Development of a capacitively coupled insert-free RF-neutralizer

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Abstract: The extraction of electrons from a capacitively coupled RF-Xe discharge is studied experimentally. RF-power and Xe flux are in the range of 0.3-50 W and 0.2-5 sccm, respectively. The constructive details and the efforts to realize plasma-bridge like characteristics for the extraction will be described. The investigation is motivated by the fact that conventional hollow cathodes used for ion beam neutralization are critical elements. Insert depletion and malfunction resulting from exposure to oxygen or water or break down of the insert heater can occur. The extraction of electrons out of RF-driven plasma avoids the use of electron emitter materials.

Abbreviations

CCD = Charge Coupled Device
EEDF = Electron-Energy-Distribution-Function
RF = Radio Frequency
RFG = Radio-Frequency-Generator
MFC = Mass-Flow-Controller

I. Introduction

Hollow cathodes with heated inserts are generally used for charge neutralization of ion beams from ion-thrusters and as cathode in Hall-effect thrusters. It is known, that the lifetime of these cathodes is limited by insert depletion and decreases dramatically if the insert temperature is higher than required or if the insert heater breaks down. Oxygen and water vapor impurities in the Xe-propellant or wrong handling before and while lift off can passivate the insert material. The insert needs relatively high operation temperature and has to be preheated, making fast switching on or off impossible. In consequence, electron sources without the critical insert are of great interest.

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II. Project Idea (Function Principle)

In this sense one may try to produce sufficient electrons in an RF- discharge, which replaces the insert of the hollow cathode (see Figure 1). The electrons have to be extracted by an electric field. One can easily estimate that each Xe atom supplied to the source has to be ionized and neutralized by contact with the chamber wall repeatedly for efficient operation. The ions hit the walls by diffusion processes, collect electrons from the wall, become neutral and can be ionized again.

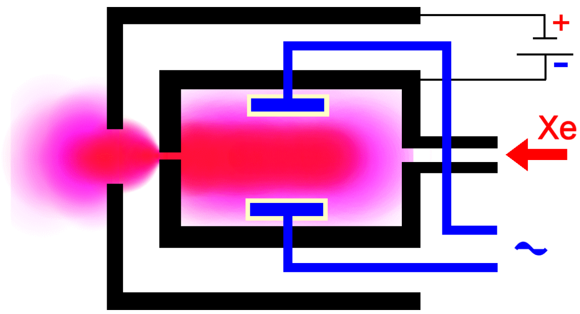

Figure 1. Principle of capacitive neutralizer – the insert has been replaced by RF-electrodes

In principle the RF-discharge can be inductively or capacitively driven. In an inductively driven discharge electrons are accelerated in circular trajectories following the induced electric eddy field. In a capacitively coupled discharge, which is the subject of the present study, the electric field is directly generated by the applied RF-voltage.

Whereas the principle sounds temptingly simple, various characteristics are inherently disadvantageous for the development of an efficient capacitively coupled RF-neutralizer device: The mean free path for the ionizing collisions of the electrons should be significantly lower than the distance of the RF-electrodes, setting a lower limit for the pressure inside the device.

Due to the low plasma density of capacitive discharges, a large orifice size is required for extraction of a high electron current. However with respect to a low consumption of gas, the orifice size is limited.

Therefore similar as for the hollow cathode, the electrons have to be conducted by a plasma bridge from inside to outside requiring a sufficiently large plasma density close to the orifice.

Besides, the capacitive coupling will provide plasma with high electron temperature causing a high diffusion rate of electrons and ions to the electrodes, a high plasma potential and electron loss.

III. Technical Concept and Realization

As mentioned before, the mean free path for the ionizing collisions of the electrons should be significantly lower than the distance of the RF-electrodes. Increasing pressure in the discharge vessel is accompanied by a reduction of the mean free path, but lowers the orifice size for an acceptable mass flow. Properly chosen magnetic fields increase the traveling distance of the electrons between the electrodes compared to the mean free path. Optimization in geometry will lower the impedance of the device and should result in lower electron temperatures for a given input power.

According to these main constraints a hexapole-configuration with crossed magnetic and electric fields is aimed for.

Six tungsten electrodes covered by alumina are placed inside a stainless steel cylinder (see Figure 2). These electrodes are alternatingly connected to the RF-voltage externally applied. The use of six electrodes (multi-pole-configuration) sextuples the number of discharges compared to dipole-configuration and lowers the impedance of such a device. Outside the cylinder, six permanent magnets are placed with alternating magnetization inside an iron-stator to provide a magnetic hexapole-field.

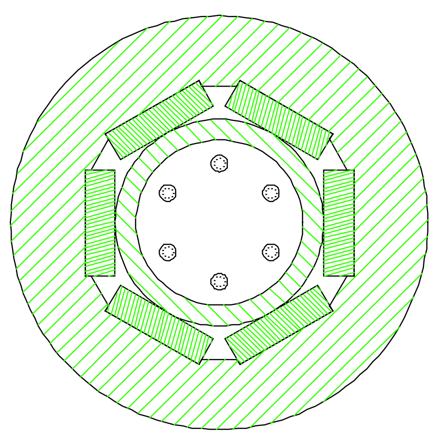

Figure 2. CAD-Drawing of neutralizer

The cylinder is topped by a steel plate, which takes the bushing for the electrodes and the gas-inlets. The opposite opening of the cylinder is covered by a diaphragm with a centered orifice made of Carbon composite. A second diaphragm made of graphite follows. This diaphragm serves as keeper electrode and is mounted in a 1 mm distance from the lower diaphragm. Figure 3 displays calculated magnetic field lines and electric equipotential lines.

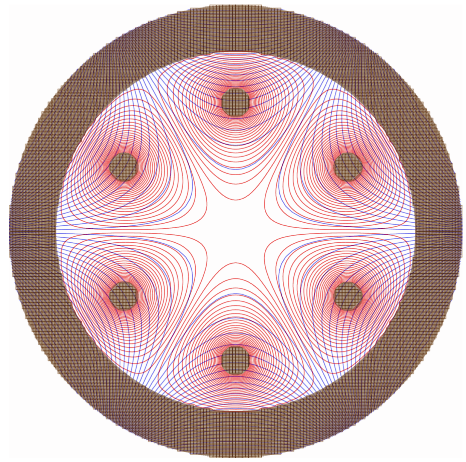

Figure 3. Simulated electric equipotential lines (red) and magnetic field-lines (blue)

The chosen field configuration spirals the electrons around the magnetic field lines. In this way the traveling path of electrons before hitting electrodes or walls and in consequence the collision frequency is increased considerably. A further advantage of the hexapole-structure is the relatively weak magnetic field in the center. In the present case it amounts to less than 0.01 T with respect to 0.2 T between the electrodes and 0.4 T at the cylinder surface. Such inhomogeneous fields are associated with a concentration effect but still permit electron extraction along the cylinder axis, though electron-collisions are the main mechanism for the electrons to diffuse to the central part of the cylinder. Nevertheless to provide sufficient electrons on the axis for extraction an additional radially directed electric field is required. This is achieved by raising the potential on the center-axis. A possible way to do so is to use a plasma bridge. The good conductance of its very dense plasma will shift the potential on the neutralizer axis and in particular near the orifice in the direction of an external potential.

It is in any case important to initiate a plasma bridge. The diffusion of electrons from the plasma boundary layer into the orifice similar to the ion extraction mechanism in gridded ion thrusters will yield too small electron currents. For igniting the plasma bridge, the keeper electrode is added.

Without an ion-beam, a suitable target is required for operation: All electrons are to be collected but no gas should be rejected. The target consists of a steel grid to provide a homogeneous electrical field and chevron lamella for good gas throughput while collecting all electrons passing the grid.

Figure 4 shows the extraction components and the target (right hand).

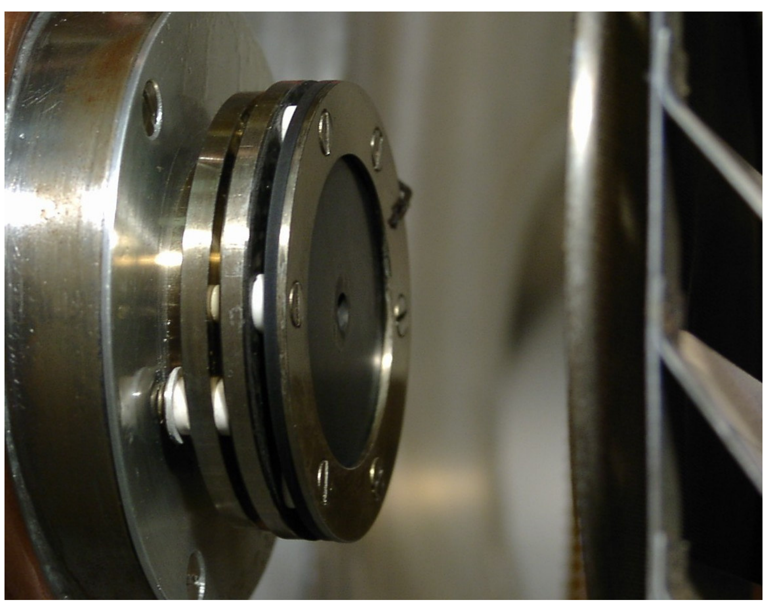

Figure 4. Neutralizer with target on the right

IV. Test Setup and Data Acquisition

The high impedance of the described electrode-configuration requires a high voltage RF-supply with symmetric outputs. An RF-transformer is used to match the low impedance of conventional RF-generators (typical 50 Ω) to the higher electrode impedance (10 kΩ - 300 kΩ, depending on prototype). The center tap is biased by a capacitor to ensure symmetric voltages (see Figure 5).

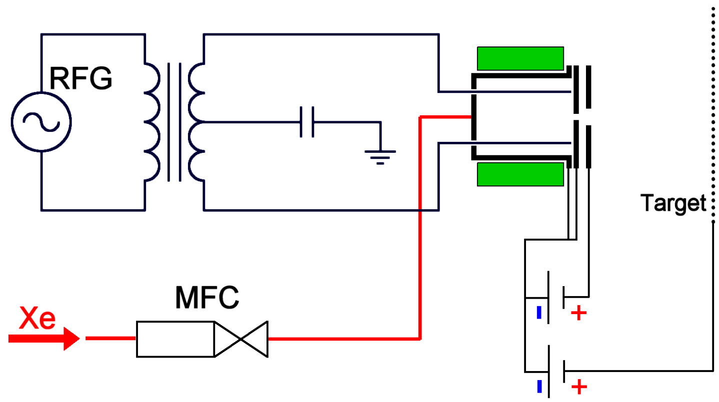

Figure 5. Schematic circuit diagram

For testing, there are two test-chambers available, named P2000 and BicMac.

P2000 has a volume of 100 l. It is equipped with a 24 m³/h rotary pump and a 2000 l/s oil diffusion pump. Pump down time is below one hour; base pressure is about 5E-6 mbar but can rise up to 1E-4 mbar at high gas-flow rates. So this chamber is best choice for rapid testing of mechanical alterations.

Three viewports provide coaxial and orthogonal optic access for visual analysis and spectroscopy. Furthermore a microprocessor-controlled positioning device is installed inside the chamber to vary the distance of a beam-target or the position of Langmuir probes.

BicMac is a chamber of 2 m³ volume. It is equipped with a 20 m³/h rotary pump and a 750 l/s turbo-molecular pump for continuous operation, a 35 m³/h rotary pump together with an 270 m³/h roots pump for rapid pump down and two cryo-panels providing 24000 l/s pumping speed for Xenon.

Base pressure amounts to 1E-7 mbar and does not rise above 8E-6 mbar during neutralizer tests. Total pump-down time is about one day. So this chamber is suitable for taking performance curves especially at higher flow rates where too large ambient pressure influences the behavior of the plasma bridge drastically. The neutralizer and the RF-electronic have been placed on a flange that can be mounted to both test-chambers without modifications.

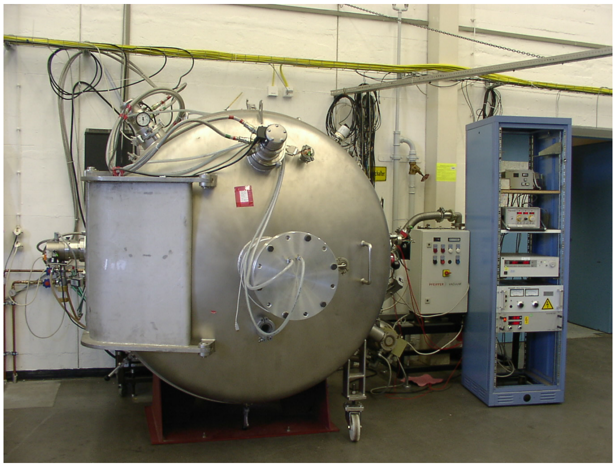

Figure 6. BicMac test chamber

The **data acquisition,** which is used at both vacuum-chambers, runs with Delphi-programmed software on an industrial PC, gathers data from various external devices via RS232 or through ADC-card. It controls the flow controller, displays all data and provides this data via TCP/IP to external diagnostic e.g. Langmuir probe unit. A relay-multiplexed multimeter acquires temperatures and monitors all DC-currents on electrodes of the neutralizer. The inserted RF-power is measured by an RF-power transducer. The amplitudes of RF-voltage and RF-current to the RF-electrodes are measured by RF-rectifier, and permit determination of the RF-impedance. The presented experimental results were obtained for a frequency of 13,56 MHz.

V. Measurements and Results

In the beginning prototypes have been built and tested, using Argon as operating gas until the present configuration was chosen.

Operation of the present prototype in the P2000 test-chamber with Ar (see Figure 7) showed extractable currents roughly proportional to the applied RF-power (see Figure 8). The target-voltage was set to 90 V, the current reached over 100 mA.

For the optimization of discharges and geometry a good knowledge of plasma parameters like electron temperature, neutral, ion and electron density is of great importance. Various techniques to determine these parameters are established. Here, electron temperature and electron density were determined by Langmuir single probes.

Inserting the Langmuir probe on the center axis halfway in through the orifice yielded the dependency of the electron density and the RF-amplitude displayed in Figure 9. The inner pressure amounted to 0.3 mbar; no electrons were extracted. Electron densities in the range of $10^{16}/m^3$ were derived, rising linearly with increasing RF-amplitude and saturating at power values above 5 W. Significant changes in electron temperature, derived to be 3.5 eV, were not observed up to 10 W; for larger values of RF-power the tendency is uncertain due to too large error bars. During extraction the electron density must be significantly higher but the determination was not yet possible.

Measurements with Langmuir probes in RF-discharges, in particular in small discharges, are difficult due to the fact that the measured IU-characteristic is a convolution of the true characteristic and the alternating plasma potential induced by the RF-voltage. Manual interpretation of any measured characteristic curve is necessary to derive reliable readings; especially the values for electron temperature are highly sensitive. Furthermore the EEDF is not necessarily Maxwellian. For that case the electron temperature reading corresponds to the low energy branch of the EEDF.

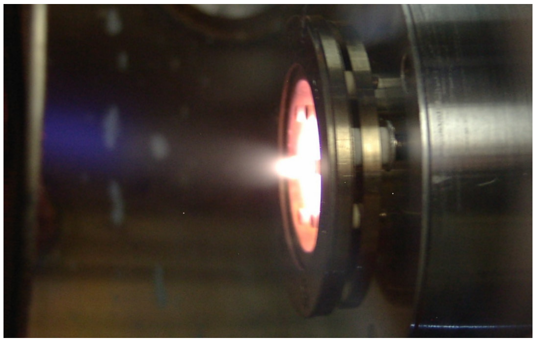

Figure 7. Neutralizer in operation (with mica diaphragm)

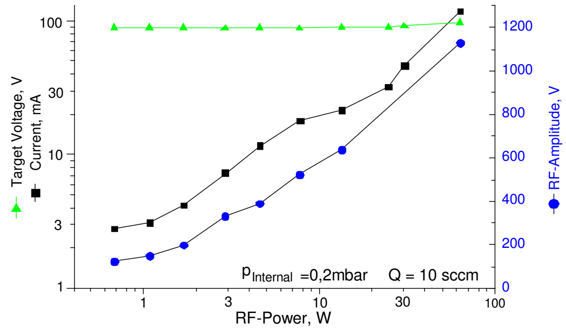

Figure 8. Extracted electron current, RF-amplitude and target voltage as function of RF-power

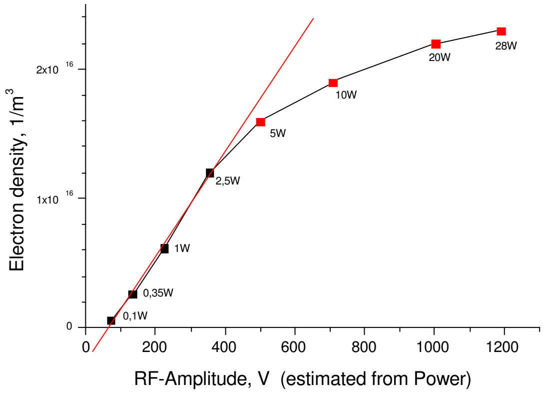

Figure 9. Electron density as a function of RF-Amplitude.

Figure 10 shows the dependency of the electron temperature on the inner pressure. The supplied RF-power amounted to 1W. As expected increasing the pressure lowers the electron temperature. For lower pressures the electron temperature reaches unfavorably high values, so operation in this regime seems not desirable due to high plasma potential. This will lead to higher energy of the ions in the plasma border layer with the consequence of higher sputter yield. The electron density was found to be constant at $6 \cdot 10^{15}/m^3$ during pressure-variation.

For discharges driven by Xe, no Langmuir probe diagnostics was applied so far. Instead, emission spectroscopy based on the intensity ratio of two lines allowed an estimate of the electron temperature. The method is based on a modeling of the excitation and deexcitation as function of the electron temperature carried out by Karabadzhak [1]. It is most sensitive for electron-temperatures between 2eV and 6eV. In Figure 11 we display the electron temperature measured by spectroscopy as function of the Xe-pressure in the discharge vessel. The supplied RF- power was 4 Watt. The derived temperature dependence corresponds qualitatively to the derived one for the Ar discharge from the Langmuir probe analysis. The larger temperatures with respect to the Langmuir measurements may result from the situation that emission spectroscopy responds more to the high-energy branch of the EEDF.

A further diagnostic application of emission spectroscopy is a comparison of intensities of single lines measured at different positions of the discharge. For this purpose, a linear array of 100 µm diameter light-wave fibers was positioned in an image of the neutralizer front-part. The outermost fibers were located near the center of one electrode and in the center of the cylinder. The corresponding linear array at the other end of the fiber bundle was adjusted into the entrance slit of a spectrometer for the visible spectral range. A CCD array detector mounted in the focus position simultaneously dispersed spectra at 16 different positions of the image. As an example of the application of the described method, Figure 12 shows the relative intensities of the XeI 6s (J = 2) – 6p (J = 1) transition at 840 nm as function of the fiber position and with the supplied RF – power as parameter. Except for the discharge area near the electrode, the intensities increase steadily with RF-power. Moreover one observes a change from flat position dependence at low power values towards a shift of the intensity maxima to the center. The line intensity can be assumed as being proportional to the product of rate coefficient, electron density and neutral density. We attribute the shift of the intensity maxima towards the

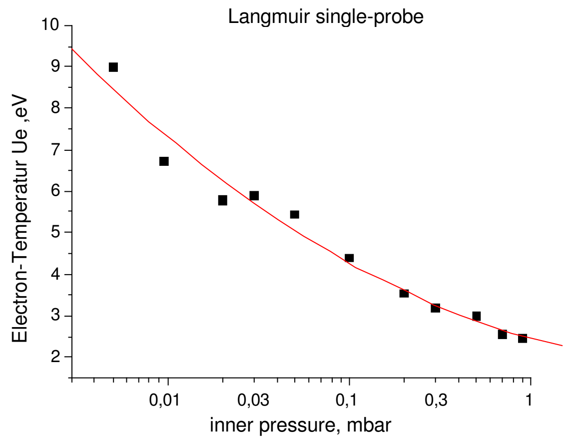

Figure 10. Electron temperature as a function of inner pressure measured by Langmuir-single-probe on center axis.

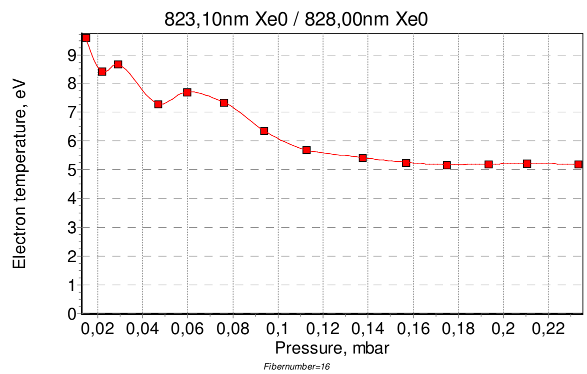

Figure 11. Electron temperature as a function of inner pressure measured by Emission spectroscopy on center axis.

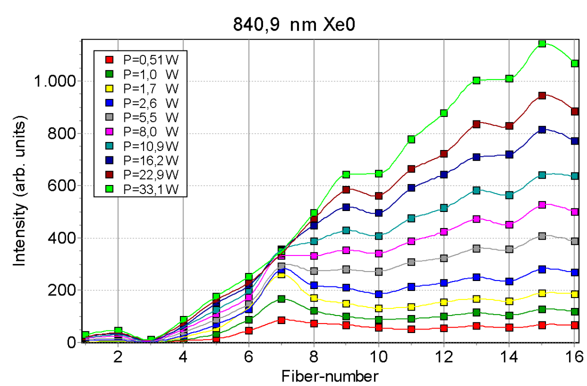

Figure 12. **Intensity versus fiber position, result of position sensitive Emission Spectroscopy.** (pos 3 center of electrode, pos 16 cylinder center)

center to an increased electron density in this area.

Recently, the neutralizer was mounted into the Big Mac test chamber. As stated above, the Xe background pressure is in the range of 8E-6 mbar, also for the largest supplied flux of 5 sccm Xe. I.e., the ignition of a plasma bridge can be studied without disturbing influence of the background pressure.

In the P2000 chamber properties of the plasma-bridge are perturbed by the background pressure, leading to a lower voltage-drop outside the neutralizer and feigning a more stable operation. This problem concerns all plasma-bridge neutralizers. For good comparability a low background pressure (preferably 1E-5 mbar or less) is mandatory, yet features of the inner domain can be fully analyzed without perturbation at higher chamber pressure.

Taken from the first series of experiments, Figure 13 presents the extracted electron current as function of the voltage of the external electron target. An RF- power of 40 W and a Xe flux of 0.5 sccm, were supplied. Two operation modes of the neutralizer are observed. At lower extraction voltages only small currents are drawn (2 mA), corresponding to the diffusion of electrons through the inner orifice. At voltages around 150 V the extracted electron current steeply rises and saturates. This steep rise is accompanied be the appearance of an intense plasma plume in front of the orifice. Such behavior is typical for the plasma-bridge mode of a hollow cathode.

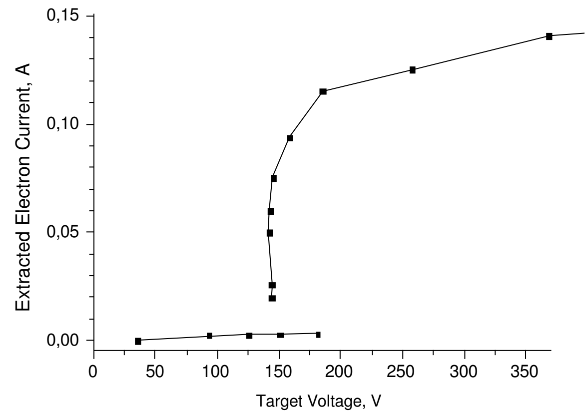

Figure 13. Extracted electron current as function of target voltage.

The saturation current rises with RF-power similar to the measurement with Argon (see Figure 8). The gas-efficiency coefficient for Xe, defined as number of extracted electrons per supplied gas atom, amounts to 3.5 for 0.5 sccm, at best 8.4 for 0.2 sccm Xe-flux and reaches the gas-efficiency coefficient of hollow-cathodes.

Further studies certainly have to aim at improvements of the energy budget.

VI. Conclusion

The extraction of electrons out of a capacitively driven RF-Plasma with plasma-bridge is feasible and provides electron currents nearly proportional to the inserted RF-Power. The device permits instant switching on and off without preheating, Up to now the needed energy for electron generation and extraction is higher than for cathodes with insert. Possibilities for improvements in energy budget, in particular considering the applied RF-power, should be studied. The gas consumption is comparable to conventional plasma-bridge neutralizers. The source proved to be insensitive to oxygen impurities. Even operation with Nitrogen and Oxygen was successfully demonstrated, permitting applications for terrestrial surface modification.

Acknowledgments

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References

[1] Karabadzhak, G.F. et al., Technical Report for ISTC Partner Project #2234p Feb 2004

[2] Weis, St; Meiß, S. , Schartner, K.-H., et al. Proceedings of 4th International Space Propulsion Conference June 2004, SP555–weis01, ESA Publication Division, ESTEC, P.O. Box 299, 2200 AG Nordwijk, the Netherlands