Experimental Investigation of Particles Fluxes to the Grid Surfaces inside Ion Optic Systems

IEPC-2015-219／ISTS-2015-b-219

Presented at Joint Conference of 30th International Symposium on Space Technology and Science
34th International Electric Propulsion Conference and 6th Nano-satellite Symposium,
Hyogo-Kobe, Japan
July 4 – 10, 2015

Maria Smirnova[1] and Sergey Khartov[2]
Moscow Avitation Institute National Research University (MAI), Moscow, Russia, 125993

and

Davar Feili [3]
University of Southampton, Southampton, UK, SO17 1BJ

Abstract: One of the main aims of this work was to find out if four electrode ion-optic systems could bring appreciable result to changing lifetime, thrust and specific impulse in accordance to the requirements specified for particular tasks in comparison with conventional three electrode systems. In addition, some estimations of efficiency and expediency of usage of four electrodes ion-optic systems for one of most prospective technologies for future applications – ion thrusters - will be presented. Benefits arising from this issue delivered as the conclusion.

Nomenclature

β	=	thruster mass efficiency
σ_F	=	grid transparency
F	=	thrust
I	=	specific impulse
I_{ac}	=	acceleration grid current, second grid in case of 3 grid system
$I_{ac/de}$	=	acceleration-deceleration grid current, third grid in case of 4 grid system
I_b	=	beam current
I_{ex}	=	extraction grid current, second grid in case of 4 grid system
I_{de}	=	deceleration grid current, third grid in case of 3 grid system and fourth grid in case of 4 grid system
I_{sc}	=	screen grid current, first grid for 3 and 4 grid system
j_{ion}	=	current dencity
m_{ion}	=	mass of the ion
q_{ion}	=	charge of the ion
S	=	grid surface area
U_{ac}	=	acceleration-deceleration grid voltage, second grid in case of 3 grid system
$U_{ac/de}$	=	acceleration-deceleration grid voltage, third grid in case of 4 grid system
U_{ex}	=	extraction grid voltage, second grid in case of 4 grid system
U_{de}	=	deceleration grid voltage, third grid in case of 3 grid system and fourth grid in case of 4 grid system

[1] PhD candidate, Department of Electric Propulsion and Space Power Plants; Senior Research Assistant, Astronautic Research Group, tdjemms@gmail.com.
[2] Professor, Department of Electric Propulsion and Space Power Plants, k208@mai.ru.
[3] Senior Lecturer, Astronautic Research Group, D.Feili@soton.ac.uk.

U_{sc} = screen grid voltage, first grid for 3 and 4 grid system
CEX = charge-exchage

I. Introduction

Future trends for space scientific, commercial and Earth observation research activities apply special demands on the spacecraft and the propulsion systems for it. Worldwide space programs and the near-earth objects infrastructure evolution analysis enable effective usage of electric propulsion for many of the delivered tasks. This work focuses on analysis of one of the best possibilities to increase the engines performances and lifetime without bringing too many changes in the thruster and system design – so called four-grid system.

In the frame of this activity, a genuine experimental method is introduced that gives insight to the flows of charged particles inside of ion optics system. The investigation of the currents on each surface of the grids in a multi-grid ion extraction/acceleration system gives valuable information about the phenomena in the extraction system. These phenomena are partly responsible for some thruster performance parameters like extracted and drain currents and can help to determine some other thruster performance parameters like the thruster mass efficiency (β). The current of the charge exchange ions on the accel (or extraction in case of four grid system) grid and back flows towards them together determine partly the erosion of the grid and therefore the lifetime of the thruster. The amount of the charge exchange is from the other side a function of the amount of neutral gas in the extraction system, which is defined by the mass efficiency of the thruster.

The paper presents the results of method used for seven apertures grid and compares the results of the three-grid and four-grid ion optics systems. The objectives of this study are to observe in frame of direct experiment particle fluxes while extracting the ion beam, to evaluate the phenomena inside of ion optic system, to discuss the difference between the tree- and four- electrodes extraction systems, and to determine possible advantages of using additional grid.

II. Ion Beam Extraction

One of the broadly used electric propulsion technologies is Gridded Ion Engine technology (GIE). In this type of thrusters processes of plasma generation and thrust production itself are divided and thus can be investigated separately. Plasma can be generated within a discharge chamber in different ways by using radio-frequency, microwave or direct current power, but no matter how the plasma production is, thrust is always generated by extraction of ions from plasma discharge and their acceleration with a help of special unit – Grid System, which for the similarity of process to optical systems got name Ion Optic System (IOS).

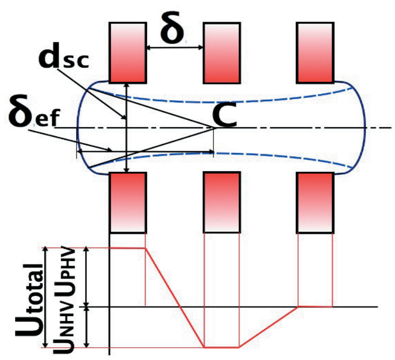

Figure 1. Schematic of the three-grid IOS aperture. *Figure shows typical voltage distribution inside of three-grid IOS. C – crossover point.*

IOS is the most important element of GIE responsible for its performances and lifetime and in most cases represented by two or three densely perforated plates – electrodes – with coaxial cylindrical apertures placed hexagonally to achieve highest transparency (σ_F) – relation of open area to the total surface (S) of the grid. Schematic of the conventional type single aperture is shown on Fig. 1. In order to accomplish the extraction and acceleration of the ions, first (screen) electrode is placed under highly positive potential, practically defining energy of the ions downstream the beam, second (acceleration or accel) electrode is placed otherwise under negative potential, preventing electrons back streaming, third (deceleration or decel) electrode (perforated plate or encircling ring) placed under spacecraft ground potential, that provides discontinuity conditions of the plasma, preventing the back flows of charged particles inside engine.

Extracted current density is limited from one side by discharge parameters and from other side by the space charge inside of IOS, which can be with some assumption defined by Child-Langmuir law[1]:

$$j_{ion} = \frac{4\varepsilon_0}{9}\frac{U_{total}^{3/2}}{\delta^2}\sqrt{\frac{2q_{ion}}{m_{ion}}} \quad (1)$$

where ε_0 – vacuum permittivity, U_{total} – potential drop between screen and accel electrodes, δ – distance between screen and accel grids, q_{ion} - ion charge, m_{ion} ion mass. This law could be also rewritten for assumption of a spherical diode, in which case distance between grids should be replaced by effective length from "meniscus" – line of ion extraction from plasma – to "crossover" – focal point of IOS. From one side, current density can be raised by increase of voltage drop between screen and accel grids or by reduction of distance between them; from other side, voltage drop is limited by electrical breakdown condition for set distance, which introduce natural limitation for the conventional IOS performances.

Thrust of the thruster is fully determined by current extracted and positive high voltage applied to the screen grid that in its turn define ion velocity and thus specific impulse of the engine. In a simplified way thrust and specific impulse could be written accordingly[1]:

$$F = j_{ion}\sigma_F S\sqrt{\frac{2m_{ion}}{q_{ion}}(U_{PHV} + Upl)} \quad (2)$$

$$I = \beta\sqrt{\frac{2q_{ion}}{m_{ion}}(U_{PHV} + Upl)} \quad (3)$$

where U_{PHV} – potential of the screen grid, U_{pl} – plasma potential.

In order to increase thrust it is necessary to increase current density or grid open area (transparency or size of the thruster) and/or positive high voltage applied. Grid open area cannot be influenced so easily due to technological issues and thermal problem occurring when grid diameter is growing. Increasing positive high voltage would mean perceptible raise of beam power that is mainly defined by voltage of screen grid and extracted current, therefore this way is not acceptable in many cases when power to the system is specified not to exceed certain numbers.

Lifetime of ion thrusters is also mainly limited by processes accompanying to the processes of extraction and acceleration in the IOS. It is direct bombardment of the accel grid by the extracted primary ions and CEX ions inside the IOS and in the neutralization region. Both processes lead to the sputtering of the accel grid material and necessity to increase its thickness.

Conventional extraction systems couple extraction and acceleration processes in one taking place between screen and accel grid. D. Fearn suggested to use another scheme well known in the region of thermonuclear fusion[1] that introduce fourth electrode in the screen-accel gap[2] decoupling processes of ion extraction and acceleration. Such method allows breaking the limitations and accelerating extracted ions to higher velocities, meaning gain higher numbers of thrust and specific impulse of engine. Numerical modelling of four grid systems was first done by Y. Nakayama and P.J. Willbur in the end of nineties of the last century[3] and after 2005 attracted intensive interest S. Gabriel group who made various numerical simulations and comparison of conventional IOS to double stage[4-7] In the frame of ESA activity group of D. Fearn together with Australian National University performed some theoretical and experimental works on the development of the four-grid dual stage thruster and investigation of its performances[8-12]. To sum up dual stage scheme suggested by D. Fearn allows forming well-focused ion beam with higher current densities and higher velocities compare to conventional three electrode systems. However, one of the aims of current study was to demonstrate other opportunities which four-grid system could introduce to GIE technology: flexibility of thruster performances optimisation and lowering power to thrust ration by redistributing potentials and/or optimising geometry of grid system.

III. Experimental Method and Instrumentation

Nowadays there are plenty of codes (both commercial and non-commercial) for numerical modeling of ion beam extraction from the plasma, but there is not many opportunities for experimental investigation on the processes taking place inside of IOS. However, input parameters for such measurements can't be determined very precise due to a lot of uncertainty in evaluation while using experimental methodic of plasma diagnostic, which themselves might influence measured parameters if they are intrusive (like Langmuir probes). Due to described reasons search for the experimental methods, which would be able to determine processes of beam extraction and acceleration more precise, was defined as necessity. This study introduce method of direct measurements of particle fluxes towards different grid surfaces.

A. Experimental Method

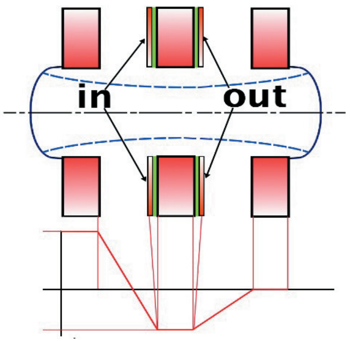

Figure 2. Schematic of IOS aperture with modified grid.

In order to measure particles fluxes separately on different surfaces of electrodes inside of IOS system was suggested and realized that schematically shown on Fig. 2. Grid or grids are being replaced by the package with the same geometry, but consisting from the sick middle electrode and two thin electrodes (“in” and “out” on Fig. 2) electrically isolated from the middle one by non-conductive layers (green lines on Fig. 2). During the operation potential of the grid should be applied to all three electrodes of a package when currents should be measured separately. There are few technological challenges associated with practical realization of the idea:

- In order to get clear separation of flows towards flat surfaces and inner edge of aperture, it’s required to decrease sicknesses of non-conductive isolators and “in”-, “out”- electrodes, which is itself complicated issue;
- Electrodes of IOS are being heated during thruster operation, in which case difference in sicknesses and/or thermal expansion coefficients between middle electrode and layers can generate stresses inside the system leading to geometrical changes and as a result – measurements of incorrect data;
- Attachment of all surfaces to each other and accuracy of production.

Figure 3 shows suggested in frame of current study realization. Grid, flows to which were to be investigate, was replaced by plate with glued on its surface Kapton layer with total sickness of 0.04mm and glued on top Aluminum layer with total sickness of 0.08mm. Apertures was produced on package as a whole, so no misalignment is assumed in frame of each package. Such setup had been preheated in order to check its resistance to the working condition. Electrical resistance between all conductive layers has been checked with Megohmmeter at regular intervals to be not less than 0.5MOhm while applying 2kV. Temperature problem was considered by using ion source with cold cathode that does not let grids to be heated to more than 70 C^{o} and thus notably change the geometry.

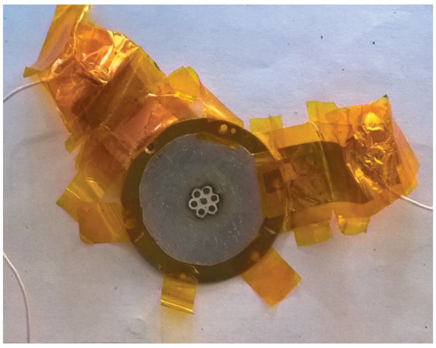

Figure 3. Grid with attached measurement layers.

B. Ion Source

A 5-cm Ion Source KLAN-53 with cold hollow cathode and exchangeable IOS is designed specially for this work. The IOS is easily adjustable for various ion optics geometries: thicknesses of electrodes, their number, apertures geometry and interspaces between grids.

Principal scheme of KLAN-53 is depicted on Fig. 4. It includes cold hollow cathode (CHC), main discharge chamber (DCh) and IOS. CHC consists from hollow body with cathode potential walls and cooling jacket; magnetic system; ignition and output electrodes; gas feeding system. DCh includes body, anode and magnetic system. IOS in original setup include screen and accel grids and decel electrode represented by encircling ring. Power Processing Unit (PPU) is the special one, produced with porpoise of Ion Source driving. PPU is shown on and it consists of following units: hollow cathode power unit (HCU), discharge power unit (DChU), beam power unit (BU), acceleration power unit (AU).

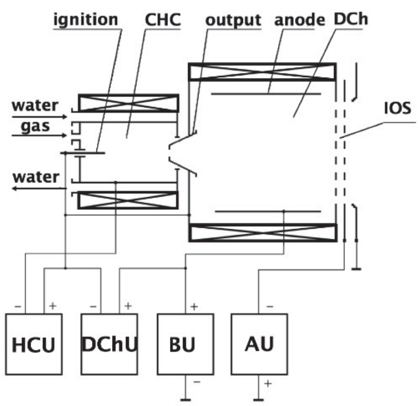

Figure 4. Schematic of KLAN-53.

The working principle of the ion source is as provided hereinbelow:

- When feeding the system with propellant, supplying the water to the cooling jacket and applying potential from HCU to ignition and output electrodes against neutralizer body, self-maintained glowing discharge is being ignited;
- When applying potential from DChU to anode against output electrode, majority of electrons from primary glowing discharge is being introduced inside of the main discharge chamber and provide main discharge ignition and maintaining the plasma;
- Extraction of ions from discharge and they acceleration is being provided as described in section II.

C. Vacuum conditions

Vacuum facility (Fig. 5) has been designed and assembled to be appropriate for the research and fast exchanges of experimental equipment inside, e.g. exchange of grid system or its parts. Working volume of the facility is 0.5 m^3. Pumping system is represented by oil-free double stage rough pump MU-603 with pumping speed of 10000 l/s for air, four turbo molecular pumps TMP-2203LM with total capacity of 8400 l/s for Xenon attached to the main volume through large gate valves, that fact let very fast venting of the main volume on the one hand and on the other hand fast changes of facility pumping speed by closing one, two or three valves simultaneously during the thruster operation. Maximum static pressure of the facility is about 2 10^{-7}mbar, dynamic - 1 10^{-5} for flow rates up to 5 sccm. Pumping time from the air condition when pumps are off is about 30 minutes, but normally there is no need to shut down the pumps, but only isolate them from main volume.

Figure 5. Vacuum facility and experimental setup.

D. Experimental Procedure and Measurements

In frame of current paper we would like to demonstrate first results obtained in the end of 2012 – beginning of 2013 by implementation of described experimental methodic to the one particular geometry set for three and four grid systems with 7 appertures. Geometry has been set with the aim to get similarity of neutral flow through the system and thus condition by which extraction and acceleration taking place in order to be able to demonstrate the differences between conventional and four-grid system if any. To do so, first, second grids and interspace between them was held the same. In case of three-grid system accel grid was produced as a package and it has been used "as is" in the four-grid system. Plasma parameters was fixed as well by giving same propellant flow and same potential-current inside of ion source discharges.

Current fluxes has been measured separately on second grid, playing role of accel in case of conventional system and extraction electrode in case of four-grid, and on third grid, playing role of accel-decel electrode depend on potential applied to the second grid in four-grid system case. Current has been measured directly by Mikroampervoltmetr M2042 having maximum error of ± 0.2% in every measurement range from 10 µA to 1000 µA and able to provide measurements in high voltage lines up to 2.5 kV.

Ion Source was operating with mass flow rate of Xenon 0.3 sccm; cold cathode parameters has been fixed on level 500 V to 0,1 A; main discharge parameters has been fixed on level 50 V to 0,2 A. In order to be able comparing measured parameters grids system geometries was chosen to be the same in the three grid and four grid system cases in order to be only additional fourth grid has been applied in some interspace after the third grid. As geometry and flow are the same we assume neutral flow to be very similar for both sets. Voltage on screen grid has been varied in range from 500 to 1500 V, voltage on extraction grid has been varied in range from -1000 to 1000 V. Results presented hereinafter was taken on the system with non-optimal geometry in order to see

IV. Results and Discussion

Figures 6a and 6b show an example of the measured currents from a four-grid system versus the varying extraction voltage by a constant beam energy (defined by voltage on the first grid of +1500V).

The values are normalized to the value of the extracted current in a three-grid system with the same +1500V on the screen grid and -200V on the accel grid. The amount of current in the four-grid system increases with the extraction voltage and as it could be expected, the curves of the four grid and three-grid system has an intersection close by 1700V of total potential drop. Figure 6b shows that the loss currents on different grid surfaces in four-grid systems compare to the level of losses in three-grid system of same geometry. The current on the second grid of the four-grid system is generally lower than the current on the second grid of the three grid-system, which would be a signature for a potential high life time of the thruster. As can be mentioned current from the plasma side tends to be higher for voltage drops exceeding 1700V, which should be sign of grooving direct drain current and thus divergence of the beam in the first gap. Same effect is partly responsible for rise of the current on the third grid of the four-grid system to come over according value of the three-grid system. However, drain currents were expected to be high due to not presented neutralization of the beam, which is extremely hard to reach on such small levels of

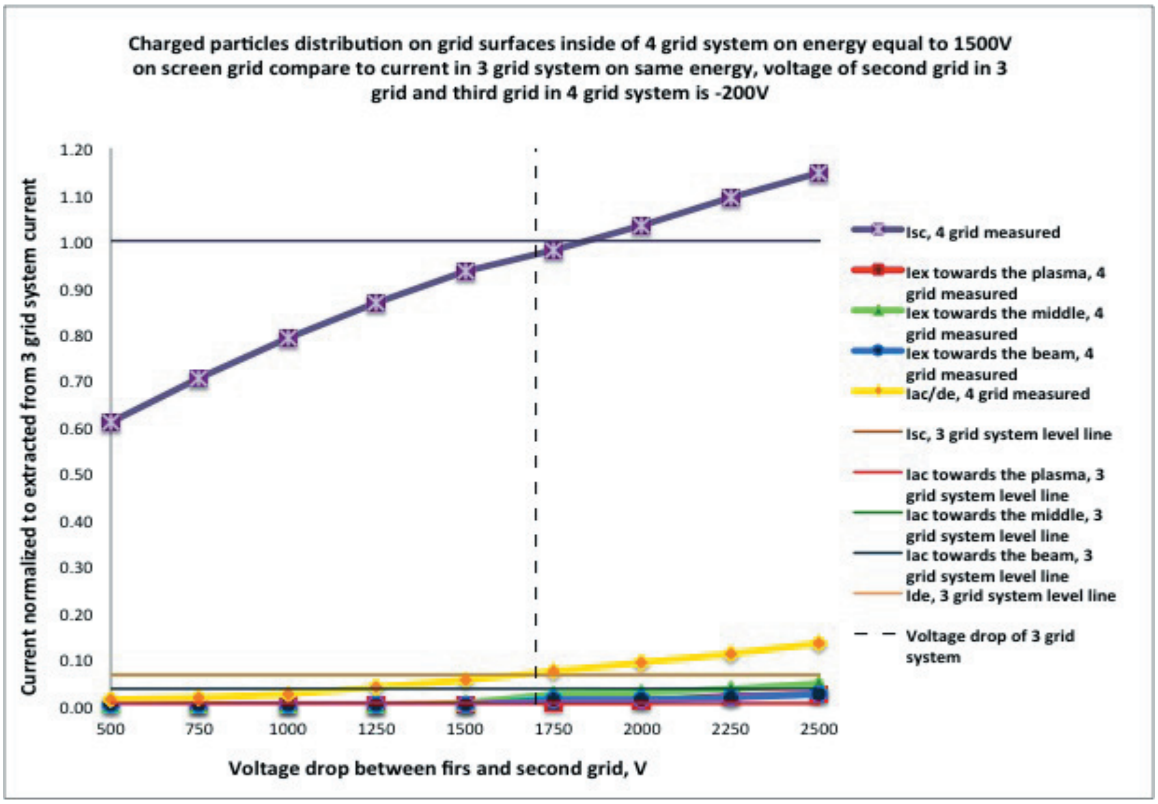

Figure 6a. **Example of the current measurements in the four-grid ion optic system.**

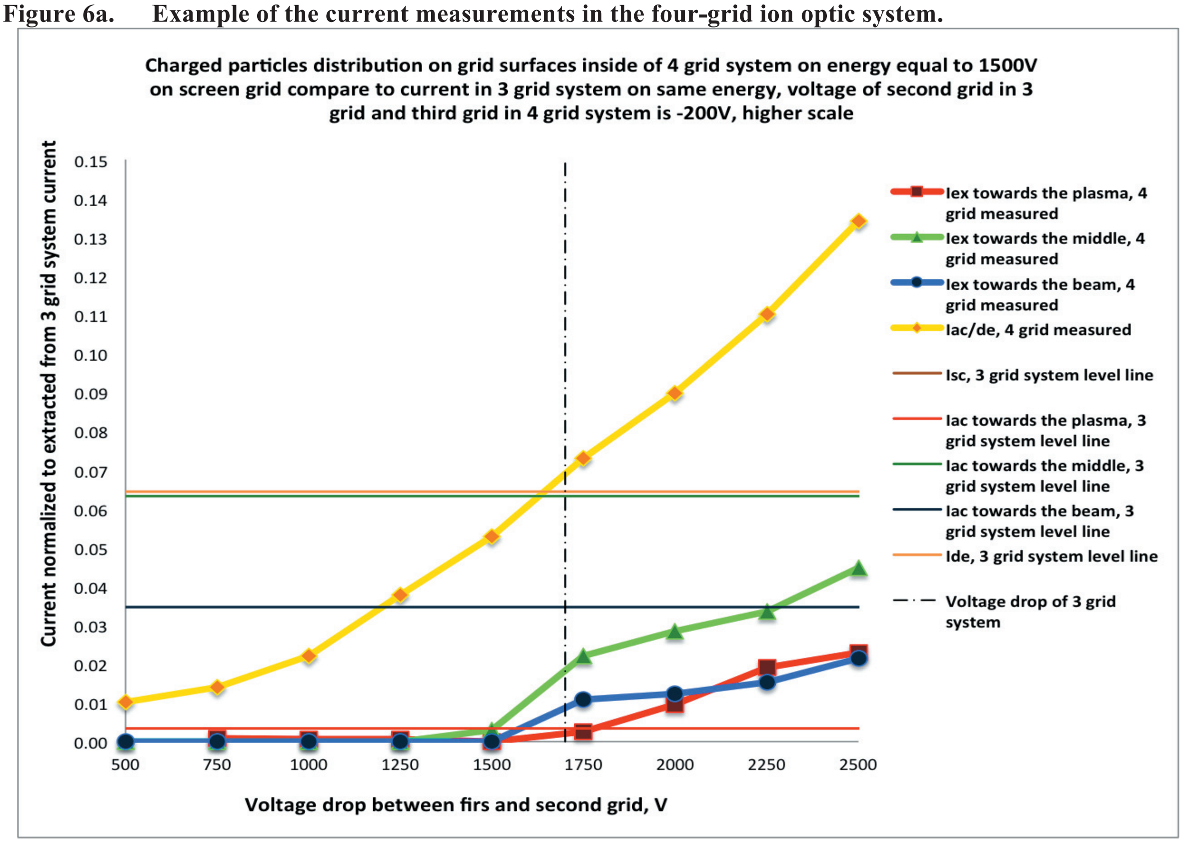

Figure 6b. **Example of the drain current measurements in the four-grid ion optic system.**

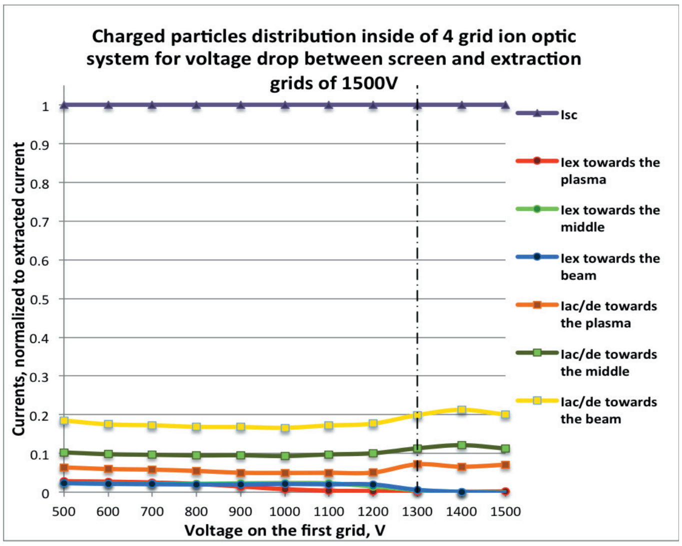

Figure 7. Measured current distribution inside of four-grid ion optic system depend on particle energies.

extracted currents. Effect of neutralization is described by the group of Prof Yoshinori Nakayama [13].

Figure 7 demonstrate changes in current fluxes inside of four-grid system while decreasing voltage on the first grid and thus energy of the beam on constant voltage drop between first – screen – and second – extraction – grids. All currents are normalized by extracted current in each measurement point. Dot-dash line demonstrate conditions of equipotentiality of the extraction and accelerartion/deceleration grids. As can be mentioned all line has pretty much linear trend except slight changes taking place on dot-dash marked region towards higher currents in case of second grid and lower currents in case of third grid. That fact clearly shows redistribution of CEX particles inside of IOS towards more negative potential grid.

V. Applications of four-grid system for mission tailored thruster performance

The modern mission analysis by the primes show a pretty strict requirement for the propulsion system of the coming generation of commercial and scientific missions Wollenhaupt et al. give the requirements on the propulsion system in terms of Isp and Thrust to Power Ratio. The "ideal" thruster for each role will be inside a triangle, which is opened by the minimum thrust to power ratio and the minimum specific impulse[14]. For orbit raising, Wollenhaupt gives the limits of thrust to power ratio and Isp as follow:

- The thrust to Power ratio between 30mN/KW and 70mN/KW,
- Isp between 1500Sec and 5000Sec.

These requirements normally predestinate Hall Effect Thrusters for such a mission. However, a gridded ion engine with such specifications would have the advantage of life time comparing to HETs, lower flow rates would give lower propellant mass and also influence of Ion Thrusters on the radio-electronic would be less compare to Hall Effect Thrusters which is important for telecommunication as well. If the same thruster could be used for the station keeping with high Isp, in a" double modus", it would have then clear advantages in comparison to HET thrusters.

Using a modeling method, which is already developed[15], it is possible to design an optimized GIT for each mission. It includes the thruster sizing, the beam voltage and the voltage drop between the first and second grid. These parameters determine also the ion beam optics geometry.

Figure 8 shows the Power to thrust ratio versus Isp for a "generic" 22cm gridded ion thruster, equipped with a fourth grid and using different beam voltages between 100V and 2100V. A 22cm GIT can then have a thrust of around 75mN by an Isp of 1600s and a power consumption of around 1600W. It makes it a candidate for SmallGeo class missions with around 6kW

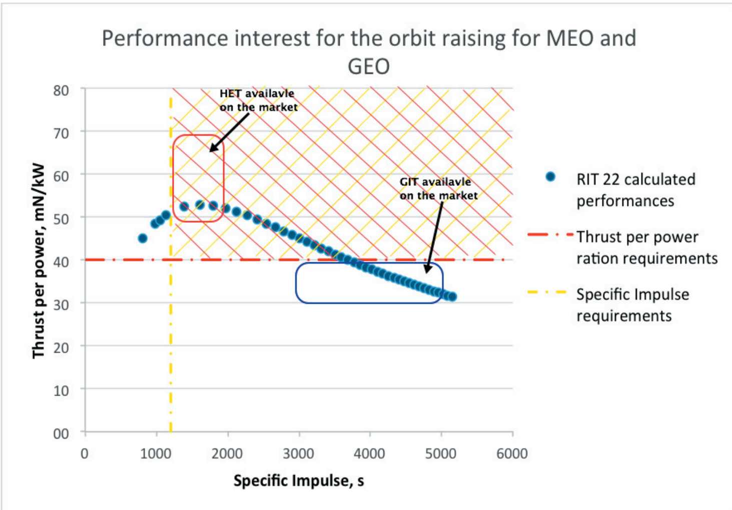

Figure 8. Schematic of the three-grid IOS aperture. *Figure shows typical voltage distribution inside of three-grid IOS. C – crossover point.*

power and 3200kg mass. The thruster can be then used in high Isp modus by around 5-6KW and the Isp of over 5300s and a thrust of 175mN with a very long life time.

However, a 22cm thruster does not have an optimized size for this mission. A larger thruster could reach higher power to thrust ratios, but the attractively of this method is the modifying of the already existing thruster to achieve different thruster performances, dependent on the mission and/or mission phases.

VI. Conclusion

This paper suggests a new method of modifying the existing GIT thrusters for different missions, requiring different power to thrust ratios, maximum thrusts, power consumptions and Isps. The method is simply adding a fourth grid to the existing three-grid ion optics system and adopting the beam and extraction voltages to the particular application of the propulsion system.

To understand the ability of utilizing four grid system for tailoring the performances of a thruster for an specific mission while accessing the design and work heritage of the thruster, it is important to compare the performance of a four-grid system with a three grid system and specially to compare the life time relevant phenomena in the grid systems. An experiment is designed to measure the phenomena taking part in the both grid systems. The measurements were aimed to gauge the current flow to different surfaces inside the ion optics systems.

These measurements show that the method of using four grid-system is able of providing different ion currents or thrusts by the same Isp. This can be used for example for thrusters with very high beam dynamics to achieve higher Isps in lower thrust region[16]. The heritage of these thrusters would be however untouched for the most part as the currents on lifetime defining parts are comparable with those in the three-grid system. However, a much vaster life time study including the modelling and experimental approaches are to be started.

References

[1]Grigoryan, V.G., *Acceleration Systems of Electrostatic Thrusters for Spacecrafts: Teaching aid,*, Moscow, MAI, 1984, 34p.

[2]Fearn, David G., "The application of gridded ion thrusters to high thrust, high specific impulse nuclear-electric missions." *55th International Astronautical Congress.* IAC-04-R.4/S.7.09, Vancouver, Canada, 2004.

[3]Nakayama, Y., Wilbur, Paul J., "Numerical Simulation of Ion Beam Optics for Many-grid Systems." *37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit,* AIAA 2001-3782, Salt Lake City, Utah, 2001. – 7p.

[4]Marques, R. I., Gabriel, S.B. "Dual Stage Four Grid (DS4G) Ion Engine for Very High Velocity Change Missions Velocity Change Missions." 31st International Electric Propulsion Conference. *IEPC 2009-157*, Ann Arbor, Michigan, USA, 2009.

[5]Coletti, M., Gabriel, S. B. "Design of a dual stage ion engine for the Hiper project." *46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit.* AIAA 2010-7113, Nashville, TN, 2010.

[6]Coletti, M., Marques, R. I., Gabriel, S. B. "Discharge Hollow Cathode Design for a 4-Gridded Ion Engine." *Aerospace Conference*, 2010 IEEE. 978-1-4244-3888-4/10/, 2010.

[7]Coletti, M., Gabriel, S. B. "Numerical Investigation of a Dual Stage Variable Isp Ion Engine." *32nd International Electric Propulsion Conference.* IEPC-2011-204, Wiesbaden, Germany, 2011.

[8]Walker, R.r, Izzo D., Fearn, D. "Missions to the Edge of the Solar System using a new advanced Dual-Stage Gridded Ion Thruster with very high Specific Impulse." *25th International Symposium on Space Technology and Science.* ISTS 2006-k-35, Kanazawa, Japan, 4-11 June.

[9]Barmanti, C., Izzo, D., Samaraee, T., Walker, R., Fearn, D. "Very High Delta-V Missions to the Edge of the Solar System and beyond enabled by the Dual-Stage 4-Grid Ion Thruster Concept." *Proceedings 57th International Astrodynamics Conference.* IAC-06-D.2.8.3, Valencia, Spain, 2006.

[10]Barmanti, C., Walker, R., Sutherland, O., Boswell, R., Charles, C., Fearn, D., Gonzalez Del Amo, J., Orlandi M. "The innovative Dual-Stage 4-Grid Ion Thruster Concept – Theory and Experimental Results." *Proceedings 57th International Astrodynamics Conference.* IAC-06-C4.4.7, Valencia, Spain, 2006.

[11]Walker, R., Bramanti, C., Sutherland, O., Boswell, R., Charles, C., Fearn, D., Gonzalez Del Amo, J., Frigot, P. E., Orlandi, M. "Initial Experiments on a Dual-Stage 4-Grid Ion Thruster for Very High Specific Impulse and Power." *42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit.* AIAA 2006-4669, Sacramento, California, 2006.

[12]Bramanti, C., Fearn, D. G. "The Design and Operation of Beam Diagnostics for the Dual Stage 4-Grid Ion Thruster." *30th International Electric Propulsion Conference.* IEPC-2007-050, Florence, Italy, 2007.

[13]Tanaka, F., Nakayama, Y. "Experimental Visualization of Ion Thruster Neutralization Phenomena". *The 33st International Electric Propulsion Conference,* IEPC-2013-107, Washington, USA October 6 – 10, 2013.

[14]Wollenhaupt, B. L., Luebberstedt, H., Schneider, A., Peukert, M. "Electric Propulsion Applications in the SmallGEO Product Line." *5th Russian-German Conference on Electric Propulsion,* Dresden, Germany, September 7-12, 2014.

[15]Feili, D., Ruiz, M., Ahedo, E., Merino, M., Smirnova, M., Dobkevicius, M. "Impulse Transfer Thruster for an Ion Beam Shepherd Mission." *30th International Symposium on Space Technology and Science 34th International Electric Propulsion Conference and 6th Nano-satellite Symposium,* IEPC-2015-382/ISTS-2015-b-382,Hyogo-Kobe, Japan, July 4 – 10, 2015.

[16] Feili, D., Di Cara, D.M., Massotti, L., Musso, F., Lotz, B., Smirnova, M., Dobkevicius, M., Collingwood, C. "Design,

Construction and Testing of a Radio Frequency Mini Ion Engine according to the Propulsion Requirements of the Next Generation Gravity Missions "NGGM".” *30th International Symposium on Space Technology and Science 34th International Electric Propulsion Conference and 6th Nano-satellite Symposium,* IEPC-2015-277/ISTS-2015-b-277,Hyogo-Kobe, Japan, July 4 – 10, 2015.