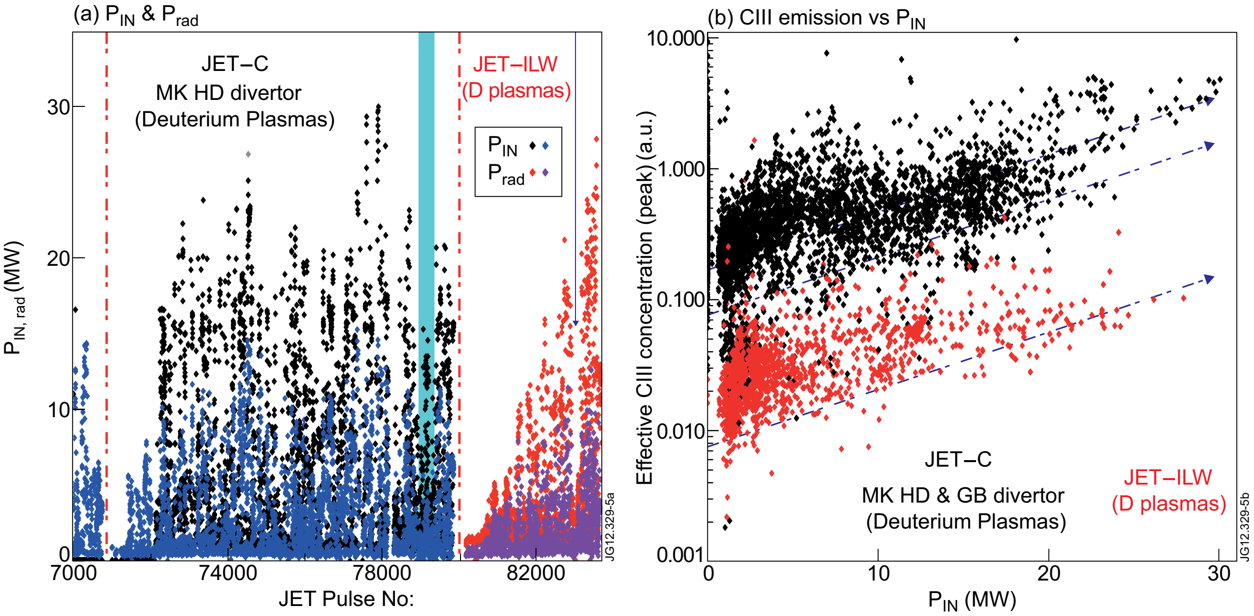
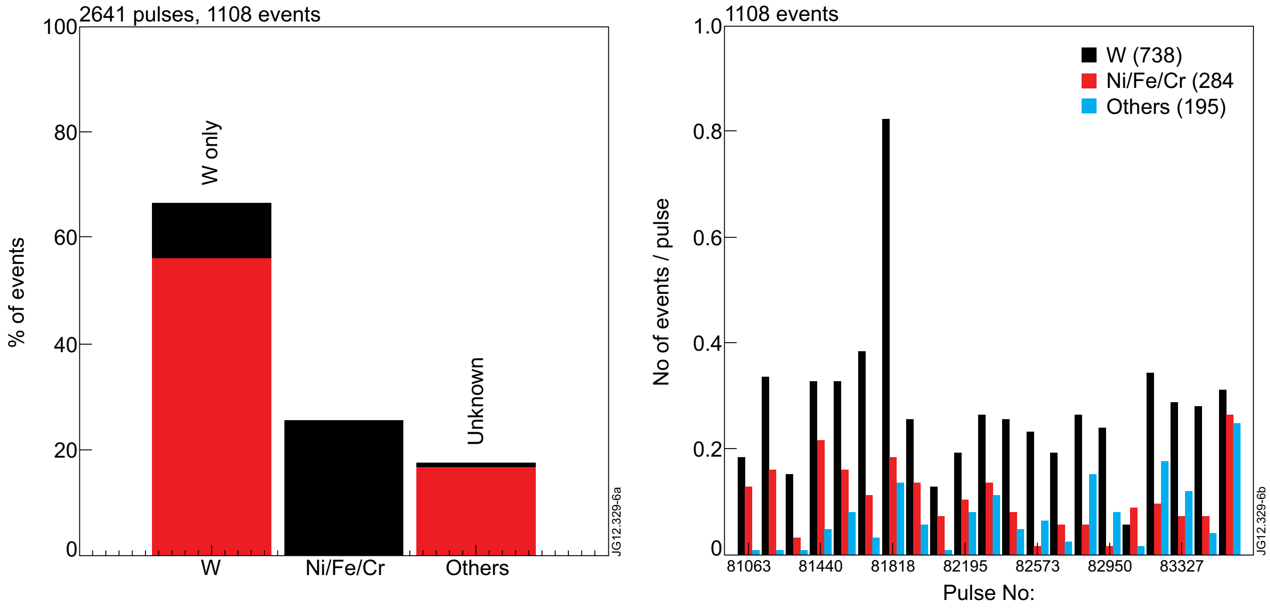


Figure 5: Data on input power and relation to effective carbon concentration/ emission for both the JET-C and JET-ILW configurations JET Pulse No: 70000-83690.



(a) Event Composition - Overview

(b) Number of events per discharge(element resolved) Details

Figure 6: Statistics of the Impurity Events during the 2011 / 2012 JET run period.