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The Second Phase of JET Operation with the ITER-Like Wall

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ABSTRACT

The first priority for the 2013 JET campaigns will be to provide relevant data for the ITER decision on the day one divertor material selection. In particular, a tungsten melt experiment using a specially modified divertor module will study the characteristics and impact of ELM induced melting on plasma operation – only JET has large enough ELMs to perform such a test. The second priority is to better understand why the change to an all metal wall has restricted access to scenarios with high normalised energy confinement (H-factor). This unexpected result may be partly due to the impact of the higher fuelling needed to control tungsten levels but in some scenarios there is also an effect related to the loss of a beneficial effect of carbon as a plasma impurity. In parallel with pushing JET's core plasma parameters as close as possible to those in ITER, we also intend to develop ITER demonstration pulses including as many of ITER's requirements as possible but not focusing on core performance. Another high priority item is the study of the generation and mitigation of runaway electrons which are so far not created in JET disruptions but are potentially very challenging for JET and ITER. Finally, there is still important work to be continued on key plasma-wall interaction issues ranging from material migration to fuel removal studies.

1. INTRODUCTION

This paper describes, in the light of the results obtained so far, the priorities for the further exploitation of the JET ITER-like Wall in the next experimental phase which begins mid-2013. JET's first campaigns with the ITER-like Wall ended in July 2012 after around 3500 pulses had been run (20 hours of plasma). The 2011/12 programme was gradual in expanding performance with commissioning phases interleaved with scientific exploitation as new capabilities such as heating power, protection systems and routine disruption mitigation were released . The programme combined scenario development with a strong focus on ITER critical plasma-wall interaction issues. Operation with the ITER-like Wall was characterised by low levels of residual carbon and oxygen [5], low fuel retention [26], extremely reproducible breakdown [11], extended detachment window and increased disruptive density limit [19]. A very significant difference to previous JET operation was that the 2011/12 remote intervention into the vessel was primarily motivated by the need to remove long-term samples for analysis.

The current reference timeline for JET operation until 2018 is shown in figure 1. At the time of writing detailed planning for the campaign from 2013 to early 2014 is in place and detailed discussion of experimental priorities for continuation with a campaign of hydrogen plasmas of about one month duration is imminent. A shutdown starting in spring 2014 will allow further removal of long-term samples for surface analysis [7, 46] and also refurbishment of the ITER-like ICRH antenna [Durodie] which will increase the potential power available for central heating which is important for tungsten control [38]. Full performance DD operation is planned for 2015 followed by a He plasma phase with He neutral beams which is relevant for the low activation phase of ITER. A shutdown in 2016 paves the way for a final DT campaign. The philosophy here is to avoid any major surprises due to isotopic effects which were a challenge in JET's first DT experiment [Keilhacker]. This will be achieved by starting with hydrogen plasmas (and hydrogen neutral beams) and changing to 100% tritium which in combination with existing deuterium plasma data will allow a complete characterisation of isotopic mass effects under conditions of low activation. The final 50:50 DT experiments are proposed to have a budget for 14MeV neutron production which is six times higher than for JET's previous DT experiment and this allows much greater possibility for plasma optimisation and to address a wider range of technological issues [Batistoni] such as neutron damage of ITER relevant functional materials.

This paper will focus on the strategy adopted for planning the 2013/14 JET campaigns and places them in the context of experimental results from the first campaigns with the ITER-like Wall [33]. The JET Task Force Leaders are set "headlines" which define the programme priorities and provide a framework for developing the detailed planning around experimental proposals submitted by participation European Fusion Associations. The headlines for the 2013/14 campaigns are:

i) Support for ITER decision on day-one armour material
ii) Assessment of ITER operating scenarios with the ITER-like Wall
iii) Physics studies essential for efficient exploitation of the ITER-like Wall and ITER

The sections in this paper mirrors these headlines.

2. SUPPORT FOR THE ITER DECISION ON DAY-ONE ARMOUR MATERIAL

The priority given to this headline is driven by the ITER Organisation's proposal to begin operation with an all tungsten divertor rather than the long standing reference configuration which has areas of carbon-fibre composite tiles at the inner and outer strike points [37]. JET data will be critical for evaluation of the risks ITER will face if the strategy is changed. Particularly important are experiments related to tungsten melting by ELMs since JET is the only tokamak with sufficient stored energy to have a realistic chance of studying this.

2.1 ELM INDUCED MELTING OF TUNGSTEN

There has been extensive work on bulk tungsten melting due to steady state heat loads in tokamaks [8, 22] and this shows that the consequences can be very significant for subsequent plasma operation [25]. It is hoped however that shallow melting by transient events in ITER is more benign [37] and will not develop in a cascading failure. The range of ELM energy density predicted to produce significant melt layers is 1-2MJ/m^{-2} for a rise time of 0.5ms. This is comparable to the parallel energy density in JET [15] which means that a tungsten edge deliberately introduced into the JET divertor which is normal to the magnetic field will experience relevant conditions for the study of ELM induced melt layers. The plasma pressure during an ELM is directly proportional to the pedestal pressure and in JET this is about 10 times lower than ITER. However, the normal component of the pressure at an exposed edge in the JET divertor will be similar to that for the divertor surface in ITER due to the difference in angle of incidence.

To study ELM induced events in JET, a dedicated module of the bulk tungsten divertor [34] has been installed which contains a deliberately misaligned tungsten lamella in the innermost row of the tile (stack A), creating an exposed edge or step between lamellas as shown in Figure 2.

The original bulk tungsten tile modules were designed to avoid exposure of edges to the parallel heat flux over a wide range of field angles and installation tolerances [34]. The new module on the other hand introduces a deliberate step which tapers from 0.25mm up to 2.40mm to allow study of the effect of gyro-radius smoothing on the heat flux and hence melting of the edge. This range was dictated by the ~1.3mm gyro-radius of a deuteron at ~500eV, which is characteristic of the typical pedestal with ITER-like Wall [3]. A decision may be taken to extend the study to include bulk tungsten melting in JET. Although this has already been studied in other tokamaks, JET would be able to look specifically at the additional effect of large ELM energy densities on re-solidified material.

3. OPERATING SCENARIOS COMPATIBLE WITH THE ITER-LIKE WALL

There are two distinct branches of research into ITER-relevant operating scenarios which are represented in the structure of the upcoming JET programme. The first has the objective of approaching, as closely as possible, the conditions in the core of ITER. These scenarios will push towards high plasma temperature at the highest possible plasma current and toroidal magnetic field. These discharges will naturally have high DT fusion reaction rates and so are also candidate scenarios for the future DT phase of JET. In the first JET DT experiment in 1997 [21] high fusion performance was achieved using ELM-free hot ion H-mode plasmas which are intrinsically transient (i.e. sustained for around one energy confinement time) and have $T_i \sim 2T_e$. The focus with the ITER-like wall will be on achieving maximum core performance in quasi steady conditions (i.e. many energy confinement times) with $T_i \sim T_e$ as will be the case in ITER.

The second branch of the strategy will focus on achieving an integrated ITER scenario with all the features demanded by an ITER baseline pulse. This will extend from relevant current ramp-up to integration of impurity seeding and ELM control. The aim in this case is not optimisation of core performance but to develop the tools ITER requires and see how a realistic set of constraints interact while pushing JET to the limits consistent with this.

Tungsten presents challenges for both core plasma optimisation and development of an integrated scenario due to its ability to radiate large amounts of power from the centre of the plasma [Puetterich NF, Neu]. Figure 3 compares the charge state distribution in coronal equilibrium for tungsten and beryllium as a function of electron temperature. Beryllium is fully ionised outside of the temperature range characteristic of the divertor and scrape-off layer where as tungsten is partially ionised at all achievable temperatures across the whole plasma and can therefore radiates power even at the centre of the plasma.

3.1 THE ITER-LIKE CORE PLASMA AND THE ROLE OF MATERIALS

One of the main challenges for developing operating scenarios compatible with the ITER- like Wall is the additional constraint imposed by the tungsten divertor. In the core of JET (and ITER), tungsten is only partially ionised and therefore radiates efficiently, unlike beryllium or carbon which are fully ionised in the plasma edge. Experience in JET with the ITER-like Wall [33] is exactly parallel to ASDEX-Upgrade [35] with an all tungsten wall, showing that to avoid core radiation collapse due to W accumulation the following strategies are required:

i) Sufficient gas fuelling / edge density to cool the divertor thereby reducing the tungsten source and also improve the divertor screening.
ii) Raising the ELM frequency by gas fuelling or other ELM control methods to enhance flushing of tungsten from the main plasma.
iii) Central heating to prevent tungsten accumulation through enhancement of anomalous transport to offset the neo-classical pinch [14].

3.1.1 The role of gas fuelling

Figure 4 shows two identical H-mode discharges with the ITER-like Wall. One has low gas fuelling and low ELM frequency (Pulse No:81913) which eventually leads to accumulation of tungsten in the core of the plasma leading to a decline sawtooth activity inside the $q = 1$ surface which ultimately results in a collapse of the central temperature [33]. Pulse No: 81829 has strong gas fuelling into the divertor at a rate of $\sim 5\times10^{22}$/s which results in a much higher ELM frequency leading to a stable and decreasing bulk plasma radiation. There are a number of transient impurity events [Sertoli] in this discharge caused by tungsten particles, the most obvious of which is at 10s. These events demonstrate that the tungsten is being effectively exhausted from the plasma. In general, JET results indicate that reductions in the source due to gas fuelling are not as significant as one might expect because ELMs become dominant in producing tungsten at higher densities [41]. The change in behaviour when fuelling H-modes seems mainly due to changes in transport in the edge and core. Fuelling may also help flatten the density profile thus reducing the neo-classical pinch which leads to peaking of tungsten at the centre of the plasma. At the same time, ELMs are thought to improve flushing of impurities from the edge and increased divertor density may improve the divertor screening [39]. Assessing the relative importance of these factors and manipulating them to allow access to lower densities with the potential for improved confinement and higher central temperatures is a major theme for the 2013/14 campaigns.

Disentangling the relative role of the different factors which allow gas fuelling to control tungsten in H-mode is difficult but one tool which will be used more in the next campaigns is the use of small vertical kicks of the plasma to trigger ELMs [Luna]. This allows us to vary ELM frequency independently of the gas fuelling rate and initial results already suggest that this can be beneficial in controlling tungsten but we do not yet know to what extent it also usefully extends the operating space. Vertical kicks are therefore an important tool for the next campaigns.

Although gas fuelling was very effective at controlling tungsten with the ITER-like Wall, gas fuelling (or the edge density that arises from it) were found to degrade the normalised energy confinement

(H-factor) in both low (δ~0.2) and high (δ~0.4) triangularity ELMy H-mode baseline plasmas [Joffrin]. This behaviour is in contrast to experience with the JET carbon wall where high triangularity plasmas tolerated relatively high gas fuelling rates thus achieving high energy confinement and high density simultaneously [44]. The finding that the all metal wall could produce such a striking change in energy confinement behaviour was a surprise which potentially has significant implications for ITER baseline scenario performance (and therefore JET fusion performance in H-mode baseline scenarios in DT). Further characterisation of this behaviour is planned for 2013/14, in particular to explore wider variations in divertor configuration and triangularity while at the same time exploring measures to control tungsten to allow stable access to lower fuelling regimes.

3.1.2 Higher plasma current

Another key ingredient for obtaining the most ITER-like core plasma in JET is to raise the plasma current and toroidal field. In the first ITER-like Wall campaigns stable H-modes have been created with up to 3.5MA of plasma current have been created [Joffrin], Figure 5. Although these have reduced energy confinement ($H_{98Y} \sim 0.7$) which may be partly due to the gas fuelling used to reduce the risk of tungsten accumulation, the plasmas are extremely clean ($Z_{eff} \sim 1.2$) [5] compared to shots with the carbon wall (typically $Z_{eff} = 1.8$-2.5). The reduced dilution will provide some benefit in terms of the thermal fusion power in the DT phase due to its dependence on the square of the deuteron density. However, raising the central temperature is still the most critical for overall fusion performance. With up to 34MW of neutral beam power available in future campaigns along with up to 6MW of ion cyclotron heating, we expect to able to reach currents of at least 4.5MA. This can only be done safely in an integrated way which respects the limits of the plasma facing components and impact of tungsten on the plasma.

3.2 OPERATION AT HIGH NORMALISED PLASMA PRESSURE (B_N)

Another route to higher core performance is to raise the ratio of input power to the L-H threshold power [30]. By operating JET at lower current, normalised plasma pressures up to β_N~2.8 [3, 29] have been obtained. High normalised plasma pressure is a feature of "hybrid" plasmas which have a more optimised current profile to control MHD instabilities and aim to provide ITER with the potential to run longer Q=10 pulses at reduced plasma current (lower risk of disruption damage). While the normalised energy confinement (H-factor) achieved with the ITER-like Wall are very similar to carbon wall results for both low and high triangularity plasma shapes [3], the detailed picture is not so simple with reduced pedestal pressure but increased core confinement which compensates. Although overall energy confinement properties are good, these discharges have proven harder to sustain than with the carbon wall. This seems to be due to the fact that when neo-classical tearing modes appear on rational surfaces they speed up transport of tungsten into the core and tungsten accumulation may in turn accelerate the growth of the modes [Joffrin]. The use of tungsten as a plasma facing material has therefore increased the priority given to avoiding or controlling such MHD modes and this will be one of the goals of the upcoming JET campaigns.

3.3 THE INTEGRATED ITER SCENARIO

The focus of this experiment will be on achieving an integrated ITER scenario with as many of the features demanded by an ITER baseline pulse as possible and less emphasis on maximising core plasma parameters. This scope will include: relevant current ramp-up and ramp-down, integration of impurity seeding, tungsten and ELM control, pellet fuelling, real time control and long flat top. Heating schemes reflecting the build-up of alpha power in ITER and proximity to L-H threshold will also be considered. The aim is to develop the tools ITER requires and see how a realistic set of constraints interact while pushing JET to the limits consistent with this. Some examples are given in this section.

3.3.1 IMPURITY SEEDING

One key element of an integrated ITER scenario is power load control by impurity seeding. Such techniques might also be necessary in achieving ITER-like core plasmas simply to stay within the thermal limits of the divertor [1]. Initial studies were made on the use of nitrogen as a seed impurity with the ITER-like wall [16]. These showed that very low inter-ELM power load and electron temperature ($T_e \sim 5$eV) could be achieved. The inter-ELM tungsten flux is reduced essentially to zero with sufficient with nitrogen seeding by reducing the impact energy of the ions below the sputtering threshold for tungsten[Rooij] but the tungsten flux during ELMs remains high due to re-attachment of the plasma. This limited ability of detached/radiating plasmas to buffer ELMs is well known and increases in significance as tokamaks get larger [27, 40]. The behaviour of the tungsten source during ELMs in a nitrogen seeded pulse is illustrated in figure 6.

One unexpected feature of experiments with nitrogen seeding was an increase in H-mode pedestal pressure, mainly temperature, and overall energy confinement time in high triangularity plasma configurations [16]. Figure 7 shows the normalised energy confinement time as a function of nitrogen fuelling rate for similar discharges with the carbon wall and ITER-like Wall. This behaviour strongly suggests that the change in confinement properties seen with the ITER-like wall is related to an absence of carbon as an impurity since nitrogen has only one more electron than carbon and so is a good substitute. The use of nitrogen seeding at first seems ideal since it can both mitigate inter-ELM power load and tungsten sources and improve energy confinement. So far however, the plasmas have been non-stationary with symptoms of tungsten accumulation. This is presumed due to a combination of the ELM related tungsten source and good pedestal confinement. Integration of tungsten control measures into impurity seeded plasmas will be a priority for the upcoming work in this area and will explore vertical target divertor configurations which may have better divertor screening of tungsten sources, central heating with ICRH to enhance the outward anomalous transport and ELM pacing to flush tungsten from the edge pedestal.

Despite the potential benefits for using nitrogen in high shape plasmas in JET and ITER, it is certain that JET will not use nitrogen seeding in a future DT campaign due to nitrogen's ability to poison the uranium beds used to store the tritium. ITER too has a potential problem if the production and exhaust of ammonia into the pumping system is too high. JET has relevant data with the ITER-like wall on this issue but an unambiguous diagnosis of ammonia in the exhaust is difficult [Gruenhagen] and so new experiments are now planned which it is hoped will resolve the issues.

Neon will be explored further as an alternative radiating species since it is compatible both with ITER and JET tritium plants. At the same time, it should provide further insight into the physics of the improvement in energy confinement seen with nitrogen since the atomic number of neon is about 3 times that of carbon. Neon will radiate further into the plasma and produce less dilution of the deuterium ions for a given Z_{eff}.

3.3.2 CURRENT RAMP UP

The integrated ITER scenario we hope to create will not only put together all the elements we think are necessary for the flat top of the discharge e.g. seeding/partial detachment under real time control, ELM pacing, disruption mitigation and tungsten control but will also consider the beginning and end of the discharge. The ramp-up phase has been concern for ITER due to flux consumption and need to enter H-mode before the full current is reached and at a relatively low density to minimise the L to H threshold power. Results from JET so far do not support the concern that entering H-mode in a relatively low density attached will cause a problem with tungsten accumulation, as shown in figure 8 [6]. Tungsten accumulation has not been a problem in L-modes with the ITER-like Wall, presumably because of poorer confinement properties.

4. OTHER PHYSICS STUDIES EXPLOITING THE ITER-LIKE WALL

There are a wide range of studies falling under this headline in the future programme but the most significant from the perspective of plasma facing materials and components are described in this section.

4.1 MATERIAL MIGRATION

The start of JET operation with a completely fresh ITER-like wall was made part of the scientific programme and provided a unique opportunity to study migration of beryllium migration to the divertor [23]. The first shutdown after JET operation with the ITER-like Wall was also an integral part of the programme in the sense that its primary purpose was retrieval of plasma facing components and long-term samples for analysis which was preceded by 2 weeks of identical H-mode plasmas to provide clear reference plasma conditions. Preliminary analysis and inspection of these items outside the machine has already produced many interesting results [46, 7, 18, 20]. The deposition rate of beryllium in the divertor seems extremely low, particularly in remote areas and overall much lower than we would have expected from the relative sputtering yields of carbon and beryllium. The overall deuterium retention is still being evaluated but also seems low compared to the deposited beryllium. The aim in the near future is for a full quantitative analysis of the data from this first ITER-like Wall intervention using a wide range of techniques. For the next campaigns the existing set of long-term samples and marker tiles have been replaced but with a few improvements. One significant change is the use of precision weighing of individual tiles prior to installation (±10mg) which will provide valuable verification of tile profile measurements which require an assumption about material density [Heinola]. Special dust collectors have also been installed which will enhance our ability to collect and characterise dust and relate it to observations of particles and dust in plasma discharges [45]. Although only ~1g of dust was recovered in the first ITER-like Wall shutdown, the conversion factor between deposits and dust would be expected to grow in time as stability limits are reached for deposited layers. Long-term monitoring is therefore a necessary aspect of the future programme.

Standard monitoring pulses were routinely run in the first campaigns with the ITER-like Wall and proved valuable for assessing the long-term evolution of impurities such as residual carbon [9]. They will continue to be used in future JET campaigns to look for signs of changing surface conditions such as erosion or delamination of tungsten coatings [43] leading to increased carbon concentrations.

Finally it is worth noting that the plan to explore plasmas in hydrogen, deuterium and pure tritium as well as helium will offer interesting opportunities for the study of plasma wall interactions. One special example is the study of surface modifications due to helium implantation in tungsten [31].

4.2 FUEL RETENTION

The results from gas balance measurements made in the first experimental campaign with the ITER-like Wall appear to confirm the ITER predictions of at least one order of magnitude reduction in long-term retention with respect to the carbon wall [4]. The use of gas balanced based on collecting gas over multiple discharges and quantifying it using JET's active gas handling system (AGHS) can provide sufficient accuracy to determine the longer term retention with respect to one day of operation, but comparison with post-mortem analysis which is half a year after end of operation requires consideration of the long term outgassing. The latter is similar in JET-C and JET-ILW and represents when integrated over long periods of time in a non-convergent function. Progress has however been recently made in understanding the physics involved [36]. Partly due to the difficulty in determining the absolute long-term retention except by surface analysis methods, the focus of future experimental work will be on fuel removal strategies (e.g. ICWC [13]) using isotope exchange between deuterium and hydrogen and on trying to understand whether the deficit in the gas balance seen with nitrogen seeding is related to pumping of ammonia by the nitrogen panel of the divertor cryopump [Gruenhagen] rather than increased trapping in the vessel.

Operation for one month with hydrogen plasmas and hydrogen neutral beams before the 2014 intervention is also planned as shown in Figure 1. Analysis of the long-term samples for deuterium will provide a good indication of the minimum fuel retention level that might be achievable in ITER after clean-up.

4.3 RUNAWAY ELECTRONS AND THEIR MITIGATION

Runaway electrons and their mitigation are critical ITER issues [Loarte NF] which are given high priority in the upcoming JET campaigns. Due the risk of melt damage runaways have not so far been deliberately created in the ITER-like Wall phase of JET and have not been an issue during disruptions due to the reduced electric field (clean plasmas) associated with the beryllium wall [Lehnen]. Runaway electrons were however produced in two discharges early in the first campaign when emergency shutdowns were initiated by a technical problem just after plasma breakdown leading to shutdown of power supplies and other systems. This procedure was applied with the carbon wall and created no problems but with the beryllium wall, shutdown of the gas fuelling led to pump-out of the density but with enough loop voltage to drive a current of around 0.5MA. After about 16s in the case of pulse 80273 (see Figure 9) the runaways hit the bottom of the inner wall guard limiter which is protected by a tungsten coated carbon fibre composite tile leading to melting of the coating [Ruset]. The tungsten particles produced in this event may have contributed to the transient impurity events seen with the ITER-like Wall [Sertoli].

Experiments have been scheduled in 2013 to generate and attempt to mitigate runaway electrons using two independent massive gas injection systems loaded with different mixtures. This however is dependent on the outcome of a detailed risk assessment involving estimations of the energy deposition by runaways in various plasma facing components which might be hit by unmitigated runways. As shown by the example of Figure 8, the potential for damaging the ITER-like wall in JET is very real which is why this work is of such high importance for ITER.

CONCLUSIONS

The next phase of JET operation with the ITER-like Wall involves a broad range of experiments in support of ITER. All but a few of these are closely linked to the issues associated with the use of tungsten and beryllium as wall materials. Even when the mission is core parameter optimisation, the most challenging constraints come ultimately from the wall via the effect on confinement properties, tungsten accumulation and power handling. This means that a more multi-disciplinary approach is increasingly being employed at JET so that all aspects can be dealt with in a more integrated way from characterisation of impurity sources to control of MHD modes. In parallel with the operation of JET is the programme for retrieval and analysis of plasma facing components and long-term samples which is considered an essential and integral part of the scientific programme with the ITER-like Wall. Preliminary results from the first such intervention are looking very positive for ITER but longer term evolution of the erosion, deposition, fuel retention and dust will have to be studied as JET moves towards full performance and some of the processes such as dust conversion reach equilibrium. With a full DT campaign a key part of the longer term plan, the prospects for advancing our knowledge of relevant plasma facing materials and components in an environment as close as possible to ITER was never greater.

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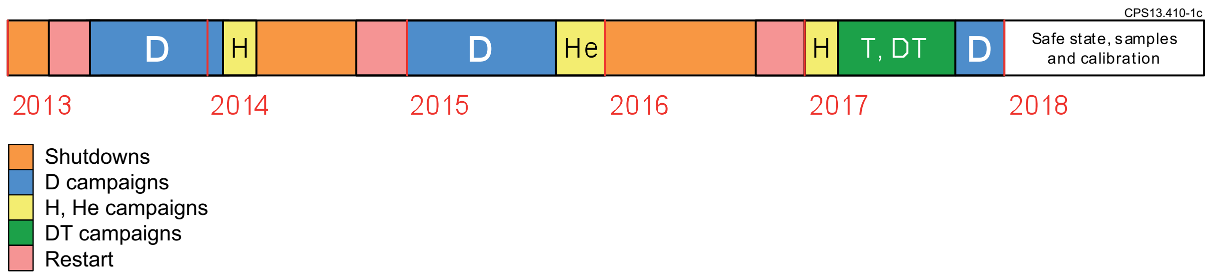

Figure 1. Reference JET forward timeline. Different plasma (and neutral beam) species are indicated for each phase.

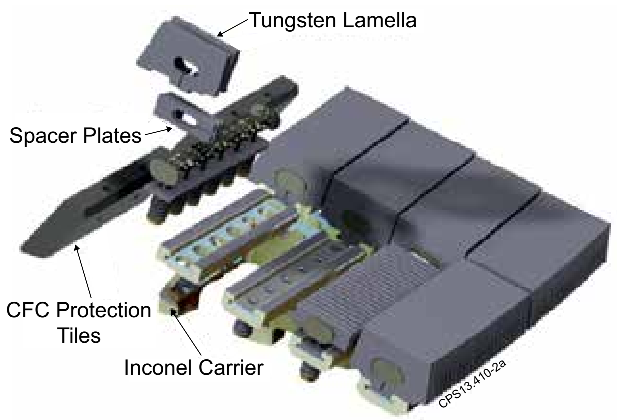

Figure 2: (a) JET bulk tungsten tile module [34].

Figure 2: (b) Special lamellas installed for the JET tungsten melt experiment.

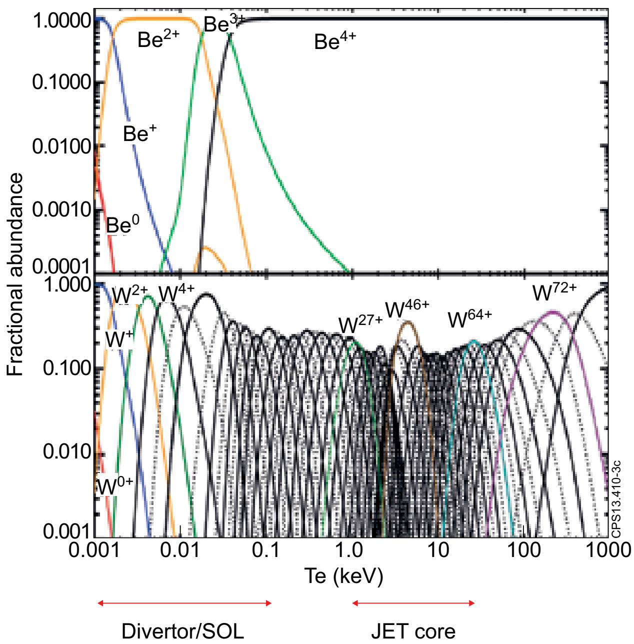

Figure 3: Charge state fractional abundances for tungsten and beryllium as functions of electron temperature calculated for coronal equilibrium using the ADAS database [ADAS]. Electron temperature ranges characteristic of the JET divertor/scrape-off layer and core are indicated.

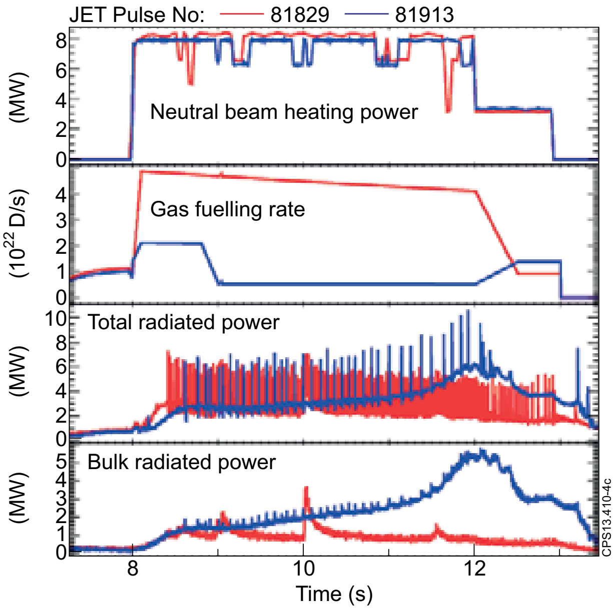

Figure 4: shows two identical H-mode pulses with low and high divertor gas fuelling rates with very different bulk (main plasma) radiation behaviour. Pulse No: 81913 has low gas fuelling, low ELM frequency and monotonically increasing radiation. Pulse No: 81829 has a high gas fuelling rate leading to stable and decreasing bulk radiation which is resistant even to transient impurity events [45] such as the one seen at 10s.

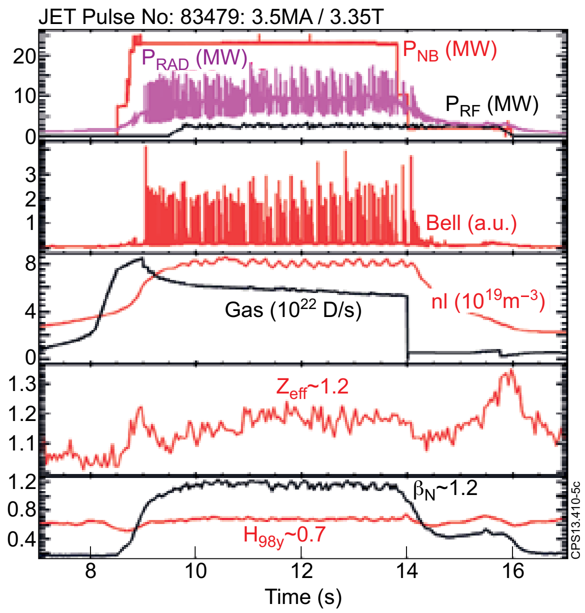

Figure 5: shows an example of the highest current (3.5MA/3.35T) pulses achieved in the first campaigns with the ITER-like wall. This pulse had around 27MW of total input power in a low shape (δ=2) baseline H-mode plasma [29].

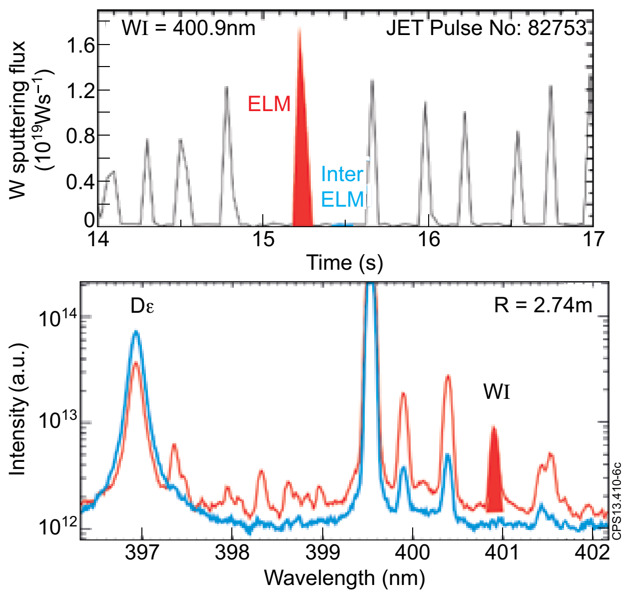

Figure 6: shows the total divertor tungsten influx in a nitrogen seeded H-mode derived from a spectrometer diagnostic which has a 100ms integration time. The inter-ELM tungsten source is negligible.

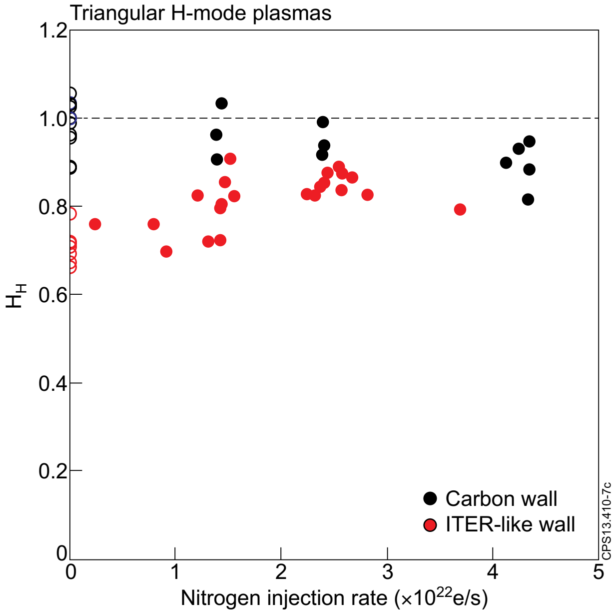

Figure 7: shows normalised energy confinement time as a function of nitrogen injection rate in high triangularity H-mode plasmas for carbon wall and ITER-like Wall [16].

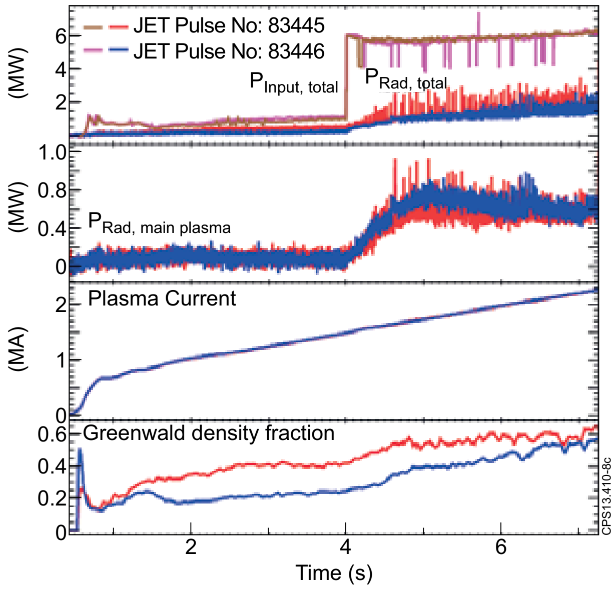

Figure 8: shows an L-H transition during current ramp up at two different densities. The main plasma radiation stays stable and low indicating that there is no problem due to tungsten accumulation, even at low density.

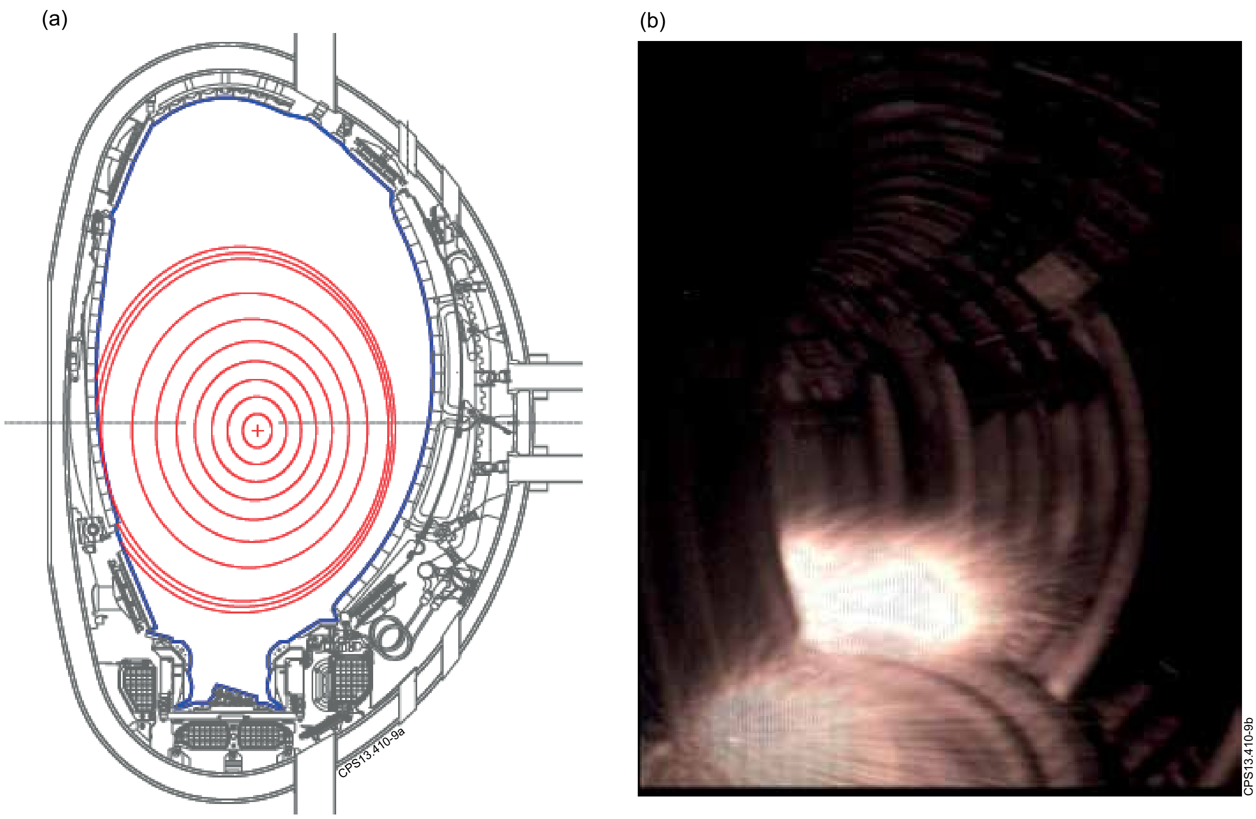

Figure 9: (a) shows the equilibrium reconstruction for Pulse No: 80273 at 16s when the runaway electons strike the bottom tungsten coated tile of the inner wall guard limiter releasing showers of tungsten particles as seen in the wide angle visible image of Figure 9(b).