Kinetic effects in tokamak scrape-off layer plasmas: non-local parallel transport and plasma-atomic reactions

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Introduction

The region of unconfined plasma in a tokamak, called the scrape-off layer (SOL), is important in determining the overall performance of these devices. It is here where plasma particles and energy are transported (primarily parallel to the magnetic field lines) from the core plasma region to the solid surfaces on the inside of the tokamak. There is much interest in understanding transport in this domain, so that accurate predictions can be made for future devices and steps can be taken to mitigate heat loads which may exceed the material constraints.

Transport in SOL plasmas is frequently treated with fluid models, where a Braginskii-like set of equations [1] may be solved. However, there are two important (and related) aspects of SOL physics for which this assumption may be violated. First, the presence of steep temperature gradients parallel to the magnetic field, as would be expected in reactor-class devices, means heat transport (particularly for the electrons) may be dominated by fast, low-collisionality particles and so becomes 'non-local'. Secondly, enhanced high-energy tails of electron distributions close to the walls, where most plasma-atomic interactions take place, may modify reaction rates (e.g. electron-impact ionisation), and therefore affect the particle, momentum and power balance.

For these reasons, here we present kinetic simulations of the electrons in a 1D SOL model. The model will briefly be presented, followed by an explanation of the simulation set-up. We will then summarise results for a set of parameter scans in input power and plasma density, followed by an analysis of atomic reaction rates and radiative losses from carbon impurities.

Kinetic modelling with SOL-KiT

SOL-KiT is a fully implicit 1D plasma code which has been used to study kinetic effects in parallel electron transport in the SOL. Here a very brief outline of SOL-KiT is presented, and the reader is referred to [2] for more details of the model.

In kinetic mode, SOL-KiT solves the electron VFP equation along the direction parallel to the magnetic field (the x-axis),

$$\frac{\partial f(x,\boldsymbol{v},t)}{\partial t} + v_x \frac{\partial f(x,\boldsymbol{v},t)}{\partial x} - \frac{e}{m_e} E \frac{\partial f(x,\boldsymbol{v},t)}{\partial v_x} = \sum_{\alpha} C_{e-\alpha}, \qquad (1)$$

where $f(x,\mathbf{v},t)$ is the electron velocity distribution, which is a function of space, velocity and time. E is the electric field along x, m_e is the electron mass, e is the electron charge and v_x is the electron velocity along x. The right hand side represents collisions between electrons and all other species. A spherical harmonic decomposition is used to solve this equation as in [3], and azimuthal symmetry is assumed about the x-axis so that the magnetic field may be ignored.

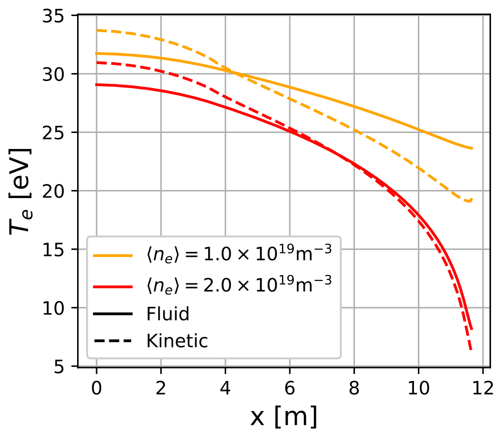

Figure 1: *Fluid and kinetic temperature profiles.*

The x-axis spans from the midplane at $x = 0$ ('upstream'), to the plasma sheath boundary at $x = L$, where L is the SOL connection length, defined here as half the parallel distance between two strike points in a divertor SOL. Power enters the plasma upstream, and leaves primarily at the sheath or through inelastic and charge exchange collisions with neutrals.

In fluid mode, moments of equation (1) are solved instead, allowing for a direct comparison between a fluid and kinetic treatment. For either kinetic or fluid electrons, the ions and neutrals which complete the SOL model are treated as fluids. In this paper, unlike in [2], both the ion and neutral fluids are treated with independent momentum and energy equations.

Simulations

The two SOL parameters we have some degree of control over in tokamaks are P_{in}, the input power to the SOL from the core plasma and the plasma density, here formulated as the line-averaged quantity $\langle n \rangle$. A total of 78 simulations (39 fluid and 39 kinetic) have been done across a range of P_{in}, from 4 to 64MWm^{-2}, and $\langle n \rangle$, from 10^{19} to 10^{20}m^{-3}, and allowed to run to equilibrium. P_{in} is distributed over the first 3m of the domain.

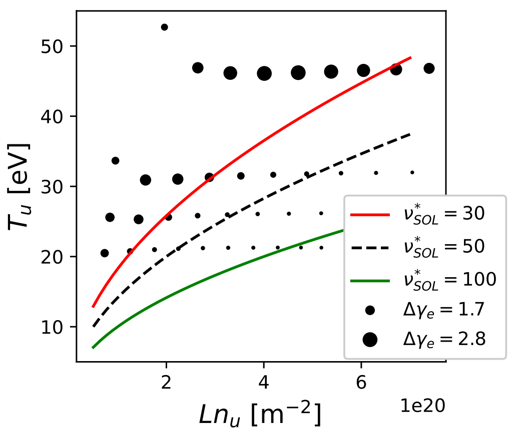

Figure 2: *Enhancement in γ_e in kinetic simulations, plotted on T_u, n_u plane; dot size is $\Delta\gamma_e = \gamma_e^{kinetic} - \gamma_e^{fluid}$.*

P_{in} and $\langle n \rangle$ are directly related to the the upstream temperature and density, T_u and n_u, which relate to the upstream collisionality $\nu^*_{SOL} \propto \frac{T_u^2}{Ln_u}$. These simulations cover ν^*_{SOL} from 8 to 114. The connection length is $L = 12$m for all simulations.

Equilibrium parameter scans

As observed in previous SOL kinetic studies, simulations with kinetic electrons demonstrate heat flux suppression, resulting in steeper temperature gradients and reduced target temperatures, T_t, as is shown in Figure 1 for two simulations.

Next, we look at the electron sheath heat transmission coefficient, γ_e. Electrons which cross the sheath boundary at the plasma-wall interface will be lost to the wall only if they have sufficient energy to overcome the ambipolar electric field. In this way the sheath boundary has a cooling effect on the plasma electrons, and γ_e is related to the magnitude of this cooling effect. In Figure 2, we compare γ_e for kinetic and fluid simulations at a given T_u, n_u, along with some lines of constant collisionality ν^*_{SOL}. From this we see strong kinetic enhancement of γ_e in intermediate collisionalities, increasing at high T_u and n_u, which is where future tokamaks are envisaged to operate.

Plasma-impurity reactions

Radiative cooling from non-hydrogenic impurity species is frequently used for edge plasma cooling in tokamaks, but excessive concentrations risk quenching the core plasma. This process depends largely on electron-impurity collisional reaction rates, which are typically Maxwellian-averaged but may depend on the electron distribution. We begin an analysis into kinetic effects here by inputting the electron distributions and plasma profiles from the kinetic simulations discussed thus far into a collisional radiative model for carbon impurities[1].

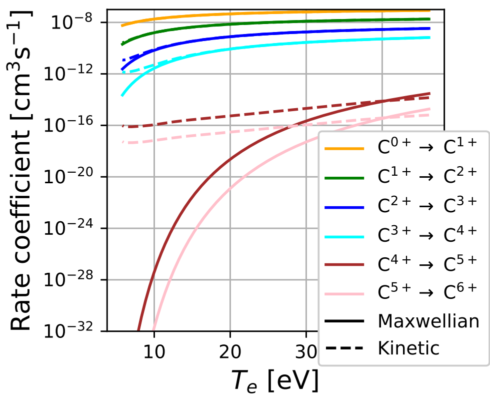

Figure 3: *Kinetic enhancement of carbon ionization rates in a SOL-KiT simulation.*

In Figure 3, ionization rate coefficients for each stage of carbon are shown for the plasma background from a SOL-KiT simulation, with the kinetic rate compared to the rate for an equivalent Maxwellian electron distribution (at the same density and temperature). At low temperatures, we see strong kinetic enhancement of the ionization rates, increasing with the ion charge.

This change results in a modification of the ionization balance, which affects the total predicted line radiation. In Figure 4 we plot the relative difference (kinetic vs. Maxwellian) of the total line-integrated radiative losses from carbon impurities, q_{rad}, for all the SOL-KiT simulations. We see here kinetic suppression of q_{rad} by up to nearly half. The behaviour is similar

[1] This model has been developed for interfacing with SOL-KiT by the author. The code can be found at `https://github.com/Plasdom/SIKE`.

to the kinetic enhancement of γ_e (Figure 2), where the strongest kinetic effects occur at low-intermediate collisionality, increasing towards higher T_u, n_u.

Conclusion

We have presented here results of 1D kinetic simulations of scrape-off layer plasmas across a wide range of relevant parameter space.

We see strong kinetic suppression of the heat flux, as compared to a fluid model, which means steeper temperature gradients are required for a given input power and temperatures close to the wall are lower. This contrasts with enhancement of the sheath heat transmission factor. At equilibrium, where P_{in} is balanced by all losses from the system, it may be expected that these effects cancel to some extent, yielding similar heat loads to the wall. This may not be the case during transient events such as ELMs, or in the presence of radiating impurities, where kinetic modifications to transport may alter the power balance.

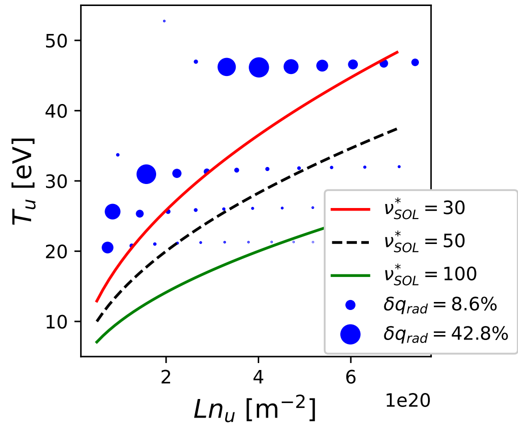

Figure 4: *Kinetic suppression of total line radiation from carbon impurities in SOL-KiT simulations; dot size is* $\delta q_{rad} = (q_{rad}^{kinetic} - q_{rad}^{Max})/q_{rad}^{Max}$.

An initial study of kinetic effects related to impurities in SOL plasmas suggests that ionisation rates can be much larger when calculated kinetically, compared to Maxwellian-averaged rates, and that this can change predictions of radiative losses from impurity species. It should be noted that this study was post-processed, and a self-consistent study which accounts for the effect of impurities on the electrons will yield greater understanding of the presence of kinetic effects in impurity transport.

All kinetic effects observed appear small at high and low collisionalities, becoming most significant at low-intermediate values of ν^*_{SOL} and increasing for large (reactor-relevant) T_u and n_u. We have not attempted to provide a physical explanation of the kinetic effects observed here. This is planned for a future publication.

References

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