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EXPERIMENTS WITH ELECTRON BEAM INJECTION IN IONOSPHERE PLASMA AND RARE GAS

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INTRODUCTION

The active experiment “Electron” is intended for the electron beam injection from a meteorological rocket in the ionosphere plasma. The beam is injected in the ionosphere plasma at a current of 0.5 A and an energy of 6.5-8 keV. The energy spectrums are given for the plasma electrons and ions. The radio-wave spectrum is measured in a RF frequency range of 100-500 MHz. The radio wave traversing through the electron beam injection region is discussed. The laboratory experiments are performed with the electron beam injection in a rare gas to model the active outer-space experiments

1. ACTIVE SPACE EXPERIMENT "ELECTRON"

The electron beams at a current of 0.5-1 A and an electron energy of 5-10 keV are widely used for the ionosphere and magnetosphere plasma investigations in the active space experiments. The active experiment permits one to study the aurora brightens, the generation of electromagnetic radiation and the beam–plasma discharge.

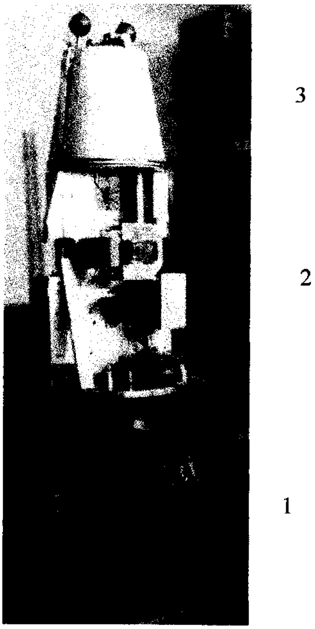

Fig. 1. Apparatus “Electron”: 1 is the electron injector, 2 is the diagnostic equipment, 3 is the AWC container, ACDC containers are removed.

The main tasks of the active outer-space experiment "Electron" are generation of the electromagnetic radiation by the modulation electron beam at its interaction with the ionosphere plasma; formation of the beam-plasma discharge (BPD); scattering of the electromagnetic wave at its traverse the beam-plasma discharge region; measurements of the plasma parameters by the rocket diagnostic; plasma scanning by three autonomous containers; measurement of the rocket body potential at the electron beam injection.

The complex "Electron" consists of an electron injector, diagnostic detectors and three autonomous containers separated from the meteorological rocket (Fig. 1). This equipment is installed aboard the meteorological rocket MR-12 to use it for the active experiments at the altitudes of 100-150 km. The distinctive features of the "Electron" equipment are the electron gun with a high perveance of 0.8 $\mu A/V^{3/2}$ generating a modulation electron beam at high and low frequencies for plasma wave excitations; three autonomous diagnostic containers and registration instruments for fast processing with a time resolution of 1 ms.

2. APPARATUS "ELECTRON" FOR ACTIVE EXPERIMENTS

Different diagnostic detectors are used for the investigations of the beam plasma interaction in the active experiments. This diagnostic equipment involves the electron and ion energy analysers; the electromagnetic wave detectors, the optical systems, the electric and magnetic field detectors. The energy grid electron and ion analysers are installed aboard the meteorological rocket in the experiment "Electron". They are used to measure of the electron and ion fluxes at a particle energy of 0.5-20 eV. Similar electron and ion analysers are placed in the autonomous corpuscular diagnostic containers (ACDC) together with a low- frequency electric and magnetic field detectors. The radio-frequency analyser is installed in the wave autonomous container (AWC) separated from the rocket in the longitudinal direction. The high-energy electron analyser aboard the rocket is used for the investigations of the missile body floating potential formed at the electron beam injection in the ionosphere plasma. The high-energy electron analyser consists of multi chamber Faraday cups (MCFC) with different retarding voltages in a range of 10-1000 V.

2.1 Autonomous containers

First active experiments with the electron beams demonstrated wide possibilities for ionosphere and magnetosphere investigations [1-5]. One of the effective methods for these investigations is the use of the autonomous diagnostic containers separated from the rocket. The diagnostic containers permit one to scan the space around the space vehicle where the electron injector is placed. Three autonomous diagnostic containers are used in the experiment "Electron". Two autonomous corpuscular diagnostic containers (ACDC) are separated from rocket in the opposite directions relative to its longitudinal axis. The ACDC equipment is used for energy analyses of the electron and ion plasma components and measurements of low-frequency electric and magnetic fields. The electron and ion grid analysing cells with different retarding voltages together with the electric and magnetic field detectors are installed in ACDC containers. The ACDC weight is 3.5 kg, the length 190 mm and diameter 125 mm. The autonomous wave container (AWC) is jettisoned from the rocket in the longitudinal direction along its axis. It has an electromagnetic radiation spectrum analyser and radio-telemetric equipment.

2.2 Electron injector

The electron injector forms a high-intensity beam with a variable perveance and energy modulation at high and low frequencies. A three-electrode gun is used for beam formation. The gun weight is 3 kg, diameter 17 cm, and length 9 cm. The gun cathode diameter is 5.3 mm. It is made of LaB_6, which requires a moderate heating power (200 W/cm^2), allows contact with air in a cold state and operation at a pressure to 10^{-2} Torr. The Pierce geometry is taken as the initial geometry. However, the control electrode had to be moved closer to the cathode to increase its perveance to 0.8 $\mu A/V^{3/2}$ and to reduce the control voltage. For beam injection at a current of 0.5 A, the control electrode voltage is +0.5 kV. The beam current is closed at a negative control electrode voltage of −1.5 kV. The processes of beam interaction with plasma and generation of low-frequency wave radiation are greatly affected by a low-frequency beam density modulation of 1 – 20 kHz. The high-voltage ripples in the injector power supply provide a 20% modulation of the gun current at the frequency of 20 kHz.

The resonance modulator produces a high-frequency electron velocity modulation in the gun. One part of the resonance contour is a plate capacitor formed by the gun anode plate and a special figure plate, which has a hole 10 mm in diameter. This plate is placed behind the anode plate on the ceramic insulators. The harmonic variable potential of this plate produces electron energy modulation. The coaxial line is an induction part of the resonance contour. The modulator resonance frequency corresponds to 150 MHz and Q=8. A 1 W generator provides excitation of the resonance contour. The RF modulation energy corresponds to 20-30 eV in the absence of the ionosphere plasma. The beam electrons are fast accelerated in the open resonator and then relatively slowly decelerated in the electric field of the modulator plate.

3. RESULTS OF ACTIVE EXPERIMENT "ELECTRON"

The electron beam injection is started on 193 s in the active experiment "Electron" when the rocket reaches the apogee at of altitude of 150 km. The beam injection is carried out all the time when the rocket trajectory altitude is reduced to 30 km. The injector works in a standard regime: the acceleration voltage is varied in a range of 0.5-8 kV, the beam current is 0.45 A, the injection repetition frequency is 3 Hz and the pulse injection time is 40 ms.

3.1 Generation of electromagnetic radiation by modulation electron beam

A distinctive feature of the active experiment "Electron" is interaction of the modulation electron beam at a frequency of 150 MHz with the ionosphere plasma. The high-frequency modulation produces a transformation of the electromagnetic wave radiation. The wave radiation becomes monochromatic if the beam modulation frequency is close to the plasma frequency. It has a complicated character with a combination of the monochromatic and wide-range frequency radiation when the modulation and plasma frequencies are not equal. However, in both cases considered high-frequency beam modulation produces an increase in the integral radiation intensity by 7-10 dB. Therefore the RF modulation at a low level of 0.2% permits effective adjustment by the parameters of the electromagnetic wave radiation produced at interaction of the modulated electron beam with the ionosphere plasma. The electron beam simultaneously works as a usual metallic antenna operated in a few-meter wave ranges and as an amplifier, which essentially increases the radio signal at its interaction with the plasma.

A panorama spectra analyser is used for the radio-wave detection in the active experiment "Electron". A high noise level is present during the on-earth wave registration (Fig. 2a). However, high-intensity signals are detected during the electron beam injection. The on-earth wave detector receives a high-intensity monochromatic signal when the beam modulation frequency coincides with the plasma frequency (Fig. 2b). The monochromatic radiation is 50 dB higher than the background radiation. The intensive electromagnetic radiation with a wide frequency spectrum is observed at the altitudes of 150 km (Fig. 2c) and 100 km (Fig. 2d). This radiation is 20 dB higher than the background radiation. The wave radiation signal makes it possible to estimate the coefficient of the electron beam energy transformation in the electromagnetic wave energy, which corresponds to 10^{-2}. The detection of the intensive electromagnetic wave radiation provides information about the plasma density. The RF detector data indicate presence of the local beam-plasma discharge at which a high-density plasma of $(2\text{-}4)\cdot 10^{8}$ cm^{-3} is produced at the electron beam injection.

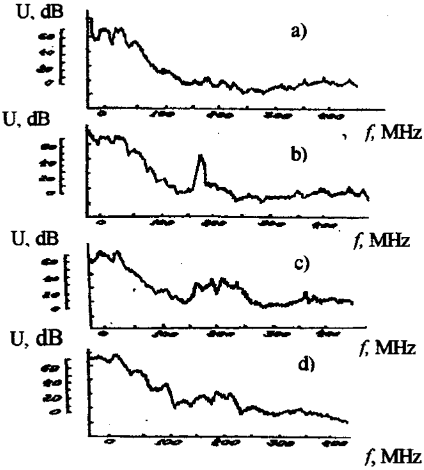

Fig. 2. Radio-emission spectra: a – 180 s, b – 190 s, c – 193 s, d – 316 s.

3.2 Radio wave tracing

In the active experiment "Electron" the radio wave tracing at a frequency of 23.7 MHz is realised through the plasma region produced by the electron beam. The radio wave source (Kazan) is placed at a distance of 850 km from the electron beam injection region (Volgograd). The scattered radio waves are observed at the angle of 60° when they pass through the rocket plasma. The distance between the rocket position and the radio wave detector (Novocherkassk) is 450 km. The large-angle radio wave scattering takes place when the wave frequency is comparable with the plasma frequency. The wave scattering at the frequency of 23.7 MHz indicates a plasma density of $6\cdot 10^{6}$ cm^{-3}, which is one order of magnitude higher than the density of the ionosphere plasma.

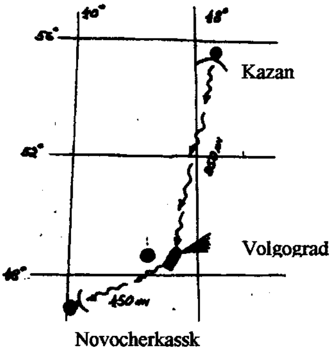

Fig. 3. Scheme of the experiment at the radio wave trace through the beam injection region

3.3 Parameters of rocket plasma

The unperturbed ionosphere plasma is measured in the experiment “Electron” by the ACDC containers when they move away from the rocket at a distance larger than 700 m (time 220 - 316 s, altitude 150 – 95 km, Fig. 4).

The low-frequency electric field at *f* <1 kHz is measured by a detector placed in the ACDC container. The electric field corresponds to 10 mV/m at the distance of 1 km in the radial direction from the meteorological rocket.

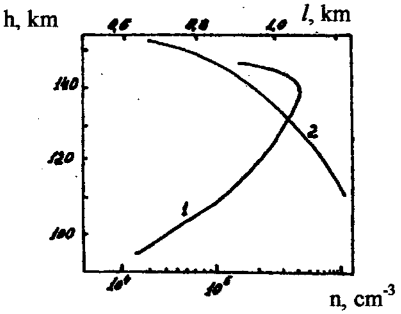

Fig.4. Dependence of the ionosphere ion density on the rocket altitude (curve 1). Dependence of the distance between the ACDC container and the rocket on the altitude (curve 2).

The electron and ion grid energy analysers aboard the meteorological rocket are used for the plasma measurements. The dependence of the electron and ion fluxes on the retarding voltages of the particle detectors are shown in Fig.5 and 6 for the time 32.6 and 49.4 ms after the beam injection starts. The electron temperature corresponds to 1.7 eV at t=32.6 ms and to

0.5 eV for t=49.4 ms at the beam injection pulse duration of 40 ms. The electron concentration is $6 \cdot 10^4$ cm^{-3} at the altitude of 110 km. At the time of 32,6 ms there are fast electrons of energy 15 eV together with thermal electrons. The fast electron density is reduced when the beam injection is over. The fast electrons are not observed at the time of 49.4 ms, which corresponds to 9 ms after the end of the beam injection pulse.

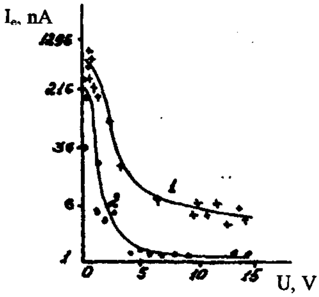

Fig. 5. Dependence of the electron current on the retarding voltage at h=110 km. Curve 1: t = 32,6 ms, curve 2: t = 49,4 ms.

The ion energy corresponds to 1.5 eV during the beam injection (t =32.6 mc). The ion energy is reduced to 0.2 eV through 9 ms after the end of the beam injection pulse (t = 49.4 ms). The ion beam current is two orders of magnitude smaller than the electron one. The ion current is related to the overcompensation of the electron beam space charge.

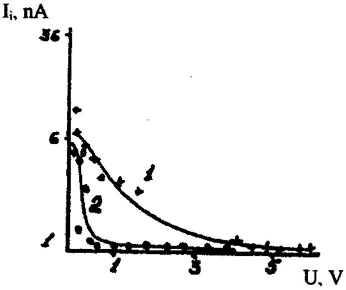

Fig. 6. Dependence of the ion current on the retarding voltage at h=110 km. Curve 1: t = 32,6 ms, curve 2: t = 49,4 ms.

The high-energy electrons are measured by the multichamber Faraday cups (MCFC) with the retarding voltages on the grid electrodes in the energy range of 10 eV – 2 keV (Fig. 7). There are two types of the high-energy electrons: electrons at an energy of 75 eV and a concentration of $5 \cdot 10^3$ cm^{-3} and electrons at an energy of 1 keV and a density of 10 cm^{-3}.

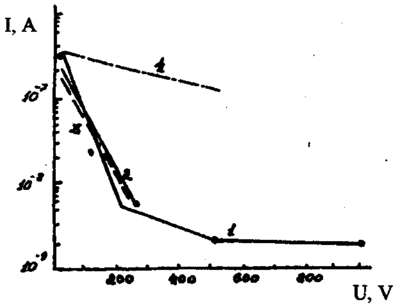

Fig. 7. Dependence of the high energy electron current on the retarding voltage at h=130 km. Curves: experiment (1); simulations with φ_r= 10 V (2), φ_r = 50 V (3) , φ_r = 500 V (4).

The electron energy spectrum strongly correlates with the electron temperature and the rocket body floating potential during the electron beam injection. As follows from Fig.7, the simulation curve and experimental data are close when the rocket body floating potential corresponds to φ_r = 50 V. The corpuscular measurements show that the electron beam injection in the ionosphere plasma results in electron heating to a temperature of 1.5-2 eV and formation of high-energy electrons at 75 eV and ion concentration of 10^4 cm^{-3}. The rocket potential corresponds to 50 V during the beam injection.

4. INJECTION OF ELECTRON BEAM IN RARE GAS IN TEST BENCH EXPERIMENTS

4.1 Beam – plasma discharge

The test bench experiments with electron beam injection in a rare gas are performed to model the electron beam injection in the ionosphere plasma and to test the equipment used in the active rocket experiments. The laboratory experiments are performed on the test bench with a vacuum chamber 1 m in diameter and 1.7 m long. The corpuscular and optical diagnostic equipment investigates the beam-plasma interaction. At a threshold electron current the beam injection in the rare gas initiates the beam-plasma discharge (BPD) and the gas brightness. A similar effect occurs in the active experiment "Electron" when at BPD ignition the electromagnetic radiation increases from 5 to 20 dB at a critical altitude (threshold pressure) of 95 km. The gas brightness increases as the pressure increases to the critical value. The further pressure increase ($P = 7 \cdot 10^{-3}$ Torr) leads to essential reduction in the BPD brightness caused by the electron-neutral atom collisions.

The detectors used in the active experiments also measure the plasma parameters in the laboratory experiments. Three kinds of electrons are formed in the laboratory plasma. The thermal electron energy corresponds to 5 eV and it is of 15 eV for the fast electrons. Also, there is a small part of high-energy electrons at 200 eV. Their density is 5 times lower than the density of the 15-eV fast electrons. The multichamber Faraday cups (MCFC) used in the experiment "Electron" measure the energy spectrum of the high-energy electrons. Dependence of the electron current in the MCFC on the vacuum pressure is shown in Fig.8 at a retarding voltage of 12 V. Curves 1 and 2 are given for the time of 1 ms (curve 1) and $t = 5$ ms (curve 2) after the start of the beam injection. The BPD is formed a few ms after the beam injection begins. The BPD threshold pressure obtained by the corpuscular detectors is in good agreement with the optical data.

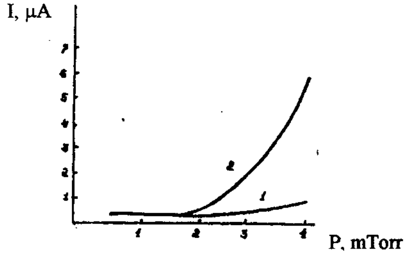

Fig.8. Dependence of the MCFC current on the residual gas pressure at a retarding voltage of 12 V and I=0,5 A. Curve 1:t = 1 ms, curve 2: t =5 ms.

The ion parameters are measured in the test bench by the ion detector used in the experiment “Electron”. To separate the ion component from the electron flux, a permanent magnet is installed at the ion detector entrance. The ion energy corresponds to 0.5 eV and its density is equal to $6 \cdot 10^{7}$ cm^{-3} at a pressure of 10^{-4} Torr when the beam-plasma discharge is not yet developed. The ion energy and density increase, to 5 eV and $2.5 \cdot 10^{8}$ cm^{-3} respectively at the BPD ignition ($P=3 \cdot 10^{-3}$ Torr). The diameter of the plasma created by the electron beam corresponds to 20 cm at a distance of 1.7 m from the electron injector. The electron beam energy loss is about 30% at the beam-plasma interaction.

The laboratory experiments indicate that under the conditions of the active experiment “Electron” (pressure $10^{-3} - 5 \cdot 10^{-3}$ Torr; $h \approx 100$ km) the electron beam forms the BPD plasma at the density of $(2\text{-}5) \cdot 10^{8}$ cm^{-3}.

4.2 Potential of autonomous insolate electron injector

The investigation of electron injector body potential is a key problem studied in the test bench experiments with beam injection from the autonomous insolated injector. The potential of the rocket body in the experiment [14] was 50 V at the altitudes of 120-150 km; however, it is equal to 1.3 kV at the same altitudes for the experiment [15].

The electron injector works from a storage battery in the test bench experiments. The electron gun body is installed on the insulators and gets a floating potential at the beam injection. The potential of the insolated injector decreases with increasing electron beam current because of formation of a dense BPD plasma and a large current of thermal electrons returned to the injector body. The insolated injector potential reaches a value of 200 V at a pressure of $P=3 \cdot 10^4$ Torr for the electron energy of E =7 keV and the beam current of I=0,4 A (Fig.9). The test bench experiments confirm that under the conditions of the active experiment "Electron" the injector body potential corresponds to a value compared with one hundred volts.

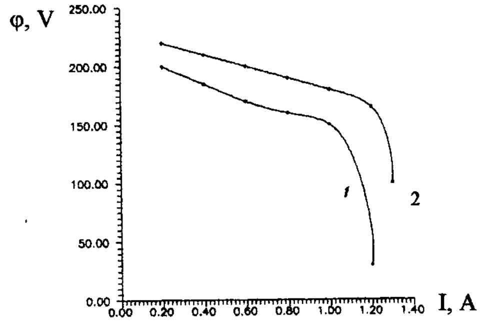

Fig.9. Dependence of the injector body potential on the beam current. Curve 1: E = 6 keV, curve 2: E=7 keV.

4.3 Stimulated beam-plasma discharge

Two insolated metallic grids are installed inside the test-bench vacuum chamber to provide a stimulation ignition of the beam-plasma discharge. The grid construction permits a positive voltage less than 100 V to be applied to it. The metallic grid with a positive potential (electrostatic barriers) provides a reduction of the gas pressure at a fixed beam current for the stimulated BPD. The stimulated BPD is related to the reduction of the ion escape from the discharge region. Two main processes govern the critical beam current and gas pressure: the gas ionization rate and the ion escape from the discharge region. The electrostatic barriers provide confinement of the plasma in the longitudinal direction.

The stimulated beam-plasma discharge at a positive potential of the insolated beam injector is one of the key tasks of the test bench experiments. The plasma particles fast escape from the discharge region along the electron beam injected by the injector with a ground potential maintained. The ions cannot escape from the discharge region along the beam when the insolated injector at the floating positive potential is used. The positive potential of the injector body prevents the ion escape and permits a decrease in the threshold beam current for the BPD ignition (Fig.10). The BPD is not developed at the beam current of $I=0.45$ A for the grounded injector body and the pressure of $P=3\cdot10^{-4}$ Torr. However, the discharge is initiated at the beam current of $I=0.3$ A (Fig.10) for the insolated injector with a floating potential. The floating injector potential provides a 1.5-2 times decrease in the beam current for the BPD ignition.

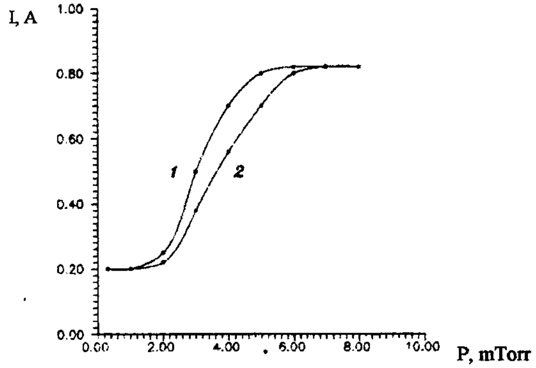

Fig.10. Dependence of the critical beam current at BPD ignition on the residual gas pressure for the grounded (curve 1) and the insolated (curve 2) electron injector.

5.CONCLUSION

The main results of the active experiment "Electron" are the generation of the monochromatic electromagnetic radiation on the electron beam modulation frequency; the formation of the beam-plasma discharge around the meteorological rocket; the scattering of the electromagnetic radio waves at their traversing at the distance of a few hundred kilometers through the plasma region around the rocket; the measurement of the plasma parameters aboard the meteorological rocket; the scanning of the plasma by three autonomous containers separated from the rocket; the investigation of the rocket body floating potential at the beam injection in the ionosphere plasma.

The test bench experiments are aimed at investigating the electron beam-rare gas interaction, stimulating the beam-plasma discharge produced by the electrostatic barriers and measuring the insolated injector potential and charge at the beam injection in the residual rare gas.

6. REFERENCES:

1. W.N. Hess, M.C. Trichel, T.N. Dams at al.. J. Geophys. Res., 76, 6067, (1971).
2. R. Z. Sagdeev, I. A. Shulin DAN USSR, 12, 874, (1975).
3. S.B. Ljahov, G.G. Managadze Plasma physics, 3, 1370, (1977).
4. E.V. Mishin, Yu.Ja. Rushin, V.A.Telegin Interaction of electron fluxes with ionosphere plasma. Gidromettehisdat, (1989).
5. R.Z. Sagdeev, G.G. Managadze, A.D. Mayorov et al. Adv. Space Res. COSPAR, 1, 77-87, (1981).
6. V.F. Bykovsky, S.B. Gorjachev, A.A. Doroshkin at al. Interaction of electron beam with ionosphere plasma in experiment "Electron-1"In the *Project APEKS, Scientific tasks and modelling in technique of experiment.* M.: ISMIRAN, (1991).
7. V.F. Bykovsky, S.B. Gorjachev, A.A. Doroshkin at al. Preprint INP, 91-62, Novosibirsk, (1991).
8. V.F. Bykovsky, S.B. Gorjachev, A.A. Doroshkin at al., Cosmic investigations, N5. (1991).
9. V.F. Bykovsky, S.B. Gorjachev, A.A. Doroshkin at al., Plasma physics, 18, N. 5, 595, (1992).
10. S.B. Gorjachev, R.M. Lapik, I.N. Meshkov, V.N. Mozgunov, E.M. Syresin Pribory, Technique, Experiments, N 2, (1991).
11. V.A. Golubev, V.I.Guselnikov, M.V. Korobeinikov, K.A. Medvedko, I.N. Meshkov, S.S. Nagaitsev, E. M. Syresin Interaction of electron beam with rare gas, In the *Physics of cosmic and laboratory plasma,* 130, Novosibirsk, (1989).

12. I.N. Meshkov, S.S. Nagaitsev, I.A. Selesnev, E.M. Syresin Plasma physics, 16, 1119, (1990).

13. I.N. Meshkov, S.S. Nagaitsev, E.M. Syresin DAN USSR, 314, N5, 1332, (1990).

14. B.C. Dokukin, Yu.Ja. Rushin Rocket potential in experiment with electron beam injection M.: ISMIRAN, (1982).

15. T.I. Gagu, Z. Kloss, A.N. Laliashvili et al. Peculiarities of plasma processes appeared in injection zone at electron beam injection from high altitude apparatus. Neutralisation processes, ICI, M.(1983).

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Эксперименты по инжекции электронного пучка
в ионосферную плазму и разреженный газ

Представлены результаты активного эксперимента «Электрон» по инжекции модулированного электронного пучка с током 0,5 А и энергией электронов 6,5–8 кэВ в ионосферную плазму на высотах 90–150 км: спектрограммы радиоизлучения в диапазоне частот 100–500 МГц, данные по тестированию радиоволн через область инжекции и спектры энергии возвратных электронов и ионов, приходящих на метеоракету, оценен потенциал ракеты. Обсуждаются данные лабораторных экспериментов по инжекции электронного пучка в разреженный газ.

Работа выполнена в Лаборатории ядерных проблем им. В. П. Джелепова ОИЯИ.

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The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

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