H-mode confinement in the pellet-enforced high-density regime of the all-metal-wall tokamak ASDEX Upgrade

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Abstract
During recent years a pellet-based system for feedback controlled core density fuelling has been developed at the ASDEX Upgrade tokamak, making the device well suited for the investigation of the reactor relevant high-density regime in an appropriate configuration. Efforts have proven that an adequately applied pellet actuator enables safe and reversible access to core plasma densities, as intended in current reactor designs and even beyond. From the analysis of a wide range of different plasma scenarios it becomes apparent that the beneficial increase of confinement with density saturates when approaching the Greenwald density. When taking this into account properly, it has emerged that for standard configurations the energy confinement can be sustained when the density is increased. However, the surplus confinement by different means, such impurity seeding or strong shaping, cannot be fully preserved. This is presumed to be attributed to a separatrix density which is not yet adequately controlled.

Keywords: fuelling, tokamak, all-metal-wall, energy confinement scaling, pellet

(Some figures may appear in colour only in the online journal)

1. Introduction

In a future fusion reactor, a sufficiently high plasma core density is required in order to generate an ample amount of output power. Accordingly, scenarios considered e.g. for the EUDEMO concept are requesting a value considerably above the Greenwald density \( n_{GW} \) [1–3] for the central density \( n_0 \). The Greenwald density [4] is an empirically operational limit for the line-averaged density that often leads to disruptions when conventional gas fuelling is applied in tokamaks. It is akin to ‘Sudo-type’ limits for stellarators, see e.g. [5,6]. Most commonly the Greenwald density is expressed as

\[
n_{GW} = \frac{I_P}{\pi a_0^2}
\]  

(1)

with \( n_{GW} \) in units of \( 10^{20} \text{ m}^{-3} \), the plasma current \( I_P \) in MA and the minor plasma radius \( a_0 \) in m [7]. Referencing to this value, the Greenwald fraction \( f_{GW} \) is introduced as

\[
f_{GW} = \frac{n_e}{n_{GW}}.
\]  

(2)

Normally, the density profile becomes very flat when approaching \( n_{GW} \), while the energy confinement decreases, see [8]. With special means such as pellet injection, it has been
found that this constraint can be overcome. The peaked density found under such circumstances [9] suggest that a limitation exists which originates from the plasma edge region. Consequently, accessing the high-density regime beyond $n_{GW}$ will require efficient core particle fuelling, e.g. by injecting mm-size solid pellets produced from frozen fuel, for instance pure hydrogen isotopes or mixtures thereof. Simple gas puff fuelling, applied in most experiments to date, is not capable of reaching the required densities and is thus most likely not an adequate solution. In most tokamak scenarios investigated so far, for gas fuelling beyond about $0.8–0.85 \times n_{GW}$, strong reduction of the energy confinement sets in [8], resulting in a loss of the desired high confinement regime (H-mode) [10]. This phenomenon is usually called the ‘H-mode density limit’. While most investigations rely on gas fuelling, there is a lack of experiments that show a high performance in the high density regime. Adversely, most confinement scaling expressions have therefore been derived from data sets which do not include many such reactor-relevant data. This also applies to the ITER Physics Basis ELMy H-mode scaling IPB98(y,2) [11], employed usually as a reference to predict the global thermal energy confinement in tokamaks for future reactor scenarios. As a consequence, reactor scenarios are frequently elaborated employing a scaling that does not cover the reactor-relevant high density regime.

The expression IPB98(y,2) was derived in 1998 by means of regression analysis on a suitable standard subset, called DB2v8, using a simple power law model. This model incorporates the central line averaged electron density $n_e$ as relevant parameter, predicting that the thermal energy confinement time $\tau_{E,th}$ increases over the range $0.2–0.85 \times n_{GW}$, at fixed other scaling parameters, with. However, this forecasted increased performance with density in H98(y,2) is in particular not valid anymore in the high density regime. In fact, effort has already recently 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 $\beta$ [12]. Furthermore, the majority of the data in the existing database was obtained for discharges with mainly carbon plasma facing components (PFCs, i.e. the divertor and first wall) in JET, AUG and DIII-D. The availability of more reactor-relevant recent data with fully metallic PFCs or a ‘ITER-like wall’ (W divertor with either Beryllium or boronized PFCs) suggests revisiting the confinement scaling issue. An updated version of the confinement database was obtained by adding high-Z wall discharges from AUG and JET, see [12]. From analysis it can be seen that, depending on plasma conditions, IPB98(y,2) tends to over predict confinement when already approaching the Greenwald limit, not only for ‘low-Z’ [13] but also for ‘purely metallic’ devices [14,15]. It is apparent that further investigation to close this gap with respect to reactor-relevant densities with $f_{GW} > 1$ is desirable. Here, we provide data from specific investigations on the achievable confinement in the high-density regime of the medium-sized tokamak ASDEX Upgrade (AUG) during a full tungsten (W) 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 expected which would induce a very useful density peaking, see [1].

2. Experimental set-up

The ASDEX Upgrade is a mid-size divertor tokamak (major radius $R = 1.65 \, m$, minor radius $a_0 = 0.5 \, m$) where plasma facing components are mainly W [16], while the walls are repeatedly conditioned by boronization. In its reactor-relevant all-metal-wall configuration, being equipped with a powerful auxiliary heating system and a versatile set of diagnostics enabling the required plasma analysis and characterization makes it well-suited for any task of this kind. Reliable access to the high density regime while sustaining good confinement requires a sufficiently deep deposition of fuelling particles as can be achieved by the injection of solid hydrogen pellets. The required technology and also appropriate operational schemes have been developed at AUG. It comprised a pellet launching system enabling injection at high speed from the magnetic high field side, i.e. from the torus inboard found essential for efficient core fuelling [17]. With this reactor-like configuration, it is particularly set up for investigations in the pellet-enforced high-density regime.

3. Investigation strategy

3.1. Control approach

It has become clear that during pellet injection phases a proper density profile shaping is required to maintain reasonable confinement properties. In order to avoid confinement degradation when approaching the H-mode density limit with too strong an increase of edge density, excessive edge fuelling must be avoided. Consequently, the additional pellet particle flux into the plasma has to be compensated for by an adequate reduction of the initial particle influx. In our experiments, therefore, two ‘actuators’ were used simultaneously—pellet injection and gas puffing. For a successful application, therefore, only scenarios allocating ample initial gas puffing could be used. This is in order to provide the necessary headroom for a compensatory reduction. Since AUG operates in an all-metal-wall environment, most plasma scenarios intended to obtain high performance need to apply significant gas puffing anyway to prevent W accumulation, see [16]. For a proper guiding of the actuation, a suitable control parameter was needed. The usually applied measurement process, using an edge chord of the deuterium cyanide (DCN) laser interferometer, faced strong perturbations by pellet-imposed fringe jumps and turned out to be inappropriate in this respect. This led us to consider another arrangement that draws on pellet-resilient measurements. Specifically, we choose the neutral gas density $n_{GW}^{Div}$ in the divertor below the dome structure. This, via neutral particle conductance, communicates with the neutrals from the private flux region. It was found in [18] from local measurements (not yet available for real time control) that this neutral pressure...
correlates well with the edge density. Hence, keeping $n_0^{\text{Div}}$, constant turned out a suitable way to keep the pedestal density well below $n_{\text{GW}}$ during pellet phases, while preventing an immediate deleterious impact on the confinement. The development of control schemes that are capable of integrating the pellet tool which imposes strong perturbations on many sensor parameters is an ongoing activity which faces a complex challenge but also bears strong relevance for a future reactor, see [19]. To achieve further performance optimisation, the simultaneous actuation of more actuators and/or better suited control parameters is most likely needed; efforts are underway for a more refined control approach. However, the best practicable approach currently available is to control $n_0^{\text{Div}}$.

3.2. Application for high-density high-confinement operation

An example showing successful application is displayed in figure 1. In order to enforce access to the high density regime, here a pre-programmed pellet sequence with fixed mass $m_p$, speed $v_P$ and frequency $f_P$ was launched (details of the experiment and the pellet system can be found in [201]). The average pellet flux $I_P = m_p \times v_P$ applied is indicated by the red solid line in box d. The initial value of $n_{\text{GW}}^{\text{Div}}$ is kept reasonably well throughout the entire sequence (see box e). This compensates the pellet-added flux by a reduction of the initial gas puff (blue solid line in box d). As a consequence of the pellet actuation, the line-averaged density as derived from several measurements by the control system (black solid line in box c) rose to about $1.5 \times n_{\text{GW}}$ (the value of $n_{\text{GW}}$ stays constant as shown by the green solid line in box c). With the pellet flux terminated, initial conditions are recovered, proving that safe and reversible access to densities significantly beyond the steady-state situation cannot be established by pellet actuation. As a consequence of the pellet fuelling to high densities with edge localised mode (ELM) mitigation by resonant magnetic perturbations (RMP). From this set of experiments a new database was created, extending an existing one derived for a single plasma scenario.

4. AUG high-density database

Several relevant experiments have been conducted, both recently and in the past, exploring the pellet-enforced high-density regime for a wide range of different plasma scenarios. 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 $\tau_E \sim n_{\text{e}}^{0.41}$ dependence predicted by the IPB98(y,2) scaling.

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 analysed and respectively re-analysed all the relevant experiments performed at AUG since it was converted into a full tungsten device. Analysed discharges span simple and robust plasmas employed for pure technical developments, a reference scenario widely used and having high performance potential by nitrogen (N) seeding or elaborated configuration shaping. From relevant shots showing good and smooth behaviour, data were taken during suitably steady phases (notably a thorough steady-state situation cannot be established by pellet actuation). In addition, data were adopted from a previous study combining pellet fuelling to high densities with edge localised mode (ELM) mitigation by resonant magnetic perturbations (RMP). From this set of experiments a new database was created, extending an existing one derived for a single plasma scenario.

4.1. Database structure

To give further detail, data sub-sets were derived for different plasma scenarios performed since 2011 until the end of the 2019 programme campaign with a mixture of additional heating methods (neutral beam injection (NBI), electron cyclotron resonance heating (ECRH), ion cyclotron resonance heating (ICRH)), compiled as:

- Initial RMP (the initial database):
  - ELM mitigation by application of resonant magnetic perturbations [9] with $I_P = 1.0 \text{ MA}$, toroidal magnetic field $B_t = 2.5 \text{ T}$, $q_{95} = 4.5$, elongation $\kappa = 1.65$, upper and lower triangularity $\delta_u = 0.12$ and $\delta_l = 0.40$, respectively.
  - Confinement enhancement by nitrogen seeding [18] with $I_P = 1.0 \text{ MA}$, $B_t = 2.5 \text{ T}$, $q_{95} = 4.0$, $\kappa = 1.64$, $\delta_u = 0.08$ and $\delta_l = 0.44$.
  - Shaping/ITER baseline (BL)
    - ITER base line and similar configurations with strong shaping [18] with $I_P = 1.0–1.2 \text{ MA}$, $B_t = 2.0 \text{ T}$, $q_{95} = 3.3$, $\kappa = 1.68$, $\delta_u = 0.33$ and $\delta_l = 0.47$.

Reference

Discharges taken as reference for investigations, e.g. on the isotope effect [21], with $I_P = 0.8 \text{ MA}$, $B_t = 2.5 \text{ T}$, $q_{95} = 5.3$, $\kappa = 1.68$, $\delta_u = 0.14$ and $\delta_l = 0.43$.

Launcher test

Tests and commissioning of pellet and control system with $I_P = 1.0 \text{ MA}$, $B_t = 2.0 \text{ T}$, $q_{95} = 4.6$, $\kappa = 1.60$, $\delta_u = 0.10$ and $\delta_l = 0.38$ run with a strong supporting gas puff.

The database contains 667 time slices from 54 different discharges altogether (shot range #26 505–#36 063). Data cover a wide density range, $n_e$ extending from 0.52–1.92 x $n_{\text{GW}}$, and the following injected auxiliary heating power ranges ($P_{\text{NBI}} < 9.8 \text{ MW}$, $P_{\text{ECRH}} < 3.3 \text{ MW}$, $P_{\text{ICRH}} < 4.5 \text{ MW}$).

4.2. Database content

For any time slice, the data set entry consists of the following information. The discharge number and the time, reference to the relevant sub-set and characterisation from the reference or pellet phase, and an indicator for soft or disruptive discharge termination; measured values of $I_P$ and $B_t$, values obtained from the plasma equilibrium $q_{95}$, $\kappa$, $\delta_u$, $\delta_l$, plasma volume $V_P$, surface $S_p$, poloidal area $A_P$, MHD energy $W_{\text{MHD}}$, $R$, $d_0$ and the calculated $n_{\text{GW}}$; measured loop voltage $U_{\text{loop}}$, applied additional heating powers $P_{\text{NBI}}$, $P_{\text{ECRH}}$, $P_{\text{ICRH}}$, calculated Ohmic
heating $P_{\text{OH}}$ and the total heating power $P_{\text{tot}}$ summing up $P_{\text{OH}}$ and all applied additional heating power. It also contains the total radiated power $P_{\text{rad}}$, determined out of bolometry measurements [22], the line-averaged density $n_e = \hat{n}_{\text{nedl}}(3)$, where $n_e$ is the local electron density and $l$ is the chord length within plasma column, taken as obtained from interferometer data or if required applying the validation algorithm [18], and $n_0$ as obtained from local measurements from the Thomson scattering system [23] or from the core density in a dynamic state estimator [19] if any is available. The applied gas flux and species (always D for fuelling, always N if additional seeding took place) is also available, as well as the pellet species (always D), $v_P$, $m_P$, $f_P$ and the calculated $\Gamma_P$.

A total energy confinement time can be calculated as

$$\tau_{\text{tot}} = \frac{W_{\text{MHD}}}{P_{\text{tot}}}.$$  

The thermal energy confinement time

$$\tau_{\text{th}} = \frac{W_{\text{th}}}{P_{\text{net}}}.$$  

can be calculated from the thermal plasma energy $W_{\text{th}}$ excluding fast ion contributions $W_a$ and the net heating power $P_{\text{net}}$, while taking into account heating power losses [24]. For this calculation, a parametric regression was applied. Recently, a deviation from the reference parametric regression was observed for AUG NBI heated discharges. However, for discharges with medium to high plasma density, with moderate $P_{\text{NBI}}$ and higher $I_P$ as is the case here, the correction was found to be small. Nevertheless, for a small set of discharges (containing at least one example from every sub-set) with all the corresponding data available for a full modelling, the database has been re-evaluated to estimate this correction sample-wise. One example from the initial RMP sub-set (details of this discharge can be found in [9]) is shown in figure 2. It displays $W_{\text{th}}$ and $W_a$ calculated by the full modelling (blue) and the reference parametric regression. The deviation turns out to be small, in particular in the pellet-enforced high-density regime with the high collisionality reducing $W_f$. Since the effect is therefore well within the scatter observed within any sub-set for the performance anyway, we kept the parametric regression approach for the entire database in order to preserve a self-consistent analysis.

5. Confinement scaling considerations

5.1. IPB$^98$(y,2) scaling

First, we consider the achieved performance with respect to the IPB$^98$(y,2) scaling. As we are considering only operation in pure D, we insert $M = 2$ for which the predicted thermal energy confinement time takes the form (in mks units) [11]:

$$\tau_{\text{th}} = 3.30930 \times 10^{-11} \times 2^{0.19} \times P_{\text{net}}^{0.93} \times P_P^{-0.74} \times R^{1.39} \times a_0^{0.58} \times R^{0.78} \times B_t^{0.15} \times n_0^{0.41}.$$  

The relative performance with respect to confinement can then be expressed by the ‘H factor’

$$H^98(y,2) = \frac{\tau_{\text{th}}}{\tau_{\text{IPB}}^{98}(y,2)}.$$  

As a measure for the achieved performance with respect to density, we take the normalised expression $n_e n_{GW}$.

Figure 3 displays these two relative assessment values plotted versus each other, illustrating the evolution of the confinement in the pellet-enforced high-density regime. Different colours represent data from different sub-sets with the dots referring to the reference and the stars to the pellet phases. The performance of launcher tests and reference shots is indicated by the black line while the band formed by the two magenta lines includes approximately 90% of the data. Beyond $n_{GW}$, the predicted advantage of confinement enhancement by density enhancement is obviously becoming lost. A behaviour disregarding the density dependence predicted by IPB98(y,2) is represented by the grey line, assuming $\tau_{E,th} \sim n_e^0$ instead and matched to the median $n_e$ value of data points in the range 0.7–0.8 x $n_{GW}$. Confirming 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 significantly overestimate the observed values. This is visualised in figure 3 by the upper and lower boundaries obtained by connecting the median values plus (upper) respectively minus (lower) a robust estimate of twice the standard deviation, calculated for 20 segments equidistant in $f_{GW}$. As becomes apparent from figure 3, in particular, $\tau_{E,th} \sim n_e^{0.41}$ becomes inappropriate.

These findings are consistent with considerations based on an extension of the ITPA confinement database, called DB5, see [12], indicating a reduction of the density exponent when approaching the Greenwald limit in all the regressions performed. This holds for both low-Z and also under an ITER-like wall condition, with the latter being somewhat more pronounced. In particular, the renewed regression analysis showed for the single-device analysis of AUG in the all-metal-wall configuration (over the density range $\{Q_{0.05}, median, Q_{0.95}\} = \{5.5, 8.1, 11.4\} \times 10^{19} m^{-3}$) $\tau_{E,th} \sim n_e^{0.055 \pm 0.057}$, while for the multi-device the according exponent ranges, depending on the analysis method, run from 0.13 to 0.29 [12].

### 5.2. ITERH06-IP(y,dd) scaling

As a result of the refined analysis, the ITERH06-IP(y,dd) scaling suggested in ITER-FEAT [25] units in [26] is regarded a more appropriate analytic expression to describe a roll-over of confinement for densities near and above $n_{GW}$. For this scaling, taking again $M = 2$ on pure D discharges, the predicted thermal energy confinement time, expressed in mks units, see [27], reads

$$\tau_{th}^{ITERH06(y,dd)} = 6.94431 \times 10^{-7} \times 2^{0.2} \times f_P^{1.1678} \times P_{net}^{-0.74} \times (R/a_0)^{2.48205} \times (R/a_0)^{-0.9 \times \ln(R/a_0)} \times R^{1.2345} \times R^{-0.37} \times B_t^{0.12} \times n_e^{0.32336} \times f_{GW}^{-0.22 \times b_{fGW}} \times \left(\frac{\rho_{GW}}{\rho_{cyl}}\right)^{0.77} \times \left(\frac{\rho_{GW}}{\rho_{cyl}}\right)^{0.41}$$

(8)
Figure 3. Performance of different plasma scenarios (dots represent reference phases without pellets) with pellet fuelling added (star symbols) in the high-density regime with respect to energy confinement predicted by the ITB98(y,2) scaling. Black solid line: average performance (straight line fit of median values) of launcher test and reference shots. Magenta lines: boundaries of entire data set, with approximately 97.5% of data below the solid or above the lower dashed boundary line. Beyond $n_{Gw}$, the predicted advantage of confinement enhancement by density enhancement is obviously becoming lost and the evolution approaches more $\tau_E \sim n_e^0$ (solid grey line).

with

$$q_{cyl} = 5 \times 10^{-6} \times \kappa_a \times \frac{B_t \times a_0^2}{I_p \times R}.$$

(9)

with $\kappa_a$ as defined in [11, 27]. As one can see, not only a roll-over of the confinement time with respect to $f_{Gw}$ is included in this scaling, but also a plasma shape factor $\frac{q_{95}}{q_{cyl}}$, which is related to the triangularity.

Evidently, now the associated ‘H factor’ becomes

$$H_{06}(y,dd) \equiv \frac{\tau_{th}}{\tau_{H_{06}(y,dd)}},$$

(10)

A comparison of the influence of both scaling expressions IPB98(y,2) and ITERH06-IP(y,dd) on envisaged operating scenarios for ITER and a DEMO device has been described in [27].

Plotting the achieved relative energy confinement versus $n_e/n_{Gw}$ now yields the characteristics shown on figure 4. For this scaling, an apparently significantly better agreement of our data with the predicted values is found. In particular, when approaching high densities, the roll-over to $\tau_{th} \sim n_e^0$ now fits quite well. One can see a clear beneficial effect, due to various methods for performance enhancement, related e.g. to shaping or N2 seeding. For phases without pellet fuelling, this is restricted to the range up to about $0.8 \times n_{Gw}$. Here, the 95% upper boundary of accessible performance (solid magenta line) is significantly enhanced with respect to the subset of data from the simpler launcher tests and reference scenarios (black solid line). Reference discharges behaved considerably differently, essentially depending on the magnitude of gas puffing and the first wall conditions. Little scatter was observed during the RMP study, due to small variations of these parameters. High performance can be gained by seeding or shaping/ITER BL, however some cases did not reach the optimum confinement, indicating the sensitivity of such scenarios.

Cases with pellet fuelling yet modest core densities also show a significant response to all performance enhancement techniques. However, these improvements slowly fade with increasing $n_e$. The reduction of improvement, already present in some phases without pellet actuation, becomes even more pronounced when pellet fuelling forces access the density regime desired by the reactor studies. At the currently envisioned target value in the vicinity of about $1.2 \times n_{Gw}$, little 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.

6. Summary

At AUG, recent experimental investigations have been performed to access a reactor-relevant high-density regime via pellet fuelling. Achievement of a high energy confinement by applying different methods was attempted. To reach this goal, simultaneous feedback control of the core and edge density has been applied. A degradation of the energy confinement can
be avoided by a proper density-profile control which essentially raises the core density. However, experiments showed a significant discrepancy with respect to the widely used IPB98(y,2) scaling. In order to shed more light on the issue, we analyse the data from these recent experiments and combine them with data gained from the re-analysis of relevant earlier investigations. A combined database was created covering a wide range of different plasma scenarios, spanning simple scenarios to more sophisticated advanced configurations. From this survey, a rather consistent picture evolves. The key findings are compiled as an itemized list in table 1.

For all the attempts, provided appropriate particle flux was applied, the pellet actuator granted safe and reversible access to the high-density regime. It is undeniable that the favourable positive density evolution as predicted by the IPB98(y,2) scaling does not continue to apply in the density regime beyond about 0.8 \(n_{GW}\). Hence, this scaling has to be tagged inappropriate for consideration when aiming for operation at accordingly elevated densities, as is the case in typical reactor studies. A clearly better choice, as recently mentioned in [12] and confirmed by this study, is the more refined scaling H06(y,dd), which predicts a saturation of performance enhancement with increasing density in the vicinity of \(n_{GW}\). Because of the simplified log-quadratic aspect ratio dependence in H06(y,dd), this scaling is not suitable for ‘non-conventional aspect ratio devices’, i.e. for machines with a \(a \beta\) outside the range 2.5–5.0, see [28] (which also contains a scaling with a more sophisticated aspect ratio dependence). Applying this scaling, a much more unobscured view of the H-mode confinement in the pellet-enforced high-density regime of the all-metal-wall tokamak ASDEX Upgrade emerges. Seemingly, the enhanced confinement as achieved by different means cannot be fully sustained when expanding the operation. Analysis also showed

![Diagram](image-url)

**Figure 4.** Performance of different plasma scenarios (dots represent reference phases without pellets) with pellet fuelling added (star symbols) in the high-density regime with respect to energy confinement predicted by the H06(y,dd) scaling. Black solid line: average performance (straight line fit of median values) of launcher test and reference shots. Magenta lines: boundaries of entire data set, with approximately 97.5% of data below the solid or above the lower dashed boundary line. While the predicted performance can be sustained in the case of moderate initial energy confinement it appears that the achieved benefits are gradually lost beyond \(n_{GW}\).

**Table 1.** Essential findings obtained by analysing the behaviour of plasma performance in the high-density regime.

- Pellet fuelling yields safe and reversible access to the reactor-relevant operational regime with high core densities above the Greenwald density.
- A database was compiled covering relevant reference and pellet-enforced high-density plasmas, containing data from eight years of operation with the all-metal-wall configuration of AUG.
- The database contains 667 data points from 54 different discharges, and 5 entirely different scenarios.
- Cases found showing no confinement degradation with increasing core density.
- The advantages of plasma performance enhancement (as achieved e.g. by N seeding, or high shaping) gradually vanish with increasing core density.
- A strong indication for the scaling IPB98(y,2) was unfounded for densities close to and above the Greenwald density.
- The scaling of ITERH06-IP(y,dd) was more appropriate, providing a realistic description of confinement roll-over in the vicinity of the Greenwald density.
a lack of sustainment when trying to expand operation from moderate towards high densities. With increasing density, the surplus in performance is reduced. At a reactor density grade level, only a fraction of initial benefits found with respect to more simple and robust scenarios remain. In contrast, those basic scenarios still turned out to be very robust when pellet-forced into the high-density regime, maintaining the entire initial confinement.

7. Outlook

Consequently, the challenge of finding better solutions for the combination of enhanced energy confinement and pellet actuation yielding high core densities remains. This requires an identification of the root cause for the declining performance in scenarios with combined actuation on energy confinement and core density.

Detailed investigations have already been made 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 [18]. Supposedly, the role of the separatrix density $n_{e,Sep}$ needs further attention. A recent study on AUG and JET unveiled the ratio $n_{e,Sep}/n_{e,cr}$ correlates linearly over a wide range of plasma parameters with the MHD-normalized pressure gradient at the separatrix. In turn, this pressure gradient confinement degradation is observed above a critical value consistent with the theoretically predicted onset of ballooning modes [29]. Any fuelling attempts raising $n_{e,Sep}$ thus can potentially hamper the confinement. An undue impact of the pellet actuator therefore has to be prevented. Of course, this has not yet been taken into account in a fully effective way by the still rather rough control approach relying on the auxiliary edge control parameter. Hence, the neutral pressure in the divertor was fixed in most experiments. Consequently, at high density the exhaust mechanisms dissipating momentum and power along an open flux tube were probably similar and the separatrix density might be more or less fixed in all of these scenarios, leaving very little impact by any of the otherwise beneficial operation modifications.

Future investigations are scheduled in order to improve this issue. They intend to apply a more advanced real time feedback control feature, e.g. by using pellet-resilient density measurements at an appropriate location. Alternatively, the impact of the pellet actuator can be anticipated by tailoring control trajectories of already available control parameters accordingly. It also has to be ensured every parameter potentially influencing $n_{e,Sep}$ is kept constant to avoid any unintended impact.

Finally, it should be noted that the high effort expected to be necessary in order to achieve enhanced confinement in the high-density regime does not necessarily imply that this will also be the case on a reactor scale. 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 the values expected in a reactor [1].

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