NON-PROPULSIVE APPLICATION OF THE RF-ION THRUSTER
FOR MATERIAL PROCESSING WITH REACTIVE GASES

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Abstract
Based on more than 25 years of experience, gained with rf-ion thrusters of the RIT-type, an rf-ion beam generator RIM 10 of 10 cm in diameter for material processing was built and successfully tested. The RIM 10 uses the electrodeless, inductively coupled rf-discharge and a redesigned three-grid ion extraction system. Performance mapping shows ion beam currents up to 300 mA at 1 W/mA specific power consumption and 0.03 sccm gas flow rate per 1 mA. The beam energy can be varied between 25 eV and 3.5 keV. The beam divergence angle is adjustable between 5 deg and 40 deg. RIM 10 has been operated with 15 different gases, e.g. Ar, O2, N2, C2H2, MgF2, CBrF3, C4H8, SF6, CF2Cl2. Owing to the absence of any filament, RIM 10 is well suited for reactive gases as oxygen or fluorinated and chlorinated hydrocarbons. At present, RIM 10 is used in forming thin films for optical and mechanical layers, in producing thin dielectric layers for condensers, and in ion beam assisted vapour deposition.

In cooperation with the company A. Pfeiffer Vakuumtechnik Wetzlar GmbH, the series production of RIM 10 and RIM 4 systems started; scaled-up sources (ionizer diameter 45 cm) are taken into consideration.

1. INTRODUCTION
In current research on surface coating the physical properties of surface layers could be improved substantially by ion beam assisted techniques. Besides this, the interest on material processing with reactive gases increased worldwide. The rf-ion sources of the RIT-type, which will be described in this paper, are well suited for these tasks.

The main characteristics of the ion beam assisted deposition are the following:
- During the vapour condensation on the substrate, the growing layer is bombarded simultaneously by ions. This results in thicker, more adherent, abrasion-proof and hard films of high chemical and thermal resistivity.
- The energy of the vapour particles range between 10-2 eV and 0.2 eV; the ion energies are varied between some 10 eV and some keV.
- An intermediate layer (mixed transition sheath) is formed between the substrate and the outer layer.
- The layer is created by a non-thermal equilibrium process. The mixing ratio can be chosen freely between the vapour particles and the irradiated ions (dynamic mixing).
- In the contrary to conventional methods less thermal stresses and no phase transformation occur, because of the low process temperature.
- The reproducibility of the coating structure is very accurate.

The essential role of the ions in this type of beam enhanced layer production can be understood from the elementary mechanisms of ion-solid interactions like sputtering, sputter cleaning, atomic displacement, and intermixing with the parent material (1). The primary advantage of the ion beam processing of materials lies in the easy and independent control of ion flux, ion energy, and ion impact angle (2) (3).

2. MATERIAL PROCESSING FACILITY
The basic configuration of a vacuum facility for material processing with ion sources is shown in Fig. 1. The main components are:
- ion source and beam forming system
- evaporator
- movable mounting with substrate
- monitors for neutrals and ions (not shown in Fig. 1)
- vacuum tank and pumping unit
Broad and uniform ion beams are generated by ion sources with a multihole extraction system.

The vapour beam (Fig. 1) can be produced by different methods: By sputtering using a second ion source as well as by thermal evaporation using Joule's heating, rf-, electron- or Laser-heating.

Fig. 2 is a photo of the test facility P 6000 B at Giessen University. The background pressure, when operating the rf-ion source RIM 10, is 0.01 Pa or less.

Ion source and evaporator are mounted - looked from the substrate - under a distinct angle (Fig. 1). From this special arrangement some interesting possibilities follow for treating the substrate:
- irradiation by ion beam only
- vapour deposition by operating the evaporator only
- common operation of ion source and evaporator
- alternating operation of ion beam and vapour beam
- variation of the impact angle by moving or rotating the substrate

3. HISTORY, EXPERIENCES
Table 1 collates the three rf-ion source families, which have been developed at Giessen for space propulsion and its spin-offs.

Based on more than 25 years of experiences (Table 1 and (4)), gained with rf-ion thrusters and rf-particle injectors (15), the work on surface treatment (Table 1) started in 1978. The rf-ion source RIT-

* now with Leybold AG, Cologne
Since 1982, sputter tests of copper onto carbon fiber reach several 10⁴ K (11), whereas the ion temperature action experiments to be done at MPI Garching (6). Growing with the field strength \( E_{\text{ind}} \), the Te-data mapped with different gases for plasma-wall interaction experiments are in progress (7). Some typical performance data of RIM 10 are shown in Table 2 for 12 different gases.

Up to now, 6 RIM-10 sources have been built at Giessen; some were already delivered to industrial orderers. Since a couple of months, the company Pfeiffer at Wetzlar started in cooperation with the Giessen University the series production of 10-cm and 6-cm ionizer diam RIM -systems. Scaling up of the ion beam sources to about 40 cm diam is envisaged.

4. EXPERIMENTAL SET-UP AND MODE OF WORKING

The photos of Fig. 3 show two views of RIM-10 (diameter and length: 15 cm).

The advantages of the rf-system over dc-types are the mechanical solid and simple structure, the modest electronic requirement, and the long lifetime, which is guaranteed by the absence of any discharge electrodes (8). The cross section of RIM 10 is given in Fig. 4.

RIM 10 was operated flanged from the outside to the vacuum chamber and also mounted inside the vacuum facility (see chapter 5.6.).

It needs only 4 supply units (Fig. 4): The gas feed system including a flow controller, the rf-generator, a negative and a positive voltage supply. The working gas is fed via the flow controller and the isolator I and the distributor D into the discharge chamber Q (made of quartz), which is surrounded by the inductive coil C of an rf-generator (1 MHz, 100 to 500 W). The inductively coupled electric eddy rf-field \( E_{\text{ind}} \) generates a self-sustaining electrodeless annular rf-discharge (9) (10). The rf-power transfer to the discharge plasma is very effective (98%).

The rf-coil generates inside the ionizer an approximately homogeneous, axial magnetic field \( B_{\text{rf}} \). \( B_{\text{rf}} \) is magnetic field constant, \( n \) = number of coil turns, \( L \) = coil length. \( f_{\text{rf}} = \text{rf-coil-current amplitude}, \omega = \text{frequency}, t = \text{time} \):

\[
B_{\text{rf}} = \omega \times \frac{Q}{2 \pi f_{\text{rf}}} \sin \omega t
\]

(1)

Because the rather short coil (compared with its diameter), the deviations of Eq. 1 are not neglectable: E.g., the field \( B_{\text{rf}} \) on the axis is remarkably smaller than near the ionizer wall.

The rf-magnetic field \( B_{\text{rf}} \) induces an azimuthal electric eddy-field \( E_{\text{ind}} \) (r = distance from the axis, \( E_{\text{ind}} = \text{amplitude of } B_{\text{rf}} \)):

\[
E_{\text{ind}} = \frac{1}{2} \omega B_{\text{rf}} \cos \omega t
\]

(2)

Because of the skin-effect and the mentioned inhomogeneity of \( B_{\text{rf}}(r) \), the induced field \( E_{\text{ind}} \) (see Fig. 4) is growing with \( r \) by a Bessel-function of the first order (10) (14), rather than in a linear way, as given approximately by Eq. 2.

The induced electrical field \( E_{\text{ind}} \) accelerates the discharge electrons to ionization energy.

In accordance with the rf-discharge theory and plasma diagnostics, the electron temperature \( T_{\text{e}} \) demonstrates the strong radial increase, which is shown by Fig. 4, growing with the field strength \( E_{\text{ind}} \). The \( T_{\text{e}} \)-data reach several 10⁴ K (11), whereas the ion temperature is about only 10³ K (12).

The diagnostically determined plasma density \( n \) (Eq. 4) depends on the coupled rf-power, \( P_{\text{rf}} \), reached with \( 10^{11} \) ions and electrons per cm², and decreases towards the ionizer walls (11). This fact is caused by carrier recombination at the walls.

The maximum extractable ion beam density \( j_i \) called "plasma yield", depends both on the plasma density \( n \) and the electron temperature \( T_{\text{e}} \), which provides a pre-acceleration of the ions in the plasma-boundary sheet (10) (13) (14):

\[
J_i = 0.6065 \times n_0 \cdot \sqrt{\frac{m_e}{m_i}} \cdot \left( \frac{kT_{\text{e}}}{m_e} \right)^{3/2}
\]

(3)

\( m_i \) means the ion mass.

Based on the radial increase of \( T_{\text{e}}(r) \) and the decrease of \( n(r) \), the extractable ion current density shows a flat profile \( j_i(r) \) (Fig. 6), which is required by many applications.

The ions, extracted from the plasma, are focussed (13) to the beam by a three grid system with 253 beamlet holes (Fig. 5) using the accel-decel technique: The 1st grid is at positive potential \( U_1 \). It defines the beam voltage. The 2nd grid is put to negative potential \( U_2 \). This increases firstly the electrostatic extraction field and provides secondly an electrical barrier to prevent backstreaming electrons from the beam region back to the discharge plasma. The 3rd grid is grounded \( U_3 = 0 \). The potential difference between the 1st and 2nd grid is called extraction voltage \( U = U_1 - U_2 \). It compensates the space charge limitation of the Langmuir-Child-law (\( E_0 \): dielectric constant of space; \( d \): effective extraction gap):

\[
J_i = \frac{4}{3} \pi \sigma \left( \frac{2eU}{m_i} \right)^{3/2} \frac{1}{d^2}
\]

(4)

and cares for beamlet focussing (the plasma boundary follows the shape of the equipotential areas forming an immersion lens). Therefore, in the grids the hole diameters are 4 mm, 2 mm, and 4 mm (Fig. 5). The total beam diameter of RIM 10 is 8.5 cm (253 beamlets). Its grid transparency amounts to 40%.

5. PERFORMANCE

The ion beam current of RIM 10 depends on the one hand on the rf-discharge power (i.e. plasma yield) and the gas flow rate (i.e. discharge power); on the other hand the extraction voltage must be well adjusted to overcome the space charge restrictions of the Langmuir-Child-law.

5.1. CHARACTERISTICS

Figs. 6 to 9 show the basic performance curves of RIM 10 for the working gases oxygen and argon. The discharge characteristics of both gases (Fig. 6 and Fig. 8) are nearly identical in the upper gas flow region (2-4 accm). At continuous operation without cooling the grids, beam currents up to 300 mA (discharge power about 300 W) had been drawn. Fluctuations in the gas flow rate do not react upon the discharge, because in a wide range (at higher flow rates) the extracted ion beam is independent on the gas flow rate.
The focusing ability of the extraction system is better for the working gas argon than for oxygen: The drain current to the 2nd grid is less for argon as you can see by comparing Fig. 7 and Fig. 9. It amounts to ≤ 4% of the beam current for Ar and ≤ 6% for O₂. The "defocusing borderline" is also shifted in the case of argon to lower beam voltages. Therefore, the neutralizers must be operated at the right hand side of the defocusing borderline, otherwise the drain current is unreasonable high and undue sputtering occurs. The minimum beam energies range down to 200 eV (Ar) and 250 eV (O₂), respectively.

By using electrothermal filament neutralizers, this minimum beam energy may be reduced by a factor of 4 at least (see chapter 5.5.2.).

In Fig. 10 three further examples are given. It shows the discharge characteristics of nitrogen N₂, bromotrifluoromethane CBrF₃, and freon-12 C₂F₅C₂F₂.

The results are in all cases encouraging:

- At a stable source operation (after burn in procedure) the beam current ranges between 50 mA and 300 mA can be drawn at a gas flow rate of about 5 sccm.
- The specific source data, discharge power per beam current and gas flow per beam current, range between 0.8 ÷ 1.1, W/ma (ionizer efficiency) and 0.02 ÷ 0.03 sccm/ma (gas economy).
- RIM 10 has been operated with 15 different gases without modifying the system. In Table 2 typical data (rf-power, current density, beam current) are quoted of some rare and reactive gases.

5.2. Optimum Extraction Voltage

For application purposes the required beam voltage U₁ is normally smaller than the extraction voltage U (determined by the space charge law). Therefore, the ions must be decelerated in the electric field between the 2nd and 3rd grid (Fig. 5). In consequence, the beamlets diverge, and the drain current to the 2nd grid increases in the worst case beyond the defocusing borderline (Fig. 7 and Fig. 9). For a fixed beam current, the borderline-extraction-voltage, called optimum extraction voltage, has been determined experimentally. It is depicted in Fig. 11 for Ar and O₂. In the range of interest, the optimum extraction voltage depends linearly on the beam current.

5.3. Beam Focussing, Decel-Accel-Ratio

In the investigated extraction system of RIM 10 (for oxygen) the deceleration procedure is still uncritical at decel-accel ratios ≤ 0.9 and at beam voltages ≥ 200 V (Fig. 12). There the beam spreading is small.

Beam focussing degrees of 90% to 97% are achieved (Fig. 12). That means the losses to the extraction grids are ≤ 3% to 10% of the total ion beam.

At the bend of the focussing curve in Fig. 12 the decel-accel ratio U₂/U₁ is 0.9. This implies a beam voltage U₁ to be higher than 10% of the extraction voltage U₁.

5.4. Gas Efficiency

The gas efficiency depends on the gas flow through the ion source and on the ion beam current (Fig. 13). For example, at a flow rate of 5 sccm and 300 mA beam current, the gas efficiency is about 95%; i.e. without being ionized, only 5% of the gas particles leave the RIT 10 source.

5.5. Beam Profile and Divergence

The user of RIM 10 is interested especially in the shape of the ion beam profiles at the location of the sample to be treated. The beam profiles depend on the plasma homogeneity (Fig. 4), on the accel-decel ratio, and on the beam neutralization.

5.5.1. Experiments Without Neutralizer. Secondary electrons from the target generally provide sufficient electrons to the beam to compensate its positive space charge. Then in the beam ions and electrons exist side by side without recombinating.

Fig. 14 represents ion beam profiles measured (by means of Faraday cups) 33 cm downstream the ion source. The initial beam radius at the exit of the extraction system is 4 cm. The beam profiles are Gaussian. At a constant ion current and at a fixed extraction voltage, the ion beam broadens with decreasing beam voltages.

From these beam profiles the beam divergence angles, shown in Fig. 15, are computed. The angle of divergence can be adjusted between 5° and 40°.

5.5.2. Experiments With Neutralizer. In the presence of electrically insulating targets or/and with low beam energies, neutralizing electron emitters are placed into the beam or near the periphery of the beam.

Fig. 16 depicts the beam radius measured by a movable Faraday cup again 33 cm downstream the RIM 10 as a function of the beam voltage (working gas argon, beam current 100 mA, extraction voltage 1.7 kV). Six neutralizer filaments, which could be supplied with negative coupling voltages, were placed at the rim of the beam. By admitting neutralizing electrons, the beam broadening is reduced considerably. The minimum beam energy amounts to 25 eV.

In Fig. 17 the beam divergence angle, computed from the data of preceding picture, are shown in dependence of the beam voltage with and without electron admittance. The minimum divergence angle is 5 degrees.

5.6. Vacuum Environment

RIM 10 had been operated
- at the atmosphere flanged to the vacuum facility P 6000 A as shown in Fig. 1 and
- mounted inside the vacuum test stand.

The performance data are identical in both cases, except of the thermal charge. In the atmosphere RIM 10 is mainly convection cooled by the surrounding air; inside the vacuum tank only radiation cooling is valid.

Fig. 18 shows the thermal behaviour of RIM 10 in the vacuum for two discharge powers (50 W and 100 W). The temperature was measured at three positions at the rf-discharge chamber. Thermal equilibrium (160°C and 230°C) was reached after an operation time of about 40 min. When we switched on the ion beam (after 80 min), we observed an additional temperature increase of 10°C to 20°C, caused by the drain power dissipated in the extraction system.

When finishing this paper the installed active cooling loops (in the rf-coil and in the extraction system) have not yet been put into operation.

6. CONCLUSION

The ability of the RIM 10 for material processing (with minimum beam energies of 25 eV) has been demonstrated. RIM 10 is simple and reliable in its mechanical construction.
Owing to the absence of the filaments in the discharge, it is well suited for reactive gases like oxygen and nitrogen or for fluorinated and chlorinated hydrocarbons. Industrial series production of RIM 10 and RIM 4 commenced.

7. REFERENCES


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<table>
<thead>
<tr>
<th>Thrusters for space propulsion</th>
<th>Working gas</th>
<th>Rf power W</th>
<th>Ion current A</th>
<th>Beam voltage kV</th>
<th>Research, development and qualification programs</th>
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<tr>
<td>RIT-4'</td>
<td>Hg</td>
<td>20</td>
<td>0.03</td>
<td>2</td>
<td>1968–1977 since 1971</td>
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<tr>
<td>RIT-10</td>
<td>Hg, Xe</td>
<td>85</td>
<td>0.13</td>
<td>1.5</td>
<td>1974–76, since 1982</td>
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<tr>
<td>RIT-15</td>
<td>Hg, Xe, Ar</td>
<td>150</td>
<td>0.25</td>
<td>1.5</td>
<td>1971–1975</td>
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<tr>
<td>RIT-20</td>
<td>Hg</td>
<td>200</td>
<td>0.5</td>
<td>2.4</td>
<td>1972–80, since 1983</td>
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<tr>
<td>RIT-35</td>
<td>Hg, Xe, Ar</td>
<td>900</td>
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<th>Injectors for fusion machines</th>
<th>Working gas</th>
<th>Rf power W</th>
<th>Ion current A</th>
<th>Beam voltage kV</th>
<th>Research, development and qualification programs</th>
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<tr>
<td>RIG-10</td>
<td>H2</td>
<td>4.5 x 10^4</td>
<td>10^11</td>
<td>30</td>
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<td>RIG-15</td>
<td>H2</td>
<td>1 x 10^4</td>
<td>2^11</td>
<td>30</td>
<td>1982–1986 since 1982</td>
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<tr>
<td>RIG-20</td>
<td>H2</td>
<td>20 x 10^1</td>
<td>18^11</td>
<td>40</td>
<td>since 1982</td>
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<td>RIG-10 x 20</td>
<td>H2</td>
<td>10 x 10^3</td>
<td>13^11</td>
<td>30</td>
<td>1982–1985</td>
</tr>
<tr>
<td>RIG-10 x 30</td>
<td>H2</td>
<td>1.5 x 10^3</td>
<td>4^11</td>
<td>30</td>
<td>1983–1986 since 1986</td>
</tr>
<tr>
<td>RIG-25 x 50</td>
<td>H2</td>
<td>&lt; 120 x 10^1</td>
<td>80^11</td>
<td>80</td>
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<table>
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<tr>
<th>Sources for material processing</th>
<th>Working gas</th>
<th>Rf power W</th>
<th>Beam voltage kV</th>
<th>Research, development and qualification programs</th>
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<td>RIT-TEX-8</td>
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<td>70</td>
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<td>RIG-10 G</td>
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<td>500</td>
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<td>3</td>
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<tr>
<td>RIT-10 LP5</td>
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<td>300</td>
<td>0.3</td>
<td>0.2 – 3.5</td>
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</tbody>
</table>

1 Number means ionizer diameter in cm
2 Rectangular
3 Hexagonal
4 Kr, Ar, O2, N2, CO, CBF3, CH4, SF6, SF2, CF3Cl
5 Full beam extraction not possible at Giessen
## TABLE 2: Some typical performance data of RIM 10 for different gases.

<table>
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<tr>
<th>Working gas</th>
<th>Rf-Power (W)</th>
<th>Beam Density (mA/cm^2)</th>
<th>Beam current (mA)</th>
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<td>Xenon</td>
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<tr>
<td>Krypton</td>
<td>170</td>
<td>7.1</td>
<td>330</td>
</tr>
<tr>
<td>Argon</td>
<td>300</td>
<td>7.1</td>
<td>300</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>200</td>
<td>4.6</td>
<td>250</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>190</td>
<td>5.7</td>
<td>220</td>
</tr>
<tr>
<td>Oxygen</td>
<td>300</td>
<td>7.3</td>
<td>300</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>300</td>
<td>7.3</td>
<td>300</td>
</tr>
<tr>
<td>Bromotrifluoromethane</td>
<td>160</td>
<td>5.7</td>
<td>280</td>
</tr>
<tr>
<td>I-Butane</td>
<td>120</td>
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<td>150</td>
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<tr>
<td>Sulfur hexafluoride</td>
<td>270</td>
<td>8.6</td>
<td>360</td>
</tr>
<tr>
<td>Freon-12</td>
<td>270</td>
<td>8.6</td>
<td>400</td>
</tr>
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**Fig. 1:** Basic configuration of a vacuum facility for material processing with ion sources.

**Fig. 2:** Test facility P 6000 B (pumping velocity 6000 1/s) for the investigation of rf-ion sources RIM for material processing.

**Fig. 3:** Two views of RIM 10.
- Upper: Seen from the downstream side to the extraction system with the cooling water connections.
- Lower: At the backplate one can identify the connections for the grid voltages (foreground), the 30 D rf-feedthroughs (background), and the gas feed (at the axis).
Fig. 4: Cross section of RDM 10 and block diagram of the supply units (G: rf-induction coil; D: gas distributor; Q: discharge chamber; S: rf-screen; G1, G2, G3: 1st, 2nd, and 3rd grid), and the radial dependence of some important discharge parameters (lower part of the figure).
Fig. 5: Forming of an ion beamlet in a three grid extraction system (solid lines: equipotential areas; broken lines: ion trajectories; \( U_1 \), \( U_2 \), \( U_3 \): grid potentials; \( U = U_1 - U_2 \): extraction voltage; \( d \): effective extraction gap).

Fig. 6: Discharge characteristics of the ion-source RIM 10 for oxygen: Rf-discharge power as function of the standard gas flow rate. Parameter is the beam current (extraction voltage 4 kV, rf-generator frequency 3 MHz).

Fig. 7: Extraction characteristics of RIM 10 for oxygen: Drain current to the second grid as function of the ion beam voltage. Parameter is the beam current at the optimum extraction voltage of Fig. 11.

Fig. 8: Discharge characteristics of RIM 10 for argon (extraction voltage 4 kV, \( U_1 = 2 \) kV, \( U_2 = -2 \) kV; rf-generator frequency 3.2 MHz). Compared to oxygen (Fig. 6) the curves are nearly identical.

Fig. 9: Extraction characteristics of RIM 10 for argon: Compared to oxygen (Fig. 7) the defocussing borderline is shifted to lower values.
Fig. 11: The dependency of optimum extraction voltage on beam current is linear.

Fig. 12: Focussing ability of the extraction system of RIM 10. The focussing degree is nearly constant for decel-accel-ratios ≤ 0.9.

Fig. 13: The gas economy depends on the gas flow and on the beam current.
Fig. 14: Beam profiles 33 cm downstream the ion source RIM 10 (initial beam radius at beam exit: 4 cm).

Fig. 15: The angle of the beam divergence depends (at a fixed extraction voltage) only on the beam voltage.

Fig. 16: Ion beam radius as function of the beam voltage with and without neutralizing electrons, measured 33 cm from the ion source (initial beam radius 4 cm). Parameter is the coupling voltage between neutralizer and ion beam.

Fig. 17: Beam divergence angle as function of the beam voltage with and without neutralizing electrons. Parameter is the coupling voltage (working gas Ar, beam current 100 mA, extraction voltage 1.7 kV).

Fig. 18: Thermal behaviour of RIM 10 inside the vacuum facility P 6000 B. After an operation time of 40 min thermal equilibrium is reached.