CONFERENCE PRE-PRINT

TUNGSTEN LIMITER START-UP EXPERIMENTS IN DIFFERENT BORONIZATION STATES IN SUPPORT OF ITER

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Abstract

To understand the performance of limiter plasma in the ITER plasma start-up phase is important for the whole pulse and a possible challenge if performed on tungsten. Experiments were done on ASDEX Upgrade, EAST and WEST to characterise limiter plasmas and to give boundary conditions and validation possibilities to edge codes, e.g. SOLPS-ITER. In addition the effect of boronizations, especially with toroidal asymmetries, has been documented on WEST and ASDEX Upgrade.

1. INTRODUCTION

The re-baseline of the ITER Research Plan [**Loarte25**], especially the change of the first wall (FW) material from beryllium (Be) to tungsten (W), requires re-validation of the foreseen operation scenarios. A critical point here is the initial ramp-up phase, which will be carried out in a limiter configuration (nominally on the inner column FW panels for ITER) until the poloidal field (PF) coil currents can be high enough for X-point formation. During this phase of the pulse, the direct plasma contact on W surfaces without the screening provided by diverted operation is expected to lead to high radiative fractions [**Pitts25**], excitement of MHD modes and even disruptions. Even if the ramp-up is successful, the increased radiation could lead to lower temperatures and an increased flux consumption, resulting in a shorter flattop duration.

In 2023 the ITPA IOS (International Tokamak Physics Activity, Integrated Operation Scenarios) group proposed a multi-machine experiment to be carried out in tokamaks with a W first wall (AUG, EAST and WEST) to better quantify the W source (usually quantified by visible spectroscopy) under

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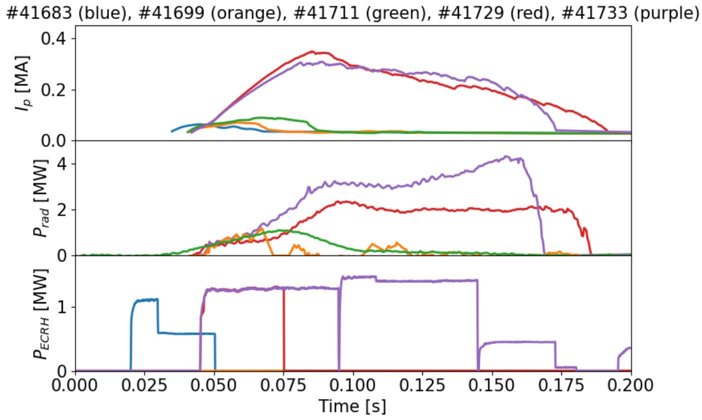
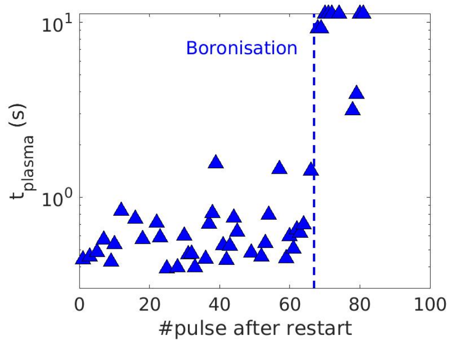


(a) AUG Top: plasma current, middle total radiated power and bottom ECRH injected power. Selected restart plasmas are shown (out of 60). The pulses with less than 100kA plasma current did not achieve burntrough. Plasmas without burntrough and injected ECRH power did not have the ECRH depositing inside the plasma.



(b) WEST: Length of plasma discharges as function of the number of pulses after restart. The vertical line indicates the first boronization.

FIG. 1. Restart with outboard limiter plasmas in AUG (left) and inboard limiter plasmas in WEST (right)

different plasma edge conditions (density, temperature and impurities) and to use this data for validating codes such as SOLPS-ITER and integrated models (e.g. JINTRAC) in order to further provide input for the optimisation of the ITER ramp-up scenario. Some of these experiments have since been performed and are reported here.

To substantiate the need for the boronization system proposed (and being designed) as part of the ITER re-baseline activity [**Pitts25**], dedicated W limiter discharges on AUG and WEST were first attempted in unboronized conditions, followed by further experiments in conditions with non-homogeneous boronization using only a subset of the glow discharge anodes (AUG) or diborane injection locations (WEST), and finally with a fully boronized machine (AUG only, WEST operated with the non uniform boronization for another 2 months, no additional wall conditioning needed). On WEST, the plasmas were run on inner heat shield bulk W tiles, installed in summer 2024, whilst start-up on AUG was performed on outboard, W-coated graphite tiles (similar to earlier outboard W limiter start-up experiments on EAST [**Pitts25**]).

2. OPERATION IN AN UNBORONIZED MACHINE

2.1. ASDEX Upgrade

The restart followed a 2 year long break to install a new upper divertor structure together with internal coils and a new cryo pump for advanced divertor studies. After the standard wall conditioning procedure a 10 day baking at 150°C, leak search and a few minutes of He and D glow discharges a startup was attempted. In addition to the intensive in-machine work also auxiliary systems, e.g. power supplies, gas handling and heating systems were improved. The first operational day was essentially spent on re-optimisation of the magnetic field null. Despite a missing prefill gas, a plasma blip was achieved by ECRH (Electron Cyclotron Resonance Heating) pre-ionisation [**Stober11**]. On the third day of operation first breakdown plasmas were created but not sustained despite attempted ECRH assist. A key problem at this point in time was a mismatch of the very narrow ECRH deposition and the actual plasma position which was not yet controlled but a legacy of the breakdown process. By adjusting the position of the field null the plasma has been moved to the ECRH deposition zone and (ECRH assisted) burntrough has been achieved and the plasmas reached ≈200ms discharge length. A summary of the restart plasmas is shown in figure 1a. Unfortunately the application of the ECRH power had to be limited due to missing interlocks and the danger that ECRH without plasma could cause significant melting in the machine.

Within those limits a current rise up to 350kA (400kA target) has been reached but the plasma could not be sustained due to the (forced) short ECRH heating interval. This was a major difference to the 2007/8 restart [**Kallenbach09**, **Neu09**] where the ECRH could be used for longer times and also NBI (Neutral Beam Injection) heating was used. The plasmas would not disrupt but they slowly decay as the temperature decreases due to excessive radiation ending up below the burntrough conditions again. The radiated power is well correlated with a strong increase in O source which is about a factor 10 higher compared to any of the limiter plasmas after boronization. The measured W source is still within the noise level of the diagnostic. Usually the W source is dominated by sputtering from low Z impurities (e.g. O), but in this case the plasma is apparently so cold that the single particle energy is insufficient for this process. A negative bye-product of this process was the creation of a significant fast electron population in 2 pulses due to the high loop voltage and low temperature.

2.2. WEST

Within the ITPA activities also WEST attempted an unboronized startup using tungsten plasma-facing

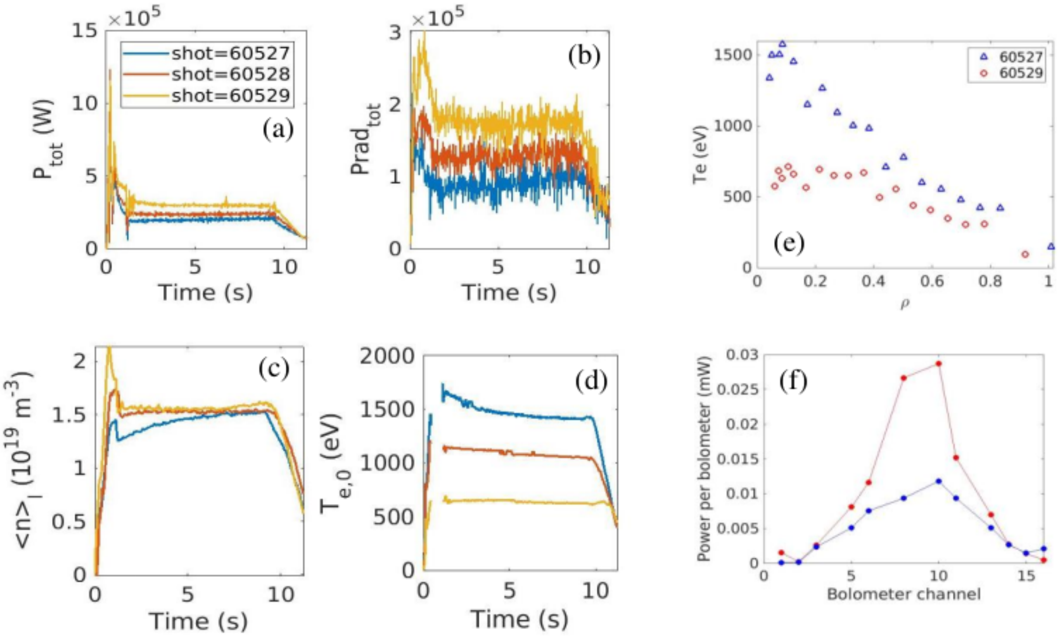


FIG. 2. WEST: Time traces of ohmic power (a), total radiated power (b), line averaged density (c) and central electron temperatures (d) for 3 identically programmed consecutive pulses. Electron temperature profiles (e) and powers received by the 16 horizontal bolometry channels (f) are shown for a time point during the stationary phase.

components on the inboard limiter. Prior to 2020 WEST already tried a start-up on W coated tiles but experienced a difficult operation with cold and MHD prone plasmas [**Bucalossi22**]. As a result, it was decided to use a low Z material (boron nitride, BN) on the inner wall to ease the startup [**Guillemaut25**]. For the 2024 campaign full W tiles were installed and the restart was attempted just after the closing of the machine and 4 days of baking at 190° and 50 hours of D glow discharge [**Gallo25**]. Discharges up to 1.5s long with plasma currents up to 600kA were achieved. In those ohmicly heated plasmas no runaway beams were observed. As on AUG the discharges were troubled by significant out-gassing, uncontrolled densities and high radiation. In contrast to AUG, a clear conditioning effect with time was observed presented in [**Manas25**]. In the 2024 restart the achieved discharge length as time progressed was similar to the restart on boron nitride without boronization, neither of them leading to a timely restart of operations. The increased radiation is mainly produced by oxygen (O) and other residual impurities from the opening like nitrogen (N) or carbon (C). Langmuir probe measurements on the inner limiter show a $T_e \approx 10$eV as plasma temperature and visible spectroscopic measurements show no W influx.

3. OPERATION AFTER BORONIZATION

3.1. WEST

As can be seen from figure 1b on WEST the boronization immediately allowed 10s long limiter pulses with an initial total radiated power fraction of 0.5. On WEST a non-uniform boronization utilising only half of the gas injection points was performed[**Gallo25**]. In the first two pulses, run at 300kA with $0.5 \cdot 10^{19}\mathrm{m}^{-3}$ for 10s, W influx lines were visible and increasing from the first pulse to the second. This trend continued in the three following pulses leading to flattening of the electron temperature profile due to increasing central radiation. The most important time traces and some representative profiles are plotted in figure 2. In WEST the impact of the wall material on these limiter discharges is large. The lack of central heating, together with relatively large W sources due to the low density leads to a) significant core W concentrations which leads b) to flat temperature profiles in the core. If the W concentration would be even higher it could lead to hollow T_e profiles and the excitation of MHD as seen previously [**Bucalossi22**]. Scans in plasma current (300-700kA) and density (15-90% Greenwald fraction) were performed showing that in general a large operational space is available. At the highest currents stronger out-gassing was observed and the limiter surface temperature increased to 600 °C. Later during the campaign low density plasmas were could no longer be run.

The addition of N can mitigate some of the negative effects of W by modifying the core transport [**Maget22**]. This has been successfully applied transiently in the limiter configuration phase during the campaign and shown to also reduce the edge W sources from the limiters.

3.2. ASDEX Upgrade

After a boronization [**Rohde25I**] using only 2 out of 4 anodes, which were concentrated on one side of the torus [**Rohde25II**], the limiter plasmas could be run for full length and without ECRH assisted ramp-up. Also the typical restart plasmas in lower single null with more applied heating power could be run without excessive radiation (≈50% radiation fraction in diverted plasmas, up to 90% in outboard limited discharges). The first 6 pulses were dedicated to outboard limiter pulses, but because those were the first sustained pulses after restart, the pulse length and heating power was increased slowly and the pulses are not directly comparable. Nevertheless they share some properties: the plasma density was rising uncontrollably trough the pulse resulting in some disruptions, the W source was very small about a factor 10 lower than during the pulses done later after full boronization, and the O source about a factor 3 higher than with full boronization (and a lot of conditioning for the machine by high power pulses). Consequently, the radiated fraction of the half boronized pulse is two times as large as the pulse after full boronization reaching more than 90% and mostly close to the inner wall (MARFE visible in camera). After 3 experimental days, it was not possible to run these pulses limited by the outboard limiters due to an uncontrolled rise in the edge radiation leading to disruption before reaching the current flattop. What actually was responsible for this decaying machine condition could not be determined. The O sources from the limiter varied within a factor of 3 without clear impact and the W source was still negligible at the end of this phase. The boron (B) source reduced by a factor of 2 in this period but also showed strong pulse to pulse variation. Other pulses, e.g. with an early X-point formation could still be run without restrictions. The effects described are slow $\approx$ 1s and are not important for ASDEX Upgrade in the start-up phase which lasts ≈ 400ms.

After the first full boronization the pulses have been repeated as the first 2 pulses. Some key time traces are given in figure 3. The plasmas in those two pulses are well controlled, the density is constant in the one and two gyrotron phases. The plasma configuration is also similar for both pulses. The pulse in red has a very low radiated fraction of $\approx 20\%$ until $t = 2.5$s coinciding with a total absence of W source and an apparent higher B source. Whereas the W measurement is on neutrals, the B measurement is on singly ionised atoms which might have been transported before measurement. The likely reason for the low W source is that the B layer was covering the plasma contact points on the limiter until $t \approx 2.4$s and then probably destructs (higher temporal B source). After this point in time the W (and also the O and N) sources become accessible to the plasma and also the radiated power increases to $\approx 60\%$. This

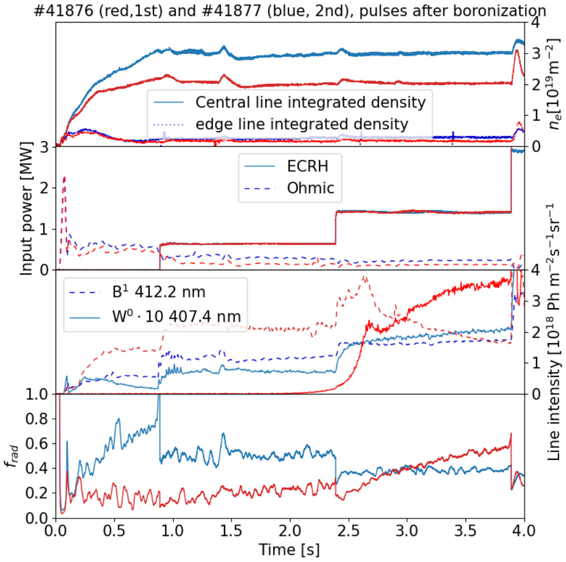
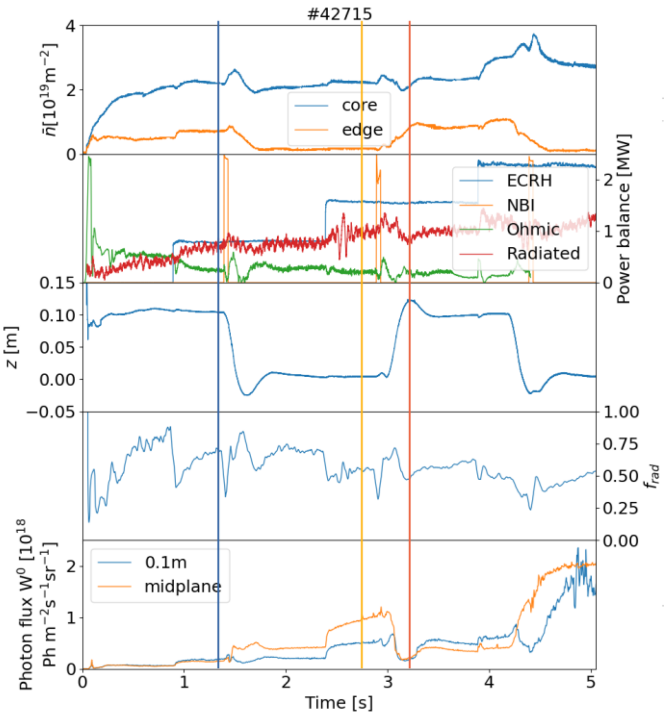


FIG. 3. AUG: First pulse after full boronization at lower density in red, second pulse after boronization at higher density in blue. Top plot contains core and edge line integrated density measurements, second plot contains ECRH and ohmic power in the plasma, third graph shows in closed lines the W influx from the contact point of the plasma on the limiter and in dashed lines the B influx at the same position.The last plot contains the radiated fraction of the plasmas.

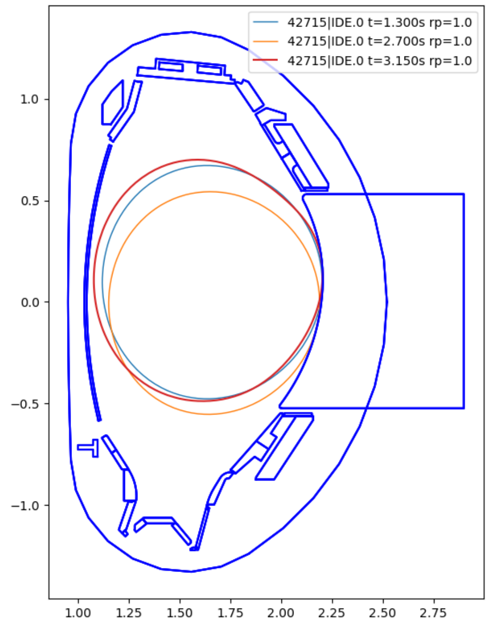
is different in the second pulse after boronization where the W (and also O) sources are visible from the beginning. Compared to the last limiter pulses before the boronization the B source doubled again, the O source is similar and the W source a factor 2 higher. The radiation profile for the pulse after full boronization is mostly flat, with no apparent radiation peaking. This is likely due to the strong central heating by ECRH which prevents W accumulation but also over compensates all possible core radiation. Even though the background plasma is constant in this phase, the W source and also the plasma radiation is increasing. The very last phase has not been analysed further. The strong increase of ECRH power to 4-5MW leads to very unstable plasmas due to melting of W on the limiters (bearing in mind that the toroidal wetted area is only ≈1.2m assuming an equal heat distribution on all limiter surfaces). Later we will see that plasmas with ≈2.3MW ECRH are still stable. 5 experimental days later the limiter plasmas could no longer be performed. As with the half boronization the density becomes uncontrollable and the radiation is increasing. In this case the O source doubles, the B source is constant and the W source halves. Again no clear reason for the change of machine conditions could be found. The changes reported here are within the scatter during the half boronization phase where more pulses were performed. And again those changes had no impact on other plasmas probably because either the typical limiter phases during start-up are much shorter or the inboard limiter is less prone to those changes in machine conditions.

4. W SOURCE AND SOL CHARACTERISATION

Unfortunately many of the SOL (Scrape Off Layer) relevant diagnostics were unavailable for the pulses described so far. To optimise the diagnostic coverage, vertical position movements have been implemented. The pulses have been performed on the second day after boronization and are stable with a low O source and similar B sources compared to the pulses described before. The pulse has been constructed so that for every heating step two different z positions are reached and some averaging is possible. The best edge profiles were obtained from the He beam diagnostic for the slightly too high z-position at $t = 3.1$s. On the other hand, the reciprocating probe (RCP) measurements have been taken at $t = 2.64$s. In figures 5a,5b,6a for $t = 3.1$s the electron temperature profile, the density profile for the 2 gyrotron phase and the W source profile for 3 different time points are plotted. The electron temperature profiles from different diagnostics are mostly consistent and are within the error bars of the integrated data analysis. The profile from the RCP gives slightly higher T_e at the LCFS (Last Closed Flux Surface) of about 60eV whereas the integrated data analysis has about 50eV with an error bar of 10eV. The density profiles are significantly different, the integrated data analysis has only $6 \cdot 10^{18}\mathrm{m}^{-3}$ whereas the RCP (Reciprocating Probe) gives $1.2 \cdot 10^{19}\mathrm{m}^{-3}$ also connected to a much steeper profile in the SOL. However, the data which is used in the integrated data analysis does not have good spatial resolution in the SOL. The reason for the discrepancy has not been resolved to date. The measured temperature and density are well within the parameter range used to predict the W sources for ITER with SOLPS-ITER [**Zhang25**]. The W source profile in figure 6a is considerably peaked around the contact point of the plasma on the



(a) Core and edge line integrated densities in top graph, ECRH power, Ohmic power, NBI blips, sum of input power and radiated power in the second box. z position of the plasma in third box. The radiated fraction in the fourth box and 2 different lines of sight measurements of the W influx in the bottom graph. Different equilibria are indicated by vertical lines.

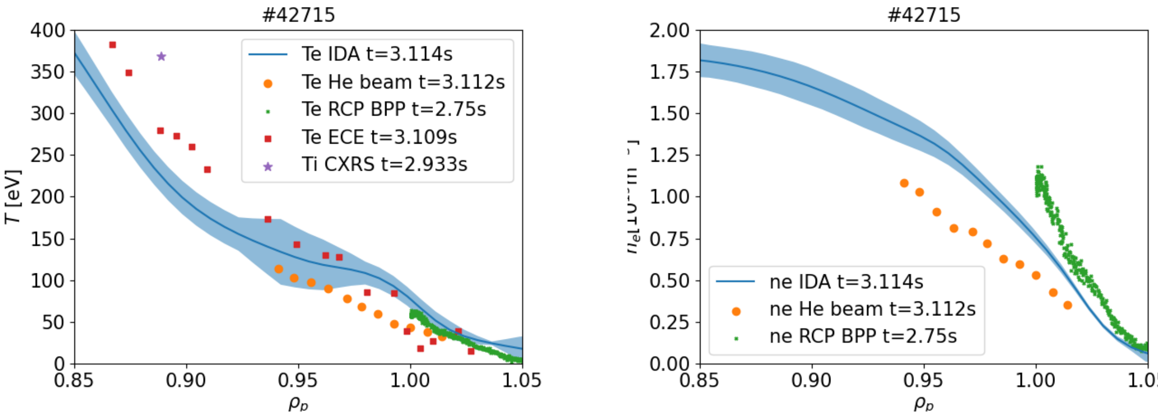


(b) Equilibria for 3 different times representative for the different phases of the pulse.

FIG. 4. Long limiter pulse for W source studies.

limiter. This is very different to earlier studies performed on the inboard side limiter[**Geier05**] in which a clear double peak in electron density, temperature and consequently W source was measured. The minimum W source was exactly at the location of the plasma contact point. This difference in W source profile is likely related to poloidal asymmetries in radiation which often is stronger on the HFS (High Field Side) than on the LFS (Low Field Side). Together with the pulse described in figures 4a,4b,5a, 5b,6a another pulse at higher density was also performed. The increase of $1 \cdot 10^{19}\mathrm{m}^{-3}$ in core density leads to significant radiation concentrated on the HFS. Whereas the SOL electron temperature profile on the LFS is rather similar, the temperature close to the inboard limiter is probably very much reduced and local detachment may be occurring. This would be consistent with the earlier observation in [**Geier05**] where the low temperature in front of the target would be detached but the far SOL still transports the energy leading to two main interaction points about 20cm below and above the midplane. On the other hand the local effects on the HFS do not have much of impact on the LFS SOL.

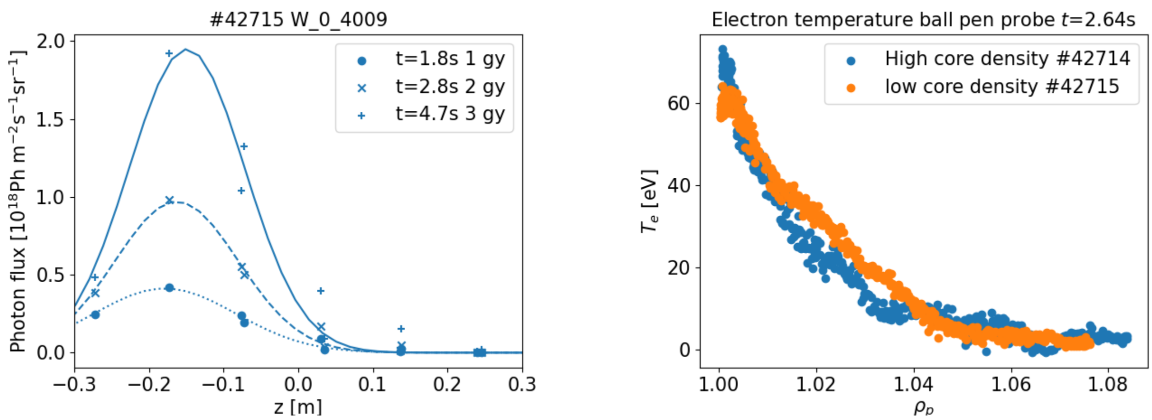
Preliminary SOLPS-ITER simulations have been run using experimental input from AUG discharges as constraint. The simulation uses a B concentration of 2% in D which is at the upper end of the error bar from CXRS measurements further inside the plasma. The transport coefficients are chosen so that with 1.5MW centrally deposited ECRH power a core temperature of 4keV, consistent with the experiment is reached. The W erosion and radiation (up to W^{40+} considered) leads then to a LCFS temperature of 45eV and the total radiated power of the ASDEX Upgrade plasma can be replicated. In this run, the radiated power is dominated by W, which is an indication that W self-sputtering might be the main source (as predicted for ITER). Further modelling steps will be to increase the LCFS temperature to 60eV as measured by the RCP and to include a small amount of O, e.g. 0.5% which is probably present in the ASDEX Upgrade discharges. ASTRA calculations can also provide better heat fluxes and transport



(a) AUG edge temperature profiles from: integrated data analysis (ECE, He beam, TS), He beam diagnostic, CXRS ion temperature, RCP ball pen probe.

(b) AUG edge density profiles from: integrated data analysis (DCN interferometer, He beam, TS), He beam diagnostic, RCP ball pen probe.

FIG. 5. AUG electron temperature and density profiles.



(a) AUG W source (W^0 line 400.9nm) measured as function of the z position on the outer limiter.

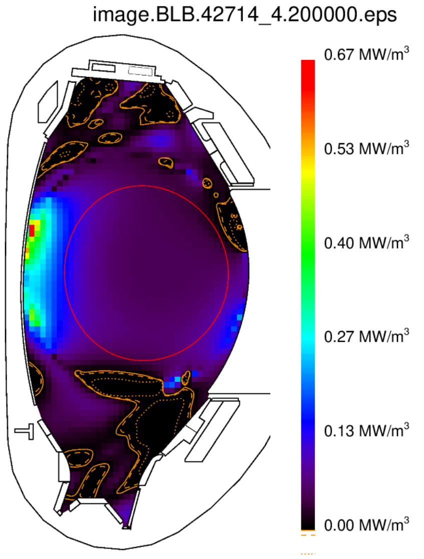
(b) AUG edge temperature profiles measured by the ball pen probe on a RCP.

FIG. 6. AUG W source for the low density pulse and edge temperature profile comparison for 2 densities.

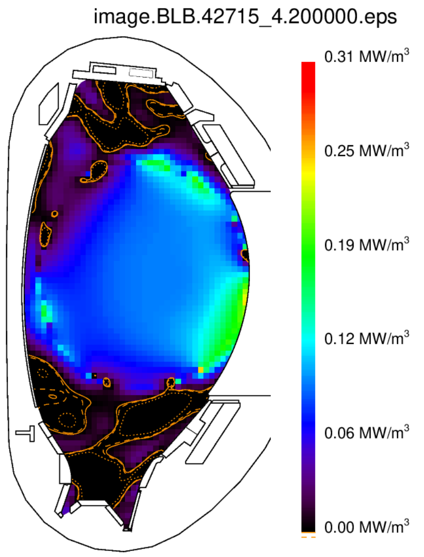
coefficients inside of the plasma.

5. SUMMARY AND CONCLUSION

This paper describes the results of dedicated experiments performed on AUG and WEST to study the limiter plasma start-up phase on tungsten plasma-facing components in support of the new ITER baseline. In the first part the start-up of ASDEX Upgrade and WEST without applying a boronization was described. On both machines the plasmas were difficult to sustain, characterised by an uncontrolled density rise and strong low Z dominated radiation. The residual oxygen left from the vessel opening was identified as main radiator, resulting in plasma edge parameters which do not lead to W sputtering and hence on WEST, plasmas on BN limiters behaved similar to W limiters under those conditions. Even a boronization with asymmetries leads to a strong conditioning effect solving the start-up problems for all kind of plasmas. After a short time ($\approx$ few seconds), the B layer at the contact point of the plasma is eroded and some W source becomes visible. Depending on the heating scheme, the W can have a strong impact on the core plasma. With central ECRH (similar to ITER) on ASDEX Upgrade core plasmas stay clean of W even with a large W source. After a full boronization the conditions improve further



(a) AUG radiation distribution for higher density pulse in 3 gyrotron phase.



(b) AUG radiation distribution for lower density pulse in 3 gyrotron pulse.

FIG. 7. AUG tomographic reconstructions of radiated power at low and high density.

and dedicated experiment to characterise the W source have been performed on ASDEX Upgrade. On the LFS the W source is peaked at the interaction point with the plasma. LCFS temperatures up to 40-60eV with $1 \cdot 10^{19}\text{m}^{-3}$ electron density have been reached - similar to plasmas calculated for the ITER limiter startup. The W source increases with heating power even though the SOL parameters are not varying strongly. The experiment data created are now used to constrain SOLPS-ITER runs for ASDEX Upgrade and SOLEDGE3X runs for WEST in order to validate the W source module but also the SOL transport assumptions used for ITER. The experiments with different boronization states have clearly shown that a start-up without boronization is at the very least time consuming and has some risk of complete failure. The number of anodes or gas injection points used for the boronization is secondary. The experiments have re-enforced the arguments that the coverage of the plasma contact points with boron is a short living and not very important. The long term effects are more distributed in the machine.

In the near future the SOLPS-ITER calculations will be refined and accompanied by core transport calculations.

ACKNOWLEDGEMENTS

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission or the ITER organization. Neither the European Union nor the European Commission can be held responsible for them.

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