Plasma fueling with cryogenic pellets in the stellarator TJ-II


Laboratorio Nacional de Fusión, CIEMAT, Madrid, Spain
1 Fusion & Materials for Nuclear Systems Division, ORNL, Tennessee, United States of America

E-mail: kieran.mccarthy@ciemat.es

Received 16 December 2016, revised 13 February 2017
Accepted for publication 7 March 2017
Published 4 April 2017

Abstract
Cryogenic pellet injection is a widely used technique for delivering fuel to the core of magnetically confined plasmas. Indeed, such systems are currently functioning on many tokamak, reversed field pinch and stellarator devices. A pipe-gun-type pellet injector is now operated on the TJ-II, a low-magnetic shear stellarator of the heliac type. Cryogenic hydrogen pellets, containing between $3 \times 10^{18}$ and $4 \times 10^{19}$ atoms, are injected at velocities between 800 and 1200 m s$^{-1}$ from its low-field side into plasmas created and/or maintained in this device by electron cyclotron resonance and/or neutral beam injection heating. In this paper, the first systematic study of pellet ablation, particle deposition and fuelling efficiency is presented for TJ-II. From this, light-emission profiles from ablating pellets are found to be in reasonable agreement with simulated pellet ablation profiles (created using a neutral gas shielding-based code) for both heating scenarios. In addition, radial offsets between recorded light-emission profiles and particle deposition profiles provide evidence for rapid outward drifting of ablated material that leads to pellet particle loss from the plasma. Finally, fuelling efficiencies are documented for a range of target plasma densities ($\sim 4 \times 10^{18}$ to $\sim 2 \times 10^{19}$ m$^{-3}$). These range from $\sim 20\%$ to $\sim 85\%$ and are determined to be sensitive to pellet penetration depth. Additional observations, such as enhanced core ablation, are discussed and planned future work is outlined.

Keywords: stellarator, pellet, ablation, fuelling

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

1. Introduction
Core fuelling is a critical issue on the pathway to the development of steady-state scenarios in future magnetically confined fusion reactors, in particular, for helical-type devices [1, 2]. Indeed, neoclassical theory predicts that, for such devices, on-axis electron cyclotron resonance heating (ECRH) necessitates a particle source situated at the same radial position as the ECRH with an analogous deposition profile shape in order to mitigate potential core particle depletion [3]. Although gas puffing is a well-established tool for creating and sustaining plasmas in most current tokamaks and stellarators, its location at the plasma edge means that it will become inefficient for very large devices [4, 5]. Furthermore, particle recycling is predicted to be minimal since plasma-wall interactions will predominantly occur in the divertor region. In addition, neutral beam injection (NBI) is also a habitual technique for plasma core fueling [6]. However, the introduction of such an energy source may become problematic from the point of view of density control, in particular in stellarators, where energy and particle transport are coupled in the core. Indeed, coupling may lead to hollow density profiles (NBI tends to reduce the hollowness of density profiles, but the energy source tends to increase it), thereby reinforcing the need for fuelling techniques that avoid such drawbacks [3]. Nonetheless, there exists a prime candidate that permits achieving relatively...
localized core fuelling without an associated energy source. It is cryogenic pellet injection, a well-developed technology that has been employed on numerous magnetically confined plasma devices for several decades [7–9].

Cryogenic pellet injection has been, and continues to be, the subject of intense research. For instance, in the case of stellarators, pellet penetration and fuelling studies performed on the W7-AS showed good agreement between measured and predicted penetration depths and indicated an influence of central electron temperature, $T_e(0)$, on fuelling efficiency [10].

Also, in the Large Helical Device, a pellet injector extended its operational regime with good energy confinement [11, 12]. More recently, in the TJ-II, where a four-barrel compact injector began operation in 2014 [13], several pellet related studies have been performed to date. For instance, one study demonstrates that, for certain operational scenarios, particle diffusive transport can redistribute some of the pellet particles towards the core, thereby compensating for, or slowing down, core depletion [14]. Another reports on the first observation of relaxation of a zonal electrostatic potential perturbation after pellet injection [15], while a third describes the transient behaviour of impurity transport on a flux surface as triggered by pellet injection [16]. Finally, it is expected that a pellet injector will become available for the recently inaugurated Wendelstein 7-X during its second phase of operation. Its goal is to deposit pellet material near the plasma core to achieve and maintain by repetitive injections, high-density plasmas. For this, studies will be needed to quantify for instance, the influence on penetration and fuelling of possible $\nabla B$-induced $E \times B$ polarized drifting of the partly ionized cloud that surrounds an ablating pellet [9, 17].

In this work, cryogenic pellet ablation and fuelling studies performed on the stellarator TJ-II are summarized and the main results are reported. For this, hydrogen pellets are injected from its low-field side (LFS) into ECRH or NBI-heated plasmas and pellet ablation is followed using silicon diode-based light-detection systems, while the temporal evolution of particles deposited in the plasma is followed using a microwave interferometer and a Thomson scattering (TS) diagnostic. With these and with additional diagnostic systems, the influence of plasma parameters, as well as phenomena such as suprathermal electron populations, can be evaluated. Finally, ratios between the number of pellet particles deposited in the plasma and pellet particle content (fuelling efficiency) are determined for a wide range of target plasma densities and temperatures.

2. Background

The ablation process of a cryogenic pellet as it penetrates through magnetically confined plasma has been intensively studied, albeit several aspects remain to be fully understood. For this, models based on neutral gas shielding (NGS) are generally utilized to characterize ablation as a pellet enters the plasma edge and penetrates to the core [18]. It is considered that plasma electrons impacting on the pellet create a cloud of neutral atoms (plasmoid) that subsequently surrounds, and travels along with, the pellet. Heat transfer from background plasma particles ionizes the ablated fuelling material, which streams out along the magnetic field lines. The surrounding neutral gas cloud subsequently checks the energy flow to the solid. Then, as long as sufficient pellet mass remains to sustain this cloud, the shielding will be maintained. Finally, once the pellet is fully ablated, the cloud dissipates, the local density quickly equilibrates, and pellet material diffuses around the plasma.

It is well known that in tokamaks a rapid outward radial displacement of ablating material occurs during pellet penetration due to a $\nabla B$ effect [9]. It is ascribed to a vertical curvature and $\nabla B$ drift current induced inside the partially ionized cloud by the radial magnetic field variation, where an uncompensated vertical drift current inside the weakly diamagnetic ablation cloud gives rise to charge separation, and hence an electrostatic field. This induces an $E \times B$ drift, with velocity that may be greater than the pellet velocity, $v_p$, towards the LFS edge of the plasma where this is manifested as a radial displacement, $\Delta R$, between the cloud light-emission profile, e.g. Balmer $\alpha$, at $\lambda = 656.3$ nm for hydrogen, and the deposited pellet electron profile [19]. As a consequence, high-field side (HFS) injection facilitates higher penetration and core fuelling efficiency [20]. However, HFS injection is limited to velocities of a few $100$ m s$^{-1}$ in order to ensure pellet survival along bent guide tubes [21]. In contrast, in stellarators, the drift changes direction depending on position along the magnetic field line, and hence the expanding ablation cloud may not necessarily drift directly outwards [16]. Indeed, the effect of this drift on fuelling may be considered modest when compared with that in tokamaks [22]. As will be seen, the TJ-II is especially suited to study such effects given that it is equipped with a pellet injector and a large number of diagnostic systems. These are outlined next.

3. Experimental set-up

3.1. TJ-II stellarator

The TJ-II is a low-magnetic shear stellarator of the heliac type. It has a major radius of 1.5 m and average minor radius, $a$, of $\leq 0.22$ m [23]. Its magnetic fields are generated by a system of poloidal, toroidal, and vertical field coils and the resultant plasma cross-section is bean shaped with $B_0 \leq 1.1$ T at the plasma centre. The device is designed to have a high degree of magnetic configuration flexibility. During experimental campaigns, plasmas are created using hydrogen, deuterium or helium as the working gas, and are heated using ECRH with one or two gyrotrons operated at 53.2 GHz, i.e. the 2nd harmonic of the electron cyclotron resonance frequency ($f_{\text{ECRH}} \leq 500$ k$\text{W}$, $t_{\text{discharge}} \leq 300$ ms). With ECRH, central electron densities, $N_e(0)$ and $T_e(0)$ up to $1.7 \times 10^{19}$ m$^{-3}$ and 1.5 keV, respectively, can be achieved. Plasmas have also been created and/or maintained by the injection of accelerated neutral hydrogen atoms ($E_{\text{NBI}} \leq 34$ keV, $P_{\text{NBI}} \leq 0.7$ MW throughput) from two tangential NBI systems. In particular, when using NBI heating only to create the plasma, this is generated by employing a single beam and initial toroidal electric fields, induced by increasing coil currents during ramp-up by up to 3.8 V/turn. In both cases, NBI heating results in plasmas with $N_e(0) \leq 5 \times 10^{19}$ m$^{-3}$ and $T_e(0) \leq 400$ eV when a lithium
coating is applied to the vacuum vessel wall [24]. Finally, the majority ion temperature, \( T_i(0) \), is \( \leq 120 \) eV for both heating schemes.

In TJ-II discharges, fuelling is normally accomplished using a set of piezoelectric valves distributed toroidally around the vacuum vessel and driven by a pre-programmed voltage signal [25]. The signal profile, defined by the desired density profile, provides both pre-fill and active fuelling before and along a discharge, respectively. The average hydrogen flow rate for each valve is \( \leq 3.5 \times 10^{19} \) particles s\(^{-1}\) [26].

3.2. Cryogenic pellet injection

A pellet injector has been operating on the TJ-II since mid-2014 [13]. It is a 4-pellet system, developed in conjunction with the Fusion Energy Division of Oak Ridge National Laboratory, Tennessee, USA. It is equipped with a cryogenic refrigerator for \( \text{in situ} \) hydrogen pellet formation, fast propellant valves for pellet acceleration (800–1200 m s\(^{-1}\)), in-line diagnostics for determining pellet velocity and mass [27], as well as straight delivery lines. See figure 1. As noted, the injection line is equipped with a light-emitting/sensitive diode combination and a microwave resonance cavity. The former provides a timing signal only while the latter provides a timing signal whose amplitude is mass dependent. For TJ-II, small pellets with 0.42 mm (Type-1) and 0.66 mm (Type-2) diameters (containing \( \leq 4 \times 10^{18} \) and \( \leq 1.2 \times 10^{19} \) hydrogen atoms, respectively) are required for experiments in which the electron density must not rise above the gyrotron cut-off limit (~1.7 \( \times 10^{19} \) m\(^{-3}\)). Also, for the standard configuration, studied here, the plasma volume contained within the last-closed magnetic surface is \( \sim 1.1 \) m\(^3\). Larger pellets with diameters of 0.76 mm (Type-3) and 1 mm (Type-4), containing \( \leq 1.8 \times 10^{19} \) and \( \leq 4.1 \times 10^{19} \) hydrogen atoms, respectively, can be injected into higher-density NBI-heated plasmas.

3.3. Ablation diagnostics

A significant advantage of the current set-up is the optical access to the pellet path through the plasma, i.e. through viewports located above (TOP) and behind (SIDE) the pellet flight paths. See figure 1. In order to collect the light emitted by the neutral, or partially ionized, cloud that surrounds an ablating pellet, amplified silicon diodes fitted with interference filters centred at 660 ± 10 nm, and a fast-frame camera, equipped with a coherent fibre bundle, are located outside these viewports, which together with the broad range of standard diagnostics available provide a powerful diagnostic capability [13]. The SIDE diode can be replaced by an avalanche photodiode (APD). In all cases, the diode output signals are digitized at 1 MHz and stored for later analysis [13]. Now, in order to estimate \( H_\alpha \) light intensities from the diode outputs (in terms of photons per second emitted by the plasmoid), the collection solid angle, the filter and fibre transmissions, the detector efficiency, and the amplifier gains are considered. Then, knowing pellet velocity and plasma entry time, a \( H_\alpha \) emission profile is created from which a penetration length can be established [13]. Although recognized that the emission profile provides an estimate of ablation rate, assuming that the former is related to pellet mass loss [9], it is currently the best indicator of ablation rate that can be made given that plasmoid temperature, density, and size are not determined in TJ-II. Next, due to the design of the pellet injector (54 mm vertical and horizontal separation between guide tubes), the flight paths into the nominal magnetic configuration for Lines-1 through -4 approach the plasma centre, while the flight paths for Lines-2 and -3 do not cross the plasma centre. Rather, their closest approaches are at \( \rho = 0.273 \) and 0.45, respectively [13], where \( \rho = r/a \) is the normalized plasma radius. Line locations are highlighted in figure 1. However, pellet Types can be interchanged between injection lines.

3.4. Plasma diagnostics

The TJ-II is equipped with a wide range of passive and active plasma diagnostics [28]. Diagnostics that are of particular relevance include a single-laser pulse (\( \leq 40 \) ns) pulse per discharge TS system that provides one set of electron density and temperature profiles per discharge [29], as well as a microwave interferometer, an 11 channel electron cyclotron emission (ECE) system and a neutral particle analyser (NPA). These follow the line-integrated electron density,
4. Experiments

In these experiments, pellets containing between 0.5 and \(1.3 \times 10^{19}\) hydrogen particles are injected into plasmas created using the standard magnetic configuration, 100_44_64, where the nomenclature reflects currents in the central, helical, and vertical field coils, respectively, \(1.56 \leq \rho/2\pi \leq 1.64\) \((\rho\) is rotational transform) and a magnetic field gradient of \(-0.9\) T m\(^{-1}\). For these plasmas, pellets are created and/or maintained with on/off-axis ECRH or by NBI heating. In order to determine pellet particle deposition across the plasma minor radius, and the subsequent radial evolution with time, the shot-to-shot technique is employed where pellets are injected into reproducible plasmas and single TS measurements are made before, during, and at several moments after pellet injection. Then, estimating plasma electron content at different radii, and the majority ion temperature, respectively, along a discharge [28]. In the case of the TS, its laser chord completely traverses the plasma, hence providing profiles of two poloidal regions (usually named \(\rho > 0\) and \(\rho < 0\)). However, for TS electron density profiles used here, data from \(\rho > 0\) are considered due to a signal contamination problem for \(\rho < 0\). These systems are located at \(180^\circ, 67.5^\circ, 123.75^\circ,\) and \(-22.5^\circ\) toroidally, respectively, from the PI. See figure 2. For all discharges studied here, the microwave-based diagnostics and the NPA system have 10 \(\mu\)s and 1 ms temporal resolution, respectively.

4.1 Pellet ablation and plasma response

In a previous work, it was outlined how a pellet ablation profile is established from the recorded Balmer \(H_\alpha (\lambda = 656.3\) nm) light, emitted by the cold neutral cloud that surrounds the pellet as it traverses the plasma [13]. In figure 3, the \(H_\alpha\) light fluxes incident on the SIDE and TOP viewports (of figure 1) are plotted as a function of distance into the plasma for a Type-2 pellet injected along Line-2 into an NBI-created and -heated plasma. For this, the timing is obtained from the in-line light-gate and microwave cavity diagnostic signals. It is apparent that ablation becomes significant only after the pellet penetrates several centimetres into the plasma and that structures in the profiles, occurring mainly in the core, are reproducible and therefore real. In this example, where the nearest approach to the plasma centre for this injection is \(\rho = 0.273\), there are no significant rational surfaces in the core, and so these striations can be attributed to repeated neutral cloud losses [31]. It can also be seen in this figure that \(H_\alpha\) signals continue, and increase momentarily, after nearest approach even though the pellet is crossing already cooled flux surfaces. In order to understand this, it is hypothesized that (i) pellet ablation continues due to impacts with the NBI-originated fast-ion population and (ii) increased \(H_\alpha\) signals may indicate the presence of a residual localized fast electron population generated during field ramp-up in the unconventional operation mode of discharge #39179. See section 3.1. Conversely, for ECRH plasmas, the \(H_\alpha\) signals decay steadily after a nearest approach. Finally, when diode light profiles are compared with fast-frame camera images, pellet acceleration is not detected parallel to the injection direction. However, toroidal deflections are observed when unbalanced NBI heating is employed [32].

In [13], it was also described how a \(T_e\) profile, as provided by the TS system located \(180^\circ\) toroidally, is perturbed by an inward travelling pellet, i.e. the passing pellet cools the local plasma instantaneously. It is found here that no inward precooling wave, as reported elsewhere [33], is observed by the ECE diagnostic, albeit in TJ-II such a wave is sometimes observed during TESPEL injections \(v_{\text{TESPEL}} \approx -200\) m s\(^{-1}\) [34]. In figure 3(b), it can be seen that for NBI-heated plasma the central \(T_e\) recovers to pre-injection values within a few milliseconds, while the central ion temperature, \(T_i\), measured by NPA recovers more slowly. In all injections here
the percentage drop is ≥15%. In contrast, for ECRH-only plasma, the ensuing $T_i$ is significantly lower than pre-injection values during an extended period and counter mirrors the electron density. See figure 3(c). The explanation for this is that increased electron density results in reduced input power per plasma electron, i.e. $P_{ECRH}/N_e$. This effect overcomes the slightly increased ECRH power absorption due to a higher electron density. Moreover, it can be seen that $T_i$ increases after pellet injection. This is a consequence of both an increase in $N_e$ and a reduction in $T_e$, since collisional coupling with the electrons is the only energy source to the ions, and it scales roughly with $N_e^2 T_e^{-1/2}$ for $T_e \gg T_i$.

Next, in figure 4, $H_α$ light profiles emitted by reproducible pellets injected into reproducible ECRH and NBI-heated plasmas highlight the reliability of the shot-to-shot technique for pellet studies in TJ-II. Moreover, in the case of ECRH, figure 4(a), they evidence that suprathermal electrons, normally located near the plasma edge, do not enhance ablation. It was shown previously that in the standard TJ-II configuration electrons with energies $\geq 70$ keV are confined between $0.67 \leq |\rho| \leq 0.9$ [35, 36] where they circulate in an anti-clockwise direction in figure 2. In contrast, for plasmas created and maintained by NBI heating only, core localized fast electrons, generated during field ramp-up in this unconventional operation mode, sometimes persist during the initial stages of the discharge with the result that locally enhanced ablation can be observed. See the red curve between $\rho = 0.37$ and $0.273$ of figure 4(b) (discharge #37984). Here, the plasma currents are ~ −2.82 and ~0.23 kA just before pellet injection for discharges #37984 and #38055, respectively. In the same figures, assuming that $H_α$ emissions can be related to pellet ablation rates [37], then reasonable agreement is found between $H_α$ emission and
The modelled ablation curve for #38055. This curve was created using an NGS-based modelling code [18, 38] that considers fast ion as well as thermal electron impacts. The fast ion distribution used for this modelling is based on that defined in [39]. In both cases, pre-injection experimental TS $T_e$ and $N_e$ profiles are employed. It should be noted that in its present form, a pre-injection $T_e$ profile is used to estimate ablation rates beyond closest approach to the plasma centre. In a future version, the option of a cooled temperature profile will be incorporated in order to reflect the impact that immediate pellet-induced thermal electron cooling has on this rate.

4.2. Pellet particle deposition and efficiency

It is observed that the evolution of the pellet electron distribution around the plasma is significantly slower than the thermal perturbation, i.e. it requires several milliseconds to achieve complete particle distribution. Thus, in order to determine pellet fuelling efficiency it is necessary to follow the electron...
density for several milliseconds after pellet injection and in this way identify a maximum.

4.2.1. ECRH plasmas. In figure 5(a), the evolution of the electron density profile for several milliseconds after injection and the resultant net increase in electron density are shown for the pellet injections of figure 4(a). This time embodies the complete ionization of the neutral gas cloud that surrounds the pellet and the subsequent transport of particles about the plasma volume. Next, by integrating these profiles over the whole plasma volume, as outlined at the start of section 4 and assuming that the electron density is flux-constant, the temporal evolution of the pellet particle population in the plasma is determined. See figure 5(b), in which the initial pellet particle deposition profiles (normalized here as number of pellet electrons located between surfaces separated by constant radial distances equal to 1 mm) are compared with the reconstructed \( H_\alpha \) profile. It reveals a significant outward radial drift between deposited electrons and the \( H_\alpha \) profile, this being a possible indicator of an \( E \times B \) outward drift of pellet material. It should also be noted that the increased \( H_\alpha \) signal that occurs inside \( \rho = 0.15 \), when the pellet is almost completely ablated, may be due to plasma current, \(-0.43 \) kA. It is postulated that fast electrons continue to reside at, or near, the plasma centre due to lower plasma resistivity, giving rise to increased \( H_\alpha \) emission from the neutral cloud. Next, in figure 6, the maximum deposited pellet electron population occurs \(-4 \) ms after pellet entry, this being followed by a loss of pellet particles and a decreasing line-averaged electron density. The apparent slower decay rate of the latter can be accounted for if a partial inward transport of pellet particles occurs [14], i.e. if pellet particles are transported inwards their effective contribution to the (line-averaged) electron density increases as they occupy ever smaller volumes. Hence, if the pellet particle population decreases at a given rate, then the line-averaged density will decrease at a slower rate, because of this inward transport. Finally, comparing net electron gain by the plasma with pellet particle content, a value of \(-36\%\) for fuelling efficiency is obtained for the injections depicted in figures 4(a) and 5 (at 3.9 ms). Here, contributions to the density increase due to possible increased neutral recycling caused by a plasma edge temperature drop are considered negligible, as such fuelling is minimal for the short time window involved.

4.2.2. NBI plasmas. A representative injection for NBI-heated plasmas is presented in figure 7. For such plasmas, the target \( T_e \)'s and \( N_e \)'s are significantly lower and higher, respectively, when compared with ECRH, while after an injection \( T_e \) is seen to recover its pre-injection value within a few milliseconds. See figure 3. In figure 7, the initial particle deposition profile for this Type-2 pellet is obtained in the same manner as in figure 5(b). Again, when compared with its \( H_\alpha \) profile, some outward radial shift of ablated material is suggested. In the case of this NBI plasma, subsequent partial inward transport leads to an increased core electron density at 18.7 ms [14]. Treating the data in figure 7 as previously, a pellet fuelling efficiency of \(-34\%\) (for 2.7 ms) is determined here for a target \( N_e(0) = 10^{19} \) m\(^{-3}\). Compared to pellet fuelling, the NBI contribution is no more than a few percent for this same time interval.
deeper penetration improves fuelling efficiency. Here, since pellet penetration is mainly determined by target plasma electron temperature \([1]\), pellets do not penetrate beyond the plasma centre for ECRH plasmas. In contrast, for NBI plasmas, \(T_e(0)\) is similar for all discharges here. Thus, penetration depth is mainly determined by target electron density. Hence, the larger scatter for efficiency values in NBI plasmas for Type-2 pellets. Next, as described in section 4.1, when pellets are injected into NBI-only created and heated plasmas, core localized fast electron can sometimes trigger enhanced ablation in the core that results in improved efficiency with respect to injections made into similar plasmas. Finally, it should be noted that when large Type-3 pellets are injected into NBI-heated plasmas a significant fraction of the pellet remains unablated and exits the plasma on the HFS, thereby leading to reduced efficiencies.

Measured and predicted plasma energy losses due to pellet injection can be compared to determine if all particles are ablated and ionized by the plasma. For instance, in figure 3, a Type-2 pellet (7.7 \(\times 10^{18}\) H) and a Type-3 pellet (1.42 \(\times 10^{19}\) H) are injected into target plasma having \(\sim 1.3 \times 10^{19}\ m^{-3}\) and \(\sim 1.45 \times 10^{19}\ m^{-3}\), respectively. Then, assuming 36.4 eV loss per ion pair due to ablation, dissociation, etc \([40]\), the plasma energy losses (26 \pm 5 and 48 \pm 4 J, respectively) measured with diamagnetic loops \([28]\) agree reasonably well with predicted losses (22.4 and 40.8 J, respectively). Here, \(E_{loss} (J) = (N_H/2) \times 36.4 \times 1.6 \times 10^{-19}\), where \(N_H\) is the number of hydrogen atoms in a pellet. It is assumed that radiation losses are <1 eV/H atom and that plasma dilution by pellet electrons is slow compared with this fast measurement (several milliseconds compared with \(\sim 200\mu s\)). In contrast, for figure 3, where a Type-1 (3 \(\times 10^{19}\) H) and Type-2 (6.9 \(\times 10^{18}\) H) are injected into ECRH plasma with target densities of \(\sim 4 \times 10^{18}\ m^{-3}\) and \(\sim 4.8 \times 10^{18}\ m^{-3}\), respectively, the plasma energy loss is difficult to distinguish from the noise (\(\pm 6\) J) for Type-1, while it is 12 \pm 6 J for Type-2. Predicted losses are 8.7 and 20 J, respectively. It is hypothesized here that a significant fraction of the neutral particles in the cloud surrounding the pellet in this ECRH plasma are swept out of the plasma before they can be deposited \([9, 19, 20]\), i.e. the ionization energy of hydrogen, 13.8 eV/atom, represents a large fraction of the assumed 36.4 eV/H ion pair. In the NBI plasma cases having higher fuelling efficiencies, fewer particles would be expelled in this way, and so larger plasma energy losses would be expected. Hence, the latter indicates that pellet injection and associated processes are mainly adiabatic and that pellets arrive intact at the plasma edge, while the ECRH case supports the existence of a rapid outward drift expelling pellet material from the plasma.

5. Conclusions

A cryogenic pellet is now fully operational on the stellarator TJ-II. Associated diagnostics have been tested and have been shown to provide pellet mass, velocity, and arrival times as well as ablation and deposited particle profiles. In addition, pellet mass and velocity reproducibility have been demonstrated and allow pellet diffusion and efficiency studies to be

![Figure 8. Pellet fuelling efficiency versus (a) target line-averaged electron density and (b) pellet penetration for ECRH and NBI-heated plasmas in the standard magnetic configuration. Efficiency data for NBI-heated plasmas with core-localized fast electrons are green.](image-url)
made. In the studies performed to date, enhanced ablation due to suprathermal electron populations at the edge of ECRH plasmas is not observed. Instead, rather good agreement is found between experimental and modelled $H_a$ ablation profiles. Next, when $H_a$ ablation profiles are compared here with deposited pellet electron profiles for injections into an ECRH discharge and into a low-density NBI-heated discharge, evidence is found to support the hypothesis that ablated pellet material is accelerated towards the LFS plasma edge in the TJ-II. Such an effect, associated with an $E \times B$ drift, has been reported for LFS injections into many other devices in which part of the partially ionized pellet cloud is expelled before it can be deposited in the plasma [9, 19, 20]. This would explain the relatively low efficiencies for pellets that do not penetrate beyond the plasma centre. Additional evidence for this is found in measurements of plasma energy losses that occur immediately after injections. In order to further investigate this, it is intended to adapt the HPI2 code [41], which considers such effects, for the TJ-II. Once functioning, it should be possible to perform relevant simulations for TJ-II that will elucidate further these fuelling efficiency observations.

In the future, given the flexibility of the TJ-II, complementary studies can be performed for a broad range of magnetic configurations, for example, a scan of iota profile or magnetic well, and target temperature and density profiles. In addition, two pellets can be injected simultaneously with the TJ-II pellet injector, i.e. with a time difference of $\lesssim 1$ ms. In this way, a small pellet ($\text{Type-1}$) can be injected initially to cool the plasma edge, followed immediately afterwards by a larger pellet so that the latter is ablated closer to the pellet centre. In this way, it may be possible to improve pellet efficiency significantly in the TJ-II.

Acknowledgments

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. In addition, it is partially financed by grants from the Spanish Ministerio de Economía y Competitividad (Refs. ENE2013–48679–R and ENE2015–70142–P). The authors thank the TJ-II team for their assistance with the work.

References

[22] Sakamoto R. et al. 2004 Nucl. Fusion 44 624
[23] Sánchez J. et al. 2015 Nucl. Fusion 55 104014
[30] Lopez Fraguas A. 2016 private communication
[33] Ledl L. et al. 2004 Nucl. Fusion 44 600
[38] Yokoyama M. et al. 2007 Nucl. Fusion 47 1213
[40] Fether F.S. et al. 1979 Nucl. Fusion 19 1061