LABORATORY EXPERIMENT ON FIELD-ALIGNED CURRENT SYSTEM

Minoru TSUTSUI and Kohei HASEGAWA

Radio Atmospheric Science Center, Kyoto University, Gokanosho, Uji 611

Abstract: An electric current system consisting of field-aligned currents and ionospheric current in the polar region is studied experimentally in a laboratory as a first step of clarifying the acceleration mechanism of auroral particles. The present experiment has been performed by using a simplified model which consists of a power source for the solar wind-magnetosphere dynamo and a loading part for the polar ionosphere and field-aligned currents connecting the two. The experiment has been performed in order to get essential properties of the field-aligned current in a magnetic mirror configuration which simulates the polar magnetosphere.

Trails of the current along the magnetic lines of force have been proved by a newly developed equipment which can measure cross-sectional distributions of electron beam currents. It has been also found that higher energy electrons are not so easy to precipitate into the mirror magnetic converging region than the lower energy ones.

1. Introduction

As for auroral particle acceleration mechanisms, several processes are proposed. They are potential double layer (SWIFT, 1975, 1976; KAN *et al.*, 1979), electrostatic shock (KAN, 1975; SWIFT, 1979), pitch angle anisotropy of precipitating electrons (CHIU and CORNWALL, 1980), thermoelectric potential difference (HULTQVIST, 1979), anormalous resistivity (KINDEL and KENNEL, 1971; KINTERN *et al.*, 1979) and electric field of Alfvén waves (HASEGAWA, 1976; GOERTZ and BOSWELL, 1979). However, when we consider the electro-dynamics in the earth's magnetosphere macroscopically, their processes can be regarded as resultant phenomena due to currents flowing along a circuit which couples the earth's magnetosphere and the ionosphere.

It is well known that the current system, so-called three-dimensional current system, in the polar ionosphere has a complicated structure. It consists of field-aligned currents, westward and eastward auroral electrojet currents and poleward and equatorward currents in the polar ionosphere. Especially, the field-aligned currents connect to the plasma sheet, the polar ionosphere and to the equatorial ring current region. From a viewpoint of electrical circuit, this complicated current system can be regarded as a combination of simplified electric circuits which consist of a source and some loads connected by some wires. When we consider such condition, the most feasible part contributing to the acceleration mechanism of electrons will be near the connected region between the field-aligned current and the polar ionosphere. Therefore, in the present experiment, we have attempted to form the simplest closed current system connected by the field-aligned currents in a vacuum and to examine essential properties of the current along the system.

2. Experiment

2.1. Experimental setup

The experiment has been carried out in a vacuum chamber whose dimension is 80 cm in diameter and 150 cm in length. For the purpose to simulate the polar ionosphere, a magnetic mirror field is formed in the chamber by a solenoid coil with a bundle of thin iron rods in the coil axis. The magnetic coil is installed at the end of the chamber. Magnetic field lines have been emarged by iron powder as shown in Fig. 1. Their intensities and directions in the experimental space have been confirmed by direct measurements and calculations of coil-forming fields. The direct measurements have been carried out at all cross points of the mesh with 5 cm spacing as seen in Fig. 1. As the calculated vectors of the magnetic fields formed by the solenoid coil are consistent with the measured values, we use hereafter the calculated values in checking the relation between the current trails formed in the experiment and the alignments of the magnetic fields.

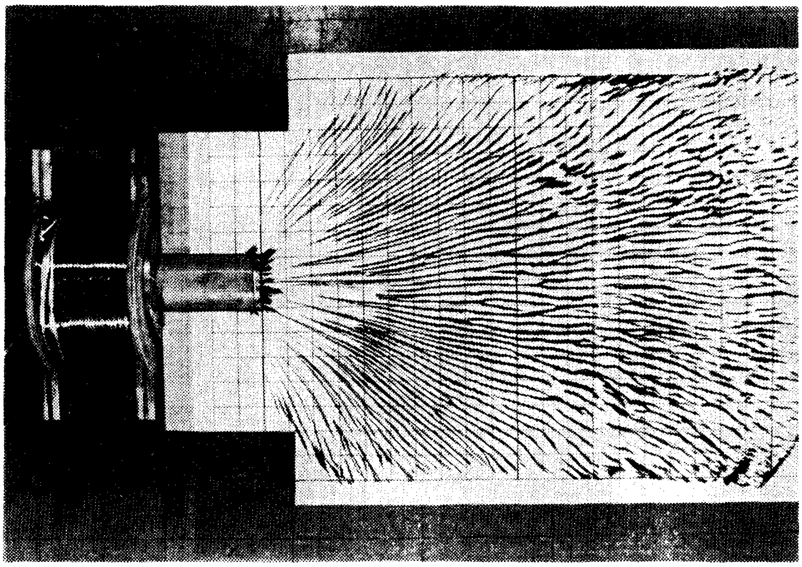

Fig. 1. Magnetic lines of force formed by a solenoid coil. They are emerged by iron powder. These field directions are consistent with direct measurements and calculated values. This field configuration is formed in the vacuum chamber for the present experiment. The maximum intensity of the magnetic field in the converging region is 350 Gauss.

In the present experiment, we have attempted to form an essential electrical closed circuit composed in the earth's magnetosphere. The experimental setup is shown in Fig. 2. In the magnetic mirror configuration, a model ionosphere is set in the converging region of the magnetic field. The most important and difficult point in the present experiment is to simulate the practical polar ionosphere. A main function of the model ionosphere in the present experiment is to play a role of electron emissions which corresponds to the upward drift of electrons for the return currents to the

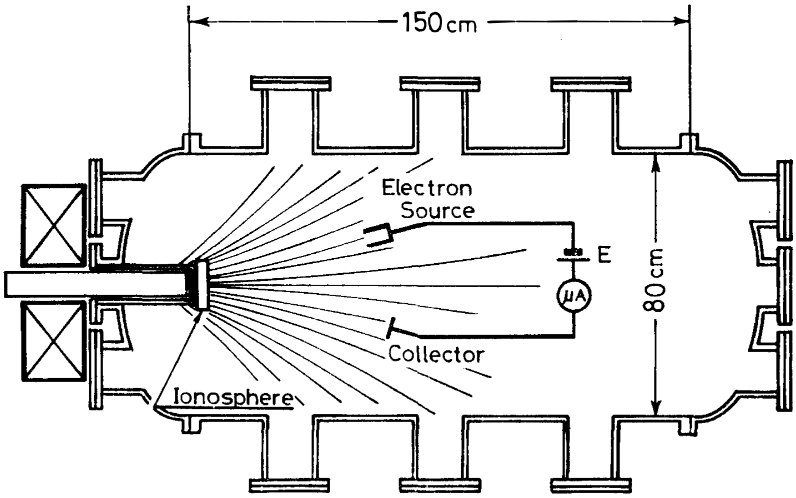

Fig. 2. Experimental setup. Electron source, collector and model ionosphere are arranged in a horizontal plane which includes the main axis of the magnetic field. The gas pressure in the chamber is order of 10^{-6} Torr.

plasma sheet. The model ionosphere consists of tungsten filaments stretched on a ceramic board (15×15 cm^2). An electron source and a collector are arranged separately in the diverging region of the magnetic mirror field, which simulates the plasma sheet in the tail region of the earth's magnetosphere. At their positions, separated two bundles of magnetic lines of force are passing through, respectively, and are connected to the model ionosphere. Though, actually, the plasma sheet as the particle source is not a point source, one point source is used for the experiment to examine the essential properties of electrons along the current system. A power supply is connected between the electron source and the collector in order to provide the currents to the system. Thus electric fields are formed in the direction from the collector to the electron source, which corresponds to those applied in direction from dawn to dusk in the tail region of the earth's magnetosphere. A configuration of the magnetic

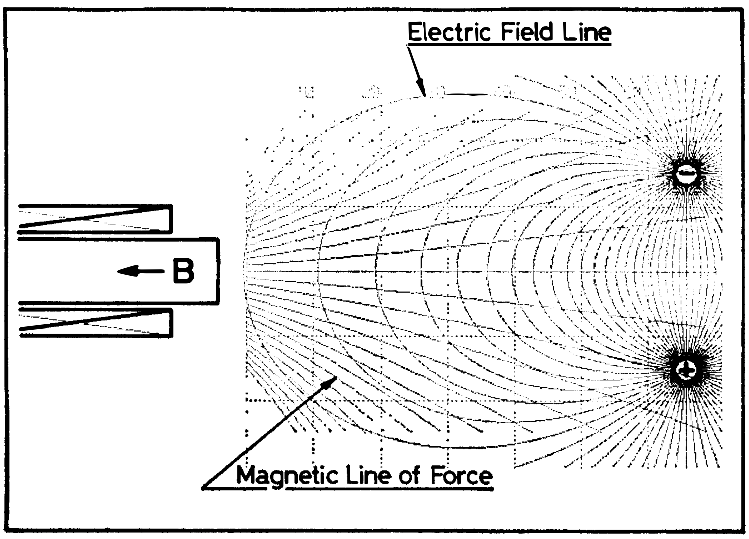

Fig. 3. Configuration of magnetic and electric fields formed in the present experiment.

and electric fields in the experimental space is shown in Fig. 3. This figure shows an initial configuration of the experiment, though the electric fields during the flowing of electrons are deformed. However, the deformation is not essential for the present experiment, because we have a hypothesis that electric fields responsible for the electron accelerations are caused by electrodynamic processes near the polar ionosphere. Under such condition, currents have been monitored by a meter connected in series to the power supply.

The power supply used for the present experiment is a constant voltage source. It is said that neutral sheet currents flowing from dawn to dusk across the magnetosphere tail region are of the order of 10^7 A. On the other hand, auroral currents are of the order of 10^5–10^6 A. Therefore, an equivalent impedance observed from the polar region to the solar wind-magnetosphere dynamo is extremely low. Therefore, we can regard the dynamo as a constant voltage source.

2.2. Measurements of trails of electron currents in three dimensional space

Trails of electron current have been measured by a newly developed two dimensional current probe. The probe can measure cross-sectional distributions of electron beam currents. Figure 4 shows a principle of the two dimensional probe, data acquisition and monitor system. This probe consists of 32×2 tungsten wires (0.15 mm in diameter) stretched every 5 mm spacing in both horizontal (X) and vertical (Y) directions, respectively. Spacings with 2 mm are held between the horizontal and vertical wires at their crossing points. The 32 wires stretched in each direction are connected to analogue multiplexers, respectively, which can select an arbitrary pair of horizontal and vertical wires. By this selection, one cross point in a two dimensional plane is selected. As outputs of the multiplexers are fed to current amplifiers, if beam electrons pass through an arbitrary cross point in the mesh, the crossing two wires would detect parts of the beam electrons. The electron currents flown into each wire are converted to voltages and then multiplied with each other. This performance is a

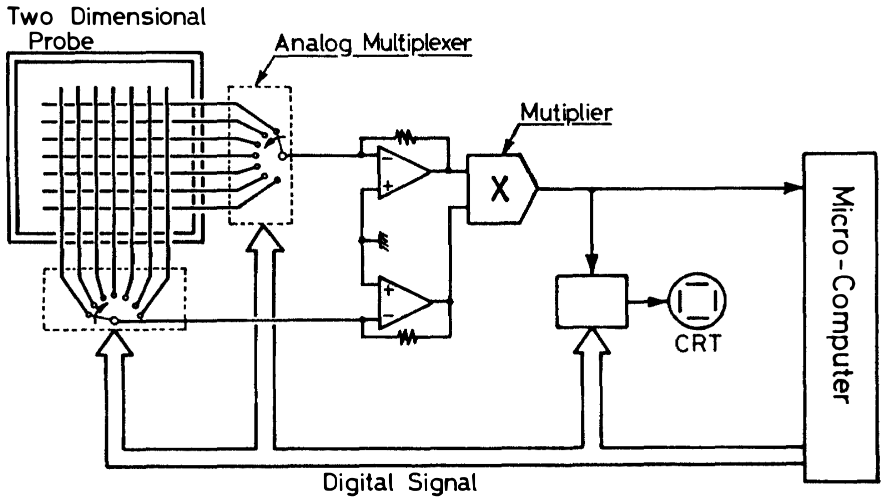

Fig. 4. Principle of two-dimensional current probe and data acquisition system. The horizontal and vertical wires are held 2 mm apart from each other. In the CRT, two-dimensional distribution of beam currents is displayed on real-time basis.

kind of a cross correlation between the flowing currents into two wires at the cross point. In this case, the output value of the multiplier indicates a high correlation coefficient. At other cross points through which no electron beam current is passing, zero values of the correlation coefficient are given principally. In total, 1024 cross points in the two dimensional plane can be selected by switching in the two multiplexers.

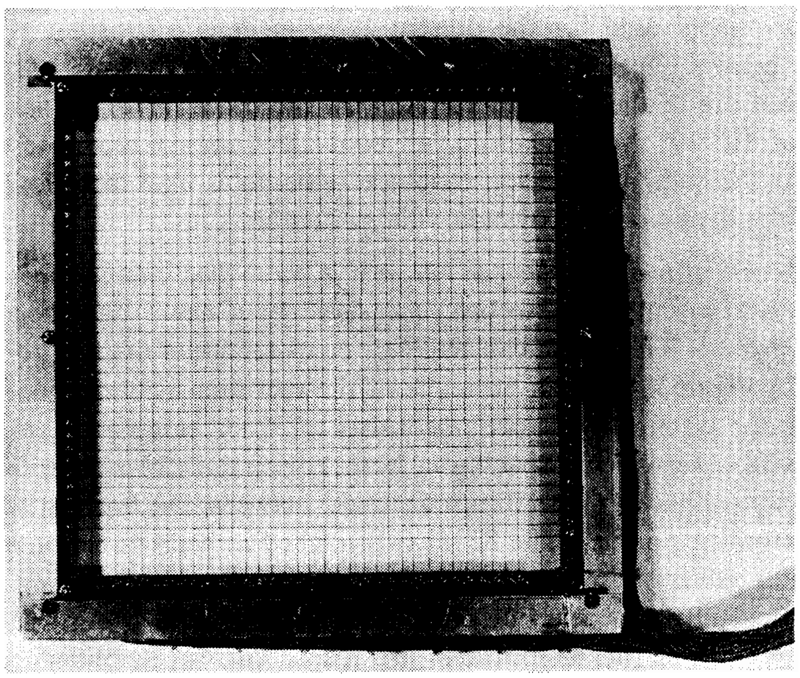

Fig. 5. Proto-type of two-dimensional current probe. 32 tungsten wires (0.15 mm in diameter) are stretched in horizontal and vertical directions, respectively. The spacings between the parallel wires are 5 mm. They are connected to multiplexers for the respective directions. The effective measurement area is 15.5 × 15.5 cm². The effective transparency of the two-dimentional probe is 94%.

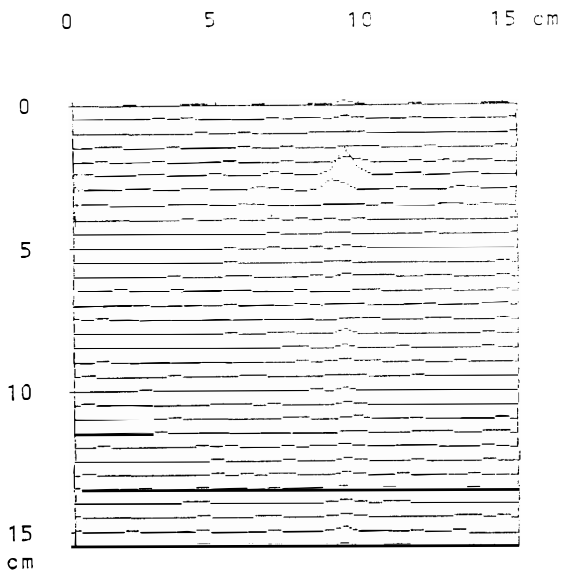

Fig. 6. An example of cross-sectional distribution of electron beam current measured by the two-dimensional current probe.

By scanning the cross points, two dimensional distribution of the correlation coefficients can be obtained sequentially. The selection of cross points is controlled by digital signals from a micro-computer. Usually, cross points are scanned horizontally from up-left corner of the probe. Since signals composed of the correlation coefficient and the scanning signal are displayed on a CRT, cross-sectional distributions of beam currents and their spatial distributions in the two-dimensional plane can be monitored on real time basis. On the other hand, correlation coefficients for each cross point are sampled sequentially by the micro-computer and stored in a floppy disk for the later analysis.

The proto type of the two-dimensional current probe is shown in Fig. 5, and an example of the cross-sectional distribution of the electron beam current measured by this system is shown in Fig. 6.

The measurement area is 15.5×15.5 cm^2, and the physical transparency of the mesh is 94%. A spacial resolution of observed distributions depends on the spacing between the mesh wires. Thus it seems to be better to densify the mesh wires. However, potentials of the mesh wires would affect the orbits of beam electrons. By this effect, the spatial distribution might be distorted. Now the effect of the mesh potential on the beam electron orbits is examined.

2.3. *Results on field-aligned current*

Current trails in the experimental space have been measured by the two-dimensional probe described in the previous section. A configuration of the measurement is illustrated schematically in Fig. 7. The electron source, collector and model ionosphere are set in the same horizontal plane which includes the main axis of the magnetic mirror fields. The volume of the measurement region among the electron source, collector and model ionosphere is $15.5 \times 15.5 \times 50$ cm^3. Cross-sectional distributions of the electron beam current (three-dimensional views as shown in Fig. 6) have been measured at positions every 2.5 cm along the chamber axis. Each three-dimensional distribution is projected onto a two-dimensional plane for a display of an overlapped beam radial distribution which is composed of 32 distributions in X or Y direction. Figure 8 shows 20 beam radial distributions arrayed at every 2.5 cm from the model ionosphere. Figure 8a shows those projected onto the horizontal plane. The electron source and the collector are shown at the right end of the figure. A current trail from a chain of the distributions can be recognized, which is nearly along the magnetic lines of force. Figure 8b shows those projections onto a vertical plane, in which the current trail deviates upward from the initial horizontal plane when the curernt reaches the converging region of magnetic mirror field. This deviation can be explained by

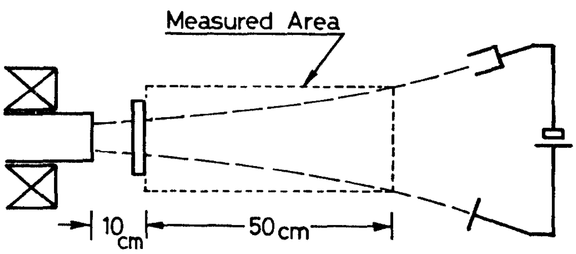

Fig. 7. Region for measurement of trails of electron beam current. An electron source, a collector and a model ionosphere are arranged in the same horizontal plane which includes the axis of the magnetic mirror fields. The volume of the measured region is $15.5 \times 15.5 \times 50$ cm^3.

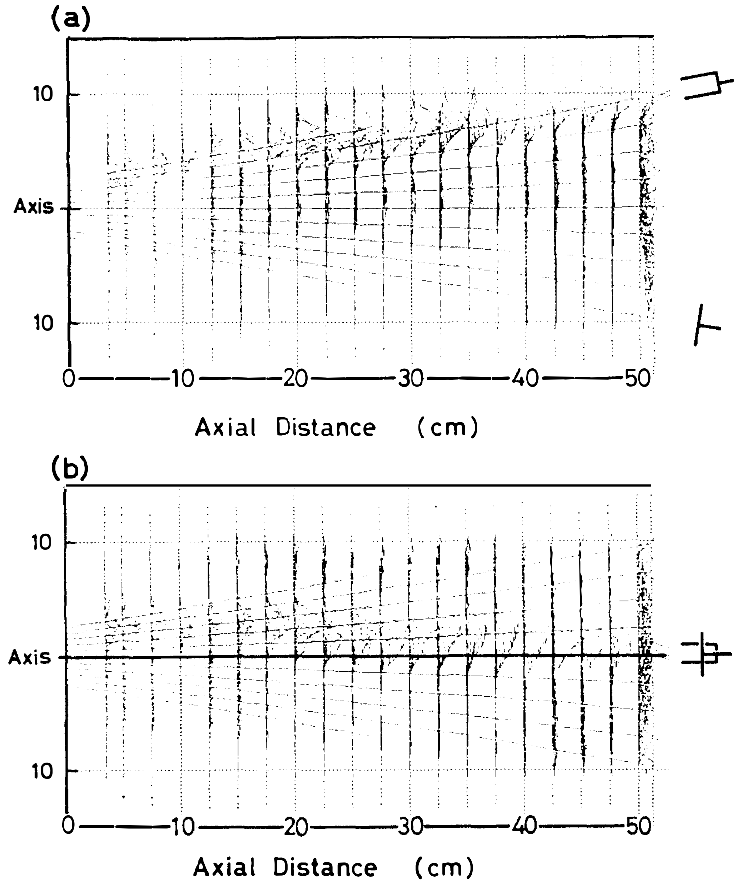

Fig. 8. (a) A series of radial distributions of the electron beam. They are projected onto the horizontal plane. (b) Those projected onto the vertical plane, which shows that the current trail deviates upward due to $E\times B$ drift from the initial horizontal plane.

$E\times B$ drift due to their fields shown in Fig. 3. The measured drifting effect is now being estimated from calculations of electron orbits. These current trails along the magnetic fields have not been formed unless both the electric and magnetic fields were supplied simultaneously.

In the present experiment, the current meter connected in series to the power supply indicates that the total current from the electron source is 10 μA. It has been found, however, that most of the current did not return via the model ionosphere, but came back to the collector by reflections due to the magnetic mirror effect. This fact has been confirmed from the observed current distributions. Principally an area under the beam radial distribution function is proportional to the beam current passing through the two-dimensional probe. In Fig. 8, the area becomes small when the beam reaches the model ionosphere, which might result from dissipations of the precipitating electrons by the magnetic mirror reflections. Figure 9 shows relative currents by the electrons precipitated into the magnetic loss cone. Measured values are normalized to those at 45 cm from the model ionosphere. Branch A and B are results for electrons with their initial drift energy of 0 and 50 eV, respectively. This result indicates that the higher energy particles are not so easy to precipitate into the

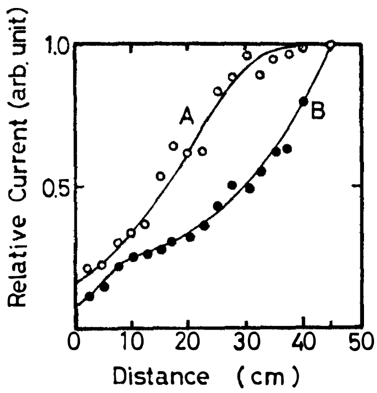

Fig. 9. *Relative currents by the precipitated electrons into the magnetic loss cone. The maximum value is normalized to that at 45 cm from the model ionosphere. Branch A and B are the results of electrons with their initial drift energy of 0 and 50 eV, respectively.*

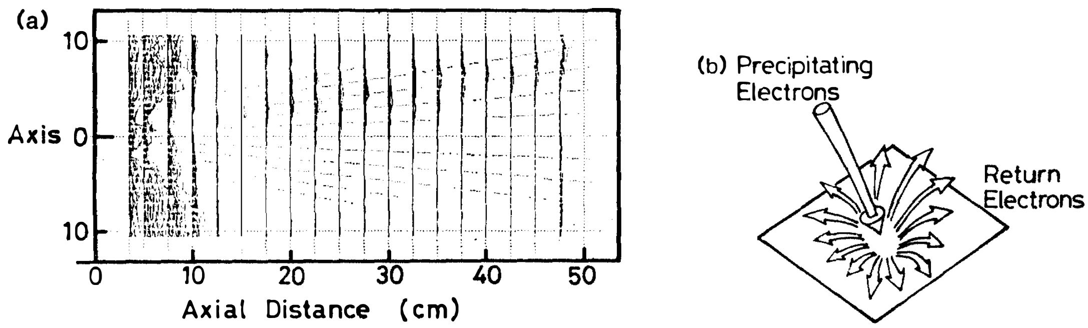

Fig. 10. *(a) An example of a current trail and distribution of electron emission from the model ionosphere. The gain of the display of the output signal from the multiplier is reduced than that in Fig. 8. Spatial distribution of the emitted electrons from the model ionosphere show a depression in the central part of the ionosphere, which comes from an effect of electron suppressions by electric field due to the charges of precipitating electrons shown schematically in (b).*

magnetic converging region. Both results show that most of electrons are reflected by the mirror magnetic field.

In the experiment shown in Fig. 8, the detection of upward drift (return) currents from the model ionosphere is very slight. Since, in the present case, the return electrons are emitted from the whole surface of the model ionosphere, the current density is much less than that of the precipitated electrons. Thus the return electron currents have not been observed clearly. An example of electron emissions from the model ionosphere is shown in Fig. 10a. In this case, as a good deal of electrons are emitted from the model ionosphere, the gain of the display has been reduced in the figure. In the central part of the model ionosphere, the spatial distribution of the electrons is depressed because of the effect of electron suppressions by electric field due to charges of precipitating electrons, which is schematically illustrated in Fig. 10b. This phenomenon might indicate the result obtained by CALVERT (1981). It would be interesting to examine this possibility by further observations in the polar ionosphere.

In the present experiment, only very small electron currents can flow along the circuit system. This suggests that the total impedance of the circuit might be large. In the next experiment, the conductivity of the model ionosphere should be more large and controllable in order to flow more large current. By the control of currents, properties of electron precipitation into the mirror magnetic field might be examined.

3. Conclusion

In order to examine the properties of electric current flowing along a circuit system composed of a solar wind-magnetosphere dynamo and a polar ionosphere connected by the field aligned currrnt, a model experiment has been attempted to form the simplified electrical circuit system connected by field-aligned currents in a vacuum space.

In the experiment, the net current along the circuit is very small. This is due to low conductivity of the model ionosphere. However, it has been found that the current by low energy electrons is larger than that by higher energy ones. This suggests that the lower energy electrons can precipitate into the polar ionosphere than the higher energy one, because the higher energy electrons are easily reflected by the pitch angle scatterings.

It is said that during auroral substorms the auroral total current flowing into auroral region exceeds 10^6 A. When we imagine a mechanism that can flow such amount of current, the conductivity of the polar ionosphere might have a very important factor for the current suction, for example negative registance in a plasma breakdown. If this mechanism occurs in the polar ionosphere, the electrons will precipitate easily into the polar ionosphere against the magnetic mirror effect. In the next experiment, properties of the currents flowing via the model ionosphere have to be examined clearly.

Acknowledgments

The authors wish to express their sincere thanks to Prof. T. OGAWA for his supporting the experiment. They would like to express their thanks to Profs. I. KIMURA and H. MATSUMOTO and Dr. K. HASHIMOTO for their useful discussions.

References

CALVERT, W. (1981): The auroral plasma cavity. Geophys. Res. Lett., **8**, 919–921.

CHIU, Y. T. and CORNWALL, J. M. (1980): Electrostatic model of a quiet auroral arc. J. Geophys. Res., **85**, 543–556.

GOERTZ, C. K. and BOSWELL, R. W. (1979): Magnetosphere-ionosphere coupling. J. Geophys. Res., **84**, 7239–7246.

HASEGAWA, A. (1976): Particle acceleration by MHD surface wave and formation of aurora. J. Geophys. Res., **81**, 5083–5090.

HULTQVIST, B. (1979): The hot ion component of the magnetospheric plasma and some relations to the electron component-observations and physical implications. Space Sci. Rev., **23**, 581–675.

KAN, J. R. (1975): Energization of auroral electrons by electrostatic shock waves. J. Geophys. Res., **80**, 2089–2095.

KAN, J. R., LEE, L. C. and AKASOFU, S.-I. (1979): Two-dimensional potential double layers and discrete auroras. J. Geophys. Res., **84**, 4305–4315.

KINDEL, J. M. and KENNEL, C. F. (1971): Topside current instabilities. J. Geophys. Res., **76**, 3055–3078.

KINTNER, P. M., KELLEY, M. C., SHARP, R. D., GHIELMETTI, A. G., TEMERIN, M., CATTELL, C., MIZERA, P. F. and FENNELL, J. F. (1979): Simultaneous observations of energetic (keV) upstreaming and electrostatic hydrogen cyclotron waves. J. Geophys. Res., **84**, 7201–7212.

SWIFT, D. W. (1975): On the formation of auroral arcs and acceleration of auroral electrons. J. Geophys. Res., **80**, 2096–2108.

SWIFT, D. W. (1976): An equipotential model for auroral arcs, 2. Numerical solutions. J. Geophys. Res., **81**, 3935–3943.

SWIFT, D. W. (1979): An equipotential model for auroral arcs; The theory of two-dimensional laminar electrostatic shock. J. Geophys. Res., **84**, 6427–6434.

(Received August 1, 1985; Revised manuscript received January 20, 1986)