The injection of cryogenic pellet series in the stellarator TJ-II

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Introduction

Cryogenic pellet injection (PI) is a well-established fuelling tool for most medium- and large-sized magnetically confined plasma devices. PI technologies are mature and systems are earmarked as critical items for future reactors. When a cryogenic pellet enters plasma, it is ablated by background plasma particles (mainly electrons). The ablated material forms a cloud of neutral and partially ionized particles that shield the pellet, thereafter giving rise to a self-regulated process [1]. Databases show that while penetration is dependent on pellet mass and velocity, as well as on plasma electron density, N_e, it is most sensitive to plasma electron temperature, T_e [2]. An issue that has come to the fore with the recent start-up of Wendelstein 7-X, a large superconducting stellarator, is core fuelling of such devices [3]. Neoclassical predictions for such devices highlight the need for a particle source situated in the core with an analogous deposition profile shape, when on-axis electron cyclotron resonance heating (ECRH) is employed, in order to mitigate potential core particle depletion [4]. Here series of pellets, with variable inter-pellet time intervals, are injected into ECRH plasmas of the medium-sized stellarator TJ-II in order to elucidate on whether pre-cooling of plasma outer regions by a small precursor pellet can enhance penetration, and fuelling, for subsequent injected pellets. Previous single pellet studies highlighted a strong fuelling efficiency to penetration depth relationship [2].

Experimental set-up

TJ-II is a 4-period medium-szed heliac-type stellarator with major radius of 1.5 m, a bean-shaped plasma cross-section with average minor radius of ≤0.2 m, and magnetic field B(0) ≤1.1 T [5]. Plasmas, created with hydrogen, are heated using 2 gyrotrons operated at 53.2 GHz, the 2nd harmonic of the electron cyclotron resonance frequency (P_{ECRH} ≤500 kW, t_{ECRH} ≤300 ms), so central electron densities, $N_e(0)$, and temperatures, $T_e(0)$, up to 1.7×10^{19} m^{-3} and 1 keV, are attained, respectively. Particle confinement is ≤10 ms when the line-averaged density, $\tilde{N}_e$, is ≤$6x10^{18}$ m^{-3}

A pipe-gun type cryogenic PI is installed on TJ-II. It consists of a gun box, in which up to 4 hydrogen pellets can be created *in-situ*. It is also equipped with a gas propellant system for pellet acceleration. Closer to TJ-II, its injection lines are equipped with light gates (light emission and detection diodes) and a microwave cavity detector (μwC). They provide timing signals to determine velocity (600 to 1200 m/s) while the μwC produces a mass dependent signal for particle accountability [6]. Note; the high velocities limit injections to the outer plasma side [5]. Finally, the system's flexibility permits pre-programming pellet series (order & number of pellets) so separation times between 2 pellets, Δt_p, can be ≥10 μs. In order to follow pellet ablation, Balmer H_α light (656.28 nm) emitted from the neutral cloud surrounding a pellet is recorded using optical fibre based diagnostic systems installed outside nearby viewports. Other plasma parameters are followed using a range of diagnostics that includes a Thomson Scattering (TS) system, a microwave interferometer and an 11-channel Electron Cyclotron Emission (ECE) system (the former is one set of profiles ($N_e(\rho)$, $T_e(\rho)$) per discharge while the latter have 10 μs resolution).

In this work, series with 2 pellets, containing between ~4 and 7×10^{18} hydrogen atoms, are injected into ECRH plasmas created using standard magnetic configurations, *i.e.*, the 101-38-62 ($1.49 \leq \iota/2\pi \leq 1.59$ in vacuum) or 100-44-64 ($1.56 \leq \iota/2\pi \leq 1.65$) where ι is rotational transform [5]. For these, the flight paths of the first (P1 with $\leq 6 \times 10^{18}$ H atoms) and second (P2 with $\geq 6 \times 10^{18}$ H atoms) pellets have nearest approaches to the plasma centre at ρ = ~0.39 and 0, respectively. This is done to experimentally determine if Δt_p has a significant influence on overall or core fuelling efficiencies. From previous TJ-II studies it is known that fuelling efficiency (ratio between number of pellet particles deposited in the plasma and pellet particle content) is sensitive to penetration depth, typically being ≤25% for ECRH unless there exists a significant population of fast electrons in the plasma core that can results in excess pellet ablation (efficiency increase to ≤40%) [7]. Moreover, low efficiencies are understood from the large radial displacement of the deposited pellet electron profile when compared to the ablation profile. Such an outwards-directed radial displacement of ablated material arises due to a large magnetic cross-field field gradient, ∇B ~-0.9 T/m, which induces a large outward directed *E*xB drift velocity [2] resulting in large losses for shallow penetrations [5]. Simulations using a TJ-II adapted version of the HPI2 code confirm this effect [8]. Thus the possibility of increasing pellet penetration, and hence fuelling efficiency, by injecting a precursor plasma-cooling pellet is evaluated here.

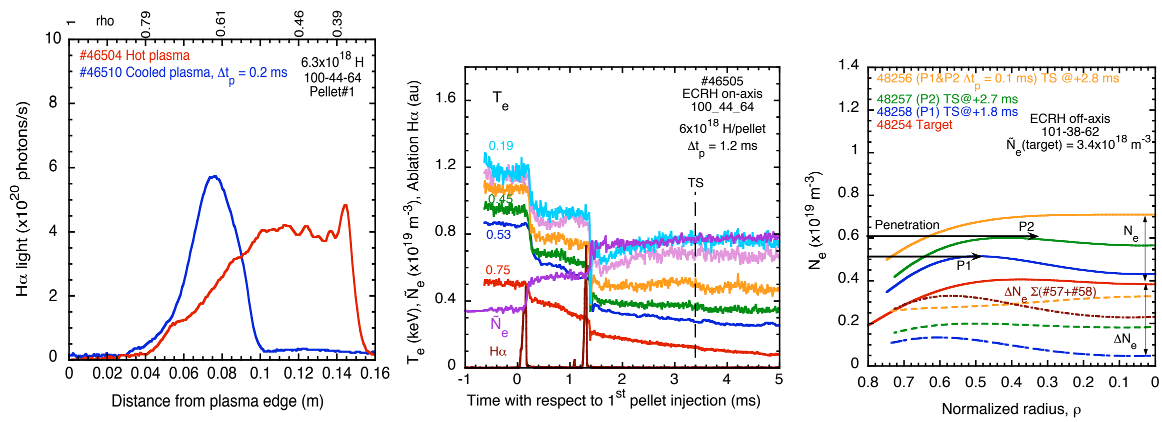

Figure 1: LHS: Hα signals recorded during pellet ablation of type P2 pellets. Red corresponds to a pellet injected into hot plasma and blue into plasma cooled by a precursor pellet with $\Delta t_p = 0.2$ ms. Centre: time evolutions of T_e at several radii before and after the injection of two pellets with $\Delta t_p = 1.2$ ms, of line-averaged electron density and of the Hα ablation signals. RHS: TS density profiles obtained after the injection of single P1 and P2 pellets and after injection of 2 pellets (P1 & P2 with $\Delta t_p = 0.1$ ms) plus before injection. Density increase profiles, ΔN_e, are also shown.

Results

In previous cryogenic pellet experiments in TJ-II, it was demonstrated that single pellet ablation has a $N_e^{0.45}\, r_p^{1.44}\, T_e^{1.72}$ dependency [2]. Moreover, ablation H_α signal profiles exhibited striations while an abrupt (≤50 μs) post-injection rise in $\tilde{N}_e$ was typically observed. However, post-injection TS density profile evolution to maximum N_e values was only achieved several milliseconds later, this delay being attributed to transport effects [5]. In parallel, a rapid drop in T_e was observed in the plasma core (within ~0.2 ms), also inside the penetration radius, while a slower T_e decay occurs for edge regions (during ~5 ms). It is considered that the rapid drop in core T_e is not a heat transport effect since the timescale of the effect is very short while the latter is attributed to the lower ablation at outer radii and to the slow pellet particle redistribution.

In discharges in which 2 pellets reach the plasma edge almost simultaneously, *i.e.*, Δt_p ~0.1ms, the overlapping ablation profiles show similar structures and penetration depths to their corresponding individual profiles. See Fig. 1. However, when the corresponding TS density profiles are compared it is seen that there is a minor, but not insignificant, increase in core density when compared to the combined density increase for two individual pellets. In contrast, when 2 pellets reach the plasma edge with ~0.1 ms ≤Δt_p ≤~1 ms, the H_α light profile of the 2nd pellet is significantly modified, *i.e.* striations are not apparent, it becomes peaked and is shifted towards outer radii, *i.e.*, the 2nd pellet penetration depth reduces. Also, although core fuelling is slightly higher there is little improvement in overall fuelling efficiency. See Fig. 2. Next, for inter pellet arrival times longer than about ~1.5 ms, pellet penetrations are as for a hot plasma, striations reappear in the H_α light profiles though the overall fuelling efficiency increases slightly with electron density peaking at ρ = ~0.5. See Fig. 2.

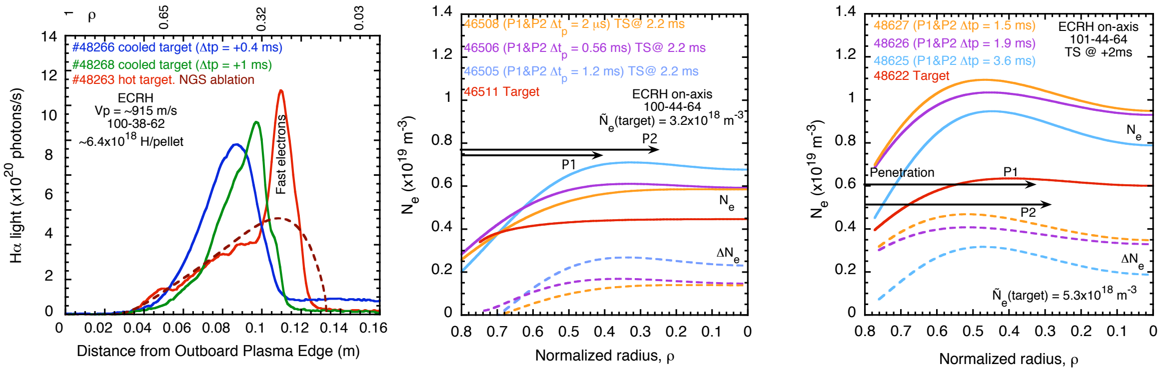

Figure 2: LHS: Hα signals recorded during pellet ablation of type P2 pellets. Red corresponds to a pellet injected into hot plasma, blue and green into plasma cooled by a precursor pellet with Δt_p = 0.4 and 1 ms, respectively, while the dashed curved is a NGS model of ablation. Centre: TS density profiles obtained before injection and after the injection of 2 pellets (P1 & P2 with Δt_p = 2 µs, 0.56 ms & 1.2 ms). RHS: TS density profiles obtained before injection and after the injection of 2 pellets (P1 & P2 with Δt_p = 1.5, 1.9 & 3.6 ms). Density increase profiles, ΔN_e, are also shown for both.

Discussion

The experiments reported here were performed to determine if pellet penetration could be deepened in the stellarator TJ-II by injecting a precursor pellet that would cool the plasma sufficiently so as to significantly increase the penetration depth of a second larger fuelling pellet that is injected within a very short time window, *i.e.*, within the particle confinement time in TJ-II for ECRH plasmas, ~5 ms. From the analysis performed it would appear that the benefit of a precursor pellet is minimal, although in cases when $\Delta t_p \leq$~0.1 ms there is a not insignificant increased core fuelling, although this is still smaller that the benefit to fuelling of a fast core electron pellet population. Nonetheless some interesting features are observed such as the influence on the ablation profile and the elimination of striations. This work forms part of on-going research in TJ-II on pellets.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. It is also partially financed by the Spanish Ministerio de Ciencia, Innovación y Universidades (FIS2017-89326-F).

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