Study of the 3-TAL Thruster Assembly Operation

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Abstract: Multi thruster assemblies (Clusters) - are considered as a key technology to create powerful electric propulsion systems for perspective space transportation systems. Operation of a such assembly, interaction between thrusters and between exhaust plasma plumes have some specific, which is not well studied yet and requires dedicated research. In this article results of experimental study of three-thruster assembly, based on D-55 anode layer thruster, are presented. Flexibility of the cluster design and operation in regard to it's size, power supply scheme and propellant management system is studied. Possibility to utilize remote cathode for cluster operation is experimentally demonstrated. Additivity of the thrust and discharge currents of the thruster assembly in a different schemes are studied, and it was demonstrated that resulted thrust value of the cluster in all studied regimes and schemes is summa of individual thrust values in all tested schemes. Sensitivity of the cluster assembly operation to non symmetrical deviation thruster regimes was studied and possibility to vary cluster thrust vector by independent variation of thruster regimes demonstrated. Discharge current oscillations of each thruster and oscillations of the summarized current of three thrusters operating from one common power supply are considered. Observed oscillations were independent in each thruster discharge circuit despite on operation from common power supply. Measured amplitude of common current oscillations is of the same order as one in individual thruster circuit. The results of complex cluster plume characterization using Langmuir probes are presented. The comparison of single thruster plume parameters and cluster ones is carried out. Presence of nonlinear effects in the cluster joint plume was identified based on analysis of calculated and measured joint plume.

Nomenclature

V_d = Discharge voltage
I_d = Discharge current
I_{sp} = Specific impulse
F = Thrust
φ_p = Plasma potential
j_i = Ion current density
T_e = Electron temperature

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I. Introduction

Combinations of advanced power systems and advanced orbital trajectories have mission designers emphasizing a significant need for a high power Hall thruster technology with high ratio of thrust-to-power[1,2]. This technology promises the possibility of significant reductions in launch mass making new missions possible with the existing launch vehicle fleet. Non-nuclear trans-planet injections, reusable space tugs for LEO-GEO transfers in less than 100 days, space solar power satellites are a few examples of missions where the electric propulsion modules based on Hall thrusters with power ranging from tens of kilowatts to in excess of one hundred kilowatts might be applied. Recent analysis of physical constraints limiting the maximum power of a single Hall thruster indicated a possibility to extrapolate state-of-the-art technology for the development of high (50-100 kW) power Hall thrusters through the scaling approach based on the linear fashion of the thruster channel size increase[3]. An alternate strategy to obtain a given power level is based on multi-Hall thruster assembly approach generally assuming large number (arrays) of comparatively small lower power thrusters assembled in one propulsion module. Dedicated comparative analysis of these options has shown that, subject to the targeted specific parameters of the mission, one option may be preferable against the other[4]. For instance, for the missions requiring high specific impulse (I_{sp}), a fewer number of high power thrusters may represent more beneficial approach to obtain given power level than a larger number of smaller thrusters. In turn, when very high power application at the lower I_{sp} is required, the trade between travel time and ground tests issues may result in quite different conclusion. Cluster EP technology provides more flexibility, reliability and new operation quality to high power EP systems[5]. Certainly, cluster propulsion configuration may at some level be a solution to overcome a real limitation represented by the requirements of the ground test programs necessitated by the development of the high power HET propulsion.

Limited efforts were made prior the current work beginning that studied technical issues of the Hall thrusters clustering and operating simultaneously. Simulation of a multi-thruster assemblies operation was performed mostly with the use of two-device arrays representing both the Thruster with Anode Layer (TAL) and Stationary Plasma Thruster (SPT) technology[6,7]. Meanwhile, there are no data dedicated to characterization of the plasma plume generated by the array of the thrusters, whereas additional complications beyond those identified for a single thruster plume may be manifested. Therefore, effort was also focused on preliminary experimental study of integration issues associated with operation of clustered HETs based on low-scale array of laboratory devices. One of its goals was to assemble and test a laboratory multi-thruster Hall propulsion module based on a three engineering TAL units. This module is supposed to be used for comprehensive basic research of the phenomena accompanying its operation and properties of the complex triple-thruster plume.

II. Goals and Objectives

Cluster approach can be deemed as essentially important for advance propulsion systems. Using a narrow range of proven engines of a relatively small power, one can overcome difficulties with ground development tests and improvement of a high-power EP system, because it will be enough to develop the components, which it contains. So, a cluster (once developed and improved) enables designing of propulsion systems, which have diverse power. It is achievable via mere scaling, just by adding available propulsion modules (clusters), and allows saving time and money necessary for improvement of a system.

In spite of visual simplicity, implementation of EP on the basis of several electric thrusters, aggregated in a system and working at a time, needs investigation of some basic aspects:

- Summarization of the thrusts of engines in a cluster (additivity of thrust);
- Interaction of exhaust plumes of engines in a cluster (to ensure correct estimation of their effect on surfaces of a spacecraft);
- Interference (cross effect) of cluster thrusters;
- Effects due to electromagnetic noise generated by thrusters of a cluster;
- Stability of a cluster in case of parameter deviations or even failure of one of the thrusters;
- …

The architecture (functional scheme) of modern EP systems on ion or Hall-effect thrusters is, as a rule, based on a linear principle - every engine has its individual cathode-neutralizer, propellant supply system, power supply and control system.

A cluster - an integrated system, consisting of several, simultaneously operating thrusters, aimed at executing a common flight task – enables application of new schemes of EP systems in which, e.g., functions of feeding and control for every thruster can be integrated in one device for all, and one cathode-neutralizer can serve for operation of several thrusters etc[3, 4, 6].

Thus, being a good solution for the main task – creation of a high-power EP system having any specified power, under conditions of a limiting range of proven engines – the cluster technology provides new capabilities: it enables achieving of maximum flexibility and reliability of an EP system with reducing its weight as compared to the design when several, actually independent propulsion systems are just put together[4].

To make these capabilities real, a number of special engineering solutions inherent to the clusters, which were not investigated earlier, need an intensive research. In particular, the following problems should be investigated:

- Possibility of operation of several thrusters from a common power supply and a common propellant feed system.
- Possibility of a cluster operation from a common cathode-neutralizer, probable limitations on the sizes of a cluster in case of the possibility.
- Optimization of the number of thrusters in a cluster.
- Probable interaction of cluster thrusters, both through plasma and through internal electric circuits.
- Stability of a cluster operation under deviations of parameters of some thrusters in a cluster.

Thus, efforts under this activity were concentrated in two main directions:

- Development and manufacturing of a cluster, its verification and study of integral performances;
- Development and verification of the diagnostic equipment for investigation of multi–thruster system plumes and initial diagnostic of a complex cluster plume.

II. Hardware description

The cluster architecture based on three D-55 thrusters with anode layer (TAL) similar to those used in the flight experiment aboard STEX spacecraft in RHETT II program[8] was chosen. Design of these TALs is the most proven one. There is an extensive base of experimental data collected from tests in Russia and USA. In future, it enables comparison and analysis of results. The program of work on a triple D-55 thruster cluster development contained several phases:

- Verification of characteristics for every engine during individual tests.
- Designing and manufacturing of a cluster assembly, systems for power supply and measurements.
- Verification of parameters for every thruster after mounting in a cluster assembly.
- Elaboration of a program of tests and experimental investigation of cluster performances.

The verification phases pursued the goal of obtaining the basic characteristics of thrusters under the same conditions and on the same test equipment, which then was used during tests of the whole cluster. The work was executed under a standard, well-known, TSNIIMASH's procedure of measurements, and is not described in details in this paper. As a result of the step-by-step verification it was obtained that in all testing modes all the three thrusters (tested under the same conditions) showed identical characteristics for thrust, specific impulse, discharge ignition voltage. A database on experimental characteristics of tested thrusters has been collected. For further investigations of the cluster, the mode with xenon consumption flow of 3,5 mg/s into the anode of a thruster and varied discharge voltage (200, 300 and 400 V) was chosen as a baseline one. The flow of 3,5 mg/s was chosen to ensure a thruster operation stability and keeping the residual pressure in the vacuum chamber at a level not less than 0.0003 mm Hg during operation of the triple-thruster cluster.

Mounting of the thrusters in a cluster assembly – which demanded (as it is shown below) changes in the relative position of a thruster and a cathode in comparison with the flight configuration of D-55[8] - resulted in no changes of integral parameters of the thrusters.

The main requirement to designing of a cluster and its power supply systems was ensuring of the feasibility of diverse functional diagrams, simulation of cluster design features and operational modes. In particular:

- Series actuation of one, two and three thrusters in the cluster.
- Simultaneous operation of the three engines, each being fed from an individual power supply.
- Operation of all the three thrusters from a common power supply.
- Operation of the thrusters with individual cathode-neutralizers.
- Operation of some thrusters with one cathode.
- Operation of each of the thrusters in the cluster in a floating scheme and in a grounded scheme (cathode-neutralizer and vacuum chamber walls are electrically connected).

It is must be explained that the last was used to simulate operating conditions for a thruster with various cathodes, because discharge voltage and floating potential can essentially vary: 1) during a cathode service and; 2) on change from one cathode to another one. Use of the grounded and floating schemes enables simulation of influence of the cathode parameters on both the thruster parameters and measurement results of plume parameters.

The measuring equipment provided measurements of the following values:

- electrical parameters in all circuits of a thruster;
- xenon flow rate into each thruster and cathode-neutralizer;
- thrust;
- oscillations of discharge current in the circuit of each thruster;
- pressure in the vacuum chamber.

Below, the developed cluster design and test-bench systems are described in detail.

The scheme of a cluster assembly based on three D-55 thrusters with anode layer was chosen as a base-line configuration for the investigations. In Fig. 1 a general view of the assembly with a common cathode mounted in the center is shown. The assembly configuration enabled also installation of several cathodes (that is described below in detail). On the basis of the results of development testing represented in the next sections of this paper, the scheme with a common central cathode was chosen to be the basic one. TSNIIMASH's laboratory cathode providing electron current up to 10 A was used in the tests. The thrusters and cathode were electrically isolated from each other and from the subplate. All necessary galvanic couplings were provided by means of commutation in the feed and control circuit outside the vacuum chamber. It enabled realization of various operation modes of the cluster without opening the vacuum chamber during the tests.

Figure 1. Overall configuration of the cluster system.

Figure 2. TSNIIMash facility external view.

The cluster was mounted on a pendulum-type, thrust measuring device in a vacuum chamber of 10 m^3 volume (1.7 m diameter, 4 m length) with five diffusion vacuum aggregates (Fig. 2).

Measurements of the thruster/cluster parameters were taken under two schemes of electrical circuit. In the first scheme the cathode negative was connected to the negative of thrusters and was connected to the ground. In the second case there was no connection to the ground (switch "Ground" Fig. 3, Fig. 4).The first scheme is the most safe whereas the second one is more closer to real onboard SC conditions.

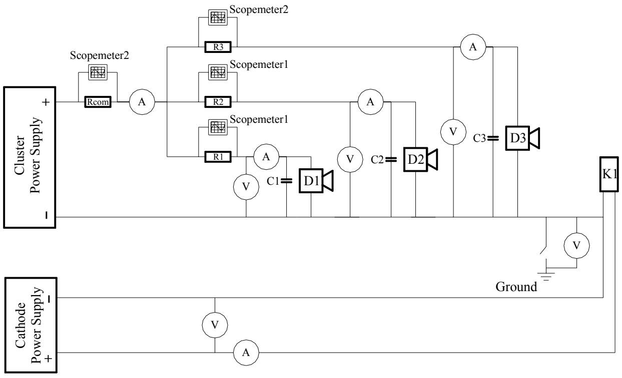


Figure 3. Electric circuit: common power supply.

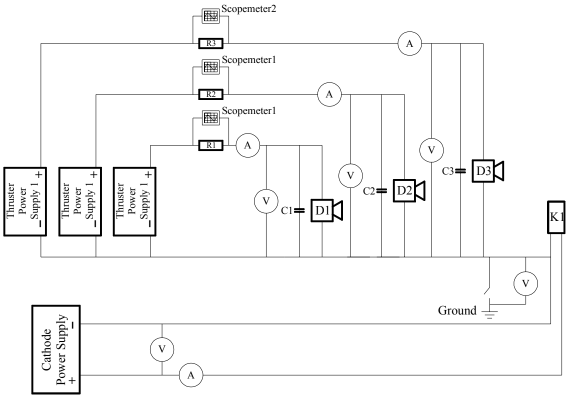


Figure 4. Electric circuit: individual power supplies.

III. Experimental investigation of the cluster

Main questions investigated during the cluster tests were additivity of the thrust and changes absence of the performance parameters of thrusters as compared to the case of individual operation of each thruster. The last was used as a criterion for verification of the workability of diverse cluster configurations. The following cluster architectures were tested:

- Operation of three thrusters from a common power supply and one cathode.
- Operation of three thrusters from individual power supplies and one cathode.
- Operation of three thrusters and one cathode at varying parameters of one of the thrusters (flow rate and discharge voltage).

To investigate the possible influence of the amount of cathodes in a cluster and position of the cathode-neutralizer on integral performances of a cluster assembly, tests were carried out for the following cases:

- Operation of three thrusters and one cathode spaced at the distances of 300 and 500 mm.
- Operation of three thrusters with two cathodes.

In the last two cases, in addition to the integral performances, radial distribution of the parameters of the plasma flow generated by a thruster was measured.

Test modes (for each thruster):

- flow rate in the anode - 3,5 mg/s;
- discharge voltage - 200, 300, 400 V;
- discharge current - 3 A.

Maximum flow rate in the anode of each thruster was limited by the capacity of the vacuum bench.

The external view of the operating 3-TAL cluster is shown in Fig. 5.

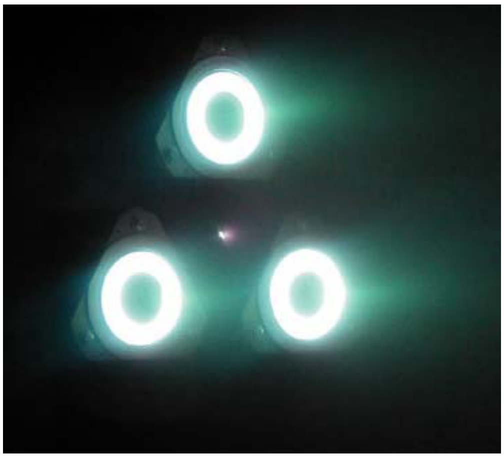


Figure 5. Operating cluster.

A. Cluster Thrust Measurements

Goal of this series of tests was identification of a relationship between the thrust of a single engine and a total thrust of three simultaneously operating engines. Before integration of the thrusters in a cluster, each thruster passed verification with its thrust measurement. The difference between the thrust values did not exceed 2% in all test modes. After the integration of the thrusters into the cluster, each engine was also verified as a part of the cluster. Measurements of thrust were taken both under the grounded scheme and floating scheme, which were then used during development of the procedure of local parameters measurements and studies of the plasma flow of a thruster. No changes in integral parameters of the thrusters after mounting in a cluster were discovered. Table 1 contains the measured thrust values for each thruster as a part of cluster in case of the grounded scheme.

Table 1

$V_f = 0$	Thruster D1		Thruster D2		Thruster D3	
Discharge voltage, V	Discharge current, A	Thrust, mN	Discharge current, A	Thrust, mN	Discharge current, A	Thrust, mN
200	3.04	43.7	3.02	43.5	3.09	44.6
300	3.03	57.2	3.03	56.1	3.06	57.0
400	2.98	65.2	2.98	64.9	3.02	65.3

From Table 1 one can see that thrust differences do not exceed the accuracy of thrust measuring device and, therefore, the thrusters can be regarded as identical in all test modes.

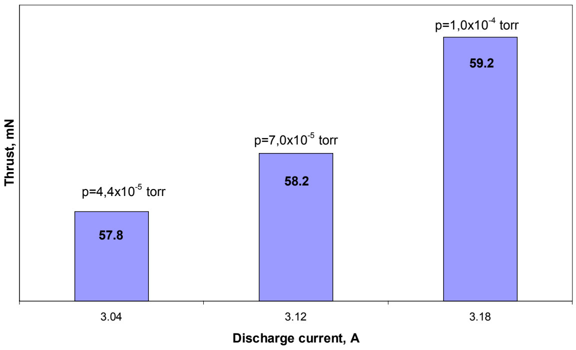


Figure 6. Influence of the pressure on the integral performances.

Since the residual pressure in the vacuum chamber during a cluster operation is higher than that during individual tests of thrusters, influence of the pressure on the integral performances of thrusters was investigated. The upper residual pressure being tested corresponds to the conditions of operation of a three-thruster cluster with the xenon flow rate of 3.5 mg/s in each thruster. The test results are shown on the diagram in Fig. 6. In the tested range of the residual pressure variation, the thrust variation of the engine at both constant xenon flow and discharge voltage did not exceed 3%, and the discharge current increase with increase of the residual pressure made up to 5%.

After verification of individual thrusters, thrust measurements of the three engines operating simultaneously were taken for two schemes of power supply:

- from one common power supply and one cathode K1 (Fig. 3).
- with use of individual power supply for each thruster (Fig. 4).

Results of measurements taken during a cluster operation from a common power supply are collected in Table 2.

Table 2

Discharge voltage, V	Thruster D1		D1+D2+D3				
	Discharge current, A	Estimated triple thrust, mN	Floating potential, B	Discharge current D1, A	Discharge current D2, A	Discharge current D3, A	Measured total thrust, mN
200	3.04	131.2	0	3.12	3.17	3.21	135.8
			15.4	3.15	1.18	3.22	136.2
300	3.03	171.5	0	3.16	3.15	3.16	176.7
			20.1	3.18	3.13	3.18	175,5
400	2.98	195.6	0	3.08	3.10	3.12	201.5
			18.5	3.10	3.12	3.17	204.1

As one can see from **Table 2** the resultant thrust of three thrusters is a sum of individual engine thrusts in all investigated modes. Comparison of the data on the thrust values of a cluster for the cases of a common power supply and supply of each thruster from an individual power source is shown in **Table 3**.

Table 3

Discharge voltage, V	Common Power Supply		Individual Power Supplies	
	Floating potential, V	Measured total thrust, mN	Measured total thrust, mN	Floating potential, V
200	0	135.81	138.85	0
	15.4	136.21	136.50	19.3
300	0	176.67	175.82	0
	20.1	175,53	175.04	20.2
400	0	201.48	204.55	0
	18.5	204.06	204.55	19.6

Data in Table 3 demonstrate that whatever the scheme of power supply is, there are no essential differences between the thrust values of a cluster in all investigated modes, and (within the accuracy of measurements) the resultant thrust is merely equal to the sum of thrusts of the three engines.

In addition to the measurements taken when the operational mode of all the three thrusters in a cluster was identical, operation of the cluster was also investigated when the operational mode of one of the three thrusters deviating from the two others. Such case is interesting from the point of view of simulation of probable emergencies onboard a spacecraft and deviations of parameters of one of the thrusters. Besides, verification of the capability for variation (control) of parameters of one of the thrusters enables control of both direction and magnitude of the thrust vector of such system. Table 4 and Table 5 represent measured thrusts for the cases of variation of discharge voltage of one thruster and flow rate (discharge current) respectively. The results are given both for the case of a common power supply, and for the case of individual sources. In case of a common power supply the value of discharge voltage on one of the thrusters was varied by means of a variable resistor built into the thruster discharge circuit.

As one can see from Table 4 and Table 5, in case of parameter changes of one of the thrusters there is no essential difference between thrust values of the three thrusters - when using both a common power supply and individual ones. The total thrust of a cluster is coincident to the sum of thrusts of individual engines in respective modes.

Table 4

Thruster	Discharge voltage, V	Common Power Supply			Individual Power Supplies		
		Floating potential, V	Discharge current, A	Measured total thrust, mN	Measured total thrust, mN	Discharge current, A	Floating potential, V
D1	200	20.5	3.23	162.0	160.3	3.18	19.6
D2	300		3.17			3.14	
D3	300		3.22			3.17	

Table 5

Thruster	Discharge voltage, V	Common Power Supply			Individual Power Supplies		
		Floating potential, V	Discharge current, A	Measured total thrust, mN	Measured total thrust, mN	Discharge current, A	Floating potential, V
D1	300	20.5	4.15	195.8	195.7	3.18	20.5
D2			3.17			3.16	
D3			3.19			4.18	

On the basis of obtained results, it is possible to make a conclusion that in all tested cluster architectures, within the investigated range of the discharge voltage 200 to 400 V and variation of the xenon flow rate 3 to 4 mg/s, the operational mode of each thruster as a part of a cluster coincided to the thruster operational mode at its individual tests, and the thrust value of a cluster was the sum of those of the three thrusters[5]. Thus, the test results confirmed the basic property of thrust additivity for a cluster based on TALs as well as capability for application of a new architecture of EP in which several thrusters, working in parallel, are supplied from one power source and with one common cathode-neutralizer.

A. Influence of cathode position on thruster and cluster performance

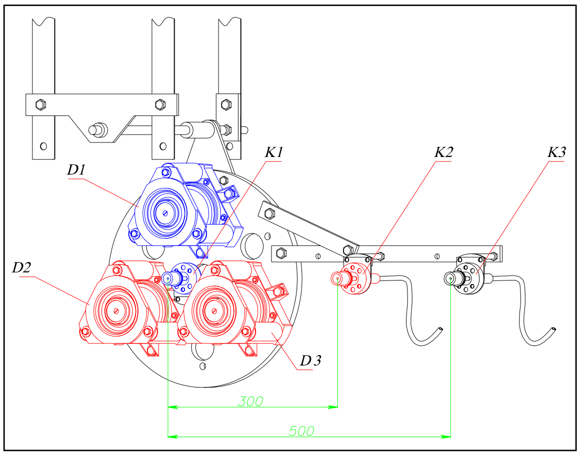


Figure 7. Scheme of the cathodes location.

At present, all Hall Effect Thrusters (HET) are equipped with individual cathodes (one or two) mounted in close proximity from the thruster exit. Potential size of a cluster, running from one common cathode, depends on the ability of a thruster in a cluster to operate with the cathode, which is not mounted in close proximity, but at a distance from the exit of this thruster. So, this spacing can affect the possible number of engines in a cluster available round a common cathode.

To study the influence of the cathode position on the performance of a thruster, LaB_6–based laboratory-grade cathodes were placed at the spacing 0, 300 and 500 mm from the cluster axis (Fig. 7). Also, the central cathode was at the distance of 90 mm from the axis of thruster D1. As it was shown during verification tests, at such placement of the cathode the performances of D-55 are completely identical to those of a flight configuration of the thruster[8].

During the tests the changes of D1 parameters were investigated when the thruster operating with each of the three mounted cathodes (K1, K2 and K3), in turn.

To estimate the influence of the cathode position, in all the three cases the characteristics were determined as follows:

- discharge ignition voltage in thruster D1;
- thrust performance of thruster D1 when operating with each cathode;
- distribution of the electrical field across the plume of thruster D1 when operating with each cathode.

The distributions of electrical field were obtained with use of an emission probe mounted on the movement drive of a "near-zone" diagnostic system[9]. During testing the following procedure was used. The cathode was ignited and kept heated by auxiliary discharge (15…20 V, 3 A). By that time the xenon flow rate in the anode of thruster had been provided, and the coils of thruster had been powered from independent supply sources. Then the voltage was supplied to the thruster and then stepped slowly up until discharge ignition in the thruster. After ignition in the thruster, the voltage was boosted up to the rated value of 300 V. On completion of taking measurements of the performances, the thruster and cathode were shut down, and the next cathode was ignited then. The procedure was repeated then.

The rated operating mode was as follows:

discharge voltage	– 300 V,
discharge current	– 3 A,
chamber pressure	– 1.2 x 10^{-4} mm Hg.

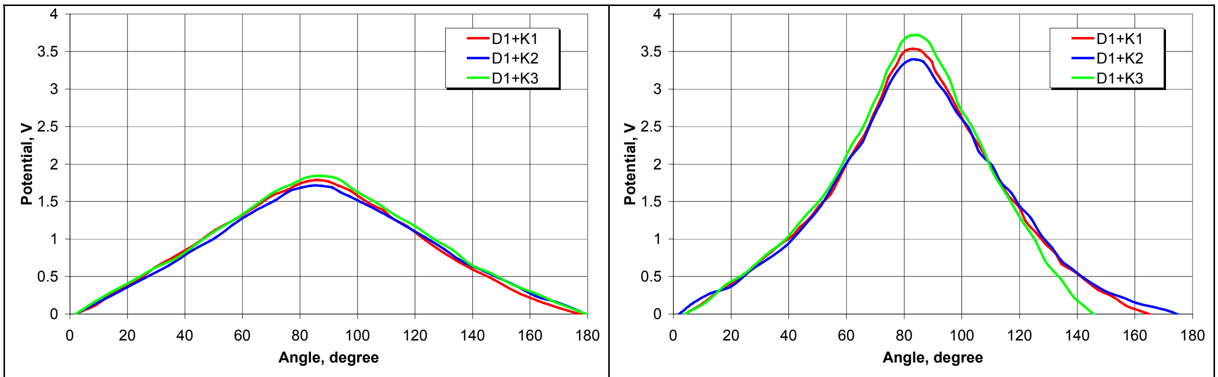
The discharge ignition voltage in a thruster in all the tested configurations was 150…170V, and no definite relation of this voltage with the cathode-thrusters spacing was revealed. In all the cases of the cathode placement, the measured thrust was 57 ± 1 mN (Table 6). The deviation of the thrust value did not exceed the accuracy of keeping the thruster operation parameters as well as accuracy of thrust measurements.

In all the three cases of the cathode placement, distributions of electrical field in a cross section of plume were obtained with the emission probe (Fig. 8).

The left part of curves corresponds to the location of cathodes K2 and K3, and the top of the curves corresponds to the center of the plasma plume. As one can see from Fig. 8, the curves keep the symmetry and practically coincide with each other irrespective of the cathode position. On the diagrams the value of potential is in relative units. In the plume peripheral zones the value of potential was assumed to be zero for all measurements.

Table 6

Cathode	Discharge voltage, V	Discharge current, A	Thrust, mN	Floating potential, V
K1	300,4	3,07	57,5	0
	300,2	3,07	58,0	16,8
K2	300,6	3,08	57,8	0
	300,4	3,06	56,8	17,2
K3	300,2	3,06	58,3	0
	300,0	3,05	56,3	18,7



Distance to the thruster exit: L=1000 mm

Distance to the thruster exit: L=500 mm

Figure 8. Normalized distribution of plasma potential in the plume cross-section.

As follows from the obtained data, no essential influence of the cathode-to-thruster spacing on the discharge voltage, thrust and electrical field distributions in a plume can be found. Such result confirms possibility for use of an integrated multi-thruster module with one cathode-neutralizer. The maximum cathode-to-thruster distance equals to 500 mm in the tests was limited by the vacuum chamber size. It can not be deemed as boundary for the effective work of thruster. Greater spacing should be investigated as it is of a particular importance with relation to additional capabilities for thrusters arrangement on a spacecraft. It is necessary to note that the obtained result is true under these test conditions and demands its verification, first of all under conditions of higher vacuum.

To confirm the results obtained during investigation of the influence of the cathode position on a thruster performances, a cluster consisting of three thrusters with cathodes also placed at the distances of 300 and 500 mm was tested (Fig. 7). The cluster was powered from a common power supply (Fig. 3). Results of measurement of the thrust of the three HETs operating with cathodes at different distances are represented in Table 7.

Table 7

Floating potential, V			Thruster	Discharge voltage, V	Discharge current, A	**Thrust, mN**		
K1	K2	K3				**K1**	**K2**	**K3**
0	0	0	D1	300,1	3,16	177,1	176,4	177,8
			D2	304,2	3,12			
			D3	306,9	3,13			
20,1	14,2	14,4	D1	298,8	3,18	175,5	176,6	172,0
			D2	303,5	3,13			
			D3	305,5	3,18			

As one can see from Table 7**,** the thrust of three engines operating from one cathode does not depend (under these test conditions) on the cathode position, and spread of thrust values does not exceed the accuracy of measurement.

On the final phase of investigation of various cluster designs, the ability of a cluster for operation with two cathode-neutralizers, functioning at a time, was tested. The thrusters were powered from individual supplies. Thruster D1 was integrated into an electrical circuit with cathode K1, and thrusters D2 and D3 with cathode K2. Data on the thrust measurements of three HETs operating from two cathodes are shown in Table 8. The scheme

D1+K1 was grounded, and scheme D2+D3+K2 was "floating" (not grounded) in order to simulate the maximum possible difference between the floating potentials of the engines working with different cathodes.

Table 8

Floating potential, V	Thruster	Discharge voltage, V	Discharge current, A	Measured total thrust, mN
0	D1	200	3.14	139.2
11	D2		3.15	
	D3		3.19	
0	D1	300	3.13	176.1
12	D2		3.13	
	D3		3.14	

As one can see from Table 8, despite that intentional increase of the asymmetry in the cluster operation, the total thrust of the triple-thruster assembly with two cathodes coincides with the thrust of the cluster with one cathode obtained in the same modes (Table 3), and is equal to the sum of individual engine thrusts. No any additional effect and unsteadiness due to differences brought into operational mode of engines were found. So, when using various electrical circuits, various positions and quantities of cathodes, and also when varying the parameters of cluster engines, the thrust of the tested cluster had property of additivity.

B. Study of oscillations of discharge current in cluster circuits

Knowledge of the kind and pattern of oscillations in circuits of a cluster as well as measured thrust is important for understanding the processes arising in such multi-thruster propulsion systems when using different schemes and operational modes. Change of amplitude, synchronization and amplification of discharge current oscillations in the cluster thrusters is one of the criterions of the mutual influence of engines at their parallel operation. Possibility for such amplification and synchronization of oscillations in the thrusters integrated in a cluster was demonstrated in Ref.[10]. This is of fundamental importance for further examination of the cluster electromagnetic compatibility via taking measurements of an individual thruster performances. To study this factor, an investigation of the oscillations of discharge current in the circuits of a cluster was started.

On the first phase of tests, a layout with a common power supply was used (Fig. 3). This scheme, on the one hand, is the most interesting if speaking of simplification of the cluster architecture, and on the other hand, is the most risky with relation to phased oscillations generation in the thrusters, working in parallel. The oscillation of discharge current were measured from the calibrated shunts placed in the circuits of each engine as well as in the common circuit. The oscillations were registered by means of Industrial Scopemeter Fluke 123.

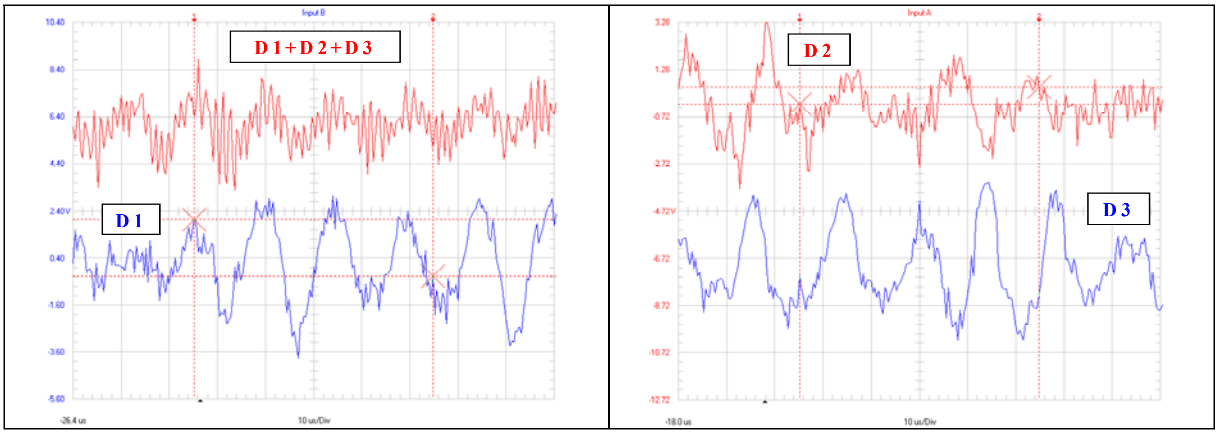


Figure 9. Oscillations of discharge currents in the circuits of cluster engines (D1, D2, D3) and in the common circuit (D1+D2+D3)

An illustration of the discharge current oscillations in circuits of thrusters D1, D2, D3 for a mode of 200 V, 3 A as well as in the common circuit D1+D2+D3 is depicted in Fig. 9. One can see that although the frequencies of oscillations in all the three engines are close, the phases of oscillations are different and vary arbitrarily in each thruster. The oscillations of two of the three tested engines are close to antiphase, and the amplitude measured in the common circuit is of the same order with the one in the circuit of one engine. This result is confirmed statistically by numerous repeated measurements, including after the shutdown and re-ignition of the cluster. The pattern of oscillations in discharge circuits for an thruster in a cluster was similar to the one observed at individual tests of the engine. Obtained result demonstrates that synchronization of the discharge current oscillations in the thrusters of a cluster is not a mandatory requirement to the simultaneous operation of several thrusters even in the layout with a common source of discharge voltage, which is the most "vulnerable" from this point of view.

This result was obtained when all the thrusters operating in identical modes and the amplitude and typical frequencies of the discharge current oscillations in all engines were close to each other. However, one can suppose that the oscillations in one of the thrusters (upon achieving some level) can have an impact on the oscillations in two other engines as well as on the common discharge current of the three engines. To study this effect the cluster was tested when one of the engines (D2) was purposely (by an intentional change of the magnetic field in its discharge) shifted into so-called "abnormal" mode when a drastic increase in the amplitude of the discharge current oscillations typically develops. The oscillograms of the discharge current oscillations in circuits of each engine and in the common circuit of a cluster powered from a common power supply of discharge voltage are depicted in Fig. 10.

As one can see from Fig. 10, the oscillations of discharge current in D2 influenced the currents in the other two engines and also the total signal from the cluster. The oscillograms demonstrate that all patterns of oscillations are similar to that of unsteady working D2. So, one can see that impact of engine D2 can spread to the whole system. Such impact can take place both via internal discharge circuits and through plasma.

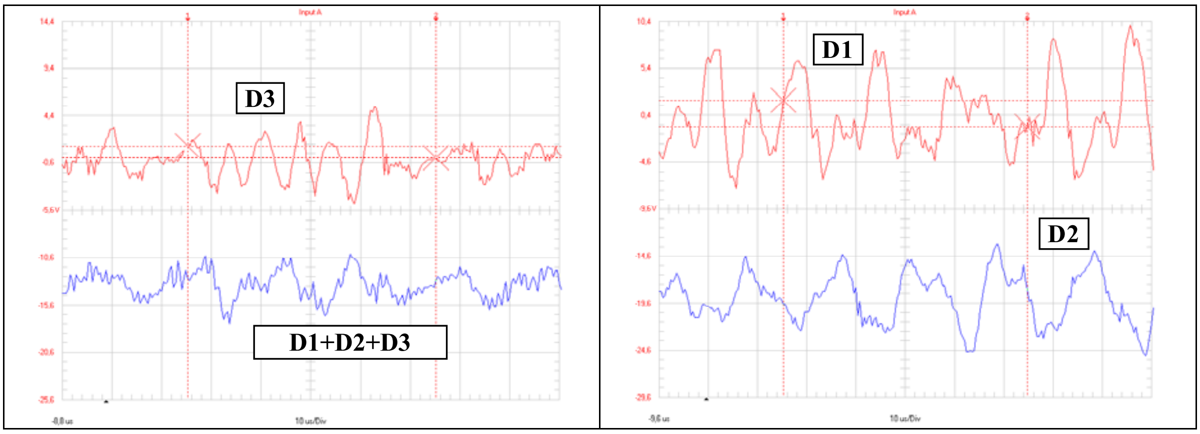


Figure 10. Discharge current oscillations when one engine (D2) is shifted into abnormal mode

Trying to resolve such dual-impact problem, a test was carried out when each engine in the cluster was powered from an independent, individual source (Fig. 4). Such electric circuit can actually eliminate the interference of engines in a cluster via internal discharge circuits.

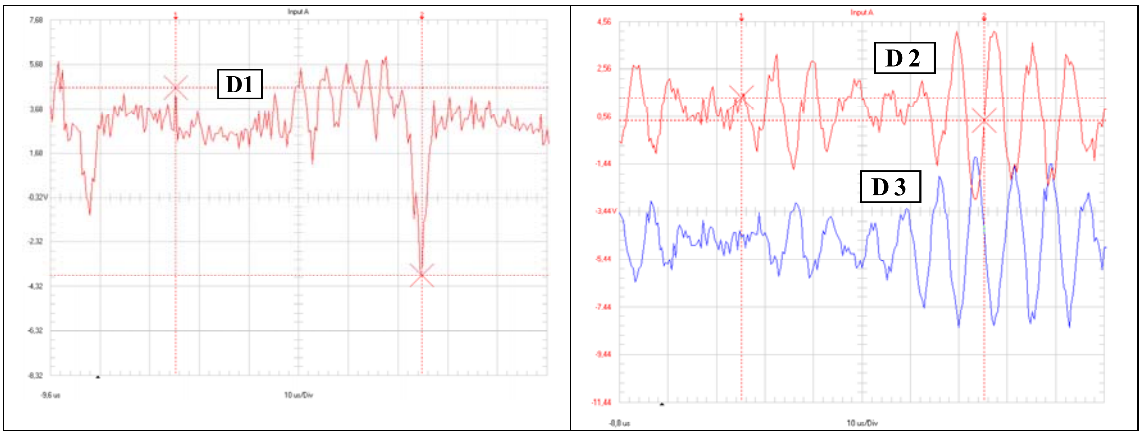


Figure 11. Discharge current oscillations when one engine (D1) is shifted into abnormal mode in case of individual power supplies

Oscillograms of the discharge currents in three thrusters in case of use of individual power supplies for each cluster engine are depicted in Fig 11. Engine D1 is in the anomalous mode. As one can see from the patterns, the remaining thrusters (D2, D3) did not change the patterns of oscillations, and there is actually no effect of engine D1. From this result one can make a conclusion that oscillations in such systems are mainly impacted via internal circuits, and not through plasma. Obviously, obtained results are rather preliminary, and require further systematic studies of oscillation processes and electromagnetic noise in the cluster, stability of a cluster operation at variations in the mode of the integrated thrusters.

Taking into account further plans in regard to the cluster plume diagnostic, it should be mentioned, that information obtained within the scope of current work allows to conclude that for future cluster plume diagnostic functional scheme of the cluster is not essential and further study can be made with existing triple-thruster cluster, power supply and xenon feed system.

IV. Characterization of plumes of three-TAL cluster system

After the study of the single thruster plume diagnostic[9] of the cluster plume has been initiated with a goal to get initial information about the cluster plume and to identify specifics of the composed cluster plume in comparison with the plume of single thruster.

2-mm flat probe measurements in different cluster cross-sections for cluster plume characterization were chosen[9].

In accordance with approved experiment program the only base operation mode was chosen for characterization of the composed cluster plume. All thruster was operated at one and the same regime with the discharge voltage equal to 300 V and discharge current equal to 3 A. Electric scheme was grounded (Fig. 4), and cathode-neutralizer K1 (Fig. 7) at the center of the cluster. Residual tank pressure was equal to 1x10^{-4} torr.

The diagnostic equipment and test procedures for the cluster study were identical to ones used for single thruster plume study and described in Ref. [9].

Plume parameters measurements were carried out in three cross-sections, marked as *1*,*2* and *3* in Fig. 12, at the distances 300–1000 mm from the cluster exit plane.

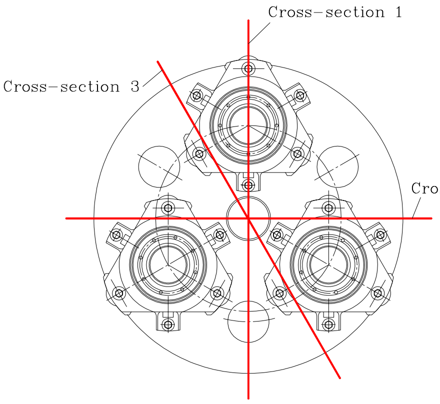


Figure 12. Cross-section map.

A. Ion current distribution in the cluster plume

Typical radial ion current density distributions measured in the three cross-section of the cluster plume are given in Fig. 13, distance between probe and cluster exit plane was equal to 500 mm.

Ion current peak corresponding to the plume of the thruster D1 (located at 90 mm from the cluster center –0 mm) can be seen in the cross-section *1*. Ion current density distributions measured in geometrically equal cross-sections *2* and *3* are in close agreement, and it is an indication of symmetry of the plume. Distribution of ion current density at the plume periphery is one and the same in all azimuth cross-sections.

Cluster ion current density space distributions measured at the distances 300, 500 and 1000 mm are given in Fig. 14.

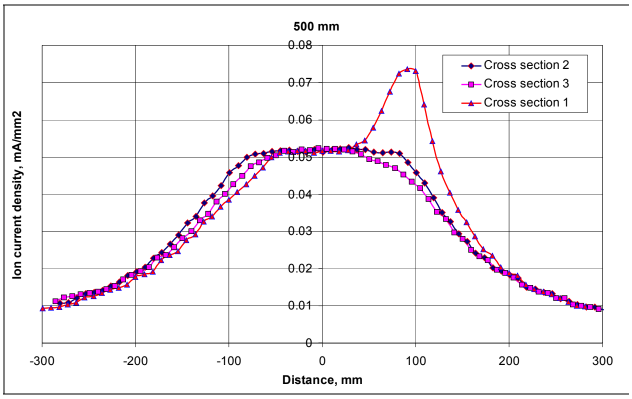
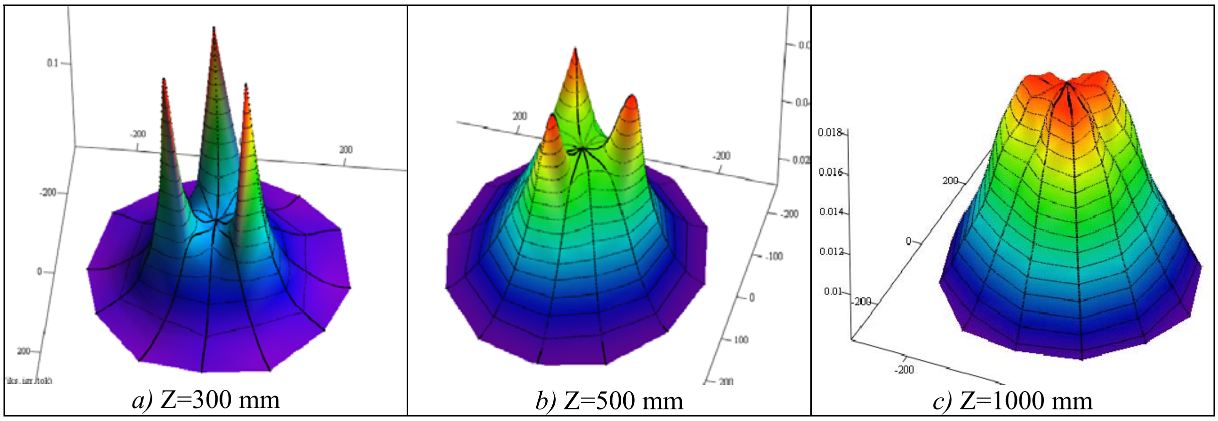


Figure 13. Distribution of the cluster ion current density.

As one can see, at the distances 300 (Fig. 14a) and 500 mm (Fig. 14b) three peaks corresponding to the plumes of three thrusters are well distinguished. With the distance increasing cluster plume transforms. At the distance equal to 1000 mm (Fig. 14c) plume areas corresponding to each thruster are almost disappeared. Thus, at long distances plume generated by three thrusters becomes similar to a plume generated by some single thruster located at the center of the cluster.

Comparison of measured cluster plume profile with calculated summa of the individual thruster plumes was made to verify additivity of the plumes. Corresponding data are shown in Fig. 15. Measured single thruster D1 (red curve) and cluster (blue curve) plume profiles are given in this figure. Black curve in Fig. 14 corresponds to the calculated cluster plume profile, obtained by mathematical adding of three single thruster ion current distributions. One can see, that mathematically obtained curve differs from the measured one in the high density area, which corresponds to the thruster D1 axis, but in remaining (periphery) areas both curves coincide. This difference exists in the central high density zone of the plume at all tested distances (300, 500 and 1000 mm) from the cluster, and radial dimension of this zone increases with the distance increase.



a) Z=300 mm *b)* Z=500 mm *c)* Z=1000 mm

Figure 14. Cluster ion current distribution.

Obtained data allow to conclude, that the cluster plume distribution is not simple sum of distributions obtained for single thrusters operation.

As far as in all studied modes (as it was shown above) the cluster thrust is the sum of the thrust values of individual thrusters, one can assume, that the ion flux generated by each operated thruster in cluster corresponds to the ion flux generated by thruster operated individually. Therefore, the most probable reason causing the difference between measured and mathematically obtained cluster plume profile, is difference of the charge exchange conditions for the cluster plume as compared with plume of the thruster operated individually. Should be noted, that measured tank pressure in all compared cases was one and the same, so average density of the neutrals was one and the same also, but local variations of the neutral atom density could be the reason of observed phenomenon.

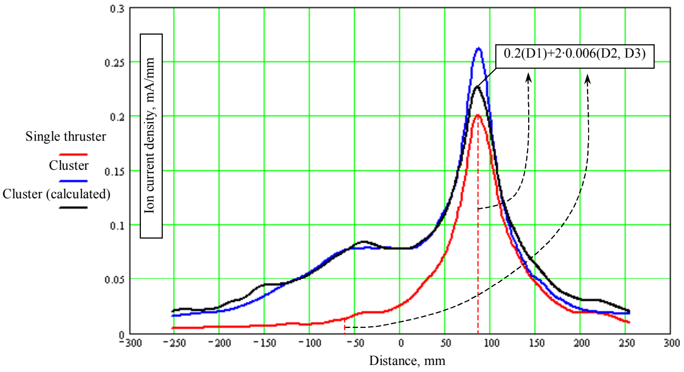


Figure 15. Ion current density distribution of the cluster and single thruster.

B. Plasma potential and electron temperature in the cluster plume

Measurements of the plasma parameters were conducted in cross-sections *1*,*2*,*3* (Fig. 12) of a plume at the distances 300, 500 and 1000 mm from the cluster exit plan..

For example, plasma potential distributions at the cross-section *1* for both the cluster and single thruster D1 measured at the distance 500mm from the exit plane are represented in Fig. 16. Corresponding distribution of the ion current density in this cross-section is given in Fig. 13. As is obvious, plasma potential distribution of the cluster has symmetrical view, in spite of nonsymmetrical distribution of ion current density in this cross-section. And expected peak of the potential associated with center of D1 thruster plume did not appear. Besides that smoothing of the plasma potential distribution in radial direction takes place. In case of the cluster total drop of plasma potential from the center to periphery is 2 V, while for single thruster – 3.5 V.

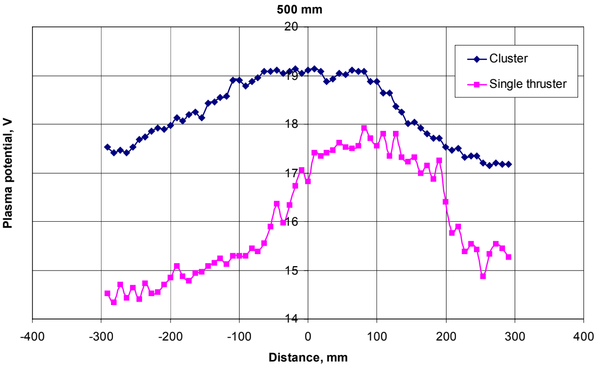


Figure 16. Both cluster and single thruster plasma potential distribution.

Electron temperature distributions in the cross-section *1* of the cluster and single thruster D1 plumes, measured at the distance 500 mm from cluster assembly exit, are shown in Fig. 17.

Electron temperature distributions in the different cross-sections *1*,*2* and *3* of the cluster plume, measured at the distance 500 mm from the cluster exit plane, are represented in Fig. 18.

As it can be observed from Fig. 17, electron temperature distribution in the cluster plume has more uniform view as compared with single thruster distribution. Data Fig. 18 show that electron temperature does not essentially change in radial and azimuth directions in the observed area of the cluster plume.

During series of experiments, which were conducted to collect statistic, instability of the cluster plume plasma potential was detected. As an example, plasma potential distributions, measured in cross-section *1* and *2* during different experimental days are shown in Fig. 19. According to Fig. 19, the plasma potential distributions measured in one and the same cross-sections and at one and the same cluster operation mode may differ from each other in both absolute value and distribution curve view. In spite of plasma potential distributions difference, ion current density and electron temperature distributions were invariable. Since controllable cluster parameters such as discharge currents and voltages, magnetic system currents, cathode and anode mass flow rates, residual pressure in vacuum chamber were retained at the constant level during all experiments, then their influence on measured plasma potential can be excluded. Observed instability can be caused by some uncontrolled process influencing ion flux neutralization, that in one's turn depends on both cathode operation condition and secondary electron emission from the vacuum chamber walls.

Detected instability necessitated to perform special experiment with single thruster D1 with a goal to identify influence of neutralization effects on the plume characteristics. In the context of the experiment three electric schemes of connection thruster D1 and cathode K1 were tested. In these schemes neutralization processes of the plume varies, and it allows to identify correlation between this variation and measured plasma plume parameters.

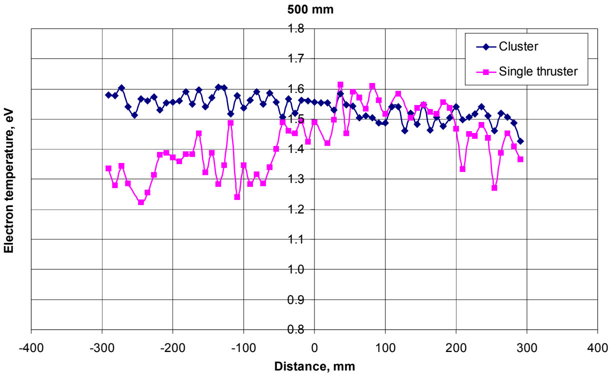


Figure 17. Electron temperature distribution for the cluster and single thruster plumes.

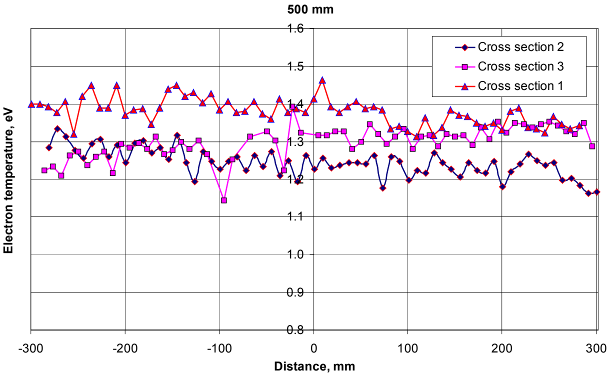


Figure 18. Electron temperature distribution in different cross-sections of the cluster plume.

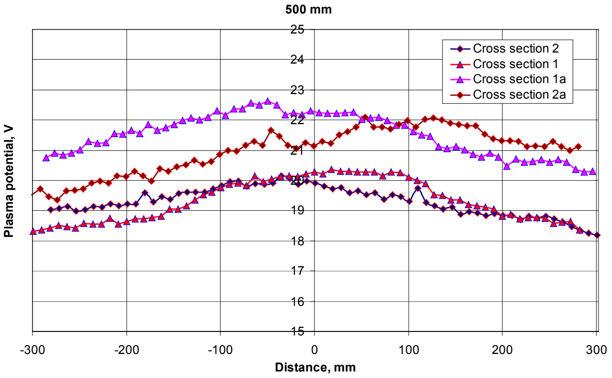


Figure 19. Plasma potential variation.

The first scheme – called "grounded" (Fig. 4), was basic one for all performed measurements of the cluster plume. Thruster body and cathode emitter are connected to the vacuum chamber ("ground"). The necessary electron current from the cathode to neutralize space charge of the plume in this scheme is about 10% of the thruster ion current. As it was determined earlier, in this scheme influence of the cathode parameters on the studied plume is minimal.

The second scheme is "ungrounded" one (Fig. 4). Thruster body and cathode emitter are disconnected from the "ground" and are floating in respect to vacuum chamber. Unlike to the first scheme, electron current from the cathode has to be equal to the thruster ion current.

The third scheme is "grounded" and similar to the first one, but the thruster body was connected to the another cathode electrode – "keeper", and both are connected to the vacuum chamber. This case is called "inverse cathode scheme". In this scheme influence of the cathode on the plume is also minimal. But in addition, potential influence of the voltage, applied between emitter and keeper to keep auxiliary discharge in the cathode, on the plasma plume potential is excluded. The plasma plume contacts only with grounded surfaces.

Thruster D1 operated at operation point 300V, 3A was used. Residual pressure in vacuum chamber was 4.4x10^{-5} torr.

Plasma potential distributions in the D1 plume, measured at the distance 500mm from thruster exit are shown in Fig. 20. Curves corresponding to scheme 1 and 2 have similar view but different absolute values. However, in the case of scheme 3, which is grounded like scheme 1, curve of the plasma potential coincides with one, measured under the scheme 2 conditions.

Despite the difference in plasma potential values, electron temperature (Fig. 21) and ion current (Fig. 22) distributions in the case of all three schemes are in close fit.

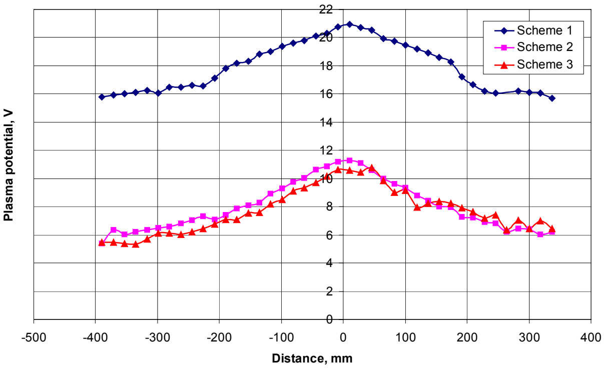


Figure 20. Plasma potential distribution in the plume of D1 thruster operated in different schemes.

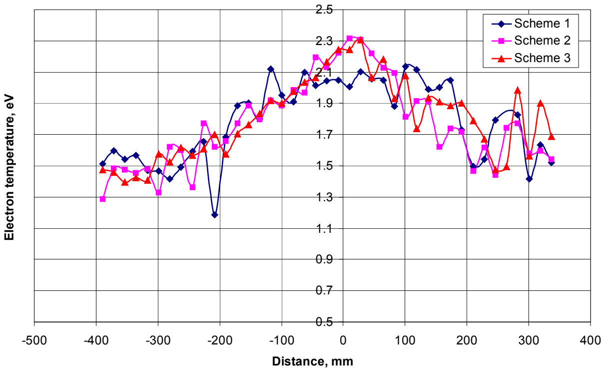


Figure 21. Electron temperature distribution in the plume of D1 thruster operated in different schemes.

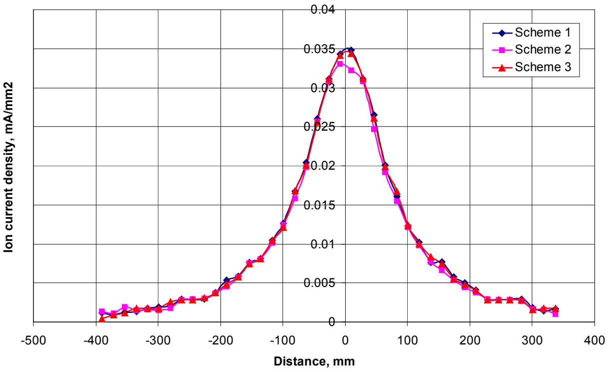


Figure 22. Ion current density distribution in the plume of D1 thruster operated in different schemes.

Thus, experiment conditions and specific of the plume neutralization have essential influence on plasma potential measurements. Probably in the case of the cluster operation some conditions, which lead to spontaneous variation of plasma potential, can arise in plasma volume.

It can be assumed, that similar spontaneous variations always exist, but for single thruster plume the effect is small and it is almost undetectable by used diagnostics, while in the complex cluster plume such effects are significantly amplified.

V. Conclusion

Three D-55 thrusters have been integrated into the cluster and tested individually and simultaneously. Resulted thrust value of the cluster in all studied regimes is summa of individual thrust values in all tested schemes.

Influence of the “cathode to cluster” distance on cluster operation has been studied. No influence on the thruster performances and start up voltages were observed for the distance variation up to 0.5 m.

Discharge current oscillations of each thruster and oscillations of the summarized current of three thrusters operating from one common power supply were studied. Observed oscillations were independent in each thruster discharge circuit despite on operation from common power supply. Measured amplitude of common current oscillations is of the same order as for one in individual thruster circuits.

Performed cluster plume study provided initial experimental complex cluster plume data and allowed to identify specific of the cluster plume as compared with one of single thruster.

In the center zone of the plume measured cluster ion current density value is not simple sum of ion currents measured for single thruster, while the periphery of the cluster plume can be considered as summa of the plumes of individual thrusters. Measured values of electron temperatures and plasma potential in the cluster plume are of the same order as one measured for single thruster. However, in part of the cluster tests some instability has been identified. This instability resulted in appearance of various plasma potential distributions. To clarify the instability nature further study is necessary.

Plume formed by three thrusters is transformed at far distances from the cluster. Ion current density peaks corresponding to each thruster disappear, and cluster ion current density distribution becomes similar to one of plasma plume generated by some single thruster located at the center of the cluster.

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