ELECTROMAGNETIK INTERFERENCE MEASUREMENTS WITHIN THE T-100 ENDURANCE TEST

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Abstract

The results of the electromagnetic measurements over the stationary plasma thruster endurance operation are presented. The spectral and energy parameters of electromagnetic environment produced by the SPT-100 thruster modification have been obtained at the nominal 1.35 kW operating point for varying length of testing time. In accordance with the testing procedures the 100-200 hours permanent thruster operation stages have been realized with the overall 2000 hours endurance test. The electromagnetic radiation and plasma oscillations measurements were made in the frequency range of 1.07-7.15 GHz that included the communications spacecraft system bands.

Introduction

At the present time, the plasmadynamic devices have widespread application as electromagnetic plasma sources and accelerators for controlled fusion, material processing technology, space experiments and electric propulsion. The efficiency of plasma accelerators depends to a large degree on the solution of the fundamental problems of electron and ion streams stabilities, power circuit oscillations and near-wall and electrodes effects in the course of plasma acceleration. The perspective applications of plasma acceleration devices in space propulsion technology are related to satisfaction of the electromagnetic compatibility requirements with spacecraft systems such as radio communications, guidance, navigation, control and scientific experiments.

The characterization of electromagnetic environment produced by electric propulsion engines is an important phase of spacecraft system evaluation. Prior to flights, electromagnetic interference measurements must be made in the course of ground-based tests and level of electromagnetic emissions can be reduced to satisfy the compatibility requirements. The purpose of the tests is to confirm that electromagnetic fields produced by the tested engines are less than the narrow band or broadband emission limits over the frequency range, where electromagnetic emissions might impact to operation of spacecraft systems.

The results of the plasma wave investigations demonstrated that electron stream instabilities in plasma flows were characteristic of electromagnetic plasma acceleration. The physical models for evaluation of plasma wave parameters and electromagnetic environment of space electric propulsion derived from the plasma instability theory [1]. According to theory conclusions and experimental data, instability plasma oscillations are located in the regions of crossed electric and magnetic fields and non-equilibrium plasma flows. The most intensive high-frequency wave generation is considered to be caused by the electron stream interactions in accelerating anode layers. The instability spectrum is determined by frequencies of electron Langmuir oscillations in near-wall and electrode regions of plasma engines.

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The fundamental types of oscillations and the frequency ranges of instabilities are discovered in a closed-drift Hall accelerator [2]:
- magnetic-sound waves in the form of transit oscillation generated by ion streams in an accelerating plasma region;
- high frequency oscillations caused by the instability of inhomogenous electron drift and classified as the fast magnetic-sound waves;
- ionization waves at the low voltage range of discharge performance characteristics with increasing voltage of discharge voltage-current dependences;
- power circuit oscillations at the negative differential resistance range of voltage-current characteristics;
- electron plasma oscillations related with unmagnetized electrons when the drift approximation to electron motion description is not applicable.

The excitation of plasma waves as a result of electron stream instability have been investigated to a smaller degree because of electron dynamics uncertainty in near-wall regions and electrode layers. The research of electron plasma waves with space technology applications is the general problem of the paper.

The investigation of the main instability effects, such as plasma turbulent heating, abnormal transverse electron mobility in crossed electric and magnetic fields, turbulent electron-ion friction with the higher ion acceleration efficiency, is incorporated in the research program. Besides, one should take account of the effects of plasma device normal operation disturbance by excited voltage oscillations and high-frequency vacuum discharges at current circuits.

**Research Design and Methods**

The main regularities of plasmadynamic processes will be instablished in the course of the experimental plasma physics research and the ground-based tests of the space plasma engines. By the research program, the theoretical foundations of plasmadynamic wave processes and electromagnetic environment formation in the vicinity of spacecrafts have been developed. The validity of the theoretical models was examined by experimental data obtained from radiophysical tests of spacecraft plasma engines. The suggested research program design is defined by the main specific aims devoted to the plasma physics and space technology.

The special feature of the research program is present as a result of the work the experimental procedures and the apparatus description for evaluation and control of wave parameters of plasmadynamic systems for their optimization. The research consist of the followings (Fig. 1):
- formulation of preliminary electron instability conceptions;
- performance of the experiments with the space plasma engines under ground-based conditions;
- improvement of the physical models of space plasma engines and the procedures of wave parameters evaluation for space technology applications;
- experimental testing of control procedures based on plasma-solutions of practical problems of plasma space technology in connection with electromagnetic compatibility evaluation of spacecraft systems and plasma devices optimization by parameters of oscillations and electromagnetic radiated emissions.
The central problem with the experimental research of plasmodynamic processes is to obtain absolute data for energy wave parameters described electromagnetic radiated emissions and plasma oscillations. The results of vacuum test facility measurements were used to evaluate the electromagnetic environment produced by the main types of the plasma engines. The measurement procedures made possible comparison of the various plasma engines by wave parameters independently of test conditions and instrumentation.

The test setup for electromagnetic field measurements will have the electric antennae and the magnetic loop transducer pleased in the vacuum test facilities in the vicinity of the test engines samples (Fig. 2). The antenna sensors were oriented to register the electromagnetic fields radiated from plasma emission contributors.

The impact of metal vacuum facilities on electromagnetic measurement results is in pronounced changes of electromagnetic radiated fields produced by plasma devices. This prevented the determination of electromagnetic energy flows from accelerating plasma regions directionally. In accordance with proposed measurements procedures, the standard radiation sources were used to estimate electromagnetic energy flows generated by plasma engines. The electromagnetic signals at radio set entrances will be calibrated with signals of the standard radiation sourced having the similar radiation geometry and known energy parameters in the designated frequency band. The calibrating electromagnetic radiation signals were produced by the discharge plasma noise generator with the thermal emission level determined by an electron temperature.

The distributions of high-frequency fields in discharge accelerating chambers and plasma plumes were defined by the high-frequency probes to evaluate the configuration of plasma instability regions and electromagnetic emission domains. These data were used for calculation of electromagnetic energy flows to the radio set antennae.
The electromagnetic radiated emissions were investigated [1] in the broad frequency band. The paper is concentrated on the frequency range of 1 to 10 GHz where electromagnetic emissions produced by space plasma engines might impact to operation of radio communication systems. Beside, this frequency band is essential for understanding of electron wave processes and plasma instability conditions. The measurements were treated as an efficient operating modes recording for space plasma engines by remote sensing procedures.

By using sensitive radio sets (Fig. 3), electromagnetic emissions were registered from the thermal level associated to the electron temperature of 1-10 eV. The thresholds of electromagnetic wave generation were determined from the discharge voltage, magnetic field strength and propellant flow rate dependencies.

The electromagnetic interference measurements in combination with the T-100 performance characteristic evaluation were carried out in the integration interval of the order of 1 s. The high-frequency signal envelopes with the discerning time of the order of 1 ms in the intervals of 1 to 5 ms were recorded simultaneously by application of a digital storage oscilloscope. In the course of the T-100 test the low-frequency oscillations of the discharge current in the power circuit were registered as well as the potential oscillations of the plasma probes and the thruster hollow cathode in the frequency range of 10 kHz to 10 MHz using the panoramic spectrum analyzer.
Fig. 3. The broadband measurement complex designed for electromagnetic emissions tests of space plasma engines.

Experimental Results

As is apparent after the measurements, at the nominal operating modes with the T-100 optimal parameters of thrust, efficiency and lifetime, the electromagnetic interference quasi-thermal level with the possible exceeding within the same order the equilibrium radiation emission. At the 200-300 hours test stage in the electromagnetic interference spectrum (Fig. 4) the non-equilibrium component is clearly defined in excess by 3-5 orders of the thermal radiated emission level. The most intensive electromagnetic interference is generated by the T-100 in the frequency range of 1.5 to 2 GHz. The electromagnetic interference generation in that frequency range is found to produce by electron plasma oscillations in the externals near-wall region of the accelerated plasma flow.

The electromagnetic interference excitation is non-steady state and can be represented by a random impulse process with noise peak duration of 0.01 to 0.1 ms and random appearance time of 1 to 5 ms (Fig. 5). The spectral electromagnetic interference density within radiation peaks reaches -70 to -60 dBW/m²·MHz, as the thermal radiation level is -103 to -100 dBW/m²·MHz. The electromagnetic interference duration and peak radiation appearance times are considerably superior to the typical duration of the dominant low-frequency oscillations, like power circuit oscillations, ionization waves, ion transit oscillations and plasma hollow cathode oscillations observed within the SPT-100 endurance test.

Attention is drawn to the fact that the intensive electromagnetic interference is generated at the 500-700 hours test duration (Fig. 6) when the abnormal erosion of the T-100 dielectric walls is most conspicuous [3].
Fig. 4. Electromagnetic interference spectra of the SPT T-100 (the dotted line is the thermal radiated emission intensity)

Fig. 5. Typical electromagnetic interference envelopes (detected outputs of the radiated emission measurement receivers)
The thruster energy losses by excitation of electron plasma oscillations and electromagnetic interference fields in the frequency range 1.5 to 2 GHz are of the order of 0.1 W when the energy efficiency of conversion of plasma waves into electromagnetic radiation in nonequilibrium plasma flows is characterized by the experimental magnitudes of $10^3$ - $10^2$ [1]. The instability-initiated plasma losses are insignificant for the T-100 energy balance evaluation but it is necessary to take into account the non-steady state electromagnetic interference fields to satisfy the spacecraft systems compatibility requirements over the T-100 endurance operation. The electromagnetic radiated emission measurements can be treated as the efficient operating modes control and the thruster lifetime prediction by the remote sensing procedures.

Discussion and Theory Remarks

When researching processes in plasma thrusters the particular significance is attached to problems of dynamic stability for electron component for reasons of importance of energy loses through oscillations, excited by electrons, and effects of anomalous plasma conduction in an acceleration channel [4]. The developed physical considerations on plasma flows dynamics meet the conditions of electron current steady-state configurations and stationarity of wave processes in accelerating electric and magnetic fields [1].
In the paper the peculiarities of electron wave processes that become apparent in a plasma thruster with closed electron drift and dielectric walls of accelerating channels have been revealed. The researches have been conducted in the frequency range corresponding to electron plasma oscillations in the outer near-wall region of plasma flow.

The excitation of electron oscillations is concerned with the possible binary structure of electron distribution function by velocities (thermal and anomalous accelerated), as well as availability of beam instability in regions of plasma flow interaction with dielectric walls of an accelerating channel [5].

The experiments results indicate the evolution of the beam instability in the near-wall region of a plasma flow. The formation of electron beams is related to possible accumulation of electrons in an accelerating channel and release of them to magnetic poles in devices with an accelerating anode layer [6]. For the stationary plasma thruster researched in the work the availability of dielectric walls inhibits realization of release mechanism of current and charge compensation of plasma flow magnetized area. In these circumstances the near-wall phenomena are substantial, and their consideration is necessary when analyzing non-equilibrium electron current configuration is the accelerating area of plasma flow. The direct recording of electron beams under conditions of the experiment that has been conducted is difficult, since fast electrons indicators and electrostatic analysers of their energy can substantially distort the structure of a plasma flow. In this connection, the performance of remote measurements of excited oscillations and electromagnetic fields for indication of electron beams, arising in the process of active plasma interaction with dielectric surface, is believed to be enough simple.

The conditions for electron plasma oscillations excitation in the outer near-wall region of a flow are realized [1] at:

$$\frac{\Delta I_{pl}}{d_e} \frac{n_e'}{n_e} \frac{\left( \frac{v_e}{\Delta v_e} \right)^2 v_e}{v_{Te}} > 1,$$

(1)

where $\Delta I_{pl}$ - the typical size of radial plasma inhomogeneity, $d_e$ - the Debye electron distance, $n_e'$ and $n_e$ - the concentrations of beam and plasma electrons, $v_e$ and $\Delta v_e$ - the mean directed velocity and velocity straggling of electrons in a beam, $v_{Te}$ - the thermal velocity of electrons being generated in the ionization zone. The spectrum of electron plasma oscillations is determined by the growth of the instability in various layers of non-uniform portion of a plasma flow with frequencies [7]:

$$\omega(k, I_{pl}) \equiv \omega_{pl} \left( 1 + \frac{1}{2} \frac{\Delta n_e(I_{pl})}{n_e} \right) + \frac{3}{2} k^2 \frac{v_{Te}^2}{\omega_{pl}}$$

(2)

(at the extent of plasma inhomogeneity $\Delta I_{pl} \gg d_e$, $d_e = v_{Te} / \omega_{pl}$). Considering the wave disturbances with the wave number component, longitudinal and transversal relative to the magnetic field, $k_\| < k_{11}$, $k_1 \rho_{Be} \sim 1$ and $k_1 d_e \sim 1$ ($\rho_{Be}$ - the larmor radius of electrons), the influence of magnetic field on electron beam interaction with a plasma flow may be disregarded - the case of propagation of electrostatic disturbances in a plasma along the magnetic field.

The duration of the process of quasi-linear relaxation of electron beams, that ends with formation of "plateau" on the electron distribution function [8], is as follows:

$$\tau_{rel} = \left( \frac{1}{\gamma} \right) \ln\left( \frac{W_{e_{max}}}{W_{e0}} \right),$$
where \( W_{\text{max}} \) is the maximum energy density of electron plasma oscillations, \( W_{\text{ev}} \) - the density of thermal fluctuations energy, \( \gamma = (n_e^*/n_e)(v_e/\Delta v_e)\omega_{pe} \) determines the maximum increment of beam instability in order of magnitude, at \( v_e > v_{Te} \), \( \gamma \sim k_i v_{Te} \). According to evaluations, \( \tau_{rel} \approx 10^4 \) s i.e. it has the order of time in which the fast electrons fly over an outer near-wall region. The duration of generation of oscillations that are observed in the experiment (Fig. 5) comprises \( 10^{-3} - 10^{-4} \) s which allows consideration of nonstationary electron beam formation as a determining factor for the plasma flow instability evolution.

References