Tests of an iodine fed RF-neutralizer

IEPC-2019-207

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

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Iodine is a viable alternative to substitute xenon as propellant at least in some mission scenarios. As a consequence reliable neutralizers for operation with the halogen are required. One suitable neutralizer concept is the so called RF-neutralizer. We show that the performance using a RF neutralizer derived from a RIT-4 design with I_2 is comparable to that with Xe as long as gas utilization factors are larger than $10\,\mathrm{mA\mu g^{-1}s}$. Simulations using a global model are in qualitative agreement with the experimental results, but also reveal that the optimal design parameters for the RF neutralizer's components such as the collector and the orifice plate will differ for the two propellants. In our studies we have not encountered any issues related to corrosion.

Nomenclature

$I_{\mathrm{collector}}$	= Current absorbed by the collectors
P_{RFG}	= RFG-power (either input or output)
j_{Bohm}	= Bohm-current-density
ν	= Gas utilization factor
μ	= Electron extraction costs
$\dot{N}_i$	= Flow of ions reaching the collector
$\dot{N}_n$	= Flow of atoms injected in the discharge-vessel
$A_{\mathrm{collector}}$	= Area of the collector
n_{i}	= Density of ion species i
m_{i}	= Mass of ion species i

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I. Introduction

THE neutralization of the ion beam is a mandatory task when operating electric thrusters, such as gridded ion engines or Hall effect thrusters. Iodine appears to be a viable option to replace xenon, since its performance has found out to be competitive with xenon operating hall thrusters as well as gridded ion engines.[2,5,7] However, the predominately used hollow cathodes with inserts coated by either barium oxide or lanthanum hexaboride when operating the electric propulsion system with xenon will not reach the required lifetimes operating with the reactive halogen. Therefore, alternative concepts are of paramount importance. One strategy is to replace the insert-material of the hollow cathode with a material which is less prone to reactions at its operational temperature. One such candidate as an alternative insert material is the electride ceramic. One advantage of this material is its reported work function of only about 0.6 eV.[6] This allows one to operate the cathode at much lower temperatures compared to the currently used inserts. The lower temperature is advantageous for several reasons: Less thermal stress, reduced chemical reactivity and a reduced power demand. An other way to circumvent issues due to corrosion of the emitting surface is to use an RF-neutralizer instead of a hollow cathode, as discussed in this paper.
The paper is structured as follows. Section II describes the operating principle of the RF-neutralizer. Section III gives a brief description of a global model implemented for the simulation of the neutralizer operating both with iodine and xenon, while section IV discusses the experimental set-up used. The experimental and theoretical results obtained are shown and discussed in section V and section VI concludes the paper with a summary and an outlook.

II. Working principle of a RF-neutralizer

The principle of the RF-neutralizer is somewhat similar to that of a radiofrequency ion-thruster (RIT). Unlike the thruster, the neutralizer does not a require a grid system, but can be operated using a simple orifice. To fulfill the quasi-neutrality condition of the plasma, an ion current of equal absolute value to the extracted electron current has to be absorbed inside the discharge vessel of the neutralizer. For that purpose a conductive ion collector is inserted into the vessel. This need not to be metallic collectors, carbon-based materials can be used instead. The choice of material influences eddy-current losses and the lifetime of the neutralizer due to sputtering and, in the case of iodine, due to additional corrosion of the collector. For tests of the RF neutralizer a positively biased anode placed about 5 cm downstream of the orifice is used to mimic the potential of the ion beam acting as an anode. A schematic image of the neutralizer is shown in fig. 1. The neutralizer can be operated in two modes, which can be distinguished by the coupling between

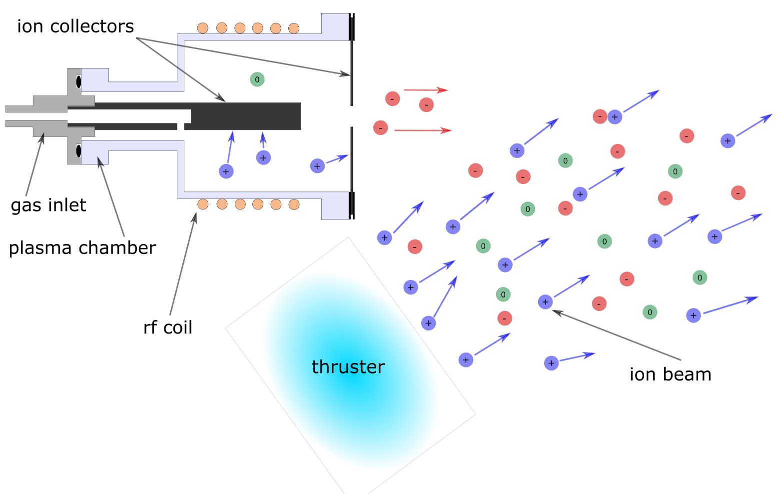

Figure 1. Schematic of the rf-neutralizer including the ion beam.

anode and collector. If the current absorbed by the collector depends on the voltage applied to the anode, a so called bridge mode is present. If this is not the case, the mode of operation is called diffusion mode. All experimental results discussed below have been obtained in diffusion mode.

III. Global model of the neutralizer

Slightly modified versions of the global models published by Grondein *et al* for iodine and Chabert *et al* for xenon were implemented for a better understanding of the behaviour of the neutralizer.[1,3] Both models solve a set of coupled differential equations to determine plasma parameters, more precisely densities and temperatures of electrons, ions, and neutral species. Both models assume a molecular flow for calculating the neutral gas loss, which may lead to a slight overestimation of the neutral densities. The published models were designed to simulate gridded ion thrusters. However, in a first approach, they can be adapted to simulate the neutralizer at least in diffusion mode. The current absorbed by the collector $I_{\mathrm{collector}}$ is calculated as the product of the area of the collector $A_{\mathrm{collector}}$ and the Bohm current density j_{Bohm}, which in turn depends on the plasma parameters. In summary, the absorbed current is calculated using:

$$I_{\mathrm{collector}} = 0.61 e A_{\mathrm{collector}} \sqrt{k_{\mathrm{B}} T_{\mathrm{e}}} \sum_{i=1}^{N} n_{\mathrm{i}} \sqrt{\frac{1}{m_{\mathrm{i}}}}. \tag{1}$$

Where e is the elementary charge, k_{B} the Boltzmann-constant, T_{e} the electron temperature, n_{i} the density and m_{i} the mass of ion species i. The probability for ions leaving the neutralizer via the orifice has been set to zero. Since the orifice-plate is also used as an negatively biased collector this approximation seems well applicable.

The Bohm current density is proportional to the inverse square root of the ion mass. Therefore an dissociative ionization of the iodine molecule may be advantageous to keep the required total ion density and, therefore, electron density low at a fixed collector current. In principle, a lower electron density requires less power to be provided by the radio-frequency-generator. This is in contrast to the operation of the thruster, where a high mass is advantageous due to the potentially large thrust to power ratio. Therefore, a good propellant in terms of power consumption of a thruster is not necessarily a good propellant for the neutralizer in that regard not vice-versa. However, the dependence of the degree of dissociation of a molecule on plasma-parameters such as electron density and electron temperature should be exploited to optimize the performance of both neutralizer and thruster.

IV. Experimental set-up

The experimental set-up consists of the vacuum chamber, test power-supply unit (TPS unit), a flow control unit, and the RF neutralizer itself. The cylindrical vacuum chamber is made of stainless steel and has a diameter of 1 m and a height of 0.7 m. The evacuation of the chamber is performed by a turbomolecular-pump of $1400\,\mathrm{l\,s^{-1}}$ backed up by a rotary-vane pump of $32\,\mathrm{m^3\,h^{-1}}$ pumping speed. The pumping system is complemented by a cryopump with a pumping speed of about $13000\,\mathrm{l\,s^{-1}}$ for xenon and atomic iodine and about $9500\,\mathrm{l\,s^{-1}}$ for molecular iodine. However, due to the extraordinary low mass flows of less than $30\,\mathrm{\mu g s^{-1}}$ required to operate the RF neutralizer, the pumping speed of the turbomolecular pump was sufficient to provide reasonable pressure conditions of less than $10^{-3}\,\mathrm{Pa}$.

The TPS-unit consists of various power supplies from the company FUG and a computer for controlling the power supplies via an Ethernet-interface. The power supply that provides the input power of the RFG is limited to a voltage of 125 V and a current of 5 A. Both collector and anode can be biased to $\pm 200\,\mathrm{V}$, the maximum current is 1.5 A. The power supplies are controlled and read out by a program implemented in Labview. The program includes a PID-controller for both the collector-current and the RFG-power.

A commercial mass flow controller (MFC) from Bronkhorst is used for controlling the xenon mass flow. Unfortunately, no commercially available MFC can provide the required flows for operating the neutralizer with iodine. Therefore, we decide to use a customized flow-control unit. The unit consists of a heatable regulation valve, an orifice of about $150\,\mathrm{\mu m}$ in diameter and a heatable capacitive pressure sensor MKS 631D with a range of 40 kPa. The valve can be manually adjusted to control the flow. The orifice is installed downstream of the valve and leads to the appearance of a choked flow. The flow is linearly correlated with the stagnation pressure on the upstream side of the orifice, which is monitored by the capacitive pressure sensor with a accuracy of better than one percent. The calibration of the flow control unit was conducted by measuring the stagnation pressure as function of a nitrogen flow provided by a calibrated mass flow controller. The equivalent iodine flow can be calculated taking the relative thermal velocity into account:

$$Q_{\mathrm{I}_2} = Q_{\mathrm{N}_2} \cdot \sqrt{\frac{M_{\mathrm{N}_2}\, T_{\mathrm{I}_2}}{M_{\mathrm{I}_2}\, T_{\mathrm{N}_2}}} \tag{2}$$

making use of $Q_\mathrm{i} \propto v_{\mathrm{th,i}}$ and $v_{\mathrm{th,i}} \propto \sqrt{T_\mathrm{i} M_\mathrm{i}^{-1}}$.

The neutralizer is based on a modified RIT-thruster with a cylindrical plasma vessel of 4 cm in diameter. Several parts of the neutralizer have multiple functions. Both, the gas inlet and the orifice, are used as ion collector in addition to functioning gas flow control elements. The orifice diameter has been chosen to be 6 mm. At first sight, the orifice diameter may seem rather large, but it is the best choice for the use with iodine. The reasons will be addressed in the following. The neutralizer has been ignited by a xenon pressure shock while one of the collectors was biased to about 1500 V. In case of iodine, the operating gas was then replaced by iodine.

V. Results and discussion

Figure 2 shows the measured electron extraction costs μ as function of the gas utilization factor ν. The extraction costs are defined as the inverse ratio of current absorbed by the collector divided by the sum of the RFG-input-power and the collector-power. The gas utilization factor is determined by the ratio of the current absorbed by the collector and the injected mass flow. For xenon the extraction costs rise with the gas utilization factor almost in the entire range covered. For iodine, a distinct minimum is visible, most pronounced at a current of 100 mA. The minimum appears to shift towards larger gas utilization with increasing current absorbed by the collector. Despite the apparently large orifice diameter double digit values of ν could be reached for both propellants in the entire range of operation. The extraction costs are similar for xenon and iodine for a collector-current of 200 mA. At the lower collector current of 100 mA xenon is generally performing better in the range covered, but not to a dramatic extent.

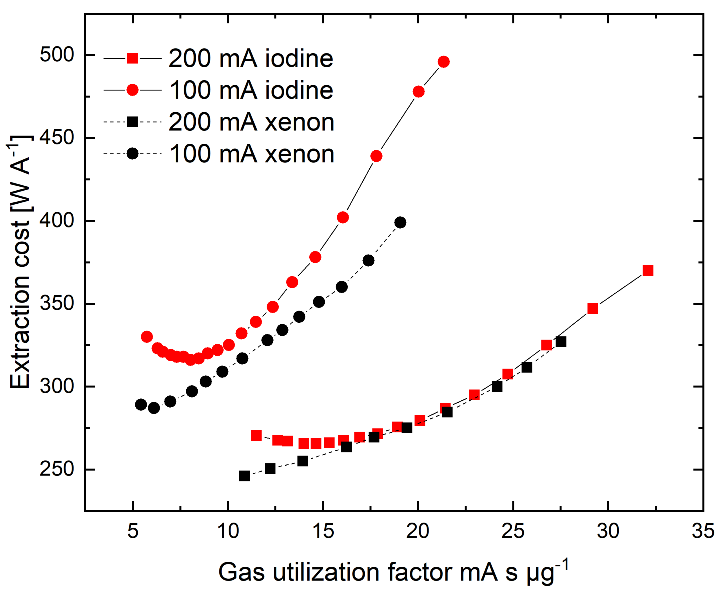

Figure 2. Measured extraction cost versus gas utilization factors for xenon and iodine for fixed collector currents of 100 mA and 200 mA. The mass flow is varied and the input voltage of the RFG is adjusted to yield the collector current.

We have further studied the dependence of both μ and ν as function of the input power of the RFG as shown in fig. 3. The gas utilization factors obtained for both propellants are almost identical and rise approximately linearly with the output-power of the RFG. The electron extraction costs are slightly lower for iodine. This result seems to be in disagreement with the results presented in fig. 2. The most likely reason may be perturbations of the iodine flow. For example, if the orifice used for regulation is covered by a homogeneous iodine-layer of only 5 µm thickness caused by resublimation of the halogen, the flow will be reduced by about

13%, which will lead to a significant change in the collector current. Therefore, small differences in the results need not be correlated to properties of the discharges alone. In general, the extraction costs are

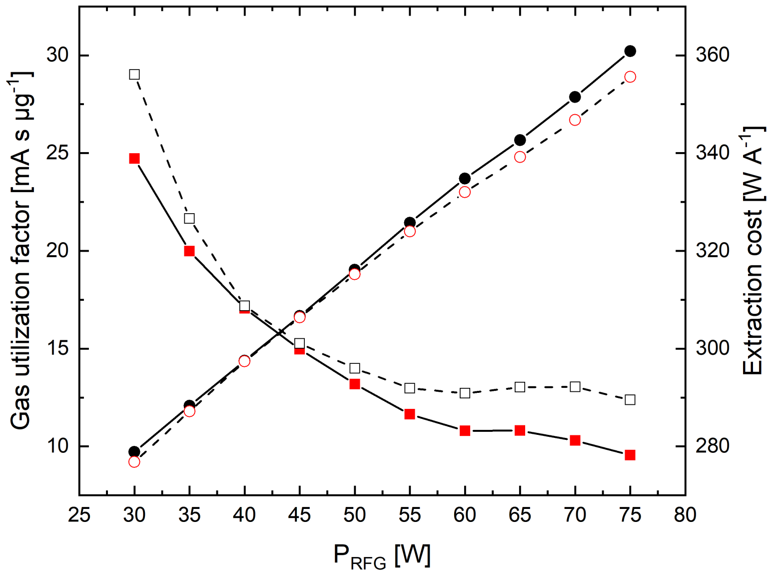

Figure 3. Measured extraction cost (squares) and gas utilization factors (circles) for xenon (Open symbols) and iodine (full symbols) as function of the input power of the RFG. The mass flow was set to 10 µgs^{-1}. The collector is biased to -30 V.

comparable and rather high. The extraction costs decrease with increasing RFG power, but remain in a range of $(320 \pm 40)\,\mathrm{WA}^{-1}$ for collector currents of about 100 mA to 300 mA. Hatakeyama *et al* achieved extraction costs of less than $100\,\mathrm{WA}^{-1}$ with an inductively coupled RF neutralizer at a gas utilization factor of $7.68\,\mathrm{mA\mu g}^{-1}\mathrm{s}$ extracting 1.5 A. Hollow cathodes can be operated at even lower extraction costs, e.g. lower than $35\,\mathrm{WA}^{-1}$ at a current of 4 A as published by Hatakeyama *et al.*[4] As fig. 2 and fig. 3 suggest, the extraction costs may slightly decrease at higher extraction currents.

Currently, the aim of our work is comparing the properties of xenon and iodine in RF neutralizers. There is certainly room for improving neutralizers in terms of performance parameters such as electron extraction costs and gas utilization. One more important reason, at least in the case of xenon, why these performance values are not optimal yet, is the rather large diameter of the orifice. It leads to increased neutral gas losses and, furthermore, prohibits an operation in the plasma bridge mode. The simulation results based on the global models in fig. 4 a) confirm that a smaller diameter is favorable when using xenon, even if one considers only the diffusion mode. The absorbed current rises monotonously by lowering the orifice diameter. The larger neutral densities lead to an increasing ion density and, therefore, higher extraction currents. Even at an orifice diameter three times smaller compared to the currently used design the optimum diameter seems still to be significantly smaller. However, this statement is not true for the halogen iodine. While the density of neutrals will increase, this is not necessary true for the ions since losses due to excitation of the atom lead to an decreasing ion density. The excitation of the molecule is not considered yet due to a lack of available cross-sections. Loss by excitation is also relevant in the case for xenon, but is only relevant at much higher discharge pressures due to significantly smaller cross-sections of the excitation process. The choice of an orifice of 6 mm in diameter appears to be already optimal concerning the operation of the neutralizer with iodine in the diffusion mode. As mentioned in section III, the global models only consider a molecular flow. The calculated pressures in the 0.1 Pa regime may be too high to neglect effects of an superimposed viscous flow. Therefore, we recently modified the calculation of neutral-flow leaving the neutralizer. Since the orifice has typically a diameter larger than its thickness, the viscous flow regime may be better described by a choked flow as compared to a laminar flow through a pipe. Since the pressure drop might be too low to fully describe the viscous flow with a choked flow, we introduced a weighing factor α for the choked flow. Figure 4 b) shows the effect of considering an superimposed vicious flow. The optimal diameter of the orifice, where the collector current is highest, is shifted significantly towards a lower value of about 4 mm. However, one has to be cautious about the interpretation of the curves shown, since in reality the weighing factor is most likely a function of the diameter of the orifice. More experimental studies are needed to clarify this point.

The operation in the plasma bridge mode using iodine will require a smaller orifice than currently used. This will inevitably lead to the requirement of even smaller mass flows of iodine than already obtained to prevent exceptional high excitation losses. On the one hand, the control of the required flows of only a few $\mu g s^{-1}$ might be challenging, on the other hand, the mass demand on propellant will be extraordinary low. For a operation time of ten thousand hours with a mass flow of $1\,\mu g s^{-1}$, the total amount of consumed propellant sums up to 36 g. This amount of iodine could be stored in a sphere smaller than an golf ball. It should be noted though, as fig. 4 a) suggests, that the use of xenon for the neutralizer is definitely better in cases where the available RF-power is strongly restricted.

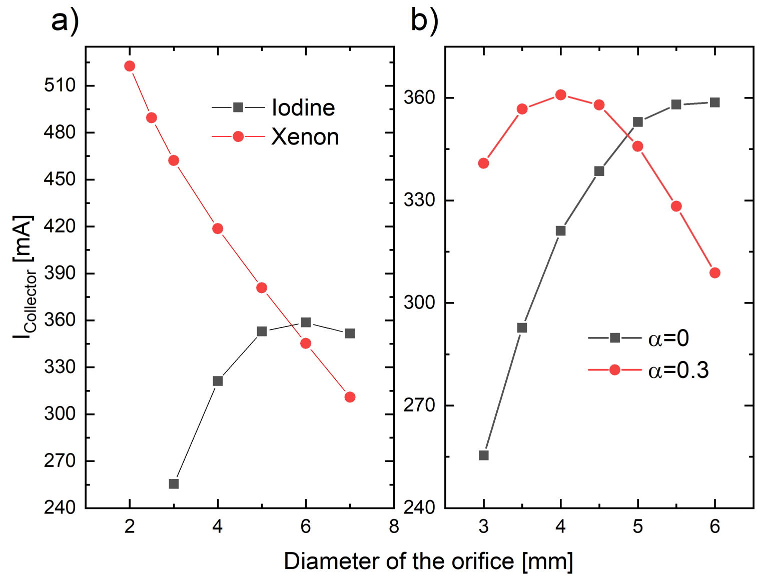

Figure 4. a) Simulated dependence of collector current as function of the orifice diameter for both xenon and iodine assuming a molecular flow. b) Simulated dependence of collector current as function of the orifice diameter for iodine assuming either a molecular flow or a intermediate flow. α is a weighing factor for a choked flow. The mass flow was set to $10\,\mu g s^{-1}$ and the output-power of the RFG to 50 W in both simulations.

VI. Summary and outlook

A prototypical RF-neutralizer was operated with both xenon and iodine for assessing differences in operation with the two chemical elements. It was shown that the performance obtained with both propellants is similar, as long as sufficiently small neutral gas densities are used. The same result was recently published for the operation of a thruster of the RIT-type.[5] The results of the experiments and global models are in qualitative agreement. Future experimental activities will focus on the operation in the plasma bridge mode and investigations of the lifetime. Furthermore, a more elaborate ignition procedure has to be developed, which allows to ignite the neutralizer without a pressure shock and, even more importantly, directly with iodine. The first results are rather promising, in particular, as the neutralizers design is not optimized yet. The room for improvements makes RF neutralizers suitable candidates for several missions using gridded ion thrusters or Hall thrusters with iodine as propellant.

Acknowledgements

This work has been supported by the Federal Ministry for Economic Affairs and Energy under contract 50RS1709.

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