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STUDY OF MULTI 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. Additivity of the thrust and discharge currents of the thruster assembly in a different schemes are studied.

Discharge current oscillations of each thruster and oscillations of the summarized current of three thrusters operating from one common power supply are considered.

Diagnostics set needed for further complex plasma flux study is discussed.

Introduction

During the last 30 years the available on space crafts (SC) electric power is increased in many times from about 1 kW to 10-20 kW for communication satellites and up to 100 kW for space stations. The availability of relatively high on-board power gives a new turn of works on high-power electric propulsion (EP) for possible orbit rising or orbit-to-orbit transfer. The usage of EP for such maneuvers can provide the significant benefit in SC payload mass or active lifetime.

Currently there are three approaches to create high power electric propulsion systems [1]:

- To use high power thrusters;
- To use expendable thruster design (size and power of the thruster can be increased by adding of relatively small "standard sections") so called "race track" configuration;
- Multi thruster assemblies/clusters – number of relatively independent and small thrusters assembled into integrated system.

The development of high power thrusters with non-condensable propellant is limited by the capabilities of ground facility.

The expendable thruster requires the extremely sensitive and precise propellant feed system in order to provide uniform conditions in accelerating chamber.

Cluster EP technology provides more flexibility, reliability and new operation quality to high power EP systems.

The present paper describes some aspects of cluster assembly study and contains the experimental results of three-units cluster.

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Cluster Approach

Cluster approach has some advantages from several points of view [1, 2]:

- **System flexibility.**

  It means that the system can be used in very wide diapason of operating parameters.

- **Reliability.**

  There are at least two factors that provide the increase of cluster reliability in comparison with one thruster system. One is the possibility to perform much more representative tests with relatively small unit and to receive more statistical data for reliability determination. The another one is that if the failure of one or even more thruster units will occur, using the rest units should complete the mission.

- **Ability to perform S/C orientation by variation of thrust value in part of thrusters in the cluster.**

  This option provides a new quality to the propulsion system. In flight it is required to change the direction of thrust vector, for example, because of changing the location of SC centre of gravity due to propellant mass changing or other reasons. Several thrust units could provide variation of thrust vector by means of their placement at some angle with respect to the main thrust direction.

- **Easy scaling of a propulsion system.**

  This property is useful during designing of propulsion systems of different power by adding ready-made thrust units. This can save a lot of time and money for pre-launch system tests.

- **Ability to utilize components (thrusters, PPU, PMS) independently for different S/C.**

  It is important during the development of new spacecraft.

- **Relatively easy facility requirements to test cluster components on a ground.**

  This is very important moment. On-ground thruster test is very expansive and requires large vacuum chambers with cryogenic vacuum pumps. The most of existing vacuum chambers allow to test thrusters not more than 10 kW. The biggest one can be used for 50 kW thruster test.

Nevertheless several aspects have to be studied and clarified for cluster application [3]:

1. Integration on a S/C
   - Additivity of thrust values
   - Interaction of thrusters plumes
   - Effects of thruster electromagnetic noise summarizing
2. Architecture of a cluster
   - An ability to operate several thrusters from common power supply and propellant management system;
   - An ability to operate cluster from one cathode, or limitations on geometrical size of cluster with single cathodes;
   - Optimized number of thrusters in a cluster;
   - Thrust vector variation;
   - "Cross talk" of the thrusters through outer plasma and through internal electric circuits and potential resonance effects;
   - Stability of the cluster operation to deviations of operation parameters in part of the thrusters in assembly.

The general directions of activity described in this paper were the following:

- Development and verification of the diagnostic equipment for plasma plume study;
- Cluster assembly, experimental verification and study of the performances;
- Study of interaction between thrusters in the cluster and interaction between thruster and cathode-neutralizer depends on distance between it.
  - Study of influence of "thruster to cathode" distance on the thruster operation;
  - Study oscillations in the cluster discharge circuits and additivity of oscillations from three thrusters powered from one common power supply circuit.

Diagnostic Equipment And Probe Selection

The methods of both single- and multi-thruster plume diagnostic have to provide determination of the following essential plasma parameters, which are critical of importance to understanding physical processes:

- Temperature of plasma components and its space distribution;
- Energy and moving direction of ion component;
- Plasma potential and electric field distribution.

Important to note, that measurement of local parameters is necessary. These requirements have predetermined the choice of electrical probe diagnostic as a method of a plume study.

Considered task have second important feature. The model of point plasma source, which was used in most of works dedicated to electric thruster plume study, is not applicable in case of cluster plume consideration. It results in necessity to apply cylindrical or Cartesian system of coordinates for selection of probe movement device kinematics scheme.

Diagnostic area of a plume potentially may be divided by two zones – "Near" and "Far" zones. The first zone is characterized by higher concentration and current density, whereas the second one has less energy level and low gradient of measured parameters. Preliminary zones were defined as a range of 0…500 mm from thruster/thrusters exit for "Near" and more than 500 mm for "Far" zone.

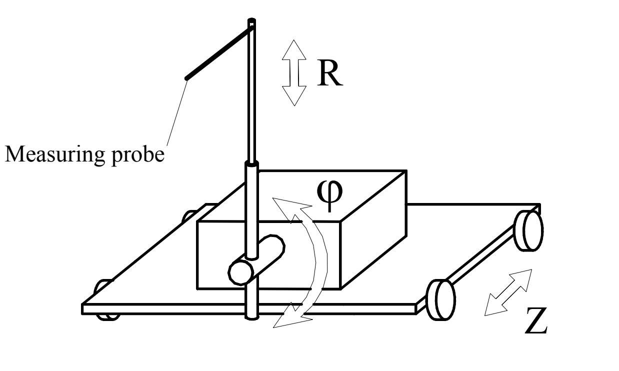
Thus, development of two diagnostic system for "Near" and "Far" zones is required.

Diagnostic system must provides the following operation:

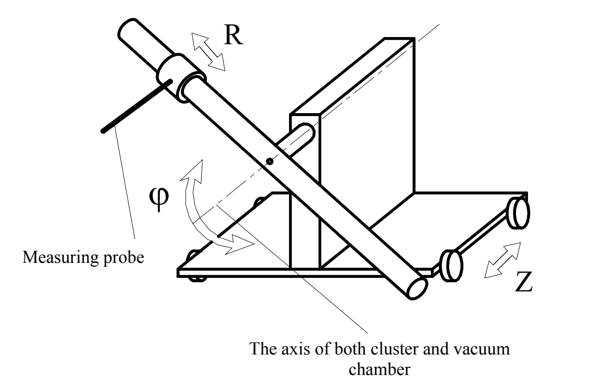
- Different probe design mounting;
- Probes movement at given point of studied space;
- Registration of probe volt-ampere characteristics at given check points.

The designed "Near" zone diagnostic system is high-velocity system, which provides minimal time of probe stay in plume to avoid their degradation. For this system a trajectory of probes movement passes through plume axis. The "Far" zone diagnostic system is system, which provides probe movement in any place of vacuum chamber.

The "Near" and "Far" systems have been developed and manufactured. The principle schemes of these systems are shown in Fig. 1. The "Near" zone system is 2D unit (z,φ, R is fixed and it does not change during a test), the "Far" zone system is 3D one. Both systems have unified joints for mounting of different probes. The systems have both manual and automatic control for plume mapping with PC registration. The velocity of probe movement and pointing accuracy of the systems are represented in Table 1.



"Near" Zone Diagnostic System



"Far" Zone Diagnostic System

Fig. 1 . Diagnostic systems schems.

Table 1

"Near" Zone Diagnostic System			"Far" Zone Diagnostic System		
Parameter	Velocity	Accuracy	Parameter	Velocity	Accuracy
Z	2 mm/s	±1 mm	Z	2 mm/s	±1 mm
φ	up to 50 dgr/s	± 0.25 dgr	Φ	up to 20 dgr/s	± 0.25 dgr
R	–	–	R	up to 60 mm/s	±1 mm

The following types of probes were chosen and tested for selection of appropriately one for further plume diagnostic:

- Cylindrical probes,
- Flat probes,
- Flat probe with guard ring,
- Emissive probes – used as verification method.

Criteria for probe selection:

- minimal size to get better space resolution,
- manufacturing simplicity,
- compliance of measured values with the ones obtained by independent method .

Comparative analysis of different probe design has been conducted on single thruster of average power D-55 [4]. For probe movement and positioning the "Near" zone system have been used. Also this system may be used for preliminary plume study on the distance more than 500 mm from thruster exit.

Studied thruster operated at regime:

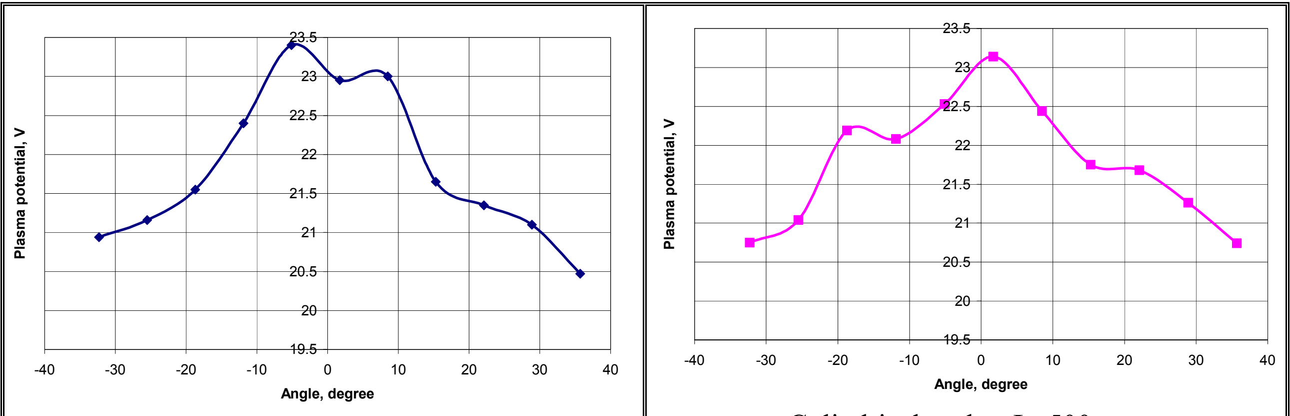
- Discharge voltage – 300 V,
- Discharge current – 4,5 A,
- Tank pressure 1.5 x 10^{-4} mm Hg

This regime was chosen as most studied one.

For the plume parameters registration the following procedure was used. In every investigated point the probe volt-ampere characteristic was obtained by accumulation method (averaging of several characteristics in every point). After that probe was moved to next check point. Obtained characteristic were mathematically calculated with the purpose of plasma potential, electron temperature and ion current density determination.

In Fig. 2, as a example, plasma potential distribution obtained by both Ø3×8 mm cylindrical probe and Ø2 mm flat probe for 500 mm distance from the thruster exit is shown.

All measurements of potential were made relatively to vacuum chamber wall.



Flat probes L=500 mm

Cylindrical probes L=500 mm

Fig. 2. Plasma potential obtained by flat and cylindrical probes.

As may be seen from Fig. 2 there is no significant difference between measured values obtained by tested types of the probes. This statement is correct for all studied distances from 200 up to 1000 mm from the thruster exit. Obtained plasma parameters are in a good correlation with data from other facility [5]. The characteristics of plasma potential have been confirmed by independent measuring method using emissive probe.

In Table 2 plume characteristics obtained by flat probe and flat probe with guard ring at the distance 500 and 1000 mm from the thruster exit are represented. These measurements were made simultaneously for one and the same operation mode.

Table 2

L	**Probe position**	Ø2 мм **Flat probe**		Ø2 мм **Flat probe with guard ring**	
		Plasma Potential, V	**Electron Temperature, eV**	**Plasma Potential, V**	**Electron Temperature, eV**
500 mm	Center of plume	14,56	1,86	14,68	1,89
	Periphery of plume	12,33	1,74	12,6	1,81
1000 mm	Center of plume	12,11	1,62	12,31	1,72
	Periphery of plume	11,62	1,61	11,90	1,72

From Table 2 one can see that difference of the obtained values not exceeds 6% for electron temperature and 2,5% for plasma potential, that is significantly less than inaccuracy of measurements by electric probe methods. The difference between ion currents measured by both probes was less that sensitivity of used equipment.

Thus, for further plume study flat probes have been chosen. Being oriented differently to ion flux this probes allow to identify flux direction also, the later is not possible with cylindrical one. Flat probes have smaller dimensions and design simplicity in comparison with flat probes with guard ring.

Hardware Description

Cluster based on three D-55 hall thrusters with anode layer and one cathode-neutralizer has been chosen as studied multi-thruster assembly. External view of the cluster is shown in Fig. 3. D-55 thruster was developed to operate at power level up to 1500 W [4]. At the present moment D-55 is the most studied thruster available at TSNIIMASH. TSNIIMASH laboratory cathode-neutralizer providing electron current up to 10 A has been chosen.

Fig. 3. Three Cluster of three D-55 assembly.

Experimental Study Of The Thruster Operation With Different Cathode-To-Thruster Distance

Currently all Hall thrusters have own cathodes (one or two) allocated at close enough distance relatively to thruster exit. Potential size of a cluster operating with single cathode depends on ability of a thruster to operate with cathode located at some distance from the thruster exit. This distance also can determine number of thrusters, which can be integrated somehow around the cathode.

To study influence of the cathode-to-thruster distance on thruster performances and distribution of electric field in the exhaust plasma beam three laboratory LaB_6 cathodes were mounted at three distances from the thruster - 0, 300 and 500mm.

The thruster was operated with each of the cathodes and thruster performances and distribution of electric field across exhaust plasma beam was measured. Electric field distribution was measured with help of emissive probe installed to device providing movement of the probe across the plume.

General view of the hardware installed into TsNIIMash vacuum tank are given in Fig. 4.

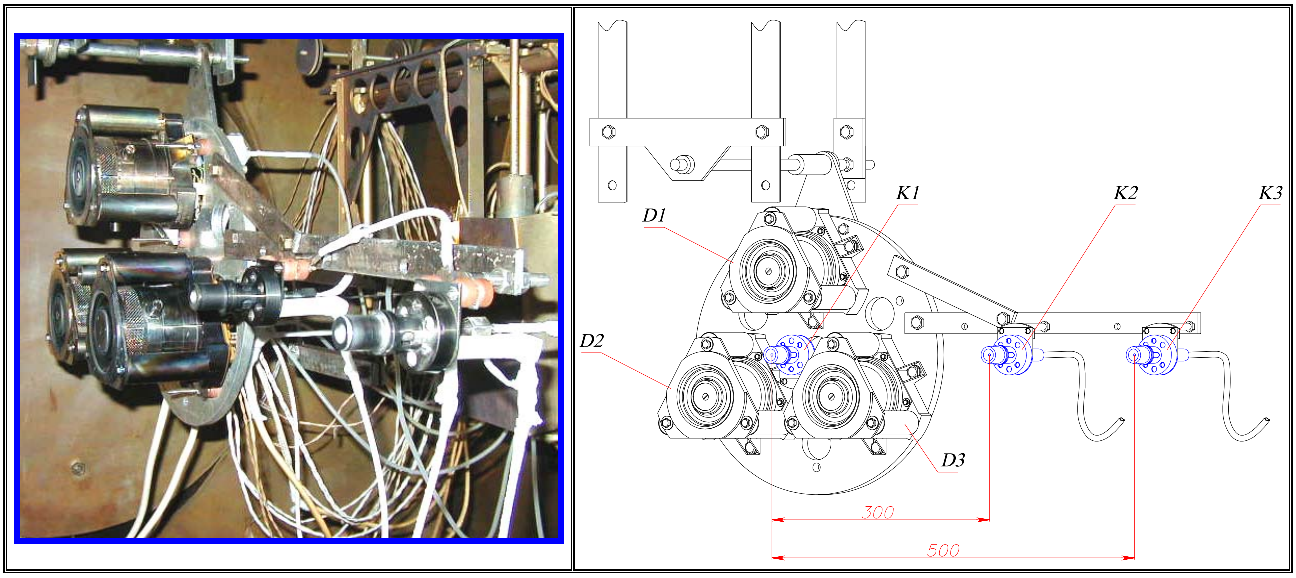


Fig. 4. General view of the D-55 thruster assembly with three cathodes.

The whole assembly is prepared for tests of simultaneous operation of 3 thrusters. The tests we discussing only one of them – the thruster marked as D1 - was used.

The following test procedure was used.

Cathode was ignited and maintained in heated condition by auxiliary discharge (15…20V, 3 A). Xenon flow through thruster anode was started, and magnetic coils of the thruster were powered by independent power supply. After that discharge voltage were applied to the thruster and gradually increased up to discharge ignition.

Ignition value was registered and then discharge voltage increased up to nominal value 300 V.

Thruster nominal operating regime was the following:

- Discharge voltage – 300 V,
- Discharge current – 3 A
- Tank pressure 1.5 x 10^{-4} mm Hg.

Thrust measurement were made by standard procedure with help of pendulum type thrust stand.

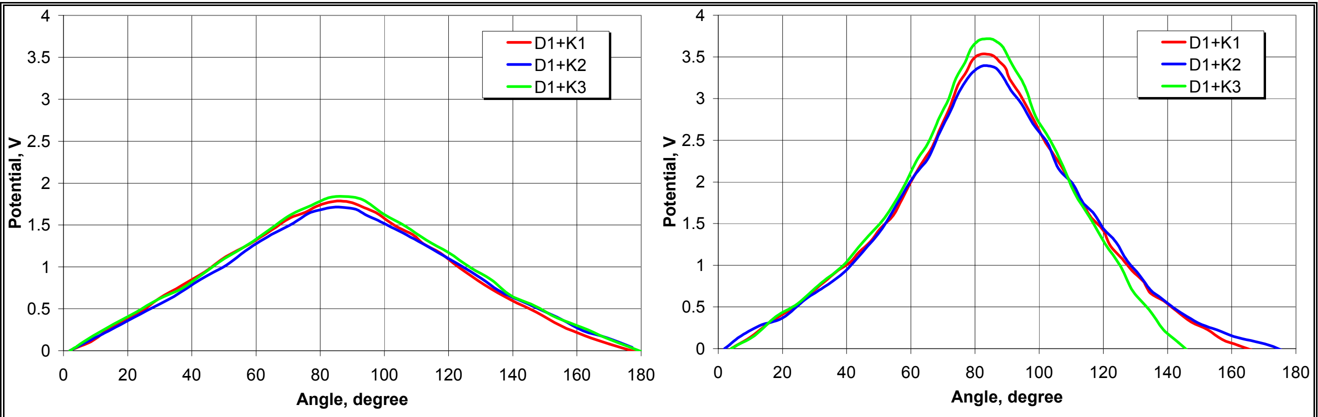
Start up voltages in all tested configurations were in a range 150…170 V, any definite relation between thruster-to-cathode distance and start up voltage was not identified.

Measured thrust at all tested thruster-to-cathode distance was 57 ± 1 mN (Table 3). The deviation of thrust value did not exceed precision of operating point maintenance and accuracy of thrust measurement equipment (±2%).

Table 3

Cathode	Discharge Voltage, V	Discharge Current, A	Thrust, mN	Floating Potential, V
K1	300,4	3,07	57,46	0
	300,2	3,07	57,95	16,8
K2	300,6	3,08	57,76	0
	300,4	3,06	56,78	17,2
K3	300,2	3,06	58,25	0
	300,0	3,05	56,29	18,7

Obtained distribution of plasma potential for all three cases are given on the Fig. 5.



Distance to the probe L=1000mm | **Distance to the probe L=500 mm**

Fig. 5. Normalized distribution of plasma potential across plasma beam.

Left side of curves corresponds to the side where the cathodes were located.

As one can see from obtained data, there is no essential influence of the cathode location of start up voltage, thrust value and measured parameters of the exhaust beam. This result confirms a possibility to use integrated multi thruster assemblies with single cathode. As for tested thruster, obtained data allows to consider assembly of even dozen of the thrusters mounted around single cathode at the distance up to 0.5 meters. As it follows from test data, value 0.5 m, limited in our experiment by the tank size, is not the boundary for effective thruster/cluster operation, and bigger distances have to studied. The late has a specific sense, because may provide additional flexibility to locate thrusters on a S/C.

Cluster Thrust Measurements

The following set of thruster operating modes have been chosen to verify additivity of the thrust values:

- Discharge voltage – 200, 300, 400 V,
- Discharge current – 3 A (in each thruster)

Before integration of the thrusters into cluster assembly individual thrust of each one was measured. Thrust value difference between the thrusters was less than 2% at all studied operating modes. After integration thruster into cluster each thruster was verified repeatedly. Integration into the cluster did not affect the thruster characteristics.

In Table 4 typical thrust measurements of each thruster in the cluster are presented.

Table 4

	Thruster D1		**Thruster D2**		**Thruster D3**	
Discharge Voltage	**Discharge Current**	**Thrust**	**Discharge Current**	**Thrust**	**Discharge Current**	**Thrust**
200 V	3.04 A	43.73 mN	3.02 A	43.54 mN	3.09 A	44.62 mN
300 V	3.03A	57.17 mN	3.03 A	56.09 mN	3.06 A	56.97 mN
400 V	2.98A	65.21 mN	2.98 A	64.92 mN	3.02 A	65.31 mN

From Table 4 one can see that difference in thrust values not exceed measuring accuracy of thrust stand unit (±2%) and all three thrusters are identical at all studied operating modes.

After thruster individual verification the thrust measuring of three simultaneously-operating thrusters have been accomplished. The results of measurements are presented in Table 5.

Table 5

	Thruster D1		D1+D2+D3			
Discharge Voltage	**Discharge Current**	**Calculated Triple Thrust**	**Discharge Current D1**	**Discharge Current D2**	**Discharge Current D3**	**Measured Total Thrust**
200 V	3.04 A	131.19 mN	3.12	3.17	3.21	135.81 mN
300 V	3.03A	171.51 mN	3.16	3.15	3.16	176.67 mN
400 V	2.98A	195.63 mN	3.08	3.10	3.12	201.48 mN

As one can see from Table 5 the resulting thrust value of cluster is summa of individual thrust of each thruster at all studied operating modes.

Cluster Discharge Current Oscillations

"Cross talk" between thrusters and amplification of electromagnetic oscillation may be expected for cluster operation. Possibility of this amplification and oscillation synchronization in thrusters integrated into cluster are shown in work [6]. This phenomenon have principle significance for further study of cluster electromagnetic compatibility based on individual thruster characteristic.

To detect this phenomenon study of cluster discharge current oscillation have been initiated at TSNIIMASH.

Three thrusters of cluster were powered by common power supply. With one hand this scheme is the most interesting from simplicity of cluster architecture point of view, and from another hand such scheme is the most predisposed to the same phase oscillation appearance in simultaneous operating thrusters.

As registration oscillation unit Industrial Scopemeter Fluke 123 was used.

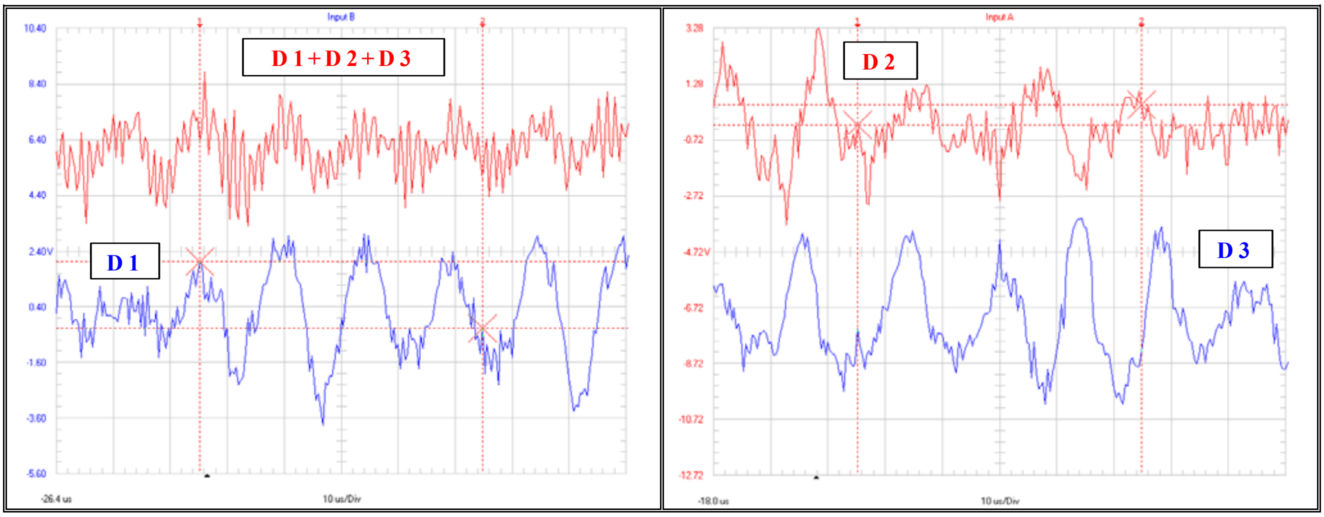


Fig. 6. Discharge Current Oscillations.

In Fig. 6 typical discharge current oscillations in D1, D2, D3 thrusters circuit and common circuit D1+D2+D3 at each thruster operating mode 200 V, 3 A are shown.

As may be seen from Fig. 6, in spite of nearness of oscillation frequencies in all three thrusters, the oscillation phases do not coincide and have arbitrary character in each thrusters. Simultaneously thruster starting did not lead to thruster oscillations synchronization. Measured amplitude of common current oscillations is of the same order as for one in individual thruster circuits.

Obviously, that obtained result has particular disposition. Systematical further study of oscillation processes, cluster electromagnetic noises and cluster stability in case of some thruster failure are required. The purpose of accomplished measurements was to verify existence of conditions with the absence of thruster oscillations synchronization. As evident from obtained results such conditions can be found.

Conclusion

Diagnostic equipment including probes and probe moving devices for near and far zone thruster plume measurements has been developed and manufactured.

Different probe designs have been experimentally tested, emissive probe and oriented flat probe have been selected for further plume study.

Influence of the "cathode to thruster" distance on thruster 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. Measured electric field distribution across thruster plume for all tested distances was one and the same.

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.

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.

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