From injection to deposition - capturing the drift of ablated pellet material in a tokamak

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Pellet injection is an important means to fuel and control discharges and mitigate disruptions in reactor-scale fusion devices. The disruption mitigation system in ITER is based on Shattered Pellet Injections (SPI), where pellets consisting of a mixture of hydrogen (H) and neon (Ne) will be shattered against a bend at the end of the guide tube before entering the plasma [1]. Shattering the pellet enables optimising the assimilation efficiency in order to quickly reach the densities required. This is important as the density increase must be sufficient to safely dissipate the thermal and magnetic energy content of the plasma uniformly through radiation, and increase the frictional drag enough to reduce runaway electron (RE) formation.

To assess the efficacy of these applications, prediction of the drift deposition of ablated pellet material is a key ingredient. While complex modeling tools exist to this end, there is a need for reduced, but still sufficiently accurate models that can be implemented in numerical frameworks. Here we present a derivation of an equation governing the drift motion of ablation clouds, from first principles, in combination with an approximate model for the cloud expansion parallel to the magnetic field. This model has been implemented in the numerical disruption modelling tool DREAM [2], which we use to compare the simulated density evolution with experiments at the ASDEX Upgrade tokamak. Finally, we investigate the prospects for disruption mitigation by SPI in ITER.

Plasmoid drift model The ablation cloud drift is modelled as derived by Vallhagen *et al* [3]. This model considers the ablated material to take the form of a continuous flowing cloud, which is homogeneous in the poloidal and toroidal directions. The flow velocity is found by solving the MHD force balance equation for the current density and integrating its divergence over a slab of the upper half of this cloud (symmetric to the lower half), assuming a large aspect ratio. The poloidal electric field, and hence the drift velocity, is then set by the balance of the ∇B-drift giving rise to the charge separation, the opposing polarisation current, and the current exiting the cloud parallell to the magnetic field lines. The effective resistivity for this parallel current is dominated by ohmic currents flowing along field lines connecting the toroidally opposite sides of the cloud [4]. This resistivity is calculated using a statistical model for the number of turns a field line circles around the torus before it reconnects to the cloud, as detailed in [3].

The obtained current balance equation is solved for the radial drift displacement Δr assuming a simplified parallel expansion model, with a constant temperature T_0 for the cloud in the close vicinity of the pellet, a constant representative temperature T during the drift motion, average charge $\langle Z \rangle$ of the involved species, cloud half-thickness Δy (equal to the radius of the initial spread of the material around the pellet), and line integrated density $\bar{n}$. In this study, we set $T_0 = 2\,\mathrm{eV}$, $T = 30\,\mathrm{eV}$ for pure D2 pellets and $T = 5\,\mathrm{eV}$ for Ne+D2 pellets. At such temperatures, $\langle Z_D \rangle = 1$ and $\langle Z_{Ne} \rangle \approx 2$. These values are similar to those found in simulations in ITER-like conditions [5], and also to those measured for AUG fueling pellets [6]. The results show a rather large sensitivity to Δy, which we therefore tune to optimise the match with the experiment. The values used here however agrees well with the estimate that $\Delta y \sim 1\,\mathrm{cm}$ from simulations and measurements [5, 6]. The line integrated density is calculated by assuming that the pellet ablation, given by the NGS model [7], adds material to the cloud during the time it takes for it to drift a distance Δy. With these considerations, it is possible to find an analytical expression for Δr given by equation (A4) in [3].

SPI simulations of AUG experiments The drift displacement model has been coupled to the SPI model in DREAM [8], by shifting the ablated material radially by a distance Δr behind the shards. For the AUG case presented here, the characteristic shard size was calculated using the model by Gebhart *et al* [9]. The mean shard speed $\langle v_\mathrm{s} \rangle$ after shattering is assumed to be given by the average of the initial speed and its component parallel to the bent part of the shatter tube, $\langle v_\mathrm{s} \rangle = v_0(1+\cos\theta_\mathrm{s})/2$, where θ_s is the shattering angle. The spread in the speed is assumed to be $\pm 0.2\langle v_\mathrm{s} \rangle$ and the opening angle of the shard plume is assumed to be 10°.

We now compare the model predictions for the density increase in AUG shot #40743, which had a non-disruptive pure D2 SPI with a pellet diameter of $D = 8\,\mathrm{mm}$, length $L = 4.5\,\mathrm{mm}$, $v_0 = 270\,\mathrm{m/s}$ and $\theta_\mathrm{s} = 25^\circ$. The profiles for the current density, free electron density and temperature used as input to the simulation are taken from the representative shot #40655, for which a high-quality equilibrium reconstruction by the IDA diagnostic [10] is available. The shots performed during this SPI campain had a core temperature of $\sim 4\,\mathrm{keV}$, electron density of $\sim 6 \cdot 10^{19}\,\mathrm{m}^{-3}$ and a plasma current of $\sim 0.8\,\mathrm{MA}$, with a core current density of $\sim 1.75\,\mathrm{MA/m}^2$.

Finally, to ensure a flattening of the density and temperature profiles on a realistic time scale, we apply a diffusion coefficient of $2\,\mathrm{m}^2/\mathrm{s}$ on the density, and $4\,\mathrm{m}^2/\mathrm{s}$ for the temperature (similarly to previous simulations of shot #40743 with the INDEX code [11]).

Fig. 1 shows the Thomson scattering [12] density measurement and simulated density profile 6.9 ms after the injection, with different drift settings. We see that without the drift included in the model, the density is strongly overestimated. However, with the drift included in the model, with $\Delta y = 9\,\mathrm{mm}$ to best match the experiment, the density measurement is reasonably well reproduced. Noteably, the assimilation rate is only $\sim 10\%$.

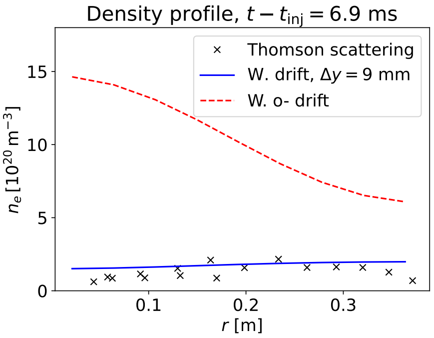

Figure 1: Measured (x-markers) and simulated densities 6.9 ms after the injection in AUG shot #40743, without (red dashed) and with (solid blue) ablation drift included.

Prospects for ITER We now investigate the effect of the drift displacement in a disruption mitigation scenario in ITER. The studied scenario is the best performing 15 MA DT H-mode scenario studied by Vallhagen *et al* [13] (labeled St4 in Appendix B therein). In this scenario, the SPI is divided into two stages, with a pure D2 pellet aiming at greatly increasing the density, to reduce RE generation without immediately triggering the disruption, followed after 5 ms by a 1.35% Ne doped pellet aimed at dissipating the energy content in the plasma through radiation. The plasma is assumed to disrupt when the electron temperature falls below 10 eV anywhere inside the $q = 2$ flux surface. At this point, we trigger an event with large transport coefficients chosen to obtain a flattening of the ion and current density profiles on a time scale ~ 0.1 ms, and a transport induced loss of thermal energy on a time scale ~ 1 ms. The whole transport event is assumed to last for 3 ms. The resulting RE current is evolved using the fluid RE model in DREAM [2]. Further details of the scenario and simulation settings are given in [13].

Fig. 2 shows the density evolution for different drift settings for this scenario. In fig. 2a), we see that without the drift, the density increase is largest in the core for both pellets. In contrast, in fig. 2b), where the drift is included assuming $\Delta y = 12.5\,\mathrm{mm}$ (similar to values found in [5]), the first pellet only gives a small density increase at the edge. If Δy is increased by 50%, as in fig. 2c), the assimilation of the first pellet increases considerably, but is still reduced and largely edge-localised. However, the lower assimilation of the first pellet leaves the plasma hotter when the second pellet arrives, increasing the ablation of this pellet. As the Ne doping strongly reduces the drift for the second pellet, by reducing the plasmoid pressure and hence the

∇B-drift through radiation, the increased ablation also leads to an increased assimilation. This partially compensates for the lower assimilation of the first pellet, so that the post-disruption density only differs by a factor $\lesssim 2$ between the three cases. As a result, the final RE current only differs by less than 10% in this scenario. Note we have however assumed rather favourable conditions for RE avoidance, in particular by assuming a rather slow transport event with a late onset. The effect of the low assimilation of the first pellet expected due to the drift thus remains to be investigated more generally.

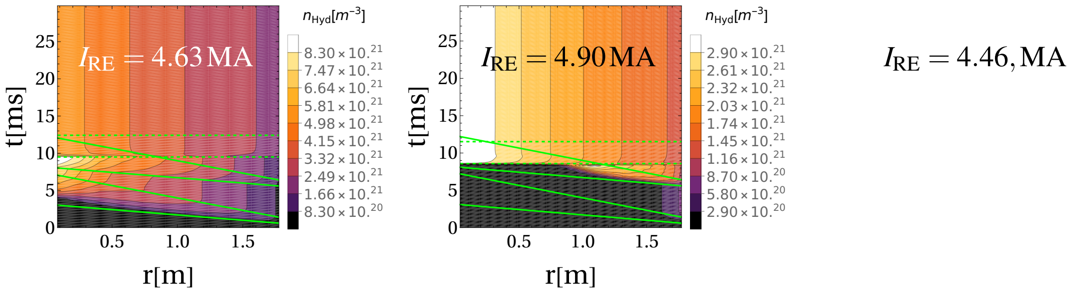

Figure 2: Simulated density evolution during a 15 MA DT H-mode ITER SPI scenario, with a) no drift, b) drift assuming $\Delta y = 12.5\,\mathrm{mm}$, and c) drift assuming $\Delta y = 18.75\,\mathrm{mm}$. The solid green lines indicate the trajectory of the fastest and slowest shards for each injection, and the temporal boundaries of the transport event are shown with dotted green lines.

Conclusions We have developed a model for the drift displacement of ablated pellet material in a tokamak, and implemented it in the DREAM code. This model was able to reproduce the density evolution in AUG SPI experiments, for model parameters within the expected range. We find that the drift decreases the assimilation of pure D2 SPIs by about an order of magnitude, in both AUG and ITER, while the effect is modest for Ne doped pellets. In a two-stage ITER SPI scenario, a first injection stage with a pure D2 pellet is not likely to result in a substantial density increase, but as this means the plasma is hotter when the second, Ne doped pellet arrives, the post-disruption density increase is not dramatically reduced. In an optimistic case, the drift might therefore only alter the RE current after such an injection by a few percent. The effect on the RE current under less favourable conditions however remains to be investigated.

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