Preparation of Space Experiment with Electric Propulsion System Based on Radio-Frequency Ion Thruster aboard the International Space Station

IEPC-2019-238

Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019

Ruslan V. Akhmetzhanov[1], Aleksandr V. Bogatiy[2], Vladimir A. Obukhov[3], Andrey P. Plokhikh[4], Garri A. Popov[5] and Maria V. Cherkasova[6]
Research Institute of Applied Mechanics and Electrodynamics of Moscow Aviation Institute (RIAME MAI), 125080, Leningradskoye sh., 5, Moscow, Russia

Karina S. Zhilchenko[7] and Andrey A. Shemukhin[8]
Skobeltsyn Institute of Nuclear Physics of Moscow State University (SINP MSU), 1(2), Leninskie gory, GSP-1, Moscow 119991, Russia

and

Viktor P. Konoshenko[9] and Olga V. Lapshinova[10]
S.P. Korolev Rocket and Space Corporation Energia, 141070, 4A Lenin Street, Korolev, Moscow area, Russia

Abstract: At present, MAI is developing the based ion propulsion system (IPS) based on the radio-frequency ion thruster (RIT) to be used in space experiment on board the international space station (ISS). The main aim of the planned space experiment is the IPS testing and obtaining of experimental data on the peculiarities of its operation under space conditions. Another aim of such space experiment is to study the propagation of the charge-cloud compensated ion beam in the ionospheric plasma, taking into account the effect of the Earth's magnetic field.

Nomenclature

B	=	magnetic induction
B_0	=	induction of the earth's magnetic field in the ISS orbit altitude
e	=	elementary charge
N	=	normal to the ISS orbit plane
m_i	=	ion mass

[1] Deputy head of department, ahmetzhanov1991@mail.ru
[2] Head of department, boga-alex@ya.ru
[3] Deputy director, deutscher@mail.ru
[4] Deputy director, plokhikh2001@mail.ru
[5] Director, popov_garri@mail.ru
[6] Senior researcher of RIT laboratory, maria-post@mail.ru
[7] Designer of the 1st category
[8] Senior researcher
[9] Head of department
[10] Leading engineer, olga.lapshinova@rsce.ru

R_0	=	the Larmor radius
r_0	=	radius of the central trajectory of the ion with energy E_0
r_1	=	radius of the internal electrode of the spectrometer
r_2	=	radius of the external electrode of the spectrometer
T	=	the period of rotation of the ion
υ	=	total ion velocity
υ_0	=	initial total ion velocity at the moment of injection
υ_{inj}	=	velocity of injected ions
υ_{ISS}	=	ISS velocity
V_1	=	voltage on the internal electrode of the spectrometer
V_2	=	voltage on the external electrode of the spectrometer
W	=	initial energy loss
δ	=	the angle of approach of the ion to the ISS
φ	=	the angle between the ISS velocity vector and the ion velocity vector in a fixed coordinate system
ψ	=	injection angle
ω	=	cyclic frequency of rotation of the ion

I. Introduction

The Moscow Aviation Institute (MAI) conducts research and development of RIT of various power levels since 2010.[1] The low-power RIT was designed, developed and tested by MAI together with the JSC KBKhA in 2013 - 2015[2].

ISS provides great opportunities for testing various space units and systems and making scientific experiments using such equipment. At present, MAI is developing the RIT-based IPS for installation on board the ISS. The work is carried out using the results obtained during the development of low-power RIT.

The aims of the space experiment on board the ISS are:

– the IPS testing and obtaining of experimental data on the peculiarities of its operation under space conditions;

– study of the propagation of the charge-cloud compensated ion beam in the ionospheric plasma, taking into account the effect of the Earth’s magnetic field.

As follows from the theory[3], as well as from the results of active experiments in space [4], the polarization processes and induction of the Hall and Faraday EMF can occur in the ion beam at the initial phase during its interaction with the geomagnetic field and ionospheric plasma. The ionospheric plasma - ISS interaction leads to a step in potential between the ISS surface and ionosphere, the magnitude of which depends on the ionosphere state at the current time moment. Induction of the Hall and Faraday EMF in the beam can lead to additional potential drop in the beam and the ion energy drop at the thruster exit plane. According to the experimental design, the xenon ion beam with the energy of 2000±40 eV will be injected at certain angles to the ISS velocity and to the geomagnetic field vector in certain parts of the ISS trajectory. The calculation shows that at certain angles it is possible to detect ion beams spiraling with a Larmor radius using the electrostatic energy analyzer oriented in a certain way. The fact of detection should confirm the model representation of the mentioned physical processes in the ion beam interacting with the ionospheric plasma and geomagnetic field.

II. Composition and functions of the scientific equipment units

The scientific equipment comprising IPS, diagnostic equipment (DE) and the interface unit BSOP will be installed on board the ISS for conducting the space experiment. Before the experiment, it is planned to install the IPS and DE units at the universal workplaces on the SPM-1 module being a part of the Russian segment of the ISS, and BSOP unit is planned to be located inside the inhabited compartment.

A. Ion propulsion system

IPS, which is a part of the scientific equipment, is developed on the basis of low-power RIT[2]. The IPS comprises: ion thruster (IT), two cathodes-neutralizers (CN), gas distribution control unit (GDCU), gas storage and supply system (GSSS) and power processing unit (PPU). The general view of the IT platform is shown in figure 1. Figure 2 shows the IPS PPU with RF-generator. The IT provides ionization of the plasma-forming gas (xenon) in a radio-frequency inductive discharge, formation and electrostatic acceleration of the ion beam[2]. CN provides a starting pulsed injection of electrons in the gas discharge chamber for ignition of the RF discharge and the injection of electrons into the ion beam flowing out of the thruster for neutralization (compensation) of its space charge. GSSS and GDCU provide xenon storage, its predetermined flow rate, distribution and stable feed into the gas IT discharge chamber and CN. PPU provides power supply and control for the main IPS units, as well as interface with BSOP and onboard systems of the ISS. Main IPS performances are presented in Table 1.

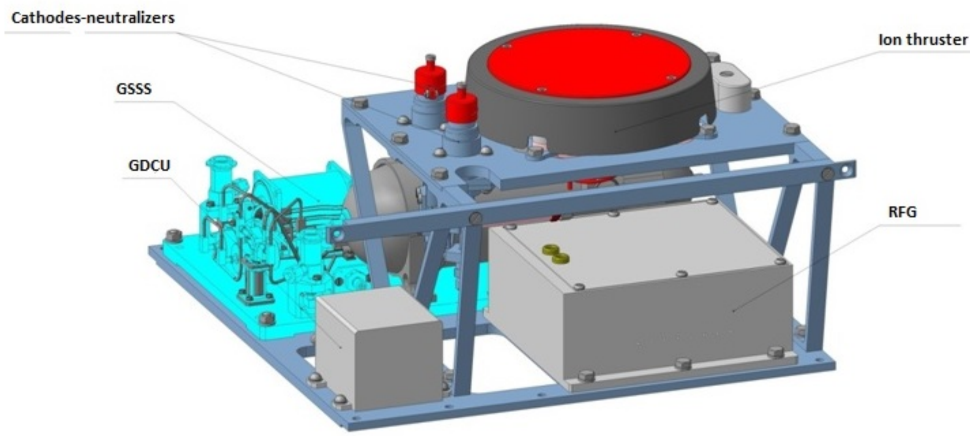

Figure 1. General view of the IT platform

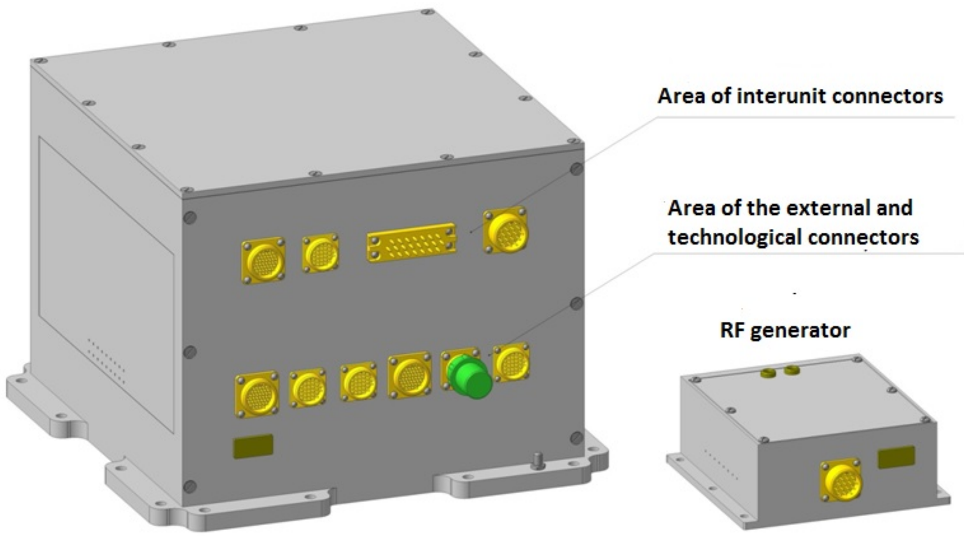

Figure 2. Power processing unit of IPS

Table 1. Main IPS performance

Performance	Value
Power consumption	400 W
Ion energy	2000 eV
Ion velocity	55 km/s
Plasma-forming gas	Xenon
Mass flow rate	0.15 – 0.25 mg/s

B. Diagnostic equipment

DE provides measurement of the parameters of injected ions at the intersection of the trajectory of their spiral motion with the Larmor radius with the ISS trajectory. DE comprises the spectrometer – energy analyzer S+Xe, which provides detection of xenon ions of the injected beam at their contact with ISS after motion in the Earth's ionosphere with the appropriate synchronization of the ISS flight and ion beam motion. For detection, the direction of beam injection and the orientation of the receiving aperture must be coordinated depending on the position of the ISS along its motion trajectory, taking into account the local value of the geomagnetic field vector. In addition, DE comprises a power supply unit intended to convert the onboard supply voltage into the operating voltage of the equipment. General view of DE is shown in figure 3.

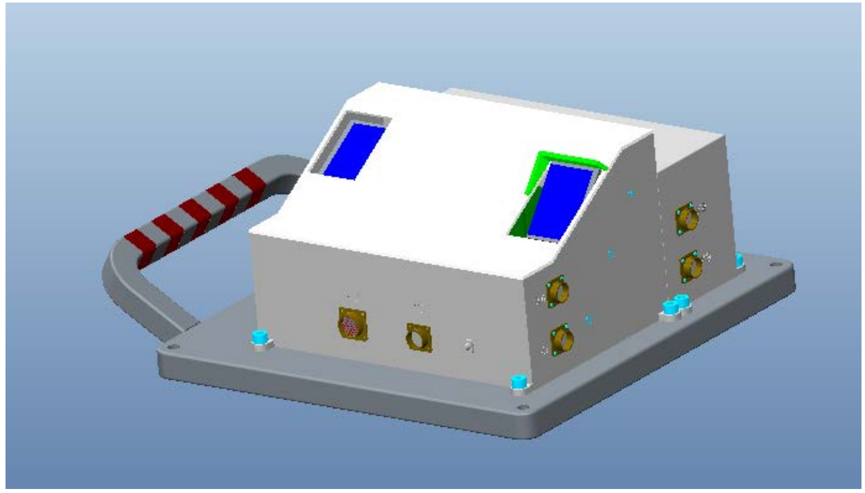

Figure 3. General view of DE

The spectrometer S+Xe is the primary component of DE; it comprises a spherical electrostatic energy analyzer (SEEA)[5], at the input of which the deflector is installed, and at the output – the secondary electron multiplier with electrometric amplifier. SEEA scheme is shown in figure 4. Photograph of the spectrometer S+Xe mock-up is shown in figure 5.

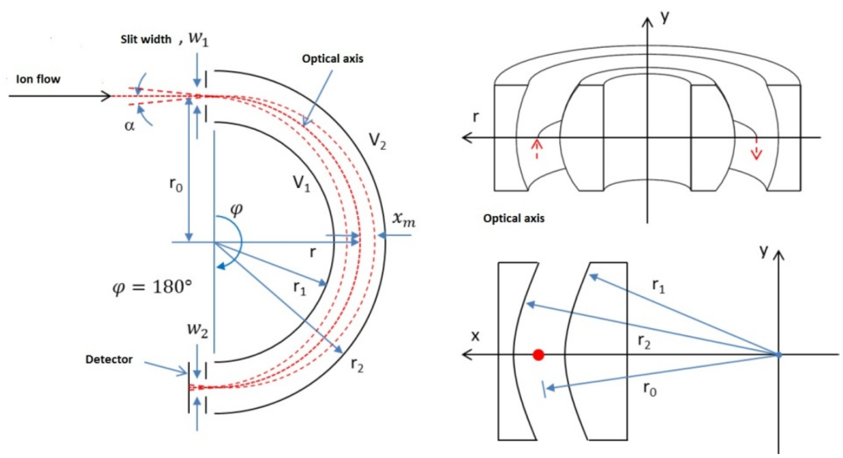

Figure 4. SEEA scheme

The following parameters are used in the developed SEEA: r_1=35 mm is the radius of the internal electrode, V_1 is the internal electrode voltage, r_0=40 mm is the radius of the central trajectory of the ion with energy E_0, r_2=45 mm is the radius of the external electrode, V_2 is the external electrode voltage. The rectangular input w_1 and output w_2 slits have a width of 1.2 mm along the axis X and 10 mm along the axis Y (Figure 4).

The voltages V_1 and V_2, of the electrodes are calculated as follows:

$$V_1 = 2\left(\frac{E_0}{q}\right)\left(1 - \frac{r_0}{r_1}\right) \quad (1)$$

$$V_2 = 2\left(\frac{E_0}{q}\right)\left(1 - \frac{r_0}{r_2}\right) \quad (2)$$

Here q is the elementary charge, E_0 is the average energy of the beam ions at the accelerating voltage of 2000 V.

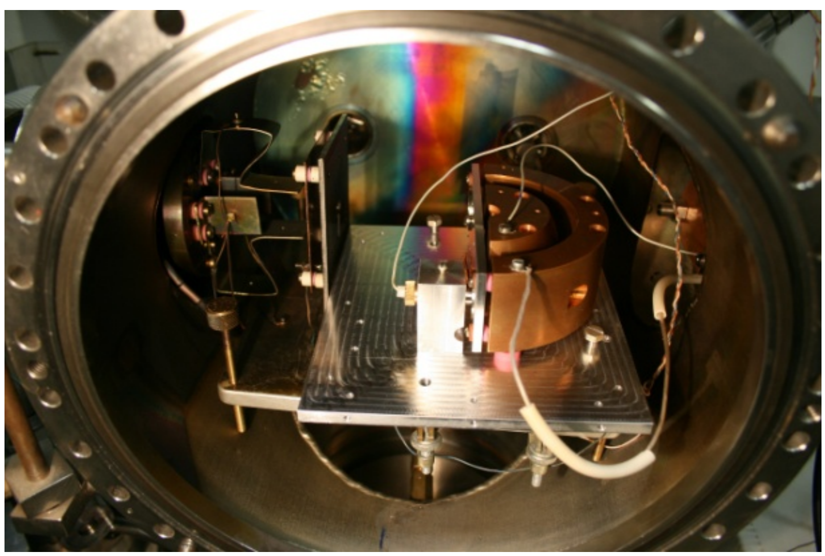

Figure 5. The layout of spectrometer S+Xe

The ion beam current that passed through the SEEA is amplified by the secondary electron multiplier VEU-6M shown in figure 6. For the selected SEEA sizes, the ion energy resolution is 60 eV, which exceeds the possible ion energy spread in the beam, estimated at +40 eV.

According to calculation, to register the signal of Xe+ ions with energies of 2000^{+60} eV, it is necessary to apply a potential of minus 571 V to the internal electrode, and that of plus 444 V to the external electrode. The calculation of the deviations of the ion trajectories due to the distribution in the angles of the entrance into SEEA showed that for the chosen geometric dimensions of SEEA the spread within ±5º is acceptable.

Figure 6. The secondary electron multiplier

C. Interface unit

BSOP is actually a specialized computer installed inside the inhabited compartment of ISS. BSOP is designed to transmit commands to the PPU of IPS, to receive diagnostic data via the digital interface RS-485, to control modes of DE operation, and to receive data from DE. BSOP provides intermediate storage of data from DE for subsequent transmission to the onboard computer system of the ISS through a local Ethernet network and further to the users of scientific information. A single-board computer of the Russian manufacturer LLC «FASTVEL GROUP» of CPC308 type with the Linux operating system of general use will be the BSOP central computer. The selected computer has all the necessary components for securing the BSOP functionality. BSOP is powered from the onboard ISS power bus, for which a secondary power supply unit based on the step-down voltage converters is integrated in it. The general view of the BSOP is shown in the figure 7.

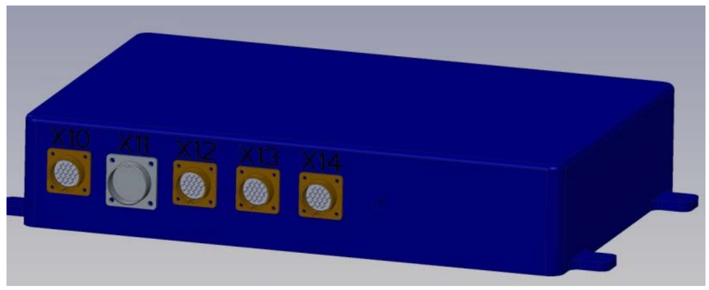

Figure 7. The general view of the BSOP

III. Performance of space experiment

A. Problem statement

One of the aims of the space experiment is to study features of propagation of the ion beam injected by RIT mounted on board the ISS. Application of ion thrusters on board spacecraft, sets, along with others, a problem of studying the motion of the flow of charged particles injected from the spacecraft in the Earth's magnetic field. The motion of charged particles in the magnetic field occurs under the influence of the Lorenz electromagnetic force, which causes a uniform rotation around a circle or a spiral, depending on the angle between the particle velocity and the direction of the magnetic field lines. This means that during their periodic rotation the particles can reach the structural elements of the spacecraft, causing negative influence on the surface of SC elements. In the framework of space experiment, the peculiarities of ion motion in the ionospheric plasma and the self environment of the ISS will be studied by the detection of xenon ions in the energy range of 2000-2060 eV downstream the Larmor circle by the onboard ion detector being a part of the DE unit of scientific equipment.

In order to make the detection of beam ions during the experiment possible, it is necessary to determine the conditions in the ion injection angles and the corresponding angles of approach to DE, taking into account the restrictions stipulated by the inadmissibility of ions contact with certain structural elements of the ISS (solar panels, foreign modules, etc.). The set of such requirements can be met at certain parts of the ISS trajectory and at certain moments of time. The aim of the computational analysis is to determine the time for the experimental sessions. For this purpose we developed a model of ions motion at different latitudes along the ISS trajectory, simulated the particle motion in the Earth's magnetic field, and determined the angles of ions injection and approach, with which it is possible to detect by DE the flows of ions injected by the ion source of ISS.

The transportation length of the ion beam in the specified energy range in the ionosphere under the influence of a geomagnetic field will be about 4 km. Due to the angular divergence of the injected beam (half-angle of ~15º) the ion flow density at the point of DE location will not exceed 10^9 ions/m^2 and the ion scatter angle during the detection may be about ±5º.

B. Ion circular motion in transverse magnetic field

Let us consider principal aspects of the possibility for the injected ion flow contact with DE mounted on board the ISS. The trajectory of ion motion in the form of a circle occurs under the condition of the ion injection perpendicular to the magnetic field lines. In this case, after injection the ion beam will birl in the Earth's magnetic field with a Larmor radius:

$$R_o = \frac{m_i \upsilon}{|e|B} \tag{3}$$

where: m_i is the ion mass; e is the elementary charge (the injected ions are singly charged); υ is the total ion velocity. Taking into account the ISS transport velocity at the moment of ion injection:

$$\vec{v} = \vec{v}_{inj} + \vec{v}_{\mathrm{ISS}} \tag{4}$$

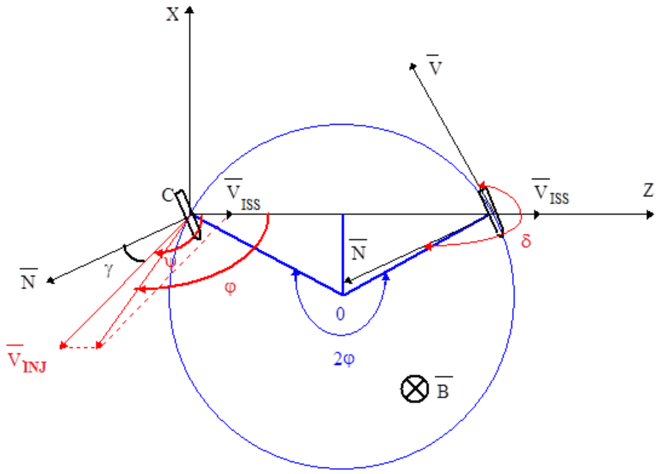

Figure 8. Ion trajectory before its contact with ISS

The ion rotational period is independent of the ion velocity and is defined as:

$$T = \frac{2\pi m_i}{|e|B} \tag{5}$$

Before entering the Larmor circle, the ions pass a transition trajectory section, characterized by deceleration of ions under the action of Hall emf (MHD-effect) and therefore by the initial loss of energy. Taking deceleration into account, the total velocity of ions moving around a circle is:

$$\upsilon^2 = \upsilon_0^2 - 2|e|\frac{W}{m_i} \tag{6}$$

where: υ_0 is the initial total ion velocity at the moment of injection.

The aim is to determine the injection angles ψ, with which the ISS will meet in its motion an ion beam. The ISS velocity υ_{ISS}=7340±30 m/s. The deceleration effect introduces uncertainty into the velocity of ions approaching the SEEA and is estimated to be υ_{inj}=54000±1000 m/s; and the energy analyzer is set to this value. With such relation of velocities, the injection angles with respect to the velocity vector of the ISS should be within 90º < ψ < 270º. Figure 8 shows the trajectory of the ion before its meeting with ISS. The following designations are accepted: ψ, φ are the angles between the ISS velocity vector and the ion velocity vector in the coordinate system, related to ISS, and in a fixed coordinate system. The ISS velocity is directed along the axis Z, vector $\vec{N}$ is perpendicular to the plane of the ISS orbit, and the magnetic field is perpendicular to the plane XOZ. The angle of ion approach to the ISS is designated as δ.

If we accept the average value of the magnetic field induction at the altitude of 400 km from the Earth's surface to be $B_0=2.6\cdot10^{-5}$ T, the ion rotation period is about T=0.216 s (cyclic frequency of rotation ω=29.3 rad/s).

It can be shown that for the angles of injection ψ the following transcendental equation is valid:

$$\sin\psi = \frac{\upsilon_{\mathrm{ISS}}}{\upsilon_{\mathrm{inj}}} \frac{1}{\sqrt{1-\frac{2|e|U}{m_i \upsilon_0^2}}} \left(\mathrm{arctg}\frac{\sin\psi}{\frac{\upsilon_{\mathrm{ISS}}}{V_{\mathrm{inj}}}+\cos\psi} + k\pi \right) \tag{7}$$

Here:

$$k = \begin{cases} n, \text{ if } \dfrac{\sin\psi}{\dfrac{\upsilon_{ISS}}{\upsilon_{inj}} + \cos\psi} \geq 0 \\ n+1, \text{ if } \dfrac{\sin\psi}{\dfrac{\upsilon_{ISS}}{\upsilon_{inj}} + \cos\psi} < 0 \end{cases}, \quad (8)$$

n=0, 1, 2, 3... corresponds to the passage by the beam of the corresponding number of integer Larmor circles after passing the arc. We should note that the beam divergence half-angle is approximately 15º. The calculations showed that the meeting of the beam with the ISS occurs within the first period during a narrow time interval from 0.1833 s till 0.1876 s at the angles between the ISS velocity and the ion velocity of 157.8º - 158.9º (for estimation, the ISS sizes were accepted to be 100×100×50 m). Accordingly, the angles of ion approach to the ISS are approximately the same due to the trajectory symmetry. Calculation by the considered model indicated the possibility of detecting the injected ion beam contact with ISS surface when the angles of the injector and DE detector are matched. The errors in the ISS attitude, the scattering of the ion beam by the atoms of the ionosphere and the underestimated influence of the mentioned MHD effect can prevent this.

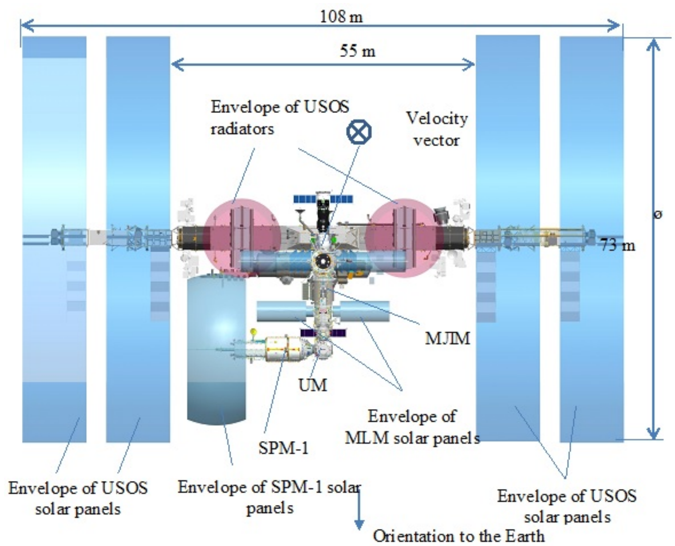

Figure 9. Expected location of the SPM-1 module within the ISS

In principle, the condition of injection plane orthogonally to the magnetic field could be met near the equator. In this case, it would be necessary to specify hard conditions for the orientation of the ISS. It is more realistic to consider the options with which the injection plane is not orthogonal and to determine conditions at different parts of the ISS trajectory under which the condition of ion detection by the onboard detector is satisfied. IPS and DE are located on the SPM-1 module (which is in the design stage). The planned location of SPM-1 as a part of the station is shown in figure 9. The SPM-1 axis is perpendicular to the ISS velocity vector (with a tolerance for the ISS orientation error). Possible location of scientific equipment is shown in figure 10.

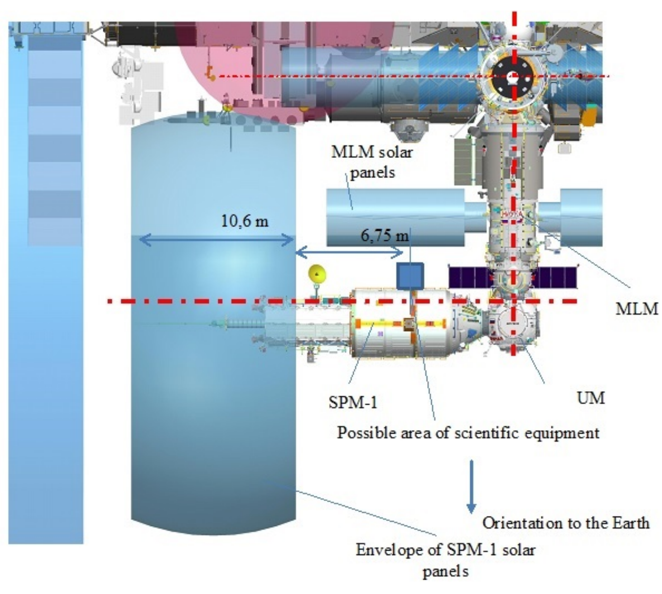

Figure 10. Location of scientific equipment

The arrangement of beam injection and detection must meet the condition of beam passage (or of the most part of it) up to DA without interaction with the ISS structural elements. In such a case, during every session there should be no interaction of envelopes of certain ISS systems marked in figures 9 and 10.

Calculations were carried out in which, with the known model of the Earth's magnetic field distribution, variants of sessions with ion detection were considered. The cross-sectional area of the ion flow and the ion current density were determined in so doing. While selecting the location and time for sessions, the condition of detection during the ion motion within the first spiral turn was taken into account to minimize ion scattering by elastic collisions with ionospheric atoms.

Table 2 shows the results of calculating the cross-sectional area of the ion flow, ion current density, the radius of the spiral turn, and injection angles in the SPM-1 coordinate system corresponding to four sections of the ISS trajectory defined by their latitude and longitude.

According to calculations, despite significant half-angle of the injected ion beam divergence, possible error in the ISS bearing of up to 10º, and fluctuation of the Earth's magnetic field, it is possible to detect ions injected from the ISS, and to do so by DE located on the ISS surface. The time for sessions with the ion beam detection will be selected in accordance with the calculated results.

Table 2. Results of ion flow parameters calculation

Latitude	Longitude	To the X-axis of SPM-1, º	To the Y-axis of SPM-1, º	To the Z-axis of SPM-1, º	Beam area near DE, km^2	Current density mA/m^2	Radius of spiral, m
Equator ±1º	92,5º	137	48	91,9	4	0,03	2074
		127	37	88	6,3	0,02	2115
19º	106,1º	52,4	141	81	2,3	0,05	2000
		41,9	131,7	86,6	3,1	0,04	2040
35º	123,2º	29,6	119,5	88,6	2,1	0,06	1715
		34,2	123,5	83,8	1,5	0,08	1712
51º	165,3º	25	113,7	97,1	4	0,03	1696

References

[1] H.W. Loeb, G.A. Popov, V.A. Obukhov. Laboratory of radio-frequency ion thrusters of the Moscow Aviation Institute - a new form of Russian-German cooperation // «Electronic journal «Trudy MAI», No. 60, 2012, 13 P. - in Russian

[2] N.N. Antropov, R.V. Akhmetzhanov, A.V. Bogatyy, R.A. Grishin, V.V. Kozhevnikov, A.P. Plokhikh, G.A. Popov, S.A. Khartov. Experimental Research of Radio-Frequency Ion Thruster. Thermal Engineering. Vol. 63, No. 13, 1 December 2016, Pages 957-963

[3] Korsun A.G., Tverdokhlebova E.M., Gabdullin F.F. Dynamics of artificial plasma formations in the vicinity of spacecraft. Collected book "Space model". Edited by Panasyuk K.I., Novikov L.S., p. 918-945. 2007 - in Russian

[4] Pushkin N.M., Mednikov B.A., Gomilka L.A., Lapshinova O.V., Mashkov A.S., Antropov N.N. Dynamics of electric fields in the near-surface region of spacecraft during plasma ejection from the Mir orbital station. Cosmic Research, Vol. 35, Iss. 4, July 1997, Pages 414-416

[5] Roy, D., and J.D. Carette. Electron Spectroscopy for Surface Analysis. Edited by H. Ibach. Berlin: Springer-Verlag, 1977