

Low Power Radio-Frequency Plasma Thruster Development and Testing

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Abstract: This paper describes the results of low power (50-100 W) RF plasma thruster development and testing activity which was carried out both at the Center for Space Studies and Activities CISAS – “G. Colombo” of the University of Padua, Italy, and at the National Aerospace University “Kharkiv Aviation Institute (KhAI) of Kharkiv, Ukraine, in the frame of the international EU FP7 HPH.Com project, whose final objective was the development of a low power RF thruster for aerospace applications. The paper describes the following research activities: 1) overview of the development tests carried out to optimize the thruster; 2) design and manufacturing of the Qualification Model; 3) measurement of the propulsive performance (thrust, specific impulse and efficiency) of the thruster by means of a thrust balance; 4) further development and testing activities after HPH.Com project finishing. The thrust of qualification model has been measured by means of a pendulum thrust balance, giving thrust efficiency between 13-19% in the 8-50W power range.

1. Nomenclature

n_e = electron density

PIC = Particle in Cell

T_e = electronic temperature

e = electron charge

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m_e = electron mass
 c = light speed
RPA = Retarding Potential Analyzer
IEDF = Ion Energy Distribution Function
RF = Radio Frequency
PMEA = Permanent Magnet Electro-Analogous
EM = Engineering Model
QM = Qualification Model

2. Introduction

The EU FP7 project HPH.com (Helicon Plasma Hydrazine combined micro)^{1,2,3,4} belongs to the context previously described. The research activities were carried out by a consortium of fifteen institutions from several European countries. The main objective was to design and develop a low-power space plasma thruster based on helicon RF technology for application to mini-satellite attitude and position control. The thruster class is 1.5 mN-50W, with a target specific impulse of 1200s employing Argon as propellant. The project was organized in the following steps: a) deep numerical-theoretical investigation through dedicated plasma-simulation tools; b) extensive experimental campaigns to validate codes, to investigate the physics phenomena involved and to prove thruster performance; c) the development of a full-scale thruster-prototype to be mounted on board of a mini-satellite to demonstrate technology feasibility; d) the study of all the critical issues related to the application to a mini-satellite.

This paper describes the experimental activities carried out at CISAS (Center of Studies and activities for Space, University of Padova, Italy) and KhAI (Kharkiv Aviation Institute, Ukraine) to develop and optimize the HPH.com thruster, along with the technological breakthroughs achieved during the project (section 2). The final outcome has been the manufacturing of a thruster prototype (section 3) which has been characterized in two different facilities; particularly the thrust has been directly measured by means of thrust balances. The characterization tests and the obtained propulsive performance are described in sections 4 and 5.

3. Experimental set-up and development test at CISAS

The experiment at CISAS is based on a 2 m long, 0.6 m wide cylindrical vacuum chamber, connected to a pumping system composed of a turbo-molecular pump (capacity: 600 l/s of Argon) and a high capacity diffusion pump (12000 l/s of Argon), backed by a rotary and a roots pump; this system is capable of reaching a vacuum level down to 10^{-7} mbar without mass flow, while during thruster operation (mass flow rate: 0.1-0.5 mg/s) the vacuum level reaches $10^{-5} - 10^{-4}$ mbar. Pressure is monitored in various points of the vacuum system by means of various Pirani gauges (10^3 - 10^{-3} mbar) while a Penning gauge ($10^{-4} - 10^{-8}$ mbar) is used to monitor the vacuum chamber pressure. A quadrupole mass spectrometer is also available to monitor the vacuum environment inside the chamber. The facility is shown in

Two thruster laboratory models were developed to operate with this vacuum facility; the first one (Figure 1) is placed externally to the tank and connected to it through its exhaust section, thus allowing a quick and easy reconfiguration of the main geometrical, electrical and gas-dynamic parameters. This feature confirmed to be of critical importance for the characterization test campaign, which required the test of an huge number of configurations.

The plasma source is made of Pyrex quartz tube with an inner diameter of 19mm. Thanks to a piston mechanism a ceramic injector can move along the axial direction thus the length of the discharge chamber can be varied within the range 20-150mm. The propellant mass flow is set through a MKS mass flow controller with a maximum range of $4.6 \cdot 10^{-7}$ kg/s for Argon. A ceramic diaphragm is located at the ejection end extremity in order to increase the neutral pressure inside the discharge chamber. Different configurations of the RF plasma source have been tested. The magnetic field has been initially provided by four electromagnets, independently powered in order to produce different field patterns with an intensity up to 1250G. Subsequently, they have been replaced by samarium-cobalt permanent magnets which can be arranged in a wide variety of configurations, both with radial and axial magnetization. The magnets are mounted in pairs on independent carriages moving

along the plasma source axis. The RF power network consist of a HP 8640b RF generator (500 kHz – 512 MHz) coupled with an RF amplifier (1.8 - 30 MHz, 300 W maximum power output). The power coupling is monitored through a custom built V – I probe and adjusted both by means of frequency variation and a matching circuit. The antenna can be moved along the source tube, in order to explore different positions relative to the magnets and the thruster exit plane.

Several diagnostics system have been used to monitored the plasma discharged performance and to measure the properties of the ejected plasma beam:

- a) Optical spectrometers: measurement of the emission spectrum of the plasma in the wavelength range 200-1100nm;
- b) Custom built Retarding Potential Analyzer for ion E.D.F. estimation (retarding potential sweep: 0-250 V DC), placed in fixed position on thruster axis at about 60 mm downstream the outlet section
- c) microwave interferometer: measurement of the plasma density with a resolution of $5 \cdot 10^{15} \text{ m}^{-3}$;
- d) Custom built Faraday probes for plume ion current measurement (nickel collection plate, $\phi=3$ mm, polarization -150 V DC) mounted on a 2-axis movement system for axial and radial plume scans
- e) 2 Basler scA1400-30fc CCD cameras with 488BP10 and 752BP10 band-pass filters (10 nm bandwidth, center wavelengths 488 nm and 752 nm respectively) for plume and plasma source observation.

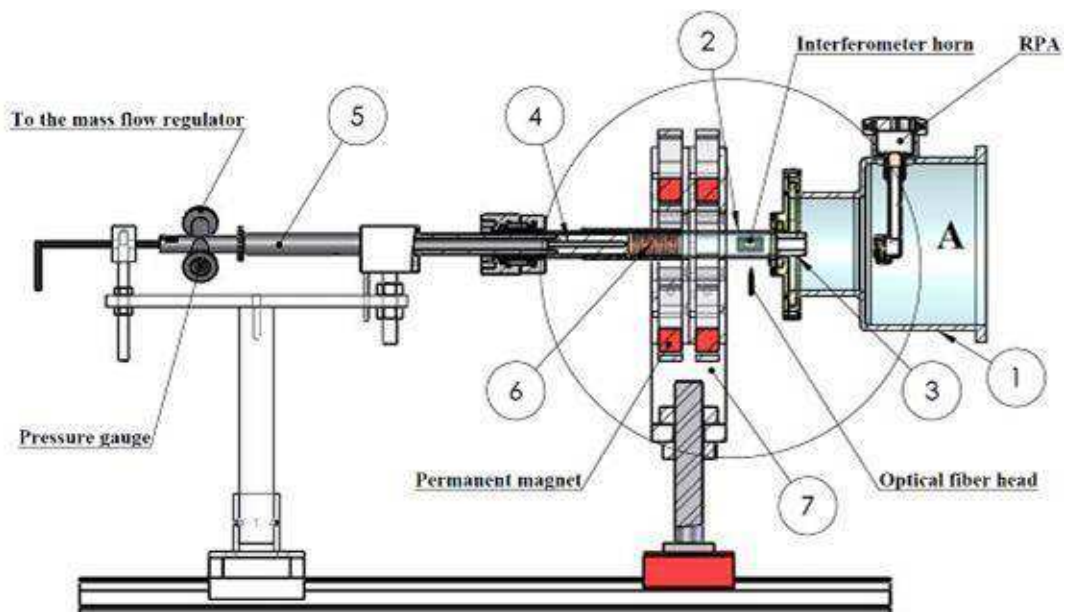


Figure 1: external experiments main components. The thruster is connected to the vacuum chamber through the expansion bell. Components: 1) pyrex expansion bell for the propellant jet; 2) pyrex source (i.e. plasma source); 3) outlet diaphragm; 4) ceramic injector; 5) injection system; 6) radiofrequency antenna; 7) permanent magnets frame

The second CISAS laboratory model was developed for operation inside the vacuum tank, in order to investigate the behavior of the most performing thruster and plasma source configurations identified with the external experiment, as well as to further optimize the thruster. This setup was considerably upgraded during the project, although while maintaining the wide re-configurability which characterizes the external experiment. The supporting frame consists of a PEEK cylindrical structure housing all the other elements. The discharge tube is the same than in the external experiment, i.e. a Pyrex tube with a inner diameter of 19mm. Both the injector and the ejection diaphragm are made of ceramic. The volume of the magnetic system have been reduced, employing smaller samarium-cobalt permanent magnets.

The effect of several parameters on the thruster behavior have been investigated through the experiments both outside and inside the vacuum vessel, particularly:

- a) magnetic field configurations and intensity;
- b) working frequency;

- c) inner diameter of the ejection diaphragm;
- d) discharge chamber length;
- e) relative positions of the antenna and magnets.

The explored power range has been 40-100W and the argon mass flow rate range $1-4 \cdot 10^{-7}$ kg/s.

The magnetic field identified for the final configuration is localized between the antenna and the thruster exhaust section, presents a peak up to 800G and is generated by two permanent magnets arrays. The magnets are arranged according to a radial magnetization direction. Visual observation of the discharge reveals that in the best operating conditions the plasma discharge presents a strong “blue” region around the axis of the system (“blue core”, Figure 2). The diameter of the core appears to be significantly smaller than the glass tube diameter and is deeply dependent on the outlet hole diameter and more weakly on the magnetic field. We believe the strongest ionization takes place in this region.

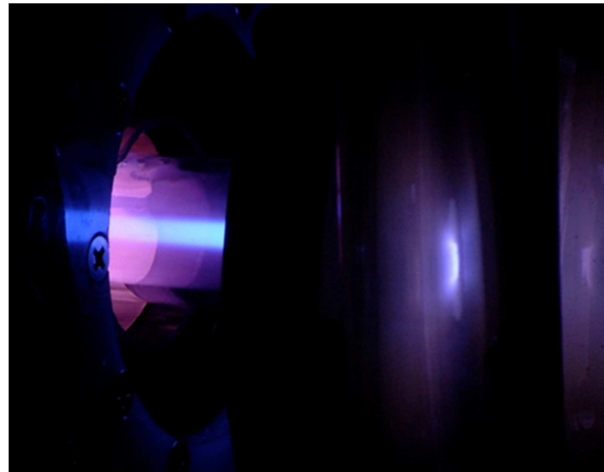


Figure 2: Plasma discharge in CISAS external experiment. The “blue core” mode is evident.

The measured properties in the plasma discharge are (for an input power of 75W, a mass flow rate of 0.2mg/s and an outlet diaphragm diameter of 5mm):

- plasma density up to $2 \cdot 10^{19} \text{m}^{-3}$;
- electron temperature up to 4.5eV.

Finally, RPA measurements show the peak of the ion distribution function for a retarding voltage up to 120V (Figure 3).

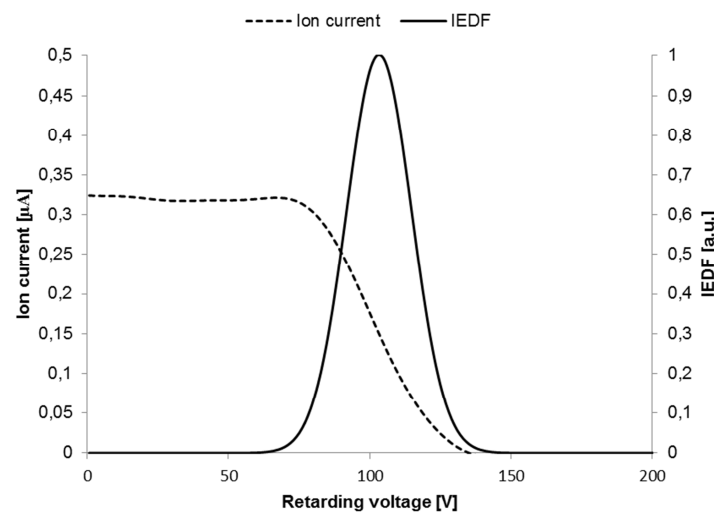


Figure 3: RPA measurement on CISAS plasma source.

4. Experimental set-up and development test at KhAI

Overall investigation description

Work structure was based on final thruster requirements, such as mass and dimensions minimization through optimization of thruster magnetic system. Since mass and dimensions of magnetic system is in proportion to magnets number and required induction value inside thruster discharge chamber, investigation of magnetic configuration influence on thruster parameters were carried out step-by-step. Magnetic induction value and magnetic system complexity were increased gradually. For every step obtained thruster parameters were compared with the goal. If the goal was not obtained, the solution to increase induction or number of magnets was accepted.

The beginning results of KhAI investigation activities during 2009-2011 years^{2,3,4} are described in previous papers. This article describes brief results investigation activities during 2011 – 2012 period.

Ion current and thrust measurements of thruster Engineering models (EM)² were shown low system performance: propellant mass utilization rate – up to 5 % and total thruster efficiency – lower than 1% for Argon mass flow rate – 0,1 mg/s and RF power level – 50W.

So after that a global investigation company was provided, the aims of which were:

- To improve antenna – plasma coupling by modernization of antenna, thruster construction and outer magnetic configuration;
- To improve plasma acceleration by outer magnetic field optimization;
- To reduce plasma losses by outer magnetic field optimization.

During investigation company serial of thruster laboratory models were developed and tested. Main models parameters were following:

- operating frequency 10-15 MHz;
- operating mass flow rate 0.07-0.5 mg/s of Argon;
- Outer magnetic induction rate on thruster central axis 0-1150 G;
- Outer magnetic field source – electromagnets, permanent magnets electro analogs (PMEA) and permanent magnets (magnetoplast and SmCo).

Experimental apparatus includes ion current Faraday probes, multi-grid (RPA) probes, magnetic probes, RF current and voltage probes and pendulum thrustbalance.

On the ground of provided experiments results qualification model (QM) construction was developed.

Antenna – plasma galvanic separation

During thruster models testing in vacuum chamber was detected, that the presence of galvanic contact between grounded antenna and plasma leads to ion current ongoing to antenna and significantly thruster parameters decreasing. Thus the specific attention was spared to galvanic separation between antenna and plasma during thruster construction and outer magnetic field topology developing.

Series of experiments were carried out for this aspect investigation. Laboratory models with quartz glass plume screens were used for interception of ion current ongoing to antenna (Figure 4).

In order to separate antenna from plasma testing of laboratory models with plume screens were provided. Ion current value on probe for experiments with plume screen was significantly higher (50-60 from 20-30 mkA) and optimum mass flow rate was significantly less (0,08 from 0,2 mg/s).

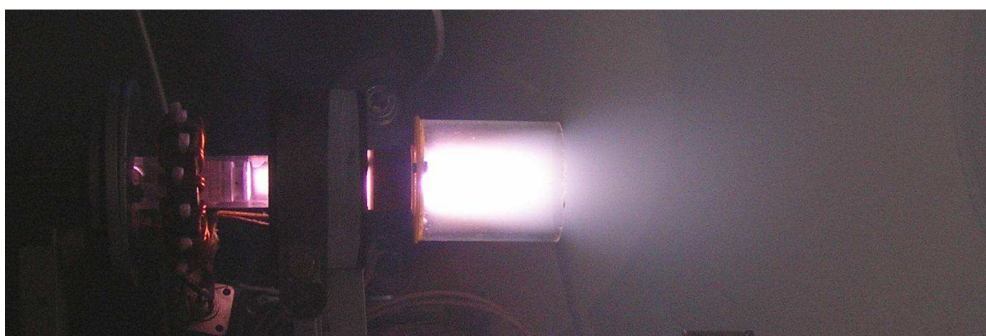


Figure 4: laboratory model with plume screen. Mass flow rate 0.15 mg/s.

Ion current measuring was provided by using of single Faraday probe in guarded ring (figure 5). Probe parameters were following: probe diameter – 3 mm; distance from exit diaphragm to probe – 100 mm; probe voltage - -180 V.

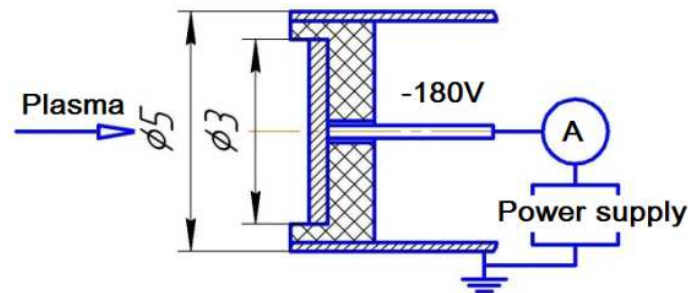


Figure 5: ion current probe scheme.

Results of ion current measurements depended from mass flow rates for dielectric and metal plume screens are shown on Figure 6. Power on antenna was calculated by multiplication of RF current, voltage effective values and phase difference.

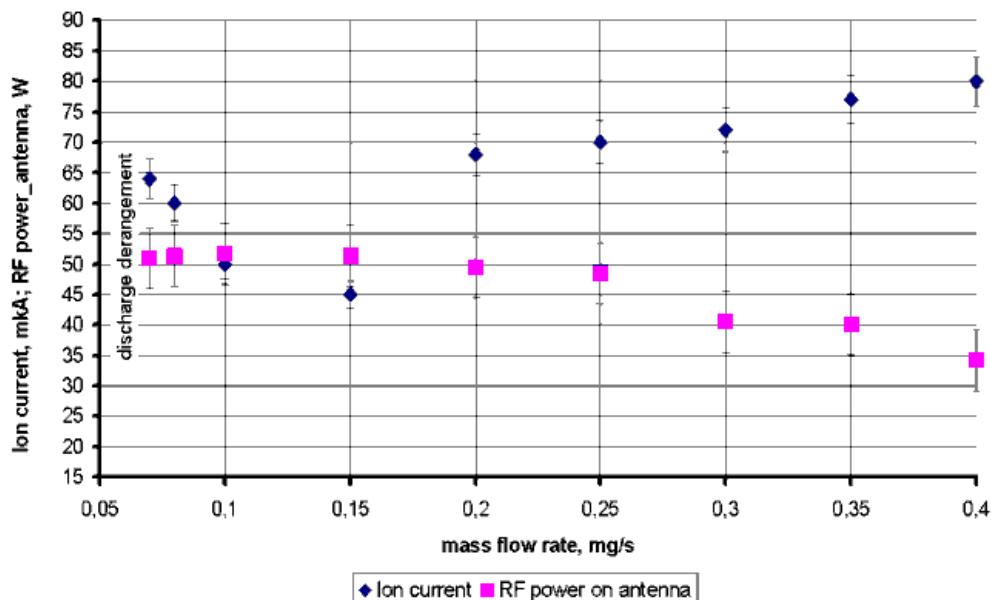


Figure 6: ion current and RF matching dependences from mass flow rate.

Obtained data is in agreed with theory. The most effective antenna-plasma power coupling is corresponding to collisionless power absorption in the range of low mass flow rates.

Obtained results were shown necessity of antenna – plasma galvanic separation in QM model construction.

Outer magnetic field configuration

During thruster EMs testing a significant influence of PMEА position relative to antenna and exit diaphragm on plume parameters was detected. For this aspect investigation an experiments with movable PMEА was carried out. Plume ion current and IEDFs were measured by RPA probe. Scheme of experiment is shown on figure 7. PMEА was movable along central thruster axis.

Ion current and ion energy dependences from axial PMEА position are shown on figure 8. Mass flow rate was 0,1 mg/s, RF power level – 50 W. For every PMEА position magnet current was selected for the optimal discharge conditions.

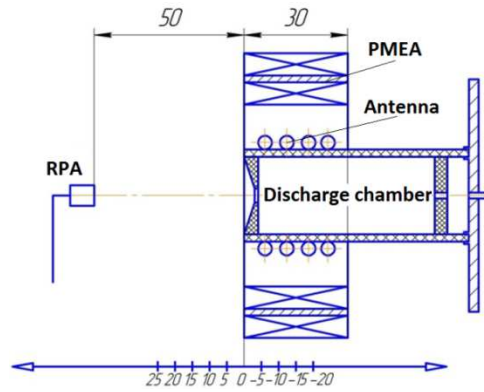


Figure 7: scheme of experiment with movable PMEA.

During RPA characteristics processing two optimal PMEA positions (with ion current and energy maximums) were detected. There were positions -20mm and +10mm. For PMEA position 0..-15mm influence of outer magnetic field on discharge parameters was only negative.

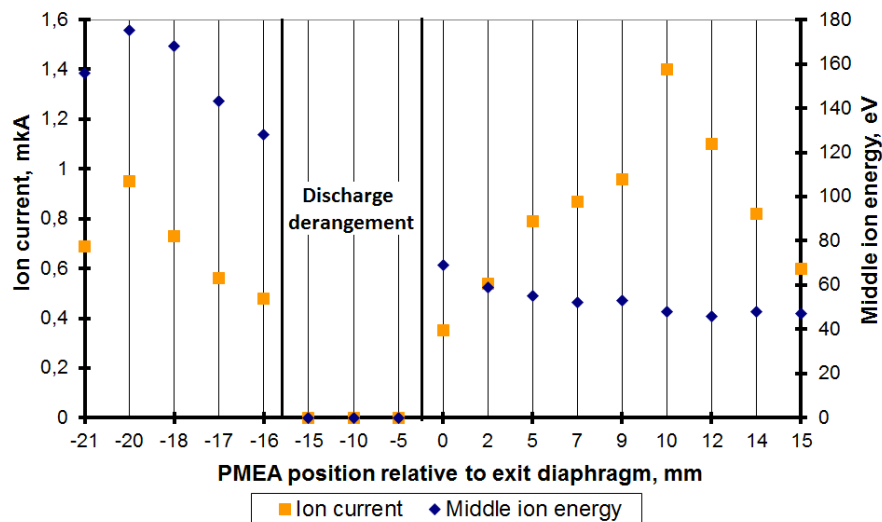


Figure 8: ion current and middle ion energy vs PMEA position.

Magnetic induction distribution along thruster axis for PMEA position -20mm is shown on figure 9. For further experiments magnetic field configurations were remained two peaks form with zero field region inside discharge chamber as the most effective. During experiments only magnetic peaks values (up to low hybrid frequency), zero field region and peaks positions were varied.

The QM outer magnetic field configuration is described in next article.

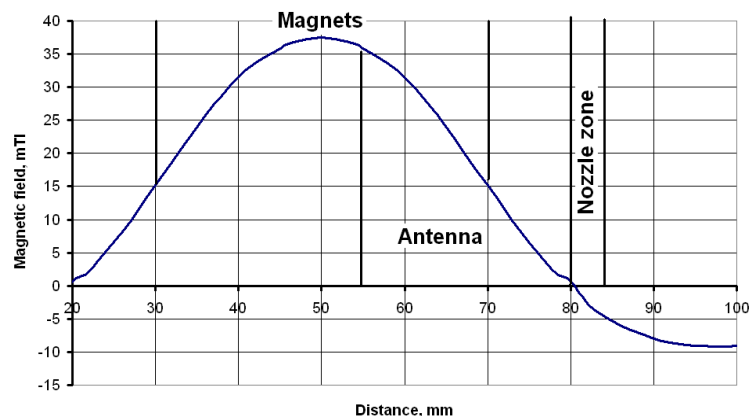


Figure 9: Magnetic induction distribution along thruster axis for PMEA position -20mm

The extensive characterization and development campaign has evidenced the following aspects:

- the ejection section of the thruster has been reduced by means of a ceramic diaphragm in order to increase the neutral pressure inside the discharge chamber which leads to an increase of mean ion energy and allows the thruster to operate with a low mass flow rate between 0,1-0,2 mg/s;
- the most effective magneto-static field configuration among those investigated presents two strong peaks of the axial component with a magnetic inversion zone between them. The optimal positions of the peaks are located in correspondence of the injector and the ejection section respectively;
- working in the lower hybrid resonance condition maximizes the ionization coefficient and thruster efficiency in the explored RF power range;
- the occurrence of a magnetic field inversion zone within the discharge chamber increases significantly the mean ion energy in the plume.
- the magnetic field distribution giving the highest performance in terms of ionization is the one which conforms to antenna RF electric field intensity distribution.
- a significant gradient of magneto-static field induction in the antenna zone produces an RF power coupling efficiency increase which in turn increases the overall thruster efficiency.

Direct thrust measurements

For thrust measurements the thruster and the amplifier were mounted together on the thrust balance, in order to avoid thermal effects in RF cable and minimize the length of the cables between thruster and RF amplifier, which generates a phase delay between voltage and current flowing to the antenna thus negatively affecting the generator – load (antenna + plasma) matching.

Along with the thruster a compact RF amplifier was developed and manufactured at KhAI (figure 10); the amplifier is equipped with a thermal accumulator, capable of in-vacuum operation for 20-40 minutes (depending on the plasma discharge regime). Mass of RF amplifier with thermal accumulator – 2 kg. Dimensions of RF amplifier with thermal accumulator are 220*120*105 mm.

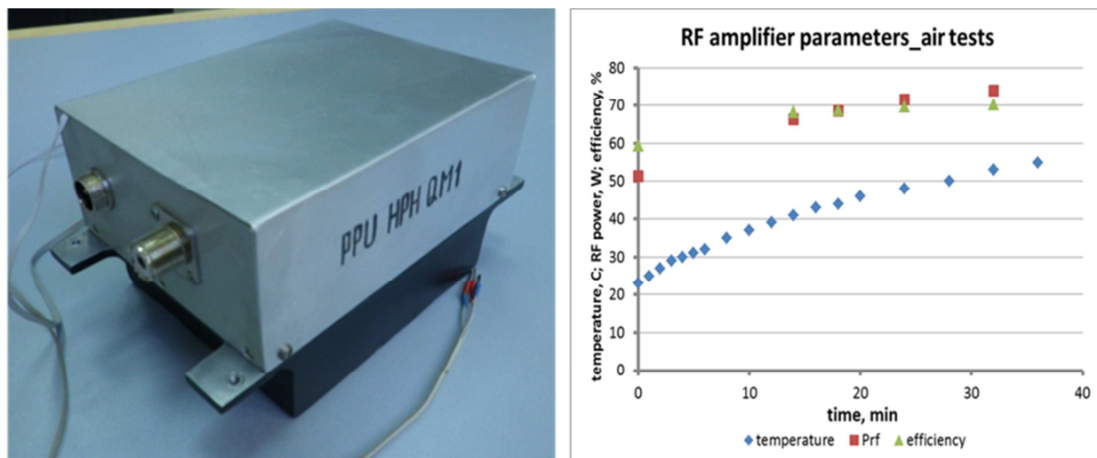


Figure 10: vacuum version RF amplifier with thermal accumulator.

Experimental scheme and thruster laboratory models with RF amplifier mounted on thrustbalance are shown on figure 11. During the measurements the thruster was characterized in different operating conditions by varying mass flow rate, operating frequency and input power; in each condition RF amplifier temperature, DC current consumption and thrust balance displacement were monitored, in order to estimate thrust, power consumption and efficiency.

RF power supplied to the thruster was calculated on the basis of output RF generator voltage and amplifier DC current consumption. These parameters were related to RF power through a preliminary calibration process, carried out at the operating frequency of the thruster with the actual cable length employed during the tests.

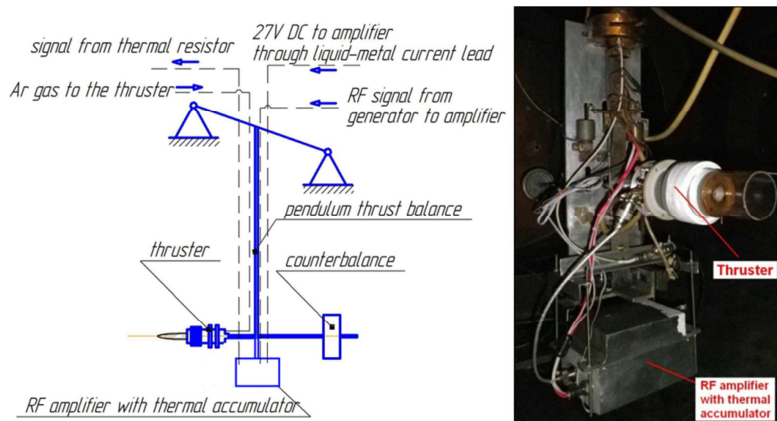


Figure 11: first direct thrust measurements of laboratory model.

Features of experiments and obtained results from thruster laboratory models testing are following:

- mass flow rate – 0,08 mg/s;
- thrust – 0,38-0,45 mN;
- RF power level – 15-40 W;
- thrust efficiency – 2-8 %;
- specific impulse – 470-560 s.

Thus large-scale experimental and theoretical companies of low power electrodeless RF plasma thruster physics and construction investigations, which were provided in KhAI and CISAS, were allowed to develop and manufacture thruster QM.

5. Qualification model construction and test results

All thruster frame elements except mounted flange were manufactured employing fiberglass on the basis of requirements to minimize parasitic RF field losses. The thruster features a conical plume screen and labyrinth insulators which thermally decouple the inner surface of the antenna from the external surface of the plasma source. The plasma source, designed according to the experience gained in the program and further optimized experimentally, consists of a 55mm long quartz tube having an inner diameter of 18 mm. The tube is closed at one end by a ceramic injector having four radial channels for propellant injection inside the chamber, while on the other end there is a ceramic outlet diaphragm with a single central hole with a diameter of 4 mm. QM views are shown on figure 12.

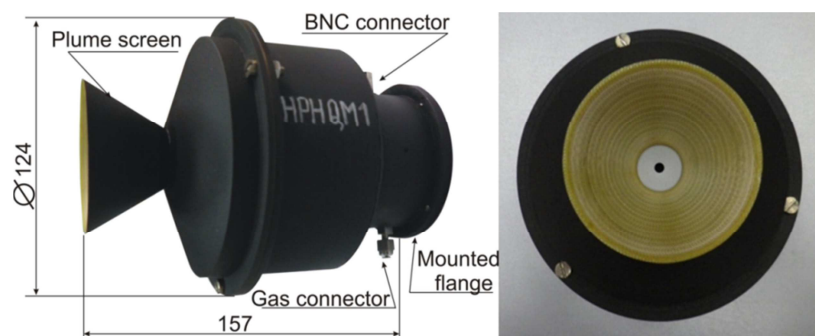


Figure 12: HPH.com qualification model.

The magnetic field is provided by 16 cubic Samarium-Cobalt permanent magnets, arranged in two circular radially-polarized arrays. The axial magnetic field distribution along thruster axis is shown in figure 13: the field presents two strong (more than 1000 G) axial peaks, positioned over the outlet and inlet sections, and a null point in the middle, in accordance to the results exposed in section 2. The magnetic lines in the ejection region present a slowly diverging shape to properly expand plasma into vacuum.

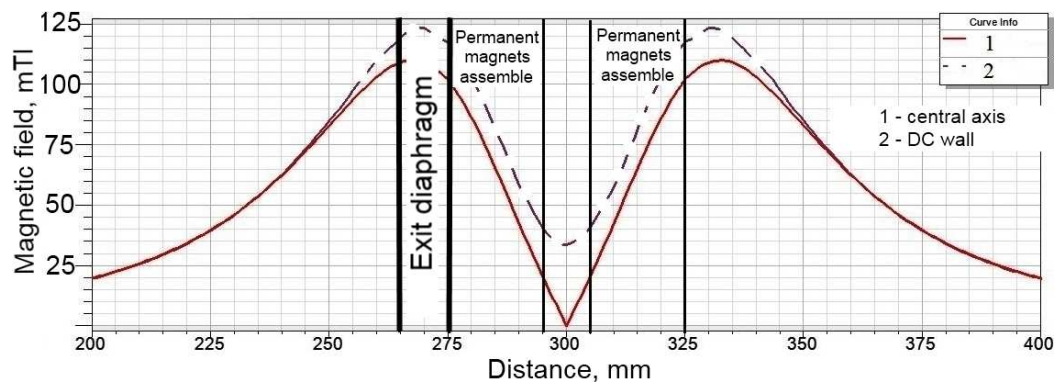


Figure 13: magnetic field configuration.

The magnetic field force lines distribution relative to thruster elements is shown on figure 14. Three characteristic regions are highlighted. Region 1 is surrounded by magnetic cusps in the radial direction and magnetic mirrors in the axial one. Region 2 is characterized by a strong radial component due to the orientation of the magnets. In region 3 the field is mainly axial and the intensity is compatible with the lower hybrid resonance for Argon. The magnets are housed inside a glass-fiber support.

The antenna is powered through a coaxial line with copper conducting element and Teflon insulator.

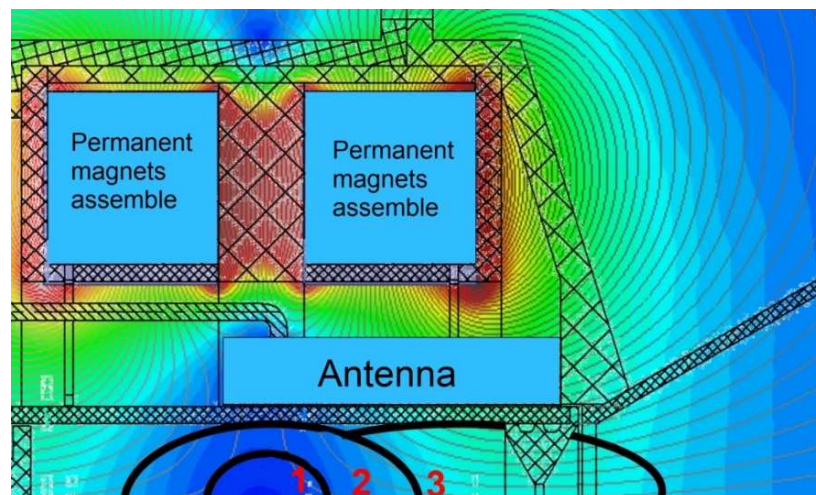


Figure 14: magnetic force lines and intensity.

During thrust measurements of QM in KhAI power had to be limited at around 7-10 W, due to significant RF noise to thrustbalance equipment. QM mounted on thrustbalance is shown on figure 15.

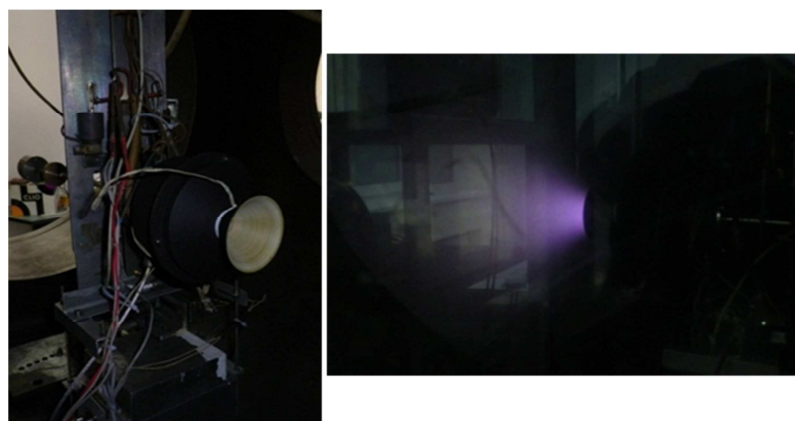


Figure 15: HPH QM testing on KhAI's thrust balance.

The obtained results, both measured directly (thrust) and indirectly (specific impulse, efficiency) are shown on figure 16.

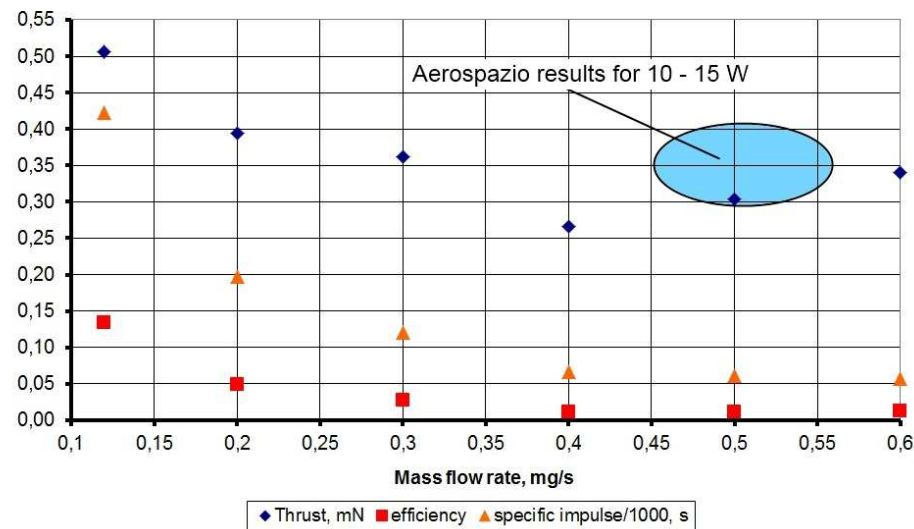


Figure 16: Thruster QM testing results (RF power level: 8W).

It can be seen that the best overall performance was achieved at low mass flow rate ($1.2 \cdot 10^{-7}$ kg/s) with an effective power of 8 W:

- thrust – 0,5 mN;
- specific impulse – 422 s;
- thrust efficiency – 13 %;
- ionization coefficient – 0,18;
- thrust cost – 16 W/mN;
- ion cost – 153 eV.

Further thruster testing (figure 17) is ongoing at Aerospazio Tecnologie s.r.l. (Rapolano Terme, Italy), a private company specialized in electric thruster testing.. This additional experimental campaign, is aimed at the confirmation of the performance levels registered at KhAI and is carried out jointly by CISAS and KhAI personnel, with the assistance of Aerospazio's staff. The experimental facility consists of a cylindrical vacuum tank approximately 4 m long and 1.3 m wide, equipped with a turbo-molecular pump and three cryo-pumps capable of providing high vacuum levels even during thruster operation (typically $1 \cdot 10^{-5}$ - $3 \cdot 10^{-5}$ mbar in HPH.com mass flow range). The vacuum tank houses a zero-displacement thrust balance, stabilized by a feedback control loop, and a rotating boom housing Faraday probes and an RPA, which can be used for angular plume scans.

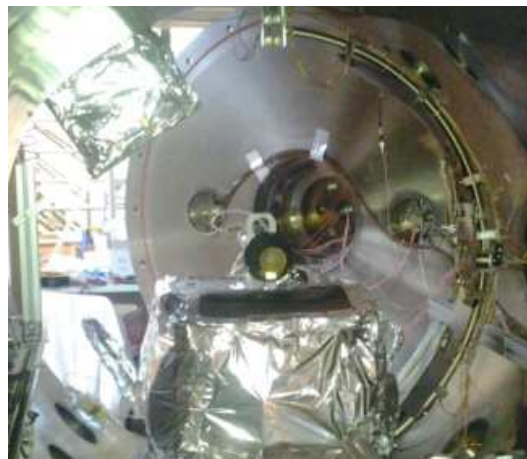


Figure 17: HPH prototype installed ready for testing in Aerospazio's facility.

A first series of measurements was performed at Aerospazio in October 2012, experiencing RF disturbances on the equipment which forced operation with a mass flow rate of about $4.6 \cdot 10^{-7}$ kg/s of Argon and an estimated effective power ranging between 10-15 W; in these conditions the thruster was capable of producing a thrust ranging between 0.3-0.35 mN and an specific impulse of about 80 s, thus replicating the results of the analogous set of measurements performed at KhAI (see figure 16).

Up to now it was possible to perform direct thrust measurements only at low power (10-15 W), well below the target power level of 50 W; however RPA and Faraday probe measurements performed at up to 50 W are available and have been correlated with existing thrust measurements and thermal measurements/simulations in order to elaborate a prediction of thruster performance up to the design power level, taking into account also the progressive increase in power losses due to the heating of the antenna and the RF circuit. The results are reported in figure 18, from which it can be seen that with an input power of 50 W and a mass flow rate of $1.2 \cdot 10^{-7}$ kg/s the thruster prototype should be capable of delivering a thrust and a specific impulse well above the target values of HPH.com.

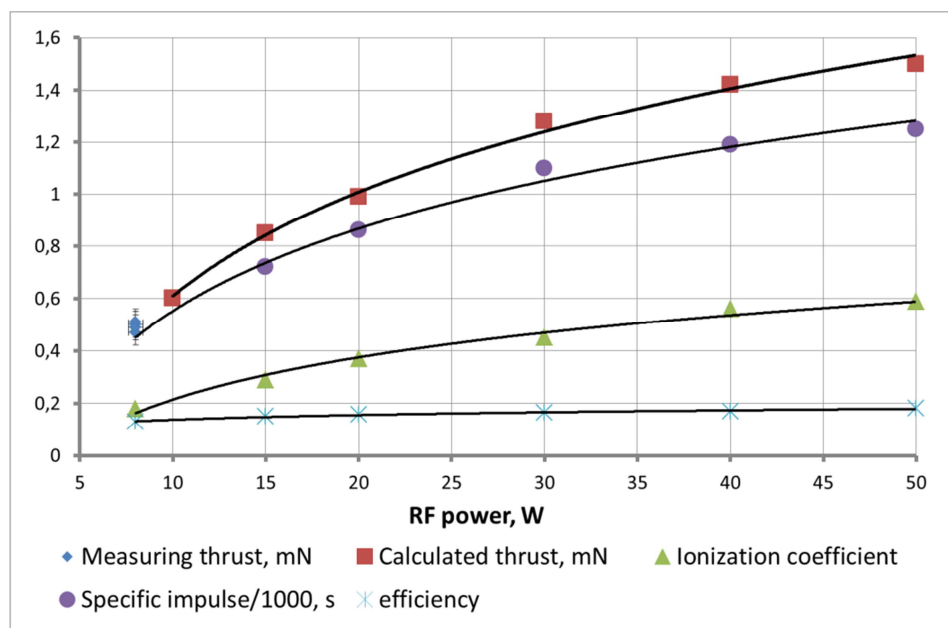


Figure 18: estimation of thruster performance scaling with power (mass flow rate 0,12mg/s)

6. Current investigations and future plans

After HPH.Com project finishing further investigations and thruster modernization were resumed in CISAS and KhAI. Carried thruster QM tests were uncovered advantages and disadvantages of manufactured model, and also were opened significant potential for further thruster efficiency increasing and mass-dimension characteristics reducing.

Detected QM imperfections were following:

- significant plume divergence (figure 19);
- mismatching and RF losses increasing during power increasing from 15 to 50 W;
- high thruster mass in comparable with other electric propulsion systems of such thrust level.

Present research activities are directed on modernization of antenna and discharge chamber geometry, and on magnetic system optimization.

These issues are currently being faced by:

- antenna construction and materials choice refinement;
- plasma discharge chamber re-design (figure 20, 21);
- magnetic system upgrade, with the investigation of the effect of nozzle magnets (figure 22,23);
- thruster structure mass reduction.

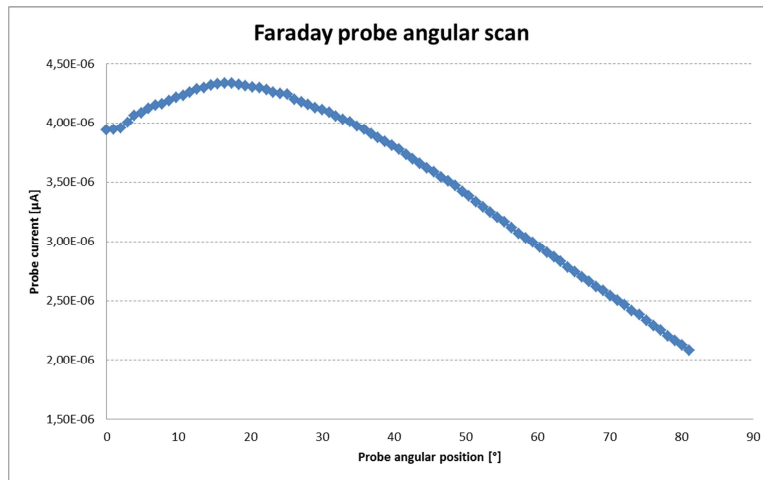


Figure 19: angular ion current scan within the plume of the thruster by means of a Faraday probe ($V_p = -150$ V, fixed)

These measures are aimed at maximizing the overall plasma source and antenna efficiency, while minimizing beam divergence and thruster mass.

One of current investigation directions is discharge chamber geometry modernization. The task was to compare cylindrical and coaxial chambers influence on thruster parameters. An idea to use coaxial canal is ground on theoretical estimations of radial plasma moving due to Hall effect and exit of skin layer value less than cylindrical chamber radius. Coaxial chamber view is shown on figure 20.

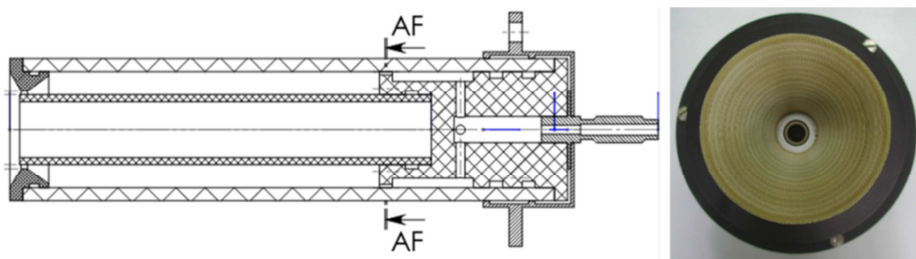


Figure 20: discharge chamber geometry re-design, with the introduction of an annular section instead of a circular one.

The results of plume ion current angel distribution for coaxial and cylindrical discharge chamber are shown on figure 21. During coaxial discharge chamber testing ion current increment on probe was 2..2,2 times for mass flow rate increment 1,2 times and same RF power level. Meanwhile the different angel distribution form was evident. For coaxial chamber using two ion current peaks on angels 40° were detected.

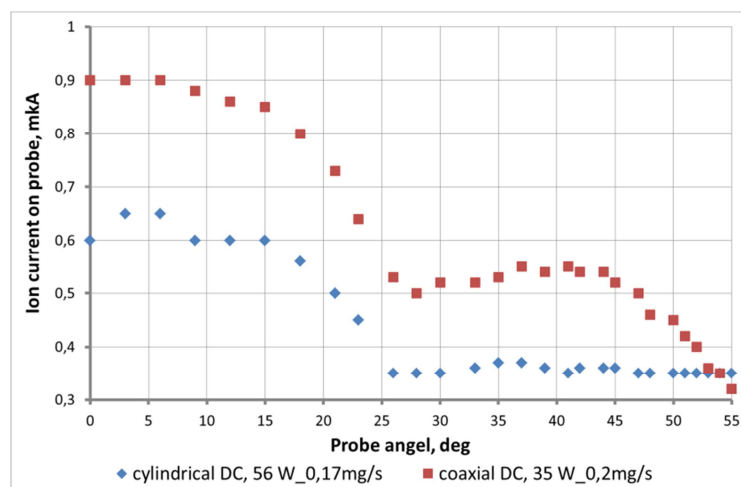


Figure 21: Comparison of the angular distributions of ion current within the thruster plume with circular (blue) and annular (red) discharge chamber cross-section.

Presence of additional peaks is indication of outer magnetic field distribution non-optimality in plasma acceleration zone and of its modifications necessary. En masse given experiment showed necessary of discharge chamber geometry modification, activities of which are ongoing now.

For reducing of plume divergence a solution to use additional nozzle magnet was proposed. For experimental confirmation of proposed theory an experiment with additional nozzle electromagnet, located around exit diaphragm, was carried. Magnetic induction and force lines distributions for provided experiment are shown on figure 22.

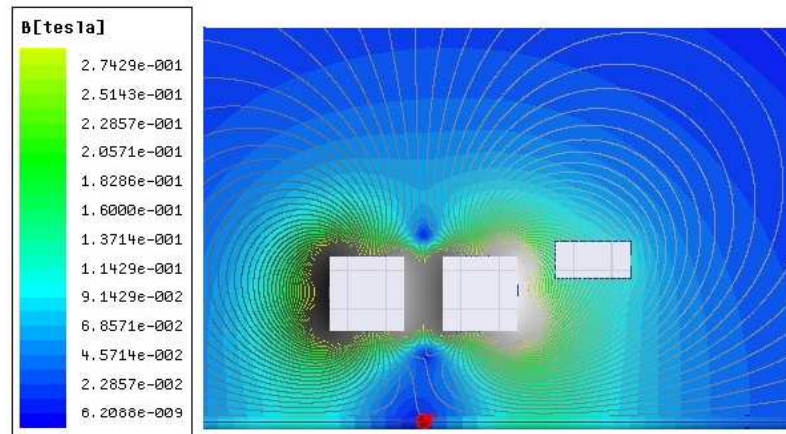


Figure 22: simulation of the magnetic field produced by the thruster magnetic system with the introduction of a nozzle magnet (on the right).

13 % magnetic induction increment in the exit diaphragm zone (figure 23) was led to 30 % increment of ion current on probe, located on central thruster axis. Ion current angel distributions measurements for different magnetic configurations in nozzle zone are current experimental task.

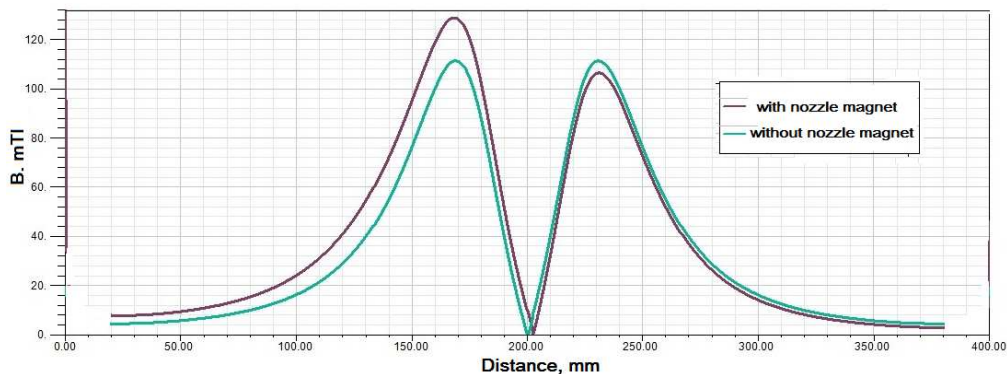


Figure 23: axial magnetic field along thruster axis with the introduction of a nozzle magnet.

Thus the foundation for new thruster model development on the base of QM will be synthesize from results of discharge chamber geometry and outer magnetic configuration optimizations and of antenna modernization, directed on RF losses reducing in circuit during thruster input RF power increasing.

In addition to the issues related to thruster performance, the employment of an external RF power source placed outside the vacuum system poses two additional problems:

- the length of the RF transmission line (1-3 m) introduces, within the operating frequency range of 10-12 MHz, considerable parasitic effects altering the impedance matching between amplifier and thruster;
- the transmission of 10-50 W level RF power to the thruster from outside, both through independent connections or passing through the thrust balance inner connections, appears to

generate very strong disturbances on the thrust balance electronics, thus preventing reliable measurements above 10-15 W.

This issue is being faced through the development, at KhAI, of an RF amplifier for in-vacuum operation, which will be installed on the thrust balance together with the thruster in a single structure. This will reduce the RF cables length to 15-20 cm, thus making cable-related parasitic effects negligible, and will eliminate the need for external power transmission lines, reducing the interference effects.

Testing of modernized thruster model in composed of thruster module (thruster – matching device – RF amplifier) on thrustbalances in KhAI and Aerospazio will be the next research step.

Further testing in Italy and Ukraine will investigate the effectiveness of these solutions and hopefully investigate thruster performance at the design power level of 50 W.

7. Conclusion

An Helicon plasma thruster prototype was jointly developed by CISAS and KhAI within the frame of project HPH.COM and tested both in Italian and Ukrainian facilities, with preliminary results at low power confirming the performance predictions, several issues were uncovered during testing and are currently being faced in cooperation between the two institutions through thruster sub-system upgrade and further testing activities.

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