Experimental Investigation of the Hollow Cathode Electromagnetic Radiation

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Abstract: This paper presents results of research study for characteristics of electromagnetic radiation (EMR) from the laboratory model of hollow cathode operating in the diode mode with the use of special anode. To reveal reasons causing radiative processes in stationary plasma thrusters (SPT), a procedure is proposed that makes it possible to distinguish radiative processes of the thruster from similar processes during cathode operation in the diode mode. The laboratory hollow cathode operated in the discharge current range from 2 to 7 A both independently, and as a part of SPT-100. As a result, EMR characteristics were defined both at the independent operation of the cathode, and at its operation as the thruster part.

I. Introduction

EXPERIENCE of long-continued application of electric propulsion thrusters (EPT) confirmed their reliability and efficiency. At the same time, some peculiarities were revealed that should be taken into account when integrating EPT with a spacecraft and its systems. So, according to the analysis of multiple results of test studies for the EPT self electromagnetic radiation, the power spectral density of such radiation falls in the range between some tens of kHz to some tens of GHz and presents an interference to the "Earth-spacecraft" channel of space communication systems.[1-2] In the investigations conducted up to now, the EMR characteristics of the operating EPT as a whole were studied, as a rule. However, various EPT components can be the EMR sources. In particular, the hollow cathode-neutralizer being an important part of modern stationary plasma thrusters (SPT), ion thrusters (IT), and thrusters with anode layer (TAL) can be such a source. So, it is interesting to study characteristics of self radiation of the cathode operating independently of the thruster and to compare them with the EMR characteristics of the thruster.

II. Test Description

A. Electromagnetic Radiation Recording Devices

Self radiation of the experimental model was recorded at different modes by the software-hardware complex presented in Fig. 1. It comprised the following basic measurement devices[3]:

1. Spectrum analyzer Agilent E4440A, frequency range 3 Hz - 26.5 GHz (with the option 122 providing digital frequency-domain and time-domain analysis within the frequency band of 80 MHz with the sampling rate of 200 Msamples/s for the central frequency belonging to the spectrum analyzer frequency range).

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2. Signal generator Agilent E8257-520, frequency range 250 kHz – 20 GHz.
3. Digital oscilloscope Agilent Infiniium DSO91304A, input signal frequency band is up to 13 GHz, sampling rate is up to 40 Gsamples/s, 4 measurement channels, memory 1 Gsamples/channel.
4. Wide-band low-noise Agilent amplifier 83017A 0.5-26.5 GHz.
5. Controllable microwave switcher Agilent 8764.
6. Calibrated antenna 1-12-440EM-NF produced by the Advanced Technical Materials, Inc., antenna Model 3115 produced by the ETS Lindgren.
7. Computer, Core 2 Duo Mobile T6600 2.2 GHz, 4 Gb.
8. Network switcher.
9. External hard disk drive.

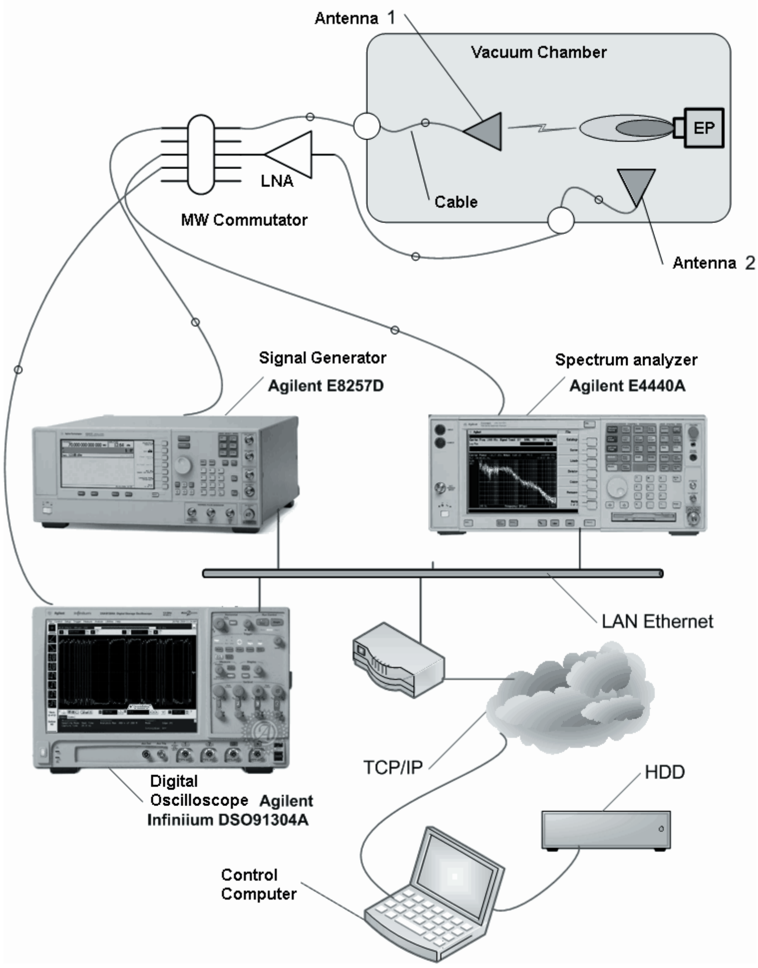

Figure 1. Software-hardware complex

Antennas placed inside the vacuum chamber were connected by the microwave cables to the controllable microwave switcher that provided adaptive control for the signals circulating in the system. To increase sensitivity of the measuring complex, signals to be measured came to the low-noise amplifier (LNA) first, and then - to the spectrum analyzer and/or digital oscilloscope.

General control for the software-hardware measuring complex was provided by the computer using the specially configured software. All measuring devices and control computer were connected to the local area network (LAN).

Measurement data and control commands were transmitted via the LAN Ethernet. An external hard disk drive or a writing optical disk drive were used for the measurement results storage.

B. EPT Experimental Model

To obtain comparative results of the self radiation study for SPT and its hollow cathode, special anode was included in the design of the SPT-100 laboratory model; it allowed hollow cathode to operate in the diode mode with the thruster OFF. Test facility is presented in Fig. 2 with the following designations used: 1 – stationary plasma thruster SPT-100, 2 – cathode-neutralizer; 3 – anode plate; 4 – pick-up antenna, PS1 – the discharge power supply unit (0-500 V), PS2 – the cathode power supply unit (0-80 V), PS3 – power supply unit for the discharge ignition (300 V), PS4 – power supply unit for the cathode discharge (0-300 V), PS5, PS6 – power supply units of the magnetic system (0-80 V), R1 - shunt resistance of 50 Ohm.

Cathode unit (elements 2, 3) was mounted in the upper part of the thruster in such a way that it was located symmetrically relative to antenna 4 and beyond the core part of the thruster plasma flow that had high density of accelerated ions.

The following modes were used to study characteristics of radiation from the thruster SPT-100 and its cathode-neutralizer in the radio-frequency range:
1. Creation of conditions for the cathode-neutralizer discharge (without the thruster start);
2. Thruster start and operation provided by the cathode-neutralizer discharge;
3. SPT-100 operation in the standard mode.

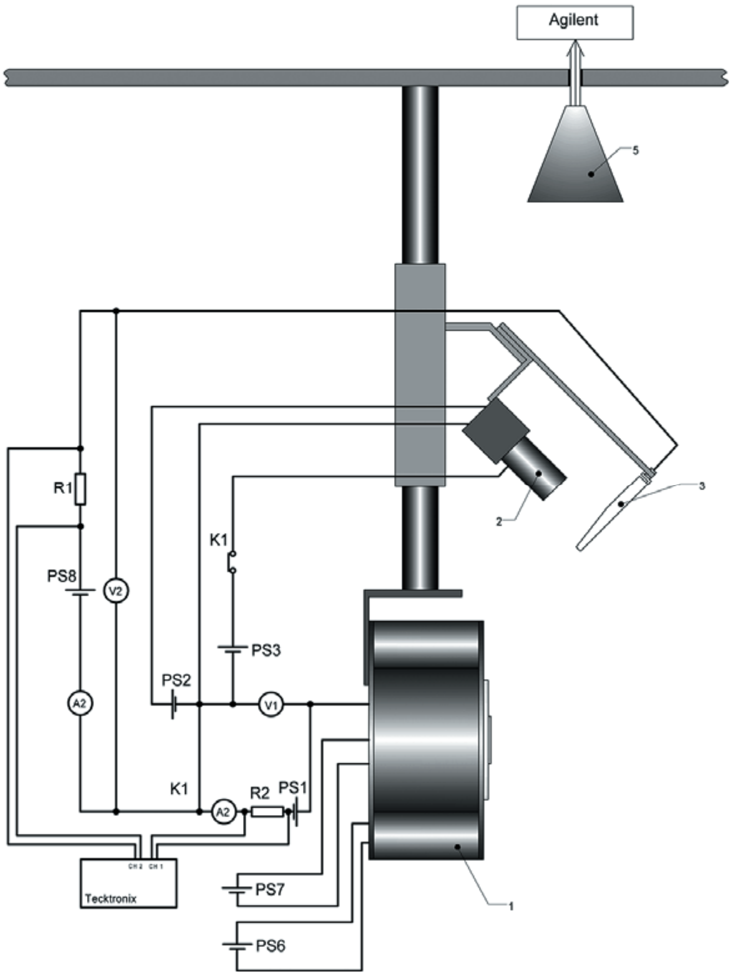

Figure 2. Test facility components and connections diagram

In the first mode, the cathode-neutralizer was heated by the power supply unit PS2 for the discharge ignition; then the potential difference between the cathode-neutralizer 2 and the anode 3 was applied from the power supply unit PS4 and the igniting voltage – from the power supply unit PS3. In that case the Xenon mass flow rate through the cathode-neutralizer was 0.45 mg/s. To eliminate instabilities in the cathode discharge operation, the shunt (ballast) resistance R_1=50 Ohm was used in the cathode-neutralizer circuit. The cathode-neutralizer heating stopped after the discharge ignition, and it continued its operation in the automatic mode with its thermal mode being maintained by discharge. It was possible to correct current in the cathode discharge circuit by varying the PS4 voltage; in the mode under study was 3 A.

To change mode 1 of the experimental model to its mode 2, the xenon was fed through the SPT-100 anode (3.3 mg/s), and potential difference was applied from the power supply unit PS1 (300 V). After the thruster discharge ignition, the cathode-neutralizer operating mode was corrected so, that the current through the cathode-neutralizer be not higher than 3 A.

With the xenon mass flow rate through the thruster anode of 3.3 mg/s and discharge voltage of 300 V, the current in the thruster circuit was 3 A also. To change mode 2 of the system to its mode 3, the voltage of the power supply unit PS4 was shut off.

III. Test Results

Self radiation of the SPT-100 laboratory model with the special anode was recorded for all three modes in the spectrum and time domains.

So, radiation levels at the oscilloscope input are compared in Fig. 3 for the modes 1 and 2, and in Fig 4 for the modes 2 and 3 in the time domain.

Similar processes at the oscilloscope input, but with shorter sweep, are presented in Fig. 5, 6. It follows from the oscillograms that the radiation was of pulsed nature in all three modes. According to the oscillograms of Fig. 3–6, the mode 1 (the cathode-neutralizer is operating only) is characterized by the presence of intense pulsed processes, which become much weaker in the modes 2 and 3. Time parameters of such processes are presented in Table 1.

To define regularities in the appearance of the above radiation pulses, the oscillograms of currents in the discharge circuits of the cathode and thruster are presented in Fig. 6-8. It follows from the curves presented, that the periods of oscillations in the discharge circuits are rather close to the periods of pulses in the received radio waves.

Spectra presented in Fig. 8 were defined for the processes presented in Fig. 5-6. The electric field intensity within the frequency band of 1 MHz converted to the pick-up antenna aperture is shown along the vertical axis. As is obvious from the plots presented, the pulse spectra for all three modes have maximums near the frequencies 0.8-1 GHz.

Table 1.

Model	Average pulse period in the received radio waves, µs	Average oscillation period in the discharge circuits, µs	Average duration of pulses in the received radio waves, µs
Cathode	29	33	3
Thruster (cathode circuit)		40	
Thruster (discharge circuit)	32	36	2
Thruster + cathode (cathode circuit)		36	
Thruster + cathode (discharge circuit)	38	36	3

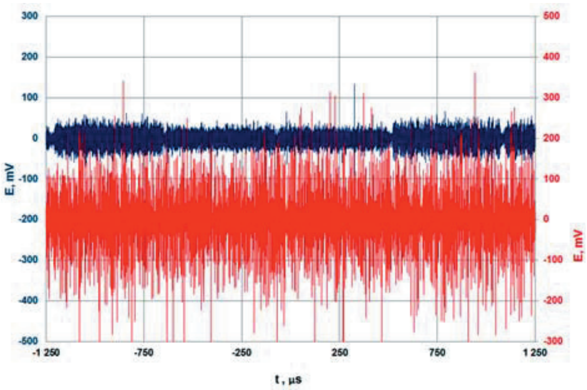

Figure 3. Pulse chain at the antenna output in the mode 3 (blue) and mode 1 (red).

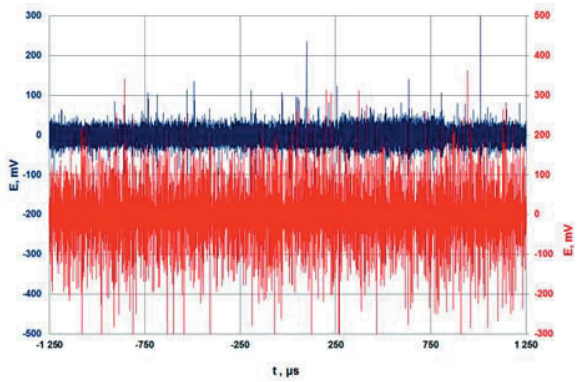

Figure 4. Pulse chain at the antenna output in the mode 2 (blue) and mode 1 (red).

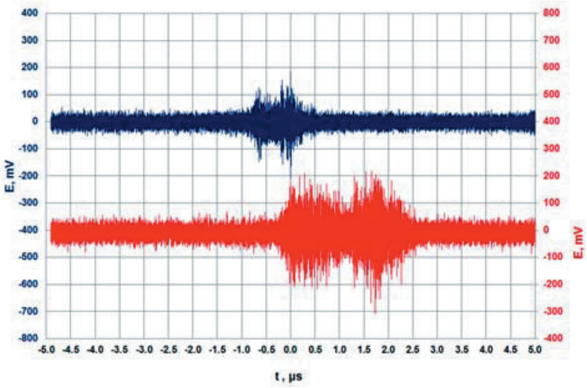

Figure 5. Single pulse sweep in the mode 3 (blue) and mode 1 (red).

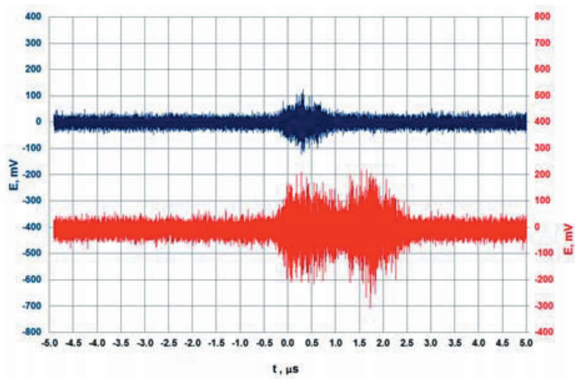

Figure 6. Single pulse sweep in the mode 2 (blue) and mode 1 (red).

This testifies of the fact that during the operation the SPT-100 laboratory model radiated into the air a sequence of quasi-periodical radio pulses with the above carrier frequencies.

Comparison of three modes showed that the highest radiation intensity corresponds to the self-sustained discharge of the cathode-neutralizer (mode 1), the carrier frequency being about 0.8 GHz. The second process (in the intensity) was the mode 3 (standard operation of the thruster), with the spectrum maximum shifted up to 1 GHz. In its behavior, the mode 2 was practically the same as the mode 1, but beginning from the frequencies of about 2 GHz the radiation level started to exceed similar level of the mode 3. It is necessary to note that comparing to the radiation spectrum of a single cathode-neutralizer, the modes 2 and 3 are characterized by additional narrow spectral peaks in the frequencies of about 2.2 GHz.

Thus, radiation of stationary plasma thrusters within the frequency range under study is mainly defined by the processes in the cathode-neutralizer, which should be studied additionally.

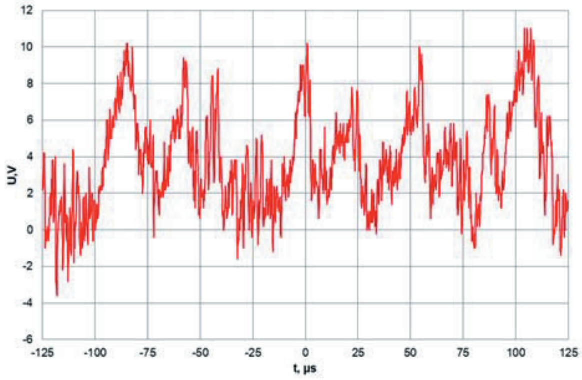

Figure 7. Signal proportional to the current oscillations in the discharge circuit of cathode-neutralizer in the mode 1.

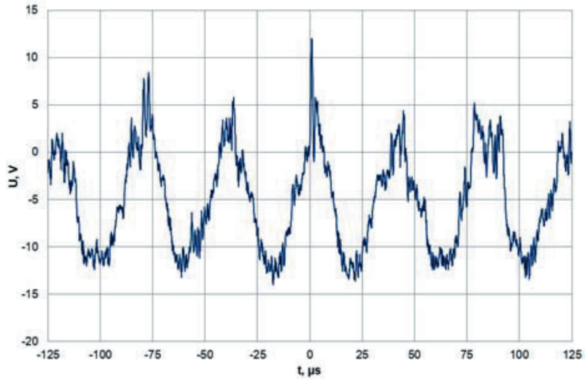

Figure 7. Signal proportional to the current oscillations in the discharge circuit of cathode-neutralizer in the mode 2.

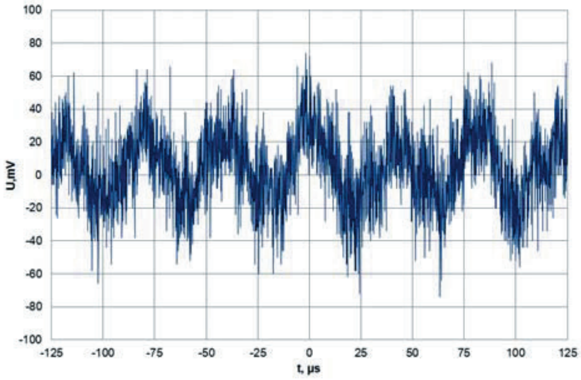

Figure 9. Signal proportional to the current oscillations in the SPT discharge circuit in the mode 3.

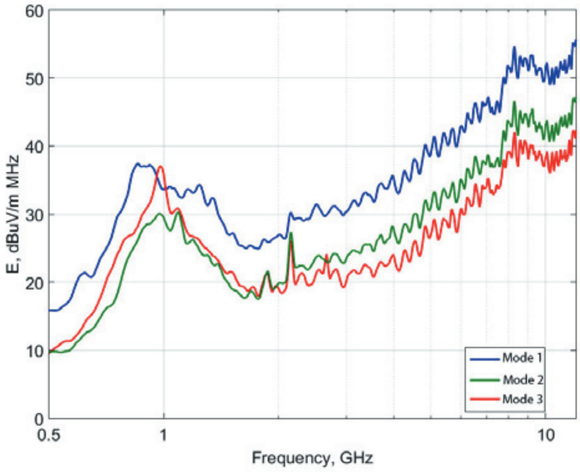

Figure 10. Pulse spectrums for three modes.

Conclusions

1. According to the analysis of the known test results obtained while studying the SPT self radiation in the radio-frequency range, the electromagnetic radiation of stationary plasma thrusters has a clearly pronounced component in the form of random sequence of radio pulses and a noise component. An experimental complex was developed to continue investigations in this area. It allows one to study the SPT spectral and temporal characteristics in the radio-frequency range.

2. The SPT-100 laboratory model comprising special anode allowing hollow cathode to operate in the diode mode with the non-operating thruster was developed to define contribution of thruster components, such as the cathode-neutralizer, into its total radiation. The model developed allowed for the following operating modes: 1 – creation of conditions for the cathode-neutralizer discharge (without the thruster start), 2 – thruster start and operation provided by the cathode-neutralizer discharge, 3 – support of the SPT operations in the standard mode.

3. According to the analysis of time-response characteristics of the SPT laboratory model radiation in the radio-frequency range, a quasiperiodical sequence of radio pulses with the average duration of about 2-3 µs was present at each of three modes. With that the repetition period was within 30-40 µs, while the maximum intensity corresponded to the pulses related to the mode of sole operation of the cathode-neutralizer. The above repetition periods coincide with the periods of current oscillations in the discharge circuits of the laboratory model.

4. It was revealed as a result of study for the spectral characteristics of the SPT laboratory model radiation in the radio-frequency range that for all three modes the recoded spectra had pronounced maximums near the frequencies of 0.8-1 GHz. Comparison of three modes showed that the highest radiation intensity corresponded to the self

discharge of the cathode-neutralizer, the carrier frequency being about 0.8 GHz. In comparison with the radiation spectrum of a single cathode-neutralizer, the modes 2 and 3 have additional narrow spectrum peaks at the frequencies of about 2.2 GHz.

5. A conclusion can be made based on the studies conducted, that in the stationary plasma thrusters of SPT type the cathode-neutralizer is one of the reasons for the appearance of radiation in the radio-frequency range. Radiation taking place at the independent operation of the cathode-neutralizer is of rather high level that becomes substantially lower during its operation as a part of the thruster. With that, basic spectral and temporal characteristics of the cathode-neutralizer self radiation have been continuously traced in the general radiation of the stationary plasma thruster in the radio-frequency range.

References

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