

Design of High-Power High-Specific Impulse RF-Ion Thruster

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Abstract: One possible image of powerful (35 kW) RF-ion thruster (RF IT) with specific impulse of 7000 s is examined in the paper. The work is supported by the RF Government Grant for supporting the scientific researches performed under the leadership of Russian distinguished scientists. The work carried out in the frames of the Grant makes it possible to integrate German experience (Giessen University) in developing the RF-ion thruster (including the large-size one^{1,2}) and Russian experience (MAI) in the field of the electric propulsion³. RF-ion thruster of 46.5 cm in diameter (RF IT-450) is examined as a basic conception. Structural features and design parameters are obtained by scaling performances of smaller RF-ion thrusters developed in the Giessen University as well as physical approaches, obtained during their investigation and development. To secure the thruster lifetime of 50 000 hours, the RF IT should operate under 60% of maximal power, which would be possible to obtain at the module with given size. The thruster's structure consists of the gas-discharge chamber made of alumina, and equipped by high-voltage unit for xenon feeding, inductor and RF generator with operating frequency of 650 kHz. Two-electrode ion extraction system contains approximately 8000 apertures for forming the beamlets with perveance acceptable for focusing. The electrodes' geometry is optimized for operating under 4500 V at the screen electrode. The emitting area is 59% of the screen electrode area. The calculations shows that at the consumed RF power of 2.1 kW and Xe flow rate 10.9 mg/s the ion beam current will be about 7 A, and the thrust 760 mN. Without considering power losses and gas flow rate in the neutralizer, the total efficiency of such RF IT is 81%. The thruster operation mode can be enhanced up to a power of 57 kW and a thrust of 1.3 N. The lifetime under the nominal mode of operation is estimated about 56 500 hours.

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I. Introduction

Since the early days of space flight, enthusiastic people dreamed about long-term or even permanent space stations on our Moon and on Mars. To realize this idea, many tons of cosmonaut equipment must be taken before by cargo ships to the envisaged landing field: a crew habitat, a shelter against meteorite swarms or solar flares, excursion vehicles, a plant to produce oxygen and water, a power station, etc.

A decision factor for choosing the best suited transportation system is doubtlessly the payload ratio of the cargo vehicles, which determines finally the overall costs of the complete mission, too. Naturally, costs could also be saved significantly, if the cargo-ships could be repeatedly used rather than only once, i.e. if cargo-shuttles might fly back and forth between an Earth orbit and a low orbit around the celestial target body.

Since K.E. Tsiolkovsky it is well known that a high specific impulse of the propulsion units saves – at a given velocity increment – propellant mass and enables hereby high payload capacities.

It is also obvious that electric propulsion engines of the ion type are well suited to generate the required high exhaust velocities. As the power source, solar arrays compete with nuclear reactor sources. The latter seem to be superior above a certain power level of some 100 kW because of their compactness and the power-to-mass ratio. Provided that a nuclear-fission energy plant and powerful electric thrusters, generating high specific impulses, would be available, the NEP drive would be best suited for a cargo-shuttle to a manned Lunar or Mars base.

II. NEP Cargo-Shuttle

A. Power Plant

In mid-2010, the President of the Russian Federation gave the green light for the development of a 1MWe nuclear reactor space power plant⁴. The 28 tons plant will be equipped with a fast reactor of highly enriched U-235, a Brayton-cycle turboelectric converter and a flat radiator. Fig.1 shows the spaceship.

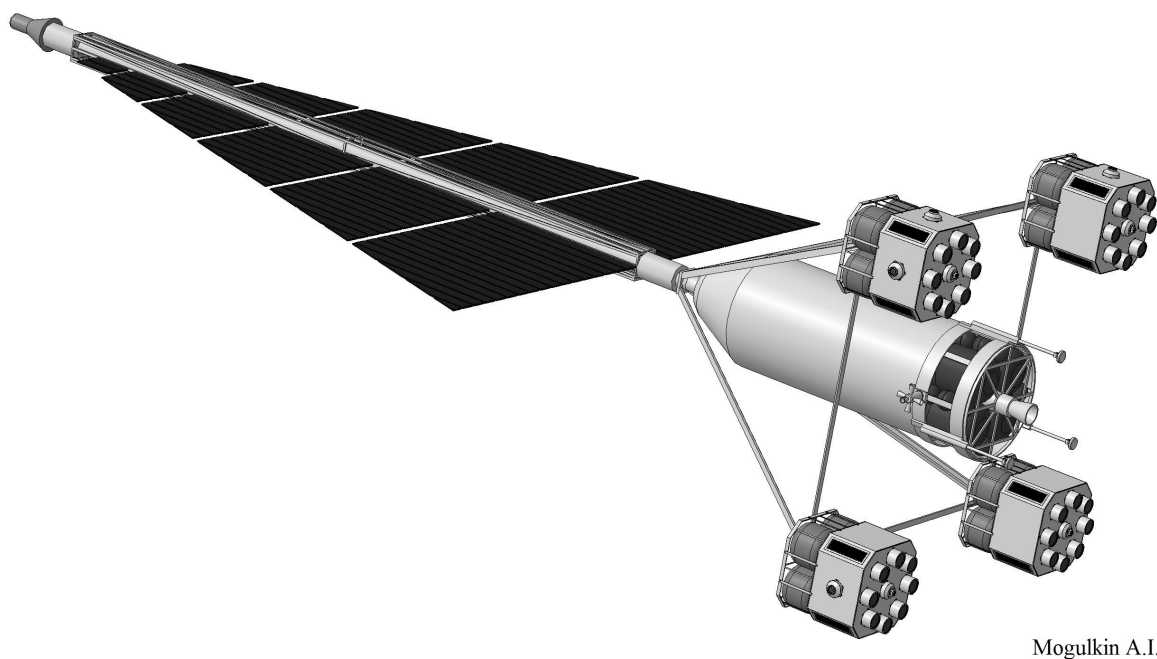
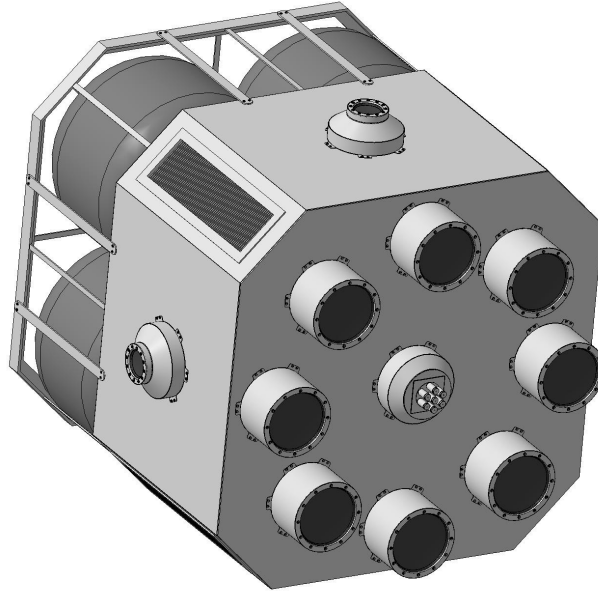


Figure 1. Artist's drawing of the planned Russian NEP cargo ferry



Mogulkin A.I.

Figure 2. Artist's drawing of a cluster of EP

B. EP-Array

At the stern of the spaceship, four clusters of EP-engines will be arranged at the edges of a square. Each cluster will consist of six running thrusters (at 35 kW each), two standby engines and another two thrusters for attitude control (see Fig. 2).

Thus, 40 EP-thrusters will be needed in total; the propulsive power requirement will amount to $P_{tot}=840$ kW.

Besides the named power input of the individual motors, two other specifications must be fulfilled by the engines:

- The specific impulse should be $I_{sp}=7000$ s. For that, the nuclear power plant will deliver a main bus voltage of +4.5 kV.
- The lifetime of each thruster should be 50 000 hours, i.e. 5.7 yrs of continuous operation. This rather hard specification is needed for the multi round trip philosophy.

With these specifications, with an overall power efficiency (including divergence and PPU losses) of 88.6% (see below), one calculates the total thrust of the EP-cluster

$$F_{tot} = 2\eta_e\eta_d\eta_{PPU} \frac{P_{tot}}{I_{sp}g_0} \quad (1)$$

to be 21.7 N. The total impulse of 24 operating thrusters during their lifetime amounts to $3.9 \cdot 10^9$ Ns.

We emphasize that the application of 35 kW electric thruster is not limited to large NEP spaceships. As a single motor or in twin arrangement and in combination with solar arrays, they may be used also for ambitious robotic missions.

C. Thruster Selection

As the NEP-spaceship put much power at the propulsion unit's disposal, whereas the propellant mass, needed for a multiple round trip, must be kept within reasonable limit, a specific impulse of 7000 s must be generated that never

had been practically realized with plasma-based EP-thrusters. Obviously, the high I_{sp} data require a high-voltage grid system, eliminating the gridless plasma thrusters from the outset.

When comparing the gridded ion thruster types with dc-discharge (“Kaufman engines”) with the electrodeless RF-discharge models, the latter show some advantages:

- As no discharge electrodes or magnets exist, no related power supply and control units must be biased on a high voltage of 4.5 kV. The RF-generator and the induction coil can be kept on ground potential because the isolating discharge vessel separates them from the high-voltage discharge plasma.
- No sputtered electrode material (e.g. baffle flakes) may cause destructive arcs between the high-voltage grids.
- Therefore, no reliability and safety reasons urge the operator to run the RF-engine in a strongly throttled mode.
- As the RF-discharge is not sensitive against oxygen impurities, the Xenon propellant must not be of high purity. This saves much money taking into account the large required mass (2 tons per engine and 50 000 hrs).

III. RF Ion Thruster “RF IT-450”

A. Design Principle

Based on the mentioned advantages and in view of the named specifications, a 465 mm ionizer-diam RF Ion Thruster has been chosen for R&D procedure.

Fig. 3 shows a cross-section true to scale of the scheduled “RF IT – 450” engine (western name: “RIT-45”). Its basic design corresponds to other RF ion thrusters, and scaling laws have been applied (see below).

The engine consists of two main components, namely the ionizer and the grid system that are clamped together⁵. Note that the individual engines have no own neutralizer, but each of the four clusters will be equipped with a common ion beam neutralizing system (Fig. 2).

The ionizing system consists of the propellant injector (GI) and the discharge vessel with the RF-coil (RFC) surrounding it. The propellant injector is inserted tightly in a tube of the ionizer vessel placed on the axis. It includes a high-voltage isolator and several narrow channels to inject Xenon jets radial into the discharge plasma.

The ionizer vessel is made of Alumina and has a special bended shape to withstand the mechanical load at launch and to minimize the inner wall surface, i.e. the wall recombination losses of the plasma ions. Following an empirical scaling law⁶, the discharge vessel has an optimal length of 12.5 cm.

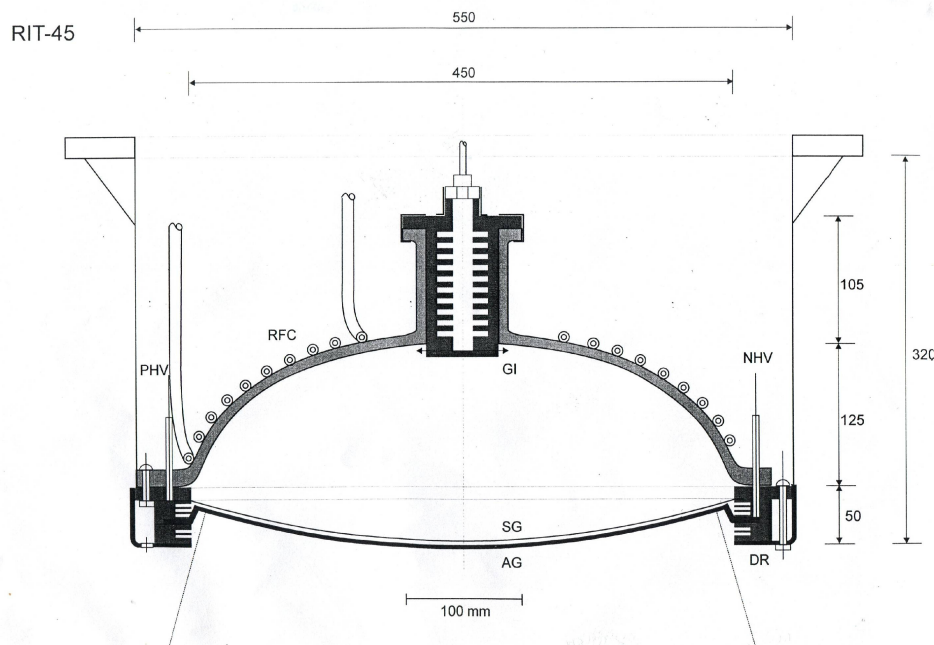


Figure 3. Schematic cross-section of the 465 mm ion thruster RF IT – 450 (without a neutralizer)

The RF-coil is made of a copper tube, has 9 turns, and is tightly wound around the ionizer. It represents the induction coil of the RF power stage of a 650 kHz generator. Note that this optimum frequency results from scaling laws of RF-engines, too.

The grid system consists of an 0.6 mm thin screen grid (SG) (or “emission grid”) made of Invar, a 2.7 mm thick accel grid (AG) of graphite, and a 2.7 mm thick decel ring (DR) of stainless steel which serves as outer wrap of the entire accelerator system, too. Macor is used for grids isolating. The grid system is dished outward with a radius of about 85 cm.

The grid system has been designed and optimized for 4.5 kV of positive high voltage (PHV) and about 500 V of negative high voltage (NHV). It may be operated between +3.5 kV (border of a beamlet focusing) and +4.7 kV (breakdown limit). For designing the grid geometry, the related scaling law derived from Langmuir-Schottky-Child’s law⁷:

$$\beta = m_i^{-1/4} \cdot j_i^{-1/2} \cdot U_{ex}^{3/4} \quad (2)$$

Hereby β means the scaling factor by which all geometrical data of the standard RIT grid system (of RIT-2.5, RIT-10 EVO, RIT-15, and RIT-22) must be multiplied (m_i = ion mass, j_i = ion current density at the screen grid, U_{ex} = extraction voltage, i.e. PHV+NHV); with $\beta=2.08$, we get the grid data of Table 1, that have been proved by ion trajectory computation.

Table 1. Grid data of a 45 cm RF engine running at 7000 s of specific impulse

Number of beamlets	8029
Open area ratio of the 1 st grid, %	59.4
1 st grid: hole diams, mm	4.0
thickness, mm	0.55
Interspace, mm	1.6
Acceleration distance, mm	3.8
2 nd grid: hole diams, mm	2.5-2.8
thickness, mm	2.5
Decel. ring: diam, mm	450
thickness, mm	2.7

The thruster case has a diameter of 56.5 cm and a length of 32 cm (see Fig. 3). The mass has been estimated for about 32.5 kg.

B. Scheduled Power and Thrusting Data

In view of the envisaged power consumption of 35 kW of each thruster (including PPU), we chose as the beam current $J_b=7.00$ A. Then, the beam power (for 4.5 kV of PHV plus the plasma potential of about $V_p=25$ V) would be 31.68 kW. Counting with an open area of the 1st grid of 1009 cm², we get as the extracted ion current density $j_i=6.94$ mA/cm². This means that the engine will be throttled for lifetime reasons (see below) and that it may be thrust-enhanced by a factor of 1.68 to run with 11.66 mA/cm² (like RIT-22 at 175 mN of thrust).

Using the known thrust formula of ion engine with a divergence efficiency $\eta_d=0.98$ and typical fraction of 1% doubly charged ions ($q_i=1.01$ e), we write:

$$F = \eta_d \cdot J_b \cdot \sqrt{\frac{2m_i}{q_i} (U_+ + V_p)} \quad (3)$$

and get a nominal thrust of 757.5 mN per engine; 24 thrusters will generate a total of 18.2 N.

To be on the safe side, we count very conventionally with ion production cost of 300 eV per ion, i.e. with an RF-power requirement of 2.1 kW.

We take for granted to keep the accel grid drain current within 1% of the beam current, that means $J_{acc} \leq 70$ mA. With $U=0.5$ kV, the NHV generator will consume ≤ 35 W. Together with the PHV generator output of 7A·4.5kV=31.5 kW and the RF-generator power, the total engine’s consumption (without the neutralizer system) will amount to 33.64 kW.

With the beam power of 31.68 kW (see above), we calculate the engine's power efficiency for $\eta_e=94.2\%$. Furthermore, we may assess the PPU-efficiency with 96%. This rather high value seems to be realistic because the bus of the nuclear power plant delivers already the required positive high voltage of 4.5 kV.

Thus the PPU - power input of a single thruster and of the 24 engines cluster will amount to 35.04 kW and 841 kW, respectively. Naturally, the power requirement of the separate neutralizer system must be added.

C. Scheduled Propellant Data

The Xenon gas flow needed for 7.00 A of beam current amounts to 97.55 sccm or 9.526 mg/s, respectively. The discharge pressure of the 46.5cm RF-thruster has been estimated by using the RIT scaling laws. With an uncertainty of some percents, we assume $p_d=1.25 \cdot 10^{-4}$ Torr.

With the calculated gas flow conductivity of the two-grid system $L=1.464 \cdot 10^6$ cm³/s, we get the neutral gas losses $p_d L=14.45$ sccm or 1.410 mg/s, respectively. Omitting again the separate neutralizer system, the total Xenon consumption at nominal thrusting amounts to 112.0 sccm or 10.94 mg/s, respectively.

Thus, the propellant mass efficiency follows to $\eta_m=87.1\%$.

With the known formula of specific impulse

$$I_{sp} = \frac{\eta_d \eta_m}{g_0} \cdot \sqrt{\frac{2q_i}{m_i} (U_+ + V_p)} \quad (4)$$

we obtain 7131 s as the I_{sp} value without neutralizer. Total throughput of a 46.5-cm RF engine during 50,000 hrs of operation will be 1.97 tons, and 24 running thrusters would consume (without neutralizers) 47.3 tons.

D. Physical Verification of the Assessments

The scheduled data, mentioned above, derived from basic equations and the application of scaling laws gained by testing Giessen's and Astrium's RIT engines with 2.5 cm, 4 cm, 10 cm, 15 cm, 22 cm, 26 cm, and 35 cm of ionizer diameter. Nevertheless it seems necessary to prove these data by investigating the physical processes inherent in the 46.5 cm engine.

Firstly, we will check the assumed ion production costs of 300 eV per extracted ion (see above).

In general, the RF-power is needed to compensate three power loss mechanisms:

- On one hand, the discharge must be sustained, i.e. the propellant must be permanently ionized. Together with other inelastic collisions like light excitation we may count the "volume losses" roughly with 25 eV per generated ion. Comparing the 1009 cm² of open grid area with the entire surface of the ionizer of 4175 cm², a total ion current of 29.8 A must be produced, requiring about 745 W.
- In the equilibrium, this total current will disappear from the plasma, partly by extraction and beam formation, partly by recombinations at the ionizer wall. An ambipolar current is driven to the wall by a plasma potential V_p which amounts to 26.4 V at 5 eV of electron temperature (being typical for RF-thrusters). Thus, we get "wall losses" of about 787 W.
- Finally, we have to add non-plasma losses (dielectric losses in the alumina vessel, eddy current losses in the first grid and the thruster case, Ohm's losses in the RF-coil, etc.). These losses are hard to quantify, but the envisaged 2100 W of RF-generator power (less two plasma loss mechanisms), i.e. 568 W seems to be more than sufficient to cover all non-plasma losses.

Our second check refers to the named 6.94 mA/cm² of ion current density. It is limited on one hand by the plasma yield, i.e. the plasma density n and the electron temperature T_e , and on the other hand by Langmuir-Schottky-Child's law, i.e. by the extraction voltage U_{ex} and the acceleration length d .

- Based on the processes in a transition sheath in front of the screen grid, in which the electron density drops from n_e to zero, the current density under plasma limitation is:

$$j_i = 0.6065 \cdot q_i \cdot n_e \sqrt{\frac{kT_e}{m_i}} \quad (5)$$

For $j_i=6.94$ mA/cm² and $kT_e=5$ eV, a plasma density of $n_e=3.67 \cdot 10^{11}$ /cm³ would be necessary. Plasma diagnostics with Langmuir probes done in different RF-thruster discharges showed that such a plasma density is quite practicable.

- The charge limited current density for $U_{ex}=5.0$ kV and $d=3.8$ mm (see Table 1) amounts to 11.7 mA/cm² which is well beyond the required 6.94 mA/cm².

E. Lifetime Assessment

It is known that the lifetime of an RF ion engine is only limited by the sputtering of the accel grid by those charge-exchanged ions which reach and impact this electrode. The end of lifetime happens when spaces between beamlet borings break. The rate of charge exchange processes $Xe^+ + Xe$ per time dt and volume element dV between and behind the grids is given by (q_{cex} = charge exchange cross section):

$$\frac{d^2 N_{cex}}{dt dV} = q_{cex} n_0 n_i v_i \quad (6)$$

With $j_i = q_i n_i v_i$ and γ as the part of the total charge exchange ion current $J_{cex} = q_i \cdot dN_{cex}/dt$ which reaches the accel electrode, we get the accelerator drain current:

$$J_{acc} = \gamma \int q_{cex} n_0 j_i dV \quad (7)$$

We calculate now the sputtered electrode mass per time dM/dt (Y = sputter rate $Xe^+ \rightarrow C$, m_c = mass of carbon atom):

$$dM / dt = Y m_c \cdot J_{acc} / q_i = Y m_c \cdot \gamma \int q_{cex} n_0 (j_i / q_i) \cdot dV \quad (8)$$

As the lifetime T is proportional to $M/(dM/dt)$, we may write:

$$T \sim (Y \cdot q_{cex} \cdot n_0 \cdot j_i)^{-1} \quad (9)$$

We will estimate the lifetime of the 46.5 cm RF-engine by using the known lifetime of the RIT-22 thruster (23,000 hours) together with the ratios of the four factors in Eq. 9. Note that the scaling factor β of Eq. 2 enters not the lifetime equation because both the grid mass M and the volume of CEX-processes depend on β^7 . Also the factor γ will not change when scaling.

- The sputter rate Y at 5 kV of extraction voltage is 1.58 times higher than at the 2.315 kV of RIT-22⁸.
- The charge exchange cross section q_{cex} within the RF IT-450 grid system is 1.12 times smaller than for RIT-22⁹.
- The discharge pressure p_d as well as the neutral gas density n_0 in the RF IT-450 grid system is 2.05 times lower than in the smaller engine RIT-22.
- The 46.5 cm thruster runs at $j=6.94$ mA/cm² in the throttled mode, i.e. the beam density is 1.69 times lower than in the case of RIT-22 when generating 175 mN.

Thus, we obtain a (theoretical) lifetime of the RF IT-450 thruster:

$$T = 23,000 \text{ hrs} \cdot (1/1.58) \cdot 1.12 \cdot 2.05 \cdot 1.69 = 56,500 \text{ hrs.}$$

F. Reinforced Operation

We mentioned already that the RF IT-450 has been designed to operate in a throttled mode in order to guarantee the demanded long lifetime. However, it may be interesting to ask for enlarged thrusting data, too. When reinforcing by a factor of 1.69, we get the maximum beam current density at the entrance of the grid system of 11.7 mA/cm², which could be extracted with 5.0 kV of voltage (see chapter III D).

In this case, the beam current would be 11.83 A; the thrust would reach the 1.28 N level, and the power and propellant requirements would be 56.9 kW and 18.5 mg/s, respectively.

Due to n_0 and j_i in Eq. 9, however, the lifetime would decrease to 33,400 hrs, the propellant throughput would be 2.22 tons.

IV. Conclusion

A 46.5 cm diam RF ion thruster has been designed for ambitious robotic missions and for cargo ferries to Lunar and Mars stations when using clustering technique and a 1 MW-nuclear reactor plant for power supply.

The three specifications – 35 kW of power input, 7000 s of specific impulse, and a lifetime of 50,000 hrs – are feasible and can be realized.

With 7.0 A of beam current and 4.5 kV of beam voltage, a thrust of 0.76 N is well within reach. Taking a lifetime penalty into account, the maximum thrust would exceed the 1 N level.

Table 2 collates some important performance data.

Table 2. Important performance data of the scheduled 46.5 cm RF ion thruster at nominal (throttled operation)

Thruster diameter	56.5 cm
Thruster length	32 cm
Thruster mass	23.5 kg
RF-generator power	2.1 kW
Discharge pressure	$1.25 \cdot 10^{-4}$ Torr
Positive high voltage	4.5 W
Negative high voltage	0.5 W
Ion beam current	7.0 A
Ion current density	6.94 mA/cm ²
Thruster power input ^{*)}	33.64 kW
PPU power input ^{*)}	35.04 kW
Propellant flow rate ^{*)}	10.94 mg/s
Thrust	757.5 mN
Specific impulse ^{*)}	7131 s
Power efficiency ^{*)}	94.2%
Propellant efficiency ^{*)}	87.1%
Lifetime	56,500 hrs

^{*)} Without neutralizer system

Acknowledgments

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