EFFECTS OF NEUTRAL GAS RELEASES ON ELECTRON BEAM INJECTION FROM ELECTRICALLY TETHERED SPACECRAFT

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Abstract. The presence of high neutral densities at low altitudes and/or during thruster firings is known to modify the spacecraft potential during active electron beam injection. Two-dimensional (three velocity) particle simulations are used to investigate the ionization processes including the neutral density required, the modification of the spacecraft potential, beam profile and spatial distribution of the return current into the spacecraft. Three processes are identified (i) beam-induced ionization, (ii) vehicle-induced ionization and (iii) beam plasma discharge. Only in the first two cases does the beam propagate away with little distortion.

Introduction

During active injection of electron beams from spacecraft in low earth orbit, the presence of high neutral densities at low altitudes and/or during thruster firings, can modify the spacecraft charging, beam propagation and induced wave emissions (e.g., Gurnett et al., 1988; Gilchrist et al., 1989; Winckler et al., 1989). The presence of such neutrals is important because they can be partially ionized, providing enhanced plasma and thereby enhanced return currents and better neutralization of the spacecraft charge. The ionization can be produced by a variety of processes (e.g. Linson, 1982; Winglee, 1989), including (i) beam-induced ionization where the beam produces the ionization directly, (ii) vehicle-induced ionization where the spacecraft is at sufficiently high potentials to accelerate the return current electrons to ionizing energies, and (iii) beam-plasma discharge where there is rf breakdown of the neutrals via electrons accelerated by high frequency electric fields associated with a beam plasma instability.

Observations of the change in the spacecraft potential associated with thruster firings during the recent CHARGE 2 mission were reported by Gilchrist et al. (1989). In this experiment, a detachable payload (hereafter daughter) was ejected from the main beam-emitting payload (hereafter mother). The daughter was electrically connected to the mother through a conducting tether wire, the aim being to generate controlled VLF emissions. Thruster firings from both the mother and daughter were seen to reduce the spacecraft potential, with the current collected by the daughter increasing during daughter thruster firings while decreasing during mother thruster firings; the spacecraft potential was smallest for mother thruster firings.

The purpose of this paper is to investigate the effects of ionization of neutrals during thruster firings under similar conditions to CHARGE 2 with the aim of identifying (i) the dominant processes responsible for the ionization, (ii) required neutral density around the mother or daughter to prevent strong charging, (iii) the spatial distribution of the currents into the spacecraft and (iv) the changes in the beam properties as the neutral density is increased.

Simulation Model

In order to investigate the ionization of the neutrals and the change in the spacecraft potential self-consistently with the dynamics of the beam-plasma interaction, two-dimensional (three velocity) relativistic electromagnetic particle simulations with collisional processes included were used (cf. Winglee, 1989). A schematic of the simulation model is shown in Figure 1. The mother and daughter payloads are indicated by the black rectangles and are of equal size of dimensions $4\Delta \times 16\Delta$, with the system size being $512\Delta \times 128\Delta$, where Δ is a plasma Debye length (i.e., v_{Te}/ω_{pe}) which is of the order of 10 cm in the present case. The two payloads are assumed to be electrically connected with their potentials being kept equal. The beam is injected at 45 degrees to the ambient magnetic field (which is in the x direction) with a parallel velocity 10 times the ambient electron thermal velocity (i.e., $v_{xb} = 10v_{Te}$) and a beam width of 2Δ. This beam width is the minimum beam width that can be easily simulated and represents some initial expansion of the beam within the first few tens of centimeters, due to the opening or cone angle of the gun and/or to beam-plasma interactions. As a result of the large beam width assumed in the simulations, the beam density relative to the ambient density is assumed to be 4 with the total beam current being similar to the maximum beam current emitted during CHARGE 2, i.e. about 100 mA. The ratio of the electron cyclotron frequency Ω_e/ω_{pe} is taken to be 2, similar to the plasma conditions during CHARGE 2. These parameters are also similar to those used in previous simulations by Winglee and Pritchett (1988) and Winglee (1989).

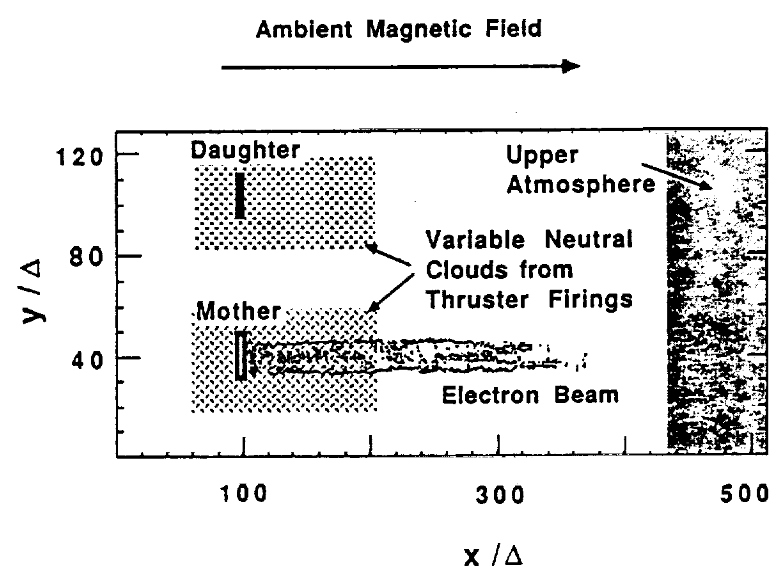

Figure 1. Schematic diagram of the simulation model.

The effects of neutrals and their ionization are incorporated into the simulations as follows. A region of neutrals with a given density is specified on the simulation grid. These neutrals (assumed to be molecular nitrogen) can be placed around the mother or daughter. A dense neutral region is also placed at near the right hand boundary representing the lower ionosphere. The ionization cross-section as given by Banks and Kockarts (1973) has the feature that it increases rapidly once the electron energy is above a few tens of eV, reaching a maximum at about 100 eV and then decreasing approximately inversely proportional to v. For numerical simplicity, the rise in cross-section at low energies is approximated by a sharp cutoff at 100 eV (i.e., $v \simeq 3.3v_{Te}$). This cutoff excludes collisional processes by nonaccelerated ambient plasma electrons which are assumed to be in equilibrium with the ambient neutrals. This cutoff has the effect of underestimating the number of low energy electrons produced by ionizing processes. This approximation is not restrictive since these low energy electrons have a large scattering cross-section which reduces their mobility and hence their contributions to any return currents.

All electrons with higher energies above 100 eV are then binned in levels of speeds relative to $3.3v_{Te}$, with the cross-section decreasing inversely with bin number. The required number of (primary) electrons determined from the collision cross-section is then chosen randomly from each bin. The velocity of the primary is reduced by about a third and a secondary electron and ion are added to the system with the secondary electron having a velocity one third of the initial velocity of the primary with a differential scattering cross-section as given by Mott and Massey (1965).

Beam Injection into Collisionless Plasma

In the absence of any neutrals, the mother and daughter payloads are subject to strong charging and the beam is strongly distorted by the formation of a stagnation region or virtual cathode (cf. Winglee and Pritchett, 1988). The charging of the spacecraft is illustrated in Figure 2 which shows the time histories of (a) the spacecraft potential and (b) the relative current collected by the mother and daughter payloads. The $v_x - x$ phase space of the beam electrons at five different times during the simulation are shown in Figure 3.

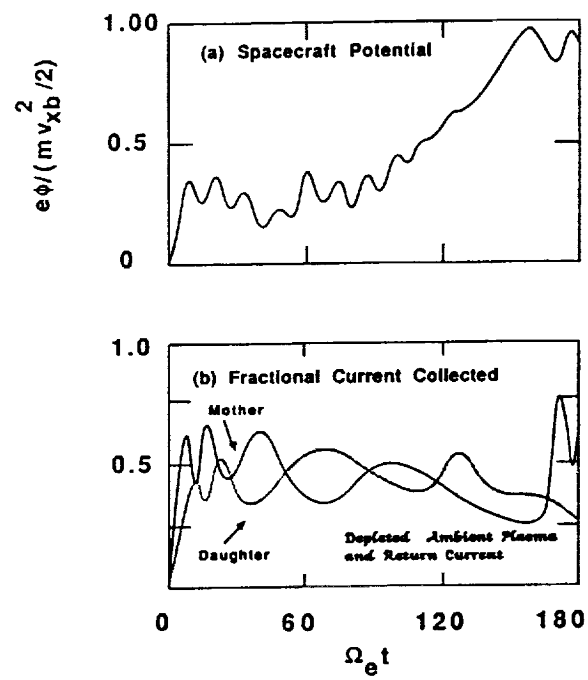

Figure 2. Time histories of (a) the spacecraft potential and (b) the relative current collected by the mother and daughter payloads for injection into a collisionless plasma. At late time the local plasma density becomes depleted, leading to a decrease in the ambient plasma return current collected, particularly by the daughter, and the charging of the spacecraft up to the parallel beam energy.

At early times before the ambient plasma has had sufficient time to respond (i.e., $\Omega_e t \lesssim 30$), the return current is much smaller than the emitted beam current so that the spacecraft rapidly

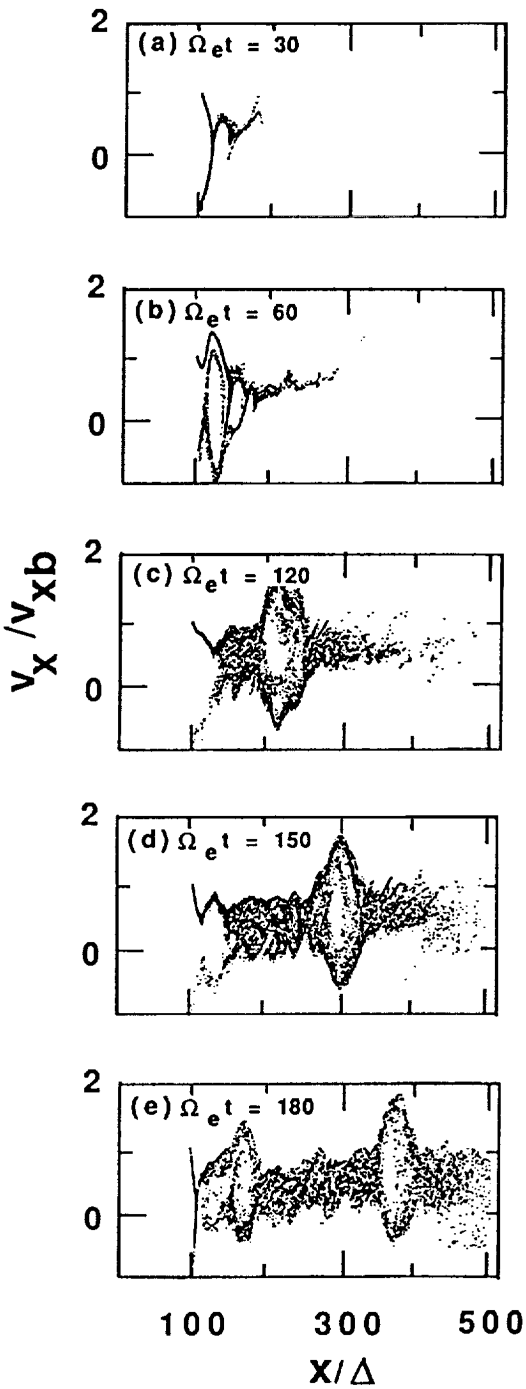

Figure 3. The $v_x - x$ phase space of the beam electrons for five times during the simulation shown in Figure 2. Stagnation regions or virtual cathodes, close in to the spacecraft, are present at both early and late times.

charges up to about 0.3 of the parallel beam energy. At this stage most of the return current into the spacecraft is collected by the mother (Figure 2b) and consists of beam electrons reflected (i.e. $v < 0$) by the formation of a stagnation region (Figure 3a). At intermediate times (i.e., $30 \lesssim \Omega_e t \lesssim 120$), the plasma is able to respond to the beam injection and supply a return current to match the beam current, with mother and daughter collecting comparable amounts of current and with little change in the spacecraft potential. The beam phases spaces in Figures 3b and c show that while the bulk of the beam is able to propagate away from the spacecraft, their average energy is reduced by more than 33% and they are dispersed in velocity and coordinate space.

Due to the inflow of plasma into the spacecraft, the plasma becomes locally depleted. As a result, the plasma return current decreases at later times (i.e., $\Omega_e t \gtrsim 120$) and the spacecraft potential increases until it approaches the parallel beam energy. At this stage, the mother collects most of the return current which again comprises of primarily beam electrons reflected within a stagnation region (Figures 3e).

Beam-Induced Ionization

If neutrals are injected into the beam region (e.g. during a thruster firing), enhanced return currents can be produced by beam-induced ionization, leading to a reduction in the spacecraft charging and beam distortion. The effects of this enhanced return current is illustrated in Figures 4 and 5 which show the same quantities as in Figures 2 and 3 except that a neutral cloud has been included about the mother with a density 5×10^{11} cm^{-3} (and collision frequency $\nu_n = 0.01\Omega_e$), a width in y of 46Δ and extending 50Δ behind the spacecraft and 100Δ forward of the spacecraft. This neutral density is about the minimum required to prevent the spacecraft from charging to the beam parallel energy, with the collision period (i.e., $1/\nu_n$) being comparable to the the spacecraft charging time in the collisionless case (cf. Winglee, 1989).

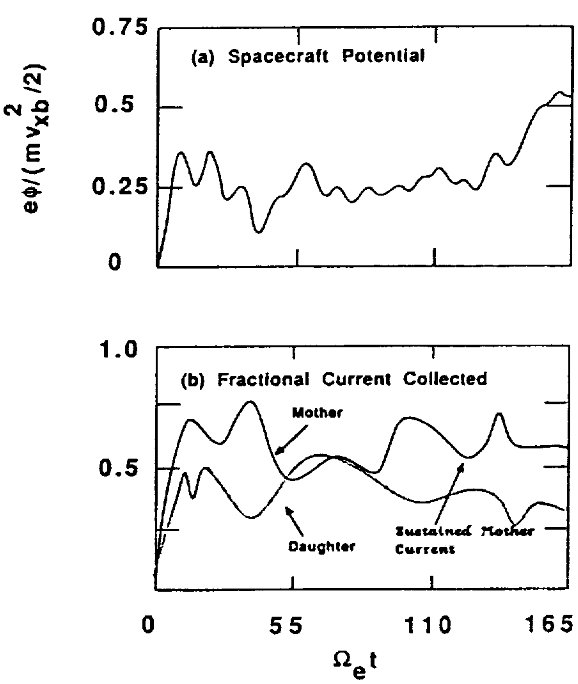

Figure 4. As in Figure 2 except that a neutral cloud around the mother payload has been added. The spacecraft potential on average is reduced by one half to one third and the return current becomes localized to the mother.

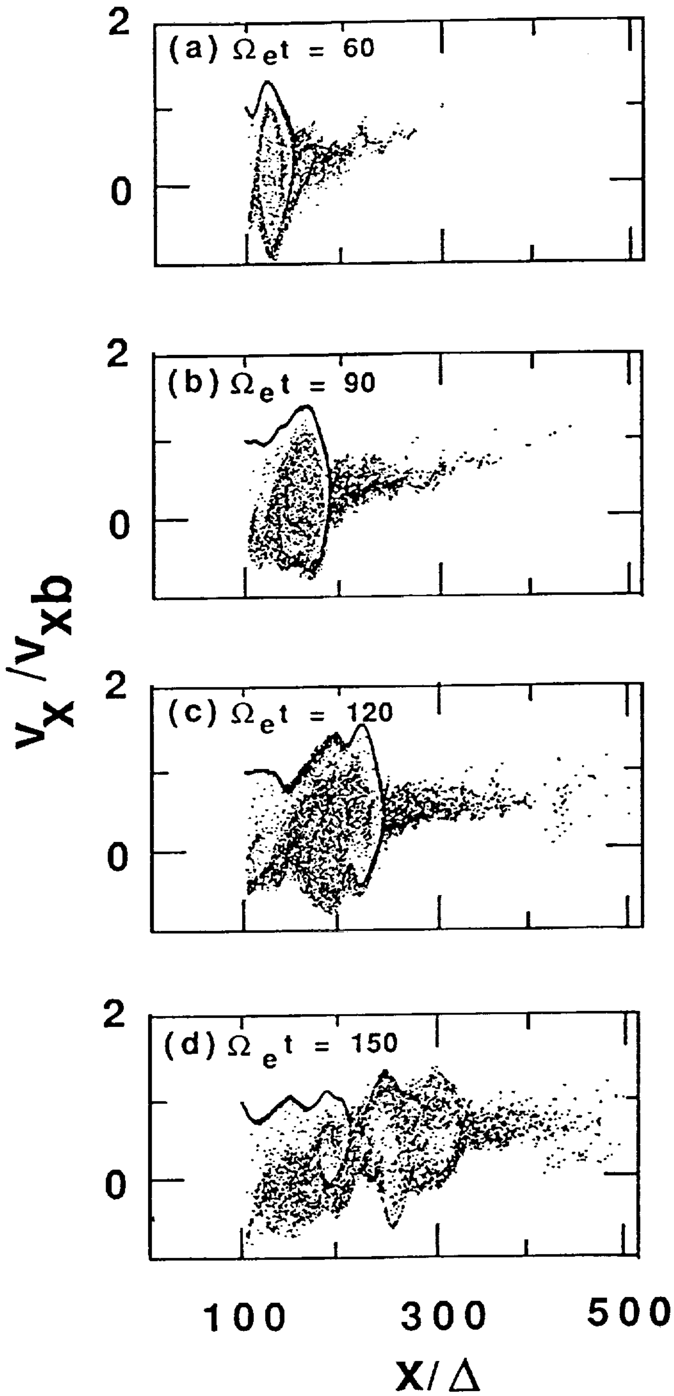

Figure 5. The parallel beam phase space for four times during the simulation shown in Figure 4. Due to the enhanced return current associated with the ionization of the neutrals, the beam is able to propagate outwards with little distortion until it reaches the neutral cloud boundary at $x/\Delta = 200$.

The introduction of the neutrals around the mother has the following effects:

(i) The ionization is predominantly due to direct ionization by the beam particles. As a result, the return current becomes localized to the near vicinity of the beam region. This effect is seen in Figure 4b where the mother on average collects the bulk of the return current into the spacecraft.

(ii) The average spacecraft potential as seen in Figure 4a is reduced by about one third to one-half of that for the collisionless case in Figure 2a (larger reductions are produced if higher neutral densities are assumed).

(iii) A well defined beam is seen in the phase spaces in Figure 5 to propagate outward with little distortion until it reaches the neutral cloud boundary at $x/\Delta = 200$ where strong beam distortion again occurs. This beam distortion is due to the fact that the plasma outside the neutral cloud cannot support the beam current as in the collisionless case and large ambipolar electric fields develop which decelerate the beam electrons and accelerates the ions outwards.

The change in potential and localization of the return current to the mother are consistent with the observations for mother-thruster firings during CHARGE 2.

Beam Plasma Discharge

In the previous example, the presence of high density neutrals in the beam region allows the enhancement of the return current which is able to neutralize the spacecraft charge and allow the beam to propagate with little distortion. Any instabilities in the beam appear relatively weak and there is no rf breakdown of the neutrals by high frequency instabilities associated with the beam plasma interaction. In other words, the above interaction does not represent beam plasma discharge (BPD). This lack of BPD appears to be due to the beam width being narrow compared with a plasma Debye length which restricts the number of modes than can go unstable in the beam region.

However, wider beams are not subject to this restriction and BPD can be excited. As an example, Figures 6 and 7 show the spacecraft potential and parallel beam phase space for the same parameters as in Figures 4 and 5 except that the beam is twice as wide and the neutral density has been increased by a factor of 2 to compensate for the increased charging rate. It is seen in Figure 6 that the spacecraft potential averaged over the duration of the simulation for the wider beam is about twice as high as that for the narrow beam. Superimposed on the overall increase in spacecraft potential are enhanced high frequency oscillations associated with the growth of instabilities made possible by the increased beam width.

These enhanced high frequency oscillations which have a frequency near the ambient plasma frequency are associated with the beam-plasma interaction and can lead to beam distortion. This is seen in Figure 7 where there is enhanced short-scale turbulence in the beam phase space (particularly at late time as in Figures 7c and 7d). As a result of this turbulence there is trapping of electrons (as evidenced by the vortices in the phase spaces) leading to local beam plasma discharge and dispersion of the beam electrons in velocity space. This beam dispersion or distortion occurs closer in toward the spacecraft for the wide beam case (e.g. compare Figures 5d and 7d).

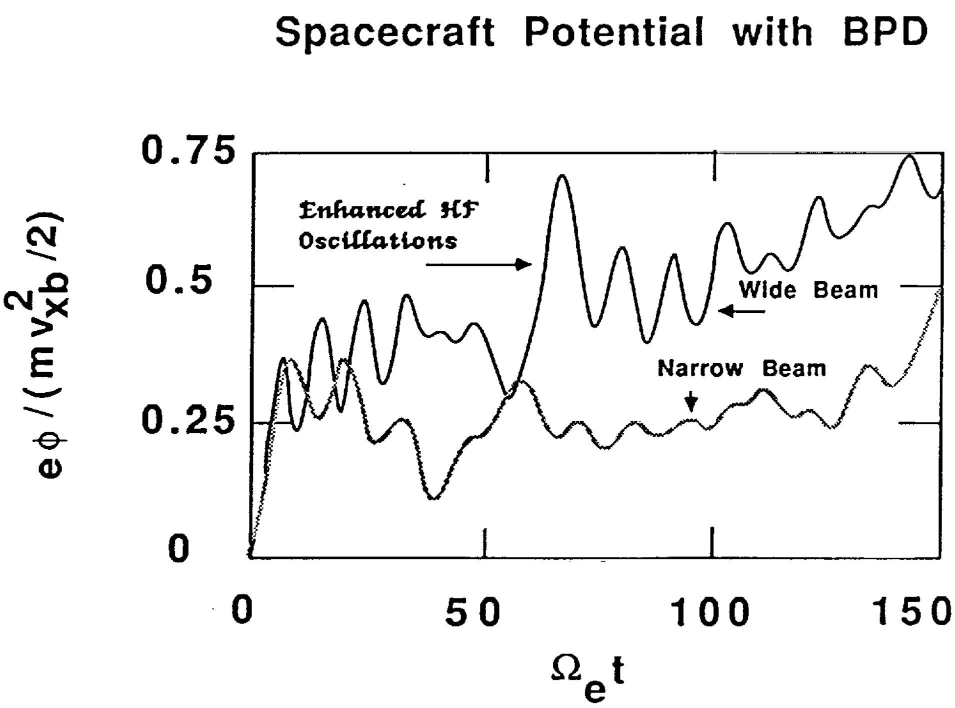

Figure 6. The spacecraft potential for injection of beams with widths of 2Δ (denoted narrow) and 4Δ (denoted wide). The neutral density for the wide beam case is twice as large as the wide beam case in order to compensate for the higher charging rate. The potential for the wide beam case is on average twice as high and subject to large-amplitude high-frequency oscillations which can produce local beam plasma discharge.

Vehicle-Induced Ionization

During certain thruster firings, neutrals need not enter the beam region. In the present application, this occurs during thruster firings from the daughter. The ionization in this case is produced by return current electrons being accelerated by the spacecraft potential to energies greater than a few tens of volts. This vehicle-induced ionization tends to be less efficient than the beam-induced ionization because the highest energy return current electrons are those close in to the spacecraft and moving toward it so that their chance of multiple ionizing collisions before impacting on the spacecraft is small. As a result, higher neutral densities are required to produce the same change in spacecraft potential.

The effects of vehicle-induced ionization on the spacecraft potential is illustrated in Figure 8 which shows the time history of the spacecraft potential for the same size neutral cloud as in the previous cases except that it is centered around the daughter rather than the mother. It is seen that, for the lowest neutral density, the spacecraft charges up to the beam energy whereas, for beam-induced ionization, this density was sufficient to prevent strong spacecraft charging; neutral densities nearly eight times higher are required before the spacecraft potential can be maintained at levels significantly smaller than the beam energy.

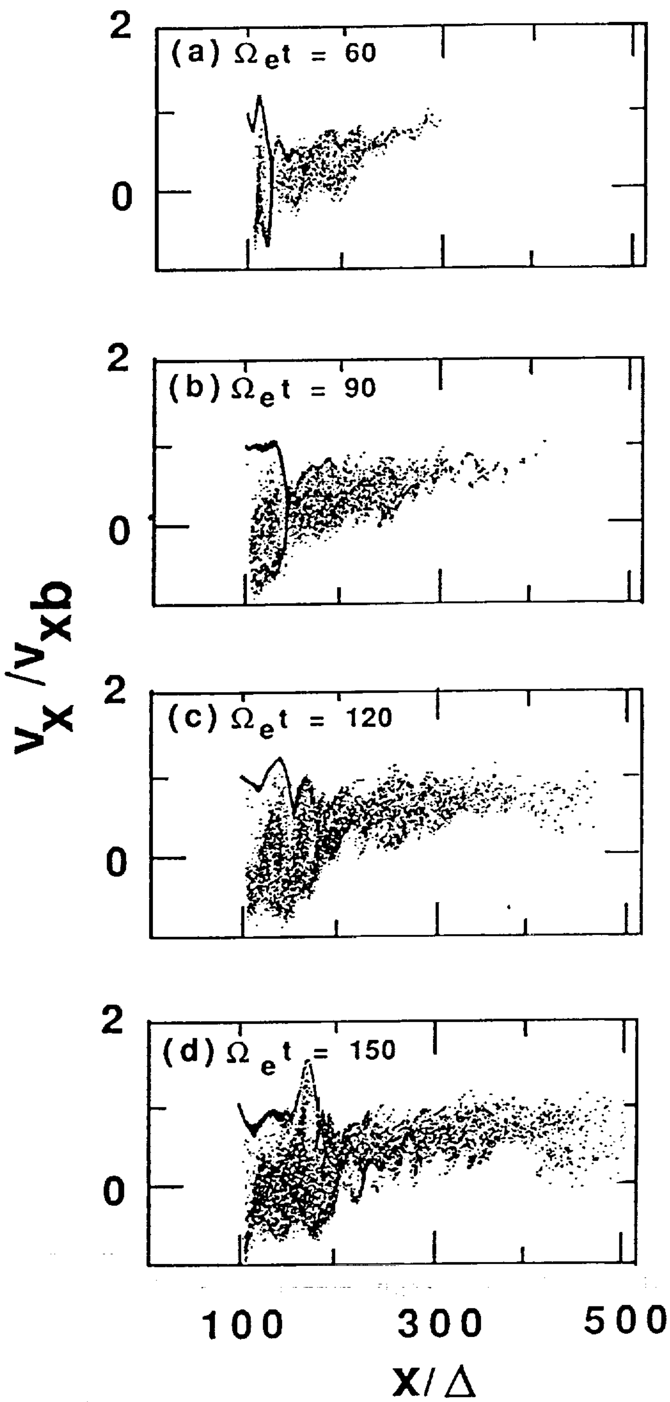

Figure 7. The $v_x - x$ phase space corresponding the wide beam case in Figure 6. The enhanced high frequency oscillations seen in the spacecraft potential appear as short scale vortices in the phase space, which cause the beam to become dispersed in velocity space, and beam plasma discharge can occur in association with these vortices.

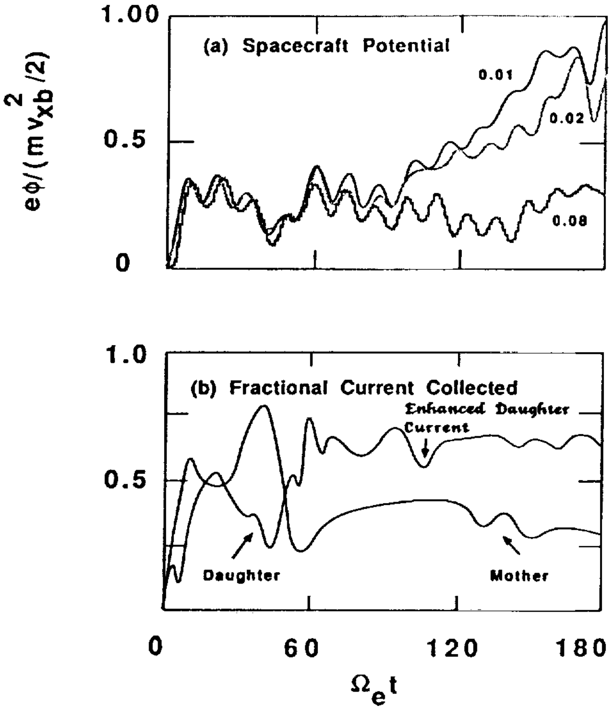

Figure 8. As in Figure 4 except that the neutrals are around the daughter payload instead of the mother. Three different neutral densities are considered with their collision frequency ν_n corresponding to $0.01\Omega_e$, $0.02\Omega_e$ and $0.08\Omega_e$. The lowest neutral density indicated is the same as in Figure 4 which was sufficient to reduce the spacecraft potential to average levels much smaller than the parallel beam energy. Due to the lower efficiency of vehicle-induced ionization, neutral densities nearly 8 times higher are required to produce the same change in potential.

The enhancement of the return current appears as an increase in the current collected by the daughter and a decrease in that collected by the mother (Figure 8a). Both the change in spacecraft potential and the relative amount of current collected by the mother and daughter payloads are consistent with the observations from CHARGE 2 during daughter-thruster firings (Gilchrist et al., 1982). In particular while thruster firings from the daughter were observed to reduce the spacecraft potential, the minimum potential was still higher than that during mother thruster firings. This higher potential arises from the requirement that it be sufficiently high to accelerate electrons to ionizing energies and the efficiency for vehicle-induced ionization associated with daughter-thruster firings is smaller for than beam-induced ionization associated with mother-thruster firings.

The evolution of the beam phase space during beam injection at the highest neutral density in Figure 8 is shown in Figure 9. Similar to the case of beam-induced ionization the beam is able to propagate into the plasma with little distortion until a distance along the magnetic field equivalent to the end of the neutral cloud (i.e., $x/\Delta \simeq 200$). At this point the ambient plasma is unable to support the beam current as in the collisionless case and large ambipolar electric fields develop which decelerates the beam electrons and accelerates ambient plasma ions outwards.

Summary

In summary, the effects of neutral gas releases on active beam injection has been studied through two-dimensional electromagnetic simulations with collisional processes included. Neutrals

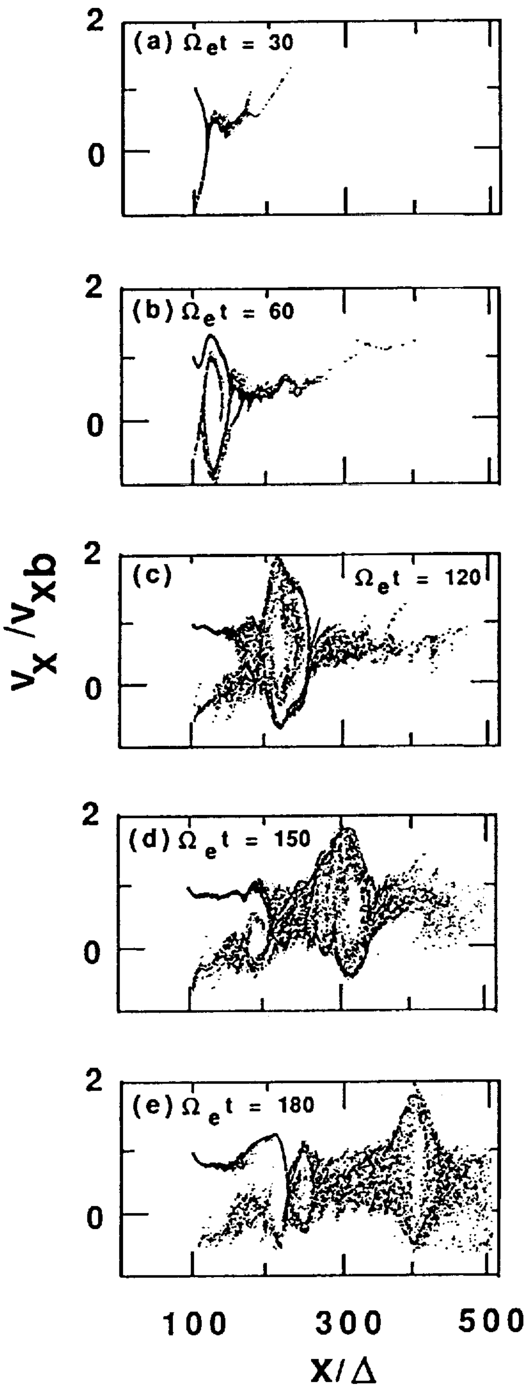

Figure 9. The beam phase space for the high neutral density case in Figure 8.

are important since their partial ionization can increase the local plasma density and provide enhanced return currents to the spacecraft, thereby reducing the amount of spacecraft charging and associated distortion of the beam. It has been shown that the ionization can be produced by (i) direct beam-induced ionization, (ii) vehicle induced ionization and (iii) beam-plasma discharge.

In the cases where beam-induced or vehicle-induced ionization are providing the return current into the spacecraft, the beam is able to propagate away from the spacecraft with little distortion until it reaches the neutral cloud boundary at which point strong ambipolar electric fields develop, causing beam distortion. Vehicle-induced ionization, however, requires high densities to produce the same drop in potential but it has the advantage that the physics of the actual beam-plasma interaction is not modified by the presence of a collisional plasma in the beam region. This latter effect could be important for active experiments where the electron beam is used to investigate beam-plasma interactions and/or to produce controlled wave generation.

Another advantage of using vehicle-induced ionization to neutralize the spacecraft charge is that beam-plasma discharge will not be excited. BPD tends to be excited when there are neutrals in the beam region and the beam is unstable to wave modes which can trap electrons in the beam region and produce enhanced ionization. This trapping tends to preferentially occur for wide beams associated with injection by guns with a large opening angle and/or injection into weak magnetic fields where the beam can expand through the beam-plasma interaction.

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