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

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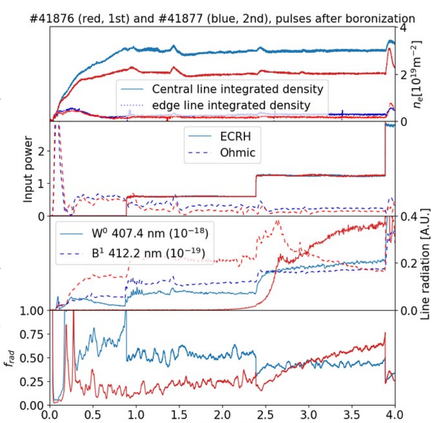
The re-baseline of the ITER Research Plan [1], especially the change of the first wall (FW) material from beryllium (Be) to tungsten (W), requires re-validation of the foreseen operation scenarios. A critical point here is the initial ramp-up phase, which will be carried out in a limiter configuration (nominally on the inner column FW panels) 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 to W surfaces without the screening provided by diverted operation is expected to lead to high radiative fractions [2], 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.

This delicate balance of plasma and material parameters makes dedicated experiments and model calculation/development necessary. Simulations for ITER with the SOLPS-ITER code, including W erosion and transport of all charge states up to W^{30+} [2] show possible W-induced radiation fractions of f_{rad} = 70-80%. The W in these first code code runs is generated by self-sputtering and self-regulated due to the high radiative power, leading to moderate last closed flux surface (LCFS) temperatures. These findings are in contrast to earlier experimental results from e.g. ASDEX Upgrade (AUG)[3]. In those experiments, the W sputtering is mainly by low and medium Z impurities, e.g. oxygen (O), with W self-sputtering only a minor contributor. Nevertheless, the increased radiation can lead to significant differences in the temperature (and current) profiles during plasma current ramp-up [4].

In 2023 the ITPA IOS 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 under different plasma edge conditions (density, temperature and impurities) and to use this data for benchmarking 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. New experiments have since been performed and are reported here.

To substantiate the need for the diborane boronization system proposed (and being designed) as part of the ITER re-baseline activity [2], dedicated W limiter start-up 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). 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 the outboard W limiter start-up experiments on EAST [2]).



*Fi*gure 1: Time traces of impurity (source) lines shortly after boronization

On AUG the unboronized restart was hampered by various technical difficulties impacting the availability of auxiliary heating and diagnostic data. Breakdown was achieved with and without electron cyclotron (EC) pre-ionisation, burnthrough of the initial radiation increase was only possible with additional EC heating. Due to the high (edge) radiation levels (mainly oxygen), no current flattop could be reached, but a limiter tile was damaged by runaway electrons (RE). The W source was below the detection limit due to the low LCFS temperatures and W did not influence the plasma behavior. After the initial partial boronization (and also after full boronization using all anodes), plasma start-up was generally associated with low radiation levels and no EC assist was necessary. In the first discharge after boronization, the boron (B) source from the loaded limiter steadily decreases through the pulse and the W source increased accordingly, indicating the how rapidly the B layer on the loaded limiter decays (Figure 1, orange). Higher power ECH phases led to overheating of leading edges and strong W sources (pre-damaged by REs). Data has nevertheless been collected for different plasma densities (n_e ~ 2-6 $10^{19}m^{-2}$, 40% – >100% Greenwald fraction), two different currents (I_p = 0.4, 0.6 MA), 2 different boronization states and three different EC heating powers (P_{EC} = 0.6, 1.2, 3-5 MW) allowing, for a detailed study of outer limiter W sources.

On WEST, an unboronized start-up [5] was conducted on the W inner heat shield limiter. Initial problems with low Z impurities (mainly O) could not be entirely overcome, but several limiter pulses up to 1.5 s duration and up to I_p = 600 kA have been run featuring sawtooth activity and no evidence of REs. At this time, EC power was unavailable and all the attempts and progress achieved were performed without external heating assist. Robust ramp-up and plateau phases could not be obtained, despite faster improvement of wall conditions compared to similar previous campaign restarts (after a vent) with boron nitride limiter tiles and without boronization. Electron temperatures measured by Langmuir probes embedded in inner limiter tiles are below 10 eV and no neutral W lines are visible in the spectroscopy. Following a non-uniform boronization using the half of the available gas injection points, plasma start-up was greatly improved and limiter ohmic plasmas have been run without problems. The decreased edge radiation allowed higher edge temperatures and W sources could start to be observed. A rapid evolution of the wall conditions at the beginning of the first session after boronization was observed, with decreased fueling and an increased W source for consecutive repeated pulses, together with decreased central electron temperatures. Density plateaus at 300 kA were obtained for a large scan in Greenwald fractions from n_{GW} = 0.15 ~ 0.9. Outgassing at 500 and 700 kA was still observed with controlled density plateaus possible only at n_{GW} > 0.8. Additional limiter plasmas were performed during the campaign, featuring higher f_{rad} (from ~60 to ~80%), when far from boronisation, with the lowest achievable electron density increasing and highest n_{GW} decreasing. Experiments with nitrogen seeding during the limiter phases on W improved conditions by decreasing f_{rad}, flux consumption and W sources and increasing the central electron temperature similarly to what was observed in previous WEST campaigns with W coated inner limiters [6]. Finally, it should be noted that starting on the new bulk W limiters did not hamper plasma operation, despite being far from the single (partial boronisation) performed to facilitate start-up, with 12.5 GJ of injected energy by the end of the campaign and 824 record L-mode pulses with lengths > 500 s.

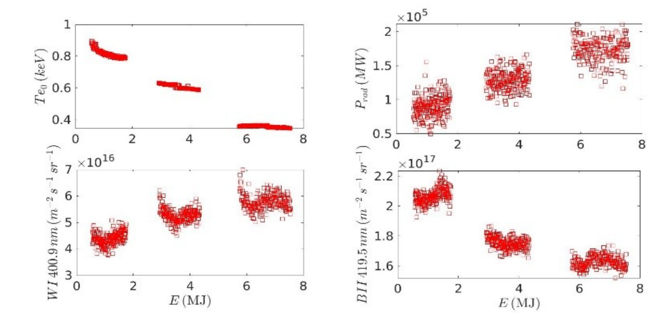


Figure 2: Evolution of the central electron temperature, radiated power, W I and B II line intensities for 3 consecutive identical ohmic shots following the non-uniform boronisation

The new AUG and WEST data is currently being further analyzed and SOLPS-ITER/SOLEDGE3X simulations are planned. These new results, together with those from EAST [2], will allow for a much improved assessment of the impact on the critical limiter ramp-up phase of exchanging ITER's FW from Be to W.

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