DEVELOPMENT OF THE RF ION SOURCE FOR USE IN ACCELERATOR-BASED APPLICATIONS

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Abstract

A helicon and a multicusp version of radio-frequency ion sources with compact permanent magnet systems have developed and tested to show the following performance data: plasma density of 10^{11}– $9*10^{12}$cm^{-3}, pressure of 2-10 mTorr, beam current densities of 10 - 130 mA/cm^2, brightness ~100 A/(m^{2}rad^{2}eV), energy spread 8-30 eV, and an rf power input into the plasma of 40 - 400 W. Possibilities for a further increase in the differential brightness of the rf ion sources are discussed.

INTRODUCTION

An ion source designed for a accelerator should have the following principal parameters: a uniform ion beam with controlled ion species content, high beam brightness, low energy spread, long service life (no less than 1000 hours), economic performance (with the lowest possible consumption of working substance and power coupled to the plasma) as well as small dimensions of the ion source itself, its power, and gas supplies. At present the increase of ion beam brightness and reduce of energy spread in accelerator-based facilities remains a challenging problem.

The brightness of a source can be calculated as:

$$B_n = \frac{I}{\beta^2\gamma^2 V_4} = \frac{2I}{\pi^2 \varepsilon_{nx}\varepsilon_{ny}}, \qquad (1)$$

where I is the beam current, $\beta = \frac{v}{c}$, $\gamma = (1-\beta^2)^{-\frac{1}{2}}$, v is the ion velocity, c is light velocity, $V_4 = \int dxdydx'dy'$ is the four dimensional phase volume, $\varepsilon_{nx} = \frac{S_x}{\pi}\sqrt{W}$ and $\varepsilon_{ny} = \frac{S_y}{\pi}\sqrt{W}$ are the normalized emittance for the xx' and the yy' projection, respectively, S_x and S_y are the areas of the corresponding emittance contours and W is the ion beam energy. High beam brightness can be achieved by extracting the beam with high current density and low emittance. The maximum current density is limited by the Bohm emission current density

$$j_+ = 0.4qn_+\sqrt{\frac{2kT_e}{m_i}}, \qquad (2)$$

where n_+ is the ion concentration in the unperturbed plasma near the emission hole and q is the ion charge. High brightness plasma ion sources must have plasma with high ion density and high electron temperature T_e. One of the most promising ways to increase plasma density (and thus, brightness) in RF ion sources is the generation of a helicon discharge with enhanced ionization efficiency[1-4].

This paper presents results obtained for two version of rf ion sources developed at the Institute of Applied Physics of the National Academy of Sciences of Ukraine (IAP NASU) viz., a helicon ion source and a multicusp rf ion source (MCRFIS). Both make use of an external magnetic field, yet the role of the magnetic field and the mechanism of RF power input into the plasma differ significantly. In the helicon source an external magnetic field is used to excite in the plasma electromagnetic helicon waves and Trivelpiece-Gould waves whose energy can penetrate deep into the plasma and be absorbed in the entire plasma volume. On the other hand, in the MCRFIS the plasma is produced by an internal rf antenna as a result of an inductive rf discharge, with the penetration depth of the rf field being limited by the skin layer thickness. The external multicusp magnetic field serves for magnetic plasma confinement and plasma isolation from the discharge chamber walls.

EXPERIMENTAL SETUP

The experimental setup for testing rf ion sources is shown schematically in Fig. 1. Measurements of the average plasma density n_e, in the rf sources were performed with an 8 mm microwave interferometer developed at the IAP NASU. The interferometer design is based on a Mach-Zender scheme in which plasma is in one of two shoulders of a twin-wave interferometer. The minimum measured phase shift of 1.5^0 corresponds to the plasma density of $3{\cdot}10^{10}$cm^{-3} and the shift of 360^0 to the plasma density of $0.9{\cdot}10^{13}$cm^{-3}, with the phase shift measurement error being below 5%. The emittance was measured with a perforated plate and a mobile vertical wire probe. The perforated plate may be placed outside the measurement area, permitting measurements of the beam profile and total current with a Faraday cup. The beam mass composition was determined using a Wien filter.

HELICON ION SOURCES

Helicon rf ion source was designed for operation in the middle current (1μA - 2 mA) mode with the ion emission current density of 1-130 mA/cm^2, the power input into the plasma not exceeding 400 W. A photograph and a schematic representation of the helicon rf ion source are shown in Fig. 2. The discharge chamber is made from quartz, its outer diameter is 30 mm and length is 250 mm. The chamber length is increased to permit a helicon dis-

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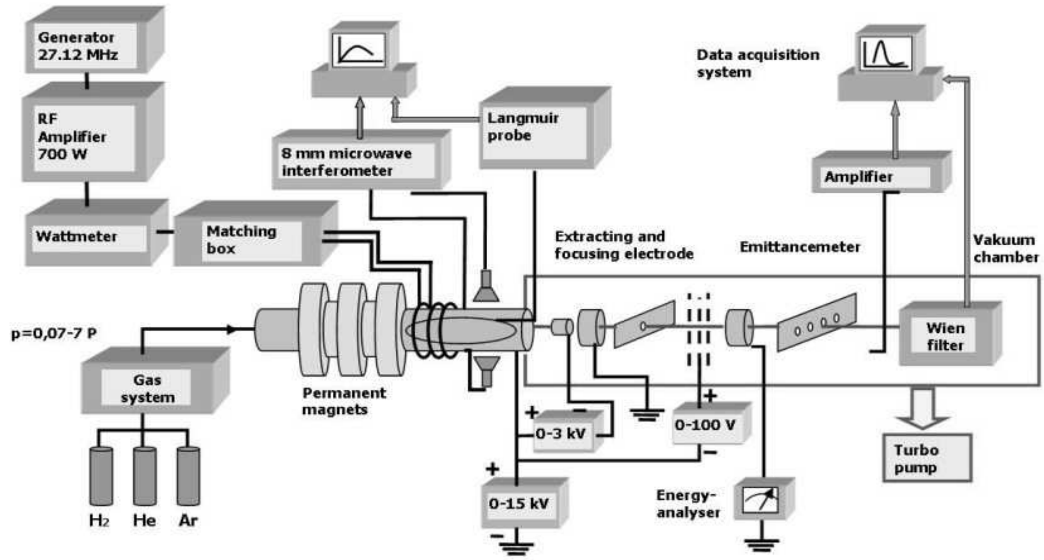

Figure 1: Ion source testing equipment.

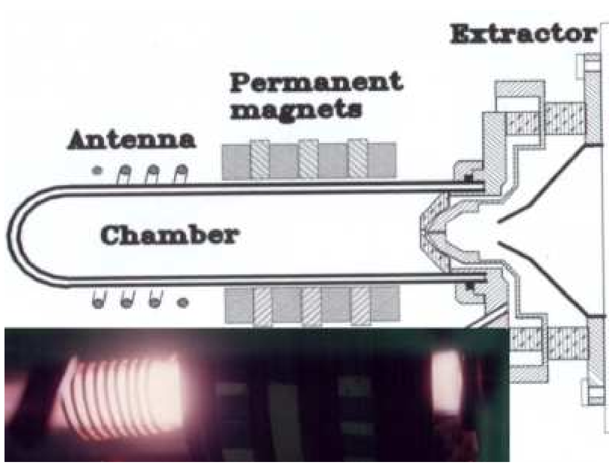

Figure 2: Helicon ion source

charge in the external magnetic field. The rf power supply comprising a driving generator (f_{rf}= 27.12 MHz), ACOM-1000 amplifier, and a matching device, provides a controlled power output of about 400 W in the continuous mode of operation. The extraction system has the following dimensions: cathode channel length is 3 mm and channel diameter is 0.6 mm (for ion current < 100 μA) and 2 mm (for ion current < 2 mA). To operate the helicon rf ion source with hydrogen/helium plasma a magnetic system with circular permanent magnets NdFeB was designed and constructed, permitting a generation of a longitudinal magnetic field B_z $\sim$100 G along the length of the RF antenna and of a longitudinal magnetic field of $\sim$1000 G with effective field length of about 10 cm to confine and transfer the plasma to the extraction system. Magnetic system in the form of parallel closely adjacent rings which are placed between the antenna and the extractor and can be moved over the gas discharge chamber surface permit a controlled magnetic field along the antenna length to be created that together with a high-frequency field generated by an inductor provide resonance conditions in the plasma for the helicon-frequency waves to be excited and efficiently absorbed. Under the resonance conditions, the greatest power input is in the center of the discharge chamber[4], facilitating more efficient plasma ionization and increased plasma density. In the vicinity of the permanent magnets the plasma is confined and transported to the ion-optic system[5]. Near the emission hole of the ion-optic system the produced plasma is compressed and thus, the beam current density is increased. In the AME mode the helium/hydrogen beam brightness is about 100 A/($m^2 rad^2 eV$) for the working gas pressure in the source < 10 mTorr and rf power input into the plasma < 150 W (f_{rf}= 27.12 MHz).

In order to elucidate the degree of correlation between the plasma density and the beam current density these quantities were measured for the helicon source with the arrangement of components as shown in Fig.1 (magnet-antenna-extractor: MAE mode). The measured plasma densities in the vicinity of the emission hole were $0.9{\cdot}10^{13}$cm^{-3} (for argon), $1.6{\cdot}10^{12}$cm^{-3} (for helium), and $6{\cdot}10^{11}$cm^{-3} (for hydrogen); between the antenna and the magnet they were $> 0.9{\cdot}10^{13}$cm^{-3} (for argon), $2.4{\cdot}10^{12}$cm^{-3} (for helium), and $8{\cdot}10^{11}$cm^{-3} (for hydrogen), with working gas pressure in the source < 10 mTorr and rf power input into the plasma < 400 W (f_{rf}= 27.12 MHz). Fig. 3 represents the saturation current density of the helium ion beam and the plasma density in the vicinity of the emission hole in the extraction system versus the rf power input into the plasma in the helicon source, for the optimum position of the magnetic system with re-

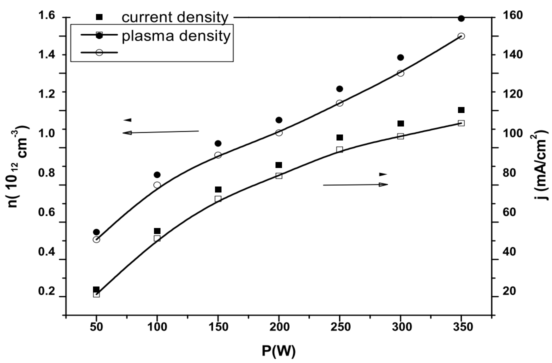

Figure 3: Saturation current density of the helium ion beam and plasma density versus rf power input into the plasma

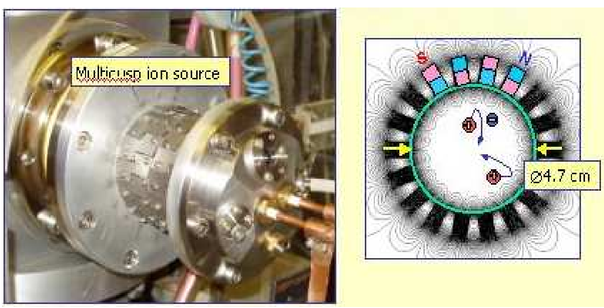

Figure 4: Multicusp rf ion source

spect to the extraction system. It is apparent from the figure that there is a good correlation between the measured plasma density and the saturation current density for helium plasma densities below 10^{12} cm^{-3}.

The beam brightness in many accelerators worldwide is highly heterogeneous, with strong flux in the paraxial region[6]. This is desirable for nuclear microprobe operation because probe forming lens systems optimized for large demagnitification magnitude can exploit high brightness of the paraxial region. By redistributing the beam phase density in the extraction zone, increasing the beam current density and using beam formation structures with low aberrations one can improve the paraxial beam brightness.

MULTICUSP RF ION SOURCE

At the IAP NASU a multicusp rf ion source has been developed with a view to decreasing the beam energy spread at the entrance to the single-ended accelerator. A photograph of the multicusp rf ion source are shown in Fig. 4. The source comprises a cylindrical duralumin discharge chamber of 47 mm inner diameter and 80 mm length. The outer surface of the chamber is surrounded by permanent magnets (Nd-Fe-B) installed with alternating polarity to produce a multicusp magnetic field configuration. The number of magnets in the line is 18; magnet dimensions are 6x10x30 mm. The magnetic field reaches the maximum value of about 300 mT at the discharge chamber wall, decreasing exponentially towards the center. In the region of low magnetic field an rf antenna is located. The antenna is made of a flexible stranded copper wire pulled through a Duran glass tube. RF power with 27.12 MHz frequency is supplied to the antenna from an rf unit. An extracting electrode (cathode) is made from molybdenum and has an extraction channel of 0.6 mm diameter and 3 mm length.

Using a grid energy analyzer the ion energy distribution functions (IEDF) of the helium beam have been measured. The multicusp version realizes operating modes with the helium ion current $\sim$ 100 μA and ion energy spread $\sim$ 8 eV for the power input into the plasma of 200 W.

CONCLUSIONS

Compact plasma generators with high plasma density ($5{\cdot}10^{11}$-10^{13} cm^{-3}) have been developed for ion-beam technology applications. Plasma density measurements were performed using an UHF interferometer. A good correlation was found between the measured plasma density and current density. Beam brightness achieved are about 100 A (m^2rad^2eV). Further improvements in brightness require combined experimental and theoretical optimization studies of helicon generators and ion source extraction systems.

To obtain ion beams with low energy spread a multicusp rf ion source has been developed with frequency of 27.12 MHz. The minimum energy spread of helium ions is $\Delta E = 8 \pm 1eV$ for the 200 w RF power.

A testing setup has been created to study physics phenomena and test both plasma parameters of rf ion sources and phase-, energy-, and mass characteristics of extracted ion beams.

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