Update on state of the art in edge modelling

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1. Introduction

The edge region of magnetic confinement fusion plasmas presents numerous modelling challenges. There are abrupt changes in magnetic field topology, large variations in plasma collisionality, multiple ion species in different ionisation states, significant interactions with neutral particles and several boundary layers surrounding the material wall. As a result, a plethora of analytical and numerical models have been developed to study different aspects of the edge plasma physics. In a previous report [1], we provided an overview of the relevant physics parameters in the edge and discussed the various approaches taken to model the plasma there. Here we provide an update to this report, focusing on recent progress in edge modelling.

2. Overview of edge codes

While there are many different models – and associated codes – used to study the plasma edge, they can all be placed into a handful of categories. At one end of the spectrum are Monte Carlo codes (e.g., DEGAS2, EIRENE, GTNEUT, NEUT2D) used to study neutral dynamics. These codes employ a kinetic treatment for neutrals due to their long collisional mean-free-path. They are often used in combination with multi-component fluid codes (e.g., SOLPS, EDGE2D, EMC3, SOLEDGE-2D, TECXY) that employ a fluid-diffusive model for transport. These codes are typically used to study transport parallel to the magnetic field with a high degree of sophistication regarding aspects of the problem such as the wall geometry, multi-component plasma effects and plasma-neutral interactions. However, they are inherently 2D, ruling out the possibility of studying turbulent dynamics. Instead, they use a crude anomalous diffusivity fitted to experimental data to model the cross-field transport. Most codes built to study edge turbulence, including cross-field transport, are fluid codes (e.g., HERMES [2], GBS [3], GDB [4], GRILLIX [5], HESEL [6], TOKAM3X [7]) based on a drift-reduced version of Braginskii's equations. These codes are typically quite mature, with a high degree of flexibility regarding the magnetic geometry – including the ability to model X-point configurations. However, they often do not treat multiple ion species or interactions with kinetic neutrals, and ultimately are limited in applicability to plasmas at relatively high density and/or low temperature. Even in such modes of operation, they cannot capture kinetic effects such as the prompt loss of particles at the material wall. This brings us to the other end of the spectrum, where there is a growing list of drift kinetic and gyrokinetic codes adapted for edge conditions (e.g., XGC [8], Gkeyll [9], GENE [10], COGENT [11]). In principle these kinetic codes should provide a more complete picture of edge plasma dynamics. However, they come with extreme computational expense, and they are less developed, both in terms of the analytical models on which they are based and in terms of the range of physics currently implemented.

3. Recent progress in edge modelling

As we are focused on developing and implementing a model for plasma turbulence in the edge of magnetic confinement fusion devices, we restrict our attention here to advances in fluid and kinetic models for turbulence. Instead of giving a list of improvements made to every code over the last couple of years, we will focus on developments that have pushed forward what is possible in edge modelling, with an emphasis on kinetic treatments.

On the analytical theory front, there have been at least a few notable advances made:

- Our own work has led to the development of a novel set of moment-kinetic equations [12] that combine aspects of fluid and drift kinetic approaches. This approach makes it easier to transition from a kinetic to a fluid treatment and has the advantage that the velocity coordinate is everywhere (and at all times) defined in terms of the local thermal speed.
- Research elsewhere has made fluid modelling of kinetic effects more accurate: An extension of the original Landau-fluid closure [13] has been developed to treat non-Maxwellian particle distribution functions [14]. This model is intended for use in the fluid code HERMES (BOUT++) [15] to improve its treatment of plasma dynamics near the wall, where, as mentioned above, the particle distribution function develops cutoffs in the velocity space due to particle losses.
- Finally, it has been shown that inclusion of kinetic electron and finite ion orbit width effects leads to a collapse of the Debye sheath at much smaller angles between the magnetic field and wall than previously anticipated based on fluid analysis [16]: In particular, this angle is found to scale like the electron-ion mass ratio rather than its square root. This is a further argument in favour of developing kinetic codes for the treatment of edge plasma dynamics.

The main advances to kinetic simulations of edge turbulence come via adding in more physics effects to existing codes, many of which already exist in some form in one or more of the fluid turbulence codes:

- At least a couple of the continuum kinetic codes have made changes to their treatment of magnetic geometry to allow for simulations with X-points. These include COGENT [17], a finite volume code with a simplified fluid model for electron dynamics, and GENE-X [18], a new code spun off from GENE that is electrostatic with Dougherty collision operator [19], has no neutrals, imposes simplistic boundary conditions, and uses low-order finite differences. GENE-X uses a flux coordinate independent approach to allow for treatment of the X point, while COGENT employs a somewhat similar multiblock approach that is locally field-aligned. These continuum codes join their PIC counterpart, XGC, in their ability to treat diverted plasmas.
- Some edge codes have been extended to include electromagnetic fluctuations. These include the kinetic code Gkeyll [22] and the fluid code GBS [23]. Simulations using Gkeyll in helical geometry without neutrals [22] indicate that electromagnetic effects could lead to a modest broadening of the electron heat flux in the scrape-off layer due to enhanced cross-field transport, while inclusion of magnetic shear [20] led to a more significant reduction in transport.
- A kinetic treatment of neutrals was also added to both GBS [24] and to Gkeyll [21]. In the case of Gkeyll, this is restricted to atomic neutrals with electron-impact ionization and charge exchange collisions: there is no treatment of radiation, recombination, or neutral-neutral collisions; and a Maxwellian approximation is used when treating ion-neutral collisiions. For GBS, the treatment additionally includes neutral molecules.

4. Areas for further improvement

Most of the physics effects of importance in the edge have been included in at least one of the existing kinetic codes, but as evidenced above, each code is missing at least some of the key ingredients. Efforts are currently underway to add many these ingredients to extant codes. However, there are at least a few clear areas where code models could be improved:

- To our knowledge each of the kinetic codes mentioned above employs some form of simplified model for electron dynamics, be it an assumed Boltzmann response, a reduced fluid model or a linearised Poisson equation (Boussinesq approximation) with the electrostatic potential solved using the polarisation density. The latter approximation is not strictly consistent with the drift ordering in the edge.
- Related to the above, we are not aware of a rigorous procedure for determining the finite Larmor radius corrections needed for a gyrokinetic model of the plasma in the edge.

- The wall boundary conditions employed are of varying levels of sophistication but require further guidance from theory to be complete. We are aware of efforts underway to extend existing kinetic models for the various sheaths surrounding the wall so that they can be used in kinetic codes.

Our approach is to first treat the issue with electron physics and obtaining the electrostatic potential before moving on to bridge the gap between the open and closed field line regions of the plasma. The moment kinetic approach we have developed should provide a natural avenue for obtaining the electrostatic potential self-consistently. As for including a separatrix, our current philosophy is that the most efficient approach would be to make use of field-line-following coordinates where possible and to use analytical theory to match between these regions and a non-field-aligned grid just around the separatrix.

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