Advanced tokamak experiments in full-W ASDEX Upgrade


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Abstract. Full W-coating of the plasma facing components of ASDEX Upgrade (AUG) in 2007 initially prevented H-mode operation with little or no gas puff, due to collapses driven by W accumulation, also due to a lack of adequate central wave heating. Additionally, the limits for power loads to the divertor were reduced. Under these conditions low density, high beta plasmas with significant external current drive were virtually impossible to operate, i.e. the operational window for advanced tokamak (AT) research was effectively closed. To recover this operational window several major achievements were necessary: the understanding of the changes in pumping and recycling, the change to a full W divertor capable to handle higher power loads, a substantial increase of the ECRH/CD power and pulse length to avoid W accumulation and to adjust the current profile and, finally, new or upgraded diagnostics for the current profile, since the original MSE system turned out to be heavily disturbed by polarizing reflections on W-coated surfaces. With these efforts it was possible to recover improved H-mode operation as well as to develop a new scenario for fully non-inductive operation at \( q_{95} = 5.3 \), \( \beta_N \) of 2.7 and 50% of bootstrap current. This result relates to a steepening of \( \nabla T_e \) over a large radial range for the highest \( \beta \)-values. In contrast to the lower \( \beta \) phase this behavior at high \( \beta \) could not be reproduced with TGLF and is currently studied with gyro-kinetic codes.

1. AT studies prior and during increasing W coverage in ASDEX Upgrade

The AT studies on AUG started in 1997 after the MSE diagnostic had been established. Before the 2001 campaign, the NBI geometry was modified in order to improve the off-axis current-drive capabilities. In 1999 the coverage of AUG with W started and was completed in 2007 with the coverage of the strike point area and a remaining part of the ICRF limiters [1]. Initially only small areas were covered with W and the influence on the AT scenario was minute. Improved H-mode operation was demonstrated in 1998 [2], meanwhile also called hybrid or advanced-inductive scenario on other devices. In parallel various scenarios with ITBs were studied. In 2000 a fully non-inductively driven high density, high \( \beta_p \) H-mode was found, though at \( q_{95} \) above 10, i.e. at low plasma current [3]. This was one of the first examples worldwide for a fully non-inductive steady-state H-mode with equilibrated current profile. A summary of this early AT work is found in [4]. With increasing W-coverage of the main chamber, additional heating was only possible in the diverted plasma, requiring a successful change of the ramp-up for all AT scenarios. Additionally, W-accumulation during phases with only NBI heating and no gas puff was observed. In figure 1 an AT example from 2004 is shown, when the majority of the main chamber was already covered with W. This was an attempt to transfer a successful fully non-inductive scenario with a broad pressure profile from DIII-D ([5]). Unfortunately, W-accumulation already disturbed the initial low-power H-mode phase, leading to a drop of \( T_e \) by 30% thus increasing ohmic current drive and current equilibration. Still, according to an ASTRA simulation [6], \( \approx 80\% \) of the current was driven non-inductively in the high-\( \beta \) phase, during which NI-power was controlled to limit \( \beta_{pol} \) below 1.9. Additionally, the available ECCD power during the main heating phase was only half of that used for the successful DIII-D experiment.
It turned out already in 2002 that localized central heating increases radial transport of W such that central accumulation can be avoided [7] and this holds even in the presence of significant W-densities at the edge [8]. The first choice for central heating was the 8 MW ICRF system of AUG. Indeed improved H-modes could be operated without gas puff in the current flattop and safety factors down to \( q_{95} = 3.2 \) [9] before coverage of the corners and toroidal parts of the ICRF limiters after the 2006 campaign. At that stage the main chamber was otherwise covered completely with W. H-mode operation without gas puff and with ICRF was only possible shortly after Boronization, otherwise the additional W-erosion from the ICRF limiters during ICRF operation would dominate its beneficial effect on W-transport resulting in increased W-concentration. After full coverage with W in 2007, ICRF could only be used in H-modes with very strong gas puff [10]. Also long H-mode phases with NBI only and without gas puff as in figure 1 lead to W-accumulation. Only ECRH remained for W control by central heating; at that time 2 systems with 0.8 MW for 2 s were available.

An additional new ECRH system, for which planning started already in 1999 came on-line in 2007 with its first unit capable of 1 MW, 10s pulses. The second and third unit were available in 2011 and the full ECRH capability of 4 MW, 10 s finally in 2014. In the following the paper focuses on scenario development with ECRH. We note that meanwhile ICRF could reduce W-production, first by using boron coated limiters and second by changing to a three-strap antenna concept (with W limiters) [11] such, that it is used again for W-control in H-modes, especially in cases which are not accessible by ECRH. So far its usage in AT scenarios has not yet been attempted again.

Apart from having enough EC power, the recovery of the AT scenarios faced other major issues. Intentionally, operation with the W divertor started non-boronized in order to investigate the W behavior with uncovered W surfaces. Much care was taken not to overload the divertor. In order to prevent W accumulation, ELM-free phases after the L/H transition were shortened to a minimum applying strong gas puff prior and after the expected transition. During this period compatibility of the W-divertor with reactor relevant divertor parameters could be demonstrated by feedback controlled impurity seeding. In AUG these parameters correspond to much higher collisionalities than for example in ITER not allowing efficient CD, such that for AT experiments in AUG more aggressive divertor conditions are required. The high power operation with hardly any \( D_2 \) puff and without mitigation of the divertor-load by \( N_2 \) was a challenge to the W divertor. For the initial W-coated graphite tiles, the achievable pulse length, determined by the real-time video-analysis safety system [12] was limited to about 3 s for the fully non-inductive scenario with up to 15 MW of input power. Significant progress has been made with the solid W divertor available from 2014 [13], which has so far not limited the AT experiments. This modification of the divertor also included an increase of the pumping ducts. The development of a ramp-up with minimum gas puff was key to reestablish of the (low density) improved H-mode as will be described in section 2. It turned out that stronger polarising reflections due to the metallic coating disturbed the MSE diagnostic. Since the current profile is a major player in the AT physics, a reliable current profile diagnostic is a key prerequisite. In section 3, diagnos-
tics and evaluation methods are discussed. Finally, in section 4 we describe the recently found non-inductive H-mode scenario at $q_{95} \approx 5.3$ and compare it to modeling with TGLF.

2. Minimum gas input and improved H-mode operation

Improved H-mode operation could be maintained even when the main chamber tiles were completely covered with W, except for a part of the ICRF limiters in 2006. In [14] improved H-modes with fishbones from that phase are compared to one from the pure carbon machine. With W-coating the density was 30% higher, but this is largely due to the increase in upper triangularity ($\delta_u$) from 0.0 to 0.12 and/or due to the increase in heating power from 5 MW to 8 MW. Already in the carbon device it has been noted that both parameters are important for the minimum achievable density [15]. In the fully W-coated device a lot of gas was used in the current ramp-up. For several years ICRF could not be used to mitigate W-accumulation. In 2011 the available power of the new ECRH system increased from 0.8 MW to 2.3 MW allowing an attempt to replace 3 MW of ICRF used in the 2006 cases by ECRH. As a guidance to adjust the gas puff it was attempted to get the same recycling fluxes as in 2006, which turned out to work quite well as shown in figure 2. Here we compare two cases with early heating resulting in small (3,2) NTMs instead of fishbones (see [14]), which are operationally easier to achieve. During the ramp-up and L/H transition dynamics of the gas fluxes to achieve a certain recycling are very different. The carbon divertor seems to store gas during ramp up (more fueling is necessary) and to release it after the L/H transition whereas with the W divertor the low density plasma builds up with hardly any fueling, but a strong gas pulse is needed as particle confinement increases after the L/H transition in order to maintain the same recycling flux. Note that both cases did not use He glow prior to the discharge. 

![Figure 2: Comparison of improved H-modes prior and after completion of the W coverage in 2007. Blueish colors correspond to the earlier discharge (see [4] for details) using IC as central RF heating. Red corresponds to the later discharge which has been developed trying to reproduce the recycling fluxes of the earlier one in the full-W machine using ECRH.](image-url)
aged density around 0.5 s The ELM-free phase when switching on the additional NBI sources (around 1.2 s, corresponding to the high $T_i$ values) is also longer in the full-W case. Both observations are in line with the general finding of a reduced L/H threshold in the fully W-covered machine [17]. The plasma parameters in the flattop phase of both plasmas can hardly be distinguished, except for a slightly higher density peaking in the full W-case. Following the same lines the fishbone-stabilized improved H-mode could be reestablished (late-heating in [14]), but the high-confinement phases with fishbones were so far less stable in time. The continuation of these studies was postponed until a reliable current profile determination could be reestablished, since this profile is assumed to be crucial to understand the changes in performance.

3. Current profile diagnostics and interpretation

The motional stark effect (MSE) diagnostic on AUG was taken into operation in the carbon device [18]. In parallel to the increasing W-coverage several massive changes of the calibration were observed. Some of them were related to a faulty photo-elastic-modulator masking a connection with the W-coverage of the first wall. In parallel to findings at Alcator C-mod [19], polarized background light was identified as a major source of error for discharges with significant gas puff and correspondingly high divertor recycling fluxes [20]. A polychromator set-up for background subtraction is under way and an absolut angle calibration has just been performed [21].

Driven by the uncertainty about reliability of the MSE data and its dependence on specific NBI configurations, two new diagnostics sensitive to the current profile were implemented on ASDEX Upgrade. One is the imaging MSE system, which utilizes the same Stark-split D-alpha light emitted by the neutral beam particles as conventional MSE systems. However, this light is led through a series of birefringent plates, a polarizer and imaged onto a CCD chip, forming an interference pattern. While conventional MSE systems typically filter out the $\sigma$- or $\pi$-lines of the Stark spectrum, IMSE diagnostics utilize all of the lines, which increases the signal to noise ratio and eliminates the need of using precisely tuned narrow band filters. Furthermore, they are not disturbed by polarized broadband light, like reflections from the metal walls. IMSE diagnostics provide a 2-D image of the polarization angle, which significantly increases the quality of the equilibrium reconstruction compared to 1D systems. A new permanent IMSE diagnostic has been in operation at ASDEX Upgrade since the 2015-2016 experimental campaign. The system has a wide field of view imaging from the outer separatrix across the magnetic axis and up to 10 cm on the high field side [22]. The optics of the AUG IMSE system are designed for very low Faraday rotation, which is monitored, together with possible drifts, using in-vessel polarized light sources. For the 2016 experimental campaign a prototype "back-end", the set of lenses and crystals designed to create the interference pattern on the CCD camera, was mounted to the new optical relay system. The prototype back-end will be replaced by a fully optimized system before the start of the 2017 experimental campaign. The new design features larger birefringent plates yielding a larger étendue, higher sta-
bility and improved calibration possibilities. The second new diagnostic is an upgrade to the far infrared (DCN) interferometer used for measurements of line integrated density. Faraday rotation leads to a tilt of the beam polarization. The amount of rotation is proportional to the integral $\int n_e B_\parallel ds$ along the laser path, $B_\parallel$ being the component of $\vec{B}$ along this path. For a given poloidal geometry, $B_\parallel$ results from the poloidal field, which is caused by external coil currents and the plasma current. In the 2015/16 experimental campaign, two interferometer channels were equipped with an additional polarimeter with an angular resolution of about 0.6°. The measurement is routinely available throughout the entire discharge and for all heating schemes. Biasing factors, such as polarized ECRH stray radiation and the pick-up of a toroidal field component due to a slight tilt of the viewing chord out of the poloidal plane, were identified and countermeasures were developed. Figure 3 illustrates the response of the measured Faraday angle as plasma current is expelled from the plasma center. Reduced central current means reduced $n_e B_\parallel$, such that the Faraday angle drops in relation to the line-integrated density.

The current profile itself is a basic constituent of the tokamak equilibrium. The omnipresent ill-posedness of tokamak equilibrium reconstructions is mitigated by an integrated approach (IDE) of combining a comprehensive set of internal and external measurements with a predictive model of the expected current distribution. The goals using a sufficiently informative set of measurements and physical modeling are to have an overdetermined equilibrium, to overcome the need for non-physical regularization (smoothing) of the source profiles entering the Grad-Shafranov equation, and to validate diverse measurements due to partially redundant information. The set of measurements at ASDEX Upgrade comprise magnetic probes including a diamagnetic flux loop, divertor tile currents, pressure profiles consisting of electron and ion thermal and fast ion pressure, loop voltage and isoflux constraints from electron and ion temperature profiles together with the above discussed MSE, IMSE and polarimetry. These measurements are complemented by flux-surface-averaged toroidal current distributions obtained by solving the current diffusion equation between successive equilibria used as a weak constraint for the time evolution of $\langle j \rangle (\rho, t)$. Additional current redistribution by sawtooth crashes identified using soft X-ray data is included by a Kadomtsev model or by a recent variant preserving the q=1 surface [23]. It turns out that systematic errors in the new diagnostics manifest themselves in data inconsistencies motivating diagnostic experts to identify the sources either in the diagnostic set up or in the numerical model of the diagnostic. Above mentioned pick-up of a toroidal magnetic field component by polarimetry could be identified this way. The recent in-vessel calibration of the MSE system [21] could reduce the absolute systematic uncertainty of the diagnostic to below 0.7°, thereby strongly reducing the freedom to fit the data by adjusting calibration factors. IMSE has not yet reached this state of precise absolute calibration, but it allows already to resolve absolute changes of the polarization angle of 0.1° at a time resolution of 5.6 ms, enabling for example the study of current redistribution during sawteeth. For selected discharges, the IMSE data was successfully integrated in the equilibrium solver producing excellent results [24].

4. Non-inductive scenario at $q_{95} \approx 5.3$

Having the necessary ingredients in place, i.e. sufficient ECRH, power handling capability of the W divertor, current profile measurements and an integrated equilibrium reconstruction, experiments on significant modification of the q-profile were taken up again, based on a shape with large wall clearance in order to minimize other sources of W due to main chamber sputtering especially during ELMs [25]. In order to connect to results from other devices, variations of $q_{min}$ for a rather flat central q-profile were performed using various combinations
of more or less tangential NBI PINs with various profiles of co- and ctr-ECCD [20]. In contrary to most AT-experiments on this and other devices AT scenarios are also developed starting from an equilibrated ohmic current profile at full current followed by a slow ramp in $\beta$, thus minimizing the influence of the sometimes poorly reproducible current profiles during the ramp-up phase of the AT scenario. In the following the results with a maximum of driven co-current are described which result in an almost fully non-inductive drive of 800 kA corresponding to $q_{95} \approx 5.3$. The experimental result is shown in figure 4. As $\beta$ rises the bootstrap current rises up to 50% of the total current. The rise in $\beta$ is achieved by feedback control of the NBI system to a pre-set $\beta$-trajectory. A higher level of $\beta$ leads to the onset of (2,1) modes combining features of (2,1)-NTMs and external kinks. The increasing NBI power (to $\approx 12$ MW) increases the NBI driven current up to 40% of the total current. ECCD (3 MW) delivers 10%. Note the broad distribution of ECCD generated by four beams (four bumps in the blue curve of fig. 4(d)). The innermost beam is also crucial for suppression of W-accumulation. Central W-concentration varies around $10^{-4}$. Note that for lower densities and higher central heating these W concentrations are acceptable. Oscillations of the time traces during the high $\beta$ phase correlate with impurity influxes at the plasma edge also observed in other high power plasmas. The recent machine opening reveals melting around the flush mounted Langmuir probes in the divertor. These areas are hardened now and it remains to be shown that this solves the problem. The discharge has been extended by 2 s to check if a full current profile equilibration has been reached ([21] and figure 3), but these oscillations mask the long term evolution, which, if any, is weak. The q-profile shown here from the IDE equilibrium reconstruction using the constraints by the experimental data agrees within error bars with the analysis using TRANSP [26,20]. At the beginning of the $\beta$-ramp $T_e(0) \approx 5$ keV is larger than $T_i(0) \approx 4$ keV. At such high $T_e$ the fraction of ion heating of the beams with 60 and 93 keV is significant and it increases further as $T_e$ rises to 5.5 keV during the $\beta$-ramp. Indeed we find that $T_i$ rises stronger than $T_e$ and in the high-$\beta$ phase it is significantly larger (8 keV) than $T_e$. In fact $\chi_i$ even drops significantly as $\beta$ increases. The black curves in figure 5 show the $T_i$-profiles, gradient-lengths and heat-conductivities during the high-$\beta$ phase for the case shown in figure 4 ($\beta_N=2.7$, lower boxes) and for a similar discharge for which the $\beta_N$-ramp was stopped at 2.0 (upper boxes). A clear reduction of ion transport with higher $\beta$ is observed. Since not only $\beta$ changes, but also other relevant quantities as $T_e/T_i$ [27,16], $\nabla v_{tor}$ [27] and the fraction of fast ions from NBI [28], it is not obvious to point at the driving quantity. In [16], the trapped gyro-fluid code TGLF [29] was tested to describe variations of $T_e/T_i$ at moderate $\beta_N < 2$. Under these conditions the simultaneous modeling of density and temperatures compared well with experimental profiles. ITG turbulence was found to be dominant even for strong electron heating. For the low beta case of figure 5 a comparison of the black and red curves shows that this is still true, although the figure shows a case in which $T_e$ and $n_e$ were kept fixed. The reason is that in the high $\beta$ case the modeling of $T_i$ is far off the experimental profile such that a common modeling of all
profiles makes no sense. The radial range where the difference is most significant for $\chi_i$ resp $R/L_Ti$ is $0.2 \leq \rho_{tor} \leq 0.5$. Increasing artificially the fast particle content by a factor of 2 allows to reach the experimental $T_i$ value in the center, but $\chi_i$ resp $R/L_Ti$ vary only inside $\rho_{tor} \leq 0.2$, i.e. generating a central ion ITB. The red curves of figure 5 were obtained using TGLF with $\vec{E} \times \vec{B}$ shear. When it is excluded (blue curves), the $T_i$-profile does not change significantly. (Note that for the TGLF results reported in [20], rotation values were used far above the experimental ones due to a scaling mistake, the effects of the $\vec{E} \times \vec{B}$ shear disappeared using corrected values.) At least for the TGLF model neither the fast particle content nor the $\vec{E} \times \vec{B}$ shear can be adjusted (within error bars) to explain the mismatch to the experiment in the high $\beta$ case. A direct electro-magnetic effect of finite $\beta$ on ITG stabilisation is so far not used in our implementation of TGLF. Recently the gyrokinetic code GENE [30] was applied to JET high-$\beta$ improved H-modes [31]. The results show that thermal and fast ion $\beta$ can have a stabilizing electromagnetic effect on ITG turbulence, in the case of JET only in the inner half of the plasma radius, i.e. in that radial range were also the reduction in ion heat conductivity is found in AUG.

5. Conclusions and Outlook

On ASDEX Upgrade it has been demonstrated that W as a first wall material is compatible with the operation of Advanced Tokamak scenarios such as the improved H-mode (advanced inductive or hybrid scenario) and steady state scenarios. We note that central heating (without creating additional W sources) is a key element for AT operation in AUG. This is expected to be different in reactor-size machines, since the relative importance of the neo-classical inward-pinch terms is much smaller [32]. In W-coated AUG, H-modes with low gas puff cannot be run anymore with only NBI heating. The necessary additional wave heating generally increases the amount of electron heating, which may reduce especially the ion confinement, but the ratio of electron to ion heating is at least closer to reactor conditions. The solid W-divertor was compatible with 15 MW for several seconds without impurity seeding and deuterium fueling and did not hamper AT operation. The natural line-averaged density with the W-wall cannot be compared exactly to the lowest density achieved with the C-wall, since divertor geometry has changed and the lowest upper triangularities used for the lowest densities in C cannot be run anymore. Definitely different is the Deuterium retention during current ramp-up. While the C-wall pumps Deuterium during ramp-up and releases it after the L/H-transition, with the W-wall much less initial gas-puff is required, but fueling during the build-up of the H-mode density is essential. In the first steady-state plasmas in fully W-coated AUG, $q_95 \approx 5.3$ and $\beta_{N,tot} \leq 2.7$ were achieved. The limit of $\beta$ to moderate values is probably due to details of the $q$-profile and definitely not related to W in the main plasma. Experiments in the next campaign will aim to optimize the $q$-profile, also based on experience from other devices in the last decade.

In order to come to a better understanding of the improvement of the heat transport in the ion channel at high $\beta$, analysis of these discharges with GENE has started. Linear cases have been...
set up, which show as expected that ITG turbulence is dominant. Non-linear analysis is planned for the near future. On a longer term we hope to isolate the important terms to an extent that faster codes like TGLF can be improved, as they are needed for the extrapolation of the AT results to future reactors.

Last but not least, the EC system of AUG is currently extended, replacing 4 old units (2 s, 0.5 MW, 140 GHz) with 4 new units (10 s, 1 MW, 140 GHz and 105 GHz). Note that in the case shown in figure 4 the old system was not in use, so the EC power can approximately be doubled for this application. The first two units shall become available early 2017, the others are planned to follow within the next year.

References