Adv. Space Res. Vol. 1, pp. 69-76.
0273-1177/81/0201-0069$05.00/0

ROCKET POTENTIAL MEASUREMENTS DURING ELECTRON BEAM INJECTION INTO THE IONOSPHERE

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ABSTRACT

The results of measurements made by the retarding potential analyzer of electron fluxes recorded during electron beam injection ~0.5A current pulses and energy 15 or 27 keV during the ARAKS experiment are analyzed. The relatively low rocket potential (~150 V) observed is explained by the formation of a highly conducting region near the rocket. Such a region can be formed via intense plasma waves generated by the beam. This mechanism also explains the heating of the electrons near the rocket. Measurements of electron fluxes with energies of 1 to 3 keV and estimate based on the beam plasma discharge theory agree very well.

MEASUREMENTS

In the Soviet-French experiment ARAKS [1,2], retarding potential analyzers, described in detail in [3], were used to study electron fluxes. Two identical analyzers (each a cylindrical planar device consisting of a collector and grid system [3]) were mounted on a lateral surface of the ERIDAN rocket during the ARAKS experiment of January 26, 1975 at the distance of about 1 m from the electron gun. The cycle time of the analyzing voltage V_R was 0.64 s, and was almost synchronized with the operation of the gun (with period 0.56 s). Collector currents and analyzer voltages were measured each 30 ms. The retarding voltage varied as a saw-tooth from 9 V to 300 V in one analyzer and, in the other, from 90 V to 3000 V to exclude non accelerated ionospheric electrons. The dinamic range of the instrument was from 10^{-10} to 10^{-6}A; the maximum current density measured by the analyzer was about 2×10^{-7} $A \cdot cm^{-2}$.

Measurements of the retardation characteristics make it possible to determine the value of the rocket potential relative to the local plasma environment on the basis of the following idealized model. At all times the collector only receives those electrons whose energies exceed the retarding voltage V_R. During operation of the electron gun the rocket can acquire a positive potential Φ which creates a negative space charge around it. If the number of collisions that an electron inside this space charge region makes is negligibly low, the cold ionospheric electrons should acquire an energy $E = e\Phi$ when incident on the analyzers. Thus, with the retarding potential $|V_R| \lesssim \Phi$, the collector current should rise sharply; Φ can therefore be determined as the value of V_R corresponding to the rapid increase of the collector current. The temperature of the heated electrons in the plasma surrounding the rocket on which an electron gun is operating can be determined from the slope of the retardation curve based on Langmuir probe theory.

This paper considers only data obtained during electron injection with a pulse duration of $\tau_1 = 2.56$ s and with the direction injection along the rocket's longitudinal axis. During one rocket spin the direction of the electron beam relative to the geomagnetic field (the injection pitch-angle) varied by only $\pm 6^\circ$.

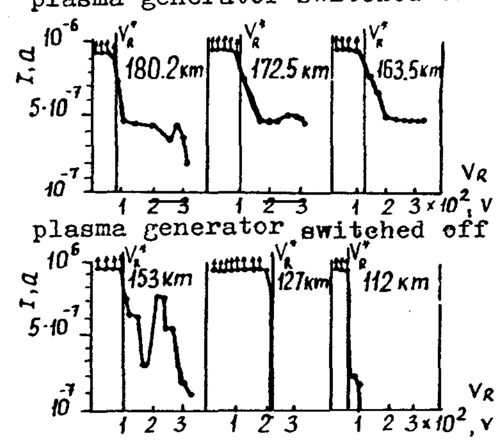

Fig. 1 Retardation curves for different portions of the rocket trajectory ($V_R \lesssim 300$ V)

RESULTS

The general character of the retardation curves was the same whether the electron injection energy was 15 keV or 27 kev, and also whether or not the plasma generator, injecting quasineutral cesium plasma with on ion current of about 10 A [1, 2], was switched on. As an example, Figs 1 and 2 give the types of retardation curves observed at different positions along the rocket trajectory. The character of the retardation curves changes considerably with height: the intensity higher energy electrons (E>200 eV increases with height above ~ 125 km.

As the retarding potential decreases there is always a sharp increase of current in the interval between 10^{-7} and 10^{-6} A. These current jumps are observed in both analyzers at different instants of time, but for the same value of V_R (< 200 V) marked V_R^* and V_R^{**} respectively. These values are taken to correspond to the potential of the rocket relative to the local plasma environment. It should be mentioned that the retardation curves observed during one injection pulse τ_1 are approximately the same (see Fig. 3): they do not depend on the orientation of the analyzer relative to the geomagnetic field. However, as seen in Fig. 3, the retardation curves show aperiodically appearing maxima and minima. Even in those cases when the retardation curves are similar and smooth between 1 kV and 2 kV, the collector current values differ by almost an order of magnitude for similar V_R values. This demonstrates that the temporal fluctuations of the fluxes observed do not depend on the spin of the rocket.

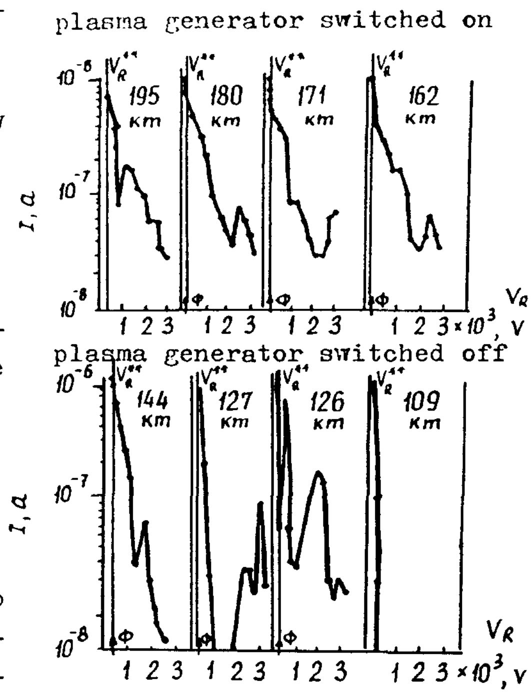

Fig. 2 Retardation curves for different portions of the rocket trajectory ($V_R \lesssim$ 3000 V)

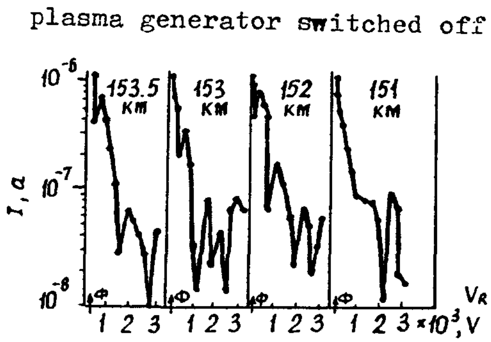

Fig. 3 Retardation curves corresponding to one injection pulse

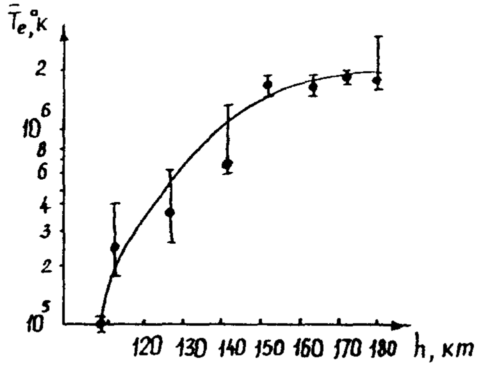

Fig. 4 The altitudinal distribution of electron temperature T_e near the rocket

At the heights h $\gtrsim$ 115 km the current jump are not so sharp as they would be if the electron currents to the rocket were created only by cold ionospheric electrons accelerated to an energy eΦ . The current-voltage characteristics in the region of the current jumps show that the electron temperature Te in the near rocket region increased with height from 10^5 to $2\mathrm{x}10^{6}$ °K (see Fig. 4).

The altitudinal variation of the rocket potential determined in this way is shown in Fig. 5,where each Φ value is averaged over four retardation curves for one long injection pulse. The variation of the rocket altitude during this period did not exceed ~ 2 km. The scatter in the observed Φ values during the time 1 is probably caused both by possible variations of the injection current and the inaccuracy of determination of the collector current jump because of heating of the plasma surrounding the rocket. The operation of the plasma generator scarcely affected the rocket potential.

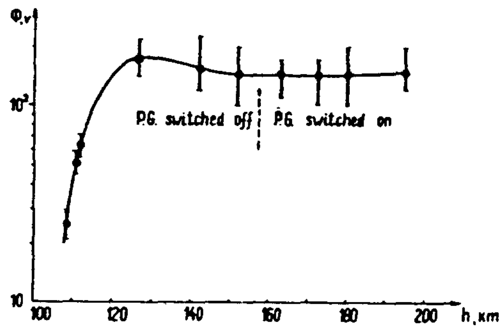

Fig. 5 Rocket electrical potential Φ (h)

DISCUSSION

It follows from Fig. 5 that the rocket potential in the experiment discussed did not exceed ~150 V at ~130 to 190 km, and decreased to 20 V near 100 km. At all heights a steady potential was reached in less than 30 ms. At the same time Figs 1 and 2 undoubtedly show considerable variations of the near rocket plasma characteristics during electron injection.

The derived Φ (h) and T_e(h) do not contradict the theoretical assumptions made. Indeed, for heights where the neutral density is high, $N > N_{min} \simeq (1 \text{ to } 3)\ 10^{10}\ cm^{-3}$, the processes of rocket body neutralization during the injection of intensive energetic electron fluxes occur by a beam plasma discharge near the rocket. Thus the electron density (n_e) and the electron temperature (T_e) increase, and this provides the neutralization [4] . In this case a region with enhanced plasma conductivity forms around the rocket. The longitudinal size of the disturbed region is determined by the length within with the intensity of plasma oscillations generated by the beam is sufficient for heating the ionospheric electrons. For the conditions of the beam-plasma discharge above 130 km [6] , this length [8] is of the order of

$$\ell_{\parallel} \simeq \frac{1}{10}\, V_b/\omega_p\, \frac{\mathcal{E}}{kT_e} \left(\frac{M}{m}\ \frac{n_e}{n_b}\right)^{1/2} (\Delta V_b/V_b)^4 \sim 10^7\ (\Delta V_b/V_b)^4\ \text{cm},$$

where $\mathcal{E} = mV^2_{b/2}$ is the beam energy, ΔV_b - is the velocity scatter, n_b is the beam density.

This estimate is in good agreement with the sizes of the disturbed glowing region observed in the Zarnitza-2 experiment [7] . The transverse size of the region is determined by the beam diameter and in this case should be $\ell_\perp \sim 1$ to 3 m taking both the extension of the beam due to electrostatic repulsion and the restriction of this process by the "magnetization" of the beam electrons into account. At great heights, where $N < N_{min}$ and $n_e \simeq n_o \simeq 10^5\ cm^{-3}$, as well as at the initial stage of the discharge, the increase of the neutralization current providing the observed low rocket potential can be explained by heating of the surrounding ionospheric electrons by the beam [5] . For these heights (for $h \gtrsim 160$ km) it is rather difficult to obtain a specific estimate of ℓ_{11}, but it can be assumed that due to a "clearing" mechanism [5. 9] , it will be rather high.

The neutralization current from the space charge region defined as $j_\perp \sim -en_e v_{T_e}$ [4] should exceed the injection current at the heights of $h \lesssim 160$ km, i.e. the rocket potential should be floating, i.e. $\Phi \sim kT_e/e$. This is inconsistent with the measurements (see Fig. 5), and points to the necessity of considering ionospheric electrons entering the disturbed region. Indeed this requires the presence of an electric field in plasma, i.e. the appearance of a positive rocket potential.

Assuming that the ionospheric electron current through the cross section of the disturbed region ($S_\perp$) is not sufficient for the compensation of the injection current ($en_o V_{Te} S_\perp < I_o$), the current must path through the lateral surface of the disturbed region. This current is mainly produced by the radial electric field originating because of the disturbed region (and the rocket) are at the potential $\sim \Phi$. Then $j_\perp = \sigma_\perp E_\perp \sim \nu_{en} \; \omega^2_p / \omega^2_{He} \cdot \Phi / r_\perp$, where $\nu_{en} \simeq 10^{-7} \; NT_e^{5/6}$ is the ionospheric electron-neutral collision frequency; $\omega_p \simeq 6.10^4 \sqrt{n_o} \; s^{-1}$, ω_{He} is the electron gyrofrequency. Now the longitudinal size of the disturbed region at whose surface the current concentrates is

$$\ell_* \sim I_o / j_\perp 2\pi r_\perp \sim 10^6 \; \left(\frac{100}{\Phi} \right) \left(\frac{0.1}{T_e} \right)^{5/6} \frac{10^{10}}{N} \quad \text{cm.}$$

In this case, the value ℓ_* does not depend on the transverse size of the disturbed region. If $\Phi \lesssim 200$ V, then $\ell_* < \ell_{11}$. When the transverse dimension of the disturbed region is so high that $en_o V_{Te} S_\perp \gtrsim I_o$, the rocket acquires a positive potential which performs work against the frictional force caused by electron scattering on the turbulent oscillations (ν_{eff}).

At lower heights, the neutral particle density N as well as the discharge plasma density are larger and the effective frequency of collisions is smaller; thus the conductivity of the disturbed region is higher and the potential Φ is lower.

Although it is expected [5, 6] that $T_e \sim {}^1/n_e$, the plasma density near the rocket is $n_e \simeq N$ for $N \gtrsim 3 \times 10^{10}$ cm^{-3}, and independent on N for $N < 3.10^{10}$ cm^{-3}. The observed fluxes of fast electrons ($E \gg e\Phi$) in the disturbed region, whose energy considerably exceeds kT_e, also agree with theoretical estimates. For this region these fluxes are approximately equal to [8] :

$$n'(E) \simeq n'_\infty (E_{min}/E)^{9/4},$$

where $n'_\infty \simeq 10^{-3}$ is the total number of particles with $E > E_{min}$, $E_{min} \simeq$ (6 to 7)kT_e is the energy above which the Maxwellian distribution is disturbed; n' (E) is the number of particles with $E > E_{min}$. At $h \simeq 120$ km, $T_e \simeq 20$ eV (see Fig. 4) and n' (1.5 keV)/ $n'_\infty \simeq 5.10^{-3}$; for $h \simeq 140$ km, $T_e \simeq 100$ eV and n'(1.5 keV)/ $n'_\infty \simeq 0.2$.

Strong temporal fluctuations of fast electron fluxes noted also in

[10], can be explained by the effects of the quasi-periodic non-linear reduction of the beam-plasma interaction; the characteristic time of the relaxation oscillations [9] is determined by the changing time $\tau \sim (\omega_p\ m/M)^{-1} \sim 10^{-2}$ s.

Thus the data obtained on electrons, with energies less than 3 keV, during electron beam injection in the ARAKS experiment can be explained by the effects of the collective interaction of the beam (beam-plasma discharge) with the ionospheric plasma surrounding the rocket.

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