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Kinetic simulation of plasma injection in neutral gas

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1. Introduction

A realistic description of the phenomena associated which the injection of a low temperature (1-10eV) neutralized plasma into a neutral background gas is obtained by using PIC/MC method, including ion/neutral collision processes with appropriate collision cross sections. In a recent paper [1] it has been discussed the formation of phase space vortices in argon due to the interaction between the injected plasma and a quasi static ion population resulting from charge exchange collisions, contrary to the common wisdom according to which collision phenomena should have a stabilizing effect on plasma instabilities. The velocity dependence of the cross section was modeled analytically by a fit to experimental transport data. In this work we generalize the previously reached conclusions in two ways: first, the plasma injection in argon is now studied in two dimensions. Second, we apply a 1.5D model to a multi-species case for realistic simulation of plasma injection in hydrogen with a comprehensive and realistic database of collision processes, each with an appropriate velocity dependent cross section resulting from transport data fit as well as quantum mechanical calculations [2].

2. Simulations of Ar^+/e plasma injection in Ar by a 2.5D model

The model of ref.1 has been extended to a 2,5D case, keeping the same hybrid structure (kinetic ions + Boltzmann distributed electrons) and the same description of ion/atom interaction via Monte Carlo method. In particular we consider a neutralized ion beam being injected into a stationary neutral gas and assume charge exchange collisions between the ions and the background to be the dominant interaction with a cross-section as a function of relative speed g approximated by $\sigma_c = \sigma_0 g^{-\gamma}$ with $\gamma = 0.18$ and collision frequency $\nu_c \propto g^{1-\gamma}$. The nonlinear Poisson equation for the electric potential $\varepsilon_0 \Delta\varphi = -\rho_i + \rho_0\, exp(e\varphi / kT_e)$ is solved using the technique described in ref.[3].

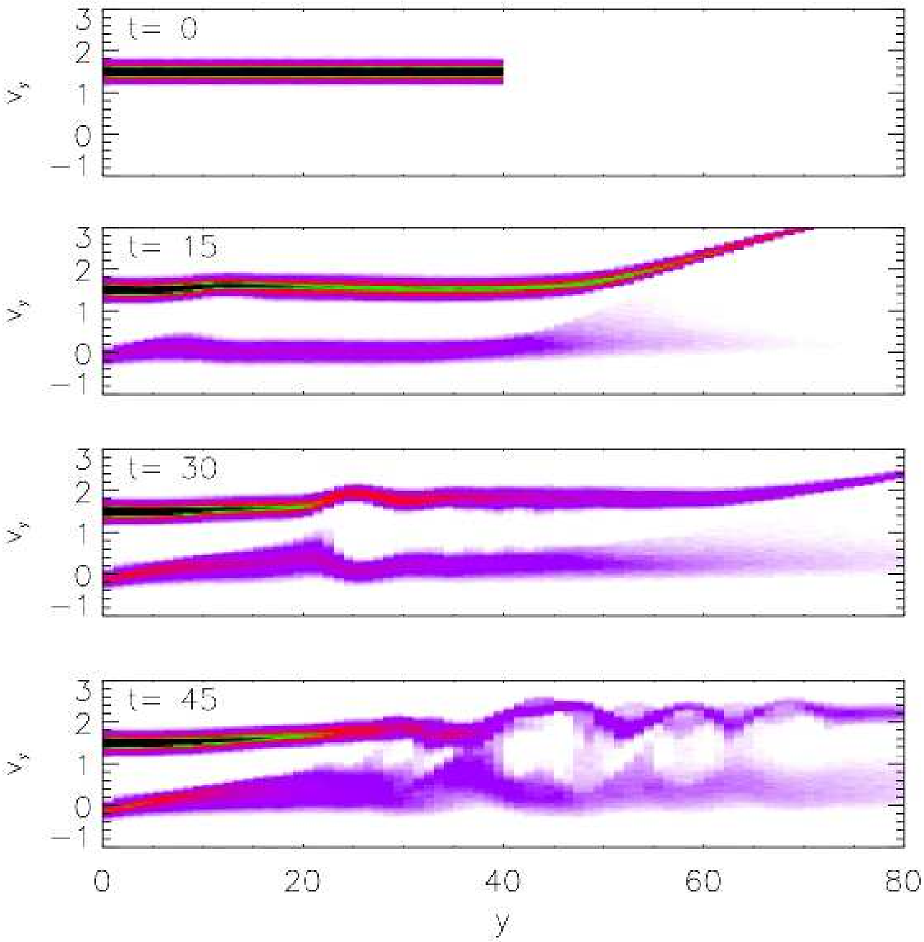

Fig.1 Ion phase space for t = 0, 15, 30, 45/ω_{pi}

In the simulation the electron, perpendicular and parallel beam, and neutral background temperatures vary as 20:1:1/3:1. The reference temperature is chosen to be that of the electrons. This means that the length unit L equals the electron Debye length. The time unit T equals the inverse ion plasma frequency. The velocity unit accordingly becomes L/T. Fig. 1 shows the phase plots of parallel velocity component along the beam axis as a function of y (parallel component) at 4 different points in time. As in ref.1 ions removed from beam are replaced by a stationary ion population creating a two-stream situation which leads to the formation of ion-phase space holes and a modified beam energy spectrum. Fig. 2 reports the ion density at four different times. The density enhancements near the beam head represent an instability with maximum growth rate at about 45 degrees relative to the beam direction.

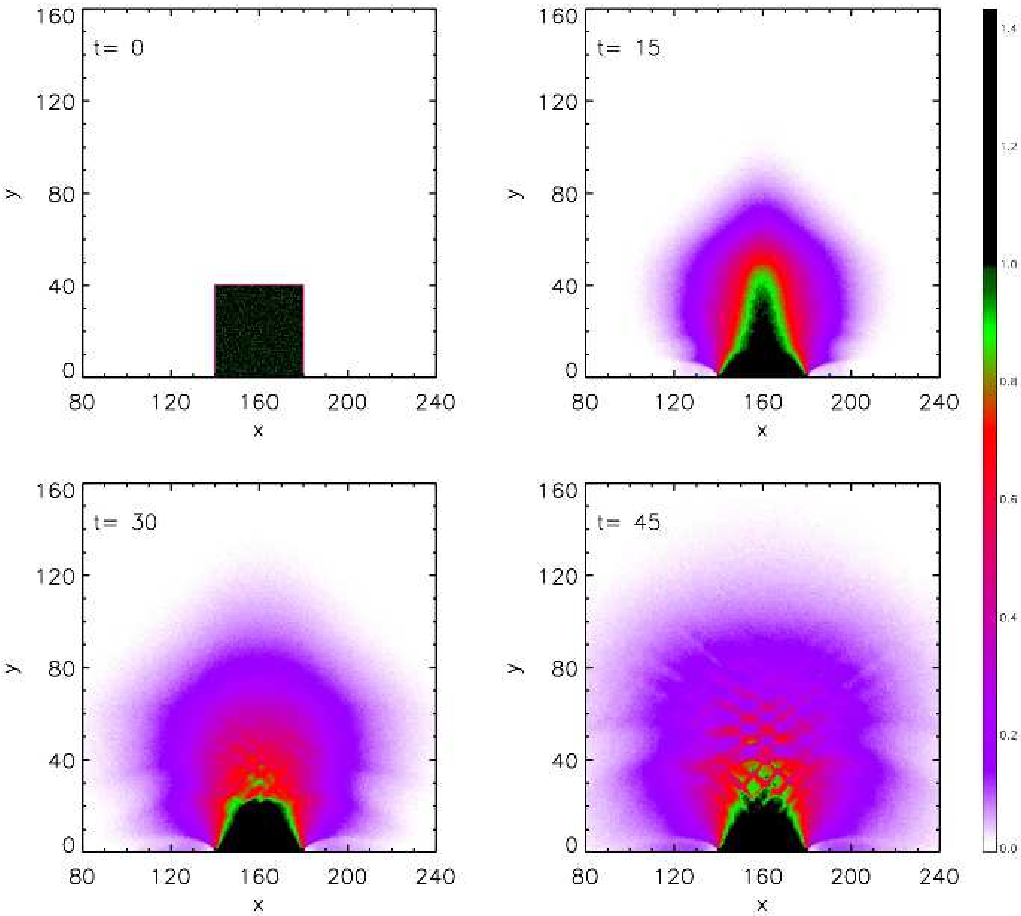

Fig.2. Snapshots of ion density. The color scale on the left ranges from 0.0 to 1.4

3. Kinetic simulation of H_3^+/H^+ /e plasma in H_2

The model of ref. [2] is applied to the study of the injection of a neutralized beam of H_3^+, H^+ and electrons in neutral H_2. The model is fully kinetic, with electrons treated as particles and four particle species representing atomic and molecular ions. The test particle Monte Carlo technique is applied to charged particle/neutral particle collisions with an extensive set of collision cross sections for elastic and inelastic processes, all tabulated as a function of the center of mass kinetic energy. Besides, the target gas is described including the vibrational level distribution of molecules in the electronic ground state X, H_2(X,v). The test case analyzed was obtained in the following conditions: gas temperature 1800 K, gas density $3.2\times10^{14}\,\mathrm{cm}^{-3}$. An absorbing wall is placed at x=0 and the plasma is injected towards the wall from a distance of 18 cm. The number density of the injected plasma is $2.5\times10^{7}\text{cm}^{-3}$, while the temperature of injected electrons and ions is 1.5eV.

The injected ions are H_3^+ and H^+ with a fraction of H^+ equal to 7%, the primary branching ratio for low energy electron ionization. Fig.3 shows the charged particle number density for different species at the steady state and the electron energy distribution function (eedf) averaged in the position range 0 < x < 3.6cm inside the sheath region as well as the eedf obtained by a different simulation where we have included the effect of the second kind vibrational reaction $e+H_2(v = 1) \rightarrow e+H_2(v = 0)$ (dashed line). A Maxwellian distribution (dotted line) is also reported for comparison.

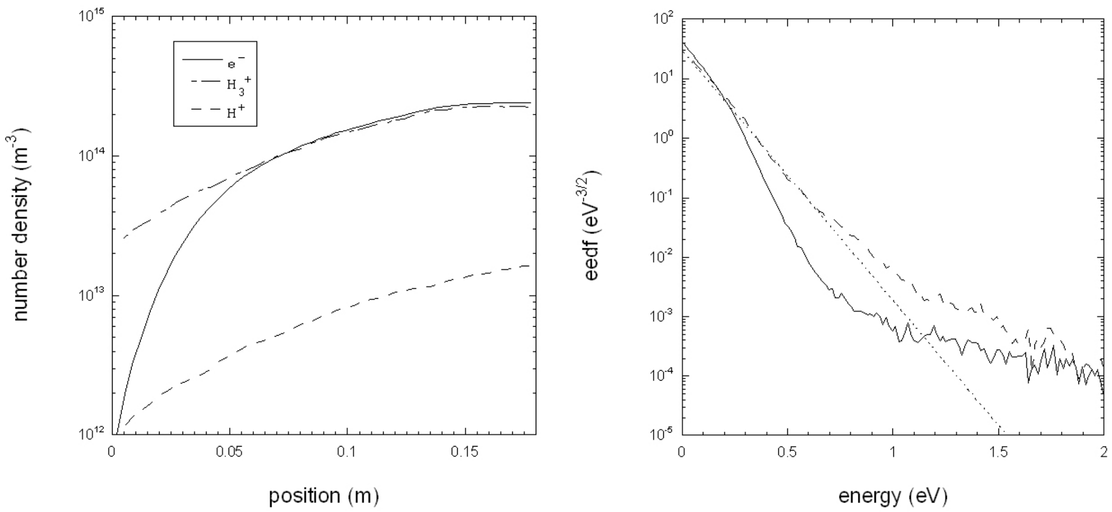

Fig. 3 Charged particle number density and eedf at steady state.

4. Conclusions

The phenomenology which follows the injection of a low temperature (1-10eV) neutralized plasma into a neutral background gas is non trivial and its realistic description by numerical modeling as well as the appropriate interpretation of model results is a scientific challenge. Particle simulation can highlight the complex interplay of plasma dynamics and charged/neutral collision processes.

References

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