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Kinetic plasma-wall interaction using immersed boundary conditions

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The interaction between the plasma and the solid wall at the divertor/limiter target in tokamak devices affects turbulence in the plasma edge, thus impacting the overall confinement [1,2]. While the gyrokinetic framework allows one to describe turbulence and transport in the core of tokamak plasmas, most of present gyrokinetic codes still lack an adequate description of plasma-wall interaction [3,4]. In this perspective, plasma-wall interaction is studied with the VOICE code in a (1D-1V) kinetic approach along magnetic field lines, assumed to have a normal incidence [Bourne 2023]. Immersed boundary conditions are used to model the wall. Two different choices are made for the penalized wall region: either currents are allowed to flow within the material boundary or not [5].
The main properties of the Debye sheath physics are recovered, whatever the description adopted for the wall region. The formation of a positively charged layer in front of the plasma boundary defines the transition to the so-called Debye sheath. This non-neutral layer is accompanied by a drop of the electric potential that confines slow electrons and accelerates ions.
Most interestingly, discrepancies are found with respect to fluid predictions [6]. First, the non-vanishing conductive heat flux observed in kinetic simulations is usually neglected in fluid analyses. Its properties and impact on the overall dynamics reveal hardly tractable within the fluid framework. Second, we show that the expression of the plasma sound speed strongly depends on the chosen closure of the fluid hierarchy. The immediate consequence is that Bohm's criterion defining the Debye sheath entrance in terms of the Mach number becomes non-operational. These departures from fluid predictions result in part from the single-species Fokker-Planck collision operator acting on the parallel transport.
Distribution functions at the sheath entrance depart from Maxwellians, leading to an ion heat transmission factor at the wall larger than usually predicted [7]. Parametric dependencies reveal that the observed kinetic sheath physics is robust: the sheath acts as a filter of high energy electrons to avoid any charge separation in the plasma on scales larger than a few Debye lengths.
Last, the lessons learnt from this reduced kinetic model are used to develop models of the sheath physics relevant to the gyrokinetic framework. We present a new approach, currently tested in the flux-driven framework of GYSELA [2,8], based on constraints on the averaged total current flowing to the limiter/divertor target.

References:
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