



EUROfusion

WPS1-PR(17) 18380

N Panadero et al.

Experimental studies and simulations of hydrogen pellet ablation in the stellarator TJ-II

Preprint of Paper to be submitted for publication in
Nuclear Fusion



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.

This document is intended for publication in the open literature. It is made available on the clear understanding that it may not be further circulated and extracts or references may not be published prior to publication of the original when applicable, or without the consent of the Publications Officer, EUROfusion Programme Management Unit, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK or e-mail Publications.Officer@euro-fusion.org

Enquiries about Copyright and reproduction should be addressed to the Publications Officer, EUROfusion Programme Management Unit, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK or e-mail Publications.Officer@euro-fusion.org

The contents of this preprint and all other EUROfusion Preprints, Reports and Conference Papers are available to view online free at <http://www.euro-fusionscipub.org>. This site has full search facilities and e-mail alert options. In the JET specific papers the diagrams contained within the PDFs on this site are hyperlinked

EXPERIMENTAL STUDIES AND SIMULATIONS OF HYDROGEN PELLETS ABLATION IN THE STELLARATOR TJ – II

N. Panadero¹, K. J. McCarthy¹, F. Koechl², J. Baldzuhn³, J. L. Velasco¹, S. K. Combs⁴,
E. de la Cal¹, R. García¹, J. Hernández Sánchez¹, D. Silvagni⁵, Y. Turkin³, TJ-II team
and W7-X team

1. Laboratorio Nacional de Fusión, CIEMAT, Madrid, Spain

2. Atominstitut, Technische Universität Wien, Vienna, Austria

3. Max-Planck-Institut für Plasmaphysik, Greifswald, Germany

4. Fusion & Materials for Nuclear Systems Division, ORNL, Tennessee, USA

5. Universidad Carlos III de Madrid, Leganés, Spain

Abstract. Plasma core fuelling is one of the key issues for the development of steady-state scenarios in large magnetically-confined fusion devices, in particular for helical-type machines. At present, cryogenic pellet injection is the most promising technique for efficient fuelling. Indeed, significant research has been done to date in this field with pellet injectors operated on medium and large-sized devices. Pellet ablation and fuelling efficiency experiments, using a compact pellet injector, have been carried out in Electron Cyclotron Resonance Heating (ECRH) and Neutral Beam Injection (NBI) TJ-II plasmas. Ablation is followed with two silicon photodiodes and a fast-frame camera system, assuming no radial acceleration and proportionality between H_α emission and ablation rate. The deposition of the material and the fuelling efficiency are estimated using the plasma electron density profiles provided by a Thomson Scattering system. Experimental results are compared with the ablation and deposition profiles provided by the HPI2 pellet code, as well as the fuelling efficiencies. In addition, HPI2 code is used to simulate that ablation and the deposition profiles of pellets of different sizes and velocities injected into relevant Wendelstein 7-X (W7-X) plasma scenarios, estimating the plasmoid drift and the fuelling efficiency of injections made from two W7-X ports.

1. Introduction

Plasma core fuelling is one of the key issues for the development of steady-state operation in large magnetically-confined plasma fusion devices. This is of particular importance for helical-type machines since neoclassical theory predicts that on-axis Electron Cyclotron Resonance Heating (ECRH) requires a particle source with the same radial profile as ECRH in order to mitigate potential particle depletion [1]. The standard method for fuelling in current magnetically-confined plasma devices is gas injection. Although this technique is well developed, it is predicted that it will not be efficient for large devices since the particle source is located at the plasma edge [2]. Hence, the most promising technique for plasma core fuelling is cryogenic pellet injection. Given that fuel is deposited well inside the last-closed flux-surface (LCFS) of the confined plasma, fuelling should be more efficient. Moreover, this particle source does not have an associated energy source unlike Neutral Beam Injection (NBI) [2].

Cryogenic pellet technology is a well-developed technology that has been employed on numerous medium- and large-sized fusion devices for several decades [3]. Initial pellet studies established a relationship between pellet mass, injection velocity, plasma parameters and penetration depth and/or fuelling efficiency [4], this giving rise

to an inter-device database for pellet injection [5]. At the same time, significant efforts were made to model the ablation rate, the pellet trajectory and the surrounding neutral cloud characteristics [4, 6]. In parallel, it was found that pellet injection leads to improved plasma confinement [4]. Later, a displacement of the ablated pellet material along the magnetic field gradient was identified [7, 8], which resulted in magnitudes related to the homogenization of the ablated material being studied or determined, *e.g.* parallel expansion of the cigar shaped plasmoid, or ionized fraction of the shielding cloud, that is created after ablation and which subsequently follows the magnetic field lines [3]; a plasma potential modification, which has been observed to be positive or negative depending on whether the pellet is injected above or below the equatorial plane [9, 10]; and plasmoid drift velocity down the magnetic field gradient [11–13]. Although such studies have been carried out in both tokamaks and stellarators, their interpretation is more difficult for stellarators due to the complexity of their magnetic fields [3]; hence there remains a need to undertake further studies for this type of device.

In parallel to experimental research on the above themes, theoretical models have been developed. For instance, first simulations were focussed on reproducing the emitted light profile (Balmer H_α at 656.28 nm) emitted as a pellet enters and crosses the plasma, which was initially assumed to be proportional to the ablation rate [6]. An example is the simple Neutral Gas Shielding (NGS) model, which only considers the protection given by the ablated neutral gas that surrounds the pellet, modelling it as a fluid and the background plasmas as an incoming heat flux [6], or the improved Neutral Gas and Plasma Shielding (NGPS) model, which also considers the shielding provided by the ionized fraction of the cloud [14] (See Figure 1). Although these simple models can reproduce quite well the measured penetration depth [5, 15, 16], the subsequent plasma density evolution cannot be reproduced, *i.e.* the particle deposition, since radial drifting of the ablated material is not considered [7, 8]. As a result, several models were proposed to explain this displacement. The main driving mechanism, common to all these models, is an induced $\mathbf{E} \times \mathbf{B}$ drift that arises due to the interaction between the confining magnetic field, $\mathbf{B}$, and the electric field, $\mathbf{E}$, that is produced by the acceleration of plasmoid charged particles, in opposite directions for electrons and ions, in the background inhomogeneous magnetic field [16] (See Figure 2). In addition, several mechanisms that either enhance [17] or reduce [17–20] such a drift have been proposed. These models can reproduce accurately the experimental results in tokamaks [3, 21, 22]. All these drift effects are included in the Hydrogen Pellet Injection (HPI2) code, developed by F. Köchl and B. Pégourié *et al.* [16, 20]. The HPI2 is the reference code for pellet simulations in tokamaks since it allows simulating both the ablation of the pellet and the homogenization of the ablated material in a self-consistent way. Indeed, pellet injection has been simulated in several tokamaks using the HPI2 code, such as JET [23, 24], MAST [25] or Tore Supra [26], reproducing closely the experimental results. In addition, it has been used for theoretical studies and design proposal for ITER and DEMO [27–30].

In contrast to the above, the situation is different for stellarators. To date, the HPI2 code has only been adapted for the Large Helical Device (LHD) [31, 32]. However, it was found that experimental results from LHD pellet injections are

qualitatively different from what is obtained for tokamaks. Although the outward shift observed in tokamaks has also been reported for LFS injections in the LHD [33, 34], the situation is different for HFS injections on LHD. Effectively, the favourable inward drift detected for HFS injections in tokamaks is not observed for such injections in LHD. Moreover, an outward drift is also measured for HFS injections [35, 36]. This situation is not fully understood; thus, further theoretical, simulation and experimental work is necessary for LHD. One current, and rather urgent, task is the adaption and benchmarking of the HPI2 for the recently commissioned W7-X device. This is critical given that pellet injection will be an essential tool to achieve its scientific goal of steady-state operation at high densities and thereby demonstrate the viability of stellarators as future fusion reactors [37]. In order to begin this work, simulations are needed to understand and quantify the influence of pellet size and velocity, of plasma parameters, such as density, temperature, magnetic configuration or heating method, and of injection location on pellet penetration, ablated material deposition and fuelling efficiency, and hence optimize the injection. For this, a prior validation of the W7-X HPI2 code is needed. One means of undertaking this is to adapt the same code to the medium-sized stellarator TJ-II on which a pellet injector has been operated since mid-2014 [38–40]. The large database of TJ-II pellet injections can then be used to benchmark the HPI2 code in its W7-X version. Such benchmarking, despite the device size and plasma parameter differences, is considered valid since the underlying drift mechanisms, related to the non-axisymmetry of the magnetic configuration, are equivalent.

In this work, after summarizing the pellet ablation and deposition code HPI2 [20], modifications made, to a version developed for tokamaks, for its adaptation to the TJ-II and W7-X stellarators are outlined and explained. Next, hydrogen pellet ablation studies performed on the TJ-II are outlined and comparisons are made between experimental results and HPI2 simulations. Then, ablation and deposition profiles are calculated for the optimized stellarator W7-X [41], on which a pellet injector will be installed for the second phase of operation. Finally, the findings are discussed, conclusions are drawn with regard to the viability of this code for stellarators, and recommendations are made for pellet studies on the W7-X.

2. Background

A cryogenic pellet injected into high temperature plasma is exposed to the incident energetic particles of background plasma that ablate it until it is completely consumed. Subsequent to ablation, the ablated pellet material is homogenized in this ambient plasma. Hence, several physical mechanisms, which come into play at different instances, are involved. The combine effect of these mechanisms determines the penetration of the pellet, the rate at which it is ablated as well as the plasma density and temperature profiles after the injection. Moreover, the fuelling efficiency depends on these; hence a full understanding of all the involved mechanisms is mandatory.

2.1. Ablation and Homogenization models

As a cryogenic pellet travels into, and through, a magnetically confined plasma, it is ablated by interactions with background plasma particles (electrons, ions and

impurities). However, it is also shielded from further direct interactions with ambient plasma by several mechanisms. The ablated material forms an expanding neutral cloud that protects the pellet in a self-regulated manner, *i.e.*, the line-integrated density of the cloud self-adapts in such a way that the heat flux at the pellet surface is just enough to maintain the shielding capability of the cloud at an adequate value [6]. This neutral shielding cloud expands spherically and, eventually, becomes partially ionized; when the ionized fraction is high enough, radial expansion ceases and the cold plasma, or plasmoid, that has been formed starts to expand along the magnetic field lines of the device, as can be observed in Figure 1 [14]. The dynamics of the cloud is not the only mechanism that protects the pellet. The presence of an electrostatic sheath at the plasma-cloud interface, which appears due to the fact that the cloud is negatively charged with respect to the background plasma, significantly reduces the heat flux at the pellet surface [42, 43]. In addition, the expanding plasmoid partially expels the ambient magnetic field, and, hence, the incident heat flux is further reduced [3]. Subsequently, the ionized fraction of the ablatant expands along the magnetic field lines until plasmoid and plasma pressures equilibrate. During this homogenization phase, the plasmoid also drifts down the magnetic field gradient and the plasma potential distribution is modified. Plasmoid pressure relaxation with the background plasma determines the dynamics of the plasmoid and it is the driving term for the $\mathbf{E} \times \mathbf{B}$ drift of plasmoid particles [16]. The main phenomenon responsible for the drift of the ionized material is the motion of plasmoid electrons and ions in an inhomogeneous magnetic field, which produces an uncompensated current

$$\mathbf{j}_{\nabla B} = \frac{2(p_0 - p_\infty) \mathbf{B}_\infty \times \nabla B_\infty}{B_\infty^3} \quad (1)$$

where p_0 and p_∞ are the pressure of the plasmoid and the background plasma (in units of Pa), respectively, and $\mathbf{B}_\infty$ is the background magnetic field (in units of T). This current is cancelled out, under open circuit conditions, by an opposing ion polarization current:

$$\mathbf{j}_{pol} = \frac{n_0 m_i}{B_\infty^2} \frac{d\mathbf{E}}{dt} \quad (2)$$

where $d\mathbf{E}/dt$ is determined, at equilibrium, from the condition of current closure. Here E is the electric field in the plasmoid resulting from charge separation, n_0 is the plasmoid density and m_i is mass of plasmoid ions, all in SI units. Hence, the resultant plasmoid drift acceleration (see Figure 2), for an arbitrary magnetic configuration, is [20]:

$$\frac{dv_d}{dt} = \frac{\frac{dE}{dt} \times \mathbf{B}_\infty}{B_\infty^2} = - \frac{2(p_0 - p_\infty) \nabla_\perp B_\infty}{n_0 m_i B_\infty} \quad (3)$$

Additionally, the change in the particle velocity distribution produced by plasmoid parallel expansion along a magnetic field line increases plasmoid acceleration [17], a mechanism known as the Parks effect. On the other hand, Alfvén-wave emission from both ends of the cloud reduces the drift acceleration since it leads to losses of accumulated charges via parallel currents [20]. Moreover, two additional effects related to the short-circuiting of external and internal currents reduce the drift acceleration. The latter is the Rozhansky effect; it is produced by the short-circuiting of internal currents that arise to balance the variation of current accumulation on the plasmoid surface due

to the rotation of magnetic field lines around the plasmoid center [18, 19]. The former effect is called the Pégourié effect and consists of the depletion of accumulated charges when regions of opposite polarization become connected during the electric potential expansion [16]. Hence, all these effects modify the plasmoid drift, and, therefore, contribute to change the deposited material profile from the one that can be expected from the ablation profile.

2.2. HPI2 Code Description

The HIP2 code was developed to simulate the ablation of a cryogenic pellet (hydrogen, deuterium or a mixture of deuterium and tritium) injected into a magnetic confined plasma created in a tokamak device as well as the evolution of the pellet plasmoid about the device (including drift-driving and -damping terms) [20, 30]. The code takes into account specific machine geometrical data, plasma energy and density profiles and magnetic field configuration of the device under consideration. In the first instance, ablation is described by an enhanced version of the Neutral Gas and Plasma Shielding model, NGPS [14]; it considers the protection provided by the neutral cloud and by the ionized fraction of the ablated material. In addition, it also includes a thermal Maxwellian energy distribution for the plasma particles, increased ablation due to fast particles, geometric effects related to particle finite Larmor radii [16], the 2D modification of the geometry of the cloud expansion [14] and the modification of heat flux due to the formation of an electrostatic sheath [42, 43]. The calculations performed to obtain the ablation rate also provide the initial plasmoid quantities, used to obtain the parallel expansion of the plasmoid from its time evolution. The plasmoid time evolution is modelled by a two-cell (plasmoid and background plasma) four-fluid Lagrangian system [16, 20, 44]. The compression of the plasma by the expanding cloud, the slowing down of the expansion by viscosity forces that develop at the cloud-plasma interface and the increase in the system inertia due to the part of the plasma put in motion by the cloud expansion are considered in the model [20]. In addition, the plasmoid drift is calculated using an equation for the averaged acceleration of a plasmoid particle that is integrated to obtain the total average particle drift [16, 20], considering all the driving- and damping- drift mechanisms. The included effects underlying the ablation of the pellet are not machine dependent. However, the relative importance of the drift mechanism does depend on the device under consideration. For instance, the drift-damping produced by external currents is the dominant effect in tokamaks, whereas internal currents are dominant in helical configurations due to shorter magnetic reconnection lengths [32]. In addition, the calculation of the drift depends on whether the device is axisymmetric or not, since for axisymmetric configuration the drift is in the major radius direction and equation 3 is reduced to [8]:

$$\frac{dv_d}{dt} = \frac{2(p_0 - p_\infty)}{R n_0 m_i} \quad (4)$$

As mentioned previously, simulations with the HPI2 code have been carried out for the LHD [32, 45]. The version of the code used for this device required its extension to the more complicated non-axisymmetric configurations by including the effect of a helical field [31]. For this, the poloidal and toroidal currents connections and the drift acceleration force due to the average magnetic field gradient were added to the HPI2

model. For that, the drift is calculated, in a self-consistent way with the evolution of both the plasmoid and the background plasma, by an equation of the following form:

$$\frac{dv_d}{dt} = a - bv_d \quad (5)$$

In this expression, the first term is the drift acceleration force, while the second represents the sum of the different damping mechanisms that depend on the q-profile and the magnetic shear. The former term, a , must be split into a radial and a poloidal component, since radial and poloidal currents in a non-axisymmetric configuration vary independently along a field line and cannot connect with each other.

$$\begin{aligned} \frac{dv_D^{rad}}{dt} &= - \frac{2(p_0 - p_\infty)}{n_0 m_i \langle \vec{B}_\infty \rangle \langle \frac{1}{|B_\infty|^2} \rangle} \langle J_\alpha \rangle \\ \frac{dv_D^{pol}}{dt} &= - \frac{2(p_0 - p_\infty)}{n_0 m_i \langle \vec{B}_\infty \rangle \langle \frac{1}{|B_\infty|^2} \rangle} \langle J_\rho \rangle \end{aligned} \quad (6)$$

Here, $J_{\alpha,\rho}$ are the geometric projection of the ∇B currents in the ρ - (normal to the magnetic surface) and α -directions (tangent to the magnetic surface) [32]. Whilst the application of the HPI2 code to LHD scenario involved its adaptation to non-axisymmetric configurations, additional modifications were done to include a generalized calculation of the exact magnetic and geometric quantities, suitable for any tokamak or stellarator configurations; and to reduce the computation time [46].

In the new stellarator version employed here, the equilibrium magnetic configuration from the VMEC wout file [47–49] is used to evaluate all drift-relevant magnetic and geometric quantities, averaged along plasmoid parallel lengths [46] by employing a library by Y. Turkin [50]. Moreover, additional minor modifications have been added; for instance, the automatic detection of events when a plasmoid barycenter is located outside the plasma last-closed flux-surface region and the drift quantities are not given [51]. This most recent version of the code, described here, allows simulations to be performed in other stellarators, such as TJ-II, provided that the appropriate magnetic configuration files (Boozer-coordinates file [52]) are available. However, as will be outlined in section 4.1, target plasmas with low electron densities may be problematic, since the pellet and plasma particle content can be similar. As a consequence, the plasma cooling effect of the pellet may be overestimated. In addition, since the magnetic field in stellarators strongly depends in the toroidal position, ϕ , it varies along the plasmoid length. However, this variation is taken into account in a simplified manner in the calculation of the plasmoid drift, since the average magnetic field along the plasmoid parallel length, $\langle B \rangle$, acting at the plasmoid barycenter is only considered. The fact that the three-dimensional variation of the magnetic field is not included in detail in the calculation of the plasmoid drift might be a limitation. However, it should be noted that, due to the finite rotational transform, in a tokamak the magnetic field strength also varies along the magnetic field line and thus along the plasmoid parallel direction (indeed, even if iota is relatively small, due to their relative compactness, the variation of B on the flux surface is typically larger than in large-aspect ratio

stellarators). Since HIP2 predictions have been validated for tokamaks [23 - 26], this provides confidence for stellarators.

3. Device description

A number of pellet ablation and plasmoid drift experiments have been carried out in the TJ-II stellarator to clarify the influence of the fully three-dimensional magnetic field of non-axisymmetric devices in the efficiency of pellet fueling. The experimental results have been compared with simulations performed with the HPI2 code. In addition, the HPI2 code is used for pellet simulations in W7-X, which can be a support for the pellet injection plans in this recently commissioned device. In this section, both devices will be described. First, the characteristics of the TJ-II stellarator, together with its pellet injection system and relevant diagnostics, are reviewed. Next, the optimized stellarator W7-X is described along with a brief introduction about the pellet injection plans.

3.1. TJ-II Stellarator

The TJ-II is a four-period, low magnetic shear ($\Delta i \leq 6\%$) stellarator located at CIEMAT, Madrid, Spain [53]. Its major radius, R_0 , is 1.5 m, and its average minor radius, a_0 , is ≤ 0.22 m. A set of poloidal, toroidal and vertical coils creates its fully 3-dimensional magnetic-field with bean shaped cross-section, central magnetic field, $B(0) \leq 1.1$ T, and total plasma volume of around 1.1 m^3 . A wide range of vacuum magnetic configurations can be obtained, which allows exploring a broad variety of rotational transforms, $0.9 \leq i(0)/2\pi \leq 2.2$. Generally, hydrogen is used as the working gas. Plasmas are created and maintained using ECRH and/or NBI. The two gyrotrons that form the ECRH system ($P_{\text{ECRH}} \leq 500$ kW, $t_{\text{discharge}} \leq 300$ ms) operate at 53.2 GHz, *i.e.*, the second harmonic electron cyclotron resonance frequency. The central electron densities, $n_e(0)$, and temperatures, $T_e(0)$, that can be achieved are $\leq 1.7 \times 10^{19}\text{ m}^{-3}$ and ≤ 1 keV, respectively. On the other hand, the NBI system is formed by two tangential injectors, one counter and the other co-counter ($E_{\text{NBI}} \leq 32$ keV, $P_{\text{NBI}} \leq 0.7$ MW throughput). Central electron densities and temperatures of $n_e(0) \leq 5 \times 10^{19}\text{ m}^{-3}$ and $T_e(0) \leq 300$ eV, when a lithium coating is applied to the vacuum vessel wall [54], can be achieved. The central ion temperature, $T_i(0)$, achieved with both heating schemes, is typically ≤ 120 eV. Hydrogen pellets are injected into hydrogen plasmas, created and/or maintained with either ECRH or NBI, or both heating systems, and with different magnetic configurations for pellet fuelling studies.

3.1.1. Pellet Injector and associated diagnostics

The TJ-II pellet injector (PI) is a four-barrel pipe gun device with a cryogenic refrigerator for *in-situ* pellet formation (10 K), fast propellant valves for pellet acceleration (velocities between 800 m/s and 1200 m/s can be achieved) and straight delivery lines (see Figure 3). It was developed in collaboration with the Fusion Energy Division of Oak Ridge National Laboratory (ORNL), Tennessee, USA [55]. The TJ-II PI is a flexible system. Small pellets, type-1 (0.42 mm diameter and containing $\leq 4 \times 10^{18}$ H atoms) and type-2 (0.66 mm diameter, containing $\leq 1.2 \times 10^{19}$ H atoms), are required to avoid raising the density above the gyrotron cut-off limit ($\sim 1.7 \times 10^{19}\text{ m}^{-3}$). Larger pellets, type-3 (0.76 mm diameter and $\leq 1.8 \times 10^{18}$ H atoms) and type-4 (1 mm diameter, containing $\leq 4.1 \times 10^{19}$ H atoms), are injected in high-density NBI-heated plasmas. The

system has four injection lines, (labelled Line 1 to 4) with 54 mm separation between lines. The toroidal angle for Lines 1 and 2 is $\phi = 14^\circ$, whereas it is $\phi = 13^\circ$ for the other two (See Figure 3). Due to their position, only pellets injected from Lines 1 and 4 approach the plasma centre for standard configurations, whereas the flight paths for Lines 2 and 3 have nearest approach at $\rho = 0.273$ and $\rho = 0.45$, respectively, where $\rho = r/a$ is the normalized plasma radius. However, this is not a limitation, since pellet types can be interchanged between the four injection lines, so all pellet sizes can be injected into a path that crosses the magnetic axis [56].

The PI is equipped with an in-line diagnostic system formed by a light gate and a microwave cavity. The signals from these systems are used to estimate the velocity and the mass of the pellet, respectively [55]. In addition, the light emitted by the neutral, or partially ionized, cloud that surrounds the pellet is collected by amplified silicon diodes and a fast-frame camera. Two amplified silicon photodiodes, fitted with interference filters centred at 660 (with full-width at half-maximum transmission width of 10 nm) follow the Balmer H_α emission ($\lambda = 656.28$ nm) from above (TOP) and behind (SIDE) pellet flight paths (see Figure 3). The SIDE diode can be replaced by an avalanche photodiode (APD). The pellet penetration depth and its ablation profile are determined, assuming that the pellet is not accelerated in the radial direction and that the H_α signal is proportional to the ablation rate. An ultra-fast CMOS camera, model FASTCAM APX-RS by Photron Incorp., San Diego, CA, normally records from a viewport located above the flight path. It is equipped with [56, 57] coherent fibre bundle and machine-vision type camera lenses; in this work, a 12.5 mm lens, model HF12.5SA-1 by Fujinon Tokyo, Japan, has been used. The field-of-view of the system allows the plasmoid perpendicular to the pellet injection direction to be recorded, thereby allowing the study of pellet deflection and acceleration, both in radial and toroidal directions [59]. Apart from that, it is possible to record the trajectory of the pellet from a tangential, TANG, viewport, hence possible poloidal asymmetries and /or deflections can be determined, along with the plasmoid drift in both radial and poloidal directions. Moreover, recording from a rear window, SIDE, is allow, thus, pellet poloidal deflections, and plasmoid parallel expansion and poloidal drift can be further studied (see Figure 4). However, since recording simultaneously from all viewports is not possible, the three-dimensional trajectory of the pellet cannot be determined and some uncertainties may be present in the analysis.

3.1.2. Plasma diagnostics

TJ-II is equipped with a wide range of passive and active plasma diagnostics [60]. The diagnostics that are relevant for pellet injection studies include the Thomson Scattering (TS) system, which provides one set of electron density and temperature profiles per discharge [61]; a microwave interferometer that follows the line-integrated electron density along the discharge, and an eleven-channel Electron Cyclotron Emission (ECE) system that follows the electron temperature evolution at different radii. The positions of these diagnostics, relative to the PI location, along with the NBI injection directions are shown in Figure 4. Due to the limited number of measurements per discharge of some of the diagnostics (e.g. TS has 1 per discharge), the shot-to-shot technique is frequently employed, i.e. pellets are injected into reproducible plasmas and a single measurement per discharge is made at a different time for every shot.

3.2. Wendelstein 7-X

The Wendelstein 7-X is an optimized stellarator [37] that was commissioned at the end of 2015 [62]. The first, and limited, phase of operation of this large device was completed in early-2016 [63]. Its main goal is to achieve steady-state operation at high normalized pressure with a volume-averaged beta, β , of about 5 %, ion temperatures of several keV and plasma densities higher than 10^{20} m^{-3} , and, hence demonstrate the viability of the stellarator as a fusion reactor. It is expected that its optimized magnetic field configuration will enable significantly better plasma performance respect to non-optimized magnetic field geometries [41, 63, 64]. This optimized magnetic field is generated by a set of 70 superconducting NbTi coils. From these, 50 non-planar modular coils provide the basic rotational transform, while 20 planar coils allow varying the rotational transform and adjusting the radial position of the plasma. In addition, 10 non-cryogenic conducting coils enable sweeping of the divertor strike lines while 5 additional coils are used for plasma edge control and error field correction. This set of coils makes achieving a maximum magnetic field of 3 T possible.

The W7-X major radius is $R = 5.5 \text{ m}$, while its average minor radius is $\langle a \rangle = 0.55 \text{ m}$; this correspond to a plasma volume of about 30 m^3 . Its main steady-state heating system is an Electron Cyclotron Resonance Heating (ECRH) system [37, 65] formed by 10 gyrotrons, with output power of 1 MW per gyrotron, that operate at 140 GHz, the 2nd harmonic of the electron cyclotron resonance at 2.5 T. It is planned to use the 2nd harmonic X-mode (X2) for plasma start-up and at low plasma electron densities, whereas, it is expected to be change to the 2nd harmonic O-mode (O2) for densities above the X2 cut-off density ($1.2 \times 10^{20} \text{ m}^{-3}$). In addition, two neutral beam injectors (NBI), with maximum pulse length, $t_{\text{discharge}} \leq 10 \text{ s}$, will provide $P_{\text{NBI}} = 1.7 \text{ MW}$ of neutral power per injector by the injection of neutral hydrogen atoms accelerated to 55 keV; deuterium injection will also be possible ($P_{\text{NBI}} = 2.5 \text{ MW}$, 60 keV) [67]. Moreover, an Ion Cyclotron Resonance Heating (ICRH) system will provide heating to complement the ECRH system [68]. During the first part of the first phase of its operation, OP1.1, pellet injections were not available on the W7-X [69]. Nonetheless, a recommissioned blower-type injector [70] is to be employed during the OP 1.2 phase while a new extrusion type injector will be available at a later date.

4. Pellet ablation (experiments and predictions)

Hydrogen pellet injection experiments have been performed in on/off- axis ECRH and NBI hydrogen plasmas of different densities and for the TJ-II standard configuration, called 100_44_64 and plotted in Figure 5 (the numbers refer to the currents in the central, helical and vertical coils, respectively) (Figure 4). Pellet ablation profiles are determined from the recorded Balmer H_α emission, assuming that this emission provides a reasonable indication of the ablation rate and the penetration depth [58]. In addition, in-line light-gate and microwave cavity signals are used to establish the timing and pellet mass. It is also assumed that the pellet is not radially accelerated while it transverses the plasma. Fast-camera images are used to verify that the radial acceleration of the pellet is indeed negligible. This can be determined from Figure 6 where a snap-shot series of pellet images for TJ-II discharge #44624, where a type-2 pellet is injected into a standard-configuration ECRH plasma; *i.e.*, nearly constant radial

separations between the emission maximum of each image, Figure 7, signify that the radial velocity is constant along the pellet trajectory and, hence, the assumption of constant radial velocity is justified (from geometrical considerations, 1 pixel $\approx$ 0.52 mm for upper injection lines (Line #1 and #4) and 1 pixel $\approx$ 0.56 mm for the other two lines).

Representative snap-shot images for individual pellets injected into ECRH and NBI plasmas recorded from above, TOP, are shown in Figure 8 a) and Figure 9 a), along with the H_α emission detected by the photodiodes (see Figure 8 b) and Figure 9 b)), where a pellet type #1 and a pellet type #2, respectively, are injected into the standard configuration. While typical images from the tangential viewport, along with the H_α emission, are shown in Figure 10 and Figure 11 for individual pellets injected into ECRH (Pellet #2 in Line # 1) and NBI (Pellet #3 in Line #4), respectively, heated plasmas. It should be noted here that the x-axis in figures Figure 6, Figure 8 to Figure 11 is directed along the device major radius, while the y-axis corresponds to the toroidal direction. It can be seen in Figure 8 a) and Figure 10 a) that the pellet trajectory for ECRH plasmas is not deviated, rather it continues along the original pellet injection line until fully ablated. However, for plasmas maintained with unbalanced NBI heating, the pellet is deflected, in both toroidal (see Figure 9) and poloidal (Figure 11) directions. Heating asymmetries have not been detected for pellets injected into either ECRH or NBI plasmas [59]; for pellets injected into ECRH plasmas, this agrees with the fact that pellet trajectory is not deviated from the original injection path. On the contrary, pellets injected into unbalance NBI plasmas are deviated without any observed heating asymmetry; thus, being associated to momentum transfer from NBI fast ions [59]. Toroidal accelerations of the pellet of the order of $10^3 - 10^4$ km/s have been reported elsewhere [71] for both co- (NBI 1) and counter- (NBI 2) injections. However, the observed poloidal accelerations are different for both type of injections; negligible poloidal accelerations are estimated for NBI 1 comparing to toroidal accelerations (of the order of 10 km/s), while poloidal accelerations observed for NBI 2 are of same order than radial accelerations, 10^3 km/s). Additionally, the direction of the magnetic field lines can be observed in the fast-camera images, since the partially ionized part of the cloud expands along these. It is also observed in Figure 9b) that, when the pellet crosses the magnetic axis, the amplitude and frequency of the striations are reduced.

Finally, the expected outwards-directed drift of the ablated material [56] is observed in fast-camera images (see Figure 12); it is also possible to determine the drift velocity of the plasmoid in the radial and poloidal directions from these images. First, using images from the TOP camera viewport, the magnitude of the radial drift is estimated. The radial asymmetry observed in the light profile of each snap-shot image (see Figure 6) can be attributed to the radial, outward-directed drift. To estimate the magnitude of this radial drift velocity, each light profile is fitted with two Gaussian curves; the main one represents the ablating pellet, whereas the second one represents the drifting plasmoid. From the differences between the radial positions of such peaks and the exposure time ($\tau_{\text{exp}} \sim 4 \mu\text{s}$), values of between 2 and 5 ± 0.003 km/s are obtained for the average drift velocity in ECRH plasmas, which are inside the expected range [12].

An equivalent analysis is carried out for tangential images, where both the drift in the poloidal direction and in the radial direction can be estimated. A representative snapshot image from #45110 (pellet #3 injected along Line #4 into almost balance NBI phase) is shown in Figure 12, where the direction of the drift is highlighted; it is observed here that the plasmoid drifts towards the LFS plasma edge and towards the plasma bottom. For ECRH plasmas, average drift velocities in the radial direction of between 6.5 ± 0.7 km/s and 7 ± 0.7 km/s are found ($\tau_{\text{exp}} \sim 4$ μ s); while for the drift velocities in the poloidal direction, the obtained values are between 2.5 ± 0.7 km/s and 5.6 ± 0.7 km/s. On the other hand, for pellets injected into NBI plasmas, average drift velocities in the radial direction of between 4 ± 5 km/s and 12 ± 5 km/s are obtained for an exposure time, τ_{exp} , of 2 μ s, while velocities of 1.4 ± 3 km/s to 10 ± 3 km/s are obtained for $\tau_{\text{exp}} \sim 4$ μ s. Whereas, for drift in the poloidal direction, the average velocities are found to be between 5 ± 6 km/s and 10 ± 6 km/s for the short exposure time and between 1.5 ± 3 km/s and 7.6 ± 3 km/s for the long one. The differences found between ECRH and NBI cases are explained considering that pellets injected into NBI plasmas are deflected and, hence, the light emitted as the pellet changes its direction, both toroidally and poloidally, is superimposed to the radial and poloidal drifts, blurring the images and increasing the uncertainties in the estimation of the drift. The reason of differences related to the exposure time will be discussed later.

Since the pellet velocity is known and there is no acceleration, the temporal evolution of the H_α emission can be transformed into a radial emission profile, and, compared with the time-integrated light profile of the images recorded with the fast camera (possible errors may come from neglected poloidal deflection in the case of upper view, and toroidal for the tangential view, since the fast-camera system does not allow studying the 3D trajectory of the pellet). Such profiles are shown in Figure 8b) to Figure 11b) for TJ-II discharges #44828, #41391, #45110 and #45091, respectively. Good agreement is found between the spatially resolved profile from the fast camera and the temporal evolution of the H_α emission when constant velocity is assumed, even though some differences are present, since fast camera lenses do not have any filter and, hence, all the visible light emitted by the shielding cloud is recorded. Moreover, the fact that the plasmoid is drifting backwards is not taken into account in the transformation of the temporal evolution of the H_α emission into spatial coordinates. In addition, it should be also considered that the fast camera may be saturated (see, for instance, Figure 11b)). Hence, it is confirmed that the supposition of no radial acceleration is reasonable.

The shot-to-shot technique is used to reconstruct the deposition profile of the ablated material and the temperature evolution of the plasma (see Figure 14) [56]

4.1. Modelling of pellet injections and comparison with TJ-II experiments

Hydrogen pellets of different sizes have been injected into both ECR- and NBI-heated plasmas having a range of plasma densities and temperatures. The previously mentioned HPI2 code is used to simulate pellet injection into ECRH TJ-II plasmas in the standard configuration. The ablation and deposition profiles, as well as the temperature evolution, obtained with this code are compared with the measured H_α emission; and with density and temperature profiles acquired with the Thomson Scattering system.

In Figure 13, ablation profiles calculated by the HPI2 code are compared with H_α emissions detected by TOP photodiode. In Figure 13a), plasma discharge #41777 (target plasma: $n_e(0) = 6 \times 10^{18} \text{ m}^{-3}$, $T_e(0) = 1.1 \text{ keV}$), into which a pellet type #2, containing $6.1 \times 10^{18} \text{ H}^0$, was injected at 804.12 m/s, through line #1, is shown. The agreement between the recorded H_α , which gives an indication of the ablation rate, and the predicted ablation profile is reasonably good, considering that the H_α emission is not directly proportional to the ablation rate. A second example, corresponding to #44614 (target plasma: $n_e(0) = 7.8 \times 10^{18} \text{ m}^{-3}$, $T_e(0) = 1.48 \text{ keV}$) is found in Figure 13b); here, a pellet type #2, containing $6.6 \times 10^{18} \text{ H}^0$, was also injected through line #1 at 894.5 m/s into an ECRH plasma. The penetration depth, i.e. distance travelled by the pellet until its complete ablation, of the pellet is well predicted by the HPI2 code, as well as the rate of the ablation, whose shape is similar to the H_α emission, considering the expected differences.

The density profile of the plasma, after the complete ablation of the pellet and homogenization of the ablated material, predicted by the HPI2 code is shown in Figure 14, together with those of the target plasma, measured by the TS. In addition, densities measured by the TS at different times after the injection of a pellet, for reproducible discharges, are plotted, so the time evolution of the plasma density can be reconstructed [56]. Moreover, the evolution of the deposition profile, i.e., the increment of the plasma density, can be observed in this figure. In Figure 14 a) the results corresponding to discharge #41777 are shown; while in Figure 14 b), results for #44614 are plotted. It can be observed in both cases that the plasma density given by the HPI2 code is shifted towards outer radii, compared to the experimental profiles. However, it should be noted that the code does not take into account the transport of the material, so the density profile, at the injection toroidal position ($\phi = 14^\circ$), is calculated when the homogenization of the material is completed (in these particular case, $\sim 0.46 \text{ ms}$ and $\sim 0.74 \text{ ms}$, respectively, after the injection of the pellet); while Thomson scattering measurements are done at a later time, since no density change can be detected until 0.8 – 1 ms after the injection (the Thomson Scattering system is located 180° toroidally from the PI [56]). Therefore, it is necessary to simulate the time evolution of this density profile, considering transport, to accurately compare the simulation result with the measured ones. The density profile at time $t = +0.8 \text{ ms}$ for #41777 ($t = +1.48 \text{ ms}$ for #44614) after the injection of the pellet is calculated using neoclassical simulations with DKES [48] as explained in detail in [38] and the result is also plotted in Figure 14. Generally speaking, it is seen that the pellet injection creates density profiles that are hollower than before. If this is the main change in the shape of the plasma profiles in the particle time scale (the electron temperature goes back to previous values on a faster time scale), neoclassical transport should lead to an increase of the core density, as discussed in [38] for TJ-II NBI plasmas. Together with this, there should be a drop of the density in the outer regions and a transiently constant density at intermediate radial positions. This goes qualitatively in the right direction, and indeed the density profiles calculated including neoclassical transport are closer to the corresponding Thomson Scattering profiles than those estimated by HPI2 only. However, the quantitative agreement is considered rather good for discharge #44614 but bad for discharge #41777. And, despite the overall good agreement of discharge #44614, we see that the neoclassical simulations predict a small reduction of the core density, which is not

observed in the experiment and it is as odds with the general description given above. We first note the radial electric field also evolves after pellet injection in the time scale of particle transport [72], and so does the ambipolar radial electric field in our simulations. We also note that in discharge #44614 the core electron temperature is extremely high, which means that the radial electric field (approximately given by eTe') is large and DKES simulations become inaccurate [73]. Finally, changes in the particle sources from the wall are neglected in these simulations.

The temperature profile after the injection of the pellet, together with the temperature of the target plasma from TS measurements, is plotted in Figure 15 for case #41777 and in Figure 16 for #44614 discharge. For #41777 case, the temperature measured by the TS system 0.8 ms after the injection of the pellet is additionally shown in Figure 15b). Since plasma cooling and recovery during and after pellet ablation are faster than plasma density changes, it is difficult to determine from TS profiles whether this cooling effect is overestimated by HPI2 calculations.

In addition to that, the magnitude of the drift velocity is predicted by the HPI2 code; for #41777, drift velocities between 0.6 km/s and 3.8 km/s are found, when the plasmoid is detached from the pellet, whereas, when the plasmoid is completely ionized, the obtained values are placed between 1.4 km/s and 3.8 km/s; and, during the homogenization phase, radial drift velocities up to 2.5 km/s to 20 km/s are reached, while poloidal drift velocities of between 1 km/s and 10 km/s are attained. The magnitude of the drift velocity predicted for #44614 is between 0.4 km/s and 5.1 km/s for the former time, while, for the latter, the calculated values are placed between 0.9 km/s and 5.1 km/s; whereas, during the homogenization phase, the maximum velocities obtained are of between 1.4 km/s and 23 km/s for the radial direction and of between 0.7 km/s and 14 km/s for the poloidal direction. Moreover, the time evolution of a single plasmoid drift velocity, corresponding to #41777 case, is shown in Figure 17, where both radial and poloidal components are plotted; here, it is observed that the drift velocity is initially accelerated (until $t \sim 35 \mu s$), and after that, it is decelerated until the motion is completely stopped. The initial acceleration and subsequent deceleration agree with the fact that the estimated average drift from fast camera images depends on the exposure time. Furthermore, the values of the drift velocities, in both the radial and the poloidal direction, calculated with the HPI2 code agree reasonably well with the average values estimated from fast camera images.

On the other hand, the direction of the drift is given by the magnetic field, in particular by the inverse curvature radius, and this, since TJ-II is a fully 3D device, depends on the parallel length of the plasmoid. So, in HPI2, as mentioned in the description of the code, the inverse curvature radius is average along the whole plasmoid length and, this average value is used to calculate the effective drift of the plasmoid. Examples of the inverse curvature radius vector field are plotted in Figure 18 and Figure 19 for plasmoids whose dimension parallel to the magnetic field lines, Z_0 , is 0.8 m and 10 m, where it can be seen that the drift is directed radially outwards and poloidally downwards for plasmoids of short parallel length and, as they expand, the drift becomes inwards-directed. In addition, the complete trajectory of each plasmoid during the homogenization phase for #41777 is plotted in both figures, so it can be seen that plasmoids drift following the direction of the inverse curvature radius at the

corresponding parallel length. It is also observed that most plasmoids drift to the plasma edge and are partially or completely lost, and only some of them are stopped before reaching the edge, explaining the density profile shifted to the LFS plasma edge with respect to the ablation profile, and the low fuelling efficiency of pellet injections in this type of plasmas, where pellets do not penetrate to beyond the plasma centre [56]. Finally, it should be noted that a detailed comparison with experimental results is not allowed with the current fast camera system, since, in addition to the time average effects from the finite exposure time, fast camera images are only able to show the drift of the plasmoid at the beginning of the homogenization phase, when the parallel length of plasmoid is short compared to the length of the field line, referred to as self-connection length [16], i.e. when no average effect has come into play yet. It is found that the direction given by the HPI2 code for plasmoids of small parallel length, agrees with the drift estimated from fast camera images (see Figure 12) and with the deposition profiles shifted towards the LFS plasma edge, effect that has been reported for LFS injections in several tokamaks [8, 12, 16] and in the LHD [34].

4.2. Simulation of pellet injections for Wendelstein 7 – X

It is foreseen to inject hydrogen pellets into W7-X plasmas with a blower-type injector to determine whether injection location is critical to achieve the required efficient core fueling, as in tokamaks, or if the beneficial inwards drift is present in W7-X for HFS injection, unlike the LHD case. With this first injector, 2 mm diameter and 2 mm long cylindrical hydrogen pellets will be injected at velocities around 250 m/s through two different injection ports, one located in the HFS part (AEL41) of the vessel and the other on the LFS (AEK41). Since both ports are toroidally close ($\phi_{\text{HFS}} = -2.22$ rad, $\phi_{\text{LFS}} = -2.24$ rad) comparison studies can be undertaken. The magnetic field section for both toroidal positions is shown in Figure 20. These simulations are performed for two different plasma scenarios; the high temperature case corresponds to ECR heating in X2-mode, whereas the second one, the high-density case, corresponds to ECRH in O2-mode. Hence, the impact of background plasma is also evaluated. The density and temperatures profiles of both plasma scenarios are plotted in Figure 21. In the simulations, possible erosion of the pellet due to friction off the inner guide tube walls is considered by using a smaller pellet diameter ($d_p = 1.5$ mm). Hence, the number of hydrogen atoms in such a pellet is 1.85×10^{20} , compared to 3.29×10^{20} for a 2-mm pellet. Ablation and deposition profiles of the four different cases are plotted in Figure 22, while penetration depth and fuelling efficiency are found in Table 1. The HPI2 code predicts that pellet injection into W7-X plasmas from the HFS allows the ablated material to achieve deeper deposition and higher efficiency, as seen in Figure 22 and Table 1. In addition, a slightly deeper deposition is expected for injections into high temperature plasmas (ECRH in X2-mode) since a larger difference between plasma and plasmoid density, due to larger ablation rate, enhances the drift (see equation 1). On the other hand, for LFS-injection, deeper deposition should be achieved for high-density plasmas (ECRH O2-mode), since lower temperature of O2-mode plasmas increases the penetration of the pellet and the larger density difference in the X2-mode ECRH enhances the outward-directed drift of the material.

In addition, two LFS injection ports are compared as a preliminary study for the design of a new pellet injection system. For that, simulations of two different pellet sizes are

carried out, varying the velocity of the pellet from 200 m/s to 1000 m/s and for the same plasma scenarios. An example of ablation and deposition profiles obtained for 2.5 mm pellets at 1000 m/s is shown in Figure 23, while the fuelling efficiency for all the different cases is plotted in Figure 24. According to the results of the simulations, it is possible to determine that, even though the penetration of the material is similar for both injection ports, AEK41 is the most suitable of them, since fuelling efficiency is higher, particularly for large and fast pellets (see Figure 24), due to differences of the inverse curvature radius. As can be seen in Figure 25, the inverse curvature radius in the toroidal position corresponding to AEE41 port is significantly larger for plasmoids of short parallel length, comparing with the plasmoid self-connection length; for larger plasmoids, average effects remove this difference.

5. Discussion

Pellet of different sizes have been injected into TJ-II plasmas. H_α emission detected by photodiodes, and fast camera images have been used to study the ablation, along with the drift velocity and direction for several plasma characteristics. In addition, TS measurements have been employed to analyse the time evolution of the plasma density profile, and to study the relation between the estimated drift and the shape of the deposition profiles.

First, the assumption of non-radial pellet acceleration is confirmed using a fast-frame camera. In addition, fast-frame snap-shot images are used to estimate the time average drift velocity. The radial component is found to be 1.4 -12 km/s, depending on the heating method and the exposure time; while time-average poloidal drift is estimated to be of between 1.5 km/s and 10 km/s. Second, under the assumption of constant radial pellet velocity, the temporal evolution of the H_α emission is transformed into a radial profile and compared with the ablation profile obtained with the HPI2 code for injections into ECRH plasmas. The agreement is found to be acceptable, considering that the H_α emission is only an indication of the ablation rate and not proportional to it. Next, the deposition profile is reconstructed from shot-to-shot Thomson Scattering measurements, and also compared with simulation results. It is found that simulated profiles are shifted to the LFS plasma edge comparing to the experimental profiles. However, it should be noted that the TS system is 180° from the PI and that transport should be considered so predictions and experimental results can be compared. Therefore, the time evolution due to transport of the density profiles obtained with the HPI2 code is estimated by neoclassical simulations using the DKES code. The profiles obtained by the combined use of the ablation and the transport codes are found to be compatible with TS measurements.

Finally, simulations are carried out for hydrogen pellets injected into W7-X plasmas. Since the agreement between TJ-II experimental and simulated results is considered to be acceptable, the predictions made for W7-X should be reliable. Therefore, higher efficiency of the fuelling and deeper penetration of the ablated material are expected for HFS injections, due to the inwards-directed drift experienced by plasmoids detached in the inner part of the plasma. In particular, injections into high-temperature plasmas are expected to be especially advantageous, since the larger difference between plasma and plasmoid pressures enhances the drift. Regarding the preliminary study for the design of

a new pellet injector for W7-X, one injection port – AEK41 – is identified as the most suitable since fuelling efficiency is higher due to the smaller inverse curvature radius, which does not have an associated outwards drift as large as the AEE41 port.

In the future, further experimental studies are intended to be carried in TJ-II; for instance, a scan of iota profile and magnetic well, which may lead to a deeper understanding of the influence of the magnetic field and the reconnection length in the deposition of the ablated material and the efficiency of the fuelling in stellarators, taking advantage of the ability of TJ-II to operate in a broad range of magnetic configurations. These experimental studies can be complemented with simulations employing the HPI2 code. In addition, images of pellets injected into co- and counter-NBI plasmas can be used to confirm whether the neutral beam injections are balanced enough to avoid the toroidal deflection caused by unbalance injection, and, if they are indeed balance, the effect of fast ions in the ablation could be simulated with this version of the HPI2 code. Moreover, optimization of the fast camera system could lead to improve estimations of the drift velocity the fast camera system; it can also be modified to follow the injection from behind the pellet. These modifications of the fast camera system may facilitate the comparison of experimental results and predictions and, therefore, complete the benchmarking of the HPI2 code for W7-X.

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.

References

- [1] H. Maaßberg *et al.*, “Transport in stellarators,” *Plasma Phys. Control. Fusion*, vol. 35, pp. B319–B332, 1993.
- [2] M. . Mikkelsen *et al.*, “Core fuelling to produce peaked density profiles in large tokamaks,” *Nucl. Fusion*, vol. 35, no. 5, pp. 521–533, 1995.
- [3] B. Pégourié, “Review: Pellet injection experiments and modelling,” *Plasma Phys. Control. Fusion*, vol. 49, no. 8, p. R87, 2007.
- [4] S. L. Milora, V. Mertens, W. A. Houlberg, and L. Lengyel, “Review Paper: Pellet Fuelling,” *Nucl. Fusion*, vol. 35, no. 6, pp. 657–754, 1995.
- [5] L. R. Baylor *et al.*, “An international pellet ablation database,” *Nucl. Fusion*, vol. 37, no. 4, pp. 445–450, 1997.
- [6] P. B. Parks, R. J. Turnbull, and C. a. Foster, “A model for the ablation rate of a solid hydrogen pellet in a plasma,” *Nucl. Fusion*, vol. 17, no. 3, pp. 539–556, 1977.
- [7] L. R. Baylor *et al.*, “Pellet fuelling deposition measurements on Jet and TFTR,” *Nucl. Fusion*, vol. 32, no. 12, pp. 2177–2187, 1992.
- [8] P. B. Parks, W. D. Sessions, and L. R. Baylor, “Radial displacement of pellet ablation material in tokamaks due to the grad-B effect,” *Phys. Plasmas*, vol. 7, no. 5, pp. 1968–1975, 2000.

- [9] W. Y. Hong, E. Y. Wang, Y. D. Pan, and X. Q. Xu, "Effects of supersonic beam and pellet injection on edge electric field and plasma rotation in HL-1M," *J. Nucl. Mater.*, vol. 266, pp. 542–545, 1999.
- [10] H. Sakakita *et al.*, "Measurement of ablation cloud parameters and plasma potential with on / off-axis pellet injection in the JIPP T-IIU tokamak," *Fusion Eng. Des.*, vol. 34–35, pp. 329–332, 1997.
- [11] H. W. Müller *et al.*, "High- β plasmoid drift during pellet injection into tokamaks," *Phys. Rev. ...*, vol. 83, no. 11, pp. 2199–2202, 1999.
- [12] H. . Müller *et al.*, "High β plasmoid formation, drift and striations during pellet ablation in ASDEX Upgrade," *Nucl. Fusion*, vol. 42, no. 3, pp. 301–309, 2002.
- [13] J. De Kloe, E. Noordermeer, N. J. Lopes Cardozo, and A. A. M. Oomens, "Fast backward drift of pellet ablatant in Tokamak plasmas," *Phys. Rev. Lett.*, vol. 82, no. 13, pp. 2685–2688, 1999.
- [14] W. A. Houlberg, S. L. Milora, and S. E. Attenberger, "NEUTRAL AND PLASMA SHIELDING MODEL," *Nucl. Fusion*, vol. 28, no. 4, pp. 595–610, 1988.
- [15] W. A. Houlberg *et al.*, "Pellet penetration experiments on JET," *Nucl. Fusion*, vol. 32, no. 11, pp. 1951–1965, 1992.
- [16] B. Pégourié *et al.*, "Modelling of pellet ablation in additionally heated plasmas," *Plasma Phys. Control. Fusion*, vol. 47, no. 1, pp. 17–35, 2005.
- [17] P. B. Parks and L. R. Baylor, "Effect of parallel flows and toroidicity on cross-field transport of pellet ablation matter in tokamak plasmas," *Phys. Rev. Lett.*, vol. 94, no. 12, pp. 1–4, 2005.
- [18] V. Rozhansky, I. Senichenkov, I. Veselova, and R. Schneider, "Mass deposition after pellet injection into a tokamak," *Plasma Phys. Control. Fusion*, vol. 46, no. 4, pp. 575–591, 2004.
- [19] I. Y. Senichenkov, I. Y. Veselova, V. A. Rozhansky, and R. Schneider, "Modeling of the pellet cloud structure in the presence of ∇B induced drift," *J. Nucl. Mater.*, vol. 337–339, no. 1–3 SPEC. ISS., pp. 446–450, 2005.
- [20] F. Köchl, "Modelling of Transport and Pellet Fuelling in ITER-relevant plasmas," Technische Universität Wien, 2009.
- [21] N. Commaux *et al.*, "Influence of the low order rational q surfaces on the pellet deposition profile," *Nucl. Fusion*, vol. 50, no. 2, p. 25011, 2010.
- [22] R. Sakamoto *et al.*, "Cross-field dynamics of the homogenization of the pellet deposited material in Tore Supra," *Nucl. Fusion*, vol. 53, no. 6, p. 63007, 2013.
- [23] D. Frigione *et al.*, "Particle deposition, transport and fuelling in pellet injection experiments at JET," 2011.
- [24] F. Koechl *et al.*, "Integrated Modelling of Pellet Experiments at JET," in *Plasma Physics (Proc. 37th EPS Conf. Dublin, 2010)*, 2010, vol. 34A, p.

O4.123.

- [25] L. Garzotti *et al.*, “Pellet fuelling physics studies on MAST,” in *ECA Vol. 38F*, 2014, pp. 2–5.
- [26] P. Klaywittaphat, T. Onjun, and R. Picha, “Effect of magnetic field on pellet penetration and deposition in ohmic Tore Supra discharges.,” *Ocs.Ciemat.Es*, pp. 8–11, 2011.
- [27] Y.-S. Na *et al.*, “On Benchmarking of Particle Transport Simulations in ITER,” 2016.
- [28] L. Garzotti *et al.*, “Simulations of density profiles, pellet fuelling and density control in ITER,” *Nucl. Fusion*, vol. 52, no. 1, p. 13002, 2011.
- [29] B. Pégourié, C. Day, A. Frattolillo, F. Koechl, and P. T. Lang, “Physical constraints on the design of the DEMO pellet fueling system,” in *ECA Vol. 40A*, 2016, vol. 97, pp. 3–6.
- [30] F. Koechl *et al.*, “Modelling of Pellet Particle Ablation and Deposition : The Hydrogen Pellet Injection code HPI2,” *JET Rep.*, no. 12, 2012.
- [31] A. Matsuyama, F. Koechl, B. Pégourié, R. Sakamoto, G. Motojima, and H. Yamada, “Modeling of drift displacement of the pellet ablated material for outboard side injection in large helical device,” *Plasma Fusion Res.*, vol. 7, no. 2012, pp. 1–5, 2012.
- [32] A. Matsuyama, F. Koechl, B. Pégourié, R. Sakamoto, G. Motojima, and H. Yamada, “Modelling of the pellet deposition profile and ∇B -induced drift displacement in non-axisymmetric configurations,” *Nucl. Fusion*, vol. 52, no. 12, p. 123017, 2012.
- [33] R. Sakamoto *et al.*, “Impact of pellet injection on extension of the operational region in LHD,” *Nucl. Fusion*, vol. 41, no. 4, pp. 381–386, 2001.
- [34] R. Sakamoto and H. Yamada, “Observation of cross-field transport of pellet plasmoid in LHD,” *Plasma Fusion Res.*, vol. 6, no. 2011, pp. 1–5, 2011.
- [35] H. Yamada *et al.*, “Configuration flexibility and extended regimes in Large Helical Device,” *Plasma Phys. Control. Fusion*, vol. 43, pp. A55–A71, 2001.
- [36] R. Sakamoto *et al.*, “Ablation and Subsequent Density Redistribution of Fueling Pellets Injected into LHD Plasmas,” *EPS poster*, vol. 26, no. June, p. 2002, 2002.
- [37] J. Geiger *et al.*, “Aspects of steady-state operation of the Wendelstein 7-X stellarator,” *Plasma Phys. Control. Fusion*, vol. 55, no. 1, p. 14006, 2013.
- [38] J. L. Velasco *et al.*, “Particle transport after pellet injection in the TJ-II stellarator,” *Plasma Phys. Control. Fusion*, vol. 58, no. 8, p. 84004, 2016.
- [39] J. A. Alonso *et al.*, “Parallel impurity dynamics in the TJ-II stellarator,” *Plasma Phys. Control. Fusion*, vol. 58, no. 7, p. 74009, 2016.

- [40] J. A. Alonso *et al.*, “Observation of Oscillatory Radial Electric Field Relaxation in a Helical Plasma,” *Phys. Rev. Lett.*, vol. 118, p. 185002, 2017.
- [41] G. Grieger *et al.*, “Physics optimization of stellarators,” *Phys. Fluids B Plasma Phys.*, vol. 4, no. 7, p. 2081, 1992.
- [42] G. A. Emmert, R. M. Wieland, a. T. Mense, and J. N. Davidson, “Electric sheath and presheath in a collisionless, finite ion temperature plasma,” *Phys. Fluids*, vol. 23, no. 4, p. 803, 1980.
- [43] L. Lengyel, V. Rozhanskij, and L. Veselova, “Electrostatic shielding of vaporizing surfaces exposed to hot plasmas,” *Nucl. fusion*, vol. 38, no. 12, pp. 1679–1690, 1996.
- [44] L. Lengyel, “Pellet ablation in hot plasmas and the problem of magnetic shielding,” *Phys. Fluids*, vol. 21, p. 1945, 1978.
- [45] A. Matsuyama, B. Pégourié, R. Sakamoto, J. S. Mishra, G. Motojima, and H. Yamada, “Over-ablation and deflection of hydrogen pellets injected into neutral beam injection heated plasmas in the Large Helical Device,” *Plasma Phys. Control. Fusion*, vol. 54, no. 3, p. 35007, 2012.
- [46] F. Koechl, “Private communication,” 2016.
- [47] S. P. Hirshman, “Steepest-descent moment method for three-dimensional magnetohydrodynamic equilibria,” *Phys. Fluids*, vol. 26, no. 12, p. 3553, 1983.
- [48] S. P. Hirshman, K. C. Shaing, W. I. van Rij, C. O. Beasley, and E. C. Crume, “Plasma transport coefficients for nonsymmetric toroidal confinement systems,” *Phys. Fluids*, vol. 29, no. 9, pp. 2951–2959, Sep. 1986.
- [49] S. . Hirshman and O. Betancourt, “Preconditioned descent algorithm for rapid calculations of magnetohydrodynamic equilibria,” *J. Comput. Phys.*, vol. 96, no. 1, pp. 99–109, Sep. 1991.
- [50] Y. Turkin, “Private Communication.” Max-Planck-Institute für PlasmaPhysik, Greifswald, Germany, 2016.
- [51] F. Koechl, “Private Communication,” 2017.
- [52] J. Geiger, “private communication.” Max-Planck-Institute für PlasmaPhysik, Greifswald, Germany, 2017.
- [53] J. Sánchez *et al.*, “Transport, stability and plasma control studies in the TJ-II stellarator,” *Nucl. Fusion*, vol. 55, no. 10, p. 104014, 2015.
- [54] F. L. Tabarés *et al.*, “Energy and particle balance studies under full boron and lithium-coated walls in TJ-II,” *Contrib. to Plasma Phys.*, vol. 50, no. 6–7, pp. 610–615, 2010.
- [55] S. K. Combs *et al.*, “Results from laboratory testing of a new four-barrel pellet injector for the tj-ii stellarator,” *Fusion Sci. Technol.*, vol. 64, no. 3, pp. 513–520, 2013.

- [56] K. J. McCarthy *et al.*, “Plasma fuelling with cryogenic pellets in the stellarator TJ-II,” *Nucl. Fusion*, vol. 57, pp. 056039–056048, 2017.
- [57] K. J. McCarthy *et al.*, “The Pellet Injector and Associated Diagnostics for Performing Plasma Studies on the TJ-II Stellarator,” in *PoS(ECPD2015)*, 2015, no. April, pp. 1–7.
- [58] C. A. Foster, R. J. Colchin, S. L. Milora, K. Kim, and R. J. Turnbull, “Solid hydrogen pellet injection into the Ormak tokamak,” *Nucl. Fusion*, vol. 17, no. 5, pp. 1067–1075, 1977.
- [59] N. Panadero, K. J. McCarthy, E. De Cal, J. H. Sánchez, R. García, and M. Navarro, “Observation of Cryogenic Hydrogen Pellet Ablation with a Fast-frame Camera System in the TJ II Stellarator,” in *ECA Vol. 40A*, 2016, pp. 6–9.
- [60] K. J. McCarthy, “Diagnostic tools for probing hot magnetically confined plasmas,” in *PUBLiCan, ediciones de la Universidad de Cantabria IV*, 2011, pp. 65–67.
- [61] J. Herranz, F. Castejón, I. Pastor, and K. J. McCarthy, “The spectrometer of the high-resolution multiposition Thomson scattering diagnostic for TJ-II,” *Fusion Eng. Des.*, vol. 65, no. 4, pp. 525–536, 2003.
- [62] T. S. Pedersen *et al.*, “Confirmation of the topology of the Wendelstein 7-X magnetic field to better than 1:100,000,” *Nat. Commun.*, vol. 7, p. 13493, 2016.
- [63] T. Klinger *et al.*, “Performance and properties of the first plasmas of Wendelstein 7-X,” *Plasma Phys. Control. Fusion*, vol. 59, no. 1, p. 14018, 2017.
- [64] C. Beidler *et al.*, “Physics and Engineering design for Wendelstein 7-X,” Garching bei München, 1989.
- [65] R. C. Wolf, “A stellarator reactor based on the optimization criteria of Wendelstein 7-X,” *Fusion Eng. Des.*, vol. 83, no. 7–9, pp. 990–996, 2008.
- [66] V. Erckmann *et al.*, “Electron Cyclotron Heating for W7-X: Physics and Technology,” *Fusion Sci. Technol.*, vol. 52, no. 2, pp. 291–312, Aug. 2007.
- [67] P. McNeely *et al.*, “Current status of the neutral beam heating system of W7-X,” *Fusion Eng. Des.*, vol. 88, no. 6–8, pp. 1034–1037, Oct. 2013.
- [68] J. Ongena *et al.*, “The dedicated ICRH system for the stellarator Wendelstein 7-X,” in *AIP Conference Proceedings*, 2014, pp. 105–112.
- [69] T. Sunn Pedersen *et al.*, “Plans for the first plasma operation of Wendelstein 7-X,” *Nucl. Fusion*, vol. 55, no. 12, p. 126001, 2015.
- [70] M. Dibon *et al.*, “Blower Gun pellet injection system for W7-X,” *Fusion Eng. Des.*, vol. 98–99, pp. 1759–1762, 2015.
- [71] N. Panadero, K. J. McCarthy, E. De La Cal, J. Hernández Sánchez, R. García, and M. Navarro, “Observation of cryogenic hydrogen pellet ablation with a fast-frame camera system in the TJ II stellarator,” in *43rd European Physical*

Society Conference on Plasma Physics, EPS 2016, 2016.

- [72] D. Silvagni, “Effect of pellet injection on the radial electric field in the TJ-II stellarator,” 2017.
- [73] M. Landreman, H. M. Smith, A. Mollén, and P. Helander, “Comparison of particle trajectories and collision operators for collisional transport in nonaxisymmetric plasmas,” *Phys. Plasmas*, vol. 21, no. 4, p. 42503, Apr. 2014.

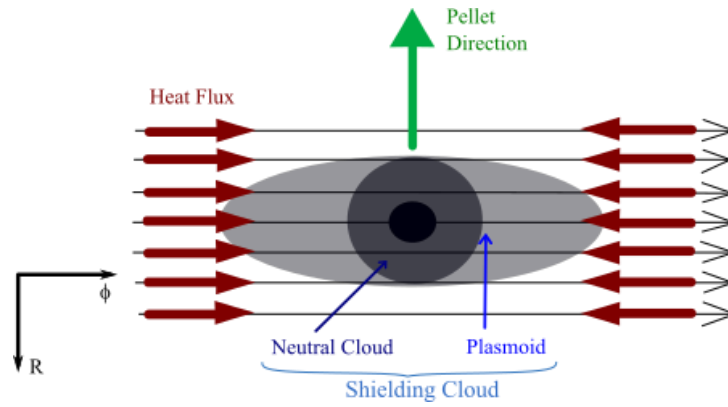


Figure 1. Schematic representation of pellet ablation in a magnetically confined plasma showing the neutral and ionized (plasmoid) regions of the shielding cloud. Also indicated are the incident plasma particles (represented as a heat flux) and the magnetic field lines. Here R is the major radius and ϕ is the toroidal angle.

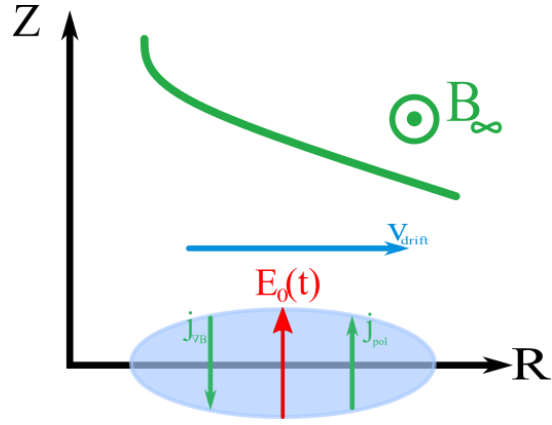


Figure 2. Schematic representation of the $E \times B$ drift towards increasing major radius. The directions of the background magnetic field and induced electric field are represented, together with ∇B - and the polarization currents. Here Z is vertical distance.

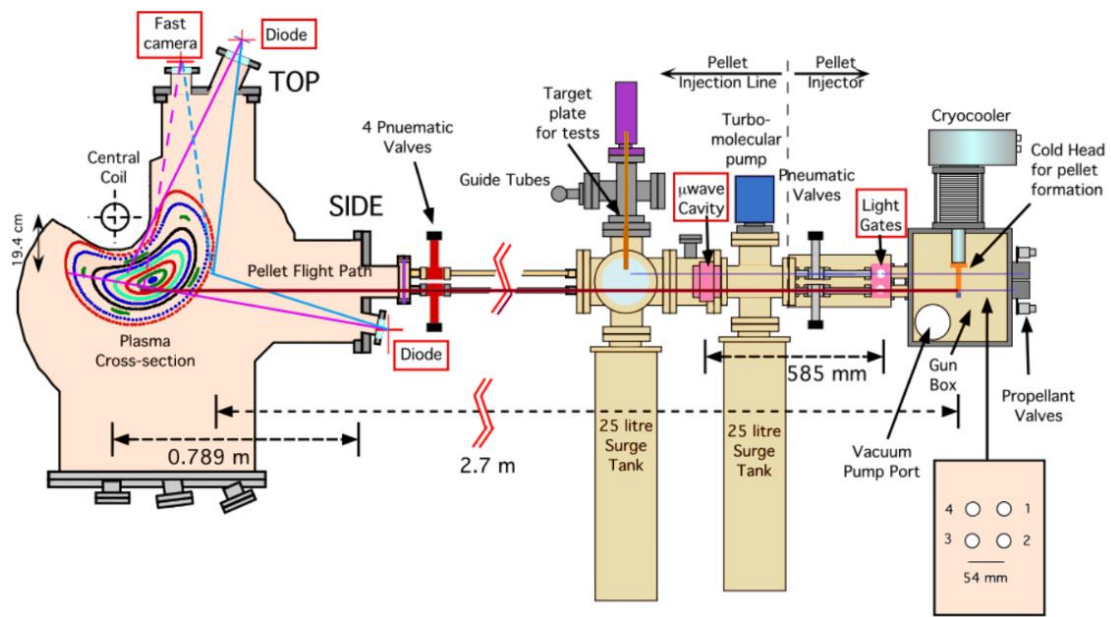


Figure 3. Cross-sectional sketch of the TJ-II vacuum chamber, magnetic surfaces, and the pellet injector. The relative locations of pellet Lines#1 through #4 are indicated with respect to the rear of the PI.

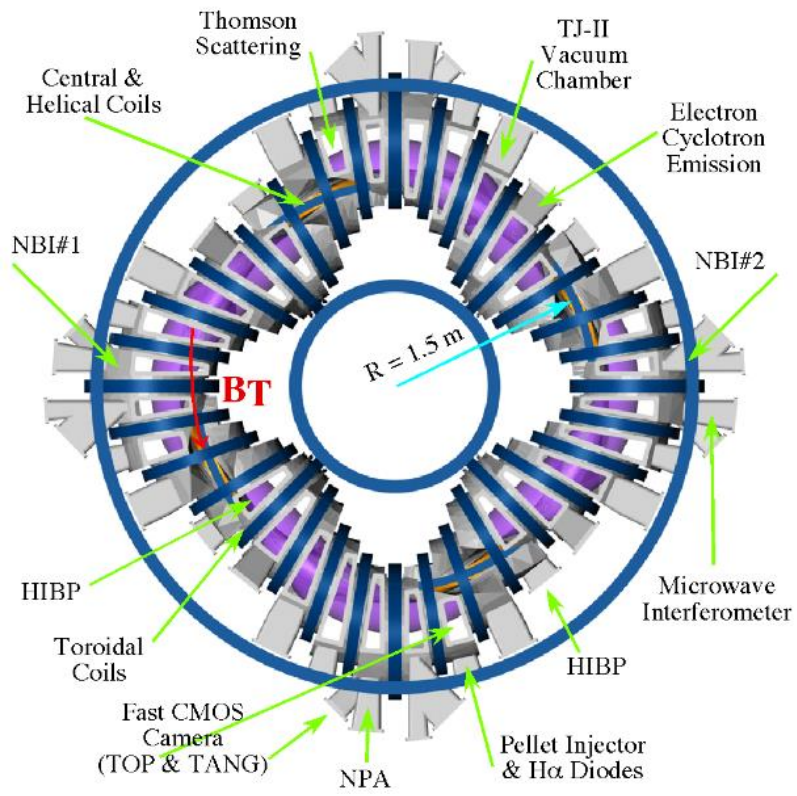


Figure 4. Bird's eye view of the TJ-II. The locations of the PI, associated diagnostic and relevant plasma diagnostics are highlighted.

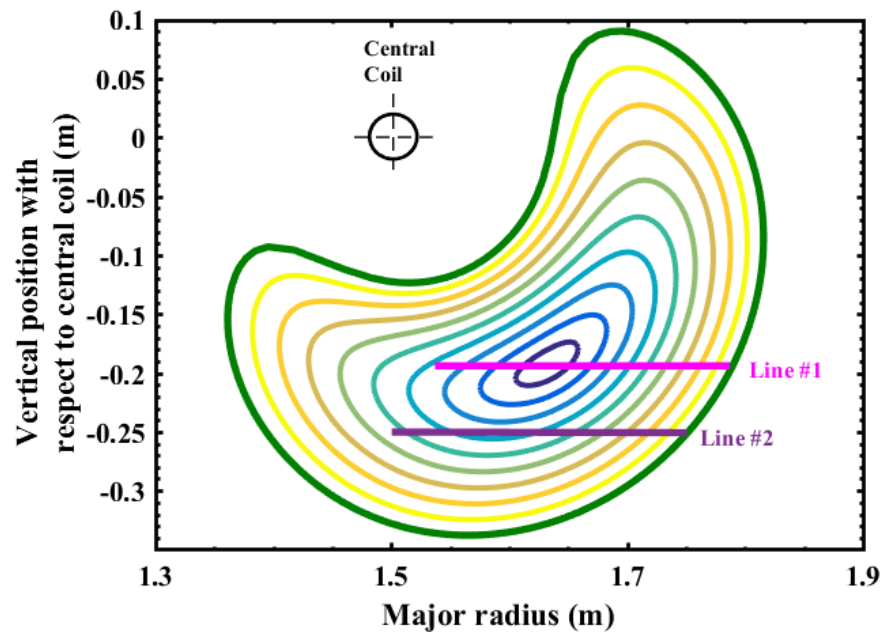


Figure 5. Closed magnetic flux surfaces of the 100_44_64 magnetic configuration for toroidal angle, ϕ , 14° . The flight paths through the plasma for lines #1 and #2 are shown.

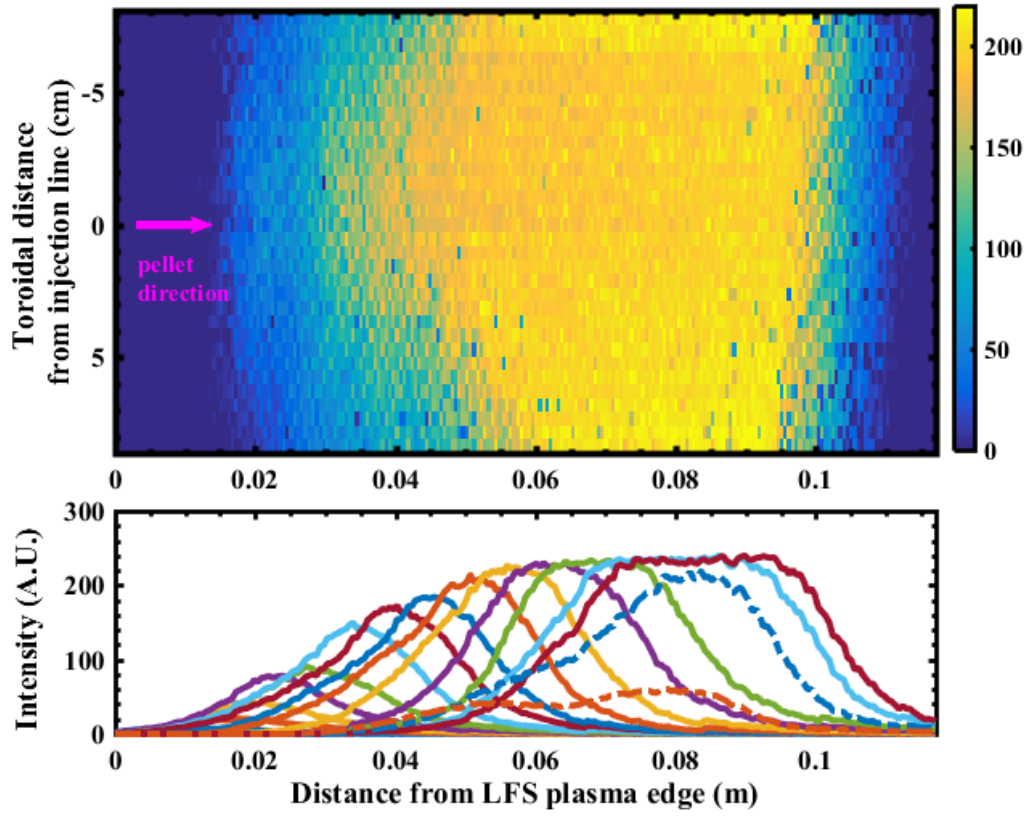


Figure 6. Top) Snap-shot images for discharge #44624 when a pellet with 6.2×10^{18} H atoms was injected along Line#1 at 912.2 ± 18 m/s (frame rate is 150 kfps, exposure time is ~ 4.1 μ s). Bottom) Radial light profiles for collected frames (the dashed profiles correspond to the drifting plasmoid that remains after pellet has been completely ablated).

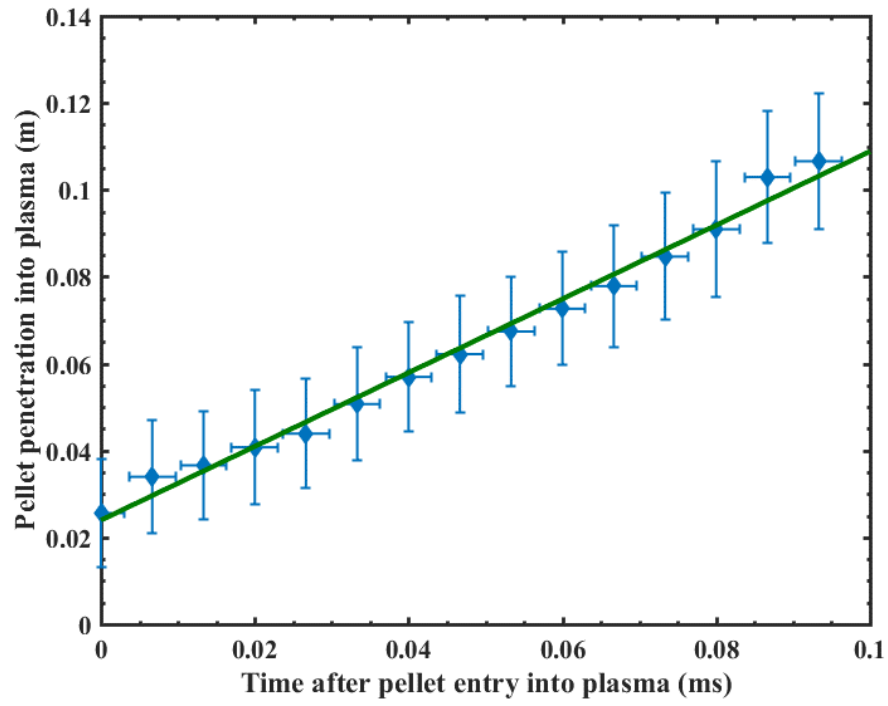


Figure 7. Pellet radial position (obtained from fast-camera images) versus time after pellet entry into discharge #44624. It is assumed that the pellet is located at maximum light intensity. The estimated velocity is 849 ± 20 m/s

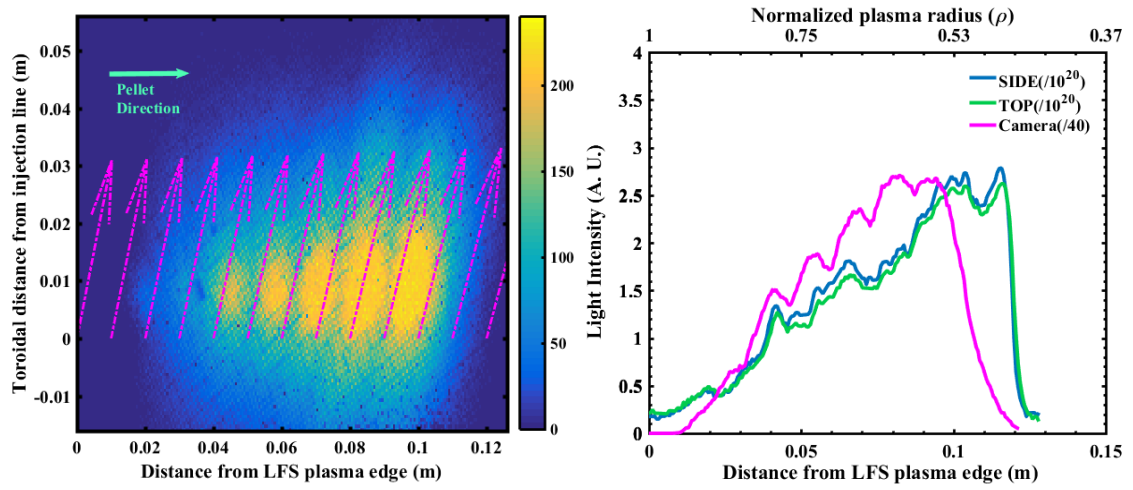


Figure 8. Left) Montage of snap-shot images (frame rate = 52.5 kfps, exposure time $\sim 4.1 \mu\text{s}$) taken from the TOP viewport versus distance into the plasma (the injection and magnetic field directions are indicated) at $\phi = 14^\circ$. Right) H_α emissions detected by the SIDE (blue) and TOP (green) photodiodes, plus the light profile obtained from the fast camera (magenta), versus distance into plasma for a pellet with 1.2×10^{19} H atoms injected into discharge #44828 at 682.22 m/s along Line#1 during the ECRH phase.

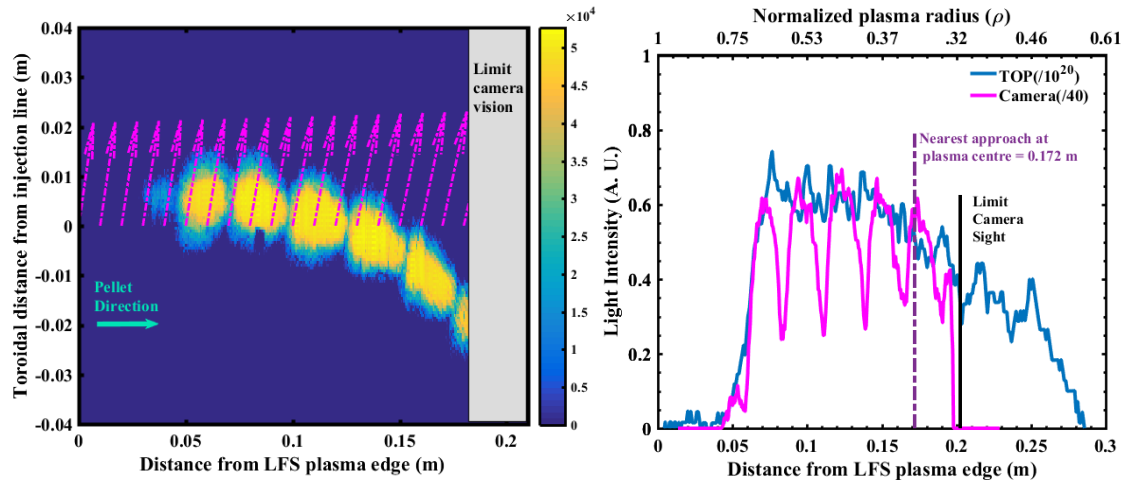


Figure 9. Left) Montage of snap-shot images (frame rate = 37.5 kfps, exposure time $\sim 26.7 \mu\text{s}$) taken from the TOP viewport versus distance into the plasma (the injection and magnetic field directions are indicated) at $\phi = 14^\circ$. Right) H_α emissions detected by the SIDE (blue) and TOP (green) photodiodes, plus the light profile obtained from the fast camera (magenta), versus distance into plasma for a pellet with 6.5×10^{18} H atoms injected into discharge #41391 at 1008.6 m/s along Line#2 during an unbalanced NBI heating phase.

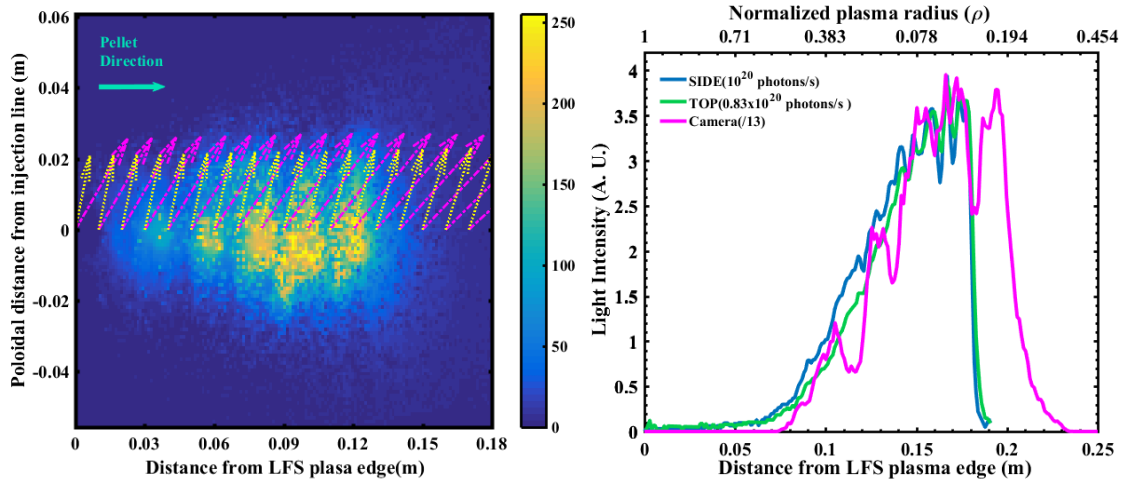


Figure 10. Left) Montage of snap-shot images (frame rate = 63 kfps, exposure time $\sim 2\mu\text{s}$) taken from the Tang viewport versus distance into the plasma (the injection and magnetic field directions are indicated) at $\phi = 14^\circ$. Right) H_α emissions detected by the SIDE (blue) and TOP (green) photodiodes, plus the light profile obtained from the fast camera (magenta), versus distance into plasma for a pellet injected into discharge #45110 along Line#1 during the ECRH heating phase.

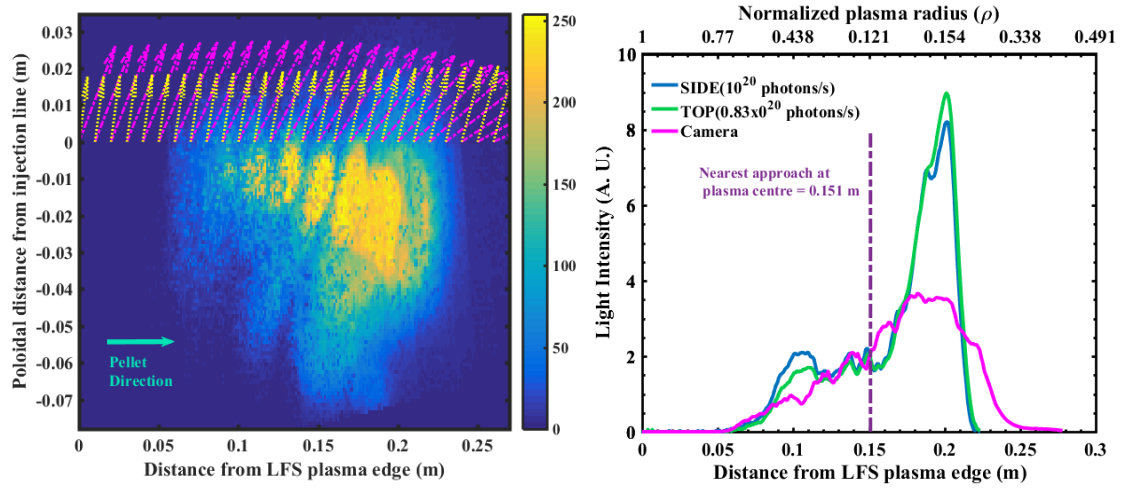


Figure 11. Left) Montage of snap-shot images (frame rate = 63 kfps, exposure time $\sim 2 \mu\text{s}$) taken from the Tang viewport versus distance into the plasma (the injection and magnetic field directions are indicated) at $\phi = 13^\circ$. Right) H_α emissions detected by the SIDE (blue) and TOP (green) photodiodes, plus the light profile obtained from the fast camera (magenta), versus distance into plasma for a pellet with 1.38×10^{19} H atoms injected into discharge #45091 at 1008.6 m/s along Line#4 during an unbalanced NBI#1 heating phase.

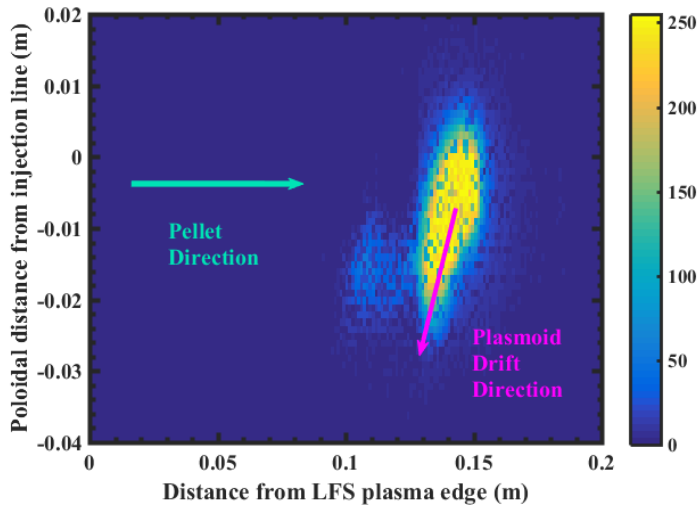


Figure 12. Montage of snap-shot images (frame rate = 63 kfps, exposure time $\sim 2 \mu\text{s}$) taken from the TANG viewport versus distance into the plasma (the injection direction is indicated) at $\phi = 13^\circ$ for a pellet with 1.06×10^{19} H atoms injected into discharge #45110 at 931.5 m/s along Line #4 during an almost balanced NBI heating phase. Plasmoid drift towards the lower LFS of the plasma can be appreciated.

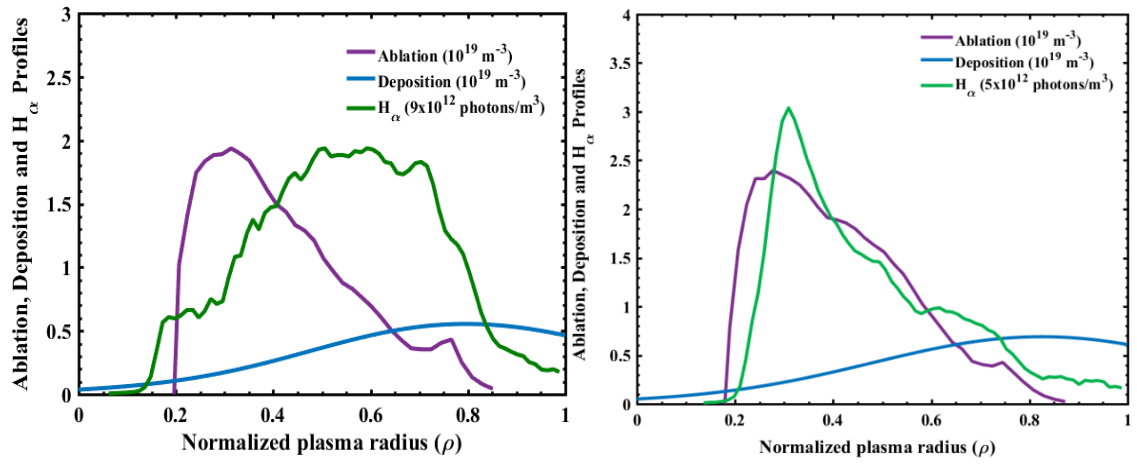


Figure 13. HPI2 simulated ablation (purple) and deposition (blue) profiles compared with measured H_α emission profiles (green) for pellet#2 injected along Line #1 into the ECRH phase of discharges left) #41777 (6.1×10^{18} H atoms, velocity = 804.12 m/s) and right) #44614 (6.6×10^{18} H⁰, velocity = 894.5 m/s).

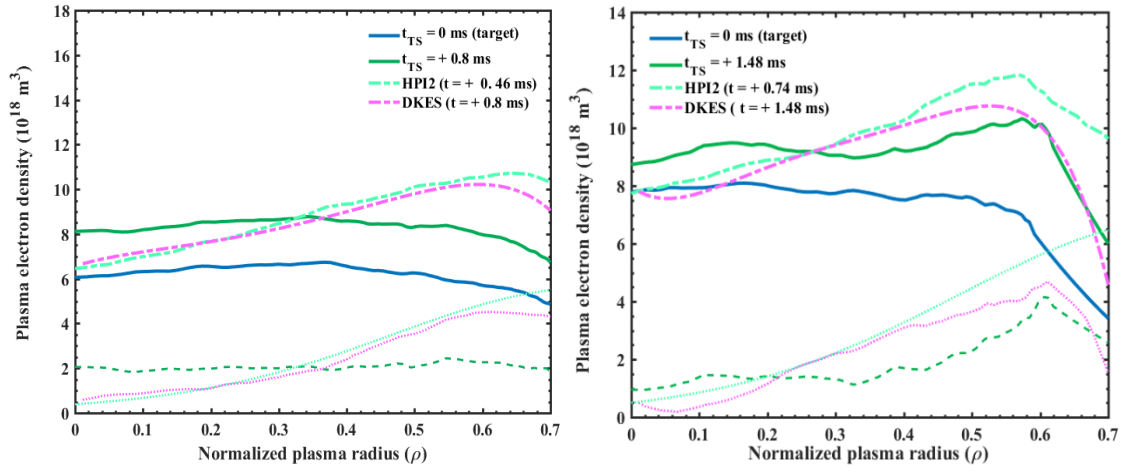


Figure 14. TS electron density profiles measured before (solid blue) and after an injection (solid green) plus density profiles obtained with HPI2 code (dashed/dotted light green) and DKES (dashed/dotted magenta). The corresponding electron density increases are also shown (green dashed lines for TS measurements, magenta dotted lines for simulations). Left) discharge #41777 ($6.1 \times 10^{18} \text{ H}^0$, velocity = 804.12 m/s) and right) discharge #44614 ($6.6 \times 10^{18} \text{ H}^0$, velocity = 894.5 m/s).

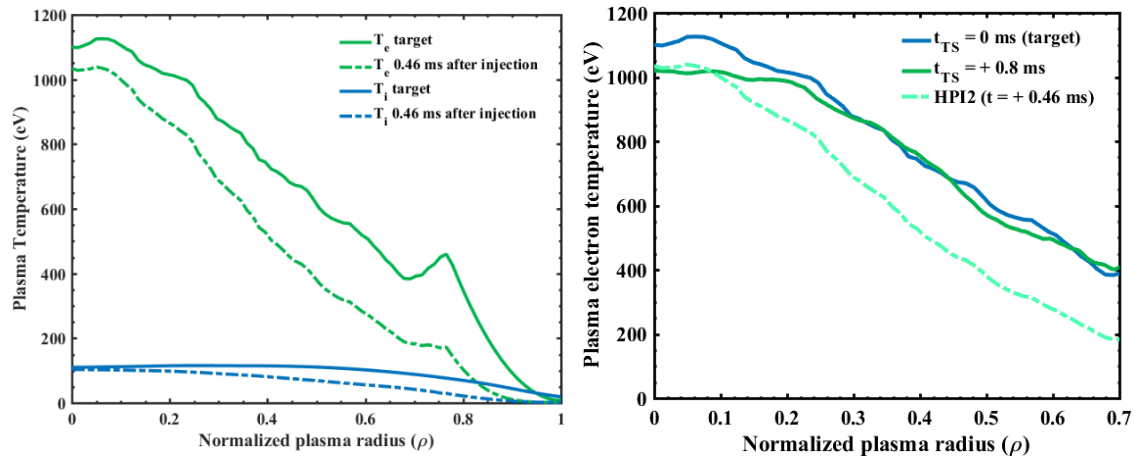


Figure 15. Left) Target plasma electron (blue) and ion (green) temperature profiles before (solid) and after (dash-dotted lines) complete pellet ablation and homogenization for discharge #41777 ($6.1 \times 10^{18} \text{ H}^0$, velocity = 804.12 m/s). Right) Electron temperature profiles of the target plasma (blue) and after pellet injection (green). A HPI2 simulated electron temperature profile (dashed/dotted light green) is also shown.

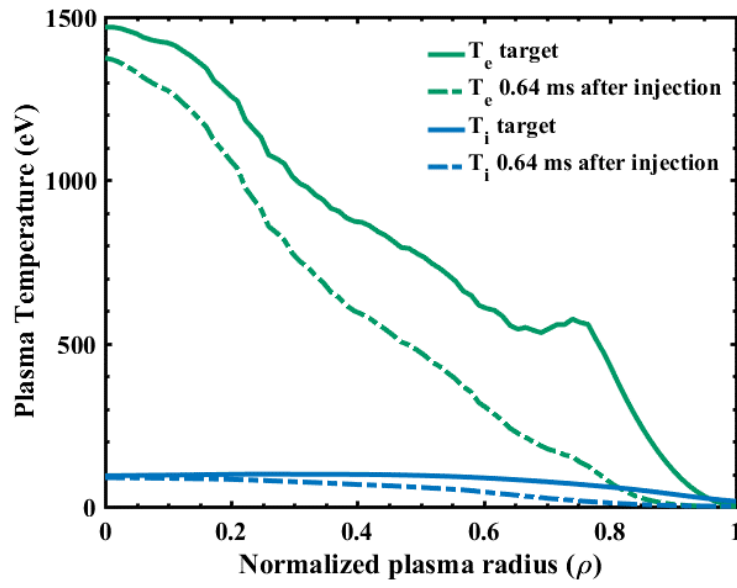


Figure 16. Electron (green) and ion (blue) temperature profiles before (solid lines) and after (dash/dotted) complete pellet ablation and homogenization for discharge #44614 ($6.6 \times 10^{18} \text{ H}^0$, velocity = 894.5 m/s).

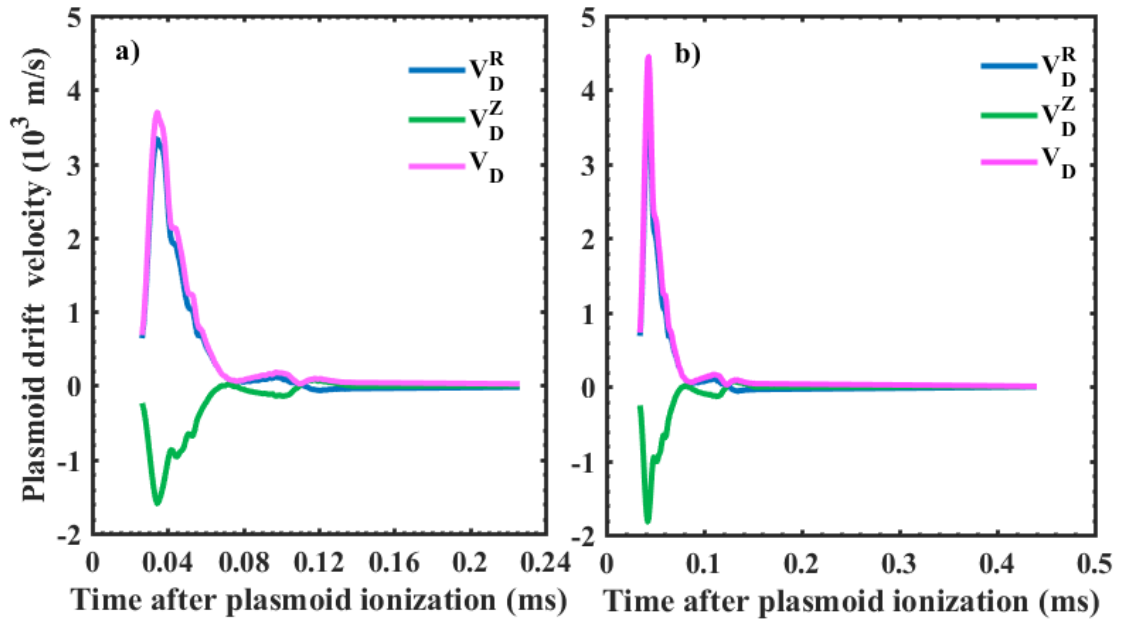


Figure 17. Simulated evolution of the plasmoid drift velocity, during the homogenization phase, in the radial (blue) and poloidal (green) directions plus the total (pink) for plasmoid #10 (originating at $\rho = 0.8$) for discharges a) #41777 and b) #44614.

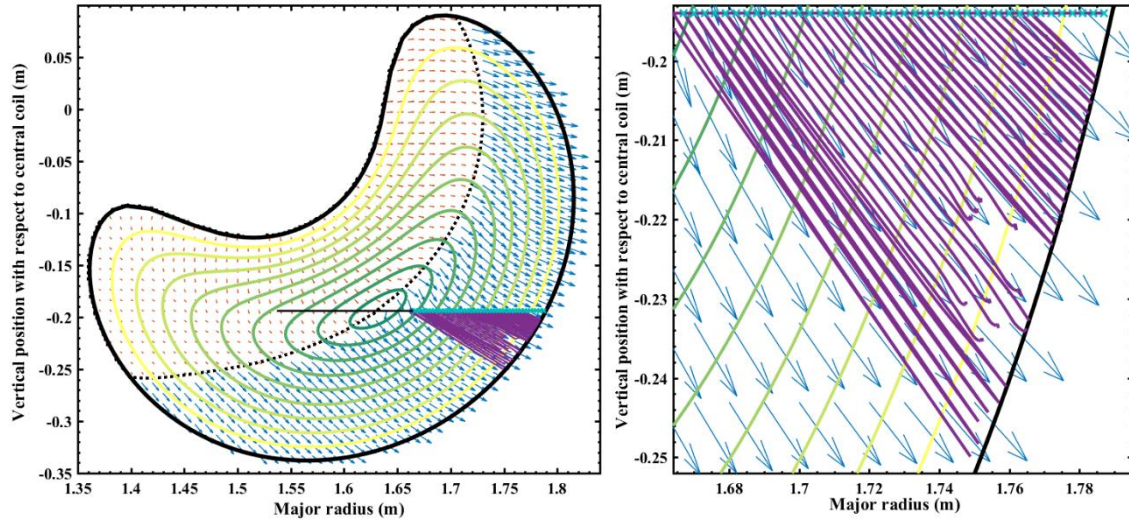


Figure 18. Left) Effective inverse curvature radius vector field for the TJ-II standard configuration, $\phi = 14^\circ$, and plasmoid of dimension parallel to magnetic field lines, Z_0 , of 0.8 m. A dotted black line separates regions of positive (upper left of curve) and negative inverse curvature radius (lower right of curve). Right) Close-up of plasma cross-section showing blue arrows that represent outwards effective drift. The trajectories of all plasmoids for the simulation of #41777 are shown (purple). Arrow lengths are proportional to plasmoid drift acceleration.

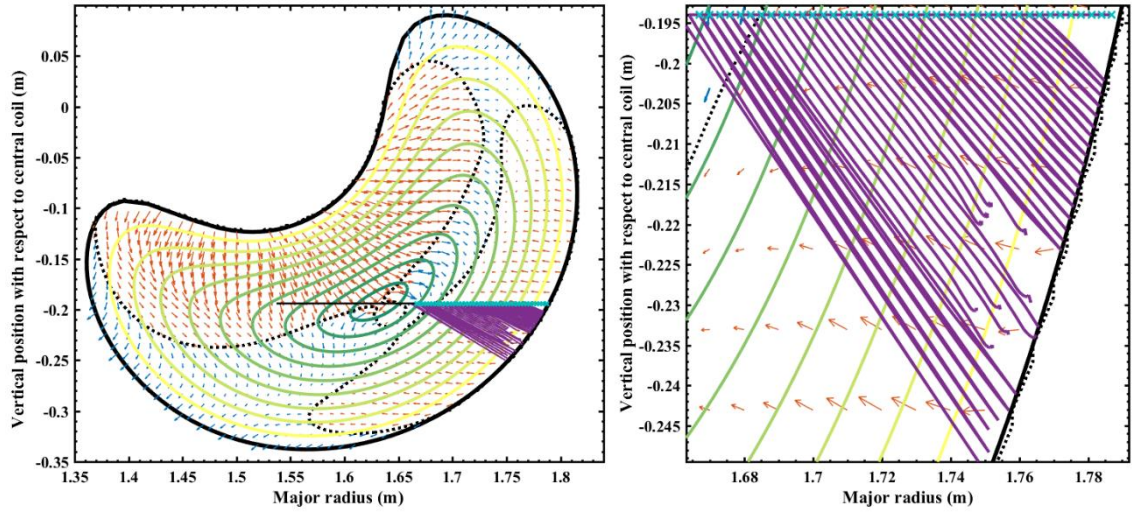


Figure 19. Left) Effective inverse curvature radius vector field for the TJ-II standard configuration, $\phi = 14^\circ$, and plasmoid parallel length $Z_0 = 10$ m (red arrows represent inwards effective drift (negative inverse curvature radius), whereas the blues represent outwards (positive inverse curvature radius). Dotted black lines separate regions of positive and negative inverse curvature radius. Right) Close-up of plasma cross-section showing the trajectories of all plasmoids in the simulation for discharge #41777 (purple). Arrow lengths are proportional to plasmoid drift acceleration.

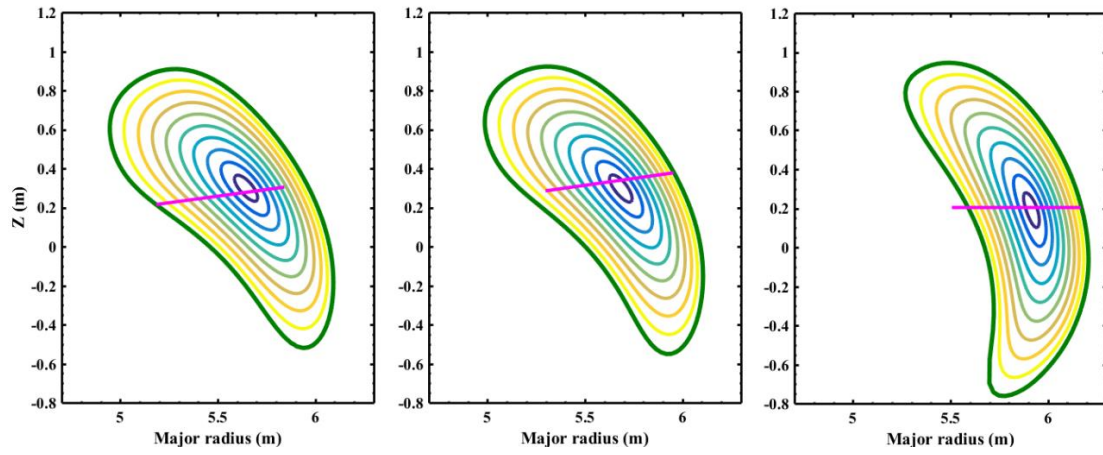


Figure 20. Plasma cross-sections for three W7-X injection ports left) AEL41 ($\phi = -2.22$ rad), middle) AEK41 ($\phi = -2.24$ rad), and right) AEE41 ($\phi = -2.39$ rad). Pellet injection flight paths are shown in magenta (the injection angles are 0.13 rad for AEL41, -3.0 rad for AEK41, and π rad for AEE41).

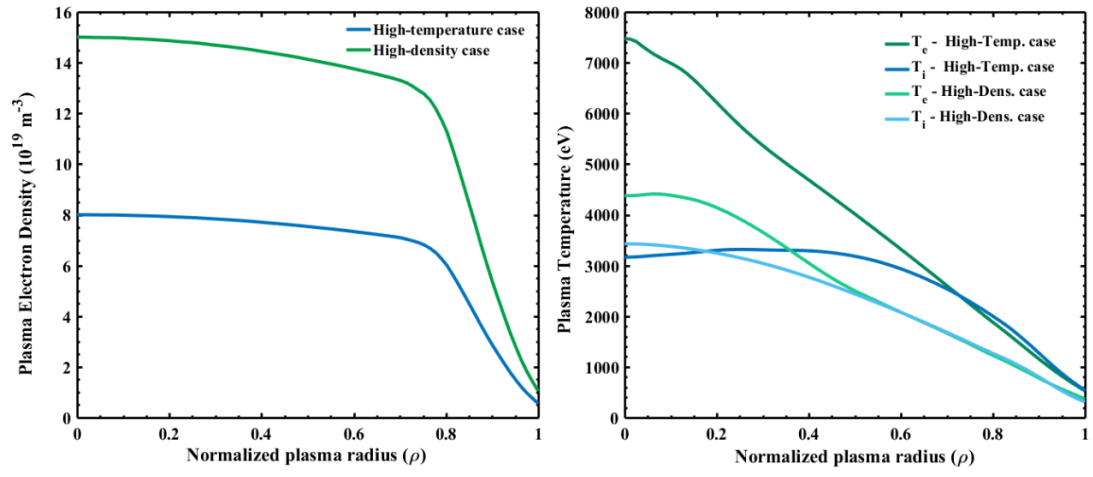


Figure 21. Profiles of left) electron density and right) electron and ion temperature, corresponding to high-temperature (ECRH in X2-Mode) and high-density (ECRH in O2-Mode) scenarios in W7-X.

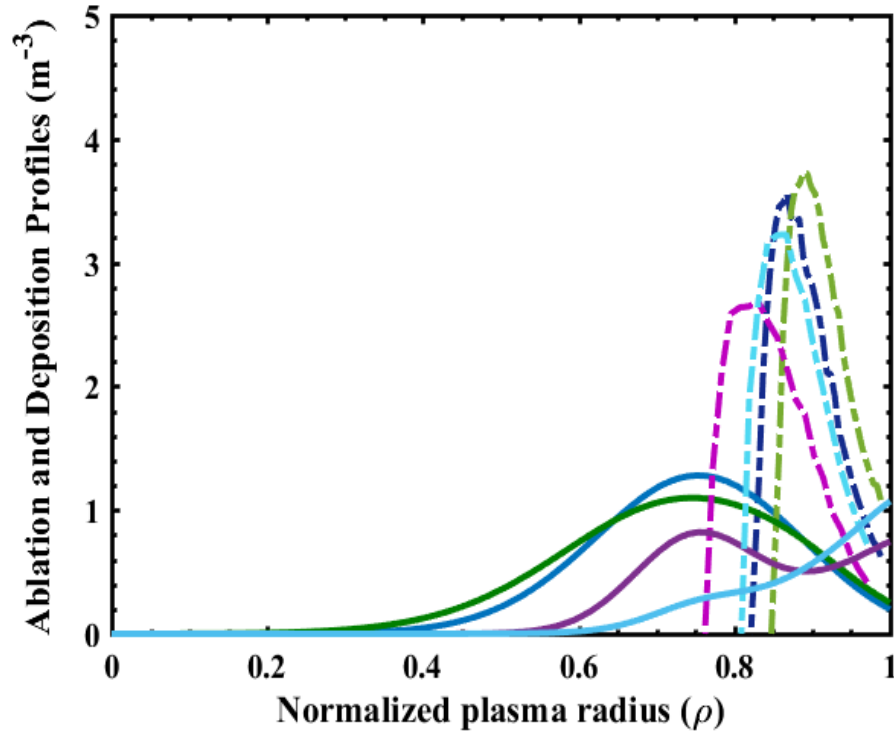


Figure 22. Ablation (dashed/dotted) and deposition (solid) profiles for HFS and LFS injections into high-density, low-temperature, plasmas of W7-X (dark blue is HFS-injection into ECRH-O2 mode heated plasma, dark green is HFS-injection into ECRH-X2 mode, purple is LFS-injection into ECRH-O2 mode, and light blue is LFS-injection into ECRH-X2 mode). In all cases pellet velocity is 250 m/s, pellet content is 1.89×10^{20} H atoms (length = 2 mm, diameter = 1.5 mm).

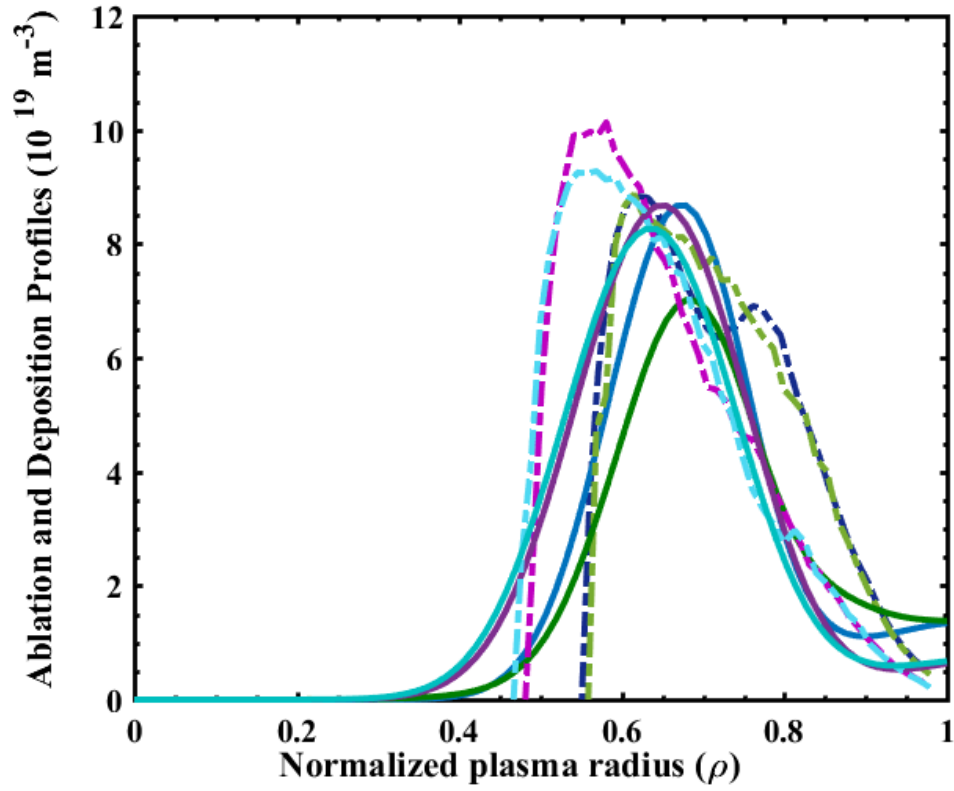


Figure 23. Ablation (dashed/dotted) and deposition (solid) profiles for 3 mm pellet (diameter = 2.8 mm, pellet content = 8.89×10^{20} H atoms) injected at 600 m/s into high-density, low-temperature, W7-X plasmas from the AEK41 and AEE41 ports (dark blue is from AEK41 into ECRH-X2 mode, dark green is from AEE41 into ECRH-X2 mode, purple is injection from AEK41 into ECRH-O2 mode, and light blue is injection from AEE41 into ECRH-O2 mode heated plasmas).

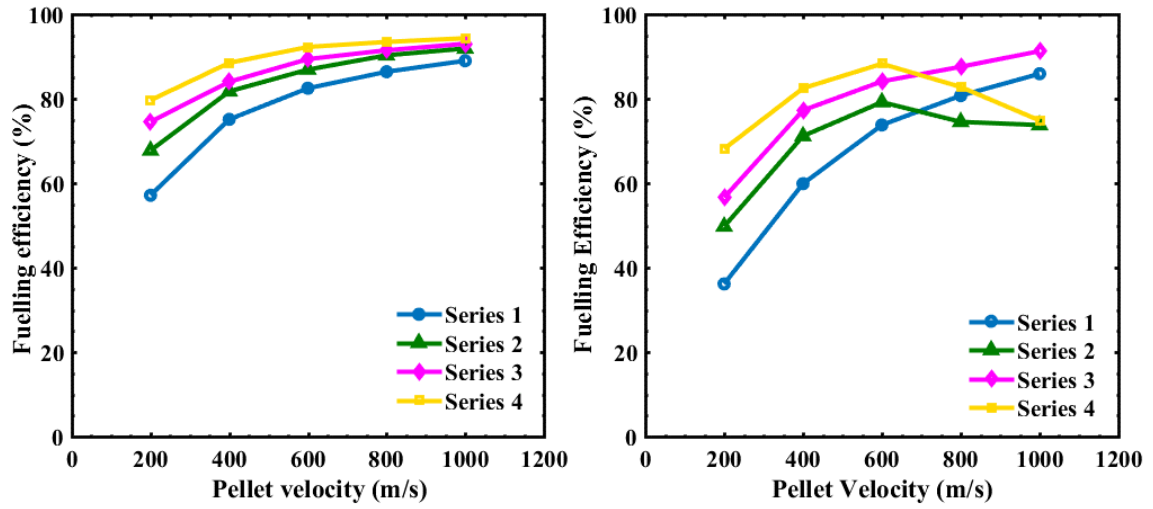


Figure 24. Predicted fuelling efficiencies for injections for series 1 (blue circles- 2.5 mm pellets into X2-mode ECR-heated plasma), series 2 (green triangles- 3 mm pellets into X2-mode ECR-heated plasma), series 3 (pink diamonds- 2.5 mm pellets into O2-mode ECR-heated plasma) and series 4 (yellow squares- 3 mm pellets into O2-mode ECR-heated plasma) from ports left) AEK41 and right) AEE41 for a range of injection velocities (from 200 to 1000 m/s).

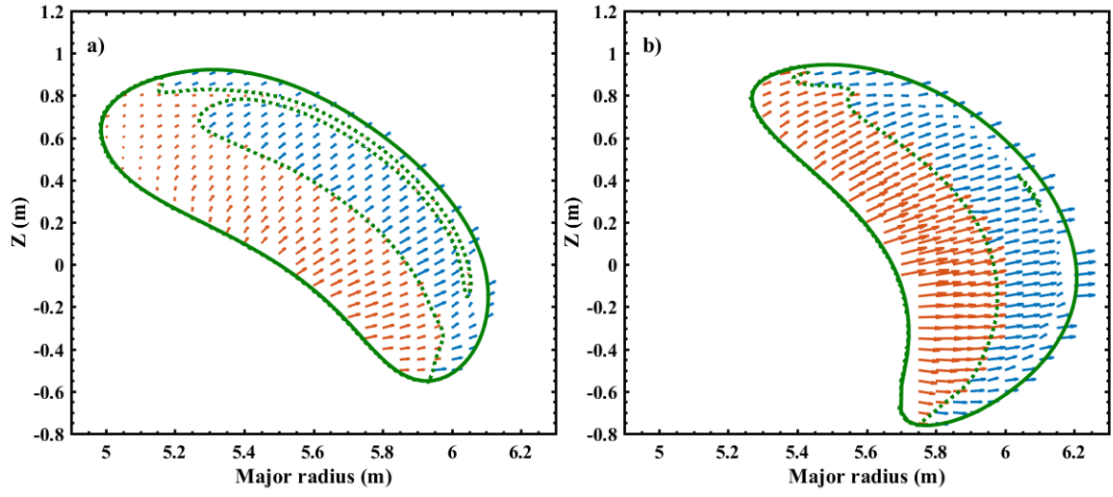


Figure 25. Effective inverse curvature radius vector fields for W7-X injection ports a) AEK41 and b) AEE41 for a plasmoid parallel length of $Z_0 = 0$ m. Red arrows represent inwards effective drift (negative inverse curvature radius), whereas blue arrows represent outwards drift (positive inverse curvature radius); dotted green lines separate regions of positive and negative inverse curvature radius.

Injection port	Heating method	ρ penetration	ρ deposition	$\Delta n_{e, \max}$	ρ of $n_{e, \max}$	Fuelling efficiency (%)
AEL41	ECRH-O2	0.82	0.33	8.7×10^{18}	0.64	98
AEL41	ECRH-X2	0.85	0.24	1.0×10^{19}	0.69	98
AEK41	ECRH-O2	0.77	0.50	1.7×10^{18}	0.72	47
AEK41	ECRH-X2	0.81	0.60	9.9×10^{17}	0.73	43

Table 1. Relevant HPI2 results for the four different scenarios considered for the OP1.2 phase of W7-X.