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Gas puff fuelling simulation with a combined neutral/HESEL model

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Simulation of neutrals in a turbulent scrape-off layer

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Introduction

In future magnetic confinement fusion devices, such as ITER, high efficiency fuelling with deep penetration is required for maintaining a sufficient plasma core density. One possible fuelling method is gas puffing, in which neutral molecules are puffed into the scrape-off layer (SOL), where they dissociate, and if the resulting atoms are ionized inside the last closed flux surface (LCFS), they fuel the plasma effectively. To investigate the direct fuelling efficiency from gas puffing in a turbulent SOL, the HESEL model for SOL turbulence is coupled to a fluid-like neutral model.

The HESEL model [1] is a 4-field drift-fluid model that describes interchange driven turbulence in the SOL region. The simulated domain is 2D slab perpendicular to the magnetic field lines, at the outboard-midplane of a tokamak. The reaction rates of the plasma-neutral interactions that shape the neutral profiles in the SOL depend strongly on both electron density, and electron or ion temperature. As fluctuations in these fields are highly correlated in the SOL, a turbulence model such as HESEL is necessary for investigating the reaction rates in a proper way.

Neutral Model

The choice of model for the neutrals is made from a series of requirements. First from Fig. 1a[†] it appears that both molecular and atomic neutrals are important for describing the interactions with the plasma. Secondly, the so-called Franck-Condon neutrals that result from molecular dissociation will have a temperature of a few eV [2], whereas neutral atoms that have undergone charge-exchange collisions typically have much higher temperatures similar to that of the ions. Moreover, it is seen from Fig. 1b that in the SOL region the cold neutrals typically have a short mean-free path (mfp), whereas the mfp for the atoms is much longer than the typical perpendicular length-scales of SOL structures that are of the order of cm. Finally, the neutral gas transport is described by a fluid model. Using a fluid model rather than a more detailed kinetic model is motivated by computational expediency, and allows for solving the coupled system of plasma and neutral transport equations simultaneously.

[†] The molecular ionization is actually a two-step process: $\mathrm{D_2 + e \rightarrow D_2^+ + 2e \rightarrow D + D^+ + 2e}$. The cross-section for the second step is, however, so high, that the dissociation can be assumed to happen immediately after ionization, and only the reaction rate of the first step is used.

The resulting neutral model is a 3-field diffusive model for the neutral densities[‡], similar to that used in [4], i.e,

$$\partial_t n_s - \nabla \cdot (D_s \nabla n_s) = S_s \,, \qquad s = \text{cold, warm, hot} \,, \tag{1}$$

where n_s are the neutral densities, the diffusivities $D_{\text{hot}} = 10^1 D_{\text{warm}} = 10^3 D_{\text{cold}} \approx 10^2 \frac{\text{m}^2}{s}$ are estimated from neutral temperatures of $T_{\text{hot}} = 20\,\text{eV}$, $T_{\text{warm}} = 2\,\text{eV}$, and $T_{\text{cold}} = 25\,\text{meV}$, ρ_s is the cold-ion hybrid thermal gyro-radius and Ω_{ci} is the ion cyclotron frequency. The neutral density sources are

$$\begin{aligned} S_{\text{cold}} &= -n n_{\text{cold}} \left(\langle \sigma_{Dis} v \rangle + \langle \sigma_{Iz} v \rangle \right) \,, \qquad S_{\text{hot}} = n \left(n_{\text{warm}} \langle \sigma_{cx} v \rangle - n_{\text{hot}} \langle \sigma_{iz} v \rangle \right) \,, \\ S_{\text{warm}} &= n \left[n_{\text{cold}} \left(2 \langle \sigma_{Dis} v \rangle + \langle \sigma_{Iz} v \rangle \right) - n_{\text{warm}} \left(\langle \sigma_{iz} v \rangle + \langle \sigma_{cx} v \rangle \right) \right] \,, \end{aligned} \tag{2}$$

where n is the electron density, and $\langle \sigma_r v \rangle$ is the reaction rate coefficient for reaction r, and the reaction rates are defined in Fig. 1a. By demanding that the neutral densities should vanish to dissociation and/or ionization inside the edge, and that the wall is absorbing a fraction γ of colliding neutrals the boundary conditions become

$$\partial_x n_s \big|_{\text{edge}} = \sqrt{\frac{S_s'}{D_s} n_s} \,, \qquad \partial_x n_s \big|_{\text{wall}} = -\gamma \sqrt{\frac{S_s'}{D_s} n_s} \,, \tag{3}$$

along with an evenly distributed auxiliary molecular neutral deuterium source on the wall boundary for simulating gas puffing. Here s again denote the different neutral species, S_s' are the source terms proportional to n_s and $\gamma = 0.2$.

Density Sources

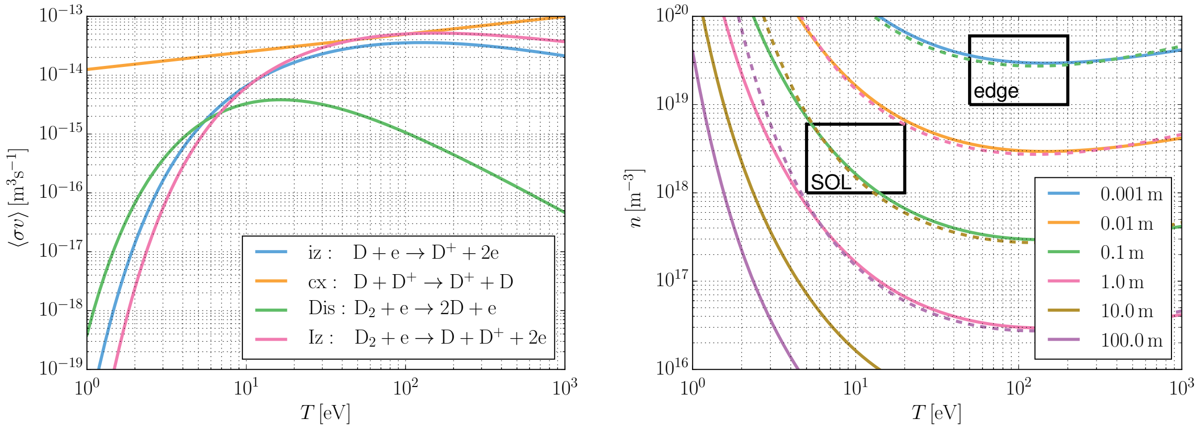
A first step in coupling the neutral and HESEL equations, is to include the 0th moment source term

$$S_{\text{n}} = n \left[n_{\text{cold}} \langle \sigma_{Iz} v \rangle + \left(n_{\text{warm}} + n_{\text{hot}} \right) \langle \sigma_{iz} v \rangle \right] \,, \tag{4}$$

in the continuity equation. Including this density source in the HESEL equations allows for probing the potential of simulating gas-puff fuelling from the outboard-midplane, as well as investigate to which extent neutrals are ionized in the SOL, and thus lost for direct fuelling purposes. Ideally higher-moment sources, such as cooling from charge-exchange collisions or ionization of warm neutrals, should be included as well. It is however believed that these sources do not affect the fuelling properties much, and including them is thus left for future work.

The molecular neutral source that imitates a steady state gas-puffing is formulated in such a way, that enough neutrals are puffed in to maintain the plasma edge density from direct fuelling.

[‡] Even though the neutral atoms experience a long mfp in the SOL, the particle transport can be well described by Fick's laws [3].



(a) *Reaction rates for dominant inelastic collisions between neutral particles and plasma. They are referred to as* iz, cx, Dis *and* Iz *respectively.*

(b) *Ionization and dissociation mfp of cold neutral molecules (solid), and ionization mfp for hot neutral atoms (dashed).*

Figure 1: *Reaction rates for neutral-plasma collisions, and mean-free paths (mfp) for cold and hot neutrals. Reaction rate coefficents are obtained from [5].*

It is found that for sustaining the plasma edge density by direct fuelling, the density flux must yield a total neutral pressure

$$P_{\text{wall}} = \sum_{\substack{s=\text{cold,}\\ \text{warm,hot}}} n_s T_s \Big|_{\text{wall}}, \tag{5}$$

of $P_{\text{wall}} \approx 0.1\,\text{Pa}$. This pressure is consistent with what is measured in experiments.

Another interesting result that the coupled model yields, is the fraction of different neutral species that cross the LCFS, and thus fuel the plasma directly. It is found that approximately 60 % of the flux is constituted by hot neutrals, that are created by interactions between blobs and warm neutrals in the SOL. The remaining 40 % of the flux comes from warm neutrals, and the amount of cold neutrals reaching the LCFS is negligible. This testifies to the importance of a dynamical treatment of the SOL plasma, as well as the inclusion of the hot neutral species. It is also observed that the fuelling briefly increases during a blob event, which can be explained by a temporary increase in the hot neutral production rate. Some of the fields and the resulting ionization rate are shown in Fig. 2.

Conclusions and Outlook

In this paper the initial results from implementing a neutral model in the HESEL code are presented. It is displayed how simulating gas puffing as a molecular neutral source at the wall yields a realistic fuelling scenario, in which the molecular neutral density self-consistently takes values comparable to those in todays gas-puffed tokamaks. It is found, that most of the direct

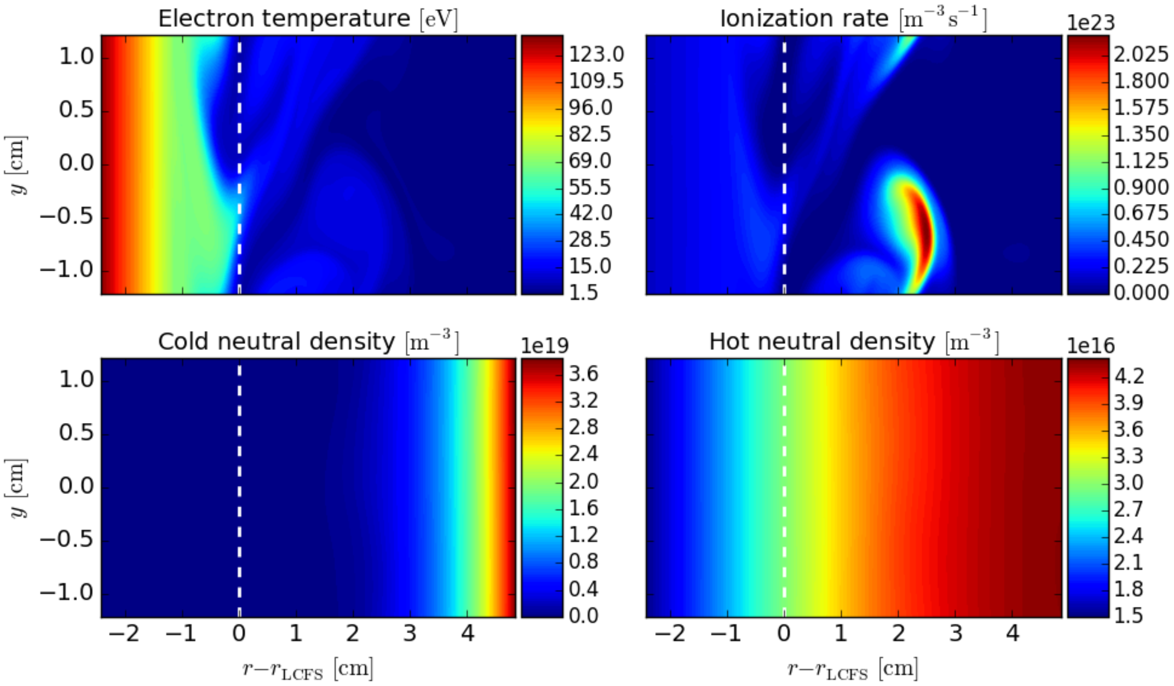


Figure 2: *Plasma and neutral fields solved by the combined neutral-HESEL simulation, and the resulting ionization rate. The dashed line indicates the position of the LCFS.*

fuelling originates from hot neutrals created in charge-exchange collisions the SOL, and also that blobs shortly increase fuelling due to a brief increased production hot neutrals with a long mean-free path.

Future extensions of the combined neutral-HESEL model will involve inclusion of higher moment sources, and consideration of wall and divertor recycling effects. This will allow for a better understanding of the influence of the neutrals on the blobs, as well as a more consistent fuelling scheme.

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