Demonstration of the ITER Baseline Scenario on ASDEX Upgrade

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1. Introduction

In ITER, H-mode operation at 15MA and q_{95}=3 is planned to achieve 500MW fusion power at Q=10 in deuterium-tritium mixtures. This so-called ITER baseline (BL) scenario is characterized by normalized parameters for plasma density $f_{GW}=n/n_{GW}=0.85$, energy confinement H_{98y2}~1 and normalized beta β_N~1.8 [1]. Based on results from tokamaks with a carbon wall, a high triangularity shape ($\delta=\delta_{average}$ ~0.4) has been identified to be best suited in ITER to combine high density operation using permanent deuterium gas dosing with good H-mode confinement. The demonstration of this ITER reference scenario on ASDEX Upgrade (AUG) has started in 2012 and is the topic of this paper.

2. Operation in Deuterium

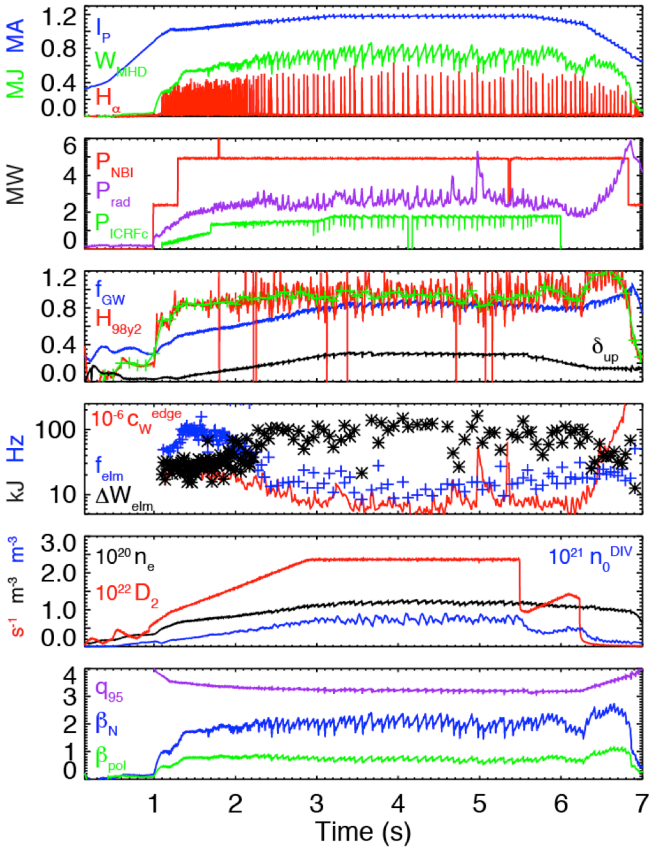

Fig. 1: Time traces, of a NBI and ICRF heated demonstration discharge(#29636) of the ITER BL scenario (see text).

The metallic wall of AUG requires central wave-heating (ECRH or ICRF) to avoid core tungsten impurity accumulation [2]. This boundary condition of needing RF power centrally deposited in the plasma, reduces the possible values for plasma current I_p and magnetic field B_t to a few practical combinations of I_p / B_t. In particular, two routes have been successfully explored for q_{95}=3 plasmas on AUG: (i) operation at 1.1MA/1.8T using ECRH at 140GHz in X3 mode and (ii) 1.2MA/2T using ICRH at 30MHz from two antennas with boron-coated protection limiter tiles.

Operation on AUG at high I_p and/or high triangularity is quickly constrained by technical limits of the flywheel generators. In order to overcome these limits the ramp-rate for currents for the vertical field coils (V2) coils has been halved to ~10 kA/s. This has considerably reduced the reactive power load on the flywheel generators allowing higher values of δ at plasma currents > 1.0MA for durations of a few seconds. The price to pay are slower ramps to highly shaped plasmas. With this setting AUG's operational space (at 1.2MA: $\delta_{low}\leq0.45$, $\delta_{up}\leq0.3$, $\delta=\delta_{average}$ up to 0.36) has been extended. As a typical example (#29636) for a demonstration discharge of the ITER BL scenario at 1.2MA / 2T a comprehensive set of time traces is shown in fig. 1. In 1.1s the discharge is ramped up to 1MA in a low-δ shape. This phase is followed by a combined slow ramp of I_p and δ (see δ_{up} in fig. 1) until the flattop is reached at t=3s and sustained for 2.4s. NBI and ICRF heating are applied from t=1s onwards. The gas fuelling rate is slowly raised up to a flattop value of $2.5 \cdot 10^{22}$ s^{-1}. Stationary behaviour is obtained in the flattop and parameters H_{98y2} and f_{GW} come close to the target values of 1 and 0.85, respectively. Although the amount of applied heating power for such discharges is already on the lower end for AUG, β_N typically stays at values 25% above the ITER target of 1.8.

During the ramp-up of I_p and δ, the ELM signature is dramatically changing (see fig. 1, 4th box). While in the low δ phase the ELM frequency f_{ELM} is high and the energy loss per ELM ΔW_{ELM} is low the situation reverses once a certain δ value is exceeded. In the fully shaped flattop ELM frequencies of 10 - 25 Hz are typical as well as ΔW_{ELM} values of 100 – 200 kJ which translates in fraction of the stored energy to significant losses of 15 – 25%.

The ramp-down starts with a slow I_p reduction accompanied with a reduction of δ_{up}. In a second phase I_p is ramped fast in a medium δ shape while keeping the divertor configuration as long as possible. This phase is not optimized yet and disruptions at I_p <0.5 MA often terminate such discharges.

The operational window for the ITER BL scenario on AUG where a stationary behaviour is possible and W accumulation can be avoided, is set by the following (inter-linked) parameters:

- Closeness to the last boronization / quality of wall conditioning;
- Deuterium gas puff level;
- Heating power in total and in particular the amount centrally deposited;

With well conditioned walls, i.e. a few days after a boronization, the gas puff level could be reduced to $1.5 \cdot 10^{22}$ being then close to the onset of W accumulation. Many stationary discharges were conduced for D puff levels between $2 \cdot 10^{22}$ and $3 \cdot 10^{22}$. Only in such phases with well conditioned walls ITER BL (IP 1.1 or 1.2 MA) discharges with P_{NBI} < 5MW could be sustained, or the central RF heating could be reduced to low values of less than 1MW.

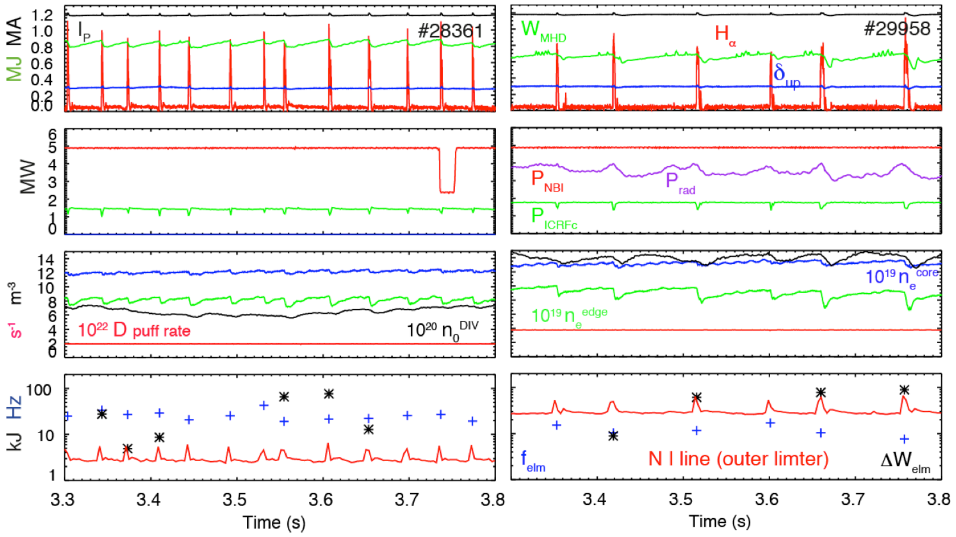

Fig. 2: Comparison of ITER BL discharges during phases of 0.5s. Discharge parameters are identical except gas puff and 'freshness' of boronization. While the discharge on the left (#28361) was conducted 1 days after a boronization, the one on the right (#29958) was done 21 days after a boronization. Different gas puff levels $1.9 \cdot 10^{22}$ and $3.8 \cdot 10^{22}$ were necessary to reach stability for discharges #28361 and #29958, respectively .

For ITER BL attempts where the beneficial effect of boronization was lacking stable discharges could only be produced at gas puff levels ≥ $3.8 \cdot 10^{22}$ and at a total heating power exceeding 6.8 MW. Only within this shrinked operational window f_{ELM} could be kept sufficiently high to allow an effective flushing of impurities necessary to avoid W accumulation [3]. The two BL discharges (#28361 and #29958) in fig. 2 mainly differ in the number of discharges performed since the last boronization. Although the gas puff is twice as high in #29958 (21 days after boronization), f_{ELM} is just half of the value observed in #28361 (1 day after boronization). The gas puff rate of $3.8 \cdot 10^{22}$ 1/s turned out to be the lower limit for the condition of #29958, because it lead to ELMs (f_{ELM} = 12 Hz) which are just frequent enough for an effective removal of impurities (in particular W) out of the pedestal. Attempts with lower gas puff rate produced even lower f_{ELM} and were terminated by W accumulation.

The intensity of a nitrogen N II emission line (399.5 nm) on an outboard limiter (4th box in fig. 2) - being a measure for the influx of medium-Z impurities from the wall – turned out to be a good indicator for the wall condition. Right after a boronization (#28361, in fig. 2) the level of this line is one order of magnitude smaller than in the case (#29958) where the effect of boronization is lacking. Thus, the considerably different behaviour of both discharges in fig. 2 is connected to the composition of the edge plasma with respect to low-Z impurities.

The observed large ELMs are intolerable in view of ITER. Therefore, three methods for ELM mitigation were tried: (i) ELM pace making with pellets (v_P = 560 m/s) of different mass (m_P = 1.5 – 2.4 $\cdot 10^{20}$ D atoms) and frequency (28-35 Hz) injected from the HFS, (ii) application of MP coils and (iii) nitrogen seeding. So far, none of these methods showed a breaking success.

In the all-W AUG (AUG-W) pellet injection ceases to be a reliable ELM trigger [4]. In phases with pellet injection f_{ELM} is slightly increased by the accompanied fuelling which lead to higher f_{GW} at reduced confinement. Astonishingly, the higher gas throughput does not increase the stability against W accumulation. However, this finding for the few attempts with pellet injection done so far, might be overlaid by a high Ne concentration in these plasmas caused by killer gas injection for disruption mitigation which had terminated the previous discharge.

AUG's ELM suppression scenario with MP, which works above a certain density threshold [5], should in principle be compatible with the ITER BL scenario. The application of MP coils in the ITER BL scenario slightly influenced both density and stored energy, but did not mitigate or even suppress ELMs. Although at least in one case (#29964) the required edge density for ELM suppression - found in another discharge (#29842) with the same plasma shape, but at much higher q_{95}=5.5 - was reached, no mitigation of ELMs was observed.

Seeding of N normally increases f_{ELM} and reduces the ELM size in AUG plasmas [6]. In a few ITER BL attempts with N seeding f_{ELM} was even reduced. Theses discharges showed a slightly improved confinement, but were even more prone to W accumulation than purely D-puffed ones. Thus, in AUG's ITER BL demonstration discharges (presumably to due the low P_{heat}) the operational space for introducing additional impurities seems to be rather limited (see also discussion of fig. 2, above).

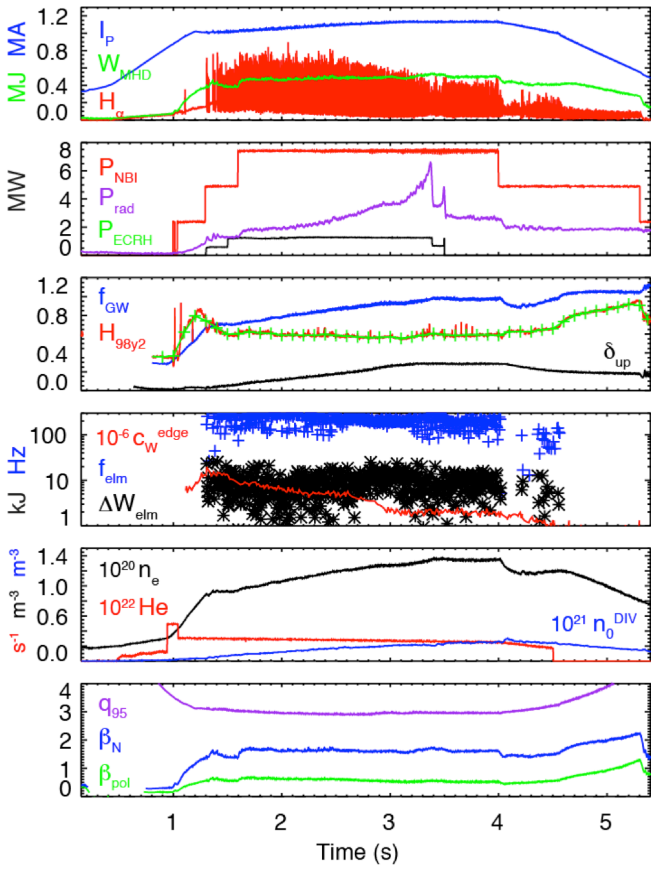

Fig. 3: Time traces, of a ECRF-heated He discharge #30015 (1.1MA / 1.8T, further details, see text).

3. Operation in Helium

In order to simulate the ITER operation in the non-nuclear phase, a few helium discharges have been performed, which were heated with deuterium NBI and ECRH (1.1MA) or in the low I_p case (0.8MA) just with deuterium NBI. Operation of such He plasmas turned out to be unproblematic. Although the discharges were conducted more than 20 days after a boronization – a phase which was challenging for operation of D_2 ITER BL plasmas – no major difficulties were observed. In particular f_{ELM} stayed around 100 Hz irrespective of δ. High densities close to f_{GW}=1 were reached. Even the switch-off of central ECRH did not lead to W-accumulation. The rising P_{rad} in fig. 3 is due to ECRF stray radiation disturbing the bolometer diagnostic rather than a sign of increasing core radiation. This interpretation is supported by the immediate reduction of P_{rad} once P_{ECRH} is zero and by the very low W concentration c_W, in particular in the phase with highest δ.

4. Summary and Conclusions

In AUG-W several ITER BL D_2 demonstration discharges at I_p= 1.1 and 1.2MA with ECRH and ICRH, respectively were performed and showed stable behaviour for many confinement times. Values for density and energy confinement came simultaneously close to the requirements of the ITER BL scenario (see fig. 4) as long as β_N stayed above 2 (typically $2.0<\beta_N <2.2$). Compared with results with a C-dominated wall (AUG-C) the operation in AUG-W is restricted to higher densities $f_{GW} > 0.75$ and confinement is on average reduced by 5-10% [7]. In fig. 4 no distinction with respect to the effectiveness of machine conditioning has been made. Thus, the lowest H-factors in fig. 4 can be attributed to high gas puff levels required to avoid W-accumulation in such phases with a vanishing effect of boronization. For the extrapolation to ITER however, the results of AUG-W with an intact, fresh boronization and thus higher H_{98y2} are the decisive ones, because B-coated main chamber walls in AUG-W together with the tungsten divertor (typically not affected during a boronization process) simulate much closer the ITER situation of a Be main-chamber-wall and a tungsten divertor.

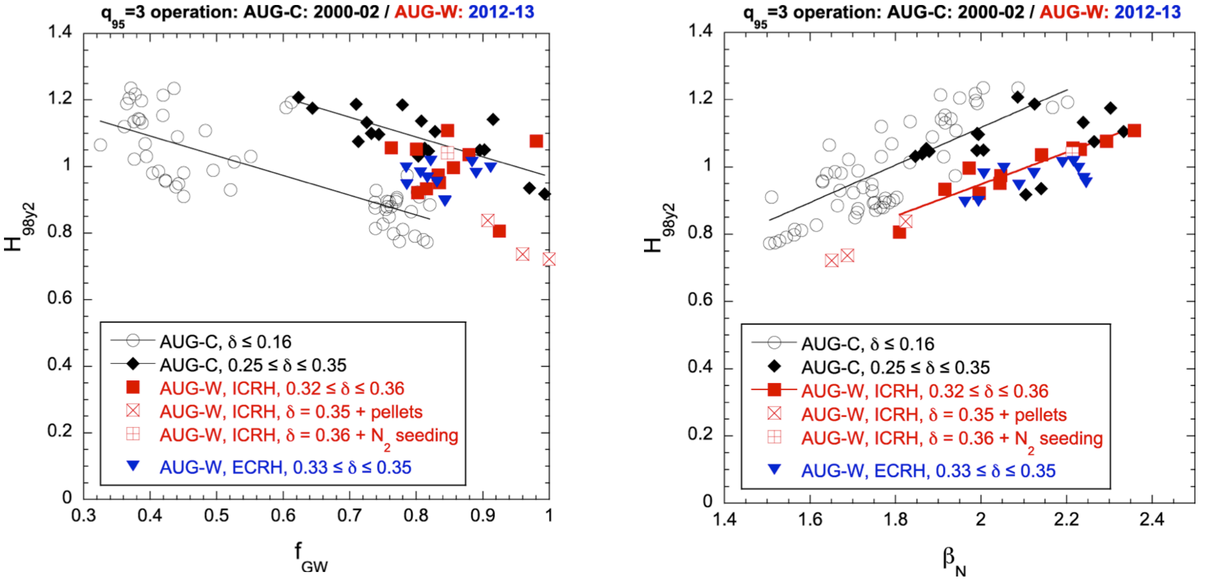

Fig. 4: Normalized confinement H_{98y2} vs. normalized density f_{GW} (left) and normalized pressure β_N (right) for operation at q_{95} = 3 in AUG-C (black symbols) and AUG-W (blue & red).

Very large ELMs occurred, which appear difficult to mitigate. The solution of this problem remains the biggest challenge for optimizing such plasmas in the coming AUG campaigns. On the other hand, no major difficulties were observed for the operation in helium.

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