Non-Inductive High-β H-Modes in Full-Tungsten ASDEX Upgrade

A. Bock[1], A. Burckhart[1], M. Dunne[1], R. Fischer[1], I. Krebs[2], M. Reisner[1],
D. Silvagni[1], J. Stober[1], T. Pütterich[1], and the ASDEX Upgrade Team
[1]*Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany*
[2]*Dutch Institute for Fundamental Energy Research, 5612 AJ Eindhoven, The Netherlands*

Introduction

Advanced tokamak (AT) plasma scenarios promise improved confinement and extended or indefinite pulse lengths due to substantial non-inductive current contributions. This makes them promising potential candidates for future fusion power plants, such as EU DEMO [1].

ASDEX Upgrade's AT programme aims at investigating the physics of such scenarios near the desired operational point $q_{95} \approx 4.5$, $\beta_N \approx 3.5$, $H_{98} \approx 1.2$ in order to develop and verify existing physics models that can then be used to design future devices with robust predictions.

This contribution will report on the progress made in developing these scenarios, in particular their dependence on environmental conditions such as divertor neutral densities and impurity concentrations.

Scenario Description

Several AT scenarios are under development, largely sharing the plasma shape (see figure 2) and $q_{95} \approx 5.3$, with the two most mature ones differing primarily in their approach to current profile shaping.

The first of these [2] can be considered more conventional and uses off-axis electron-cyclotron current drive (ECCD) and neutral beam current drive (NBCD) to slightly elevate the q-profile centrally, which avoids low mode-number resistive MHD instabilities and also increases the plasma's self-generated bootstrap current $j_{bs} \propto q\nabla p$. A drawback of this approach is that the resulting broader current profile is more unstable against ideal MHD instabilities than more peaked current profiles with $\beta_{N,max} \approx 2.8$.

The quasi-linear fluid code TGLF [3] and the non-linear gyro-kinetic code GENE [4] were verified against the observed heat confinement. While both were able to reproduce the observation, their explanation varied with TGLF relying on an $E\times B$-shear effect and GENE on non-linear fast particle effects. This contradiction could be resolved through dedicated experiments [5]. See also this conference, contribution O5.102.

A second AT scenario under investigation is building on the phenomenon of anomalous flux redistribution, or flux "pumping". In AUG, this pumping is thought to be caused by a saturated 1,1-interchange-mode creating a dynamo effect in the plasma centre [7], although it should be noted that previous observations of a similar nature in the DIII-D tokamak pointed towards saturated 3,2-modes as an explanation [9]. As a consequence of the mode, the central q-profile is clamped to unity near the magnetic axis as the mode imposes an additional loop voltage profile to maintain the 1,1-helicity such as shown in figure 1.

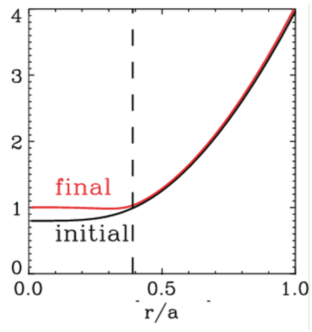

Figure 1: q-profile with (red) and without (black) anomalous flux redistribution [6].

The attractive upside of such scenarios is that due to the mode's redistribution, external co-current drive can be applied near the magnetic axis, where conditions for CD are most favourable. This can be seen in figure 2, where the bulk of the ECCD occurs on-axis in the flux pumping case. Consequently, current drive efficiency is considerably higher in the flux pumping case than in the conventional AT scenario described above as can be seen in figure 3. Nevertheless, the mode maintains the clamped q-profile – thereby avoiding the resistive sawtooth-instability – and a peaked current profile more robust against ideal MHD instabilities with $\beta_{N,max} \approx 3.6$

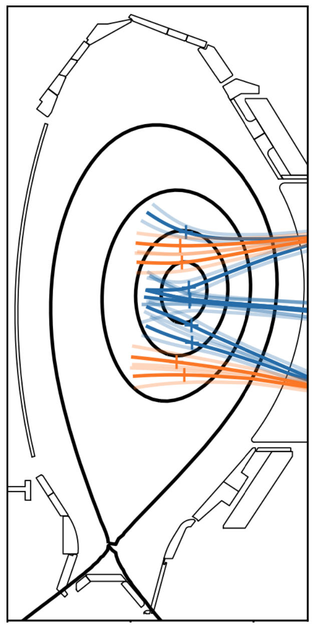

Figure 2: Plasma shape and ECCD deposition locations for scenario with and without flux pumping in blue and orange, respectively.

The 1,1-mode is expected to be driven by the plasma pressure, so increasing β should cause flux pumping to increase as well, eventually preventing the q-profile to dip below unity thereby eliminating sawtooth crashes. Similarly, it should be possible to overwhelm the mode's pumping capability by excessive on-axis co-ECCD. This prediction has been systematically tested in AUG, and qualitative agreement has been found as shown in figure 4. See also this conference, contribution P2.1034.

Impact of Environmental Conditions on Confinement

During the course of the studies a strong variation of the confinement quality was observed.

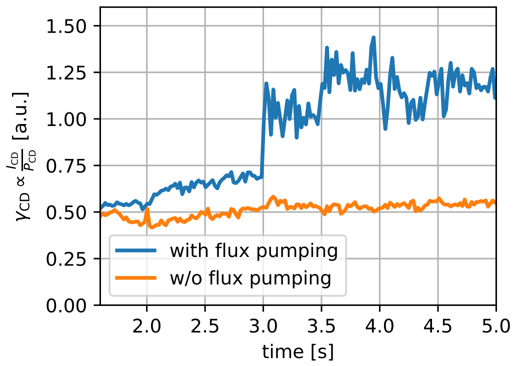

Figure 3: ECCD efficiency for conventional AT scenario (orange, #32305) and flux pumping scenario (blue, #36635).

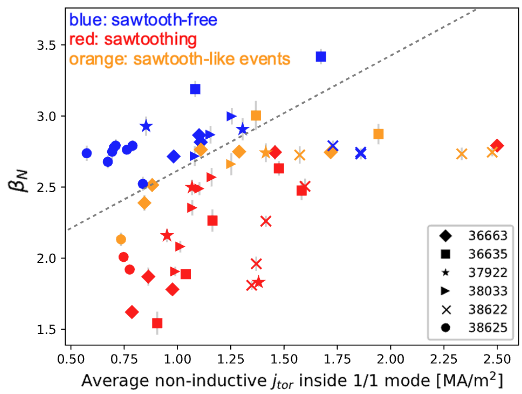

Figure 4: Phase diagram showing the presence of sawtooth crashes [8].

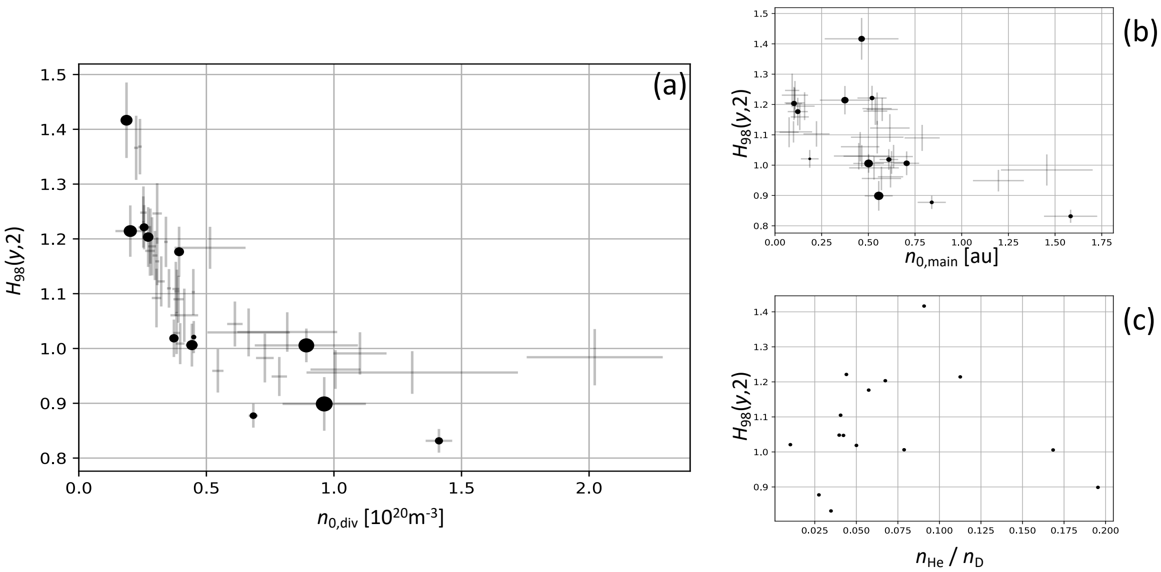

Figure 5: (a) Confinement factor $H_{98}(y,2)$ plotted against divertor neutral density $n_{0,\mathrm{div}}$. Shown is a database of AUG AT discharges with comparable plasma parameters at the same time point. Circles indicate discharges were helium concentration data $c_{\mathrm{He}} = n_{\mathrm{He}}/n_{\mathrm{D}}$ were available with the circle area $A_{\mathrm{circle}} \propto c_{\mathrm{He}}$. A strong improvement of the confinement quality at low $n_{0,\mathrm{div}}$ is clearly discernable, dwarfing any potential He effect. (b) Ditto for the main chamber neutral density $n_{0,\mathrm{main}}$. The same trend is visible, but is much less pronounced. (c) $H_{98}(y,2)$ plotted against c_{He}; no clear trend is visible.

Although initially attributed to residual helium from the frequent boronisations used to condition AUG's walls for low-density experiments, it was found through a database analysis that the divertor neutral density $n_{0,\text{div}}$ is the key environmental quantity correlated with the confinement quality. Figure 5 shows data from up to 55 AT discharges, with and without flux pumping, all taken at similar times in the discharge run. Whereas there is no clear trend visible for the helium concentration in sub-figure (c), a very clear picture emerges from sub-figure (a), and to a lesser extent (b). Below $5 \cdot 10^{19}\text{m}^{-3}$, a strong increase in H_{98} can be observed. Such values can only be reached in full-tungsten AUG with minimal or no gas puffing and after sufficiently conditioning the walls to drain them of their gas inventory, i.e. not routine operation. It should be noted that decreasing the fuelling rate in this manner eventually leads to a loss of ELMs, which causes the plasma to become unstable, i.e. this method cannot be used to achieve arbitrarily high confinement in AT scenario discharges.

Although the improved confinement can already be attributed to a pedestal effect, the exact physics mechanism behind it remains under investigation. Initial analyses of these low-fuelling cases suggest an increase in pedestal stability linked to a reduced separatrix density, whose relation to the divertor conditions is well established [10].

Summary and Conclusion

AT scenarios are routinely investigated in AUG to develop scenarios compatible with future fusion power plants and benchmark present physics models to aid in their design. Novel insights have been gained into the reasons for improved heat confinement in such scenarios as well as the physics behind flux pumping. Finally, the drastic impact of the divertor conditions on the main plasma confinement quality in AT scenarios has been documented.

Acknowledgment This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] H. Zohm *et al.*, Nucl. Fusion **57**, 086002 (2017)
[2] A. Bock *et al.*, Physics of Plasmas **25**, 056115 (2018)
[3] G. M. Staebler *et al.*, Physics of Plasmas **14**, 055909 (2007)
[4] F. Jenko *et al.*, Physics of Plasmas **7**, 001904 (2000)
[5] M. Reisner *et al.*, Nucl. Fusion **60**, 082005 (2020)
[6] P. Piovesan *et al.*, Nucl. Fusion **57**, 076014 (2017)
[7] I. Krebs *et al.*, Physics of Plasmas **24**, 102511 (2017)
[8] A. Burkhart *et al.*, IAEA FEC **28**, EX/4-1 (2021)
[9] F. Turco *et al.*, Physics of Plasmas **22**, 056113 (2015)
[10] A. Kallenbach *et al.*, Plasma Phys. Cont. Fus. **60**, 045006 (2018)