Energy confinement in the pellet-enforced high-density regime at ASDEX Upgrade

P. T. Lang[1], C. Angioni[1], M. Bernert[1], O.J.W.F. Kardaun[1], B. Ploeckl[1], W. Suttrop[1], G. Tardini[1], M. Wischmeier[1], H. Zohm[1], ASDEX Upgrade Team
[1]Max-Planck-Institut für Plasmaphysik, Boltzmannstr. 2, 85748 Garching, Germany

INTRODUCTION

Operation in a future fusion reactor will aim to establish a high plasma central density n_0 in order to harvest a maximum output power. Hence, for example the presently considered EU-DEMO1 concept foresees operation at n_0 values at or even beyond 1.2 the Greenwald density n_{Gw} while keeping the edge pedestal density below n_{GW} [1]. Like for most envisaged reactor scenarios this approach employed the ITER Physics Basis ELMy H-mode scaling expression IPB98(y,2) [2] as a reference for the predicted global thermal energy confinement in tokamaks. The scaling relation was derived 1998 by means of regression analysis on the standard subsets DB2v8 using a power law model. This model implicates the central line averaged electron density $\overline{n_e}$ as relevant parameter, predicting that the thermal energy confinement time $\tau_{E,th}$ increases, at fixed other scaling parameters, with $\overline{n_e}^{0.41}$. However, the data set employed for deriving this scaling contained a limited amount of data from the high density regime. This is related to the fact that a significant loss of confinement sets in when gas puff fuelling is applied, encountering the H-mode density limit at about 0.8 - 0.85 x n_{Gw}. In fact, recently effort has been made to extend the coverage by the confinement database on which the IPB98(y,2) scaling is based, improving in certain regions of the parameter domain expected to be relevant for operation of future fusion reactors, in particular regimes close to n_{Gw}, with low safety factor q_{95} and high normalized pressure β [3]. Furthermore, as the majority of the data in the existing database was obtained in machines with carbon plasma facing components (PFCs), availability of data from more reactor-relevant devices with fully metallic walls suggests revisiting the confinement scaling issue. Here, we provide data from specific investigations on the achievable confinement in the high-density regime of the medium-sized tokamak ASDEX Upgrade during a full tungsten PFC period. Access was enforced here by deep pellet penetration creating peaked density profiles while in DEMO, due to the low collisionality, a strong inward pinch is predicted to foster the peaking [1].

INVESTIGATION STRATEGY

Reliable access to the high density regime while sustaining good confinement normally requires the injection of fuelling pellets, mm sized bodies formed of solid hydrogen. The required technology and also appropriate operational schemes have been developed at ASDEX Upgrade. This comprised a pellet launching system enabling for the injection at high speed from the magnetic high field side, i.e. from the torus inboard for efficient core fuelling. As well, proper density profile shaping is achieved applying pellet resilient measurements. While doing so, the edge density has to be kept sufficiently low in order to avoid confinement degradation. Hence, both pellet and gas fuelling actuators were used simultaneously. A typical example is shown in figure 1. During the pre-programmed pellet sequence, the initial gas flux was reduced to compensate the added flux by the pellets. As resilient signal to control the edge density, here, the neutral gas density in the divertor below the dome structure has been chosen. This, via neutral particle conductance, communicates with the neutrals from the private flux region. Local measurements confirmed the pedestal density was kept well below n_{Gw} also during the pellet phase (red solid line in figure 1). Moreover, even for all configurations analysed in this study, it turned out that this neutral pressure correlates well with the edge density. Details on the feed-back control, including the pellet system in the actuator tool box, can be found in [4].

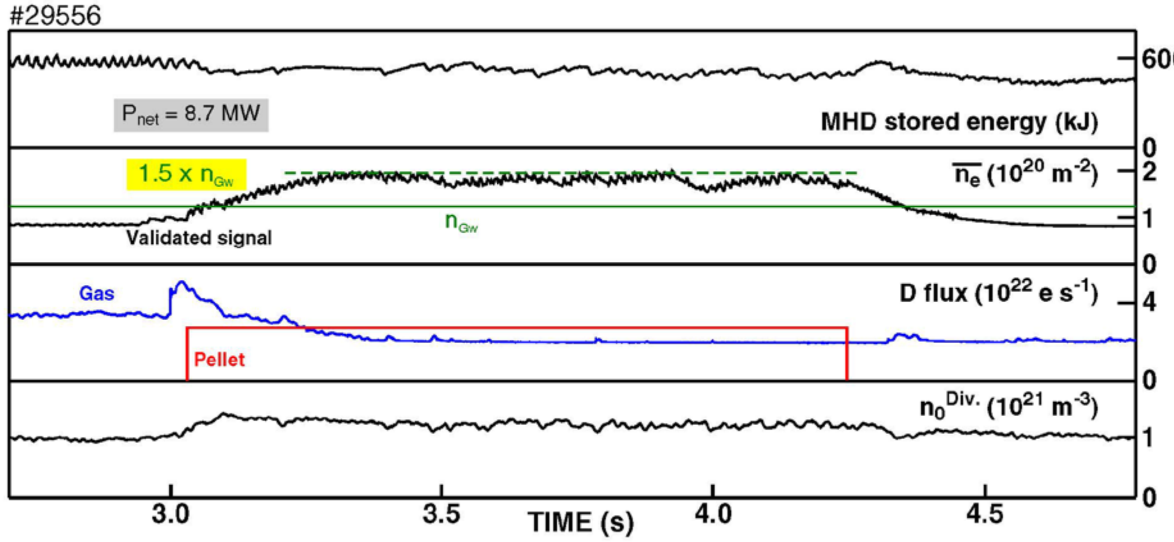

Figure 1: Accessing the high-density regime by pellet injection. To avoid confinement degradation, the gas flux is reduced by maintaining a constant divertor neutral gas density. Typically, no energy confinement enhancement can be achieved anymore beyond n_{Gw}.

Our investigations showed encouraging results, as is displayed in the example in figure 1, which proves that a safe and reversible access to the high-density regime can be achieved with pellets. Moreover, with the control approach developed, even an appealing plasma performance could be attained. However, although these experiments did prove that H-mode operation at trans-Greenwald density can be realised for many different plasma scenarios, the achievable confinement never showed the favourable $\tau_E \sim \overline{n_e}^{0.41}$ dependence. To shed more light on the topic of plasma confinement in the high-density regime and facilitate the elaboration of more adequate scaling relations in this region, we re-analysed all the relevant experiments performed at AUG since it was converted into a full tungsten device.

AUG HIGH-DENSITY DATA BASE

In order to provide a better understanding of the confinement behaviour in this pellet generated high-density regime, a new data base was created extending an existing one derived for yet a single plasma scenario. The plasma scenarios performed since 2011 with a mixture of additional heating methods (NBI, ECRH, ICRH) now include:

- ELM mitigation by application of resonant magnetic perturbations [5] ("Initial RMP", the initial data base) with plasma current I_P = 1.0 MA, toroidal magnetic field B_t = 2.5 T, q_{95} = 4.5, elongation κ = 1.65, upper and lower triangularity δ_u = 0.12 and δ_l = 0.40, respectively.
- Confinement enhancement by nitrogen seeding [4] ("N_2 seeding") with I_P = 1.0 MA, B_t = 2.5 T, q_{95} = 4.0, κ = 1.64, δ_u = 0.08 and δ_l = 0.44.

● ITER base line and similar configurations with strong shaping [4] ("Shaping/ ITER BL") with I_P = 1.0 – 1.12 MA, B_t = 2.0 T, q_{95} = 3.3, κ = 1.68, δ_u = 0.33 and δ_l = 0.47.

● Discharges taken as reference for investigations e.g. on the isotope effect [6] ("Reference") with I_P = 0.8 MA, B_t = 2.5 T, q_{95} = 5.3, κ = 1.68, δ_u = 0.14 and δ_l = 0.43.

● Tests and commissioning of pellet and control system ("Technical") with I_P = 1.0 MA, B_t = 2.0 T, q_{95} = 4.6, κ = 1.60, δ_u = 0.10 and δ_l = 0.38 run with a strong supporting gas puff.

Altogether, the data base contains 598 time slices from 47 different discharges (shot range #26505 - #34873). They represent truly steady-state conditions during phases without pellet injection while for the pellet phases, where a fully steady-state evolution can never be achieved for obvious reasons, averaging over stable intervals was performed. Data cover a wide density range, $\overline{n_e}$ extending from 0.53 – 1.85 x n_{GW}, and the following injected auxiliary heating power ranges (P_{NBI} < 7.5 MW, P_{ECRH} < 2.5 MW, P_{ICRH} < 4.5 MW).

CONFINEMENT SCALING CONSIDERATIONS

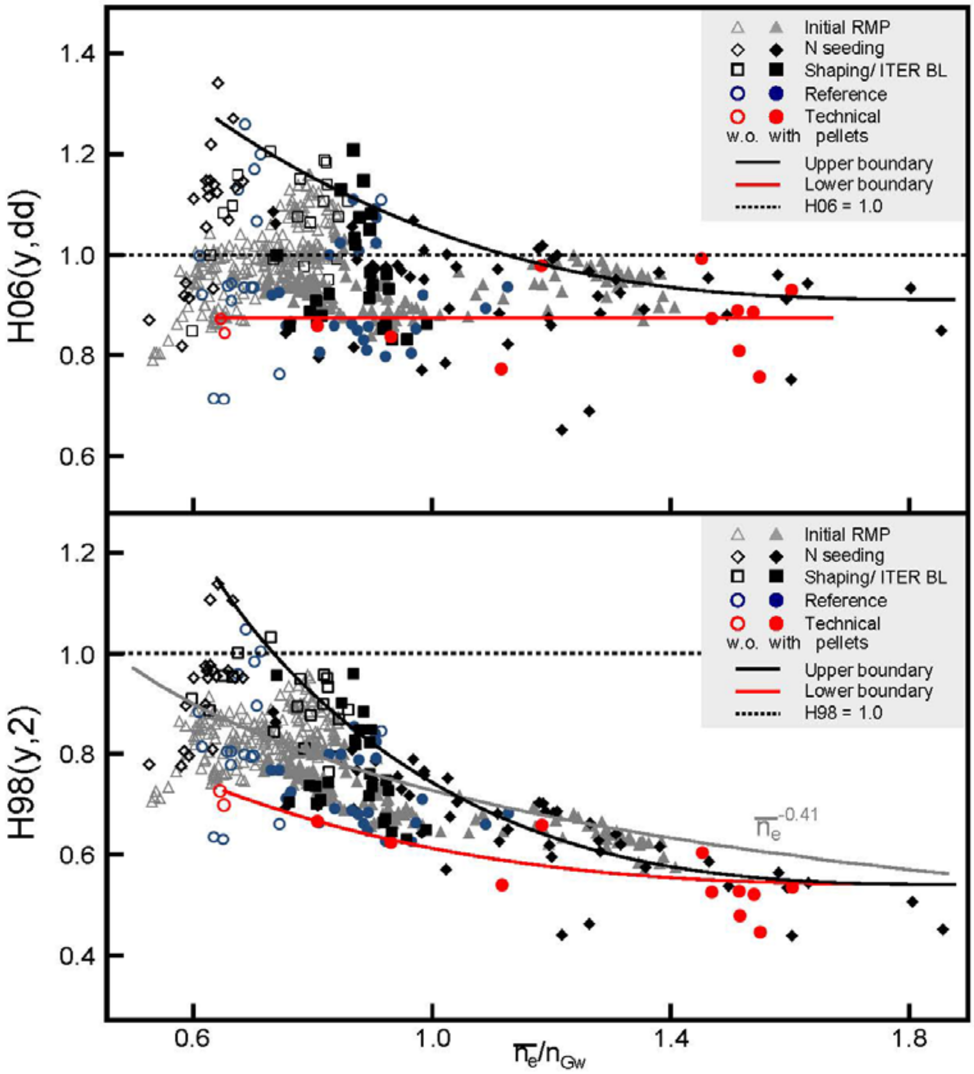

Figure 2: Comparison of $\tau_{E,th}$ achieve in a variety of scenarios to values as predicted by both scaling expressions considered. Beyond n_{GW}., obviously the advantage of confinement enhancement by density enhancement is getting lost, The performance of simple technical shots in red and the upper quantile region (with improved confinement) in black are indicated by the solid lines.

Confirming our earlier observations, data above 0.8 x n_{Gw} show a systematic deviation with respect to the predictions of the IPB98(y,2) scaling, which are significantly overestimating the observed values. This becomes apparent from the lower box of figure 2, displaying the ratio of observed against predicted $\tau_{E,th}$ ("H factor") versus n_e normalised to n_{Gw}. In particular, $\tau_{E,th} \sim \overline{n_e}^{0.41}$ becomes inappropriate as indicated by the solid grey line (evolution disregarding the IPB98(y2) density dependence). Our finding are consistent with considerations on the new ITPA confinement database [3], indicating a reduction of the density exponent when approaching the Greenwald limit in all the regressions performed. This holds for both low-Z and, even more pronounced, under ITER-like („high Z", i.e. tungsten type) wall conditions, notably at AUG and JET. Ibidem, the ITERH06-IP(y,dd) scaling is suggested in [3] as an appropriate analytic expression describing a roll-over near n_{Gw} [7]. For this scaling, as shown in the upper box of figure 2, significantly better agreement of our data with the predicted values is found. In particular, when approaching high densities the roll-over to $\tau_{E,th} \sim \overline{n_e}^{0}$ fits quite well. One can see a clear beneficial effect, due to various methods for performance enhancement, related e.g. by shaping or by N_2 seeding. For phases without pellet fuelling, this is restricted to the range up to about 0.8 x n_{Gw}, thus the boundary of accessible performance (indicated by the black solid line as guide to the eye) is significantly extended with respect to the simpler and more robust scenarios (red solid line). However, these improvements are very quickly fading away with increasing $\overline{n_e}$. Already present in the phases without pellet actuation, the reduction of improvement becomes even more pronounced when pellet fuelling forces access to the density regime desired by the reactor studies, see e.g. [1]. At the currently envisioned target value in the vicinity of about 1.2 x n_{Gw} almost no visible improvements remain. Remarkably, in the high-density regime the achievable plasma confinement becomes virtually insensitive to all the measures usually found effective for low and moderate densities. In the case of N_2 seeding, this behaviour can be attributed to the impact of the pellet fuelling on the edge profiles of density and temperature changing the stability and hence the pressure pedestal [4]. A detailed analysis is still required for the remaining cases. In particular, the role of the separatrix density needs further considerations. The neutral pressure in the divertor was fixed in most experiments. Hence, at high density therefore probably the exhaust mechanisms dissipating momentum and power along an open flux tube is similar and thus the separatrix density might be more or less fixed in all of these scenarios leaving therefore very little impact by any of the operation modifications. Finally, it should be noted that the severe difficulty to achieve enhanced confinement in the high-density regime does not necessarily imply that this will be the case on a reactor scale as well. Parameters governing the underlying physics and hence the mechanisms determining inward pinch and pedestal differ quite significantly, in particular the collisionality in our experiments is quite high compared to values expected in a reactor.

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.: Nuclear Fusion 53 (2013) 073019

[2] ITER Physics Basis: Chapter 2, Nucl. Fusion **39** 12 (1999) 2175–2249

[3] G. Verdoolaege et al., Proc. 27tht IAEA Fusion Energy Conference (Gandhinagar, India), EX/P7-1 (20018)

[4] P.T. Lang et al., Nucl. Fusion 58 (2018), 036001

[5] P.T. Lang et al., Nucl. Fusion 52 (2012) 023017

[6] P.T. Lang et al., Nucl. Fusion 59 (2019) 026003

[7] O.J.W.F. Kardaun, et al., Proc. 21st IAEA Fusion Energy Conference (Chengdu, PRC), IT/P1-10 (2006)