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ONE-DIMENSIONAL ELECTROSTATIC (ES1) SIMULATION OF THE IONOSPHERIC ELECTRON BEAM-PLASMA INTERACTION

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ABSTRACT

The 1-D Electrostatic, ES1 code, developed by Langdon & Birdsall is used, here, to observe the effects of ionospheric electron beams on the plasma properties. The diagnostics include the displays of the kinetic energy of the particle species, the electrostatic energies of the excited modes and the total energy of the system, as functions of time. It is observed that the linear instabilities developed fully in a very short time and a nonlinear stage, in the form of amplitude fluctuations, quickly sets in. The rate at which the electron beam and the ionospheric electrons lose their (kinetic) energies to the ions and the wave modes (in form of growth rates) are estimated.

1. INTRODUCTION

The ionosphere is a partially ionized medium, containing electrons with thermal energy, $E_{th} \sim 0.03 - 1$ eV. As a plasma, having a density $n \sim 10^6\ cm^{-3}$, it can support electromagnetic waves, and many other waves and instabilities. The ionosphere lies from about 80km above the earth to about 1000km. The ionospheric plasma is not totally ionized but contains neutral particles such as H, O atoms, N_2, O_2 molecules and also bigger particles as dusty grains in plasma. Typical magnitude of the Earth's magnetic field is 5.10^{-5} T.

The sun is a source of charged particles. The solar wind is a means by which activity in the sun is communicated to the earth through the magnetosphere. This interaction depends on a weak field of a few nano-Tesla carried by the plasma. The precipitation of charged particle has been observed, into the near regions of the magnetosphere and the outer ionosphere Characteristic ionospheric electron beams parameters are presented in Table 1 below.

Table 1. Ionospheric Electron Beam Parameters (Duwa & Chike-Obi, 1999)

Altitude Km	Energy KeV	Total Energy Erg/s cm	Electron Flux el/ (s cm^2)	Energy Flux Erg/s cm^2	Pitch Angle deg.	Velocity cm/s	Burst Duration s	Latitude deg	Period hour
<1000	< 40(~10)	200-2000	5x10^{10}	6	< 10°	3-5x10^4	0.1	60°-80°	All
	> 40		10^4		≤20°	5x10^4	4 - 6	45°-77°	Midnight
	< 40		10^7	.2	15°				Daytime

There are a large variety of models for simulating plasmas and, basically, they are of two types, particle models and fluid models. In a particle model, the motion of a large number of charged particles in their self-consistent electric and magnetic fields are followed. In the fluid model, the plasma fluid equations are adopted (Tajima, 1989).
In this work a study is made, by the method of particle simulation, of the effects of the incoming electron beams on some properties of ionospheric plasma system. The Particle-in-cell (PIC) type of simulation, developed by Birdsall and Langdon (1985) and commonly referred to as ES1, is used in the analysis. The key physical quantities that are gained in this simulation are exchanges in energies between the participating particle species and growth rates of the excited waves due to beam-plasma instability.

2. THE ES1 SIMULATION

Many particles, with charge q and mass m, having any positions x, y, z, are weighted to a grid to produce a charge density at the mesh points. The particles have any velocity vx, vy, vz, produce currents q**v**, which are also weighted to grid faces to produce **J** on the grid. Then (, **J**) are used as source terms to obtain the electric and magnetic fields on the grid (**E**, **B**), by solving the Maxwell field equations:

$$\frac{\partial \mathbf{D}}{\partial t} = -\mathbf{J} + \nabla \times \mathbf{H} \text{ and } \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

The fields are then weighted back to the particles. Next, the particles equations of motion:

$$m\frac{d\mathbf{v}}{dt} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \text{ and } \frac{d\mathbf{x}}{dt} = \mathbf{v}$$

are integrated to produce a new velocity **v** and new positions **x**. The cycle is repeated several times. For electrostatic models, such as the ES1 program presented here, Poisson's equation is solved, using , to produce the potentials, and, hence the electric field E on the grid.

A theoretical model ionospheric electron beam-plasma system consists of three interacting particle species; a super-thermal electron beam and thermal electrons and ions (Maggs, 1976; Maggs & Lotko, 1981) with Maxwellian velocity distributions. The plasma is infinite, fully ionized and embedded in the Earth's magnetic field. In our simulation model a super-thermal electron beam interpenetrates a warm, periodic, collisionless plasma. If there were no collective interaction and no instability, the beam would pass without any effect on its kinetic energy. In reality there is an instability that develops and react on the plasma particles.

Our input data, in the required format, for the ES1 Fortran program is as follows:
nsp------------l----------dt-----------nt------mmax-----l/a

3 6.283185307 0.20 600 3 0

ng----iw----epsi-------a1------a2-------E0-----w0
1024 3 1.00 0.00 0.00 0 0

SPECIES 1: super-thermal Electron Beam
n----nv2---nlg---mode
64 0 1 1
wp----wc-----qm-----vt1----vt2---v0
0.1 0.00 -1.00 0.50 0.00 1.00
x1----v1---thetax--thetav
0.01 0.00 0.00 0.00

SPECIES 2: Warm Electron plasma
n----nv2---nlg---mode
1024 0 1 1
wp----wc-----qm-----vt1----vt2---v0
1.00 -1.00 -1.00 0.10 0.00 0.00
x1----v1---thetax--thetav
0.01 0.00 0.00 0.00

SPECIES 3: Warm ion Plasma
n----nv2---nlg---mode
1024 0 1 1
wp----wc-----qm-----vt1----vt2---v0
1.00 0.00 1.00 0.10 0.00 0.00
x1----v1---thetax--thetav
0.001 0.00 0.00 0.00

nsp is number of species, l is length of the system, dt **stands for time step, nt is** total number of steps to be run, ng is total number of grid points, n is number of particles, wp is plasma frequency, wc is cyclotron frequency and qm stands for charge divided by mass (q/m). Conservation of energy in the system is ensured with iw = 3. Explanations of all the parameters can be found in Birdsall and Langdon (1985).

3. RESULTS AND DISCUSSIONS

The results of the simulation are given in form of the plots of the characteristics parameters, used to describe the physical properties of the plasma systems, as functions of time. Figure 1 shows the evolution of the kinetic energies. The kinetic energy, KE1, of the electron beam is seen to be decreasing. So also is the kinetic energy, KE2, of the plasma electron. However, it observed that the kinetic energy, KE3, of the ions, increases with time. Therefore, one can conclude, here, that energy is being transferred to the ions from the other two particle species. The total energy curve is almost constant with time.

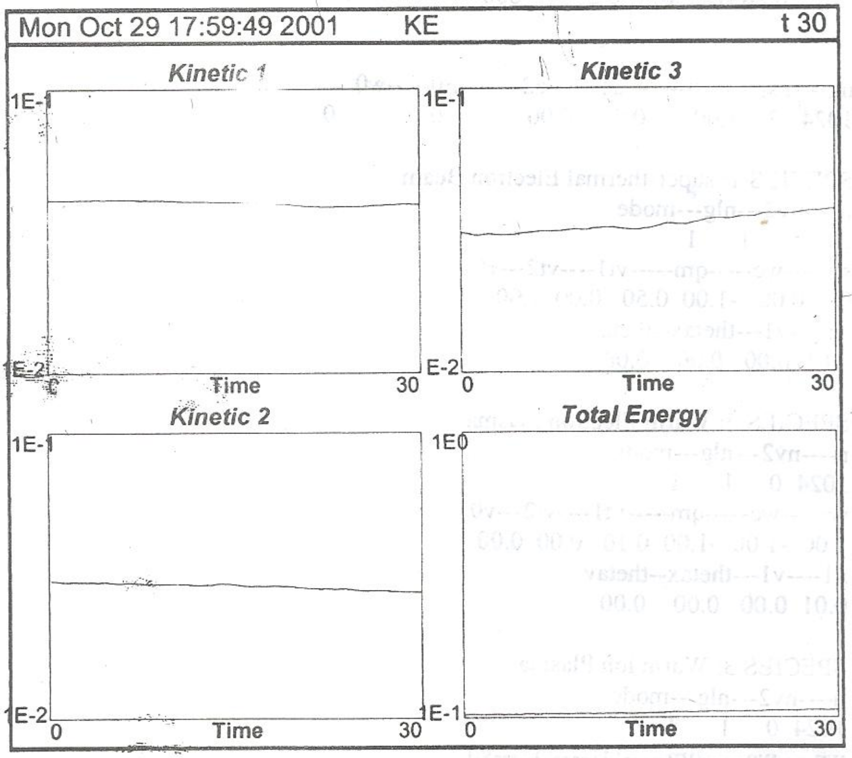

Fig. 1. The displays of the kinetic energy (KE) of each particle species and the total Kinetic energy.

The electrostatic energies, ESE, are modes of the spatially decomposed electrostatic field energy. Figure 2 is the diagnostics for the Fourier transforms of the electrostatic energies, *ESE(k)i* (i = 1,2,3), of the first three excited modes of oscillation and the field energy FE.. The linear growth and damping that appear in ESE1 are due to the collective interactions. The instability occurs as a result of the energy gained from the electrons by the waves. Some of this energy is subsequently lost to the ions, through the Landau damping process. In the diagrams for the ESE2 and ESE3 some successive nonlinear growths and dampings fluctuations could be seen to occur after the saturation of the instabilities

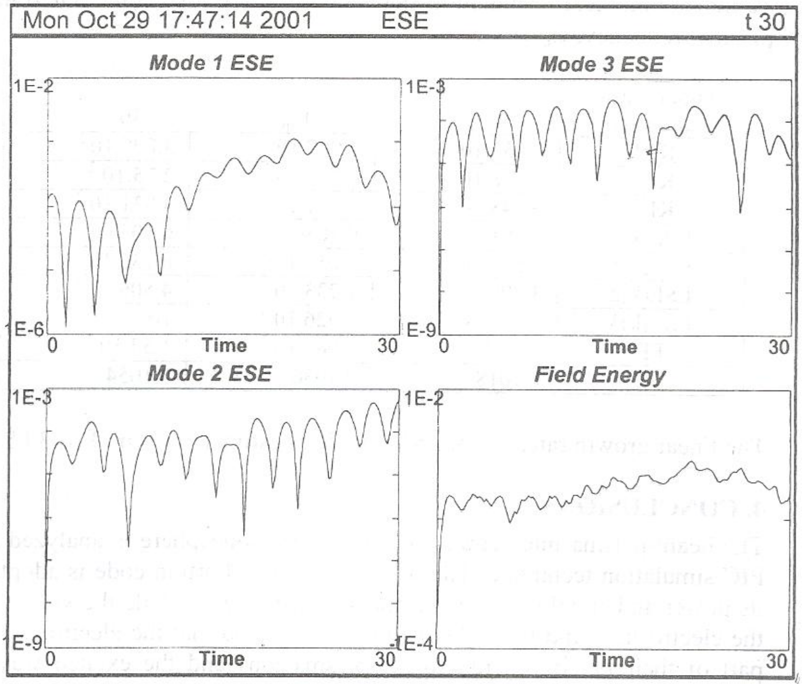

Fig. 2. Graphs, showing the time evolutions of the electrostatic energies, of the first three excited modes, and the field energy.

The growth rate is measured on the field energy semi-log plot. In fact, after the maximum in the field energy is reached, some electrons are captured in the wave potential in the nonlinear stage of the system evolution.

Values of some of the parameters deduced from the simulation are given in Table 2.

Table 2. Numerical results of the simulation, where time is measured in units of plasma frequency, ω_p.

Output Plasma parameters	$t = 10\ _{p}^{-1}$	$t = 20\ _{p}^{-1}$	$t = 30\ _{p}^{-1}$
KE1	$4.037.10^{-2}$	$3.967.10^{-2}$	$3.899.10^{-2}$
KE2	$2.898.10^{-2}$	$2.799.10^{-2}$	$2.75.10^{-2}$
KE3	$3.248.10^{-2}$	$3.511.10^{-2}$	$3.831.10^{-2}$
Total KE	0.1018	0.1036	0.1054
ESE(k)1	$6.579.10^{-5}$	$7.055.10^{-4}$	$6.136.10^{-5}$
ESE(k)2	$3.899.10^{-5}$	$1.233.10^{-4}$	$4.806.10^{-4}$
ESE(k)3	$1.874.10^{-4}$	$5.926.10^{-4}$	10^{-5}
FE	$1.52.10^{-3}$	$2.081.10^{-3}$	$1.52.10^{-3}$
TE	0.1018	0.1036	0.1054

The linear growth rate, γ , of ESE1 mode as estimated from FE is 3.88 ω_p

4. CONCLUSIONS

The beam-plasma interaction occurring in the ionosphere is analyzed using the PIC simulation technique. The widely used ES1 Fortran code is adopted due to its power and simplicity. The diagnostics displayed include the kinetic energies, the electrostatic and the field energies. It is found that the electron species lose part of their kinetic energy to the plasma ions and the excited wave modes. ESE1 shows a large linear growth rate, the amplitude having a sudden growth in a very short time as the result of the interaction with the electrons species of the plasma. The linear growth rate of the instability is estimated from the graph of the field energy. However, Landau damping of the wave is observed at a later time due to ion-wave interaction. ESE2 and ESE3 present completely nonlinear excitations that drive to saturation right at the beginning of the interactions. Numerical results of the simulation are tabulated.

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