Kinetic plasma instabilities due to charge exchange and elastic collisions

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Abstract.

With numerical particle-in-cell simulations, we study kinetic plasma instabilities induced by collisions between plasma particles and neutral background in magnetized drifting plasmas. We consider the role of charge exchange as well as elastic collisions in the evolution of the system. Charge exchange collisions can give rise to velocity distributions in the form of loss-cone or ring shaped distributions that can become linearly unstable. Elastic collisions also lead to the instability, but in this case the principal mechanism may be attributed to the generalized two-stream instability. We investigate the growth rates and saturation levels for instabilities associated with these collisional processes, and find higher saturation levels and stronger fluctuations for the case with charge exchange collisions. Characteristics of the studied system are similar to the E- and F-regions of the Earth’s ionosphere. Our results are relevant for explaining some of the low frequency oscillations observed in the lower parts of the Earth’s ionosphere, and are also relevant for some laboratory experiments.

1. Introduction

In the lower parts of the Earth’s ionosphere, the plasma collisional processes can dominate the plasma dynamics. In those regions, the collision rates between the charged particles and neutrals can surpass the rates of collisions between charged particles \([1]\). In general, the frequency of collisions with neutrals strongly depends on the altitude, and this process is mostly relevant for the ionospheric E-region, which extends above ca. 100 km. In the lower E-region, the ions can become effectively unmagnetized, which can give rise to the two-stream like instabilities \([1, 2]\). In the upper E-region and lower F-region, all charged particles are magnetized, and the plasma is weakly collisional, and is in general drifting due to external electric and magnetic fields in the \(\mathbf{E} \times \mathbf{B}\) direction. In those regions, the collisions may significantly modify the ion velocity distribution functions. Similar conditions can be found in dedicated laboratory experiments \([3, 4]\).

Distorted ion velocity distribution functions can lead to different kinetic microinstabilities. For example, charge-exchange collisions can give rise to loss-cone or ring shaped velocity distribution functions that can become linearly unstable. These distributions will generally not be cylindrically symmetric \([5, 6]\). Elastic collisions can, on the other hand, distort the \(\mathbf{E} \times \mathbf{B}\)
drift of the ions, and in a limiting case, give rise to a generalized two-stream instability [7]. Since
the instability origin is often due to distorted velocity distribution functions, one should use a
kinetic approach or first-principle particle simulations to address this problem.

Different ion-neutral collision types can thus lead to distinct instability regimes. In this
paper, we focus on two limiting cases, where we consider charge exchange or alternatively elastic
scattering for ions in two-component plasmas. We address the problem with a self-consistent
particle-in-cell code that accounts for collisions. By simulating weakly collisional plasmas, we
investigate nonlinear plasma dynamics with the emphasis on the question on how the collision
type affects instability characteristics such as the instability growth, level of the electrostatic
potential fluctuations, and the potential distribution.

2. Numerical Model

Our analysis is carried out with a three-dimensional, electrostatic particle-in-cell (PIC) code.
We simulate the dynamics of electrons and ions in self-consistent fields in a periodic system,
and account also for external electric and magnetic fields, as well as collisions with a neutral
background gas. The code is based on our previous PIC codes, with details on its numerical
implementation given in earlier works [5, 8]. Collisions between plasma particles and neutral
background are implemented with the null-collision method, which allows for arbitrary, energy
dependent collision cross-sections. In the present work, however, we choose to use a constant
collision frequency $\nu$ in order to focus on the basic physical mechanisms associated with a given
collision type. We account for charge exchange collisions or alternatively elastic collisions for
ions. In both cases the electrons experience elastic collisions.

The simulated system is a box of size of 0.5 m in each direction, and spatial grid resolution
of 0.7 cm. Initially, the system is spatially homogeneous. The plasma density is $n = 10^{12}$ m$^{-3}$,
with the electron temperature $T_e = 8.6$ eV, and the electron to ion temperature ratio $T_e/T_i = 4$.
The external magnetic and electric fields are $B_0 = 0.005$ T and $E_0 = 550$ Vm$^{-1}$. The $E \times B / B^2$
drift $v_d$ is supersonic, with $v_d = 2\sqrt{T_e/M}$, where $M$ is the ion mass. The ion collision frequency
is $\nu_{in} = 3.52 \cdot 10^5$ s$^{-1}$, which is lower than the ion gyrofrequency $\Omega_{ci}$, $\nu_{in} = \Omega_{ci}/5$, while
the electron collision frequency is given by $\nu_{en} = \nu_{in}\sqrt{M/m}$, where $m$ is the electron mass. For
computational reasons, we use the reduced mass ratio $M/m = 500$, while keeping the electron
mass realistic, and the mass of cold neutral species $m_n = M$. This reduced mass ratio speeds up
the simulations, while it still gives credible results [9]. We typically run large-scale simulations
for times up to $t = 95000\Delta t$, which corresponds to 19 ion gyroperiods with a timestep $\Delta t$ being
a fraction of the electron gyroperiod.

The simulated plasma parameters can be related to scaled conditions in the upper parts of
the ionospheric E-region, where the plasma is only weakly collisional [1, 2, 5]. However, while the
respective ratios of the parameters are within the relevant range, the one-to-one correspondence
is not maintained; rather the scaled system is simulated. Thus, while we expect that the main
phenomena will be present in the simulations, some of the ionospheric processes might be not
well represented.

3. Results and Discussion

In the simulated system, the charge exchange collisions lead to an asymmetric ring distribution
function for ion velocities, which after one ion gyroperiod, when the full ring shape velocity
is formed, becomes unstable and triggers the instability [5]. This instability mechanism is
equivalent to the loss-cone instability discussed in the context of fusion research [2, 10]. The
instability grows during a few ion gyroperiods until the ring in the distribution function is
filled-in in the velocity phase-space. It is characterized by an enhanced level of fluctuations in
the electrostatic potential distribution, and the growth of harmonics in the wave spectra. A
partially filled ion velocity distribution at a later stage is shown in Figure 1(a). In Figure 2 we
Figure 1. Ion velocity distribution function for the charge exchange (a) and elastic (b) collisions at $t = 4 \cdot 2\pi/\Omega_i$.

show the absolute value of potential fluctuations as a function of time for different collision types averaged over a chosen subset of grid points in the simulated system. The average amplitude of potential fluctuations in the case of charge exchange collisions increases by a factor of three during the simulation, and is characterized by strong fluctuations in the saturated stage with amplitudes up to seven times the initial value. For elastic scattering the growth rate is similar as in the charge-exchange case, while the saturation level is lower, being characterized by much smaller fluctuations. We observe that the elastic scattering modifies the ion-velocity distribution function by strongly broadening the distribution, see Figure 1(b). Thus, the mechanism for the instability will be different than in the case of charge exchange collisions, where the typical loss-cone instability due to non-Maxwellian distribution can be expected [6]. Moreover, in this nonlinear regime there may also be a competition between several other instabilities, thus the instability due to collisions might act to only modulate other instabilities present in the system [1, 11].

The potential structures in the saturated stage of instability are strongly aligned with the $B$-field. The long wavelengths along $B$ can be crucial for the dynamics of the system [1, 12]. However, to study waves at small wavelengths, it suffices to consider only the plane perpendicular to the $B$-field direction. In Figure 3, the potential distribution in the plane perpendicular to the direction of magnetic field is shown for charge exchange collisions, together with the corresponding potential distribution at the beginning of the simulations and at the onset and saturated stage of instability. Initially, the potential distribution is normal, with the maximum values of $\pm 5$ V, and there are no coherent structures observed, see Figure 3(a). Coherent structures start forming during the onset of the instability, and in the saturated stage large, coherent structures propagating in the $E \times B$ direction are observed (i.e., in the negative $\hat{z}$ direction, see Figures 3b-c). The angle of propagation of these structures with respect to the $E \times B$ direction can be related to the supersonic drift regime. As the amplitudes of the fluctuations increase, the potential distribution becomes more shallow, but can still be approximated by a normal distribution.
Figure 2. The amplitude of the potential fluctuations $\|\Phi\|$ averaged over a part of the simulation box as a function of time for elastic (dashed line), and for charge exchange (full line) ion-neutral collisions. Time is normalized to the ion gyroperiod.

Figure 3. The potential distribution in the plane perpendicular to the direction of the magnetic field in the middle of the box together with the corresponding distribution of potential fluctuations in the whole system. The $\mathbf{E} \times \mathbf{B}$-drift is in the negative $\hat{z}$-direction. The results shown are for charge exchange collisions in the beginning of the simulations (a), at the onset of instability (b), and for the developed stage of the instability (c). Note that the range of the $F(\Phi)$-axis in (c) is reduced.
4. Conclusions
With numerical PIC simulations, we have studied the kinetic plasma instabilities in the $\mathbf{E} \times \mathbf{B}/B^2$-drifting weakly collisional plasma, with the parameter regime that can be relevant for ionospheric conditions. Two limiting cases have been considered: charge exchange and elastic collisions. For the case with charge exchange collisions, a significant saturation level for the amplitudes in the potential fluctuations is reached after a few ion gyroperiods. Elastic collisions give rise to much smaller potential fluctuations and a lower saturation level. While the ion velocity distributions are different for these two collision types, the instability growth rate is the same for both cases. It is expected that in this nonlinear regime there is a competition between several instabilities, and thus further detailed analytical and numerical studies are required to identify different competing and dominant processes in the evolution of this system.

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