Double-Probe Potential Measurements Near the Spacelab 2 Electron Beam

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As part of the Spacelab 2 mission the plasma diagnostics package (PDP) was released from the shuttle as a free-flying satellite. The PDP carried a quasi-static electric field instrument which made differential voltage measurements between two floating probes. At various times during the free flight, an electron beam was ejected from the shuttle. Large differential voltages between the double probes were recorded in association with the electron beam. However, analysis indicates that these large signals are probably not caused by ambient electric fields. Instead, they can be explained by considering three effects: shadowing of the probes from streaming electrons by the PDP chassis, crossing of the PDP wake by the probes, and spatial gradients in the fluxes of energetic electrons reaching the probes. Plasma measurements on the PDP show that energetic electrons exist in a region 20 m wide and up to at least 170 m downstream from the electron beam. At 80 or more meters downstream from the beam, the double probe measurements show that the energetic electron flux is opposite to the injection direction, as would be expected for a secondary returning electron beam produced by scattering of the primary electron beam.

1. INTRODUCTION

As part of the Spacelab 2 mission, a spacecraft called the plasma diagnostics package (PDP) was released from the shuttle to survey the plasma environment around the orbiter. At various times, an electron beam was ejected from the shuttle so that the effects produced in the plasma might be studied. In this paper we report on efforts to measure the quasi-static electric fields in the plasma with the PDP, focusing on those times when the electron beam generator was operating. The PDP, a scientific instrument package containing 14 instruments, was designed and constructed at the University of Iowa, and is described by Shawhan [1982]. The electron beam generator, flown as part of the vehicle charging and potential (VCAP) experiment provided by Stanford University and Utah State University, is described by Banks et al. [1987]. The PDP and the electron beam generator were previously flown on the STS-3 flight [Shawhan et al., 1984].

Prior to the shuttle flights, a number of electron beam experiments were performed in plasma chambers and from rockets. Using the same PDP and the same electron beam generator later flown onboard Spacelab 2, quasi-static electric fields of the order of a few volts/m were measured within a few meters of the beam in a large plasma chamber at Johnson Space Flight Center [Shawhan, 1982]. Denig [1982] questioned the reliability of these measurements because of the possibility of differential charging on the measuring probes, and because the fields seemed too large to be sustained in the given apparatus. Kellogg et al. [1982] also reported measuring fields of a few volts/m in a similar chamber test. Measurements of the quasi-static electric fields have also been reported in association with electron beams emitted from rockets in the ionosphere. In the Polar 5 experiment, fields of the order of 0.1 V/m were detected over 100 m away from the beam source [Jacobsen and Maynard, 1978]. During the Echo 6 experiment, Winckler and Erickson [1986] measured fields of the order of 0.2 V/m at a distance of 40 m from the flux tube on which the beam was expected to be centered. All the measurements mentioned here involved differential voltage measurements on floating probes. Considering the chamber and rocket experiments, we expected on the Spacelab 2 mission to detect fields on the order of 1 V/m associated with the electron beam.

The Spacelab 2 mission was launched into a nearly circular orbit, of inclination 49.5°, at a nominal altitude of 325 km. The PDP was in free flight roughly 6 hours, during which the shuttle performed two complete fly-arounds of the PDP. During the fly-around the shuttle was maneuvered to regions upstream and downstream of the PDP. The fly-around included four magnetic conjunctions during which the shuttle was targeted to pass through the magnetic field line passing through the PDP. The electron beam generator was operated at various times throughout the free flight, both in a steady (dc) mode, and in a pulsed mode. During several of these times large signals were detected by the quasi-static electric field instrument. The purpose of this paper is to describe the large signals associated with the electron beam firings and to determine the origin of these signals.

2. INSTRUMENTATION

The PDP quasi-static electric field instrument made potential measurements on two floating probes. These floating probes consisted of conducting spheres mounted on insulated
booms on opposite sides of the spacecraft. The sphere-to-sphere separations was 3.89 m, and the diameter of the spheres was 10.2 cm. A diagram of the PDP, showing the dimensions of the main chassis and the locations of spherical probes 1 and 2, is presented in Figure 1. Two types of measurements were made: the differential voltage, $V_{\text{diff}}$, between the two probes was measured at both a high gain and a low gain, and the average potential, $V_{\text{ave}}$, of the two probes relative to the PDP chassis was measured. The following relations describe the two measurements:

$$V_{\text{diff}} = V_2 - V_1$$
$$V_{\text{ave}} = (V_2 + V_1)/2$$

where $V_1$ and $V_2$ are respectively the potentials of sphere 1 and sphere 2 relative to the PDP chassis. Typically, the differential voltage divided by the antenna length is interpreted as a measurement of the electric field. The basic instrument parameters and dynamic ranges are given in Table 1. Since the floating potential of an object in a plasma is dependent on the

<table>
<thead>
<tr>
<th>Table 1. Instrument Parameters and Dynamic Ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
</tr>
<tr>
<td>Electric field high gain range</td>
</tr>
<tr>
<td>Electric field high gain precision</td>
</tr>
<tr>
<td>Electric field low gain range</td>
</tr>
<tr>
<td>Electric field low gain precision</td>
</tr>
<tr>
<td>Electric field sample rate</td>
</tr>
<tr>
<td>Average potential range</td>
</tr>
<tr>
<td>Average potential sample interval</td>
</tr>
<tr>
<td>Spherical probe separation</td>
</tr>
<tr>
<td>Spherical probe diameter</td>
</tr>
</tbody>
</table>
surface materials, it is also important to describe the surface properties of the spacecraft and spheres. The PDP chassis was covered with a teflon-coated fiberglass cloth which in turn was covered with an aluminum mesh to provide a uniform conducting surface. Potential measurements were referenced to the aluminum mesh. The spherical antenna probes were coated with a conducting graphite-epoxy paint.

After release from the shuttle, the PDP was made to spin by the action of an inertia wheel within the PDP. When spinning at its maximum rate, the spacecraft had a spin period of 13.1 s. The spin axis was oriented approximately perpendicular to the orbital plane. Thus the spacecraft velocity vector lay approximately in the PDP spin plane.

The electron beam generator was mounted in the shuttle payload bay. A beam was produced as electrons emitted from a heated tungsten wire filament were accelerated through a 1-kV potential. The generator operated at beam currents of either 50 mA or 100 mA, producing either a steady or a pulsed beam. The beam was pulsed at frequencies up to 800 kHz.

3. Observations

During most of the free flight, the $V_{\text{diff}}$ signals were of the order of the induced potential due to the orbital motion of the spacecraft, $|V \times B| \cdot L$, where $V$ is the spacecraft velocity and $L$ is a vector pointing from sphere 2 to sphere 1. These signals were typically 0.4 and 0.8 V. The $V_{\text{sw}}$ signal was usually between zero and a few volts positive. That is, the PDP normally floated at a slightly lower potential than the antenna probes. The $V_{\text{sw}}$ signal also showed a periodic variation synchronous with the spacecraft spin period. The periodic variation was found to be related to the operation of the PDP low energy proton and electron differential energy analyzer (LEPEDEA) [Tribble et al., 1988]. The LEPEDEA utilized a current collecting plate whose voltage jumped to +2 kilovolts every 1.6 s. The plate collected a large thermal electron current, and the PDP potential decreased by several volts, recovering to its initial value within 1.0 s. The $V_{\text{sw}}$ signal was spin modulated because the degree of charging of the spacecraft was less when the LEPEDEA aperture faced the spacecraft wake, than when the aperture faced the ram direction. For the $V_{\text{diff}}$ measurement, a large negative potential on the PDP was equivalent to a large positive common mode signal on the probes. Because of limitations in the common mode rejection, the $V_{\text{diff}}$ signal was disturbed whenever the PDP potential exceeded several volts negative. The magnitude of the instrument output due to the common mode signal was generally much less than $|V \times B| \cdot L$. Thus the common mode signal was large enough to make the interpretation of the measurements difficult when the difference between the $V_{\text{diff}}$ and $|V \times B| \cdot L$ was small. However, for $V_{\text{diff}}$ signals larger than $|V \times B| \cdot L$, the common mode rejection problem was not important.

At five times during the free flight when the electron beam generator was operating, $V_{\text{diff}}$ signals were recorded that were significantly larger than $|V \times B| \cdot L$. The signals for these events are shown in Figure 2, and the events are numbered 1–5. At no other times during the PDP free flight were signals this large recorded. Of these five events, the beam was operated in a steady mode for three events, and in a pulsed mode for two events. The beam injection pitch angle varied widely among the events. Table 2 lists the beam operation mode, injection pitch angle, beam current, and several other important parameters regarding these five events.

The basic periodicity of the $V_{\text{diff}}$ signals in Figure 2 is due to the spinning of the spacecraft. In addition to the overall variation at the spin period, the signals have a number of unusual features. During event 1 the instrument saturates. Thus, the difference voltage on the probes is greater than 8 V, which corresponds to an inferred electric field strength in the spin.
plane greater than 2 V/m. Event 2 has a "spiky" character, and events 3, 4, and 5 all show a "double peak" character. At the end of event 3 (around 0049), there is an apparent higher frequency structure to the signal. This structure is associated with the pulsing of the electron beam. Note that as long as the beam was pulsed at 1.2 kHz, then no effect of the pulsing should be apparent in the beam pulse frequency. However, during event 3 the beam pulse frequency was much greater than the Vdiff sample frequency structure to the signal. This structure is the result of a beating effect that occurs near the Vdiff sample frequency of 20 Hz. The apparent higher frequency structure is the result of a beating effect that occurs between the beam pulse rate and the Vdiff sample rate.

In order to understand the origin of the large signals, the phase angle of the spinning PDP was investigated. Arrows are plotted in Figure 2 at the top of the graph to indicate the times when the electric antenna was aligned with the spacecraft velocity vector. Recall that the velocity vector lay approximately in the PDP spin plane. Arrows are plotted in Figure 2 at the bottom of the graph to indicate times when the antenna was aligned with the magnetic field projected onto the spin plane. In general, the magnetic field vector did not lie exactly in the spin plane, but made an angle of between 10° and 24° with the spin plane. The angle for each event is given in Table 2. Inspection of Figure 2 reveals that for cases 2, 3, 4, and 5 a voltage peak occurs when the antenna is aligned with the spacecraft velocity vector, and for cases 3, 4, and 5 a second peak occurs when the antenna is aligned parallel to the magnetic field projected onto the spin plane.

Figure 3 shows the trajectory of the PDP in a plane perpendicular to the magnetic field during all times that the electron beam generator was operating. The direction V_ indicated in the figure is along the component of velocity perpendicular to B. The origin represents the position of the magnetic field line on which the beam lies. V_ is the component of velocity perpendicular to B.

![Fig. 3](image)

**TABLE 2. Beam Parameters, Sunlight Conditions, PDP Orientation**

<table>
<thead>
<tr>
<th>Event</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance from PDP to shuttle</td>
<td>206 m</td>
<td>218 m</td>
<td>93 m</td>
<td>90 m</td>
<td>235 m</td>
</tr>
<tr>
<td>Distance from PDP to flux tube of beam</td>
<td>26-3 m</td>
<td>9-40 m</td>
<td>87 m</td>
<td>84 m</td>
<td>143 m</td>
</tr>
<tr>
<td>Ø, Angle of B to spin plane</td>
<td>22.9°-23.6°</td>
<td>15.4°-15.7°</td>
<td>15.1°-19.4°</td>
<td>10.8°-12.1°</td>
<td>15.4°-16.6°</td>
</tr>
<tr>
<td>Day/night</td>
<td>day</td>
<td>night</td>
<td>night</td>
<td>night-sunrise</td>
<td>night-sunrise</td>
</tr>
<tr>
<td>Beam current</td>
<td>50 mA</td>
<td>100 mA</td>
<td>100 mA</td>
<td>100 mA</td>
<td>100 mA</td>
</tr>
<tr>
<td>Beam injection direction</td>
<td>down</td>
<td>up</td>
<td>down</td>
<td>up</td>
<td>up</td>
</tr>
<tr>
<td>Beam injection pitch angle</td>
<td>&lt;7.5°</td>
<td>2.4°-10°</td>
<td>54°-70°</td>
<td>68°-69°</td>
<td>38°-45°</td>
</tr>
<tr>
<td>Beam mode</td>
<td>dc</td>
<td>1.2 kHz</td>
<td>54 s dc</td>
<td>dc</td>
<td>dc</td>
</tr>
<tr>
<td>Beam current</td>
<td>50 mA</td>
<td>100 mA</td>
<td>100 mA</td>
<td>100 mA</td>
<td>100 mA</td>
</tr>
<tr>
<td>Bev V_</td>
<td>600 Hz stepped down to 10 Hz</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The trajectories during the five large events are shown in Figure 3 as solid segments, and the trajectories during times when the beam generator was operating but the measured differential voltage was small (i.e., less than \((V \times B)\)), are shown by the dashed lines. During events 1 and 2, the length of time the electron beam generator was turned on was longer than the length of time large signals were recorded, indicating that the spatial region over which large signals occur is limited. For each of events 3, 4, and 5, large signals were recorded for the entire period the beam generator was on. Note that events 1–5 occur at times when the PDP was in a region downstream of the flux tube carrying the electron beam. Except briefly during event 1, the perpendicular distance from the PDP to the flux tube of the electron beam was much greater than the 2 to 4 m predicted beam radius, so that the PDP was well outside of the region of the primary beam.

The average potential measurements for events 1–5 are
shown in Figure 4. The largest changes in the average potential measurements associated with the electron beam are seen during events 1 and 2, where the average potential of the probes goes from positive values of +2 to +4 V to negative values of -2 to -4 V. The spin period variation of the signal discussed above can be seen in the graphs for events 1 and 2 during the times before and after the large negative excursions of the signal. During events 3, 4, and 5, the average potential does not change by a large amount, but the smooth spin period variation of the signal is disrupted.

4. INTERPRETATION

Because the determination of the quasi-static electric field with the PDP is based on measurements of the differential voltage between two floating probes, the results can be affected by energetic beam electrons striking the probes. It is easily shown that a small flux of energetic electrons may alter the floating potential of the probes by a large amount [Fahleson, 1967]. Arnoldy and Winckler [1981] reported a population of energetic electrons in the region around an electron beam, causing the floating potential of the Echo 3 rocket to become several volts negative. A similar observation was made on Echo 6 [Winckler et al. 1984]. Thus we might expect to find that the PDP potential is affected by energetic electrons around the beam. In fact, during each of events 1–5 discussed here, the LEPEDEA on the PDP detected energetic electrons at energies nearly up to the beam energy (W. R. Paterson, personal communication, 1987). Further, data from the PDP Langmuir probe seems to indicate that the PDP charged to at least -4.3 V during event 2, and to at least -7.6 V during event 1 (A. C. Tribble, personal communication, 1987). Therefore there is reason to suspect that the probes also charged. If the charging is different for the two probes, then \( V_{\text{diff}}/L \) cannot be safely interpreted as a good measure of the electric field.

To determine the possible effect of energetic electrons on our measurements, we perform a simple calculation of the floating potential. This is done by considering the balance of currents to the object of concern (see, for example, Kasha [1969]). The possible current sources are (1) thermal (background) electrons, (2) thermal (background) ions swept up by the motion of the spacecraft, (3) energetic electrons (energies \( \gg kT_e \)), (4) energetic ions (energies \( \gg 5.0 \text{ eV} \), the ramming energy), (5) secondary electron emission, and (6) photoelectron emission. Measurements made with the LEPEDEA indicate that the current from energetic ions is much less than that from the ramming ions (W. R. Paterson, personal communication, 1987), so this current can be neglected. The maximum secondary electron yields for aluminum (PDP surface material) and graphite (probe surface material), are 1.0 secondaries/primary for 300-eV primaries [Whetten, 1985]. Thus secondary production would reduce the negative charging effect of the energetic electrons by some fraction. Photoemission would also reduce the negative charging. But since we wish to obtain a worst case estimate of the spacecraft potential, we neglect both secondary production and photoemission. We consider then the following current balance equation for an object at potential \( V < 0 \):

\[
A_p n_e u_e (1 - eV/E_e) - A_p n_i (kT_i/2\pi m_i)^{1/2} \exp(eV/kT_i) - A_p J_s = 0
\]

(1)

The first term in the above equation includes the ion current due to the sweeping up of the isospheric ions by the spacecraft motion plus some effect of the attraction of ions to the negatively charged object. The second term is the electron current from the thermal electrons. The third term is the current to the object due to energetic electrons. The variables in (1) are identified in Table 3.

Using the representative parameters given in Table 3, equation (1) was solved numerically for various values of \( J_s \) and \( n_p \). The floating potential was determined from (1) for both the
TABLE 3. Parameters Used in Evaluation of Equation (1)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_{sc}$ spacecraft velocity</td>
<td>$7.8 \times 10^7$ m/s</td>
</tr>
<tr>
<td>$A_s$ cross-sectional area for ion collection:</td>
<td></td>
</tr>
<tr>
<td>PDP probe</td>
<td>$0.869 \ m^2$</td>
</tr>
<tr>
<td>PDP total surface area:</td>
<td>$4.52 \ m^2$</td>
</tr>
<tr>
<td>$E_i$ ion energy in spacecraft reference frame</td>
<td>$5.08$ eV</td>
</tr>
<tr>
<td>$T_e$ electron temperature</td>
<td>$0.2$ eV</td>
</tr>
<tr>
<td>$n_e$ plasma density</td>
<td>$5.0 \times 10^{11} \ m^{-3}$</td>
</tr>
<tr>
<td>$J_b$ current density of energetic electrons</td>
<td>$0-5.5 \times 10^{-4} \ amp/m^2$</td>
</tr>
</tbody>
</table>

spherical probes and for the PDP chassis. The current collecting area of the PDP was taken to be its surface area. Unfortunately, the current collecting properties of the spacecraft body are complicated, and this estimate is to be taken only as a rough approximation. The solution for the floating potential as a function of the energetic electron current density is plotted in Figure 5. Measurements from the LEPEDEA during beam event 1 indicate that $J_b$ was as high as $4 \times 10^{-4}$ amp/m² (W. R. Paterson, personal communication, 1987). The Langmuir probe measurements indicate that during event 1, $n_e$ was of the order of $1 \times 10^{11} \ m^{-3}$ (A. C. Tribble, personal communication, 1987). From Figure 5 one can see that under the conditions of event 1 the PDP floating potential could easily be lower than $-10$ V. This is consistent with the Langmuir probe observation mentioned previously that the PDP charged to at least $-7.6$ V during event 1. More importantly for the $V_{diff}$ measurements, under the conditions of event 1 differences in $J_b$ on the order of $10^{-5}$ amp/m² lead to floating potential differences on the probes of several volts. During events 2, 3, 4, and 5 the Langmuir probe measurements indicate that $n_e$ was of the order of $1 \times 10^{10} \ m^{-3}$ (A. C. Tribble, personal communication, 1987). For this lower ambient density, Figure 5 shows that differences in $J_b$ of the order of $10^{-6}$ amp/m² lead to floating potential differences on the probes of several volts. Figure 5 also shows that for a fixed value of $J_b$, small differences in the ambient plasma density lead to floating potential differences of several volts.

Using the differential voltage between the probes to infer electric field values can produce erroneous results if the two antenna probes receive different amounts of current from any of the various current sources. Current differences can occur if one of the probes is shielded by the PDP chassis from a current source, or if the plasma environment is nonuniform over the length of the antenna. During events 2, 3, 4, and 5 the peaks in $V_{diff}$ are associated with specific orientations of the antenna with respect to the velocity and the magnetic field, and therefore can be primarily attributed to shadowing effects. Shadowing effects of this type were observed by Winckler et al. [1984] during the Echo 6 experiment. In that experiment, large signals at the payload spin frequency were attributed to shadowing of one probe from a magnetic field aligned plasma flow. At the time, the electric probes were stowed in the payload body. During events 3, 4, and 5 the "double peak" character of the signals indicates that two different shadowing effects are occurring. These two effects are discussed separately below.

For events 3, 4, and 5 one finds a voltage peak, and therefore a probable shadowing of one probe, when the antenna is aligned with the magnetic field projected onto the spin plane. Because the local ion larmor radius is much larger than the PDP, a shadowing along field lines suggests a shadowing of electrons. We explain the signal peak in the following manner. For events 3, 4, and 5 the beam was injected in the direction of B. At the time when the antenna was aligned with B in the spin plane, the probe on the boom pointing in the direction of B was at a lower potential than the probe on the boom pointing in the direction of $-B$. Thus we conclude that some energetic electrons are moving in the direction of $-B$, and one probe is shielded from them. So, for the three events when the PDP is 80 or more meters from the beam, the energetic elec-

![Fig. 5. Solution of equation (1) using values from Table 3. Model of floating potential as a function of energetic electron current. Antenna probe and PDP chassis have different floating potentials because of their different current collecting surface areas.](image-url)
injected upward, the effective mean free path will be approximately 10 m -3, which yields 2 ≈ 1400 km. So for electrons downward, it is quite reasonable that electrons reflected by collisions with neutrals could reach the PDP. Since the atomic oxygen density is smaller at higher altitudes, the mean free path becomes longer. At an altitude of 400 km, the density is approximately 10^7 cm^-3 [Johnson, 1965], which yields a mean free path of 140 km. Because the atomic oxygen density is larger at lower altitudes, the mean free path becomes shorter. Thus for events 1 and 3 where the beam was injected upward, it may seem unlikely that the PDP could be affected by reflected electrons. However, it is not necessary that most electrons have a preferred direction, which is opposite to the injection direction. This explanation is consistent with the report by the LEPEDEA group of a secondary electron beam in the shuttle wake [Frank et al., 1987]. The shadowing of one probe from electrons moving downward is pictured in Figure 6a. Consideration of Figure 6b shows that if the angle θ of the magnetic field to the spacecraft spin plane is too large, then shadowing along the field lines will not occur. The range of angles where shadowing is possible is θ < 20.4°. Referring to the values of θ listed in Table 2, one finds that shadowing along field lines is possible for events 2, 3, 4, and 5.

The energetic electrons moving down the field lines and charging the probes in events 3, 4, and 5, may be attributed to reflection of beam electrons by collisions with atmospheric neutrals, or to a beam plasma interaction. First, consider reflection of electrons by collisions. Given the distance of the PDP downstream from the beam for these events, and the spacecraft velocity, one can determine the time of flight for the energetic electrons to be around 10 to 20 ms. For 1-keV electrons, the corresponding total distance traveled is about 200 to 400 km. For comparison, the mean free path of electrons for collisions with oxygen atoms can be roughly estimated by λ = 1/(n_oσ), where n_o is the atomic oxygen density and σ is the collision cross section. We use a value for σ of 7 × 10^{-16} cm^2, the total scattering cross section for 100 eV electrons measured by Sunshine et al. [1967]. At an altitude of 300 km, n_o is approximately 10^8 cm^-3 [Johnson, 1965], which yields a mean free path of 140 km. Because the atomic oxygen density is larger at lower altitudes, λ will become shorter at lower altitudes. Thus for events 1 and 3 where the beam was injected downward, it is quite reasonable that electrons reflected by collisions with neutrals could reach the PDP. Since the atomic oxygen density is smaller at higher altitudes, λ becomes longer at higher altitudes. At an altitude of 400 km, n_o is approximately 10^7 cm^-3, which yields λ ≈ 1400 km. So for electrons injected upward, the effective mean free path will be ≈ 1400 km. For events 2, 4, and 5 where the beam was injected upward, it may seem unlikely that the PDP could be affected by reflected electrons. However, it is not necessary that most of the beam particles be reflected. The solution of (1) showed that the measured signals are explained by differential energetic electron currents of the order of 10^{-6} amp/m^2, and this current can result from only a small percentage of beam particles being reflected. An alternative explanation for the presence of energetic electrons is considered by Wilhelm et al. [1985]. In the SCEX experiment, Wilhelm et al. measured energetic electrons in the region downstream of an electron beam. They discuss the possibility that the energetic electrons are the product of a beam plasma interaction. Both explanations are possible, and without a further more detailed analysis we cannot say which is correct.

A different shadowing effect occurs for events 2, 3, 4, and 5 when the antenna is aligned with the velocity vector. Because the local ion thermal speed is less than the spacecraft velocity, ions are swept up by the spacecraft motion. The electron thermal velocity is much greater than spacecraft velocity, so the electrons are not swept up. However, because quasi-neutrality must be maintained, both the ion and the electron densities are reduced behind the spacecraft, forming a plasma wake. The solution for the density at later times is given by

\[ N = N_0 \exp \left( \frac{x}{S_0 t} + 1 \right) \]

where \( S_0 \) is the ion sound speed. To obtain an estimate of the density at the probe when the probe is in the wake, we use (2) and take for x the radius of the PDP, x = 0.53 m, and for t the time for the ionospheric plasma to flow a distance of half of the antenna length relative to the PDP, t = 2.5 × 10^{-4} s. Assuming an electron temperature of 0.2 eV, and assuming ions are atomic oxygen, the ion sound speed is estimated to be...
cause the entire region where the large electric field signals electrons and an electric field. We cannot rule out the possibility that we have measured the electric field. However, being only to within a few meters.

Figure 7 shows that the peaks in voltage are not consistently detected as in Figure 3. The Vdiff signals first becomes larger than \(|V \times B| \cdot L|\), and the gradient in the energetic electron flux first becomes significant, when the PDP is about 10 m away from a line extending directly downstream from the center of the beam. The Vdiff signal, and thus the gradient in the electron flux, become larger as the PDP gets closer to this line. The gradient vectors tend to point toward the line. The indicated picture is that of a region of energetic electrons downstream from the primary electron beam. The region is not homogeneous but rather the electron flux is peaked along the line extending directly downstream from the primary beam.

The presence of a gradient in energetic electron flux can account for the large magnitude (larger than 8 V) of the Vdiff signals during event 1. If the magnitude of the gradient in \(J_{0}\) is estimated from the LEPEDEA measurements, then the Vdiff signal that would result from such a gradient can be estimated. As stated previously, the LEPEDEA measured a peak value of \(J_{0}\) of about \(4 \times 10^{-4}\) amp/m². We assume that the flux of energetic electrons is peaked on a line extending directly downstream from the center of the beam, and is symmetric about that line. Since the region where large signals are detected is about 20 m wide, the spatial gradient \(\Delta J_{0}/\Delta x\) is approximately \(4 \times 10^{-4}\) amp/m²/(10 m) = \(4 \times 10^{-5}\) amp/m. The resulting Vdiff can be estimated by

\[
V_{\text{diff}} = (\Delta J_{0}/\Delta x)(\Delta V/\Delta J_{0})(L \sin \theta)
\]

where the quantity \(\Delta V/\Delta J_{0}\) must be determined from Figure 5, \(L\) is the antenna length, and \(\theta\) is the angle of \(B\) to the spin plane. For \(n_{0} \approx 1 \times 10^{11}\) m⁻³ and \(J_{0} > 4 \times 10^{-5}\) amp/m², \(\Delta V/\Delta J_{0} = -1.6 \times 10^{4}\) V/amp/m². The antenna length is 3.89 m (see Table 1) and \(\theta\) is about 23° (see Table 2). Using equation (4) with the given values, we obtain \(V_{\text{diff}} \approx 9.7\) V. Thus a gradient in the energetic electron flux of the magnitude indicated by the LEPEDEA measurements could easily produce the Vdiff signals recorded during event 1.
Analysis of all five events suggests that energetic electrons are found in a region about 20 m wide extending up to 170 m downstream from the injected electron beam. Consideration of event 1 indicates that very close to the beam, there is a large spatial gradient in the energetic electron flux: the flux increases as one approaches the line extending directly downstream from the center of the beam. We expect that the energetic electron flux is symmetric about this line. For events 3, 4, and 5, in which the PDP was 80 or more meters away from the beam, the signals are explained by the presence of energetic electrons having a preferential direction of motion along the magnetic field line, but in a direction opposite to the beam injection.

Although the main features of the $V_{diff}$ signals during events 1-5 are understood in terms of the discussion given above, some features remain unexplained. For example, the voltage peaks during event 4 are bumps on a signal that is otherwise sinusoidal. The peaks in event 4 are explained by alignment of the antenna with the magnetic field or with the velocity vector in the presence of energetic electrons. However, the $V_{diff}$ signal for event 4 shown in Figure 2 would also provide a reasonably good fit to the function in (4). Yet, since the shadowing effects are apparent in the measurements, a fit of the signal to (4) would be difficult to interpret. It is not clear why event 4 has a more sinusoidal character than events 3 or 5. Similarly, the large peaks in the signal during event 2 can be attributed to alignment of the antenna with the velocity vector in the presence of energetic electrons, but the signal remains $> [V \times B] \cdot \mathbf{J}$ when the probes are not in the spacecraft wake.

Finally, we consider the average potential measurements. The measurements show that during periods of no beam operation, the average probe floating potential was several volts higher than the PDP chassis floating potential. The solution of (1) (see Figure 5) indicates that the probes should float to a potential which is much less than a volt higher than the PDP potential. During events 1 and 2 the average probe floating potential became lower than the PDP potential. The solution of (1) indicates that the average probe floating potential should always be higher than the PDP chassis potential. The reasons for these discrepancies are not clear. However, we speculate that explanation involves the properties of the PDP surface materials. In solving (1) for the PDP potential, we assumed the PDP to have a uniformly conducting surface. However, the potential of the aluminum mesh on the PDP surface may be influenced by the fiberglass cloth which underlies it. The fiberglass cloth may be charging to a different potential than the aluminum mesh. Katz and Davis [1987] analyze some of the effects of the fiberglass cloth-aluminum mesh arrangement for the situation of the PDP attached to the shuttle. The ultimate effect on the mesh potential for the PDP in free flight is uncertain.

5. Conclusions

Our conclusion from this analysis is that the large signals measured by the PDP quasi-static electric field instrument during electron beam operation can primarily be attributed to three causes. First, at times when the electric antenna is aligned with the projection of the magnetic field into the spin plane, the spacecraft body shields one probe from energetic electrons moving along the magnetic field lines. The two probes receive different amounts of electron current, thereby causing large signals. Second, at times when energetic electrons are reaching both probes, but one probe is in the PDP wake, the wake produces asymmetries in the plasma density at the two probes, thereby causing large signals. Finally, spatial gradients in the energetic electron fluxes between the two antenna probes produce differences in the energetic electron current to the two probes, thereby causing large signals. When the electron beam generator is operating, energetic electrons are found in a region about 20 m wide and up to 170 m downstream from the injected electron beam. Because the region is so narrow, the spatial gradients are significant even over the extent of the PDP antenna. For events 80 or more meters away from the beam, the electric field results are explained by the presence of energetic electrons having a preferential motion back down the magnetic field line on which the beam was injected.

On the Spacelab 2 mission, it was demonstrated that with the shuttle it is possible to carry out detailed studies of electron beam effects under carefully controlled conditions. Thus, it should be possible to obtain a good map of the electric field near an electron beam. However, our experience indicates that double probe floating potential measurements are not reliable in the region near the beam. The floating potential of an object in a region with substantial fluxes of energetic electrons can be many times $kT/e$ more negative than the plasma potential. A small difference in energetic electron current collected by each probe of a double probe system can then lead to differential voltages much higher than those due to any electric field in the plasma. Reliable potential measurements probably will require biased probes, such as described by Fahleson [1967], or emissive probes such as described by Bettinger [1965]. These active potential measurements are not as sensitive to energetic electrons. An example of a biased probe system is found on the ISEE-1 spacecraft [Mozer et al., 1978]. In general, though, active potential measurements have not been widely used because of the appealing simplicity of floating potential measurements. However, for future spacecraft electron beam experiments, active instead of passive potential measurements will probably have to be considered.

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