Study for the Influence of Stationary Plasma Thruster Operating Modes on its Electromagnetic Emission

IEPC-2011-094

Presented at the 32nd International Electric Propulsion Conference,
Wiesbaden • Germany
September 11 – 15, 2011

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Abstract: Issues related to the investigation of self-emission characteristics of stationary plasma thrusters (SPT) are considered in this paper as applied to the problems of electromagnetic compatibility (EMC) of electric propulsions (EP) with onboard systems of spacecraft (SC). SPT selection as a subject of research was dictated by the fact that the thrusters of this type have been successfully used on board domestic and foreign SC for many years already and their application continues to expand. EMC problems related to such thrusters require more detailed investigation in view of the fact that in the not distant future it is planned to use 4-5 kW thrusters in a single module capable of operating at the modes with different values of specific thrust pulse. The problem of studying characteristics of electromagnetic emission at the variation of their operating modes becomes especially actual with this. Such study was made using modified laboratory models of SPT-100…140 thrusters. According to the results obtained, such thrusters are capable of efficient operation at discharge voltages of 800 V and higher, ensuring specific thrust impulse of about 2800 s.

Facility similar to the one described in [1] was used to study characteristics of electromagnetic emission for the modified SPT models. It was based on the metal vacuum chamber of 2 m in diameter and 4 m in length. Taking into account that those tests were aimed at the comparative assessment for the variation of electromagnetic emission characteristics of SPT laboratory models at different modes of their operation, relative assessments for the emerging emission power levels at certain operating modes were used to study characteristics of electromagnetic emission. In that case the use of metal chamber without the additional means providing for anechoicness appeared to be rather efficient and simple.

Measuring antennas, overlapping frequency band under study, were mounted perpendicularly to the plume axis in the exit plane of the thruster at a distance of 0.8 m from it. In order to prevent plasma from reaching their apertures, they were covered with protective film similar to Kapton with the thickness of 100 μm.

In order to reveal effects originating during the operation of different SPT models, both interferences appearing during the thruster operation at different modes and background signals with the shut-down thruster were registered. In the course of measurements the spectrum analyzer formed assessment for the input signal power $P_{SA}(f)$ (dBm) within the band of the spectrum analysis filter $\Delta f_{RBW} = RBW$.

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The root-mean-square value of electric field intensity in the antenna aperture was calculated by the following formula:

$$E(f)_{dB\mu V/m\,MHz} \approx P_{SA}(f)_{dBm} - 10\lg \Delta f_{RBW\ Hz} - K_{cb}(f) + A_F(f)_{dB\,1/m} + 167_{dB} \quad (1)$$

where $K_{cb}(f)$ is the feeder circuit transmission factor that takes into account the low-noise amplifier presence in the circuit; $A_F(f)_{dB\,1/m}$ is the antenna factor; the load resistance was assumed to be equal to 50 Ohm.

Measurements were made with the use of computerized measuring complex comprising spectrum analyzer and control computer allowing selection for the measurement mode and parameters, measurement execution control, saving and real-time visualization of results. Results were saved as spectrum-analyzer data files on the control computer hard disk. Primary data processing was realized in the MATLAB environment after measurements. Collected data were displayed as plots and analyzed[3,4]. Spectrum smoothing was made to increase demonstrativeness of results.

Assessments for the interference power spectral density and root-mean-square value of electric field intensity at the antenna input within the frequency range of 1-18 GHz for different modes of operation of SPT laboratory models described hereinafter were the primary results of measurements.

I. Spectral Characteristics of Emission for the Laboratory Model SPT-100-1

SPT-100-1 is the SPT-100 modification. It is designed for the operation in high-voltage modes and is provided with enhanced magnetic system. Such model was used to study influence of discharge voltage within the range of 300 - 800 V at the fixed propellant mass flow rate of 2.95 mg/s. Fig. 1 shows final measurement results for the SPT-100-1 emission spectrum for the frequency resolution $\Delta f_{RBW} = RBW = 1$ MHz. It is obvious that maximum excess of the EP emission level over the background is observed in the region of 1 GHz and comprises about 16 dB. The emission spectrum level increases with the discharge voltage growth, but at the discharge voltage of over 600 V the emission spectra become comparable.

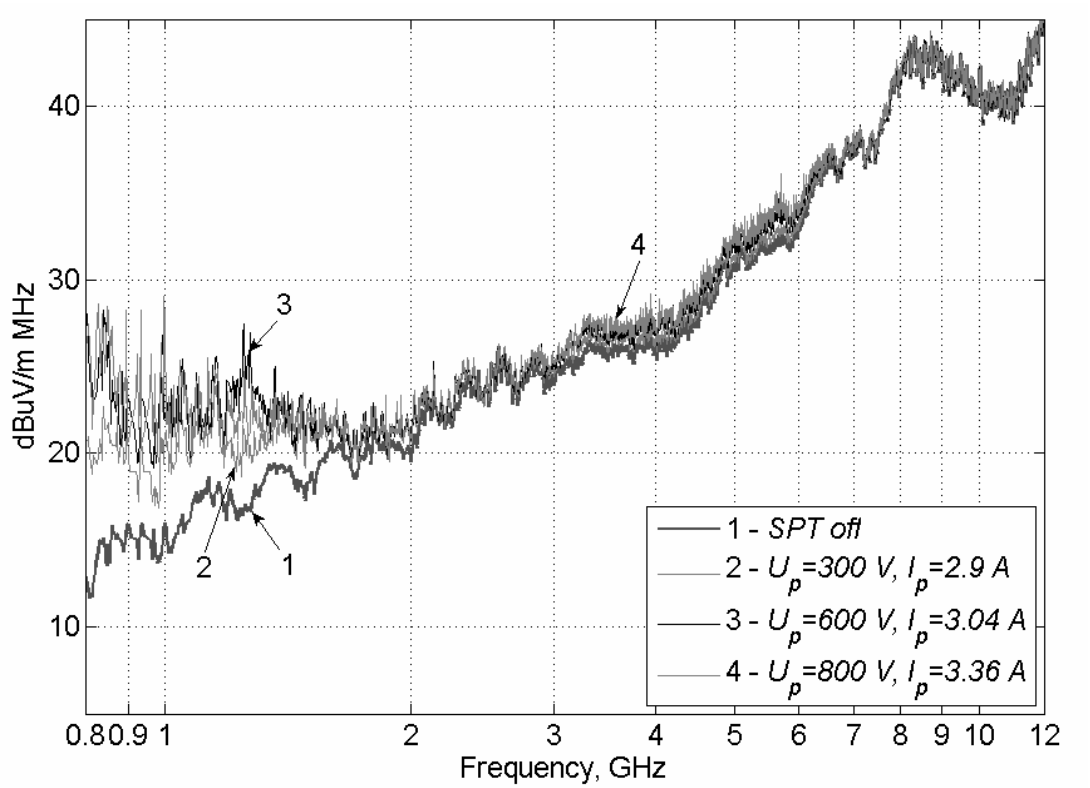

Figure 1. SPT-100-1 emission spectrum.

II. Spectral Characteristics of Emission for the Laboratory Model SPT-100-2

SPT-100-2 is the SPT-100 modification. It is designed for the operation in high-voltage modes and is provided with optimized magnetic system. Basic modes of its operation are presented in Table 1. Measurement results for the SPT-100-2 emission spectrum are shown in Fig. 2. Similar spectra smoothed by the filter with transmission band of 200 MHz are presented in Fig. 3 for better visualization.

Table 1. SPT-100-2 Operation Modes

Operation mode	Voltage U_p V	Current I_p, A	Propellant mass flow rate, mg/s	Magnetization current I_{m1}, A	Magnetization current I_{m2}, A
1	300	2.51	2.73	2.36	3.30
2	400	2.64	2.73	3.57	3.25
3	500	2.72	2.73	2.61	2.88
4	600	2.77	2.73	2.65	3.02
5	700	2.85	2.73	2.87	3.29
6	800	2.95	2.73	2.75	3.41

It is evident from the obtained dependencies that for the discharge voltage of up to 400 V the basic spectral components of the SPT-100-2 emission are within the frequency range of up to 2 GHz. Besides, the root-mean-square values of the electric field intensity for interference may be as high as 30 dBμV/m/MHz, that being higher than the background by 16 dB.

At the discharge voltage of 500 V and higher the registered frequency range occupied by the emitted interference widens to 12 GHz. In this case the root-mean-square value of the electric field intensity for interference is as high as 50 dBμV/m/MHz (1.5 GHz), 45 dBμV/m/MHz (6 GHz), and 46 dBμV/m/MHz (8.5 GHz), that exceed the background level of measuring equipment by 30 dB, 10 dB, and 15 dB, respectively. Attention is drawn to the presence of extrema in the emission spectrum at the frequencies of 1-1.5 GHz, 4-6 GHz, and 8-9 GHz.

The plot of Fig. 4 allows assessment for the dynamics of emission spectrum shape variation for the SPT-100-2 laboratory model after its operation start. Emission spectra registered just after the operation start and in the steady-state mode (40 minutes after the thruster start) are presented in this Figure. It is obvious that at the start moment the level of spectral components within the range of 3-9 GHz is lower substantially than the values typical for the steady-state mode. During the process of reaching steady-state mode of operation, the level of emission in the range of 2-9 GHz grows by 3-10 dB depending on the specific frequency value.

The fact of considerable influence of a combination of parameters describing SPT operation upon the spectral characteristics of its electromagnetic emission is verified by results presented in Fig. 5. It is evident that even at the same values of discharge voltage and current (curves 6 and 7), but different mass flow rates (2.25 and 2.73 mg/s, respectively) and different magnetization currents, the EP emission spectra differ substantially. In this case, reduction of the propellant mass flow rate and variation of the plume parameters due to the magnetization current variation allow decrease in the EP emission level by 10-20 dB within the range of 0.8 - 12 GHz.

Thus, by selecting the EP operation mode it is possible to control the level of EP electromagnetic emission within certain limits, and this is extremely important from the point of view of securing efficient and reliable operation of the SC onboard systems.

III. Spectral Characteristics of Emission for the Laboratory Model SPT-100-3

Those studies were made with the model SPT-100-3 that represented by itself an engineering model based on the SPT-100-2 that allowed prompt variation for the discharge chamber parts for simulating different degrees of wear of the latter.

Three degrees of the discharge chamber wear were considered:

a) the discharge chamber state close to the initial one after several tens of hours of operation (Set 1);
b) wear of output parts of the discharge chamber walls by approximately a half of their initial thickness (Set 2),
c) wear of the discharge chamber output part by 85% of the initial thickness (Set 3).

Comparative data on the EP emission for different points of the discharge chamber lifetime are presented in Fig. 6. It is obvious that difference between the EP emission characteristics of Set 1 and Set 2 is relatively not big. But in the case of Set 3, a stable increase is observed in the EP emission level by 6-10 dB within the range of 0.8-2.8 GHz comparing to Set 1 and Set 2.

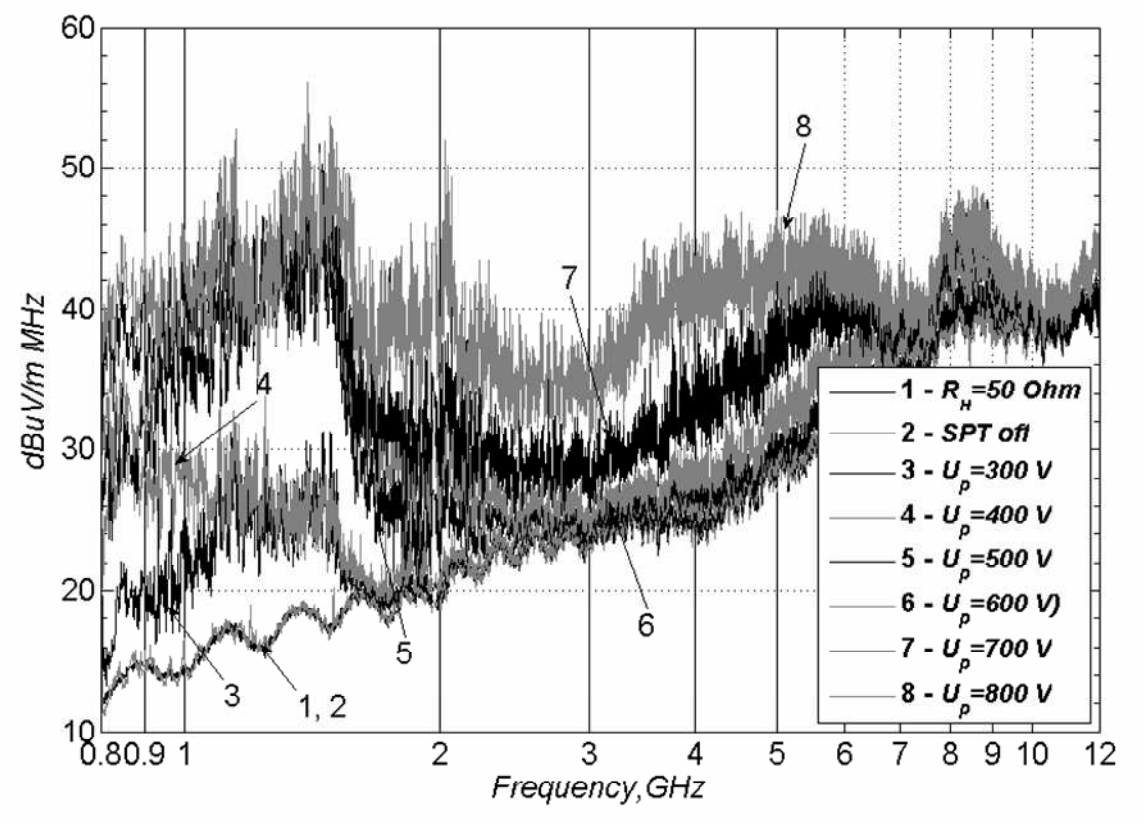

Figure 2. SPT-100-2 emission spectrum.

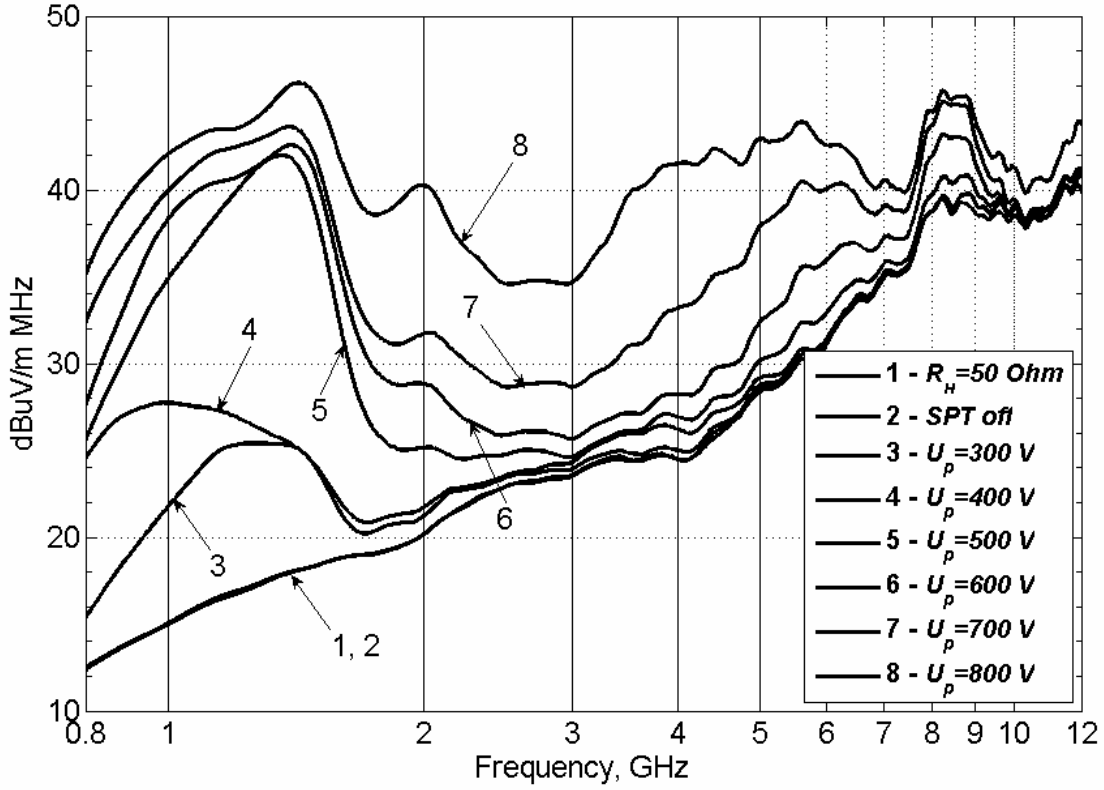

Figure 3. Smoothed emission spectrum of SPT-100-2.

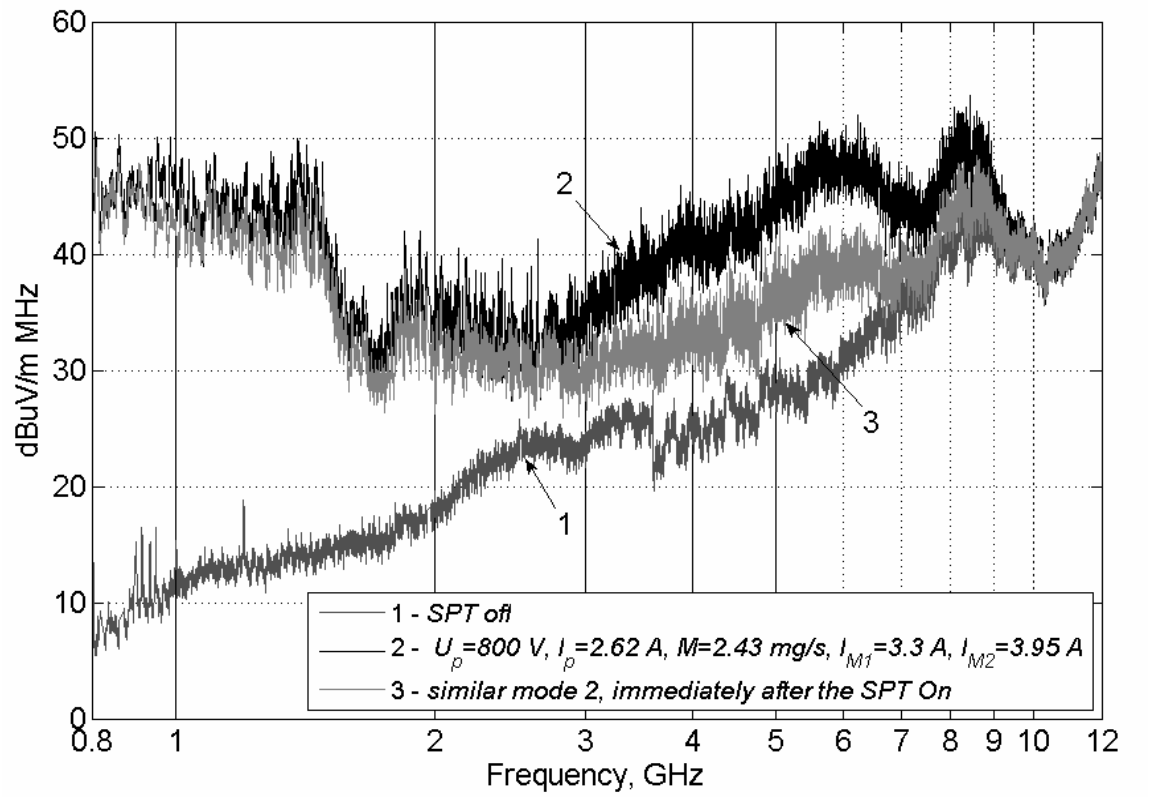

Figure 4. Variation of spectral characteristics of SPT-100-2 emission at the thruster start.

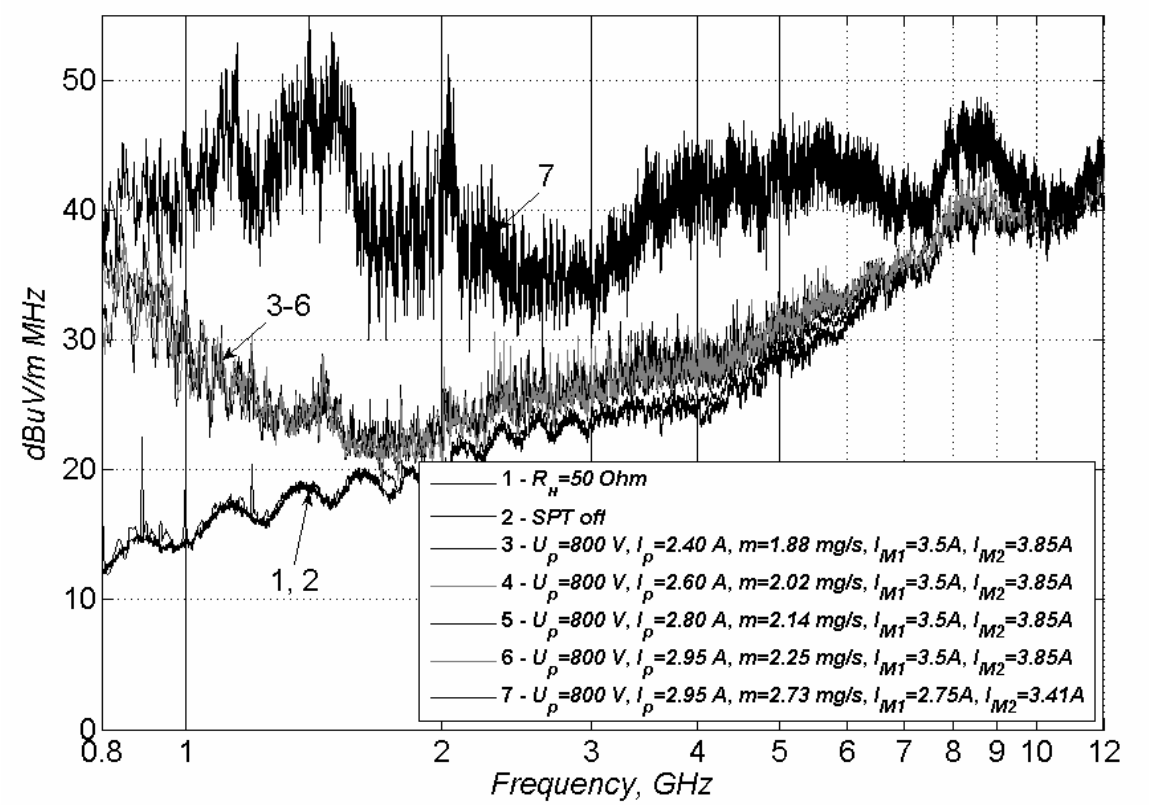

Figure 5. Influence of operation mode on the spectral characteristics of SPT-100-2 emission.

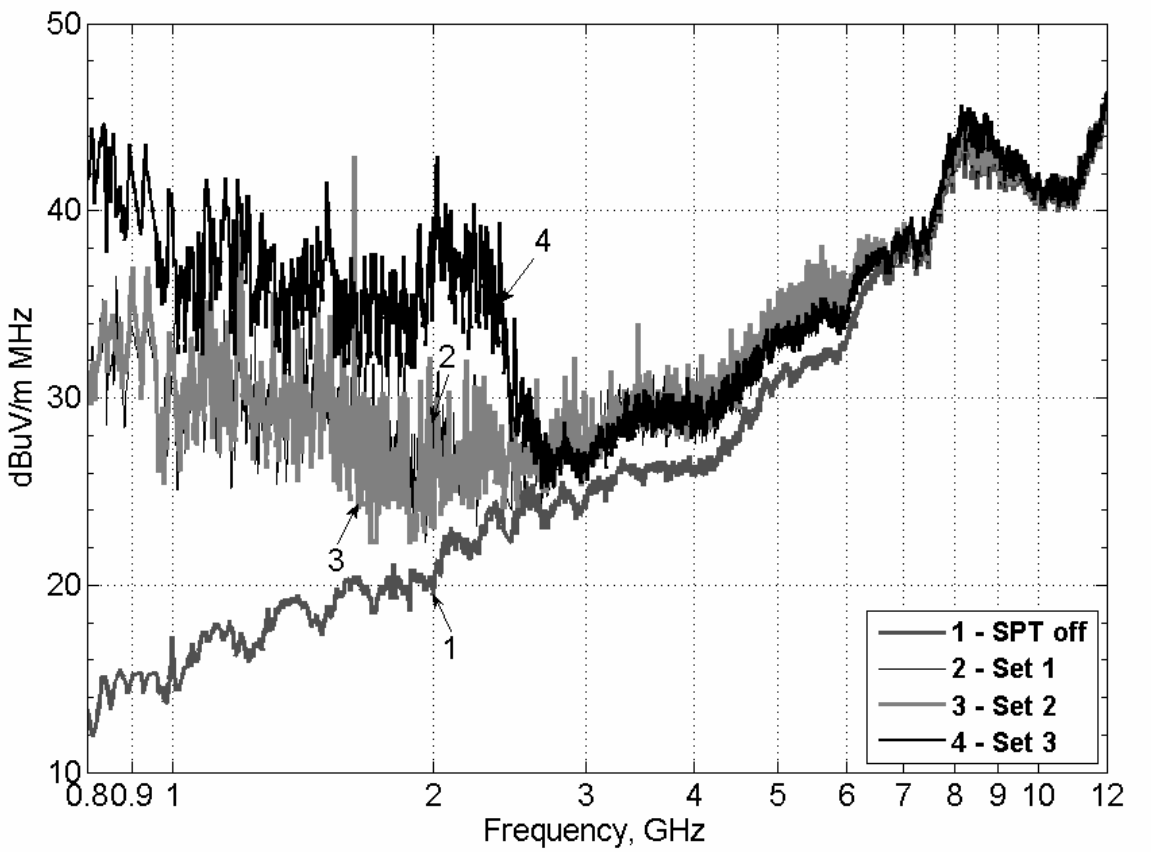

Figure 6. Operation duration influence upon the spectral characteristics of the SPT-100-3 laboratory model emission.

Some increase in the emission level by 1-1.5 dB takes place in the range of 8-9.5 GHz also. And in the range of 4-7 GHz, on the contrary, insignificant reduction of emission level, by 1-3 dB approximately, is possible.

In general, the obtained data give evidence of the fact that the SPT discharge channel wear leads to the origination of rather intense emission within the frequency range of 1 - 7 GHz, as well as to the appearance of noticeable emission within the frequency range of 8-9 GHz.

IV. Spectral Characteristics of Emission for the Laboratory Model SPT-140-1

SPT-140-1 is the SPT-140 modification. It is designed for the operation in high-voltage modes and is provided with enhanced magnetic system. For this model the operation models were grouped relative to three values of propellant mass flow rate: 3.0; 5.55 and 7.05 mg/s at the discharge voltage variation from 300 V up to 800 V with the step of 100 V.

Analysis of obtained results revealed that the discharge voltage and propellant mass flow rate have substantial influence upon the electromagnetic emission characteristics of the model SPT-140-1. With the minimum propellant mass flow rate (3 mg/s) the thruster emission is insignificant at any values of discharge voltage. With other mass flow rate values (5.55 and 7.05 mg/s) the expected trend was observed - monotonous growth of emission level with the discharge voltage increase. In that case the shape of the spectrum remained unchanged practically. So, at the variation of discharge voltage from 300 V up to 800 V the spectrum maximum grew, at an average, by 6 dB (4 times). This is shown in Fig. 7 for the mode with 5.52 mg/s. Fig. 8 shows the plots (test and approximation) for emission power increment relative to the mode with nominal discharge voltage of 300 V and mass flow rate of 3.00 mg/s.

Presented results are in a good agreement with the results of similar studies presented in [2] for the case of using an anechoic chamber for measurements.

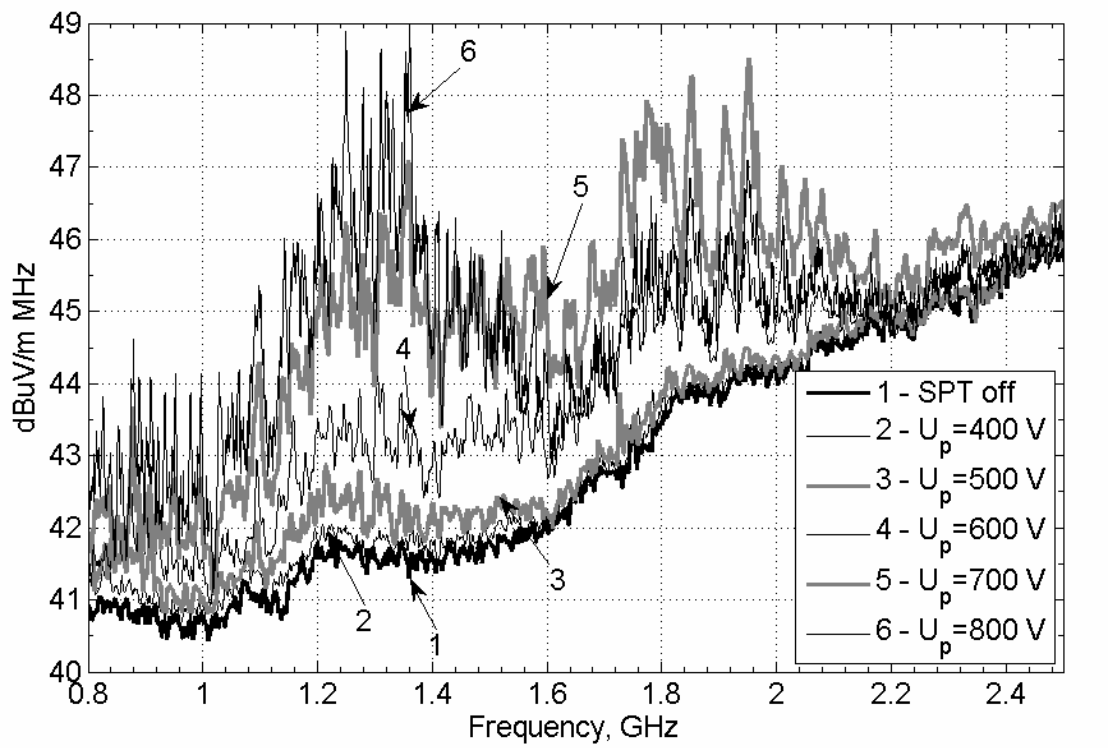

Figure 7. Discharge voltage influence on the spectral characteristics of SPT-140-1 at the mass flow rate of 5.55 mg/s.

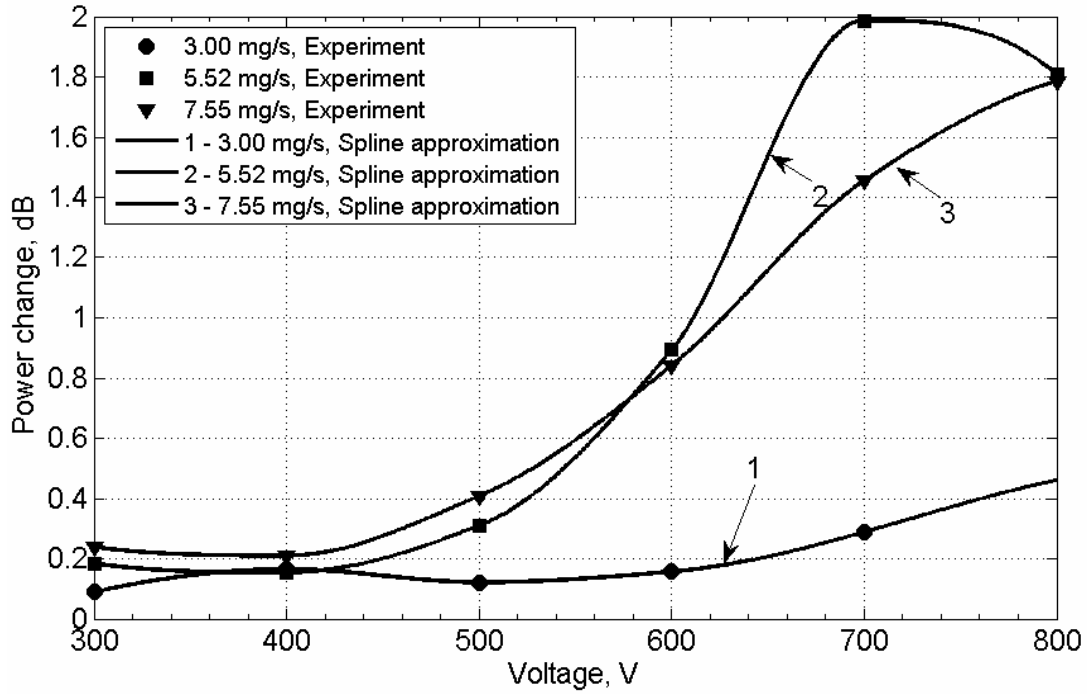

Figure 8. Relative variation of the SPT-140-1 emission power as a function of discharge voltage.

V. Spectral Characteristics of Emission for the Laboratory Model SPT-140-2

SPT-140-2 is the SPT-140 modification. It is designed for the operation in high-voltage modes and is provided with optimized magnetic system. Measurements were made for the modes presented in Table 2.

Table 2. SPT-140-2 Operation Modes

Operation mode	Discharge voltage U_p, V	Discharge current I_p, A	Mass flow rate, mg/s	Mass flow rate through the cathode, mg/s	Magnetization current, A
1	600	7.5	6.79	0.4	5.5
2	800	6.0	5.37	0.4	5.5
3	900	5.0	4.43	0.4	5.5

Measurement results for spectral characteristics of SPT-140-2 emission are presented in Fig. 9. It is evident that the frequency ranges of 0.8-2 GHz and 3-7 GHz are the main spectral regions, in which the SPT emission is concentrated. Within these ranges the level of emission for discharge voltage of 900 V exceeds the background level by 5-28 dB and 5-10 dB, respectively. In general, the level of EP electromagnetic emission grows with the discharge voltage increase.

Final dependence of the average total power flow density in the measuring antenna aperture exceeding the background level upon the discharge voltage for the models SPT-100-1, SPT-100-2, and SPT-140-2 is presented in Fig. 10.

Conclusion

General approaches to the determination of modern EP electromagnetic emission are considered in the paper. Effects appearing at the application of SPT operating in high-voltage modes are assessed. A problem is stated and solved for comparative assessment of variation of electromagnetic emission characteristics for the models of thrusters SPT-100 - SPT-140 at different modes of their operation. Procedure is refined and test study is made for the electromagnetic emission of such thruster models within the frequency range of 1-18 GHz, and the following results were obtained:

- main power of the SPT-100 - SPT-140 emission spectrum is concentrated within the frequency range of 200 MHz – 3 GHz (at the fixed level of instrumentation noise);
- at the transition from low-voltage modes of operation to the high-voltage ones the emission level grows substantially. So, for example, for SPT-140-1 at the voltage variation from 300 V up to 800 V (mass flow rate was 5.55 mg/s) the maximum excess of the EP emission electric field intensity over the background was 7 dBμV/m/mHz at the frequency of 1.35 GHz, and the total emission power grew more than 1.5 times.

Test data relating to the multi-mode operation of SPT, which are presented in this paper, are new and will be used for a next step in the development of new physico-mathematical models of SPT as of the interference sources.

References

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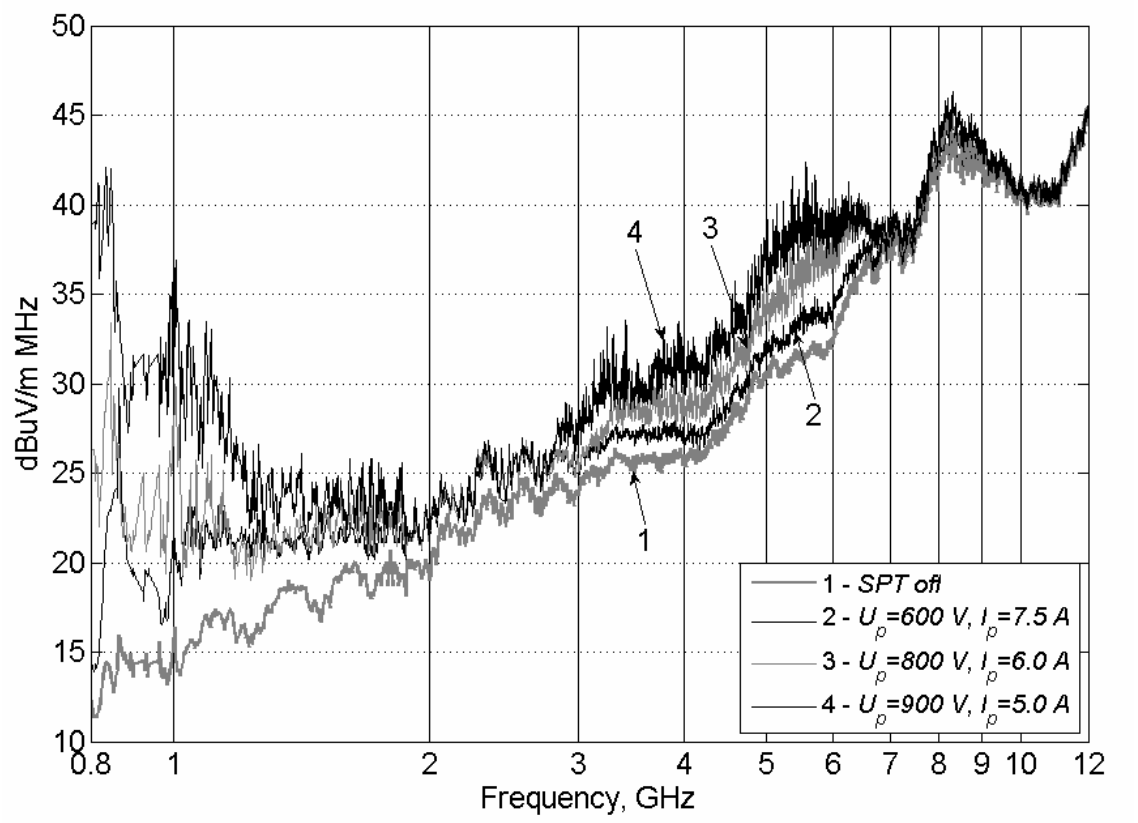

Figure 9. Spectral characteristics of SPT-140-2 emission for different discharge voltages.

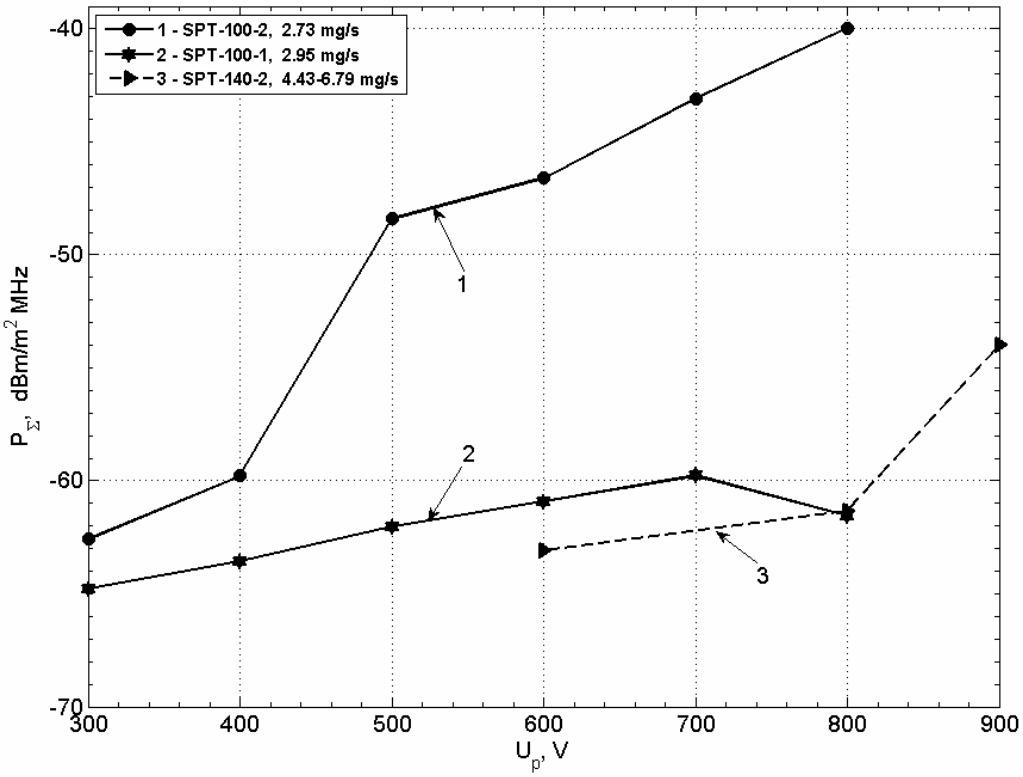

Figure 10. Power flow density at the measuring antenna input as a function of discharge voltage for different SPT models