Modelling of shattered pellet ablation: a discussion

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1. Introduction

The electron density (n_e) required to unconditionally suppress the runaway electrons (REs), generated during the disruption of a reactor-relevant tokamak plasma, is 2-3 orders of magnitude larger than the n_e of the target plasma. An estimate for a worst case ITER plasma disruption at full current and magnetic field can be found in [1]. The density needed to reduce the RE seed and the final RE current to an acceptable level (e.g. < 1 MA) is smaller, i.e. O(10 - 100)$\times n_e$, and it was calculated by R. Martin-Solis for ITER [2] and for DEMO plasmas [3]. Shattered pellet injectors [4] are being considered for disruption mitigation and particularly for RE suppression in ITER; it is also being debated, whether they can fulfill this purpose or not.

In modelling the RE generation, the density increase can be imposed with a Heaviside function. Nevertheless, in the reality, the matter must be injected into the plasma in the form of pellets from the edge and must cross the plasma to reach its center. The spatial distribution of the material deposited in the plasma is determined by mostly-known physics mechanisms and it depends on pellet and plasma parameters. Since the deposited matter cools the plasma, induces the fast growth of tearing modes and causes the thermal quench, it must be delivered in the plasma within the so called pre-thermal quench time interval, which lasts a few milliseconds. The pellet velocity depends on the type of injector, it is limited and it ranges from a few 100s m/s to a few km/s.

This contribution presents a discussion of what is required, in terms of number of frozen deuterium pellet, of pellet radius and pellet velocity, to increase the plasma density of a factor of (let's say) 20 within a few milliseconds over the whole plasma cross section of a DEMO-like plasma [5]. The Neutral Gas Shielding (NGS) ablation model [6] is used in the following section for parametric studies of the ablation of deuterium pellets. A simple model for the density increase following multiple pellet injection is discussed in section 3. More detailed simulations of the ablation of one single deuterium pellet have been carried out with the HPI2 code [7] and are briefly discussed in section 4.

2. Parametric study of matter deposition with the NGS model

Although it is oversimplified, the NGS model predicts the parametric dependence of the ablation rate of pellets in existing devices over a wide range of plasma and pellet parameters. Different additional ablation mechanisms, not included in the model, have been found to cancel out [8]. According to the model, the ablation rate of a spherical pellet is described by

$$\frac{dN_p}{dt} = C_* \, n_e^{1/3} \, r_p^{4/3} \, T_e^{5/3}, \qquad C_* = 4.12 \times 10^{16} \qquad [9] \qquad (1)$$

$$N_p = \frac{4}{3}\pi\eta_p r_p^3, \qquad \frac{dN_p}{dt} = 4\pi\eta_p r_p^2 \frac{dr_p}{dt} \qquad (2)$$

or equivalently by

$$\frac{dr_p}{dt} = C\, n_e^{1/3}\, r_p^{-2/3}\, T_e^{5/3}, \quad C = \frac{C_*}{4\pi\eta_p}, \quad r_p(r) = \left(r_p(a)^{5/3} - \frac{5}{3}\frac{C}{v_p}\int_a^r n_e^{1/3}\, T_e^{5/3} dr \right)^{3/5} \tag{3}$$

$$\Delta n_e(r) \equiv \frac{\Delta N_p(r)}{\Delta V_{ol}} = \frac{dN_p(r)}{\cancel{dr}}\frac{\cancel{dr}}{dt}\frac{1}{4\pi^2 r R_0 k v_p} \tag{4}$$

N_p in the number of deuterium atoms in the pellet of radius r_p; η_p is the pellet number density (6×10^{28} atoms/m^3 for frozen deuterium); v_p is the pellet velocity; T_e is the background temperature (expressed in eV throughout the paper) at the radial position r; a and R_0 are the minor and major radius respectively; k is the plasma elongation; Δn_e is the increase of the density on the flux surface.

Fig. 1 shows the density increase achieved by injecting a large D_2 pellets ($r_p = 2.1$ cm and $N_p = 2.3 \times 10^{24}$ atoms) into a burning DEMO plasma ($n_e(0) = 10^{20}$ m^{-3}, $T_e(0) = 40$ keV). The pellet velocity was scanned from 500 m/s up to 10 km/s, velocity at which the pellet reaches $\rho = r/a \sim 0.2$. Therefore, according to the NGS model, one single deuterium pellet, able to increase the electron density by a factor of circa 20, must be launched at a velocity higher than 10 km/s in order to reach the plasma center. This upper velocity is extremely large if compared to the velocity of the present cryogenic pellets (300-1200 m/s) or e.g. to the muzzle velocity of selected pistols and rifle guns (<1400 m/s [10]), and it is probably not realizable. Increasing only r_p at a realistic velocity, e.g. 1200 m/s, does not foster the deposition of the ablated material beyond $\rho \sim 0.5$ (calculation not shown). These results suggest to investigate the injection of multiple pellets.

During the current quench of a disruption, the electric field is maximum in the plasma core, where the toroidal current is the largest. Therefore, the density increase (and the material deposition) required to suppress the REs, must take place in the plasma center. The pellet penetrates up to the plasma center when the following condition is satisfied

$$r_p(0) = 0 \rightarrow r_p(a) = T_e(0) \left(\frac{5}{3}\frac{C}{v_p}\int_a^0 n_e^{1/3} \left(\frac{T_e}{T_e(0)}\right)^{5/3} dr \right)^{3/5} \propto T_e(0) \tag{5}$$

(from eq. 3). Let's assume that the T_e of the target plasma can vary in the range 1 - 40 keV and that the pellets do not interact with each other while ablating. It follows that a disruption mitigation system, built to inject simultaneously a number $N_{pellets}$ of pellets, must be designed to vary this number within a factor of 6.4×10^4 according to the target T_e. In fact

$$N_{pellets} = N_{needed}/N_p \propto T_e(0)^{-3}, \qquad [(max\, T_e(0))^{-3}, (min\, T_e(0))^{-3}] \propto [1, 64000] \tag{6}$$

Eq.s 5 and 6 are strong conditions aimed to optimize the use of the injected gas (i.e. N_{needed}) and minimize the gas inventory in the torus and pumping/exhaust system. The assumption, that many pellets can ablate simultaneously, is not realistic and the ablation of a packet of pellets is considered in the following.

3. Multiple pellet injection

A realistic injection scheme will not be simultaneous or sequential but a combination of the two. Let's assume that a number $\mathcal{N}_p$ of pellets are launched as a rectangular packet of dimension $D \times D \times L$, and that the ablation of the single pellet is not influenced by the presence of the other pellets. Then, the rate of density rise on the flux surface becomes

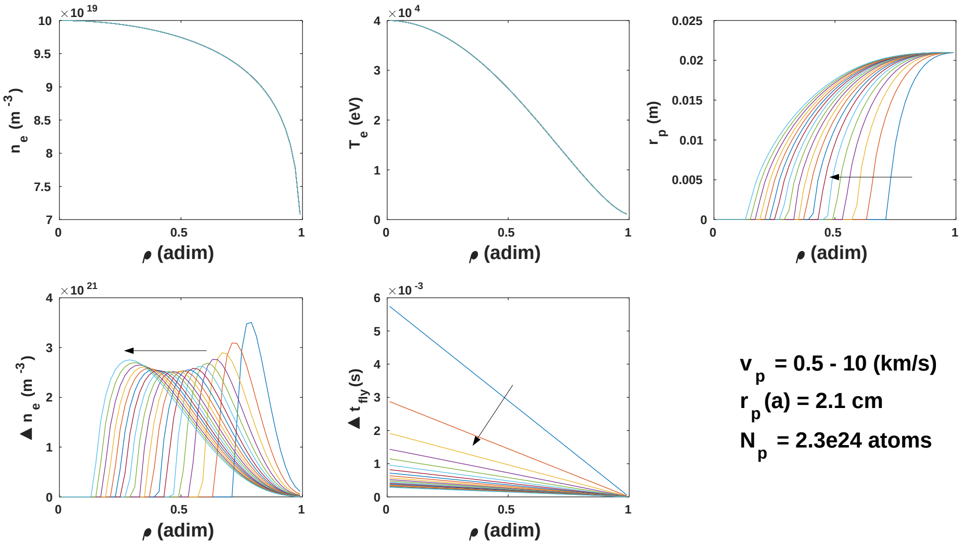

Figure 1: *Radial profiles ($\rho = r/a$) of the density increase (Δn_e), of the pellet radius (r_p) and the penetration time (Δt_{fly}) for pellets of different velocities (v_p).*

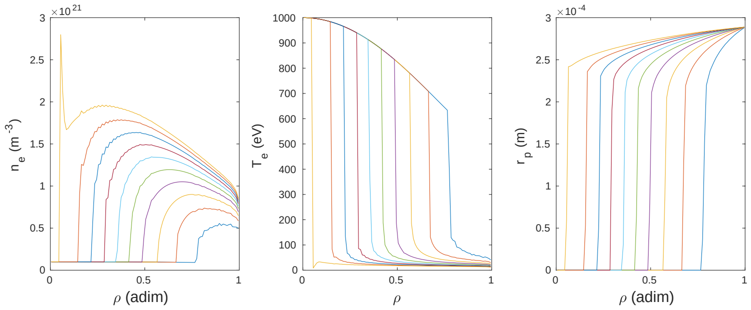

Figure 2: *Time evolution of the density (n_e), of the temperature (T_e) and of the pellet radius (r_p) following the injection of $N_p = 8.4 \times 10^5$ ($r_p = 0.29$ mm) pellets.*

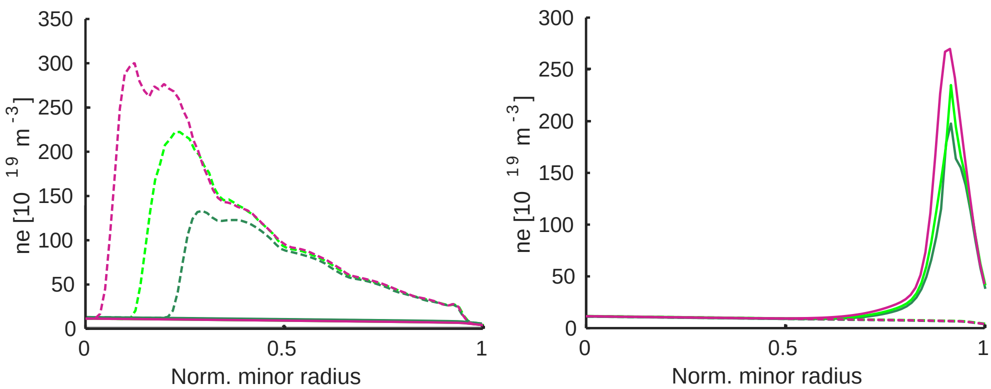

Figure 3: *Three cases of final density (n_e) calculated by the HPI2 code after the ablation and assimilation of one massive deuterium pellet in a DEMO-like plasma ($N_p = 1.0, 1.3, 1.5 \times 10^{24}$ deuterium atoms) without (left) and with (right) plasmoid drift.*

$$\frac{\partial n_e}{\partial t} = \frac{dN_p}{dt}\frac{n_p D^2 \Delta r}{4\pi^2 r R_0 k \Delta r} = \frac{dN_p}{dt}\frac{\mathcal{N}_p}{4\pi^2 r R_0 k L}, \qquad n_p = \frac{\mathcal{N}_p}{D^2 L} \tag{7}$$

The temperature on the flux surface can be recalculated assuming instantaneous matter redistribution and thermal equilibration of the electrons: $n_e(r,t)T_e(r,t) \simeq n_e(r,0)T_e(r,0)$. Calculations of Δn_e following the injection of multiple pellets were carried out for different $T_e(0)$. Fig. 2 illustrate the case with $T_e(0) = 1$ keV: a packet of $\mathcal{N}_p = 8.4 \times 10^5$ pellets with $v_p = 1200$ m/s and $r_p = 0.29$ mm could increase the core n_e of a factor of circa 20. The same total density increase and pellet penetration up to $\rho = 0.05$ (final $n_e(r)$ more peaked toward the center in this case; not shown) is obtained with $\mathcal{N}_p = 837$ ($r_p = 2.9$ mm) pellets into a plasma with $T_e(0) = 10$ keV. These calculations confirm the scaling $r_p(a) \propto T_e(0)$.

4. Modelling massive pellet ablation with HPI2

The HPI2 pellet code was used to simulate the ablation of single massive deuterium pellets in DEMO-like plasmas. Fig. 3 shows the time traces of the evolution of the density profile for three different pellets with $N_p = 1.0, 1.3, 1.5 \times 10^{24}$, $v_p = 1200$ km/s, into the DEMO-like plasma of fig. 1 and 2 ($T_e(0) = 40$ keV) without (left) and with (right) drift. If the calculation of the plasmoid drift is suppressed, the largest pellet generates a $\Delta n_e(0) \sim 27 \times 10^{20}$ close to the plasma center. Nevertheless, the strong outward drift, due to the high temperature of the target plasma, prevents the penetration of the ablated material. The NGS model predicts a penetration of the largest pellet up to $\rho = 0.65$. Therefore, this benchmark shows that the NGS model is not adequate enough for the calculation of the density increase in a DEMO-like plasma.

5. Discussion and outlook

The ablation of cryogenic deuterium pellets and the deposition of matter in a plasma is determined by pellet (material, radius, velocity and number) and plasma (dimension, electron density and temperature) parameters. Most of these parameters are either fixed or constrained. For a given device, the plasma dimension, the density, the plasma current - and therefore the density increase required for RE suppression - are fixed. The maximum pellet velocity is limited by the injector technology and the minimum by the pre-thermal quench duration; reasonable velocities for reactor relevant plasmas are in the range 1-1.5 km/s since they translate into a pellet transit time from edge to plasma center - of 2-3 ms. Essentially, only the pellet radius, and consequently the number of pellets, can and must be varied to obtain the required density increase. The NGS model indicates a strong dependence of the ablation rate on the plasma temperature. Since the temperature of the target plasma - to be shut-down by the disruption mitigation system - can vary considerably (e.g. by a factor of 40 in DEMO, and $r_p(a)$ must vary proportionally, see eq. 6), the injection system must be extremely (unrealistically?) flexible.

Future work will address the validity of the NGS model (by benchmarking it with the HPI2 code and against experiments), the validity of the non-interacting multiple pellet injection model and the presence of impurities in the plasma or/and in the pellets.

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