RIT-µX - The New Modular High Precision Micro Ion Propulsion System

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RIT-µX is a radio frequency ion engine for micro propulsion applications. The ionization of the propellant by electro magnetic fields offers inherently highest thrust control, -stability and resolution. The function principle of the engine and the specific advantages are explained and the layout of a propulsion system is presented. Challenges for system design are the selection and development of appropriate electronics, neutralization and Xenon flow management. Principle approaches are provided and discussed.

I. Introduction

Mini ion engines are considered as suitable solution to overcome difficulties and limitations of existing propulsion concepts for low and lowest thrust application. A crowing number of missions combines the demand for high specific impulse, long lifetime, high total impulse and last but not least highest thrust resolution, accuracy and controllability.

Reducing the altitude of earth observing satellites in low earth orbits evidently increases the resolution of the data from the measuring instrumentation. On the other hand the atmosphere's influence on the spacecraft increases. A compensation of the atmospheric drag becomes mandatory. This is challenging for the propulsion system, as high

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thrust controllability and resolution is required combined with sufficient total impulse. Moreover the high amount of atomic Oxygen requires a robustness of the engine against this aggressive element. Concerns with respect to any technology which requires (hot) cathodes exists.

The installation of formation flying satellites forming one large virtual instrument offering a significant higher resolution than any large single instrument is considered as a break through for several types of (deep) space observation missions. Such experiments will deliver important impacts for fundamental physics and our understanding of the universe. For these formations again the controllability and the thrust resolution are from importance. High specific impulse and total impulse are highly desirable to maintain the experiments over years.

Ultra fine thrust control is required for some missions dealing with the measurement of gravity waves. Goal is a propulsion system with a thrust starting with zero to some tenth (hundreds) of micro Newtons. As these experiments will take place far from Earth, for example at the Lagrangian point L2 also a higher thrust in the range of some milli Newtons for the cruise phase to the destination is required.

The strong need for micro-propulsion is identified by the scientific community, industry and the space agencies. Astrium's micro propulsion solution is called RIT-µX. The name "RIT-µX" follows Astrium's convention to label the Radio Frequency Ion Thrusters with an X as long as the thruster is in an early development status (see RIT-XT and RIT-22). The Greek "µ" emphasizes the special abilities of the engine for micro propulsion.

The work presented in this publication is performed under a contract granted by the European Space Agency ESA in the frame of the GSTP programs. Under lead of Astrium, Business Line "Equipment and Propulsion" a study and development team has been formed bringing together the competences in all relevant fields. Astrium is a well known system house with a long term heritage in electric propulsion. For more than 3 decades a fruitful co-operation with Giessen University exists. The Radio Frequency principle was invented in Giessen in the early sixties of the last century by professor Horst.W. Loeb, later-on a whole family of ion engine prototypes was developed under his lead[8][9] [10].

During the last 3 years Giessen University has focused its activities on micro-propulsion [3]. The successful work has been the basis for the activities described here. Naturally, Giessen University is a strong partner in this project. Giessen University provides knowledge of thruster physics, scaling and layout. Moreover Giessen provides test services for development and endurance testing. Another experienced long-term partner in RIT development is the Institute for Surface Modification (IOM) Leipzig. The IOM has the lead for ion optics and lifetime analysis.

Although hardware activities are limited to the ion engine itself the RIT-µX project comprises system engineering too. An essential part for any ion engine is the required power supply and control logic (PSCU). Elaboration of the electronics system is performed by Astrium Satellites GmbH (Friedrichshafen). Design and layout of the flow management system is supported by University of Stuttgart, Institute for Space Systems (IRS).

II. Micro Propulsion Missions and Requirements

A. Missions

"The use of electric propulsion is now commonly recognised within ESA for application on Telecommunication Satellites (ARTEMIS, ALPHABUS), Scientific Spacecraft (SMART1, BepiColombo and LISA Pathfinder) and Earth Observation Missions (GOCE).

Over the last few years another emerging market has been recognised which implement a distributed spacecraft to improve instrument resolution. In order to achieve adequate signal reconstruction, this application requires close control of the spacecraft separation and attitude through formation flying. This typically implies fine thrust control of the order of µN. Moreover, in order to reduce the time for re-pointing manoeuvres higher thrust levels of the order of mN are beneficial.

The ESA Science Directorate has recently issued a call for future scientific missions, Cosmic Vision 2015-2025. Two of the candidate astrophysics missions are formation flying observatories, DARWIN and XEUS.

ESA is currently preparing in the frame of the GST-Programme the formation flying technologies and techniques which will be proven within the ESA PROBA3 project, the first Agency Formation Flying Technology Demonstration mission. PROBA 3 will be used also as test bench for micro-propulsion systems in order to verify compliance to the specific propulsion and control needs of formation flying applications.

B. Requirements for micro propulsion

Based on the on-going studies on the above described application, the critical performance requirements identified for a micro-propulsion system include high specific impulse, precise thrust modulation in the µN to low mN range, very precise thrust level resolution and response rate. A preliminary set of requirements is summarized in Table 1

Moreover the design of the propulsion system needs to comply with the need of those spacecraft to perform full 3-axis (6DoF) attitude control, with their limitation in mass, volume and power availability and with the very high total impulse required.

Thrust range (fine)	(1) 5µN-150µN
Thrust range (coarse),	(3) 200µN-4mN
Thrust resolution	~0.1 µN
Thrust noise,	~0.1µN/ □ Hz for thrusts under 150 µN
Thrust regulation capability	<0.5 µN At least 0.7% full range
Thrust response time	<10mS
Total Impulse Fine: Course	 <1400Ns tbc @ 30 µN < 40kNs @ 3000µN

Table 1 Summary of preliminary requirements for RIT-µX ion engine development.

III. The RIT-µX Ion Propulsion System

A. RIT-µX Basics

Heart of the new RIT-µX small ion propulsion system is the radio frequency ion thruster RIT-µX with the unique electrodeless ionization of the propellant by electromagnetic waves. RF-ionization is known as a very effective way to ionise neutral gases. The implementation of this ionisation principle is very simple as merely two components are necessary: An ionisation chamber made of an isolating material and an RF-coil which surrounds this chamber. No other parts are required inside or outside the ioniser with respect to ionisation of the propellant! This makes the overall concept very simple, robust and erosion free.

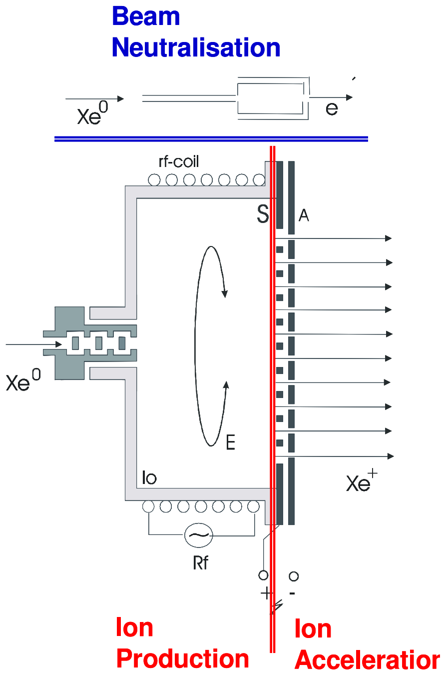
If an RF-current is applied to the the thrusters RF-coil a primary axial magnetic field is induced inside the ioniser. This field generates a secondary circular electric field *(E).* Whereas the effect of this electro-magnetic field on neutrals or ions is negligible, free electrons gain sufficient energy for impact ionisation of the propellant: The propellant is set into the plasma state. Once the ionisation process is initially triggered the process is self-sustaining. All electrons required for a steady state operation are generated in the discharge itself. There is no need for an additional electron source, e.g. a main cathode, inside the ionisation chamber.

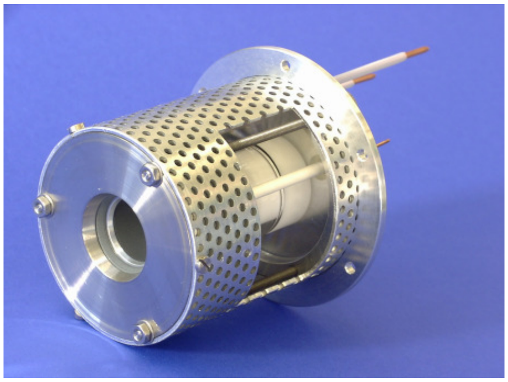
In ion thruster technology the rf-principle is unique, but there exists a broad field of applications where rf-ionization is used. It is employed in plasma- and ion sources for material processing (solid state physics, semiconductors, plasma chemistry…) as well as for neutral injector sources for fusion plasma heating. So the physics behind are well understood. Some special properties, which also apply for ion thrusters, make the RF-plasma very favourable for propulsion purposes and especially for micro propulsion.

B. Physical Background

High Discharge Efficiency: The plasma generation by RF is one of the most efficient methods to set a gas in the ionized plasma state. The efficiency is so high that no additional support, like external magnetic fields for plasma confinement is required. *RF-thrusters work without permanent magnets or additional solenoid.*

Low Electron Temperature: [6][7]The plasma's electron temperature is comparably lower than for Kaufman thrusters. Therefore the potential drop, which in a first order is directly proportional to the electron temperature, between the quasi neutral inner plasma and its surroundings remains below the sputter thresholds of the materials used for the ionisation chamber and the screen grid. *Neither the plasma sided grid nor the ionisation chamber are subject to any kind of erosion processes.*





RIT-2 Ion Thruster

A = Acceleration Grid
S = Screen Grid
Io = Ionisation Chamber
Neut = Neutraliser
Ins = Gas Inlet and isolator
Rf = Radio Frequency Generator

Figure 1 Operating Principle of an RF-Ion Thruster

Low amount of multiply charged ions: [6]The power to thrust ratio of any gridded ion engine is increased, if multiple charged ions occur in the ion beam. A low electron temperature means a very small amount of multiple charged ions in the ioniser and the ion beam. *The low amount (typ. <1%) prevents sputter and erosion processes at screen grid and ionization chamber and ensures highest possible thrust efficiency*

Linearity between plasma-density and rf-power: The plasma density is approximately proportional to the applied RF-power. This means that an increase of RF-power primarily increases the number density of ionized atoms instead of increasing the energy of the electrons (cf. electron temperature) and the amount of multiply charged ions. *Compared with Kaufman thrusters a smaller engine design is possible. It is the basis for a simple and effective thrust control strategy.*

Inherent stability of ionization process: The rf-plasma is inherently stable. Ions and electrons are generated inside the "bulk plasma", that means in the volume of the discharge chamber, the amount depends on the supplied rf-power. On the other hand electrons and ions re-combine at the surface of the ionizer vessel. The equilibrium between ionization and recombination is stable. As a result the RIT principle offers i*nherent, natural thrust stability*

C. Engineering and Application

Limited Thermal Restrictions: The RIT is the only known gridded ion thruster which operates without external static magnetic fields for the plasma confinement. For Kaufman-Thrusters this confinement is mandatory to achieve an efficient ionisation whereas the magnetic field is necessary for ECR-Thrusters to establish the electron cyclotron resonance conditions. Using permanent magnets the operational temperature of the thruster is limited to the magnet's Curie temperature T_C which is typically in the range of 300°C. Some Kaufman-Engines omit the permanent magnets by using electromagnets with coils instead. The required number of turns for these coils makes an electrical isolation indispensable. Therefore the thermal restrictions are quite similar to that of permanent magnets. In contrast, the RF-coil of the RIT-Thruster is not covered by isolating materials because the distance from turn to turn is sufficient to achieve isolation.

Inherent High Voltage Isolation: The ionized propellant (plasma) is an excellent electrical conductor. So the high voltage provided to the screen grid (or an anode) is "visible" for any component in contact with the plasma. In case of the RIT this voltage is inherently isolated from surroundings. The non-conductive ionizer vessel is a natural barrier. In a RIT system only the cabling to the grid is on high voltage potential. In Kaufman engines also the entire cathode system and the anode are on high potential. Special care is required, also for the layout of the PPU where several modules are on high voltage potential.

Thrust control: The clear relationship between applied RF-power and extractable ion current and the inherent stability of the ionisation offer an effective thrust control strategy. Also without any regulation the beam current is constant as long as no other operational parameters alter (e.g. mass flow). For example, stability better than 0.3% over 100h was multiply demonstrated with the large RIT-22 engine. During this test no active thrust regulation was employed. With a simple closed loop between ion beam and RF-supply a high precision thrust control is realized. The stability only depends on the accuracy of the employed electronics. Neither external magnetic fields have to be controlled nor does any restriction by additional fields apply. Using high precision laboratory power supplies and the closed loop concept the thrust stability achieved with RIT-22 is better than 0.1‰ (+/- 1mA @ 2380mA beam current)

Ultra Fast Thrust Control: If the rf-power is varied the ionization responses to a new equilibrium within some rf-periods. So within a few *micro*seconds the thrust reaches a new state. The time thrust resolution of the overall propulsion system depends on the speed of the electronics around the engine. It is not limited by the thruster itself. In contrast to the rf-ionization any engines requiring cathodes are limited in there response by the thermal capacity of the cathode.

Thrust noise: The inherent thrust stability in combination with the fast thrust response offers excellent low thrust noise. The extreme low thrust noise is a challenge for any measurement.

D. Generic RIT-µX System

A RIT µX ion engine requires propellant and electricity for operation. The propellant flow to the engine and the neutralizer is controlled by a flow control unit (FCU), the required electric power is provided by the power processing unit (PPU). Beside the thruster unit the PPU controls also the FCU.

A system consisting of the thruster unit, the power processing unit and the flow control unit is called "Radio Frequency Ion Thruster Assembly - RITA". Function and tasks of all RITA components are explained in the following section.

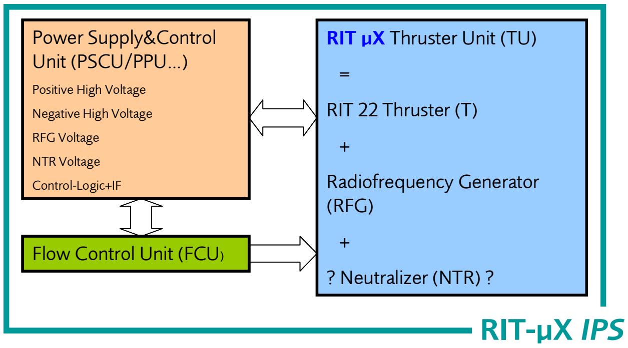


Figure 2 Generic RIT-µX IP System Layout

IV. System Aspects

A. First elaborated RIT-µX Electronics System

The availability of suitable electronics is a key factor for the RIT-µX Ion Propulsion System (IPS). As the thruster physics ensure highest thrust stability, ultra fast thrust response and high thrust resolution the system performance is driven by far more by the engine's electronics than by the thruster itself. When the engine is operated with a beam voltage of 900V a beam current of 1mA is corresponding to a thrust of 5µN. It means the operational range of the electronics for the RIT-µX is very different in terms of current and power from previously developed electronics for engines like RIT-10 and RIT-22.

Another principle difference is the number of engines to be operates simultaneously. For north-south-station keeping, typically only one engine is operated. For extended orbital maneuvers (orbit toping etc.) the operation of two engines is considered. A similar picture is shown considering interplanetary probes. Typically, one or two engines are operated at the same time.

For a mini ion engine system the situation is different. The system shall provide full 6-axis control. Taking into account all circumstances, systems operating up to eight thrusters simultaneously are under discussion. As the system studies are not finalized and the demands might differ from mission to mission a flexible modular approach is required. The answer is a modular scalable Power Supply and Control Unit (PSCU).

For each engine the following elements are required:

- Positive High Voltage Supply (PHV)
- Negative High Voltage Supply (NHV)
- Hardware Beam Current Controller including Beam Current Sensor, Beam Current Reference, Regulator
- Power Supply for the Radio-Frequency Generator

In addition the PSCU has to provide the interfaces to the spacecraft's power and data bus. The PSCU has to control also the Flow Control System and the neutralization.

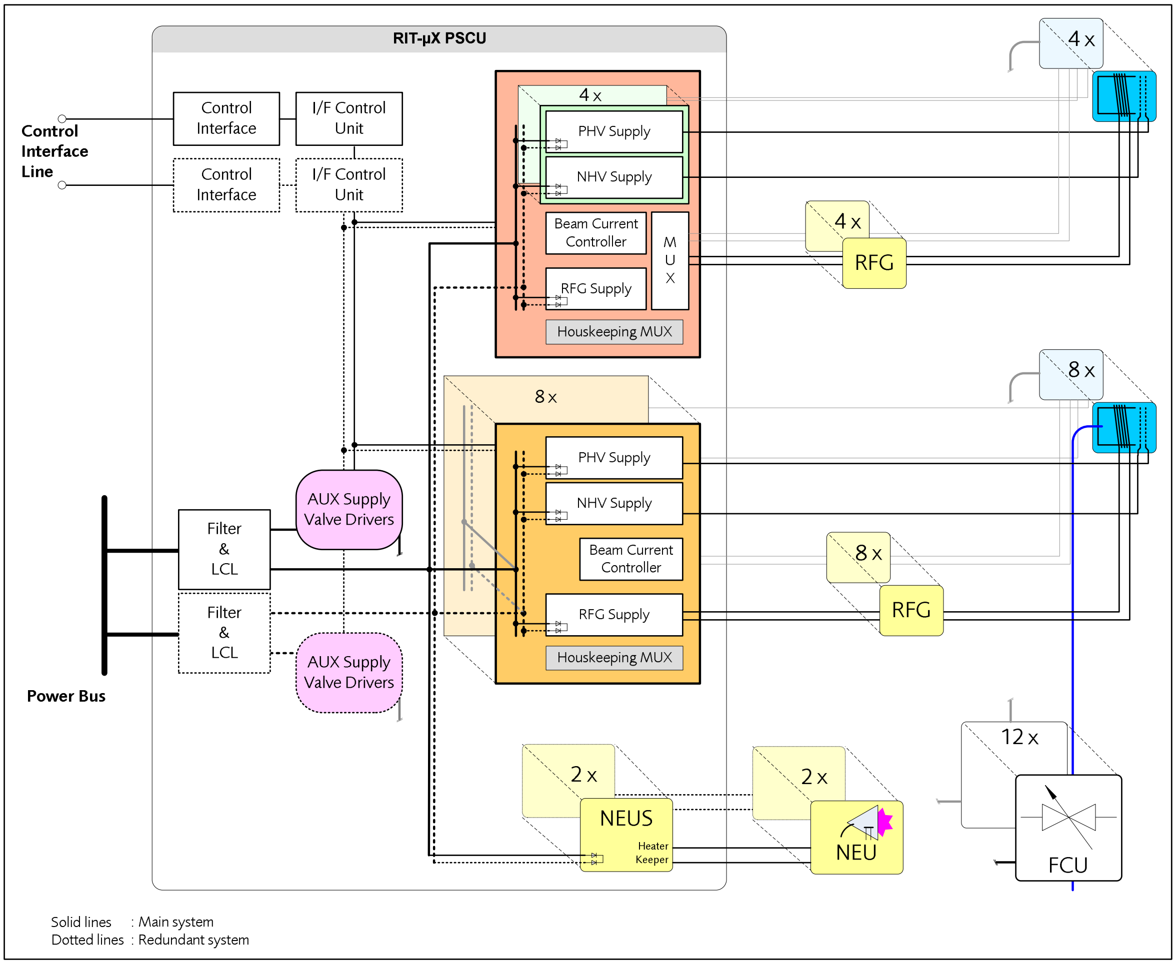


Figure 3 Principle Layout of a Power Supply and Control Logic for a RIT-µX Ion Engine System.

B. Neutralization

As any other gridded ion thruster RIT-µX expels positively charged ions only through its grid system. Consequently a source of negative charges is required in order to compensate the ion current. Different technologies are available with specific pros and cons.

Plasma bridge neutralizer:

This is the classical device as used today for larger ion engines. An inert gas (typ. Xenon), flows into the cathode chamber where it is ionised by electrons emitted from an insert (made of porous tungsten for example, impregnated with chemicals to reduce the work function for electron extraction). The insert is brought to termionic emission temperature (about 1200 °C) by an electrically powered filament (Heater) wound around the cathode tube and insulated by a potting material. Depending on the neutralizer, the heater is powered via AC or DC current.

An electrode (Keeper), biased positive with respect to the Hollow Cathode body, accelerates the electrons and assists in initiating and stabilizing the electrical discharge.

Once the discharge has been ignited, the heater is switched-off. Now the discharge between anode and cathode is self sustaining. The bombardment of ions from the plasma to the cathode heats up the cathode and ensures emission of electrons. The understanding of all processes inside the neutralizer is difficult. Especially a proper description of the "Hollow cathode effect" is a challenge. On the other hand plasma bridge neutralization is a technique with comprehensive heritage. Any SPT or Gridded Ion Thruster in space is equipped with a plasma bridge neutralizer.

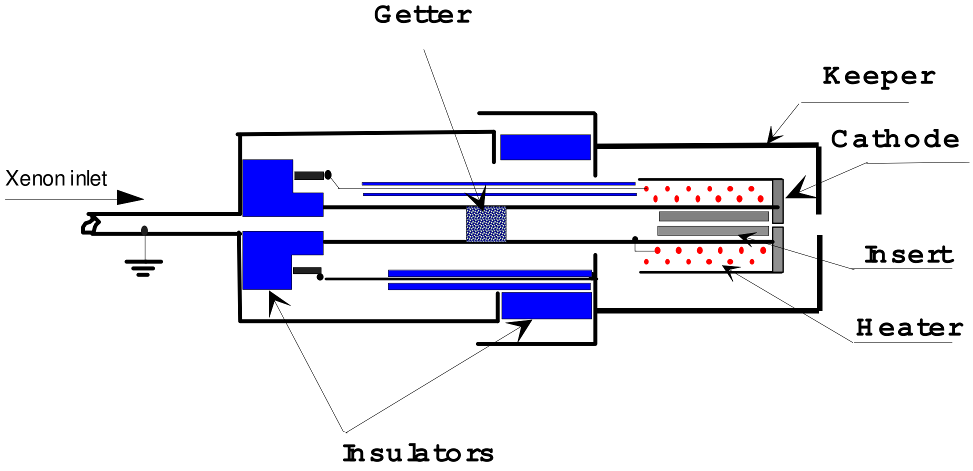


Figure 4 Hollow Cathode Neutralizer configuration

The main disadvantage of a plasma bridge neutralizer is the additional Xenon consumption. The use of a neutralizer as available (designed for "small" ion engines as RIT-10, T-5 or XIPS 13) might need more propellant for neutralization than for the complete set of ion engines. On the other side the plasma bridge concept has an inherent advantage: The electron current via the plasma bridge into either beam or free space counterbalances the ion current exactly without any additional control efforts.

Gas free neutralization:

In contrast to the small conventional ion engines as mentioned above the ion current and thus the required electron current for RIT-µX is at least one magnitude lower. This is the key for use of gasless systems. One example is described hereafter: On the basis of space qualified traveling wave tubes THALES Electron Devices has developed a low power gas free neutralizer for up to 11 mA of electron current. The improvement of the specific impulse by use of a gasless neutralizer is evident. Moreover the use of such devices simplifies the flow control structure of the propulsion system and it improves the system's specific impulse.

THALES Electron devices' technology bases on an impressing space heritage and ground heritage. Since 1991 more than 174,000 hours were successfully accumulated in ground tests. In orbit the devices did and are doing their jobs on missions like ERS 1, ERS 2, ENVISAT, CASSINI….

As mentioned, the maximum current of this type of neutralizer is limited to 11 mA. So it represents a suitable solution for a RIT-µX working in the micro-Newton regime.

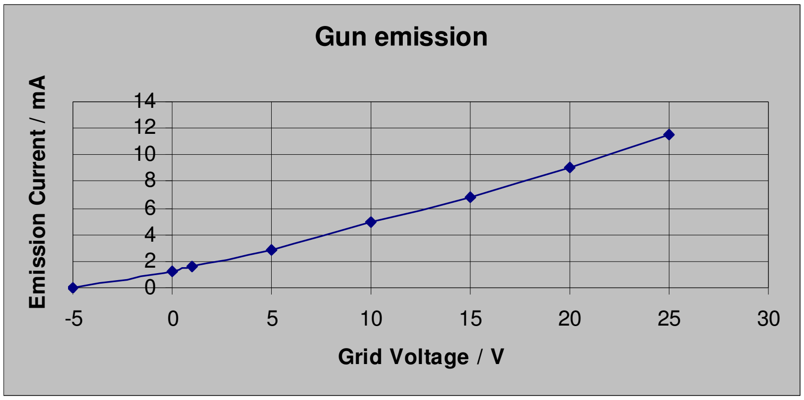


Figure 5 Emission characteristics of gas free cathode developed by Thales Electron Devices.

RF sources as neutralizer:

Availability of classic plasma bridge neutralizers as well as gasless systems ensure that there will not be any deadlock for the further RIT-µX development and most probably one of these two options will be selected, but it is worth to mention a third option.

Although the plasma bridge neutralizer and the gasless Thales system are working fine on ground on and in space they have a common disadvantage: The cathodes are very sensitive against contamination by humidity and oxygen. In worst case a contamination leads to a full loss of function. So, special care is required during storage, handling and operation of the neutralizers. Another concern is the process of ground verification onboard the complete spacecraft: For operation high vacuum conditions are mandatory.

The sensitivity against ATOX might become a strict show stopper for missions in low and lowest Earth Orbit. The high amount of atomic oxygen might reduce the system lifetime drastically.

Following the rf-principle of the RIT-technology the idea of an 'RF electron source' was born. The ionization is similar to an RF- thruster. Instead of ions electrons are extracted from the discharge plasma. This technology is cathode free. Under research contracts of the German Space Agency, these types of electron sources are under development at the 1st Institute of Physics of Giessen University and the IOM Leipzig.

C. Flow Control Management

A real challenge for the development of an RIT-µX system is the Xenon management. The use of an conventional Flow control systems is not satisfying mainly for three reasons:

- The mass of the required valves is high compared with the mass of a RIT-µX ion engine
- The power consumption of conventional valves compared with the total system is high too
- Open and close of the valves might introduce additional momentum to the spacecraft. For most application this aspect is negligible, but for some advanced scientific missions intended to investigate extremely small forces it might be relevant.

In the following, the design of a traditional flow control system is described and the tasks of the system are derived. This is the point to start over with advanced concepts.

The Xenon feed system represents the interface between Xenon tank and ion engine. It reduces the high pressure at the tank to an adequate level and it controls on of the engine's key parameters, the Xenon mass flow. The accurate control of the Xenon flow is mandatory to ensuring engine operation with maximum specific impulse and minimized grid erosion. The Xenon feed system consists of fill and drain valves, isolation valves, filters, tubing and the pressure and flow control system.

Classical pressure and flow control systems have dual stage architecture: a pressure regulating stage feeds the propellant into a flow restrictor downstream. As electric propulsion gains currency, the xenon feed systems are evolving but the dual stage architecture is remaining.

The pressure control stage is typically either a mechanical or an electrical pressure regulator and the flow control stage contains a fixed restrictor, a proportional valve or a thermal restrictor.

Pressure Control Stage

Pulsed Valve Regulation System

The Pulsed Valve Regulation System (Bang-Bang) is a simple electronic pressure regulator. It includes the use of a solenoid valve in conjunction with an accumulator tank (plenum). The solenoid valve is the "regulator" in the system and the plenum reduces the pressure spikes and smoothes oscillation. Nevertheless the resulting flow characteristic is a saw tooth (e.g. Moog Model 51E186 (200g)) [2].

Proportional Valve

Evolved from the Pulsed Valve Regulation System, the proportional valves offer a compacter design and a faster response time. There are plenty of different valves available which differ among others in the type of actuator used. Designs base on magnet- restriction, proportional solenoids, piezo effect and squeezed flexible tube exist.

Flow Control Stage

Proportional Valve

A typical flow regulation method is the use of a valve. The flow rate varies as the distance between a valve seat and a valve cap is changed [12.

Fixed Restrictor

Fixed restrictors like an orifice, a capillary or a tube with build-in wire are throttling the flow depending on the attached pressure and temperature. Flow control is achieved by regulating the system pressure upstream of the restrictor, which responses with a specified flow rate at a given pressure and temperature.

Thermal Restrictor

Controlling the flow via a Thermal Restrictor is a very simple technique used for fine control. Gaseous xenon is directed through a capillary which is in contact with a heater. An increasing gas temperature leads to an increasing viscosity and a decreasing density. Therewith the mass flow declines and the achievable turn down ratio is around 1:5 (e.g. Marotta UK Capillary Thermal Flow Controller (20g)) [12]. The effect of thermal expansion is negligible with the use of a capillary. While on the contrary flow through an annular gap with a sufficient radius uses the thermal expansion in addition to the change in density and viscosity (e.g. Marotta Thermal Throttle(11g)). The flow turn down ratio coming along with this design is infinite.

Integrated Pressure and Flow Control System

As mentioned before a complete AOCS system consists of numerous engines, up to 8 in the case of 6-DoF operation, not counting the redundant ones. To prevent unnecessary grid erosion and loss of specific impulse each RIT-µX demands for separate control of the Xenon flow. Using conventional components leads to a heavy and power consumptive flow control unit. Both, mass and power demand can be significantly reduced by use of fully integrated miniaturized design. Savings in the order of a magnitude seem feasible. [14].

Figure 6 illustrates the way forward froma conventional flow control concept to an advanced approach base on micro mechanics. In an intermediate step classic valves are replaced by miniaturised components. In the final step all required components are integrated into on chip. Besides the reduction of weight and size the introduction of micro structures might lead to a significant cost reduction. NanoSpace is one of the European companies working in the field of Micro Electro Mechanical System based (MEMS) xenon feed systems: Silicon wafers are stacked together in a modular building concept. The different wafer stacks contain several components and functions such as isolation valves, filters, flow control valves, and thermal flow restrictors. The feed system uses a flow regulation valve for coarse tuning. In addition, fine tuning is achieved by a thermally-actuated flow restrictor. The fine tuning modulation is in the order of 25-30% at constant inlet pressure [14].

A similar system is under development at Thales Alenia Space (Florence, Italy)

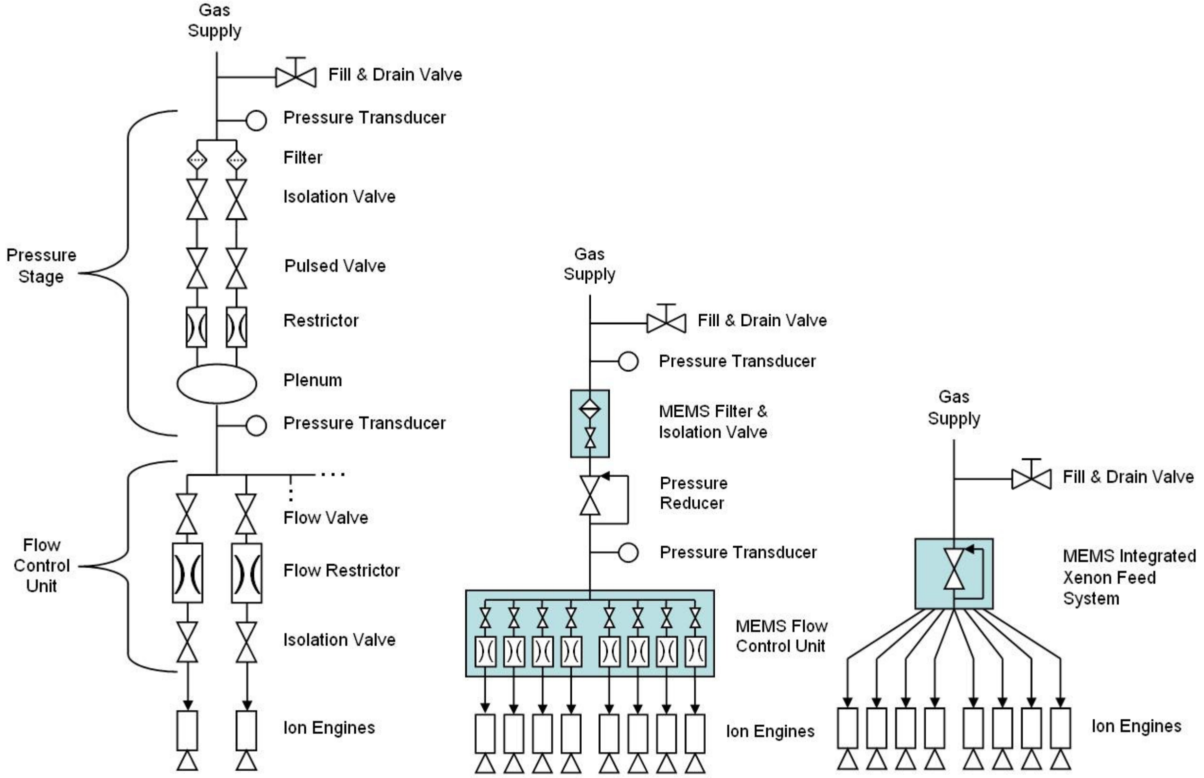


Figure 6 Schematics of a generic xenon feed system using discrete components, schematics of the xenon feed system based on Micro Mechanical Xenon Feed System by Nanospace and schematics of the next integrated xenon feed system (from left to right) **[14].**

	Eurostar 3000	Artemis	SMART-1	MEMS Integrated Xenon Feed system
Pressure stage mass	5,62 kg	2,8 kg	8 kg	0,8 kg
Flow control unit mass	4 x 0,58 kg	4 x 2 kg		
Total mass of XFS	7,94 kg	10,8 kg	8 kg	0,8 kg

Table 2 Comparison of Xenon Feed System masses of miscellaneous satellites with the NanoSpace MEMS Integrated Xenon Feed System.

IV. RIT-µX Thrust Control

The development of a RIT-µX micro propulsion system requires efforts for the development of the power supply and control logic, the neutralization and the Xenon flow control system. On the other hand RIT-µX offers excellent thrust control combined with lowest thrust noise. Results of a measurement are shown in Figure 7 and Figure 8 . For a detailed description of the test setup please refer to **[2]**

The thruster was operated at a constant thrust level using the stabilization of the BCC device. As any RIT allows a trade-off , power versus mass efficiency, a high mass efficiency has been selected to reach an ISP of 2700s.

The beam current has been sampled over a period of about 10 hours at a data acquisition rate of 50Hz (integrating) and finally the equivalent thrust was calculated.

As displayed in Figure 7, the thrust is very constant over the measured period. The typical noise is in a band of 10nN, but it seems there is also an amount of spikes of higher amplitude. For a better understanding of these spikes a histogram of the thrust values of the full dataset has been compiled. Figure 8 shows the frequency of the measurement of a specific thrust level. In contrast to the thrust versus time plot the histogram clearly indicates, that the above-mentioned spikes are rare in occurrence. The optical impression of the simple thrust vs. time plot is misleading. The standard deviation of the thrust is only 2.3nN. Although the spikes seem high compared to the average noise all of them are covered in a band of less than 0.1µN. This demonstrates the potential of the RIT technology to provide reliably a very constant thrust even over long periods and at low thrust levels.

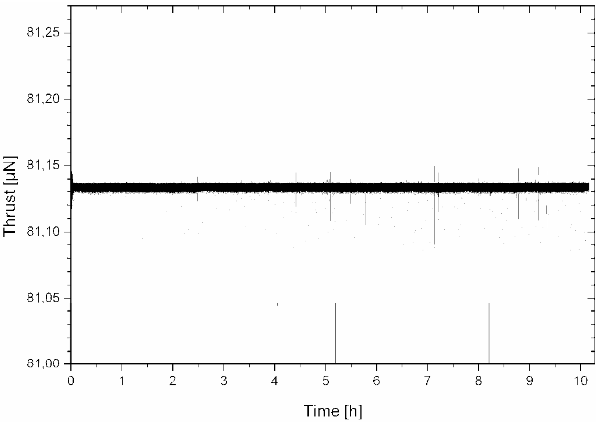


Figure 7 Thrust over a period of 10 hours, sampling frequence 50Hz

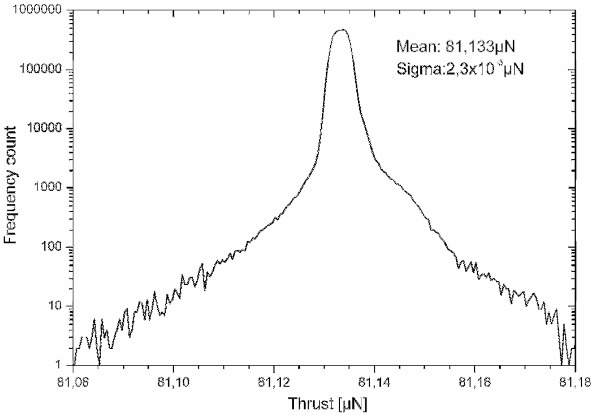


Figure 8 Histogram of the Thrust measurement

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