1. Introduction

The function of core particle fueling in the next-step experimental reactor-scale tokamak device ITER and in the planned demonstration fusion power plant EU-DEMO [1] is by no means a trivial one. The injection of pellets, cryogenic mm-sized bodies of solid fuel, taking place at high speed from the magnetic high-field side into the plasma column is expected to be the most suitable approach for this task. Currently, this technique is regarded as the sole option to meet the multiple requirements for fuel delivery (at the needed quantity and quality) sufficiently deep inside the core plasma [2]. Applying the pellet tool is aimed at achieving a central density close to or even beyond the Greenwald density \(n_{Gw}\) [3], while keeping...
the edge density sufficiently low. When simple gas-puff fuelling is applied, in tokamaks the Greenwald density, originally derived for L-mode and Ohmic discharges [3], is commonly recognized as a rather general empirical density limit. When operating in the high-confinement regime (H-mode) even more severe limitations are faced [4]. Occasionally, spontaneous density profile peaking was observed, under specific conditions, at DIII-D, which resulted in operation above the Greenwald density, while maintaining good energy confinement [5]. The deadlock mostly faced with gas fuelling was found to be released by pellet fuelling. This was attributed to different behavior with respect to conditions in the plasma edge. Recent experiments demonstrated core density control at a reactor grade level of about 1.25 \( n_{\text{Greenwald}} \), while keeping the H-mode [6]. Hence, pellet core particle fuelling can be considered as an essential technique of nuclear fusion; however, a couple of physics and technology issues still need further consideration. In contrast to present-day research devices, regulatory safety restrictions and economical aspects will become major factors restraining the design of commercial fusion power plants. As a consequence, the total inventory of tritium (T) must be as low as reasonably possible, while the effort for processing the exhaust gas has to be kept at a tolerable level [7]. This exhaust gas will be composed of unburned fuel, T and deuterium (D), as well as the fusion ‘ash’ helium (He). For operational reasons it is also likely that additional gases have to be inserted into the reactor vessel in order to dissipate the radiative power and enhance plasma performance. Finally, for example, to maintain an economically reasonable design of the protium (H) removal system in the EU-DEMO fuel cycle, a low fraction of H to the total number of plasma particles has been mooted as acceptable [7]. As a consequence, the pumped exhaust gas will be a multi-species composite, subject to handling within the fuel cycle. Ultimately, also the fuel delivered as input for the pellet launching system (PLS) will likely consist of several components, rather than pure D and/or T. It is understood that the processing of the gas mixture provided to the PLS has to guarantee that all key task requirements can still be fulfilled. However, it is worthwhile to consider whether the injection of composite pellets formed from a gas mixture (e.g. D, T, Ne, Ar), exhibit specific advantages, both for the pellet injection performance and efficiency of the fuel cycle.

In this paper, we pursue two different ideas. The first one, representing the major part of this investigation, refers to the approach to control the isotope mixture in the plasma center directly via the pellet isotope mixture. Evidently, our experiments performed at the tokamak ASDEX Upgrade (AUG) employed a mixture of H and D, which mimics the fuel composed of D and T in a reactor. Data from these experiments were employed to study the isotope effect. This effect, the dependence of energy and particle transport on the effective ion isotope mass, is of fundamental interest for the understanding of turbulent transport and, therefore, for the accurate prediction of confinement in burning devices. It has been found to originate from a multi-facet underlying physics, and a recent up-to-date overview can be found, for example, in [8]. The second idea, which is discussed only briefly in this paper, considers the production and application of pellets doped with additional elements. In the example shown, we added a small amount of nitrogen (N). N is widely-used in AUG anyway, as it was found to be an efficacious plasma enhancement gas (PEG) improving the plasma energy confinement [9].

2. Set-up

The set-up employed in the present investigation is very similar to that employed in a recent study where more details can be found, see [6]. Here, some basic elements are briefly repeated and supplementary information on issues specific to this investigation is provided. AUG is a mid-sized divertor tokamak (major radius \( R_{\text{maj}} = 1.65 \) m, minor radius \( a_{\text{min}} = 0.5 \) m) with a reactor-relevant all-metal-wall configuration. It is equipped with a versatile auxiliary heating system, a broad set of diagnostics that enable sophisticated investigations as well as an elaborated discharge control system; however, the device is not designed for T handling. The PLS allows for reactor-relevant and efficient pellet injection from the torus inboard side at repetition rates up to 83 Hz, providing pellets of variable particle content \( m_P \) and speeds \( v_P \). The applied pellet parameters \( m_P \) and \( v_P \) were pre-selected and fixed for every discharge. Three different cuboid-shaped pellet sizes are available, delivering an initial particle content \( m_P \) of either 1.4, 2.8 or 4.3 \( \times 10^{20} \) D atoms. For this study, only the largest size \((1.9 \times 1.9 \times 2.0 \text{mm})\) was used. The accessible speed range \( v_P \) covers 240 – 1050 m s\(^{-1}\). The pellet frequency \( f_P \) is employed to control the pellet particle fluxes \( \Gamma_P = m_P \cdot v_P \), because pellet acceleration takes place in a stop-cylinder type centrifuge [10] that rotates at a preselected revolution rate \( f_C \), \( f_P = f_C / n \) with an integer. Thus, only a discrete spectrum of \( f_P \) and \( \Gamma_P \) values is available. Pellet production takes place in a batch process. Ice rods with a preselected cross-section are extruded from a reservoir into a storage cryostat where they are kept until the pellets are cut on request, accelerated and guided into the torus. Due to the finite length of the stored ice rod, the number of available pellets per discharge is limited (in the case of large-sized fuelling pellets) to 96. Initially, the system was designed to handle either high-purity H\(_2\) or D\(_2\) for the ice formation. Recently, gas handling and extrusion control capabilities have been improved in order to create and handle gas mixtures [11]. In this study, we made use of this facility to produce ice from a mixture of H\(_2\) and D\(_2\) gas, which was taken from a high-pressure bottle initially filled with H\(_2\) and D\(_2\) gas at a ratio of 1:1. Since the bottle was stored afterwards for several months allowing for HD formation by isotope exchange reactions, samples of the actual gas composition were taken and analyzed in a stationary high-resolution mass spectrometer. Absolutely calibrated residual gas analyzers (RGAs) survey the residual gas pumped from the vacuum vessel at different toroidal locations at the inner and outer divertor and the outer mid plane. For the analysis of the isotope ratio, a fitting routine was used [12, 13] on the RGA data. The routine is based on a model [14] defining a probability distribution for all of the possible hydrogen isotope analogues of a molecule, based on its average hydrogen isotope ratio. A common signal
of the hydrogen isotope ratio is created by averaging over the isotope ratios reported by the RGAs at different locations.

The H:D ratio in the edge and divertor region was determined from Balmer spectra that were measured on five lines of sight, which cross the inner and outer divertor leg. The spectra of the Balmer-δ lines (transition $n = 6 \rightarrow n = 2$) of H (at 410.174 nm) and D (at 410.063 nm) and of the Balmer-ε lines (transition $n = 7 \rightarrow n = 2$) of H (at 397.008 nm) and D (at 396.904 nm) were recorded with 4 ms temporal resolution. The spectra were fitted taking the Stark broadening of the corresponding lines into account [15]. The ratios of the line radiances $L$ were used to calculate the H-fraction $H/(H+D)$, i.e. $\frac{L_H}{L_{H+D}}$ and $\frac{L_D}{L_{H+D}}$. The H-fractions obtained from the two lines agreed, within statistical uncertainty, the estimated standard deviation of $H/(H+D)$ varying between 0.02 and 0.04.

To obtain information on the H:D ratio for the core plasma, the thermal neutral fluxes are measured with an $E-M$ mass spectrometer-type neutral-particle analyzer (NPA), see [16]. The neutrals that leave the plasma and are measured by the NPA originate from plasma ions and background neutrals. Therefore, they contain information about the plasma composition.

The neutron yield turned out to be a useful indicator of the H:D ratio in our investigations. It is measured with an absolutely calibrated array of five detectors, which cover a wide range of count rates, see [17].

3. Qualifying the HD pellet actuator

In a first step, the pellet actuator was commissioned to control the H:D isotope mixture in the AUG plasma. Ultimately, the goal is to achieve and keep an equipartition of H and D in the plasma center; however, a real-time measurement that enables feedback actuation is still lacking. Instead, a feed-forward hit-or-miss test was envisaged by choosing a 1:1 ratio for the pellet HD fuel, in spite of the fact that this is not expected to be precisely the required composition in the plasma, due to different particle sustainment times of both species.

A bottled gas mixture was procured, formed by high-purity H₂ and D₂ molecules in a ratio of 1:1. In such a gas mixture, due to isotope exchange reactions, HD molecules are gradually formed and finally a composite mixture of three isotopologues with a H₂:HD:D₂ ratio of 1:2:1 is approached, see [18]. For the predominant conditions in the bottle, reaction rates are rather low. Hence, the number of HD molecules increases only slowly. Mass spectrometric analysis of the gas in advance of the investigations showed that, in our initial gas mixture, the fraction of HD molecules was only 1.2%. Although the HD formation does not alter the H:D ratio, the handled gas mixture was composed of three hydrogen isotopologues. Notably, the pellet system used is designed for the purposes of AUG only. Ice and pellet formation are based on a slow batch extrusion process and hence operational experiences are not necessarily applicable for a fast continuous extrusion process required on a reactor scale. The system is able to handle either pure H₂ or D₂; for both cases conditions to achieve reliable operational performance have been elaborated. Correspondingly, the main process parameters (temperature and pressure) for the freezing, annealing and extrusion of the ice had to be adapted for the gas mixture. It turned out that their progression at about 15 K is closer to those elaborated for pure D₂ (at 17 K) rather than for pure H₂ (at 10 K). However, the acceptable temperature range turned out to be much narrower than for the mono-isotopic cases; hence the HD handling required higher processing precision. Nevertheless, after some experimentation, reliable and reproducible formation of intact and stable HD ice could be achieved and the pellets launched were found to be suitable for our purposes.

The first topic of our investigation was the characterization of the pellet actuator. This was done by injecting the HD pellets into the pre-evacuated torus, surveying the released gas with the RGA. The results achieved by injecting (fuelling-sized) pellets, which consumed two entire 192 mm long ice rods, are shown in figure 1. Consecutive sequences of three
pellets were launched into the torus; after each sequence the residual gas was analyzed. For each data point shown, its ‘rod position’ refers to the initial position of the ice rod when cutting sets in for this sequence. In addition, the RGA takes samples from the gas released from all previous pellets, hence representing the composition of the entire rod consumed so far. Since RGA count rates increase with increasing pressure in the torus, measurements become more precise with every sequence and hence the error bars of consecutive data points become smaller. After several sequences, the torus had to be re-evacuated; thus, essentially three rod sections are analyzed separately. For both rods the results are shown in a separate box, and a spatial average overlaying these data is displayed in the lower box. The dashed lines represent the average isotope composition of the three sections; values displayed an error-weighted average of all data displayed in the box. In fact, the arriving pellets show a H:D ratio very close to 1:1; obviously neither ice production nor pellet transfer altered the initial ratio. However, compared to the initial gas analysis, a significantly higher fraction of HD molecules was found by the RGA. This is attributed to reactions at the wall of the plasma vessel.

4. Actuation on the H/(H + D) ratio

The next step was to sound out the efficacy of the HD pellets for isotope mixture control. For this we selected a scenario used in a previous investigation on feedback-controlled high-density operation, see [6]. The scenario was chosen to robustly handle strong pellet-particle fluxes that result in a high core density. Hence, it is most suitable for the present investigations, although it did not yield a high performance in global plasma energy confinement. In addition, a few discharges performed using pure D for all relevant actuators in global plasma energy confinement. In addition, a few discharges were run using a pure D plasma, three NBI sources (D0 injection at 60 and 90 kV, respectively) with each source delivering about 2.5 MW were employed, supported by up to 4 MW ion cyclotron resonance heating (ICRH) at 36.5 MHz. In the HD discharges, four NBI sources (H\(^{\text{12}}\)) injection at 50 and 70 kV, respectively) with each source delivering up to about 1.8 MW were employed; however, since ICRH was hampered here by the presence of H it had to be substituted by electron cyclotron resonance heating (ECRH) at 140 GHz. To cope with the resulting high densities, the polarization of the ECRH was changed from X-2 mode into O-2 mode shortly before pellet injection in view of its higher cut-off density. In addition, to guarantee proper ECR absorption, the core temperature was intended to be kept above 3 keV. Occasionally, during high flux phases, the core temperatures dropped to about 2 keV.) At the time of these experiments the available ECRH power in O-2 mode was restricted to about 1 MW. Therefore, in order to avoid losing efficient core heating and/or suffering from impurity accumulation in the core, the pellet rates were increased carefully step by step. The maximum available pellet rate was only applied once, briefly at the very end of the pre-programmed sequence.

The basic aim of these experiments was to replace the initial gas puff gradually by the HD pellets and study the impact on the plasma isotope mixture. From the D reference discharges it became clear that during pellet actuation the edge density must be kept at a constant level, in order to avoid a loss of energy confinement. Evidently, this can best be achieved by feedback-control acting simultaneously on gas and pellets, which finally implies density profile control. However, here higher priority was placed on studying the actuator impact and hence the gas and pellet fluxes were kept constant for fixed periods yielding a stable H:D ratio in the applied fuelling flux. Consequently, pre-programmed feed-forward requests were executed by the gas puffing system and PLS. The stepwise increase of the pellet flux was anticipated by an approximate compensatory reduction of gas puff. Laid out for studying the actuation, these experiments were not optimized for physics investigations with respect, for example, to the isotope effect on the plasma performance.

As well as for D pellet fuelling, HD pellet actuation proved most suitable for operation at high density. Due to its higher fuelling efficiency with respect to gas puffing, replacing gas on a par with pellet fuelling results in a significantly higher density. This can be seen from figure 2, which shows a discharge of the series where HD pellets were employed. Displayed there are the applied auxiliary heating power and the radiation (box (a)), the plasma stored energy (b), the center density from the Thomson scattering (TS) system (red diamonds) and the line-averaged density derived in real time from a simple algorithm employing measurements from the laser interferometer and the Bremsstrahlung, see [19], (box (c)), the center temperature from TS (d), the gas and the pellet particle flux (e) and the ratio H/(H + D) from divertor spectroscopy as well as from NPA (f). It is obvious that both line-averaged and central densities increase with increasing pellet fuelling. During phases of almost constant particle flux, the energy confinement is also almost constant. The final part of the discharge with reduced fuelling showed higher confinement, but this situation is very prone to core impurity accumulation and hence not suitable for steady operation. Yet, despite the limited power, core ECRH turned out to be sufficient to avoid this. During the pellet phase a moderate gradual decrease of the impurity content (B, C, N and W monitored) is observed. This decrease, however, does not influence the radiative losses significantly and is mainly attributed to a reduced impurity influx after forming an X-point configuration. In a short concluding pellet sequence, while applying maximum flux, the density profile is somewhat peaked, while the central density reaches the Greenwald density. Next-step investigations should thus envisage applying feedback control of the core density.
The discharge shown and discussed so far was only one of a series of three consecutive ones, applying the HD pellets in different combinations of the initial gas puff. The experiment was performed right after a phase of D plasma operation during the transition towards H plasma operation. To prepare for H operation, glow discharges in H were run in order to reduce the D content of the wall. Nevertheless, conditions with respect to the wall loading by H and D have still been transient and are not fully consistent with the aim of our approach. In every discharge, the strong initial gas puff was replaced in several steps by the HD pellets, keeping the total particle flux approximately the same. In the first discharge, the gas puff was purely D₂. Pure H₂ gas was puffed in the second shot. This is the discharge shown in figure 2, which contains a short final high flux phase in the pellet sequence. Here, the maximum \( f_P \) was applied to gain access to very high densities. In the last shot, which aimed at establishing a plasma with the desired isotope mixture, both H₂ and D₂ gas were puffed at a ratio of 1:1. The results are shown in figure 3, which displays the temporal evolution of the three cases. The upper boxes show the particle fluxes from the gas valves (blue D₂, green H₂) and from the pellet launcher (red, calculated from a set parameter). In the lower boxes, the H/(H + D) fraction as calculated from the total particle flux (consisting of both gas and pellets) is plotted as a solid gray line. This parameter is also displayed as ‘measured by divertor spectroscopy’. The corresponding diagnostics observes the divertor region (indicated by red crosses). It is noted that the spectroscopy results are in very good agreement with the RGA data, of which the latter provides less temporal resolution.

During the first two shots, the pellet actuator definitely provides its key feature by changing the isotopic ratio in the required manner. In the third case, the isotopic ratio established during the initial gas phase is virtually unaffected by the switch to pellet fuelling. In the initial phases and also during phases with a low particle flux there are cases where the isotope mixture of the plasma and applied flux deviate significantly. This is attributed to a wall reservoir not yet fully equilibrated. However, once a sufficiently high flux is applied—either by gas, pellets or a combination of both—the plasma H/(H + D) fraction approaches the target value within about 1 s. For the discharges performed here, even the 1:1 hit-or-miss choice made for the isotopic ratio in this first test turned out to be suitable for establishing the required plasma isotope composition.

5. Analysis of the H/(H + D) ratio

In order to achieve full control of the plasma isotope mixture, knowledge of the plasma composition is required in real time. Yet, such data are not routinely available. Corresponding effort is now under way; during the present study various available diagnostic systems have been adapted to this task. Hence, cross-checking of their results is part of this investigation, too. In the following, the isotope ratio is represented by the hydrogen fraction H/(H + D).

5.1. Edge and divertor region

The data from spectroscopy and RGA were made available already shortly after a discharge. Therefore, the diagnosis of the plasma edge and divertor region turned out to be
straightforward and reliable. In addition, within their specified range of reliability, both measurements agree very well, which can be seen from figure 4. This figure displays the H/(H + D) ratio (measured directly by divertor spectroscopy and RGA), plotted versus the estimated total particle flux. The latter was calculated by gas fluxes that were delivered via valves from different H and D reservoirs, and by estimating the applied pellet flux based on the required rate and while assuming H/(H + D) = 0.5 for the pellets. Evidently, in the region of interest, H/(H + D) is about 0.35–0.65, and so the estimated applied total flux ratio very well matches the ones measured by divertor spectroscopy and RGA. For this region (with an almost balanced isotope distribution) all the data shown in figure 4 refer to phases where a significant flux is applied.
For cases with one of the two isotopes used solely or as the dominating majority, significant deviation is found between the particle flux and isotope mixture of the edge plasma. Most of these data correlate to phases with low flux rates (as discussed before). During these phases, apparently the flux from the wall reservoir contributes a much larger fraction of the total plasma influx. And since the wall reservoir cannot equilibrate as quickly as the plasma inventory, a stronger deviation takes place. Hence, with respect to the isotope composition of the target plasma in the edge and divertor region (where reliable data are available), this first control approach turned out to work fairly well when sufficient flux was applied. Aiming at high-density operation, the latter condition is to be fulfilled anyway.

5.2. Core plasma

The reactor-relevant region of interest for isotope control is unquestionably the plasma center. Due to differences in the transport properties of the different hydrogen isotopes, the ratio occurring at the plasma edge will not necessarily be the same as the ratio in the center. The H/(H + D) core ratio however cannot be directly measured, but needs a sophisticated analysis of the data. Subsequent to the first isotope-control experiment, an analysis of NPA data and the neutron rate was performed to obtain information about the H/(H + D) ratio in the core region. In addition, this investigation might foster the development of these diagnostics towards a serviceable control tool.

5.2.1. NPA

The fluxes of neutral H and D measured with the NPA carry information about the isotope composition of the core plasma. The reconstruction of birth profiles from the measured neutral fluxes needs to take the different mean-free paths of H and D into account. The mean-free path was determined by simulating the attenuation of neutral fluxes due to charge exchange and ionization with the NPA model, see [20] of the 3D Monte Carlo code FIDASIM [21]. By taking the birth profiles for different isotopes into account, one can estimate the expected isotope composition of the plasma. This is shown in figure 4 by black circles. The ratio of measured neutral fluxes (gray circles) would suggest an isotope composition, which is between 1.1 and 1.3 above. This deviation, determined for the plasma parameters in this particular experiment, is expected to change with collisionality. The (weighted) average birth position of the neutrals is near a normalized poloidal radius \( \rho_{\text{pol.}} \sim 0.9 \), and therefore, well within the pedestal top. This observation suggests a higher fraction of H in the confined plasma than observed in the SOL. The reason for this difference is still under investigation.

5.2.2. Neutron rate

Since only H\(^0\) beams have been injected in the HD control approach discharges, no beam-target reactions usually providing the major component of neutron production in AUG took place. Therefore, and because of the high H fraction, the only essential contribution in these discharges is from thermal particles producing neutron rates that are about 1000 times lower than in the reference discharges heated by D\(^0\) NBI (several 10\(^{14}\)/s instead of several 10\(^{14}\)/s). Despite the rather low intensity, the neutron rate was found to be utilized for checking the H/(H + D) ratio determined from the other methods as discussed previously in this chapter. According to [17, 22], the thermal neutron rate \( S_{\text{th}} \) is (approximately) proportional to,

\[
S_{\text{th}} \sim T_i^2 n_D^2,
\]

with \( T_i \) the ion temperature and \( n_D \) the D density. Assuming equal ion and electron temperature, \( T_e = T_i \), which is usually well justified for high densities and disregarding profile changing effects, we used the quantity,

\[
\hat{S} \equiv S(J^2) = \left( W_{\text{MHD}} \left( 1 - \frac{H}{H + D} \right) \right)^2 ,
\]

as a measure for the predicted neutron rate in order to compare it with the measured neutron rate. This is done with respect to a fixed data set where the ratio H/(H + D) has been estimated in several ways. Specifically, the ratio has been calculated from:

(I) Total applied particle flux (gas and pellets).
(II) Total applied particle flux (gas and pellets) restricted to H/(H + D) values within the range 0.35–0.65.
(III) Divertor spectroscopy measurements.
(IV) RGA measurements.
(V) Divertor spectroscopy and RGA measurements.
(VI) NPA flux ratio measurements.
(VII) NPA (modeled).
(VIII) Divertor spectroscopy measurements and NPA (modeled).

For each of these eight replication sets the analysis was performed assuming a linear regression model on normal scale without intercept.

The results are shown in table 1, which displays the product-moment correlation coefficient \( R \) with respect to the fitted regression function and corresponding 95% confidence interval estimates based on Fisher’s Z-transformation, see for example [23], as well as the regression coefficient \( c \) for every

| Replication data set | \( R \) | 95% confidence interval | \( c \left( \frac{1}{2} S \right) \) |
|----------------------|------|------------------------|-------------------|
| Total flux          | 0.26 | 0.20–0.73              | 10.5              |
| Total flux—restricted range | 0.922 | 0.90–0.984 | 17.0 |
| Spectroscopy        | **0.953** | **0.95–0.988** | **15.0** |
| RGA                 | 0.930 | 0.93–0.982            | 16.1              |
| Spectroscopy and RGA| 0.946 | 0.94–0.987            | 15.5              |
| NPA measurements    | 0.853 | 0.85–0.962            | 36.2              |
| NPA modeled         | 0.907 | 0.90–0.976            | 31.2              |
| Spectroscopy and NPA modeled | 0.943 | 0.94–0.986 | 21.0 |

Table 1. Empirical correlation coefficients \( R \), with respect to the fitted regression line, 95% confidence interval estimates and regression coefficients \( c \) estimated from eight different replication data sets that are based on varying methods to obtain the H/(H + D) ratio.
replication set. Each replication set contains 31 data points, except for the restricted total flux set, which contains only 19 observations.

Apart from the replication data set composed using the total applied particle flux, for any set a strong correlation (between 0.87 and 0.99) is found. For the entire total applied particle flux set, the deviation is caused by the strong wall impact for the low flux and H or D dominated cases, as discussed before. The highest correlation has been found for the divertor spectroscopy data set, and the corresponding correlation plot is displayed in figure 5. Therefore, the neutron flux (divided by \(W_{\text{MHD}}\)) appears to be a good indicator to estimate the \(H/(H+D)\) ratio of the plasma for cases with \(H_0\) beams and could be used for real-time feedback control actuation. This can also be seen from the estimated \(H/(H+D)\) ratio obtained by reverting the linear regression function, i.e. adopting the measured neutron rate for \(S\) as an explanatory variable, while taking \(W_{\text{MHD}}\) as a good estimate for the plasma stored energy. Taking \(c = 15.0 \text{ J}^2 \text{s}^{-1}\) for calibration, the data plotted in figure 4 illustrate this procedure in principle.

6. Analysis of the \(H/(H+D)\) ratio impact on plasma energy and particle confinement

In order to investigate the impact of the H ratio on the plasma performance, a data set was constructed taking advantage of the three HD discharges discussed and three reference shots run entirely with D. The plasma performance is often attributed to the quality of energy and particle confinement, characterized according to their confinement times, while the HD discharges were performed using merely feed-forward pellet and gas flux. Experiments in D employed feed-forward fuelling as well. However, in some phases density profile control by double feedback on gas and pellets was also applied. In all cases, the largest possible pellet size and the same launching speed of 560 m s\(^{-1}\) was utilized. For the D pellets (with \(m_p = 3.7 \times 10^{20} \text{ D}\)), due to less matter density of H with respect to D, the matter flux of HD pellets is about 6% reduced with respect to pure D pellets. Taking into account the fact that transfer losses and delivery efficiency vary, the pellet performance varies from shot to shot anyway by an at least comparable magnitude; this effect was regarded as marginal. The D reference shots showed outside of the pellet phases a reasonable performance with an energy confinement about 0.95 times the value predicted by the scaling H98(y,2) [24]. There, type-I edge-localized modes (ELMs) with a frequency of typically 50 Hz occurred. With increasing density in the pellet phases, the ELM behavior changed into a regime with higher frequency and smaller amplitude, while the energy confinement was somewhat reduced. The entire data set was assembled by recording the values of all characteristic parameters during reasonably steady phases only, i.e. excluding phases with significant transient behavior. In the HD pellet cases, \(H/(H+D)\) values as measured by spectroscopy were adopted, since by this method the best consistency with the neutron rates has been obtained. For the D pellet cases, \(H/(H+D) = 0\) was always set although the data showed values up to 0.07.

6.1. Energy confinement

The energy confinement time \(\tau_E\) is one of the main figures of merit of magnetically confined plasmas and defined as a function of the global plasma energy content, \(W\), and the applied total heating power, \(P\) as,

\[
\tau_E = \frac{W}{P - \frac{dW}{dt}}.
\]

To evaluate the influence of the H ratio on \(\tau_E\), it became necessary to take into account the rather strong impact on the plasma energy, estimated here by \(W_{\text{MHD}}\), from the differences in total heating power and plasma density. First, the effect of heating power variation was taken into account, as far as possible. For our small data set, this influence can be seen by plotting \(W_{\text{MHD}}\) versus the total applied heating power (ohmic and auxiliary), see figure 6. There, data taken for the HD discharges are represented by the red dots, while D reference phases are indicated by the blue dots. Due to the available higher ICRH power.
the D reference points cover a much wider range. In order to consider only comparable phases, data with heating power in excess of 9 MW were disregarded for the further analysis in this paper (gray shaded area in figure 6). The remaining D data are fitted (gray solid line) applying a $P^{0.31}$ power dependence, which yields a fair reproduction for the considered power range below 9 MW.

To take into account different $P$ values for the mixed isotope data set, the $W_{\text{MHD}}$ data are normalized with respect to the total applied heating, ‘ceteris paribus’ as,

$$W_{\text{PN}} = W \left( \frac{P}{P_{\text{ref}}} \right)^{0.31}.$$

An experimental point with $P_{\text{ref}} = 7.528$ MW and $W_{\text{MHD}} = 417$ kJ has been chosen as reference. For this normalization, the $P^{-0.69}$ power dependence in the expression for $H98(y,2)$ [24] has been used. (Since we assume a negligible contribution of fast particles in this density regime due to the high collisionality, $W_{\text{MHD}}$ is expected to be close to the plasma thermal energy $W_{\text{th}}$.)

Second, an attempt was made to relate the influence of the density on confinement. The density dependence is visible from figure 7, where $W_{\text{PN}}$ is plotted against the obtained central density, as measured by TS [25], and normalized to $n_{\text{GW}}$. Core density data were used, since their absolute values are regarded as more reliable than $n_{\text{e}}$ data hampered by fringe

Figure 6. Plasma energy versus applied total heating power for the discharges with HD (red dots) and D (blue dots) pellet injection. Restricting the analyzed data set to heating power below 9 MW, the remaining data are normalized by taking the power dependence as predicted by the H98($y,2$) scaling. The reference value $P_{\text{ref}} = 7.528$ MW is indicated by ‘$R$’.

Figure 7. Stored plasma energy normalized with respect to heating power versus core density normalized to the line-averaged Greenwald density formula. Solid line shows a fit to the pure D data from the reference discharges with heating power below 9 MW and core density below $n_{\text{GW}}$; dashed line fits the mean value of $W_{\text{PN}}$ above $n_{\text{GW}}$. Inset shows the peaking factor $n_0/n_{\text{e}}$; dashed line indicates that the peaking factor increases with the normalized core density for the pure D plasmas.
jumps. It is noted that in these discharges \( n_{GW} \) was very nearly constant; the normalization with \( n_{GW} \) has been done nevertheless for ease of comparison to theory and other experiments. Data from the restricted range in heating power are represented by the same symbols as in figure 6; data as already deselected previously (with heating power above 9 MW) are indicated by black circles. Significantly higher core densities are achieved in the pure D reference discharges, presumably due to a higher particle confinement time, as discussed in the following chapter. Again, in order to consider only comparable cases, a further restriction of the data set was imposed by excluding core densities above \( n_{GW} = \frac{n_e}{\tau_{fuell}} \) (indicated by the gray shaded area in figure 7). From the figure, one can see that in this regime (indicated by the white area) for the D reference discharges \( W_{PDN} \) decreases with (normalized) central density \( n_e^0/n_{GW} \). Fitting these data by a simple power law yields \( W_{PDN} \) proportional either to \( n_{GW}^{0.46} \) or to \( (n_e^0/n_{GW})^{-0.46} \), as indicated by the solid gray line. Above \( n_{GW} \), \( W_{PDN} \) remains approximately constant. The dashed gray line fits the mean value of \( W_{PDN} \) in the range \( n_e^0 \) between 1.0 and 1.82 \( n_{GW} \). The core density \( n_e^0 \) is not a plasma parameter used in the H98(y,2) scaling. In the inset of figure 7, one can see that the peaking factor of \( n_e^0/\pi \) increases in the region where \( W_{PDN} \) remains approximately constant. In the region below \( n_{GW} \), it is not clear whether the peaking factor increases, but according to the available data it does not seem to decrease. The observed behavior of \( W_{PDN} \) with \( n_e^0 \) is therefore not expected to be well in agreement with the H98(y,2) scaling, which used \( \pi^2 \) instead of \( n_e^0 \). For the pellet-accessed high-density regime the scaling is regarded as inapplicable anyway, since it is well beyond about 0.85 times \( n_{GW} \), where gas puffing encounters the H-Mode DL [4], pellet fuelling can at best keep the plasma energy constant. The observed declining energy confinement with increasing core density indicates this type of discharge is not optimized for high-power density operation.

To take into account the influence of both heating power and density, the normalization (reference point indicated again) finally gets,

\[
W_{PDN} = W_{ref} \left( \frac{P}{P_{ref}} \right)^{0.31} \left( \frac{n_{e0}}{n_{e0,ref}} \right)^{-0.46}.
\]

With this normalization, the relation between the H ratio on the confinement can be visualized by figure 8, where \( W_{PDN} \) is plotted versus \( H/(H+D) \) for the selected data points. To both the D data (blue dots) and the HD data (red dots) a fit was performed taking, from H98(y,2), the \( M^{0.19} \) dependence on the average ion mass \( M \). Clearly, both fits show a significant deviation indicating the absolute influence of H here is approximately \( M^{0.19} \) with a point estimate of \( \delta M \) in the range 0.7–0.9. This is considerably more pronounced than predicted by several scaling expressions such as H93-P, EPS-97 and H98(y,2) as well as the rather weak isotope dependence observed at JET, see [26] section 5. Possibly, this can be attributed to the specific scenario. However, in addition, it seems there is not a smooth power law-like transition between the integer \( M \) values. From figure 8, one can see that a significant drop of confinement occurs already when just a small amount of H is added to the initial D plasma. This possibility of one species pulling down energy confinement stronger than anticipated by the scaling needs further investigation, in particular since then the scaling derived for integer \( M \) values only no longer holds for intermediate values. As a consequence, for the reactor aiming to operate close to \( M = 2.5 \), scaling-based reactor modellling could systematically overestimate the expected energy confinement by approximately some 5\% or so.

6.2. Particle confinement

A first approach to analyze the particle confinement time \( \tau_p \) from the fuelling behavior was performed. This approach
takes into account the fuelling efficiency defined as plasma particle inventory $N$ (or central density) enhancement per applied particle flux $\Gamma$; hence $\tau_P = \frac{N}{\Gamma}$ respectively $\tau_P = \frac{n_e}{\Gamma}$. However, although the applied pellet flux is quite precisely known, the influx stemming from gas puffing and wall release is not and hence the precise quantity of $\Gamma$. Thus, a precise quantitative result cannot be achieved, but a qualitative one from the significant difference observed between D references and HD discharges. This can be seen in figure 9, showing a comparison between a pure D plasma (left) and the case with the H/(H + D) ratio of about 0.6 (right, case with pure H gas puffing). The two cases differ slightly with respect to the applied total heating power (8.6 and 8.0 MW), and is even stronger with respect to the achieved plasma energy (boxes (b)); according to the energy confinement times estimated to be about 50 and 40 ms. Compared to the D reference, more frequent smaller ELMs are observed in the HD case (boxes (a)). Particle fluxes applied are very similar in both cases (boxes (d)). Nevertheless, a striking difference is found for the impact of the fuelling. While a rather strong density build-up takes place for the D case, only a moderate one is observed in HD discharge (boxes (c)). Hence, even when taking into account the difference of both discharges, the drastically lower fuelling efficiency is strongly indicative of a lower particle confinement in the presence of H with respect to pure D discharges.

A more quantitative result can be obtained from the temporal evolution of the pellet-imposed density perturbation. For this, the pellet particle sustainment time $\tau_P^*$ was analyzed. This was done for both the D reference and HD case, taking phases without a significant persistent density profile evolution, indicated by the gray shaded areas in box c of figure 9. In both cases, 11 pellets arriving at 47 Hz result in a similar repetitive temporal perturbation, yet keeping a quasi-steady-state situation. Hence, the two pellet ensembles were selected for a statistical analysis comparing the dynamics in particle transport and taking $\tau_P^*$ as an indicator for $\tau_P$. The result is shown in figure 10. To monitor the evolution of the plasma density, the data from the DCN laser interferometer (box (a)) were taken, since only they provide sufficient temporal resolution. However, since pellet-induced fringe jumps falsify the absolute density values, only the relative post-pellet density evolution can be taken. Taking the pellet ablation monitor (box (b)) as the synchronization marker, for both ensembles an average over the pellets selected was performed, assuming all 11 pellets are identical. Fitting an exponential decay to the resulting averaged post-pellet density evolution finally yields the required pellet particle sustainment time $\tau_P^*$ for both cases (boxes (c)). It should be noted that the confidence range for the fit and hence the uncertainty on $\tau_P^*$ is largely due to the remaining uncertainty when estimating the unperturbed density baseline from TS measurements unaffected by the pellet perturbation. Furthermore, a significant difference in the pellet-induced density increase is observed. There are two possible reasons for this behavior: a lower efficiency of the pellet particle deposition process (fraction of the arriving pellet particles deposited in the core plasma just after the ablation phase has come to an end) or higher losses in the guiding
estimates for the energy confinement times—
tions of pellet particle sustainment times with respect to the
when $D$ is replaced to a large fraction by $H$. Taking the rela-
for the significant reduction of the particle confinement time
of the phenomena summarized as an isotope effect.

and transport studies, which could shed further light on details
changes of the energy confinement time suggest turbulence
—weaker

system. Further investigations are required to shed more light
on this issue.

The results show that $D$ pellets result in a significantly
stronger density increase; this is most likely due to their larger
initial particle content, but also to much lower transfer losses in
the guiding system. Despite the higher plasma energy, $D$
pellets penetrate deeper into the plasma, as shown
by typical ablation radiation measurements for single pellets ($d$).

The careful comparison of doped and pure $D$ reference pellet
injection showed a content of 0.8% $N_2$ in the evaporated
pellet material [28]. With this basic qualification of the
multi-component pellet approach

Beyond its application for high-density operation and control
of the isotope fraction, an advanced and fully optimized pellet
tool can certainly be used for even more applications, e.g. the
efficient transfer of PEG, gases for radiative power, or of rare
and expensive gas species. Efficiency in this context means to
achieve the task with a minimum particle flux resulting in a
relaxed burden on the exhaust purification system. Moreover,
it seems likely that such an approach could also have syn-
ergetic effects, fostering the fuelling performance. The
admixing of, for example, small amounts of $N$ to the $D$ has
been found to harden the ice and consequently the pellet made
from this ice. This leads to lower mass losses due to reduced
abrasion along the guide pathways in the transfer system [27].
Doping the fuel can also result in enhanced power dissipation
in the ablation cloud surrounding the pellet and thereby
reducing the power flux to the pellet and hence the ablation
rate. Thus, radiative pellet shielding would result in deeper
pellet penetration and in turn effectuate a higher fuelling effi-
ciency. Hence, studying pellet actuation with added elements
has potential benefits.

In recent experiments, the presence of $N$ in the plasma has
been found to be advantageous in combination with pellet
fuelling to achieve high-density high energy-confinement
operation. Furthermore, pellet actuation enhanced the diverter
compression of $N$ and thus resulted in better divertor cooling
[6]. Hence, $N$ was regarded as a prime candidate to use as
a doping element in pellets. Although there are no known
limits to the amount of $N$ that can be added for either the ice
formation or pellet handling, for our test technical limits
restricted the $N$-doping percentage. For the centrifuge
acceleration device used, the specific layout of the stop cyl-
der, which is designed and optimized for pure hydrogen
operation, restricts the maximum doping grade to about 1%. Higher amounts increase the ice hardness significantly and
were found to cause damage. This restriction would be easy
to overcome with an improved set-up; however, this was not
available at the time of these experiments. Accordingly, the
first experiments applying $N$-doped pellets were performed by
producing ice from a gas mixture of $D_2$ with 1% of added $N_2$.
Again, first the characterization of the pellet composition was
done by injection into the evacuated torus without plasma.
The careful comparison of doped and pure $D$ reference pellet
injection showed a content of 0.8% $N_2$ in the evaporated
doped pellet material [28]. With this basic qualification of the
actuator, pellets were finally injected into a suitable available
discharge. One should note that this test had to be performed
during a set of experiments that introduced $N$ via gas puffing
for a different purpose. Since $N$ is sustained in the vessel for
several discharges [9] after injection, this caused a significant
$N$ background level during these experiments. Nevertheless,
the pellet-induced $N$ fuelling could be clearly seen.

An overview of this test discharge is shown in figure 11,
which displays from top to bottom: applied auxiliary heating

7. Nitrogen-doped pellets as subject to test the
multi-component pellet approach

Figure 10. Determination of the pellet particle sustainment time
$\tau^*_P$ for a pure $D$ (left) and a HD plasma (right) from the post-pellet
density decay averaging over each of the 11 virtually identical
pellets ($c$). Data are taken from the DCN laser interferometer
($a$) eliminating fringe jump by taking advantage of the pellet
ablation monitor as the synchronization marker ($b$) and calibration to
Thomson data. $D$ pellets penetrate deeper into the plasma, as shown
by typical ablation radiation measurements for single pellets ($d$).
Figure 11. High-density operation achieving a core density in the vicinity of $n_{Gw}$ by pellet injection. Doping the D host pellets by N (0.8% found in the released gas) yields an enhancement of the N concentration in the plasma, while the impurity level, here represented by the W concentration, is reduced.

and radiation (a), plasma energy (b), line-averaged and core and edge local densities compared to $n_{Gw}$ (c), the ELMs (d), pellet ablation (e) monitor signals, applied gas and pellet particle fluxes (f), tungsten density (g) and N concentration (h) in the core plasma. Pellet fuelling shows the usual positive impact on the density evolution, namely a high-density phase with a central density in the vicinity of $n_{Gw}$. The enhanced density phase correlates with enhanced ELM activity, slightly higher radiative losses and a mild loss of energy confinement. The enrichment of N by the pellets is also nicely demonstrated concomitant with a drastic reduction of the unwanted tungsten density. The N content is seemingly increased despite an enhanced outward particle flux during the pellet phase due to a higher ELM rate and, possibly, to a reduced particle confinement time.

8. Conclusive summary and outlook

The safe and efficient operation of future fusion power plants will require core particle fuelling by pellet injection. In order to fully qualify the pellet tool for the tasks ahead, a couple of technical problems and physics questions still have to be solved. Research and design activities to foster this topic are an essential part of the AUG research program. In this direction, it has recently been shown [6] that operation at the required high core densities, while keeping high confinement, can be achieved. To do so, feedback control of the density profile is required. This necessitates the establishment of a set of control parameters that are resilient against the pellet-imposed perturbations. As a next

continuative step, experiments aimed at incorporating the plasma isotope mixture into this control scheme were performed, and presented in this work. For this purpose, it is evidently necessary to further investigate e.g. observed discrepancies between the NPA measurements and the simple neutron model used by more sophisticated modeling of the neutron fluxes.

Our proposed scheme to control the plasma isotope mixture in a future fusion reactor suggests a direct control via adjustment of the pellet isotopic mixture. Since for this scheme, a single pellet train is already sufficient, the necessary technological effort can be kept rather low. Following this approach, in a reactor both the density and isotopic mixture in the core would be controlled by this single pellet train. While the density would be adapted on a shorter time scale by controlling the pellet rate and hence the flux, the DT mix in the core, possibly monitored by the fusion output power, would be matched by the DT mix of the pellets on a longer time scale. This is quite different with respect to the original plans of ITER, which aimed at controlling both quantities by combining two pellet trains, one formed from D or D-enriched pellets and the other of T or T-enriched pellets. Recently, modelling investigations [29] showed difficulties for achieving a stable isotope core mix by employing such a combination of two pellet trains.

In our experiments, the reactor-relevant mix of DT was mimicked by the use of HD. Successful reliable and reproducible formation of HD pellets with the desired isotope mixture was achieved; these pellets were applied for a demonstration of the envisaged plasma isotopic mixture control. However, it
turned out that additional effort is still needed in order to allow for a reliable real-time diagnosis of the core isotope mixture. Valuable data were derived as a spin-off of the control experiments, indicating that H in D reduces the energy confinement, potentially already significantly when yet present at a small ratio. The latter might emerge as a potential deficiency when using a simple factor $M^{\text{min}}$ for the isotope effect, which was done with $\alpha_M = 0.19$ in H98(γ,2).

Also, H in D reduces the particle confinement; this effect presumably is even stronger than the impact on the energy confinement. As a result of the particle confinement lowered in comparison to pure D reference plasmas, HD pellet action thus results in less density build-up and a significantly faster decay of pellet-imposed density surplus. Due to the technology-optimized approach, results are providing a rather qualitative indication yet. However, the experiments also demonstrate the potential use of the pellets in experiments planned focused on dedicated physics, e.g. by allowing for a detailed insight into the particle dynamics by analyzing the pellet particle sustainment time or by introducing precisely dosed amounts of H to investigate the confinement evolution with increasing small amounts of H. The continuation of the presented investigation by such experiments which had indeed already been in preparation when the AUG campaign 2017 was forced to stop by a major technical problem and this program became subject to a major postponement. Once HD pellet experiments can be resumed, it is also planned to combine isotope mixture control with feedback-controlled operation aiming to achieve simultaneously high density and high confinement, sounding out the capabilities of different plasma scenarios and regimes for this goal. Hence, the pellet tool can become quite serviceable for the investigation of the isotope effect. In agreement with our findings, the isotope effect on confinement has been found favorable with respect to increasing $M$. Accordingly, findings are reported from many devices and are attributed to multifaceted physics effects [8, 30, 31].

Beyond their fitness to serve standard fuelling tasks, pellets have also been tested to act as a host for other gases employed for different accessory tasks such as e.g. plasma performance enhancement, radiative cooling, divertor buffering or enhancement of plasma heating schemes. By doing so, it became possibly conceivable that synergetic effects can boost both the efficiency for supplying the added material and the fuel, the latter potentially also benefitting from pellet hardening and penetration enhancement due to radiative pellet shielding. Despite the technical limitation of our system layout not foreseeing this kind of operation restricting the amount of added material, first tests with N have already shown very encouraging results. Further investigations are considered respectively already in preparation as e.g. solving small amounts of the prized $^3$He reported feasible [18] in order to assist the ‘three-ion’ heating scenario [32].

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 under grant agreement No. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

ORCID IDs

P.T. Lang https://orcid.org/0000-0003-1586-8518
R.M. McDermott https://orcid.org/0000-0002-8958-8714

References

[1] Wenninger R. et al 2017 Nucl. Fusion 57 016011
[2] Lang P.T. et al 2015 Fusion Eng. Des. 96–7 123
[3] Greenwald M. et al 1998 Nucl. Fusion 28 2199
[4] Bernert M. et al 2015 Plasma Phys. Control. Fusion 57 014038
[5] Osborne T.H. et al 2001 Phys. Plasmas 8 2017
[6] Lang P.T. et al 2018 Nucl. Fusion 58 036001
[7] Hörstensmeyer Y.N., Butler B., Day C. and Franza F. 2018 Fusion Eng. Des. 136 314–8
[8] Maggi C.F. et al 2018 Plasma Phys. Control. Fusion 60 014045
[9] Dunne M.G. et al 2017 Plasma Phys. Control. Fusion 59 014017
[10] Andellinger C. et al 1993 Rev. Sci. Instrum. 63 983
[11] Ploeckl B. et al 2013 Fusion Eng. Des. 88 1059
[12] Neuwirth D., Rohde V., Schwarz-Selinger T. and ASDEX Upgrade Team 2012 Plasma Phys. Control. Fusion 54 085008
[13] Drenik A. 2017 Fusion Eng. Des. 124 239
[14] Price G.L. and Iglesia E. 1989 Ind. Eng. Chem. Res. 28 839
[15] Potzel S. et al 2014 Nucl. Fusion 54 013001
[16] Bartiromo R. et al 1987 Rev. Sci. Instrum. 58 788
[17] Tardini G. et al 2013 Nucl. Fusion 53 063027
[18] Sours P.C. 1986 Hydrogen Properties for Fusion Energy (Berkeley, CA: University of California Press)
[19] Rapson C.J. et al 2017 Fusion Eng. Des. 123 603
[20] Schneider P.A. et al 2015 Rev. Sci. Instrum. 86 073508
[21] Geiger B. et al 2011 Plasma Phys. Control. Fusion 53 65010
[22] Strachan D. et al 1993 Nucl. Fusion 33 991
[23] Kardaun O.J.W.F. 2005 Classical Methods of Statistics (Berlin: Springer) p 102
[24] ITER EXPERT GROUPS et al 1999 Nucl. Fusion 39 2175
[25] Kurzan B. and Murmann H.D. 2011 Rev. Sci. Instrum. 82 103501
[26] The JET Team (presented by K. Thomsen) 1999 Plasma Phys. Control. Fusion 41 A617
[27] Lang P.T. et al 2002 Nucl. Fusion 42 388
[28] Ploeckl B. et al 2015 Fusion Eng. Des. 96–7 155
[29] Poleyvai A. et al 2018 Integrated modelling of ITER scenarios with D–T mix control 45th EPS Conference on Plasma Physics (Prague, 2–6 July 2018) P5.1050
[30] Laggner F. et al 2017 Phys. Plasmas 24 56105
[31] Schneider P.A. et al 2017 Nucl. Fusion 57 066003
[32] Kazakov Y.O. et al 2017 Nat. Phys. 13 973