The influence of hot neutrals in simulations of gas puff modulation

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Introduction

Experiments utilizing the gas puff modulation technique have been carried out in JET for the purpose of studying plasma fueling as well as particle transport [1]. It is of great interest to simulate such experiments, as this allows for deeper insight in the mechanics that determines the fueling rate when applying gas puffing, as well as providing knowledge of the dynamics of neutral particles. This has to some extend been achieved in numerical simulations, which have proved successful in reproducing profiles for the modulation experiments in [1].

In this paper we make progress towards a simple to use model which allows to explore parameter space in a dynamical fashion and can treat modulation experiments in a meaningful way. We present numerical investigations on how the gas puff modulation characteristics are affected by the neutral particle model. Two 1D models are studied; the first model includes only one species of neutral atoms originating from the gas puffing, whereas the second model also accounts for the hot neutrals created in charge exchange collisions between hot plasma and the cold neutrals $\left(ion_{\mathrm{hot}} + neutral_{\mathrm{cold}} \underset{\mathrm{cx}}{\rightarrow} neutral_{\mathrm{hot}} + ion_{\mathrm{cold}}\right)$.

It is found that the neutral model does not affect the transport of the modulated signal significantly, but the amplitude of the modulation is several times larger in the two-species neutral model. Also, the hot neutrals are seen to penetrate deeper into the edge, which along with the increased amplitude for the hot neutral model indicates a significant difference in fueling in the two models.

Models

To simulate the transport of heat and particles, we apply a system of 1D transport equations [2]. The density equation for the quasi-neutral plasma species reads

$$\partial_t n_{\mathrm{p}} + \frac{1}{r}\partial_r \left(r\Gamma_{\mathrm{p}}\right) = S_{\mathrm{p}}\,, \qquad \Gamma_{\mathrm{p}} = -D_{\mathrm{p}}\partial_r n_{\mathrm{p}} + v n_{\mathrm{p}}\,, \tag{1}$$

[*] See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia

where n_p is the plasma density, v is vthe convective velocity, $D_{\rm p} = D_{\rm p}(\chi_{\rm e})$ is the diffusion coefficient and S_p is the plasma particle source. The electron temperature equation reads

$$\tfrac{3}{2}\partial_t\left(n_{\rm p}T_{\rm e}\right)+\tfrac{1}{r}\partial_r\left(r\left[q_{\rm e}+\tfrac{5}{2}T_{\rm e}\Gamma_{\rm p}\right]\right)=Q_{\rm e}+\frac{\Gamma_{\rm p}}{n_{\rm p}}\partial_r\left(n_{\rm p}T_{\rm e}\right)\,,\qquad \frac{q_{\rm e}}{n_{\rm p}}=-\chi_{\rm e}\partial_r T_{\rm e}+uT_{\rm e}\,, \tag{2}$$

where u is the electron heat convection velocity, $\chi_{\rm e}$ the heat diffusivity and $Q_{\rm e}$ is the heat source. In order to account for turbulent effects, the electron heat diffusivity is described by a critical electron temperature gradient model [3], such that the heat diffusion grows when the electron temperature gradient exceeds a critical level κ

$$\chi_{\rm e}=\chi_{\rm e0}+\lambda T_{\rm e}^{\alpha}\left[\frac{|\nabla T_{\rm e}|}{T_{\rm e}}-\kappa\right]^{\beta}H\left(\frac{|\nabla T_{\rm e}|}{T_{\rm e}}-\kappa\right)\,, \tag{3}$$

where H is the Heaviside step function, $\chi_{\rm e0}$ is the collisional heat diffusion coefficient and λ a coefficient.

Two models for the neutral particles are applied. In the two-species model the neutral population consists of a cold neutral species which enters the system by gas puffing, and a hot neutral species which is created in charge exchange collisions between hot plasma and cold neutrals. Both hot and cold neutral densities $n_{\rm n_{c,h}}$ are described by a diffusion model

$$\partial_t n_{\rm n_{c,h}}+\tfrac{1}{r}\partial_r\left(r\Gamma_{\rm n_{c,h}}\right)=S_{\rm n_{c,h}}\,,\qquad \Gamma_{\rm n_{c,h}}=-D_{\rm n_{c,h}}\partial_r n_{\rm n_{c,h}}\,, \tag{4}$$

where $D_{\rm n_{c,h}}$ are the diffusion coefficients.

The plasma and neutral equations are coupled through the sources

$$S_{\rm p}=\left(n_{\rm n}k_{\rm iz}-n_{\rm n_c}k_{\rm cx}\right)n_{\rm p}\,,\qquad Q_{\rm e}=-k_{\rm iz}n_{\rm n}T_{\rm iz}\,, \tag{5}$$

$$S_{\rm n_c}=-\left(k_{\rm cx}+k_{\rm iz}\right)n_{\rm n_c}n_{\rm p}\,,\qquad S_{\rm n_h}=\left(n_{\rm n_c}k_{\rm cx}-n_{\rm n_h}k_{\rm iz}\right)n_{\rm p}\,, \tag{6}$$

where $n_{\rm n}\equiv n_{\rm n_c}+n_{\rm n_h}$, $T_{iz}=13.6\,{\rm eV}$ is the ionization energy and $k_{\rm iz}$ and $k_{\rm cx}$ are the ionization and charge exchange rates which both depend on the plasma temperature [4]. External plasma and cold neutral sources are imposed through boundary conditions, and in particular the gas puffing is simulated by modulating the cold neutral source on the wall.

The one-species model for neutrals is similar to the above, but the charge exchange reaction rate $k_{\rm cx}$ is quenched such that no hot neutrals are created.

Results

By solving the system of equations (1)-(6) numerically we obtain the neutral profiles shown in Figure 1, modulated plasma density profiles in Figure 2 and phase shift and amplitude for the modulation in Figure 3. The plots for experimental data shown in Figures 2 and 3 are constructed from a measured plasma density profile in phase 1 of JET shot #87425 with GIM7 modulation (for details, see [5, 6]). These, along with experimental electron temperature data, were also used when the free parameters of the model were estimated.

In Figure 1 it is seen, that in both models the cold neutrals have a small penetration depth and the densities vanish inside the last-closed-flux-surface (LCFS) which lies at approximately at $R = 3.80\,\mathrm{m}$. The hot neutrals have a much lower density at the wall (at $R = 3.864\,\mathrm{m}$), but penetrate far deeper into the plasma edge. This indicates that hot neutrals may play a significant role in plasma fueling.

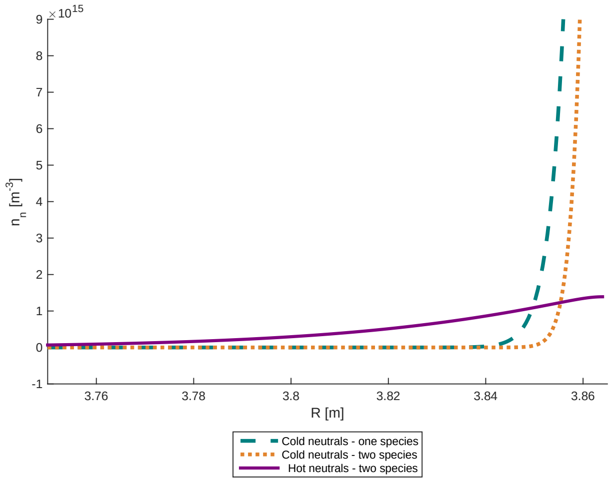
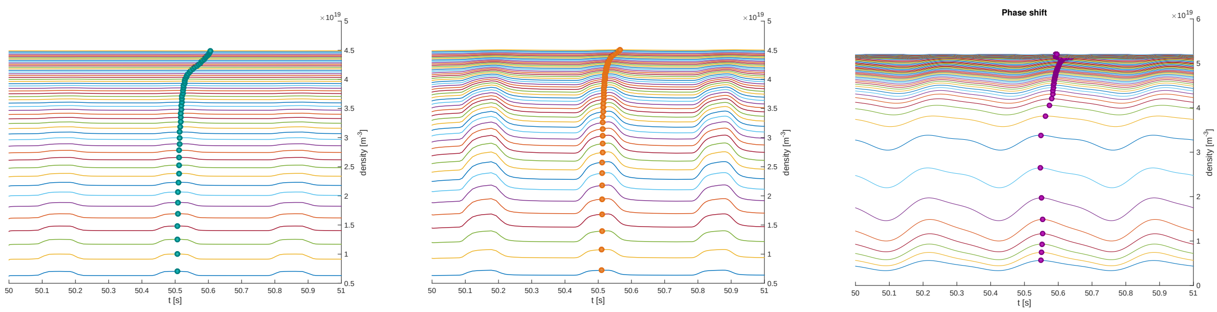


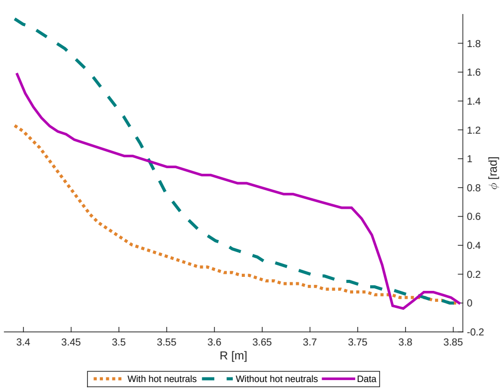
Figure 1: Neutral profiles in steady state, shown both for the one-species model (dashed), and for the two-species model with cold (dotted) and hot (full) neutrals for JET geometry.

Figure 2 shows the modulation of the density as a function of time. Both simulations mimic the plasma behavior to gas puffing well by reproducing a modulation phase shift which increases, and an amplitude which decreases when approaching the center. The phase shift and amplitude are depicted in Figure 3. This shows that the calculated phase shift only depends weakly on which of the two models is applied, and that the ionization source region is deeper for the model which includes hot

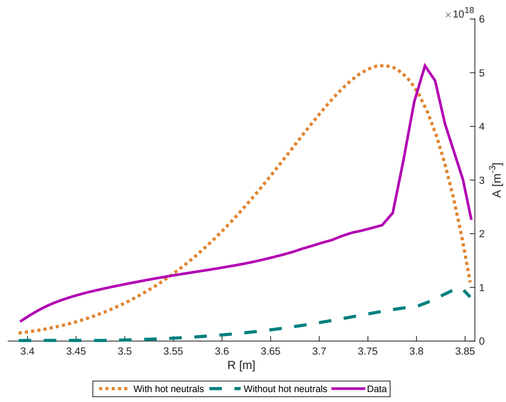


(a) One neutral species. (b) Two neutral species. (c) Experimental data.

Figure 2: Simulations of and experimental data for gas puff modulation of plasma density. One of the perturbations is tracked and marked by colored circles.



(a) Phase shift.



(b) Amplitude.

Figure 3: Phase shift and amplitude of plasma density modulation for one-species model (dashed), two-species model (dotted) and experimental data (full).

neutrals. The latter is concluded from the flatter phase shift of the two-neutral-species model in the outer region. It is also observed that the amplitude of the modulation is several times larger for the model that includes hot neutrals. This effect is due to the deeper penetration of the hot neutrals inside LCFS.

Discussion and conclusion

The effect on the gas puff modulation characteristics are investigated for two different models for neutral particles. A comparison shows that the phase shift in the plasma density modulation is similar for the two neutral models, whereas the amplitude of the modulation is significantly larger for the model which includes hot neutrals produced in charge exchange collisions.

The weak influence on the phase shift suggests that the choice of neutral model is not significant for the plasma particle transport. In contrast the strong influence that the choice of neutral model has on the amplitude of the density modulation indicates that the fueling rate inside LCFS is very dependent on whether hot neutrals are included or not.

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