Multi-thruster Electric Propulsion System architecture and ways of simultaneously operating thrusters interaction

Leonid E. Zakharenkov and Alexander V. Semenkin
SSC Keldysh Research Center
8 Onezhskaya street, Moscow, 125438, Russia
e-mail: kerc@comcor.ru

Abstract

Development of transport space vehicle with electric propulsion system (EPS) implies application of several simultaneously operating thrusters. Due to limitation of high power single thruster ground testing possibility and difficulties of large-size thruster manufacturing such EPS development direction is the only option. However there is a number of specific features that should be studied to put in practice this design solution. Possible ways of thrusters interaction and cluster assembly operating features are considered in the paper. Results analysis of different cluster systems research and development programs are presented in the paper.

1. Introduction

At present stage of development and application, electric propulsion (EP) is characterized both with increasing number satisfactions of long-life spacecraft ordinary needs, and also with expansion of the mission range to be resolved with EP.

Projects aimed at EP use for final insertion of spacecraft into high operating orbits (including GEO), and for needs of cruise flight during deep space missions to distant planets are under consideration. Power-to-weight ratio of modern spacecraft grows: for advanced telecommunication systems the level of on-board electrical power reaches 20...40 kW and projects of interplanetary missions with EPS power level up to 1MW are considered. So development of high power EPS is needed.

There are two possible ways for creation of higher-powered EP systems:

- development and use of higher- and higher-powered thrusters;
- use of bunches of several, simultaneously working thrusters, i.e. thruster clusters.

A number of activities have been dedicated to investigate capabilities of the two different ways as well as a rational combination of the both [1, 2, 3].

It follows from the available data that the cluster approach can be deemed as essentially important for advance propulsion systems. Using a narrow range of tried 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 engines.
- Effects due to electromagnetic noise generated by engines 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, at-a-time operating engines, 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 [4, 5].

Thus, being a good solution for the main challenge – creation of a high-power EP system having any specified power, under conditions of a poor range of tried 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.

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 for operation of several engines from a common power supply and a common, working fluid (propellant) feed system.
- Possibility for a cluster operation from a common cathode-neutralizer, probable limitations of the cluster size.
- 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.

Following conditions should be met for studying of operating of any cluster system based on EP thrusters:

- The basic thruster should be fully characterized (volt-ampere characteristics, thrust, specific impulse, efficiency, discharge voltage and current oscillations, plasma plume characteristics and lifetime for every operating modes).
- Every thruster should be verified before and after its operation in the cluster assembly. Its integral characteristics during single operation in the one and the second cases should be coinciding.
- During joint thrusters operation in the different cluster configurations (electric scheme, geometrical placement, quantity of thrusters and cathode-neutralizers) its characteristics (according to the first item of the list) should be compared with ones obtained during its single operation.
- Characteristics of the cluster complex plume, generated by several simultaneously operating thrusters should be studied for every cluster configuration.
- Data obtained should be compared with single thrusters plume data for development of cluster systems calculation methods based on single thrusters characteristics.

Meeting all these conditions is a complex and hard enough task. The cluster integral characteristics obtaining is not enough for its operating features revealing. The cluster complex plume data are needed, that by-turn requires special equipment development and bulk data processing.

Results analysis of different cluster systems research and development programs close to the above mentioned list of conditions are presented in the paper.

2. Hardware and test condition description

Multi-thruster assemblies based on main types of electric propulsion thrusters (thrusters with anode layers, stationary plasma thrusters and ion thrusters), which are main candidates for transport missions required high power EPS are considered in this paper.

2.1 *3*-TAL multi-thruster assembly

The cluster architecture based on three D-55 TSNIIMASH thrusters with anode layer (TAL) similar to those used in the flight experiment aboard STEX spacecraft in RHETT II program was chosen [6]. 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.

For 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 0.0001 Torr 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 [6] - resulted in no changes of integral parameters of the thrusters.

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 [7]. In Figure 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 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.

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

Measurements of the thruster/cluster parameters were taken under two different connection schemes [8]. 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. The first scheme is the most safe whereas the second one is more close to real onboard SC conditions.

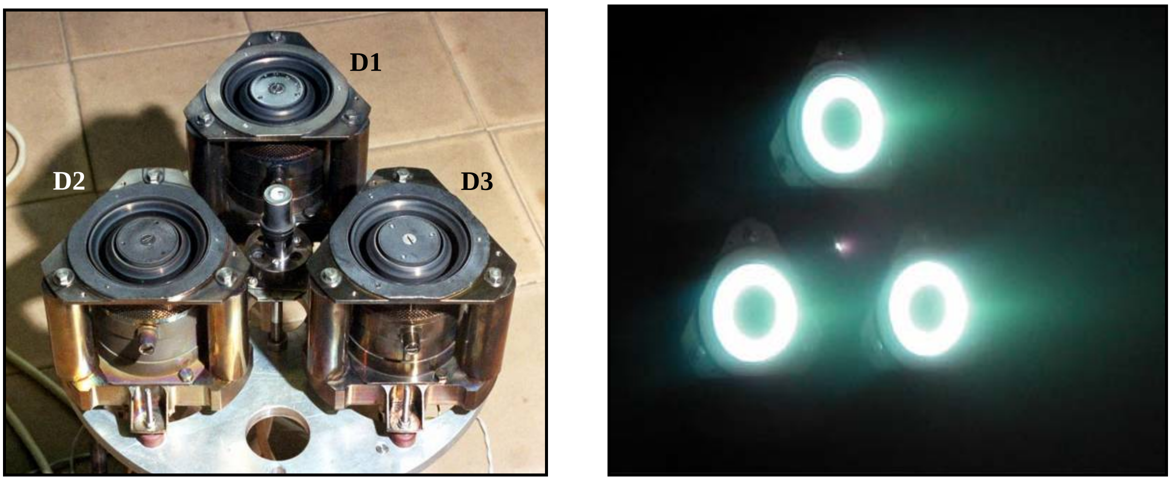


Figure 1. Three D-55 thrusters cluster.

2.2 *4*-SPT Hall thruster cluster

The cluster was based on four stationary plasma thruster BHT-200-X3 manufactured by Busek Co [9]. The thruster was developed for operating at nominal power level ~ 200 W. The thruster had mean diameter value equal to 21 mm and used xenon as a propellant. Thrusters assembly placement configuration was 2x2 square. Distance between two neighbor thrusters was about 11.5 cm. The thruster typical parameters values of the BHT-200-X3 were: Discharge Voltage – 250 V, Anode Mass Flow Rate – 8.5 sccm, Specific Impulse – 1300 s, Thrust – 12.4 mN and Efficiency – 42 %.

For the cluster nominal configuration every thruster was independent from others. However the cluster was tested in alternate configurations also. For the cluster nominal configurations every thruster had its own cathode-neutralizer and laboratory power supply. The cluster photo is given in the Figure 2.

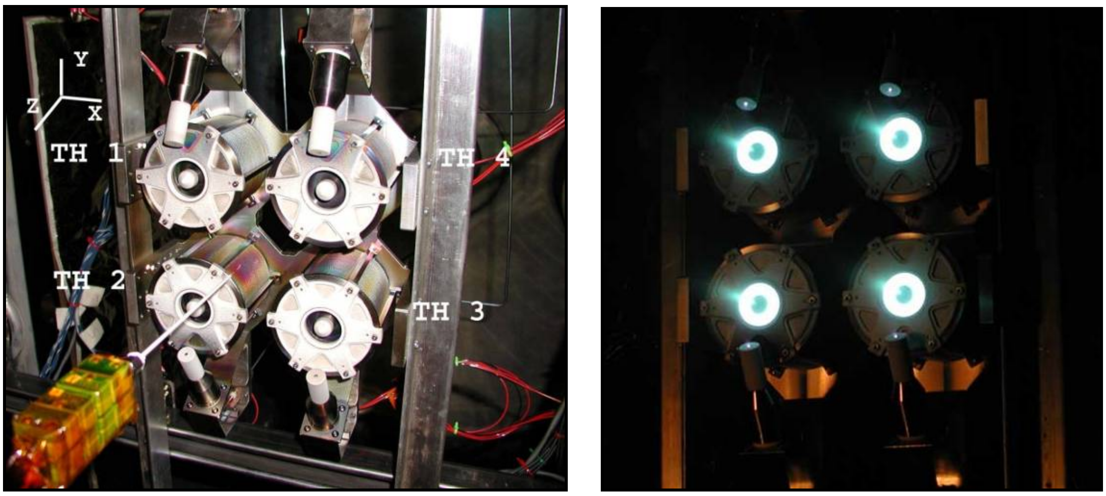


Figure 2. External view of the cluster based on BHT-200-X3 thrusters.

The experiments were conducted in two separate vacuum facilities. The first was Chamber 6 at AFRL, which measures 1.8 meters in diameter and 3.0 meters in length. Final evacuation of Chamber 6 is accomplished using four single-stage cryopanels and one two-stage cryopump. The second chamber used for testing of the thruster cluster was the Large Vacuum Test Facility (LVTF) at the University of Michigan. The LVTF is a 6x9 meter, cylindrical vacuum chamber that is evacuated by seven cryopumps. During thruster operation, the background pressure typically rises to 6.1×10^{-6} Torr for single-thruster operation and to 2.3×10^{-5} Torr for four-thruster operation. Both pressures are corrected for xenon.

2.3 *NEXT* multi-thruster array

Multi-thruster assembly was based on four engineering models of ion thrusters NEXT (EM1, EM2, EM4 and EM5), manufactured by NASA Glenn Research Center [10, 11]. The NEXT thruster design characteristics are: Power – 6860W, Specific Impulse – 4190 Sec, Thrust – 236 mN and Efficiency – 0.708. The cluster configuration had geometry 3+1 (three operating and one in reserve – thruster EM2, see Figure 3). The thruster placement was chosen in accordance with design of Titan orbital module with EPS based on ion thrusters NEXT [12]. For the cluster nominal configuration every thruster was independent from others and had its own cathode-neutralizer. Every thruster had separate propellant feed system and power processing unit for ground testing. All kinds of testing were carried out at NASA Glenn Research Center tank VF6. The vacuum chamber is 7.6 m in diameter and has 22.9 m length. It is equipped by twelve vacuum pumps for space conditions modeling. In the case of 3-thrusters operation at full power the value of background pressure was 3.0×10^{-6} Torr.

It should be noted that mentioned above thrusters have some distinct features. The thruster 4 was developed with 40 cm optic system and underwent 2000 hours of lifetime testing. At a later date its optic system was modified down to 36 cm in diameter for the thruster characteristics improvement and its aperture outer part erosion reducing. So the thruster became part of the cluster assembly with aperture 36 cm in diameter and newly manufactured discharge chamber. Thrusters 1 and 5 had aperture 40 cm in diameter. However the thruster 5 had the lesser gap between ion grids than the thruster 1 [13, 14]. In addition the thruster 1 was preliminary tested and the thruster 5 was newly manufactured.

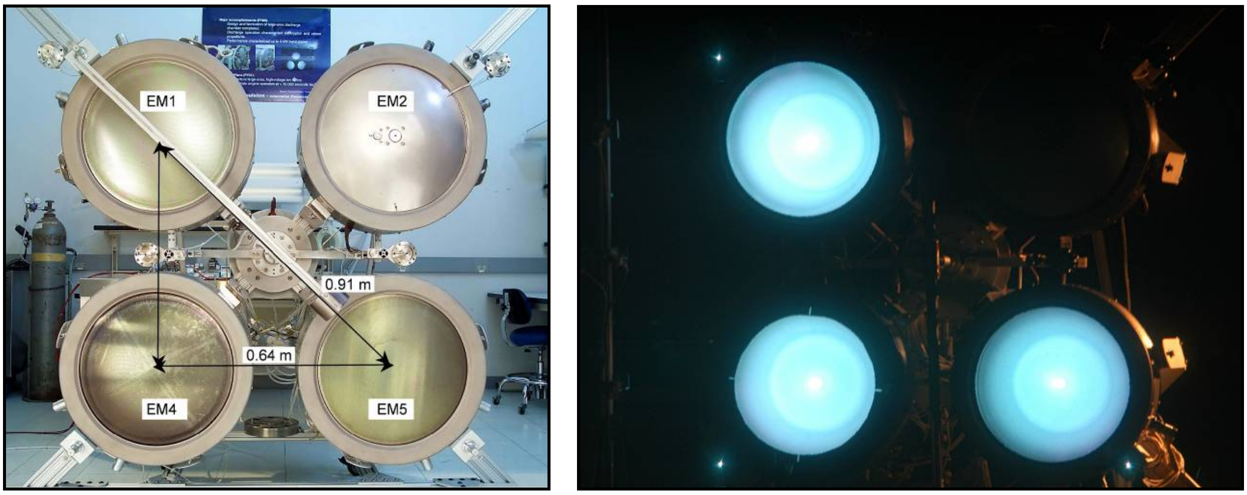


Figure 3. NEXT multi-thruster array.

3. Cluster Operating with common and separated power supply unit for every thruster

Electric propulsion system includes thruster, power processing unit (PPU) and propellant feed system (PFS). Architecture of typical flight qualified EPS which are under utilization is the following: each thruster has its own PPU and PFS elements.

Multi-thruster EPS can be designed with help of two distinct approaches:

- Integration of several independent EPS;
- Creating of cluster assembly with several simultaneously operating thrusters, common PPU and PFS.

In the second case it can be considered as a single multichannel thruster.

Two ultimate cases of EPS architecture are given in figures below:

1) Independent EPS architecture (see **Figure 4**) includes a set of independent thruster modules. Each module consists of single thruster, cathode unit, PPU and PFS. Propellant storage tanks and onboard power system could be common.
2) Common EPS architecture (see **Figure 5**) is divided into functionally independent subsystems. Such subsystem includes several thrusters, cathode unit, PPU and PFS. Thus single PPU, single PFS and single cathode unit provide operation of a number of thrusters.

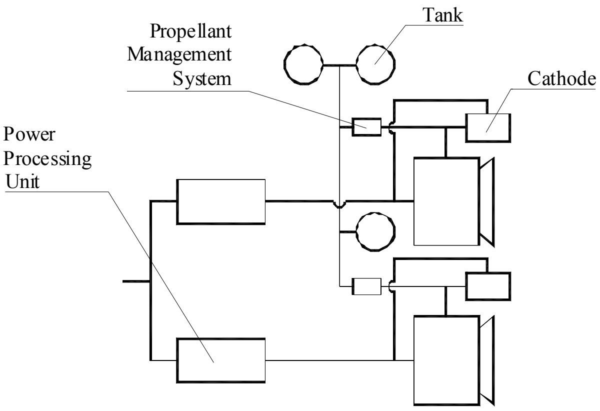


Figure 4. Independent EPS architecture.

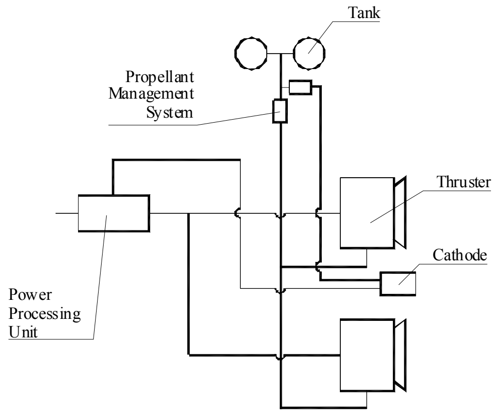


Figure 5. Common EPS architecture.

Common EPS architecture allows getting significant EPS mass profit, it also provides EPS parts nomenclature reducing and correspondingly total cost decreasing. However, thrusters interaction should be taken into account while developing the assembly design.

3.1 *3*-TAL multi-thruster assembly

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. Thrust measurements of three engines operating simultaneously were taken for two connection schemes:

- with single common power supply and one cathode K1 is installed in the centre of the cluster.
- with use of individual power supplies for each thruster.

Results of measurements taken during a cluster operation from a common power supply are collected in Table 1.

Table 1

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 the table 1 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 the Table 2.

Table 2

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

Presented data demonstrate that whatever the scheme of power supply was, there were 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.

An illustration of the discharge current oscillations in the case of common power supply using 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 **Figure 6**. One can see that although the frequencies of oscillations in all the three engines are close to each other, 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 any 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.

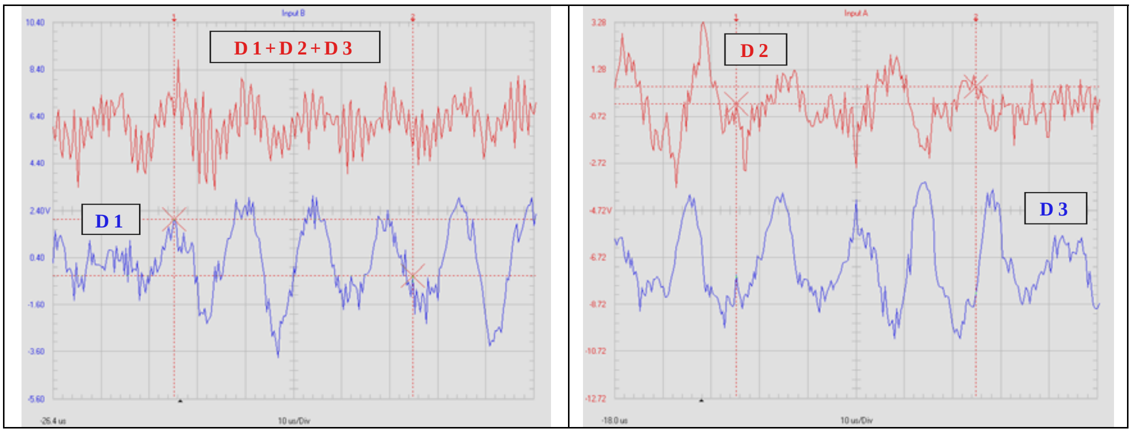


Figure 6. Oscillations of discharge currents in the circuits of cluster engines (D1, D2, D3) and in the common circuit (D1+D2+D3)

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 Figure 7.

As one can see from Figure 7, 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.

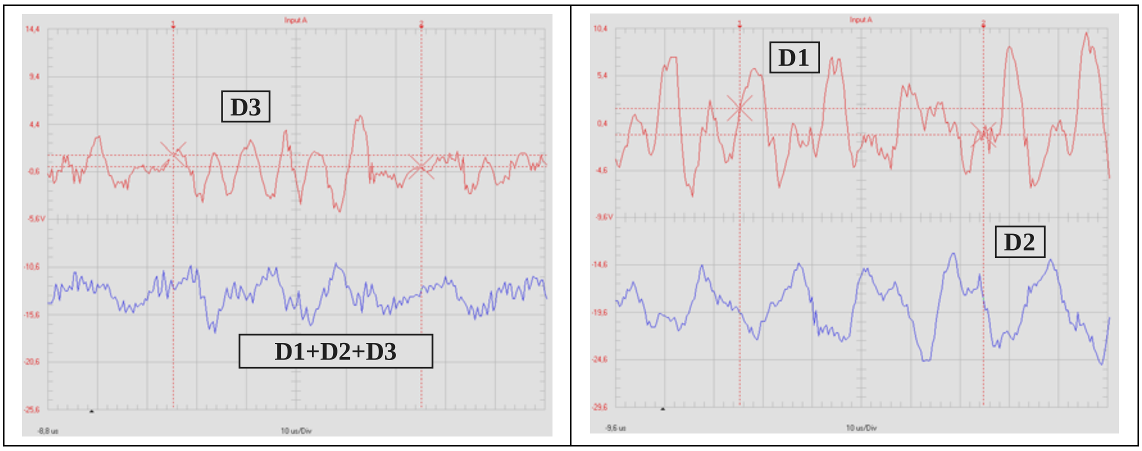


Figure 7. Discharge current oscillations when one engine (D2) is shifted into abnormal mode.

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. Such electric circuit can actually eliminate the interference of engines in a cluster via internal discharge circuits.

Oscillograms of the discharge currents in three thrusters in case of use of individual power supplies for each cluster engine are depicted in **Figure 8**. 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 are not impacted through plasma.

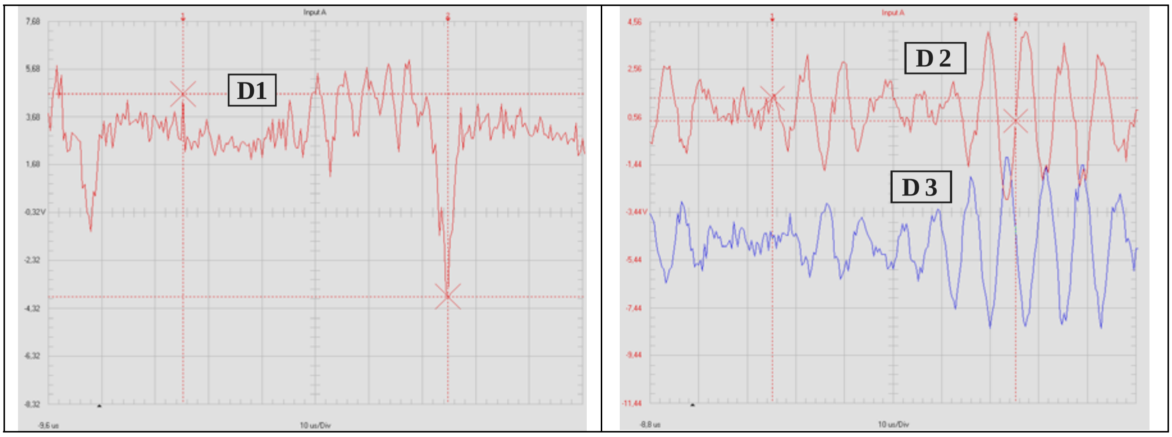
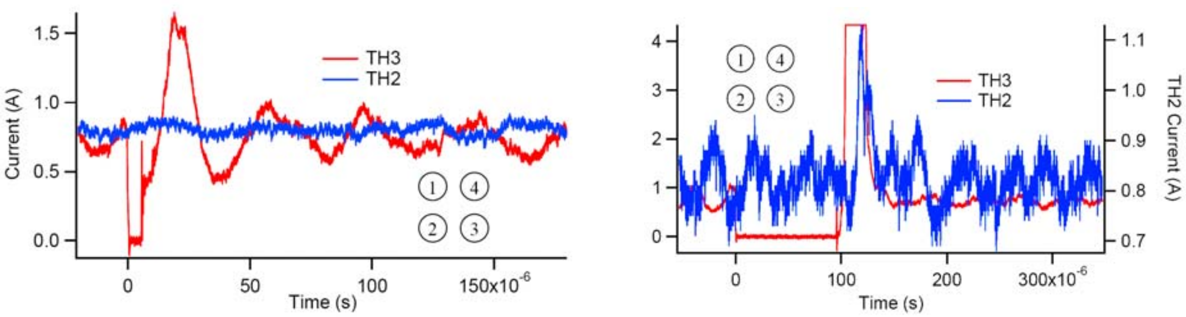


Figure 8. Discharge current oscillations when one engine (D1) is shifted into abnormal mode in case of individual power supplies.

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.

3.2 *4*-SPT Hall thruster cluster

During this series of experiments the cluster assembly thrust characteristics had not measured due to technical feasibility absence [16]. Thrusters discharge currents oscilloscope pictures were studied for investigation of thrusters interaction feasibility in the case of separate power supply units using. Discharge current interrupter was placed in the thruster 3 anode circuit. It interrupted the circuit during the simultaneous thrusters 2 and 3 discharge currents oscillography. Oscilloscope pictures with the thruster 3 ten microseconds interrupting time are given in Figure 9 *a*.
It is shown that the thruster 2 discharge current is not influenced by the thruster 3 impact. However in the case of the thruster 3 discharge current one hundred microseconds interrupting time, the thruster 2 discharge current amplitude has a peak (see Figure 9 *b*, the thruster 2 discharge current amplitude scale was illustratively increased). In addition the thruster 2 discharge current reaction is appeared in the end of the procedure, when the thruster 3 is repeatedly switched on. This fact was not single and was measured time and again during repetitive experiments.



a) b)

Figure 9. Oscilloscope pictures of discharge current TH2 and TH3.

Since thrusters 2 and 3 are electrically uncoupled, so it can be supposed that their crosstalk happens in generated plasma due to plumes interaction. The most probable explanation of this fact is the plasma specific resistance variation. So far as Hall thruster plume can be considered as a partly ionized medium, its specific resistance is inversely proportional to charged parts density. In that case local plasma specific resistance increasing due to the thruster 3 switching off neutral gas rapid ionization would lead to insignificant plume resistance reducing. Accordingly the thruster 2 discharge current can insignificantly increase due to resistance reducing. As it was shown above for the cluster based on thrusters with anode layer in case of separate power supply units using such phenomenon was not revealed. However despite on instability was artificially created in one of the TAL thruster its discharge current was not interrupted.

Oscilloscope picture for thrusters 2 and 3 discharge current in the case of common power supply unit operating with separate cathodes-neutralizers is presented in Figure 10. As it shown one of the cathode-neutralizers current tends to zero value (keeping current value 0.5 A was subtracted). And the thruster 3 cathode-neutralizer current is close to summary current value required for thrusters normal operating. It is possible that such the thruster’s 3 cathode-neutralizer domination happens due to its better conditions for electron emission providing. So it has lesser resistance for discharge current circuit closing. At the beginning of operation cathode-neutralizers currents have larger values due to currents of heaters which are switched off upon stable modes reaching.

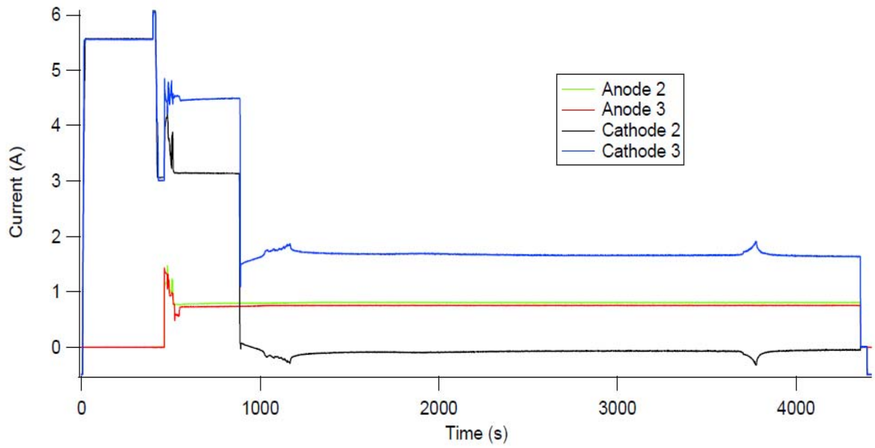


Figure 10. Oscilloscope picture for thrusters 2 and 3 discharge current in the case of common power supply unit operating with separate cathodes-neutralizers.

3.3 *NEXT* multi-thruster array

The cluster was tested with separate power supply units. Single thruster characteristics and characteristics of simultaneous operating of two and three thrusters were studied. Every thruster had its own cathode-neutralizer. Every thruster was started up and was regulated to the full power, intermediate power and low power modes. Thrusters were started up sequentially one by another. To determine the cluster array characteristics single, two and three thrusters characteristics were measured and compared to the every thruster design characteristics.

The full power mode cluster characteristics are given in Table 3. At three thrusters full power modes simultaneous operating the array had following integral characteristics: power was about 20.6 kW, summary thrust was about 711 mN, specific impulse average value was about 4190 s and efficiency was 70.8%. All thrusters are operating at comparable input parameters, cathode-neutralizers modes, discharge chambers cathodes and so on. Differences in thrusters characteristics were negligible and mainly connected with previously considered design differences. Differences absence was demonstrated in the case of joint operating of thrusters 1 and 4 in comparison with joint operating of thrusters 1 and 5. Thrusters 1 and 4 are 0.64 m distant from each other and thrusters 1 and 5 are 0.91 distant from each other. Thus absence of apparent interaction between thrusters which are 0.64-0.91 m distant from each other was shown.

It should be noted that thrusters characteristics (specific impulse, thrust and so on, see table) were calculated with help of standard procedures. Values of mass flow rates, power levels and correction coefficients for propellant utilization efficiency in the thruster discharge chamber depending on tank pressure rising were used for calculation. While calculating the assumption was used – absence of the difference of the single NEXT thruster plume divergence in case of separate operating and in case of the thruster operating as a part of the array. It was shown below.

Table 3. Array Performance.

Test Configuration/Thruster	Performance				
	P_{in},W	Specific Impulse, Sec	Efficiency	Thrust, mN	Ja, mA
EM1					
	6870	4185	0.707	237	12.18
EM1 + EM5					
EM1	6850	4175	0.706	236	17.05
EM5	6820	4185	0.712	237	17.84
EM1 + EM4					
EM1	6870	4170	0.707	237	16.67
EM4	6875	4175	0.707	237	18.16
EM1 + EM4 + EM5					
EM1	6900	4195	0.708	238	21.67
EM4	6840	4170	0.706	236	23.82
EM5	6865	4195	0.711	237	21.25

Table 3 data show that accelerating grid current in the thruster operating as a part of array is higher than in the case of single thruster operating. The current increasing is connected with ions charge exchange process due to the local neutral component density rising. It happens because array summary value of propellant mass flow rate is higher than the single thruster mass flow rate value.

Experimental data showed that the thruster operating as a part of the array did not lead to its characteristics significant changing. It was also fair for integral characteristics, back stream electron current and cathode-neutralizer operating. In addition there were no apparent thruster-to-thruster interactions for stationary mode operating and for characteristics regulation during the two and three thrusters joint operating.

4. Influence of cathode-neutralizer placement, their quantity and connection scheme upon cluster operating

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.

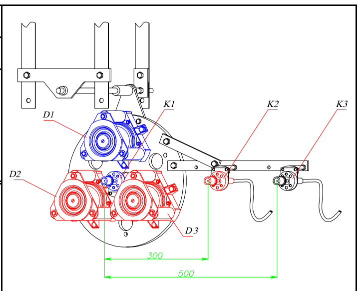
4.1 *3*-TAL multi-thruster assembly

To study the influence of the cathode position on the performance of a cluster, laboratory cathodes were placed at the spacing 0, 300 and 500 mm from the cluster axis. Also, the central cathode was at the distance of 90 mm from the axis of thruster D1. 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 [6].

The cluster was powered from a common power supply. Results of measurement of the thrust of the three TALs operating with cathodes at different distances are represented in Table 4.

Table 4

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 4**,** 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 TALs operating from two cathodes are shown in Table 5. 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 5

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 5, 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, 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.

4.2 *4*-SPT Hall thruster cluster

There were no revealed significant phenomena in the case of simultaneous thrusters 2 and 3 operating with common (thruster 3) cathode-neutralizer and individual power supply unit for each thruster. However, there were some features at the only thruster 2 operating in combination with thruster's 3 cathode-neutralizer. Figure 11 shows discharge current and cathode-neutralizer potential oscilloscope pictures in the case of thrusters 2 and 3 and common (thruster 3) cathode-neutralizer simultaneous operating. Thruster 2 and thruster's 3 cathode-neutralizer joint operating is characterized by increased values of discharge current and oscillation amplitude in comparison with nominal configuration. However, these values are decreased down to nominal ones after the thruster 3 is started. If the thruster 3 is switched off the thruster's 2 discharge current is back to the abnormal value.

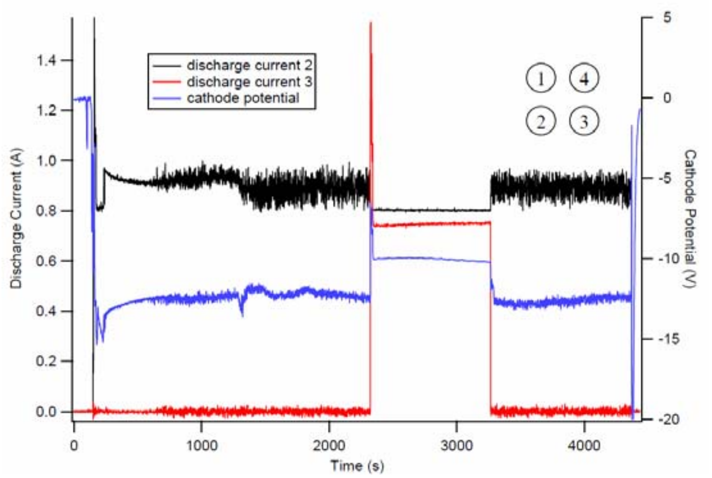


Figure 11. Discharge current and cathode-neutralizer potential oscilloscope pictures.

While the thruster is operating with distant cathode-neutralizer, all electrons reaching the thruster's anode are generated by the distant cathode-neutralizer itself. When the second thruster (located between the first thruster and cathode-neutralizer) begins to operate, it works like a generator of additional electrons for another thruster. Such mechanism returns the whole system to the almost nominal state.

4.3 *NEXT* multi-thruster array

To verify the system flexibility alternative array architecture was experimentally investigated. Experiment includes connection scheme with single cathode-neutralizer using for two and more plumes neutralization and connection scheme with distant (another thruster's) cathode-neutralizer using to neutralize the thruster plume (cross commutation). This studying allows estimating the whole system reliability in case of one or several cathode-neutralizer failures happening.

Thrusters characteristics and array characteristics in case of common cathode-neutralizer operating (with two and three thrusters simultaneous operating) were compared with characteristics obtained in case of thrusters with separate cathode-neutralizers operating (three thrusters and three cathode-neutralizers). Data of single thruster 5 with distant thruster's 1 cathode-neutralizer operating were compared with data obtained in case of single thruster 5 with its cathode-neutralizer operating. Common cathode-neutralizer using for thrusters 2 and 3 did not revealed any influence upon their operating. Thrusters 2 and 3 starting up and their complex plume forming in case of common thruster's 1 cathode-neutralizer using had also no influence upon the array operating. In addition cathode-neutralizers emission current changing (redistribution) was not observed even in case of cathode-neutralizers common points joining and two or three thrusters simultaneous operating with separate cathode-neutralizers.

One of the thruster's cathode-neutralizer using as a common leads to others thrusters characteristics significant improvement especially for low power modes. Three thrusters low power mode characteristics in case of common thruster's 1 cathode-neutralizer using are given in the Table 6. One can see that efficiency and specific impulse of thrusters 2 and 3 increased by 11…13% and 400 seconds correspondingly. Characteristics increasing was obtained due to non-operating cathode-neutralizers mass flow rates values exception from the efficiency and specific impulse calculation.

Table 6.

EM1 + EM4 + EM5 (low power) with 1 neutralizer	Performance					
	P_{in},W	**Specific Impulse, Sec**	**Efficiency**	**Thrust, mN**	**Mn, sccm**	**Vg**
EM1	1105	2445	0.535	49.2	3.00	-11.98
EM4	1060	2845	0.649	49.2	0.00	
EM5	1035	2860	0.667	49.2	0.00	

Characteristics of two thrusters simultaneous operating at full power modes in cases of separate cathodes-neutralizers using and common cathodes-neutralizer using are given in the Table 7. Data table show that efficiency is higher by 7% and specific impulse is higher by 300 seconds for the of common cathode-neutralizer using. Case of three thrusters at full power modes simultaneous operating with common cathode-neutralizer using was not tested. Since the cathode-neutralizer emission current allowable value is 13 A and three thrusters operating would require higher value of electron emission current. However the testing results demonstrated that one cathode-neutralizer was able to neutralize several thruster's plumes and thrusters quantity was limited by maximal cathode-neutralizer emission current value.

Table 7.

EM1 + EM5	Performance					
	P_{in},W	**Specific Impulse, Sec**	**Efficiency**	**Thrust, mN**	**Mn, sccm**	**Vg**
EM1	6925	4215	0.712	238	4.01	-10.23
EM5	6835	4190	0.711	237	4.01	-10.75
EM1 + EM5 with 1 neutralizer	**P_{in},W**	**Specific Impulse, Sec**	**Efficiency**	**Thrust, mN**	**Mn, sccm**	**Vg**
EM1	6850	4190	0.708	236	4.00	-11.25
EM5	6795	4500	0.768	237	0.00	

5. Cluster assembly plume parameters measurement

5.1 *3*-TAL multi-thruster assembly

Base operation mode was chosen for characterization of the composed cluster plume. All thrusters were 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, and cathode-neutralizer K1 at the center of the cluster. Residual tank pressure was equal to 1×10^{-4} Torr.

The diagnostic equipment and test procedures are described in Ref. [15].

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

Typical radial ion current density distributions measured in the three cross-section of the cluster plume are given in Figure 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.

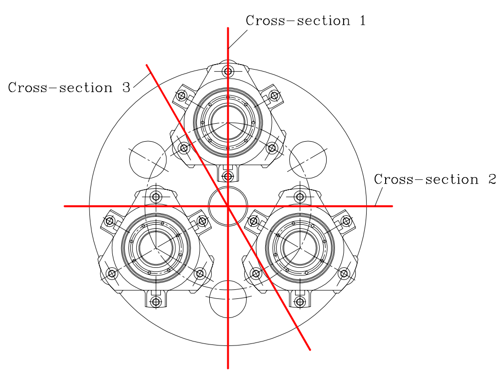


Figure 12. Cross-section map.

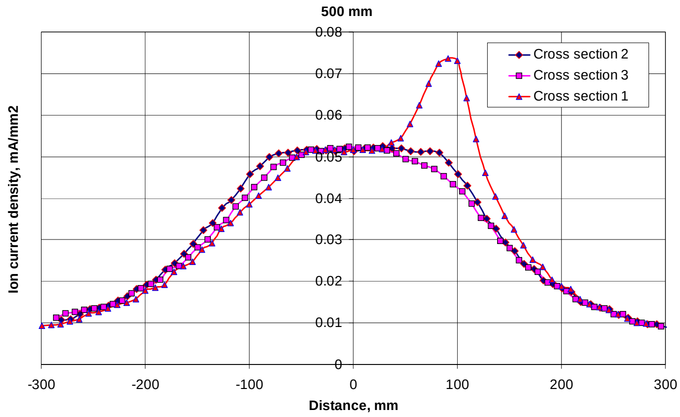
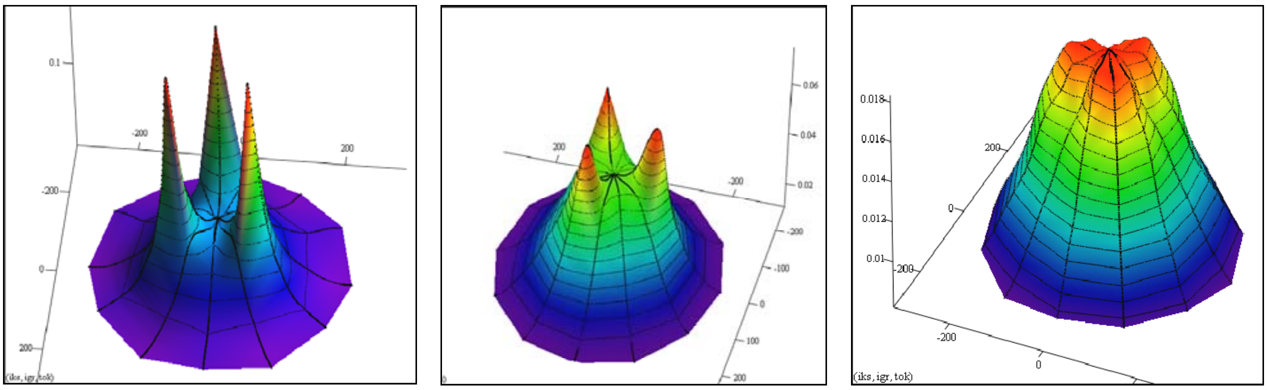


Figure 13. Distribution of the cluster ion current density.

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

As one can see, at the distances 300 (Figure 14a) and 500 mm (Figure 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 (Figure 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.



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

Figure 14. Cluster ion current distribution.

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 Figure 15. Measured single thruster D1 (red curve) and cluster (blue curve) plume profiles are given in this figure. Black curve in Figure 15 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.

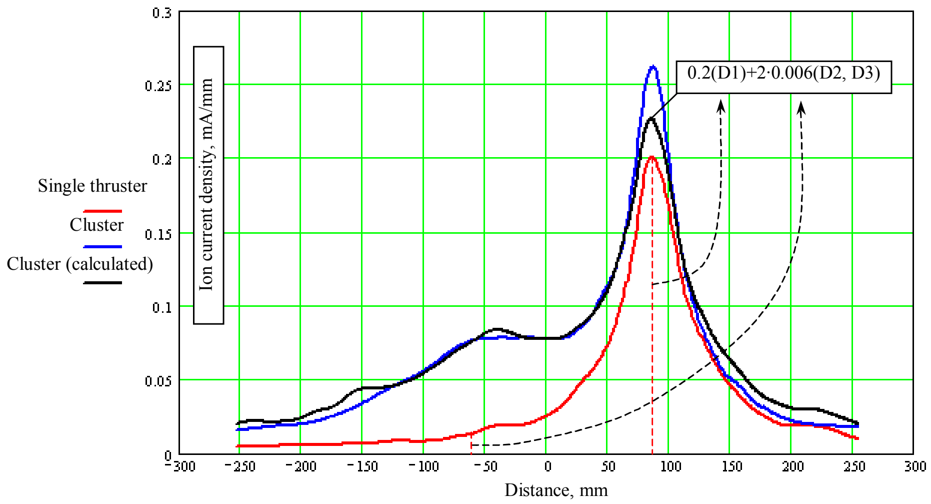


Figure 15. Ion current density distribution of the cluster and single thruster.

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.

Measurements of the plasma parameters were conducted in cross-sections *1*,*2*,*3* (Figure 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 **Figure 16**. Corresponding distribution of the ion current density in this cross-section is given in Figure 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.

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 **Figure 17**.

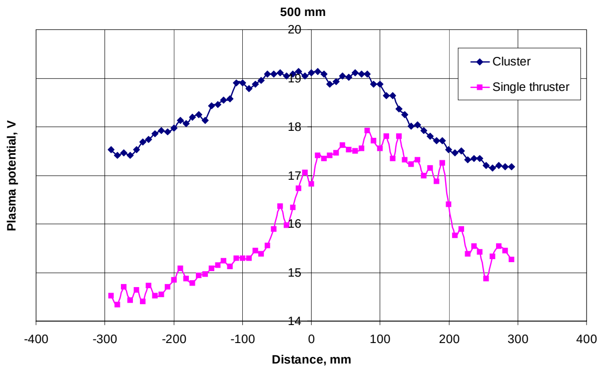


Figure 16. Both cluster and single thruster plasma potential distribution.

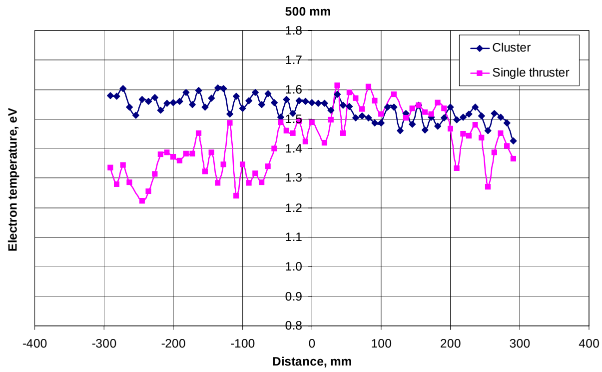


Figure 17. Electron temperature distribution for the cluster and single thruster plumes.

As it can be observed from **Figure 17**, electron temperature distribution in the cluster plume has more uniform view as compared with single thruster distribution.

5.2 *4*-SPT Hall thruster cluster

Langmuir probe was used for plasma density measurements [16, 17]. Characteristics were measured in the cross sections of thrusters: 2 and 3; 3 and 4 [18, 19]. Measurements were taken in case of single thruster operating and two thrusters operating for every of these cross sections. Plasma density distribution for distances 100 and 250 mm from the cluster's plane exit in case of thrusters 3 and 4 simultaneous operating is given in Figure 18.

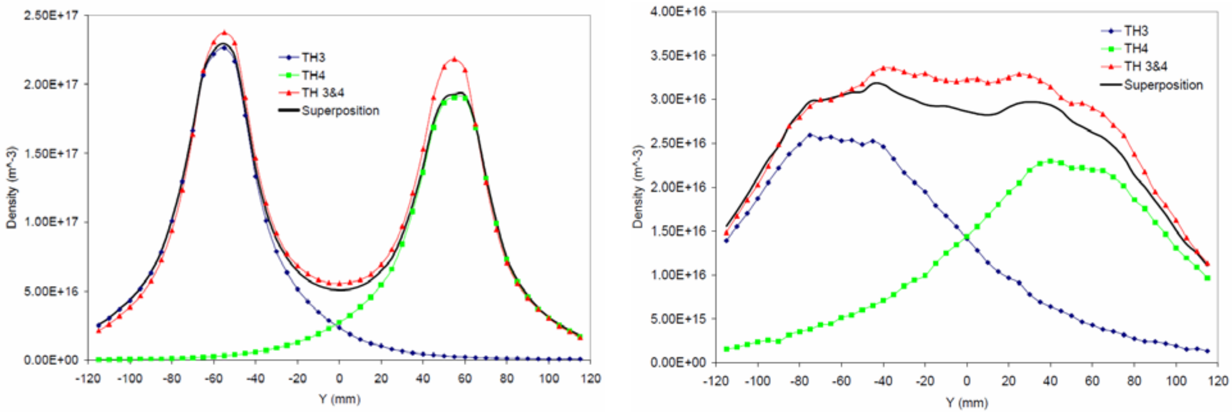


Figure 18. Plasma density distribution for distances 100 and 250 mm from the cluster's plane exit.

One can see that the plasma density value decreases rapidly enough while moving away from the cluster exit plane. And for 250 mm distance it becomes close to constant value along the cluster's cross section so the cluster's plume can be considered as plume of one large thruster. Single thruster operating plasma density distributions and calculated by summation plasma density distribution of all thrusters are also given in the figure. Summarized value is about 10% lesser of than measured one. It should be noted that largest difference between calculated and measured values is in areas with plasma density maximal values.

Thrusters 3 and for 4 in cases of their single and simultaneous operating electron temperature distribution profiles for distances 100 mm and 250 mm from the cluster's exit plane are given in the Figure 19. Electron temperature is slowly decreases and it becomes almost constant at the 250 mm distance.

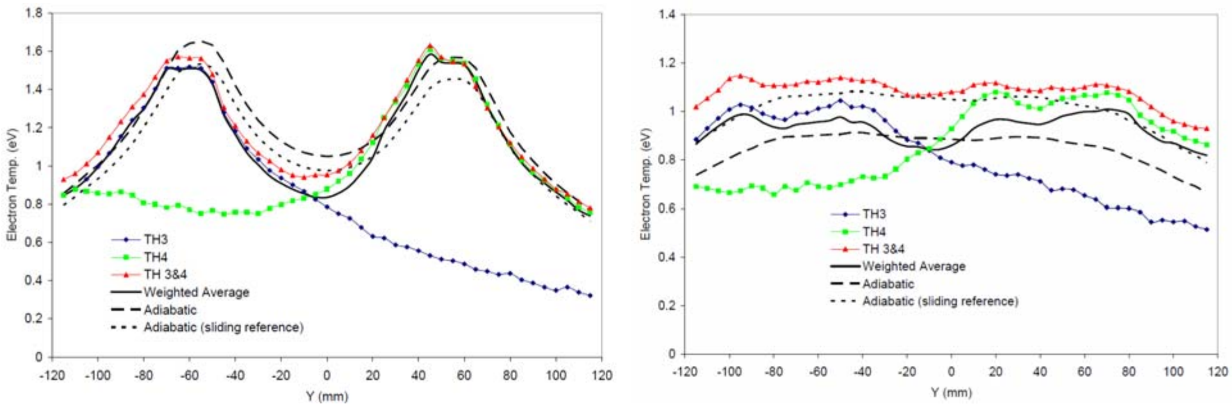


Figure 19. Electron temperature distribution profiles for distances 100 mm and 250 mm from the cluster's exit plane.

Plasma potential distribution profiles measured by filament probe at the distances 60, 100 and 140 mm from the cluster's exit plane in case of single and simultaneous thrusters 3 and 4 operating are given in the Figure 20. One can note that for practically all areas (except one) plasma potential value decreases with distance from the cluster's exit plane increasing. Area with plasma potential value increasing is located between thrusters 3 and 4.

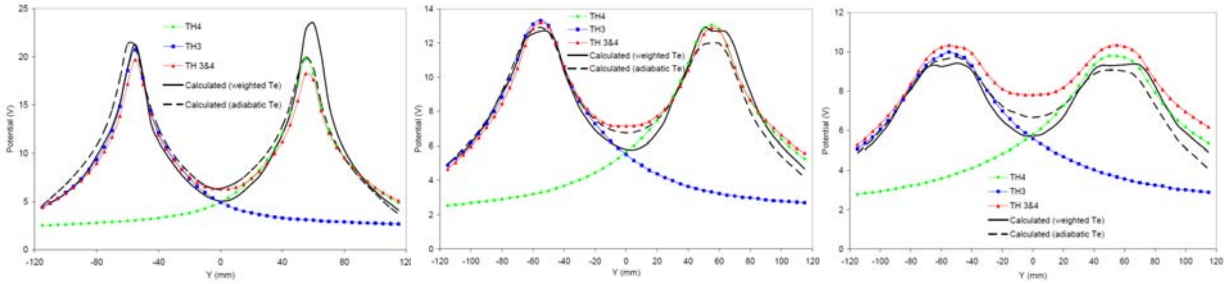


Figure 20. Plasma potential distribution profiles measured at the distances 60, 100 and 140 mm from the cluster's exit plane.

The reason for such plasma potential increasing in the area between thrusters can be reversed electric field, which can be created by particles charge exchange process and following ions acceleration in the direction of cluster.

Ion current density distributions (given in logarithmic scale) measured along the arc with centers between thrusters 2 and 3 by Faraday probe at 500 mm distance from the cluster's exit plane are presented in the Figure 21 [20].

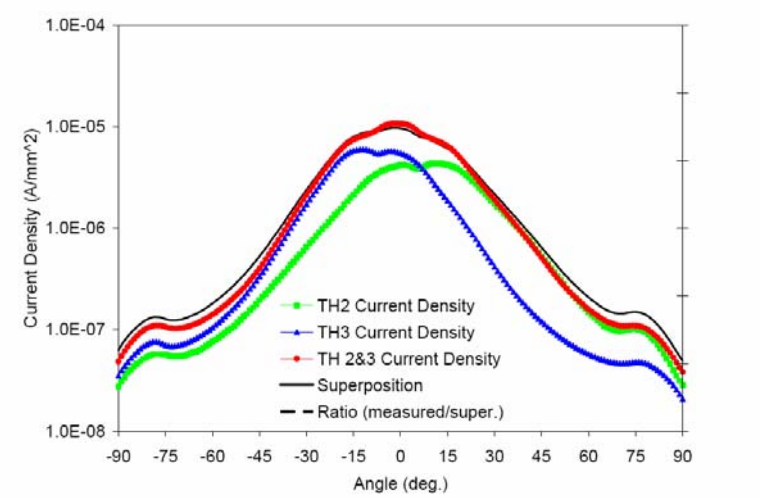


Figure 21. Ion current density distributions.

Ion current density value measured at the cluster axis was about 13% higher than one calculated by summation of single thrusters densities values. However there was a contrary condition for plume periphery area, calculated value is about 20% higher than measured one. There was a plasma potential minimum observed in the area between two thrusters for the case of their simultaneous operating. It can lead to the situation, when ions generated by one of the thrusters and accelerated in the cluster center directions could be deflected by thruster-neighbors plasma potential peaks, so the whole cluster plume divergence could be decreased.

5.3 *NEXT* multi-thruster array

Planar Faraday probes were used to characterize the ion density distribution [21]. Each probe had round collecting surface of 1 sm^2 area and was equipped by grounding guard ring. The probes of such kind were installed on vertical bar, which had a possibility to move in 2-axis direction (across and along cluster axis) in accordance with Figure 22 The measurements in the two cross-sections including EM1, EM2 and EM4, EM5 centerlines were of general interest.

Ion current density measurements were taken during three thruster (EM1, EM4 and EM5) simultaneous operation. Ion current density profiles at different distances from array exit plane collected in the cross-sections 1 and 3 are shown in Figure 23. As it can be seen from Figure 23 overlap of EM4 and EM5 thrusters beams is occurred as early as at the distance 250 mm from array and ion current density between the thrusters is increased downstream the plume defining its final divergence.

To gain a better understanding about multi-thruster assembly influence upon main performances of a complex plume the investigation of a quantity operating thruster influence on total cluster ion current density profile were conducted. According to this goal each thruster ion density profiles collected during their individual operation were compared with cluster one (EM1, EM4 and EM 5 simultaneous operation). The results of given comparison for distance 250 mm from the array exit plan are shown in Figure 24. Ion current density distributions measured in cross-section 1 in the cases of individual EM1 operation and its operation as a part of array have a slight difference from each other.

However, it must be noted, that maximum magnitude of ion current density measured on centerline of the EM4 during array operation is slightly lower in comparison with value measured in case of single EM4 operation.

Ion current density profile of EM4 and EM5 thrusters measured during both individual and array operation in cross-section 3 are close enough to each other. Profiles are in a good coincidence near the thruster's centerlines where thruster beams overlap is not occurred yet. In one's turn in the cluster centerline ion current density distribution is defined by superposition of the given thrusters distributions.

To determine level of beams interaction in their intersection area – namely in the centre of the array, the comparison between experimentally obtained ion current density distribution of array and distribution based on simple summation of individual thrusters experimental data was carried out. The result of such comparison at the 250 mm distance from the array set is presented in Figure 25. As one can see from Figure 25, simple summation of individual thruster profiles is closed enough to measured cluster profile. However, negligible difference is present. This difference is particularly visible on EM4 centerline. It is possible to suppose that presence of difference is caused by the greater impact upon EM4 beam from neighbor thrusters than EM1 and EM5 beams since EM4 is equidistantly located from adjacent thrusters. Nevertheless, as in the case of TAL and SPT clusters the ion current density distribution of multi-thruster assembly based on ion thrusters for the first approximation can be estimated by simple summation of profiles of cluster's individual thrusters.

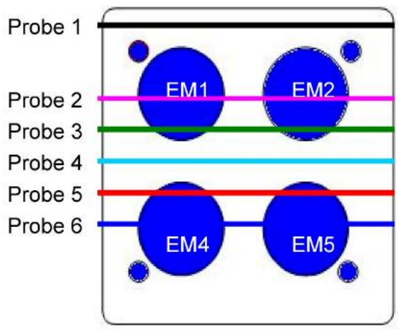


Figure 22. Cross-sections map. (Probe 2 –cross-section 1; Probe 4 –cross-section 2; Probe 6 –cross-section 3)

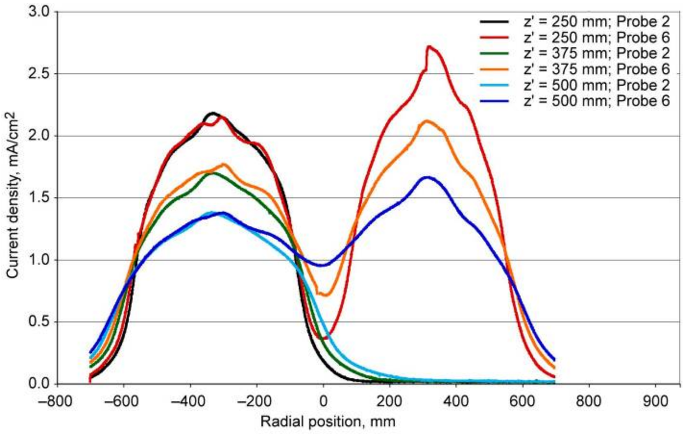


Figure 23. Ion current density distribution during three thruster simultaneous operation.

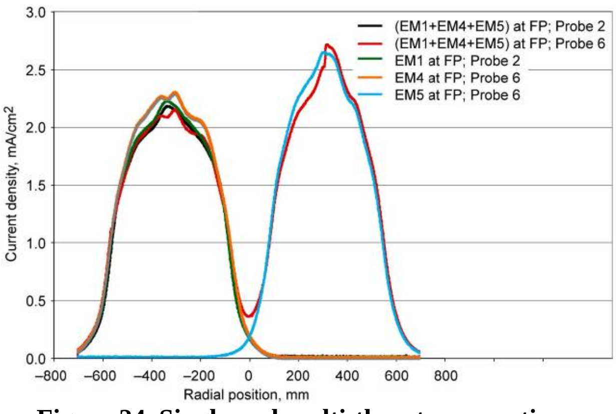


Figure 24. Single and multi-thruster operation comparison.

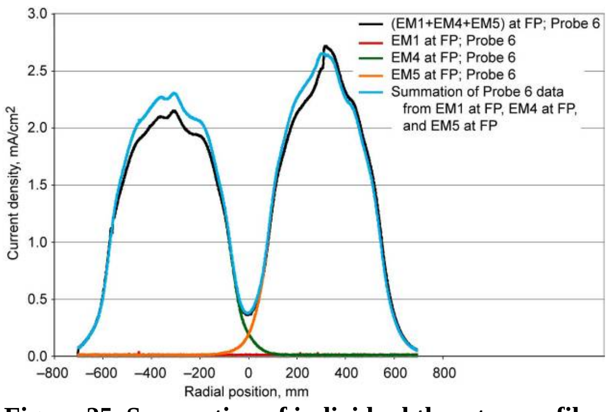


Figure 25. Summation of individual thruster profiles.

To measure both plasma potential and electron temperature distributions of the array based on NEXT thrusters Langmuir planar probes were used [22].

In the left of the Figure 26 shows the plasma potential distribution measured in cross-section 1 at the different distance from cluster exit plan.

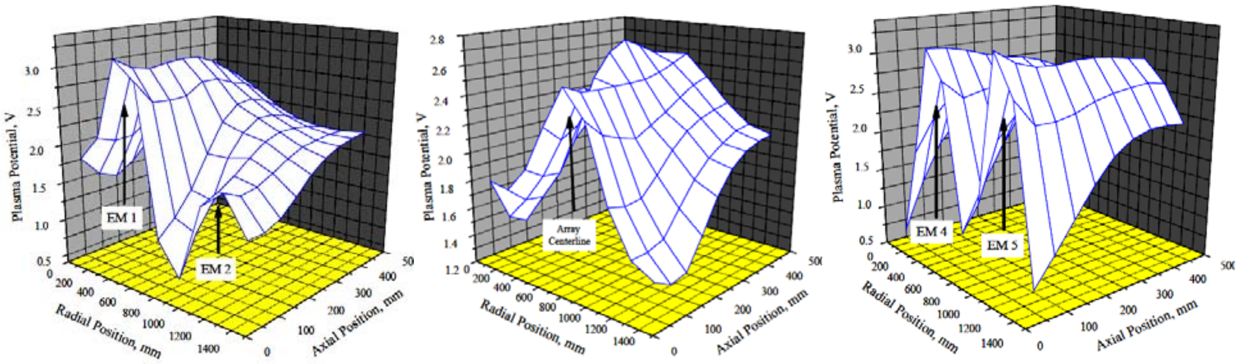


Figure 26. Plasma potential profiles.

As it can be seen, there are two peaks of the different magnitudes with tops corresponding to EM1 and EM2 centerlines. The peak corresponding to EM1 thruster is about in 1.7 times higher than EM2 centerline peak. It must be noted that EM2 thruster was not active. However, at the nearest cross-section to the cluster exit the profile of potential plasma at the exit EM2 looks like operating thruster. It could be assume that the presence of the small peak is a result of ion change exchange processes connected with simultaneous operation of adjacent thrusters EM1, EM4 and EM 5. During traveling downstream from cluster exit the profile of non-active thruster EM2 looses similarity to profile of active thruster. Plasma potential magnitude on the EM2 centerline increases and tends to EM1 thruster magnitude. In the area between EM1 and EM2 thrusters near the cluster exit the plasma potential value tends to “ground” potential. It could be explained by sufficient quantity of plasma absence and surfaces (such as thruster’s construction elements) under “ground” potential in immediate proximity presence.

Plasma potential distribution in the centre of array (cross-section 2, in the center of the Figure 26) has peak in the radial direction of a cluster. Due to cluster centre is rounded by the three operating thrusters such profile may be occur in consequence of intensification of charge exchange ions on the cluster centerline generated by EM1, EM4 and EM5 beams. During traveling downstream from the exit plane the peak is flattening and plasma potential magnitude is increasing due to apparently thruster beams overlapping as early as at 250 mm distance from array exit plane.

The plasma potential distribution in the cross-section 3 is presented in the right of the Figure 26. There are two peaks close to array exit plane corresponding to EM1 and EM5 thruster centerlines. With increasing of a distance from assembly exit the plasma potential magnitude along thruster centerlines goes down monotonically. From distance of 200 mm the plasma potential profile becomes practically flat and steady. Between EM1 and EM5 thrusters plasma potential in the closed to exit plane zone tends to “ground” potential analogous to previous case. With downstream distance increasing the plasma potential between EM1 and EM5 thrusters is raising and flattens just about at 250 mm distance where the beams overlapping becomes essential.

Electron temperature profile measured in cross-section 1 is shown in the left of the Figure 27. As one can see, the electron temperature magnitude has its maximum at the boundary of scanning in radial direction and between thrusters. It can be explained by presence of electrons with sufficient energy to overcome potential barrier inside thrusters beams, which are able to penetrate into given area.

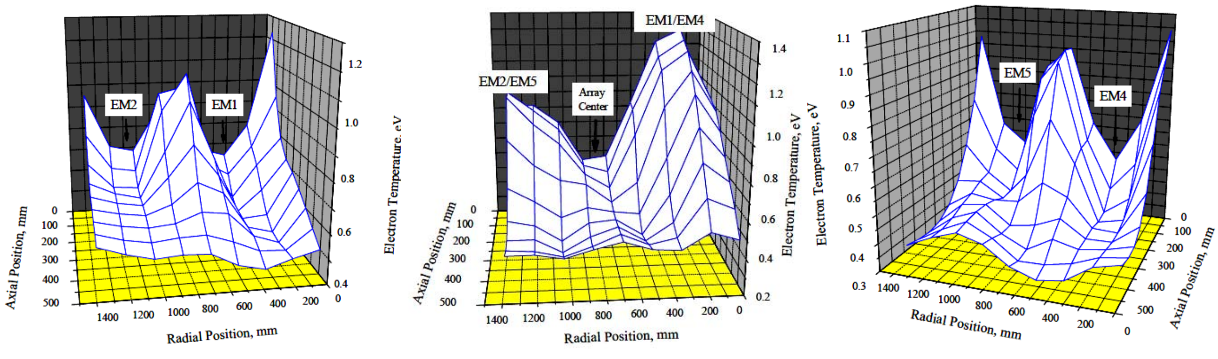


Figure 27. Electron temperature profiles.

In the immediate vicinity of cluster exit the minimum electron temperature magnitude is observed in the thrusters 1 and 2 centerlines. The electron temperature distribution near the thruster exit looks like operational thruster one despite EM2 is still non-operating. From downstream distance of 50 mm electron temperature begins to decrease and at the distance of 350 mm it flattens. Over the distance of 350 mm the plume formed by three thrusters looks like the single large thruster plume.

Electron temperature distribution measured in the cross-section 2 is shown in the centre of the Figure 27. Maximum of electron temperature is observed in the area between EM1 and EM4 thrusters in the immediate vicinity of array exit. During downstream traveling from point between EM1 and EM4 thruster the electron temperature is decreasing. Such decreasing could be partially explained by plasma potential gradient presence along this direction. With further moving away from the array exit plane the plasma potential gradient is decreasing retaining electrons with lower energy and allowing higher energy electrons to leave given area and to disappear in the space. Similar but not such obvious decreasing of electron temperature values is observed along the line from point between EM2 and EM5 to downstream direction. In the cluster centerline electron temperature has local minimum, which is slightly raising with distance from assembly increasing.

The electron temperature distribution in the cross-section 3 is shown in the right of the Figure 27. Distribution has symmetrical view due to operation of two thrusters EM4 and EM5 in given cross-section. With moving away from the array exit plane the electron temperature is decreasing and at the long distance it flattens. The peak of electron temperature value is observed between thrusters beams area and in the area outside of the beam. Thus, in the near field of the cluster plume electron temperature distributions look like mirror reflection of the plasma potential ones.

Accordingly, plasma potential and electron temperature distributions are compliant with thruster plumes form and their overlapping structure. Peaks of the plasma potential and electron temperatures values in the near field correspond to thrusters centers. Electron temperatures and plasma potential distributions are flattening with increasing of distance from array exit plane due to essential beams overlapping.

6. Discussion and Conclusions

The main objective of given paper was not to determine absolute magnitudes of clusters performance characteristics but to display features of such kind systems behavior and potential cross-interactions of their components depending on different configurations and thruster types.

Cluster assemblies based on TALs D-55 and SPTs BHT-200 thrusters were considered as scale models for future powerful multi-thruster systems whereas NEXT array assembly of 20 kW power may be considered as a flight unit prototype. The total power levels of 3-TAL and 4-SPT were about 3 kW and 800 kW correspondingly. During low power modes cluster investigation it was supposed that all obtained parameters and features may be extended for higher power systems. The criteria of basic thruster selection for exploratory assemblies were assigned by level of thruster studying, absence of thruster scale factors associated with low power and by test facility features (vacuum system capability mainly). D-55 definitely has no scaling problems as compared with a bigger TALs with power up to 50 kW, and working processes are one and the same for these thrusters at corresponding operation modes [[23]]. BHT-200 thruster with 200 W power has untypical design in comparison with others SPTs due to its lesser overall dimensions and that may lead to appearance of some additional scale factors associated with low power Hall thruster [[24]].

In the case of basic clusters configurations it was indicated that multi-thruster system thrust value was a simple sum of thrust values of thrusters forming a cluster. This statement was demonstrated by direct thrust measurements for 3-TALs cluster and by calculations based on NEXT array experimental data.

The possibility cluster operation in the case of one cathode-neutralizer using for several simultaneously operating thrusters was also confirmed. Characteristics obtained in case of individual power supply units using for each simultaneously operating 3-TAL cluster's thrusters with shared cathode-neutralizer and single thruster operating with own cathode-neutralizer characteristics were in a good coincidence. In the case of NEXT array the possibility of operating with shared cathode-neutralizer was additionally confirmed by cluster ion current density measurements in cases of shared and individuals cathode-neutralizers operating. The differences in measured profiles for given two cases were not observed. However, some features were observed for two BHT-200 thrusters operating. Significant phenomena during simultaneous thrusters operation with shared cathode-neutralizer were no revealed in comparison with individual power supply units using for each thruster. Nevertheless if the first thruster was shut down the second thruster was characterized by increased values of discharge current and oscillation amplitude in comparison with nominal values. However, the second thruster characteristics values were decreased down to nominal ones after the first thruster was started. During 3-TAL cluster operation the same phenomena was not observed. Moreover in the case of cluster operation with common power supply unit for all thrusters measured amplitude of common current oscillations was the same order as for individual thruster operating oscillation amplitude. Performance characteristics of 3-TAL cluster powered by common power supply and by individual ones had no significant differences.

It should be pointed that clusters complex plumes characterization is the one of the most critical tasks. Despite of significant differences absence between performance characteristics of single and common thrusters operating their beams parameters and cluster complex plume parameters may have some differences. Features of multi-thruster assemblies plume formation revealing is of critical importance for influence plasma flow upon spacecraft surface estimating.

In the case of BHT-200 cluster the minimal distance between position of measurements and cluster exit plane was 50 mm due to low power level of the thrusters and consequently low beam current density. During more powerful 3-TAL investigation the main data were collected at the farther distance from the exit plane (300 mm). Since the approach of the electrical probes closer to cluster exit could result in their damage by accelerated plasma flow. Moreover in the near field of the 3-TAL plume the amplification of probes influence upon plume characteristics due to high value of plasma current density was occurred. In the case of NEXT array the minimal distance between position of measurements and cluster exit plane was 50 mm. It was also possible due to lower as compared with Hall thrusters beam current density.

Despite of difference in thruster types and power level of considered cluster assemblies some common rules of cluster plume forming were determined:

- Measured cluster ion current density value is not simple sum of single thruster's ion currents.
- Measured values of electron temperature and plasma potential in the cluster plume are of the same order as ones measured for single thruster.
- 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 generated by some single thruster located at the center of the cluster.

In spite of all obtained results relate to particular cases, one can conclude:

- Cluster is a quite universal technology and it can be used for development of high power EPS based on different thruster types. The cluster integral characteristics: summary thrust, power, mass flow rate and stable operating range could be well defined with help of corresponding single thrusters parameters.
- Thruster operating as a part of the cluster could have some distinct features in comparison with separate thruster operating. Conditions of such features appearing require further investigation.
- For all cluster configurations researched differences between cluster's plume parameters measured and cluster's plume parameters which can be predicted with help of separate thrusters plumes simple summation model were experimentally observed. So there are plumes interaction mechanisms which require development and verification of corresponding physicomathematical complex plumes models.

References

[1] Tverdokhlebov S.O. et al. Development Strategy for 100kW-class Hall Propulsion. – IAF-00-S.4.07.

[2] Tverdokhlebov S.O., Semenkin A.V. et al. Consideration of Cluster Design Approach for High Power Hall Propulsion. – AIAA-2003-0494.

[3] Zakharenkov L.E., Semenkin A.V. et al., Study of multi thruster assembly operation, IEPC-2003-0311, 28th International Electric Propulsion Conference, March 17-21, Toulouse, France.

[4] Rusakov A.V., Kochergin A.V., Semenkin A.V., Tverdokhlebov S.O., Garkusha V.I., Multiple Thruster Propulsion Systems Integration Study, IEPC-97-130.

[5] L.E. Zakharenkov, A.V. Semenkin et al., "Study of the 3-TAL Thruster Assembly Operation", IEPC-2005-185, 2005.

[6] A.V. Semenkin et al., "RHETT/EPDM Flight anode layer thruster development", IEPC-97-106.

[7] G.F. Karabadzhak et al.: Studying of Atomic and Molecular Processes in Rarified Hypervelocity Expanding Flows by Methods of Emissive Spectroscopy, Final Technical Report for ISTC Partner Project #2234p, TSNIIMASH, Feb. 2004.

[8] Garkusha V.I., Zakharenkov L.E., Semenkin A.V. et al., "Research of multi-thruster assembly consisting of several simultaneously operating thrusters", Tsniimash, Korolev, Moscow Region, Russia, 2006.

[9] Hargus, W.A. and Reed, G., "The Air Force Clustered Hall Thruster Program", AIAA Paper 2002-3678, July 2002, Indianapolis, IN.

[10] Patterson, M.J., Foster, J., McEwen, H., Pencil, E., Van Noord, J., and Herman, D., "NEXT Multi-Thruster Array Test – Engineering Demonstration," AIAA-2006-5180, Joint Propulsion Conference, July 2006.

[11] Patterson, M.J., Benson S.W., "NEXT Ion Propulsion System Development Status and Performance", AIAA-2007-5199, Joint Propulsion Conference, July 2007.

[12] K. E. Witzberger and D. Manzella, "NASA's 2004 In-Space Propulsion Refocus Studies for New Frontiers Class Missions", AIAA–2005–4271.

[13] Soulas, G.C. and Patterson, M.J., "NEXT Ion Thruster Performance Dispersion Analyses," AIAA–2007–5213, July 2007.

[14] Herman, D.A., Soulas, G.C., and Patterson, M.J., "Performance Evaluation of the Prototype–model NEXT Ion Thruster," AIAA–2007–5212, July 2007.

[15] L.E. Zakharenkov, A.V. Semenkin et al., "Measurement Features and Results of TAL D-55 Plume", IEPC-2005-184.

[16] Beal, B.E., "Clustering of Hall Effect Thrusters for High-Power Electric Propulsion," Ph.D. Dissertation, Aerospace Engineering Dept., the Univ. of Michigan, Ann Arbor, MI, 2004.

[17] Beal, B., Gallimore, A., and Hargus, Jr., W. A., "The Effects of Clustering Multiple Hall Thrusters on Plasma Plume Properties," 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Huntsville, AL, 2003, AIAA-2003-5155.

[18] Beal B.E., Gallimore, A.D., Hargus, Jr., W.A., "Plasma Properties in the Plume of a Hall Thruster Cluster," *Journal of Propulsion and Power*, Vol. 20, No. 6, Nov.-Dec. 2004, 985-991.

[19] Beal, B. E., Gallimore, A. D., and Hargus, W. A., "The Effects of Cathode Configuration on Hall Thruster Cluster Plume Properties," 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Tucson, AZ, July 10–13 2005, Paper AIAA-2005-3678.

[20] Beal, B. E., Gallimore, A. D., and Hargus, W. A., "Preliminary Plume Characterization of a Low-Power Hall Thruster Cluster," *Proceedings of the 38th AIAA Joint Propulsion Conference*, AIAA Paper No. 2002-4251, AIAA, Washington, DC, 2002.

[21] Pencil, E.J., Foster, J.E., Patterson, M.J., Diaz, E., Van Noord, J., and McEwen, H., "Ion Beam Characterization of NEXT Multi- Thruster Array Plume," AIAA-2006-5182, Joint Propulsion Conference, July 2006.

[22] Foster, J.E., Pencil, E., Patterson, M.J., McEwen, H., Diaz, E., and Van Noord, J., "Plasma Characteristics Measured in the Plume of a NEXT Multi-Thruster Array," AIAA-2006-5181, Joint Propulsion Conference, July 2006.

[23] A.V. Semenkin, S.O. Tverdokhlebov, V.I. Garkusha, Sergey D. Grishin. TAL Thruster Technology for Advanced Electric Propulsion Systems. 20th International Symposium on Space Technology and Science. Gifu, Japan. May 19-25, 1996.

[24] L. Zakharenkov, A. Semenkin, G. Chislov. Study of low power TAL characteristics. IEPC-2001-041. Pasadena, October 15-19, 2001.