Efficient high beam density reactive ion source

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Abstract

Inductively coupled plasma sources have been developed using Helicon type exciting antenna and spiral type antenna at 13.56 MHz frequency and magnetic systems for plasma magnetisation. A grid extraction system is used for ion beam extraction. A high density plasma (n>10¹⁷ m⁻³) is obtained in a 5 cm and 10 cm internal diameter discharge chamber in nitrogen and oxygen. A 4 mA/cm² current density is achieved. A high efficiency and a high content in atomic ions (40 %) is evidenced by time-of-flight ion beam analysis. Optical emission spectroscopy confirms that a high dissociation degree is achieved.

I - Introduction

High current ion sources and the simulation of ion beams extraction from high density plasma sources have been developed in the last years for ion thrusters [1] and for surface treatments. In the frame of the ion source development based on a simulation code and an experimental set-up (presented in § 2), three different discharge configurations have been investigated. A high efficiency and a high content in atomic ions is evidenced by ion beam analysis and the plasma characteristics are presented in part 3. The performances in terms of ion sources are presented in part 4.

II - Experimental set-up

The experimental set-up (fig. 1) is based on a vacuum tank with a plasma source located outside the vacuum tank (i.e. not immersed). The vacuum tank length is 1 m and the diameter is 0.5 m. A turbo molecular pump (1800 l·s⁻¹) achieves a residual pressure of 5·10⁻⁵ Pa. Three discharge chambers have been used with :

Fig 1 : (a) Discharge chamber (b) Extraction optic (c) Power supply (d) Matching Box (e) Gas feeding (f) Ion beam (g) Vacuum vessel (h) Turbo molecular pump (i) Analyser
- A RF (13.56 MHz) helicon plasma discharge with magnetic coils around the discharge tube and small permanent magnets near the extraction region (fig. 2a). The working value of the magnetic field generated by the coils is 0.08 T in the centre of the tube (the tube length is 20 cm and the diameter is 5 cm).

- A RF (13.56 MHz) helicon plasma discharge with permanent magnets round the discharge tube and small permanent magnets near the extraction region (fig. 2b). The value of the magnetic field generated by the magnets is 0.1 T near the tube surface.

- An flat inductively coupled discharge working at 13.56 MHz with permanent magnets (fig. 3). The chamber diameter is 10 cm and the thickness is 3 cm. The antenna is a two turns spiral.

Fig 2: The schematic diagram of the discharge chambers:
- a. The helicon plasma discharge with magnetic coils.
- b. The helicon plasma discharge with permanent magnets.
- c. The flat inductively coupled discharge.

The ion extraction system is achieved by using an electrostatic three grid optic (fig. 3). The grids (made of stainless steel or titanium) are drilled with 2 mm holes. The thickness of the grids can be changed from 0.8 mm to 0.5 mm. The typical value for the plasma grid (G1) and the acceleration grid (G2) are respectively of 800 V (Φ1) and −200 V (Φ2). The last grid (G3, the deceleration grid) is connected to the ground (Φ3 = 0 V). The RF (13.56 MHz) power supply is a 2 kW generator used in the range 0-600 W. The reflected power (<2%) can be controlled with a matching box. The working pressure is 10⁻³ Pa in the diffusion chamber for a typical flow rate of 7 sccm. Due to the conductance of the extraction system, the pressure in the discharge chamber is higher and a 7 sccm flow rate of Argon leads to a pressure of 0.46 Pa inside the discharge tube.

The discharges have been characterised for gases such as N₂, O₂, Ar and Xe using Langmuir probes, beam imaging, grid current studies and single beam divergence analyser.

The atomic fraction in the extracted ion beam is obtained by using a small scale time-of-flight analyser (see companion paper by M. PRIOUL & al). The radial distribution of the ion beam current density is recorded by a movable small size ion collector.

A self consistent ion beamlet formation simulation code in an extraction system (where ions are treated by a particle in cell (PIC [2]) code and electrons by Boltzman equilibrium) has been developed. The simulation code (named SEFI [4]) deals with the extraction of positive ions (the code manages multi-species plasmas such as N₂/N³⁺/N₂⁺) from...
a high density plasma using a n-grid extraction optic with one hole and uses an axial symmetry. The simulation space is shared in several parts and parallel computing is used (via
the PVM library [3]) with PC computers or with high performance computer facility. According to given plasma parameters (temperature, density), the code gives information on
the extracted current, the current flowing through the grids, the ion (fig. 3) and potential
distributions in the simulation space.

III - High density, highly dissociated plasma in nitrogen and oxygen

The plasma densities obtained in Nitrogen and Oxygen are measured in the tube and
across the tube diameter near the grid system by using negatively biased thin Langmuir
probes. The density has peak values of $10^{18}$ m$^{-3}$ on the tube axis in the center of
the discharge, for 7 scem gas flow and 400 to 500 W RF power (helicon sources) and this value
decreases to several $10^{17}$ m$^{-3}$ near the extraction optic.

The time-of-flight measurements of the beam content show that significant variations
of the proportion of molecular oxygen and atomic Oxygen are obtained by changing the

![Fig 4: Extracted current ion an Oxygen ion source. (Helicon source with coils, 7 scem. The extraction voltages are 800, -200, and 0 V.)](image)

injected RF power, as presented on fig. 4. It has been checked that a proportion of 60 % O$^+$
and 40 % O$_2^+$ in current can be obtained.

The variation of the beam content is similar for the oxygen and the nitrogen source.

![Fig 5: Atomic and molecular line intensities as a function of the injected power in Nitrogen (Helicon source with magnets). Whereas the intensity of atomic line is nearly zero at low power (capacitive coupling), a strong intensity is observed for the inductive mode.](image)

However it has been checked that the dissociation level is lower in the nitrogen source
inducing a lower proportion of atomic nitrogen in the beam. This is associated with a higher sustaining power of the nitrogen plasma compared to the oxygen plasma. In order to evidence the high dissociation level in the discharge for the inductive coupling (a low power capacitive rf coupling can also be observed but the corresponding density is lower by a factor of 10), spectrum have been recorded in the range of 380 nm-800 nm. Two components are evidenced in this spectral range: molecular band (first positive band 391 nm) and atomic lines (742 nm, 744 nm, 747 nm). A very strong dissociation level is evidenced in the inductive coupling regime by comparison with a known source [5] confirming the time-of-flight measured. A nearly linear relation between the plasma density and the injected power is obtained (fig. 5).

IV - High density reactive ion beam source

Typical extraction voltages used both for nitrogen and oxygen sources are +1000 V,-200V and 0V applied respectively to the plasma grid, the acceleration grid and the decceleration grid. The plasma potential has been measured to be a few ten eV higher than the plasma grid potential (40 to 50 V).

As the extraction conditions of the ions from the plasma change with the plasma density, the radial uniformity of the plasma density in front of the extraction optic influences not only the total extracted current but also the uniformity of the ion beam properties. As presented on fig. 6, the radial density profile is significantly affected by the discharge configuration and it has been found that several configurations cannot be used for ion sources due to variations along the radius.

When looking at the current density distribution across the ion beam a local minimum in the beam center can be observed on the axis. This result is consistent with numerical simulations [4] and is due to the poor extracting conditions in the grid center where a high density plasma is observed. This shows that even better data could be obtained by a new grid design.
The ion beam current reaches 40-50 mA for Xe and Ar, 70 to 80 mA for N\textsubscript{2} and O\textsubscript{2}. Those values have been achieved with the three sources but with different injected powers and with different extraction surfaces (fig. 7). The two helicon sources prove to be able to deliver a high current density (up to 4 mA/cm\textsuperscript{2} in Oxygen and 2 mA/cm\textsuperscript{2} in Xenon) assuming a high value of the injected power (500 W) whereas the inductive source proves to be able to work at lower power (100 W). The total extracted ion beam current is 70-80 mA for an Oxygen gas flow of 7 sccm and a power level of 500W. It means that a efficiency of 15 \% is achieved, in terms of gas consumption, in these conditions.

V - Conclusion

The helicon discharges proved to be able to deliver a high current density but some configurations induce radial inhomogeneities that are inconsistent with correct extraction conditions. The inductive discharge shows the capacity to work at lower injected power keeping a sufficient discharge efficiency and homogeneity. High current densities (3-4 mA/cm\textsuperscript{2}) have been obtained in Oxygen and Nitrogen and the sources prove the ability to deliver a high current density in Xenon and Argon. The time-of-flight measures and the spectra comparisons have shown a high content in atomics ions in the ion beams. The flat inductive source seems to be the most promising and further works will be done at different RF frequencies.

References
