"High-Power Hall Devices: Status and Current Challenges"

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Abstract

Consideration of the high power electric propulsion (EP) orbit transfer vehicles, interplanetary robotic and manned missions from one side and successful application of Hall thrusters onboard of numerous GEO satellites (Russian EXPRESS and YAMAL series), European scientific mission SMART-I on the other side stimulate interest to high power Hall devices, suitable for the future applications.

Current experience for the Hall flight thrusters is limited by 1-***kW***-class of propulsion systems. At the same time, engineering thrusters have demonstrated power level about 25 kW (Fakel Design Bureau, Russia) and almost 100 kW (NASA GRC) with using xenon as a propellant, 150 kW for bismuth thruster (TSNIIMASH, Russia). It is necessary to underline, that principal limits have not been identified for the further increasing of the thruster size and power. This makes the Hall devices at least very competitive for high power application as compared with other types of electric thrusters: MPD and ION thrusters.

For high power EP systems two typical operation modes may be considered, namely "*high specific impulse (Isp)*" and "*high thrust*" modes. Correspondingly challenges to develop Hall EP system are different for each one. For "high thrust" mode the development issues associate with increasing of propellant flow and thruster size. Discharge voltage to get "high thrust" regime with best power-to-thrust ratio should be 150…300 V, and it is inside of well studied operation range of Hall thrusters. For "high Isp" mode required discharge voltage in several times higher, than one for flight qualified Hall EP systems, while mass flow does not essentially exceed already achieved level.

The unique feature of Hall systems is an ability to operate in both potentially required modes: with high Isp up to 8000 sec and to provide high thrust up to several N. But "an ability to provide" demonstrated on experimental hardware does not guarantee technical characteristic of flight thruster yet. Problems and nearest activity of high power Hall system development are discussed in the paper.

The issues associated with development of High Power Hall devices may be structured as follows:

1. Scaling of the thruster:
- physical effect (discharge instability, lifetime changes and etc);
- engineering problems (operating temperatures, thermal expansion of the thruster part, etc);
- technological and manufacturing problems (available size of row materials, necessity to involve new technologies, etc);
- test facility limitations;
- lifetime tests and EP system reliability demonstration.

2. Integration with propulsion subsystems and primary S/C power source.

3. Influence of the EP thrusters on S/C subsystems (EMI, perturbation of radio signals and parameters of antennas, coating by condensable propellant and sputtered materials…)

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Depending on required operation mode - “high Isp” or “high thrust” – different issues will be critical for powerful Hall system development.

Most of scaling issues can be overcome based on implementation of cluster approach – using simultaneous operation of several relatively small thrusters. The level of integration between the thrusters can be varied from the fully integrated multi channel device with common magnetic system and common discharge power supply up to propulsion system with several independent thrusters and independent subsystems. The first approach allows to reduce mass and complexity of the propulsion system. The second one potentially has better reliability due to multiple redundancy of each component. The design challenge is proper balance between these two tendencies. Cluster approach has been proven for Hall systems consisting of *two*, *three* and *four* thrusters. Both types of Hall devices – SPT and TAL have been tested. The most extensive study has been made for *three-TAL* cluster at TsNIIMASH. Additivity of the thrust values has been demonstrated, at the same time, unlinear effects in the cluster discharge current oscillation and interference of the plumes have been observed.

Achieved level of individual thruster power – 10^2 kW – in combination with cluster approach make megawatt class Hall systems fully realistic. In turn, there are several specific effects, associated with cluster operation: interaction of the plumes, additivity of the thruster electromagnetic noise, etc. But these problems are similar to ones for single high power thrusters and should be considered anyway.

It may be said, that power level of 10^2 kW for the individual xenon thruster is close to the upper limit for “high thrust” mode, because only few facilities in the world can provide necessary pumping speed to test the thruster. Power level for high voltage thrusters (Isp =5000…7000 sec) and thruster using condensable propellants can be higher, but this option requires more study.

Integration of the EP thrusters with S/C primary electric system can affect choice of optimal Isp and corresponding discharge voltage of the Hall thrusters. Modern electronic power supplies convert 28 V or 110 V from bus power system to hundreds volts for thruster discharge voltage. Probably for megawatt class EP system another solution should be found to replace this complex electronic device. The direct drive approach looks like an obvious option, but the possibility to increase “bus” voltage up to kilovolt level is a subject to study, from the other hand new requirement for the thrusters have to be formulated. For example, ability of a thruster/EP system to operate with unstabilized voltage, acceptable level of oscillation and transient processes generating by the thruster in the primary power line and etc.

Among the problems, associated with interaction of the high power EP with S/C subsystem, to-day electromagnetic interference may be put on the first position due to lack of data (dependencies between thruster power, discharge voltage and level/spectrum of generated electromagnetic noise). For Hall thrusters potential possibility to reduce the noise or, at least, to select less noisy mode, has been identified. But available data base and even using experimental methods and apparatus are not sufficient to make proper choice of the thruster operation mode or cluster system design.

Based on analysis of modern status of high power Hall thrusters development the following direction may be considered for nearest research activity:

1. Development and study of High voltage/multi mode thrusters, both options - inert gases and condensable propellant - are subject of interest,
2. Study of the basic dependencies between thruster operation mode and erosion processes, level and spectrum of generating oscillations, accelerated plume angular distribution.

3. Identification and verification of scaling laws for cluster approach with emphasis on interaction of plumes and electromagnetic oscillations in the plume and discharge circuits.

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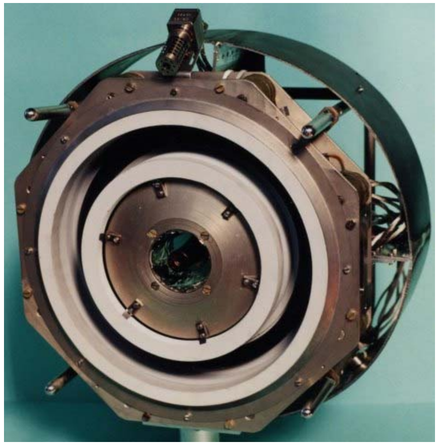
STATE-OF-ART AND FURTHER EVOLUTION OF HALL PROPULSION SYSTEMS

Flight qualified Hall thrusters - more that 20 years of successful application for orbit keeping	**Further evolution of Hall system**
SPT-70 *0.7* **kW,** *1600* **sec** **SPT-100** *1.35* **kW,** *1600* **sec** **PPS-1350** *1,35* **kW,** *1800* **sec** **TAL-WSF** *0.7…1.35* **kW,** *1600* **sec**	**Orbit keeping** *1-10* **kW class,** *2000…4000* **sec** **Orbit transfer** *10-100* **kW class,** *1000…2000* **sec** **Interplanetary** *100…1000* **kW class,** *3000…6000* **sec**

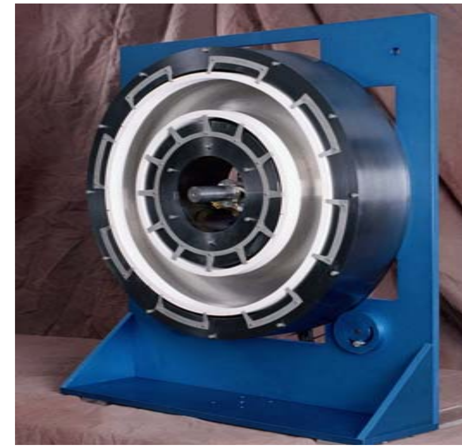
Two operation modes/thruster types are required for future EP systems: "High Isp" and "High Thrust"

Depend on operation mode different factors can determine selection of thruster size and power.

MOST POWERFUL EXISTING HALL THRUSTERS


M 290


TM-50

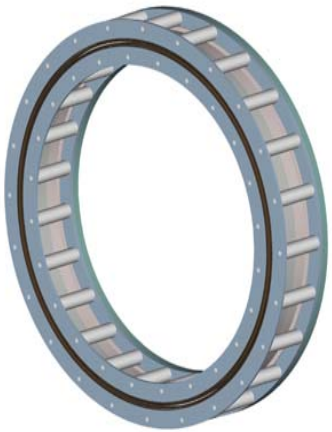

NASA-457M

	Status	Thruster type and design specific	Propellant	Achieved power, kW	Achieved Isp
SPT 290	Laboratory hardware	One stage stationary plasma thruster	Xenon	30	3200
TM-50	Laboratory hardware	Two stage anode layer thruster	Xenon	30	5500
NASA-457M	Laboratory hardware	One stage stationary plasma thruster	Xenon	96	3100
D 5 (D-160)	Laboratory hardware	Two stage anode layer thruster, Water cooled	Bismuth	150	8000

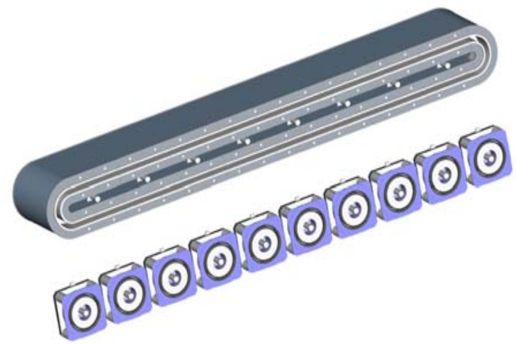
Principal limits preventing further increasing of the thruster size and power have not been identified during performance tests.

WAYS TO INCREASE THRUST AND SPECIFIC IMPULSE

Increase thrust means: to increase propellant mass flow = discharge current = thruster size



Monolithic thruster



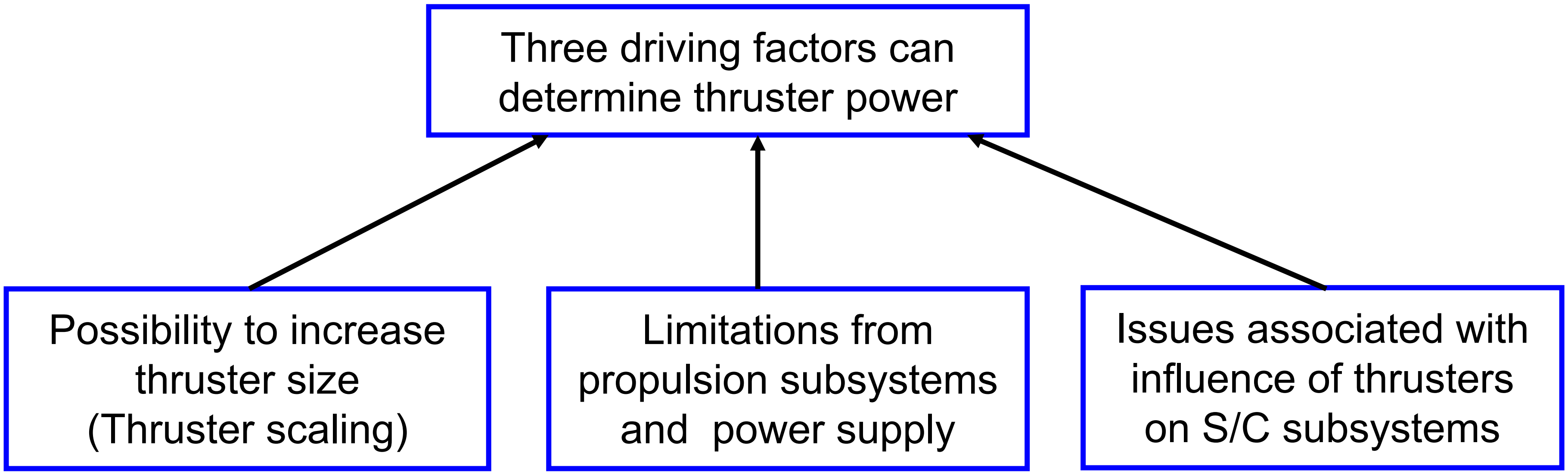
Race track and multi channel thruster

Big monolithic thruster may have circular or “race track” configuration, which, in turn, may be integrated from unified sections.
Multi channel thruster has advantages from reliability and scalability point of view as compared with any monolithic one.

Increase of Isp means **– increase of discharge voltage, it leads to usage of two stage thrusters,**
- usage propellants with smaller atomic weight (Kr, Ar, Cd, Na+K)

Combination of required thrust and Isp drives thruster size and design selection

SELECTION OF THRUSTER SIZE & POWER



SELECTION OF THRUSTER SIZE & POWER (CONTINUED)
Scaling of the thruster

Issue	•Positive •Neutral •Essential concern •Critical
Physical effect (discharge instability, lifetime changes and etc)	Not critical for existing thrusters Nonlinear erosion variation has been identified with increasing of Isp
Engineering problems (operating temperatures, thermal expansion of the thruster part, etc)	Not critical for existing thrusters operating at Isp 1000…3000 sec For "High Isp" operation mode available data not enough for reliable consideration
Technological and manufacturing problems (available size of row materials, necessity to involve new technologies, etc);	Have been overcome in the existing thrusters, but the experience is limited by laboratory hardware
Test facility limitations	Critical for gaseous propellants, NASA 457M thruster is close to upper limit of the pumping system of one of the best facility in the world Not essential for condensable propellants
Lifetime tests and reliability demonstration	Analysis methods have to be elaborated and implemented in practice to reduce expansive and long lifetime tests

Power level of thrusters operating on Xe in "High thrust" mode for most of facilities in the world is limited by level 25…50 kW, the similar size thruster can operate at 50..100 kW level at "High Isp" mode.

We can create bigger thruster until we can test it

SELECTION OF THRUSTER SIZE & POWER (CONTINUED)

Availability of power processing unit (PPU) with necessary power level can drive thruster power level

Type of discharge power supply	Comment
Semiconductor type	Sensitive to operation temperature, may has heat dissipation problems 10-kW class power units have been tested in laboratory, System study is necessary to determine reasonable upper level
High temperature plasma electronic	Can operate at high temperatures Available data are not enough for detailed analysis
Motor-generator	Are able to provide MW level of power Operation with thruster demonstrated on laboratory level, detailed specific needs to be studied
Direct drive from main S/C power system	Demonstrated on laboratory level, detailed specific needs to be studied

Specific of Hall thruster operation with different power sources needs to be studied

SELECTION OF THRUSTER SIZE & POWER (CONTINUED)

Influence of the powerful EP thrusters on S/C subsystems - to-day there are more questions than answers

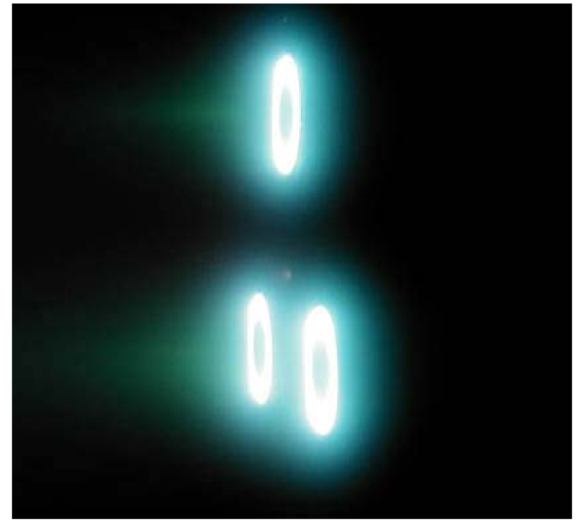
EMI – power of thruster electromagnetic noise will increase with thruster power increasing
Level of electromagnetic noise can drive selection of thruster operation mode and total power of EP system
Radio communication - plasma flux can cause perturbation of radio signals and parameters of antennas,
Additional limitation on shape and density of plasma cloud generating by EP system and relative location of thruster and radio equipment may be required
Coating of sensitive S/C surfaces is most critical for application of condensable propellants.
A possibility to protect S/C requires dedicated study
…..

Dedicated study is necessary to identify and to quantify potential limits on EP system and thruster power from S/C.

CLUSTER APPROACH

Most of scaling issues can be overcome based on implementation of cluster approach – using simultaneous operation of several relatively small thrusters.

Assembly of three thrusters



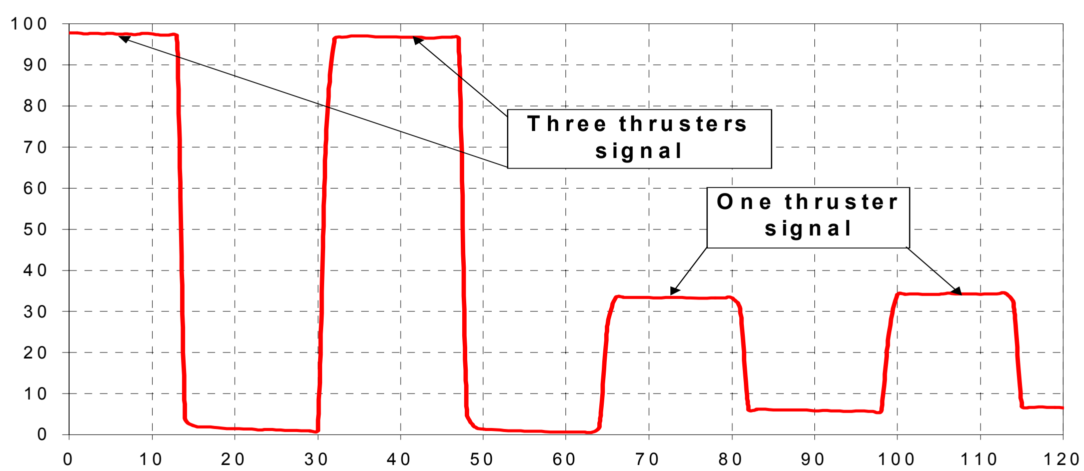
Operating three-TAL cluster

Integration between thrusters, power supplies and propellant feed lines can provide additional benefit in cluster system mass and reliability as compared with several independent propulsion systems.

Achieved level of individual thruster power – 10^2 kW – in combination with cluster approach make megawatt class Hall systems fully realistic.

CLUSTER STUDY

Need to be studied:	Obtained results:
Thrust additivity	Demonstrated
Sensitivity of the cluster operation to deviation of individual thruster parameters	Stable operation has been demonstrated with three TAL cluster tests under artificial disturbance of thrust operation regimes.
Interaction of the thruster plumes	Nonlinear effects have been identified
Specific of the discharge circuits oscillations	Amplitude of oscillations in common cluster discharge circuit are significantly less than one may be expected from individual thruster tests
Electromagnetic noise	No data



Cluster operation has own specific, which needs to be studied prior to implementation of this technique into practice.

DIRECTIONS OF FURTHER RESEARCH ACTIVITY

Single thruster

1. Development and study of High voltage/multi mode thrusters, both options - inert gases and condensable propellants - is subject of interest.
2. Study of the basic dependencies between thruster operation mode and erosion processes, level and spectrum of generating oscillations, accelerated plume angular distribution.

Cluster

3. Identification and verification of scaling laws for cluster approach with emphasis on <u>interaction of plumes</u> and <u>electromagnetic oscillations</u> in the plume and discharge circuits.