CHARACTERISTICS OF LOW POWER RF ION SOURCE

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The paper presents the main characteristics of a low-power inductive RF ion source, designed for use in the injector of a compact nuclear microprobe of the IAP NASU as a source of $^1H^+$ ions. The source parameters are as follows: working gas is hydrogen, diameter of the extraction aperture is 0.6 mm, RF power <10 W, frequency is 45 MHz, ion current ≤ 4 μA. The mass composition of the beam was measured using a Wien filter. The beam is composed of $^1H^+$ and molecular ions ($^2H^+$, $^3H^+$). The proton ($^1H^+$) ratio is about 10%. The axial energy spread of the beam was measured with the use of a retarding field energy analyzer. Depending on the beam energy, the measured axial ion energy spread is 8-16 eV. The emittance of the beam was measured by means of an electrostatic scanner. At energy of 7 keV the beam emittance is 10 π·mm·mrad, normalized emittance is 0.037 π·mm·mrad.

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1. INTRODUCTION

Modern nuclear microprobe installations represent one of the analytical complex end stations based on electrostatic accelerators. These systems are designed for local, non-destructive microanalysis of objects of various origins and for manufacturing high-quality three-dimensional micro- and nanostructures. At the microprobe end station entrance, according to the classical scheme, electrostatic accelerators with beam currents of hydrogen or helium ions up to 100 μA are used to accelerate ions to energies of several megaelectronvolts [1-3].

However, due to collimation within the microprobe end station, only a small fraction of the ion beam, with a current of a few nanoamperes, is utilized, resulting in inefficient use of the initial beam. Additionally, mass analysis of the beam occurs after acceleration, requiring the use of a large analyzing magnet with a high-current power supply, which is inefficient in terms of energy consumption and system cost.

Therefore, the concept of a compact nuclear microprobe [4, 5] has been proposed at the Institute of Applied Physics NAS of Ukraine. This concept is based on the use of ion sources with a beam current not exceeding a few nanoamperes and a low energy spread, aimed at reducing the effects of chromatic aberration.

This paper presents the results of a study on an RF ion source developed for use in a compact nuclear microprobe of the Institute of Applied Physics of NAS of Ukraine. The source operates at low RF power (< 10 W) and is intended for generating a $^1H^+$ ion beam required for standard techniques such as PIXE, RBS, and proton beam writing.

The source will operate as part of the nuclear microprobe injector, along with a small-sized Wien filter and an einzel lens. The Wien filter is used to separate the proton component of the beam, while the einzel lens focuses the selected proton beam into a crossover, which can be used as an object for microprobe formation.

The article reports the results of measurements of the main ion source characteristics: ion beam current, mass composition and a proton ratio, an axial energy spread and an emittance of the ion beam.

2. RF ION SOURCE

The schematic of the ion source is shown in Fig. 1. The RF source consists of a cylindrical quartz bulb with an outer diameter of 34 mm and a length of 70 mm. The tube is surrounded by 6 turns of copper wire coil with diameter of 4 mm. An RF voltage with a frequency of 45 MHz is applied to the coil. Inside the quartz bulb, hydrogen gas is maintained at a pressure of ~1 Pa. The alternating magnetic field of the coil induces an azimuthal RF electric field, the energy of which is absorbed by electrons inside the gas volume. The oscillating electrons excite and ionize the gas particles, creating plasma. The resulting positive ions are drawn from the plasma using an extraction electrode. The ion beam is focused by means of an acceleration electrode. The diameter of the extraction channel is 0.6 mm and a length is 3 mm.

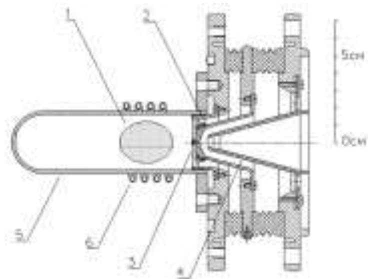

Fig. 1. Scheme of the inductive RF ion source:
1 – plasma volume; 2 – extractor; 3 – diaphragm;
4 – acceleration (focusing) electrode;
5 – quartz bulb; 6 – induction coil

The ion current of the plasma sources is proportional to the plasma density, which in turn is related to the RF power absorbed by the plasma [6, 7]. However, increasing the RF power leads to a significant increase in the energy spread of ions in the beam, which negatively affects the microprobe formation due to the action of chromatic aberrations. Since a proton beam current of ~10 nA is sufficient for a compact nuclear microprobe, it becomes feasible to design a RF ion source of low power. This facilitates the operating temperature conditions of the source and reduces high-frequency electromagnetic interference that could affect electronic measuring equipment.

Considering the above, the power of RF generator was chosen to be < 10 W. The generator is built using a GU-29 lamp according to the scheme of a push-pull oscillator. The anode voltage of the lamp is 250…280 V, with a current consumption of 25…30 mA. Thus, the power consumed by the generator is 8 W. Taking into account the generator efficiency, the RF power absorbed by the plasma does not exceed 5 W.

3. RESULTS AND DISCUSSION

All measurements of the RF ion source characteristics were carried out on a test bench for studying the parameters of ion sources. The ion source was connected to a vacuum chamber which was evacuated by a turbo-molecular pump “Leybold-360” to a base pressure of $2 \cdot 10^{-4}$ Pa. The working gas (hydrogen) is supplied to the source via the SNA-2 gas supply system. In the operating range of gas supply, the hydrogen pressure in the source bulb varied within p=1…3 Pa.

3.1. ION BEAM CURRENT

The ampere-volt (I-V) characteristics of the source, which represent the dependence of the ion beam current I_i on the extraction voltage U_{ext} were measured using a Faraday cup positioned 100 mm from the source. The extraction voltage varied within the range of U_{ext} = 10…300 V, the accelerating voltage U_{acc} ranged from 1 to 7 kV.

The I-V curves showed that the ion current increases monotonically with the extraction voltage, reaches saturation, and then decreases. As the accelerating (focusing) voltage increases, the ion current also rises. The maximum extracted current is higher in the low-pressure mode ($p \leq 1$ Pa) and is equal to I_i = 4.2 μA at U_{ext}=280 V, U_{acc} = 7 kV.

The ion source demonstrated good stability over time. The ion beam current I_i was recorded for more than one hour. Measurements showed that during this time the beam random current fluctuations is $\delta I_i < 1\%$.

3.2. MASS COMPOSITION OF THE BEAM

The mass composition of the beam was measured using a Wien filter. In the Wien filter, a constant magnetic field is created by the coils of the electromagnet and is directed vertically. A constant potential difference is applied to two parallel electrostatic plates, creating an electric field in the horizontal direction between them. As the ion beam passes through the crossed electric and magnetic fields, ion separation by mass occurs. The mass spectrum was scanned by varying the magnetic field of the Wien filter.

The typical mass spectrum of the ion beam displays characteristic peaks for hydrogen ions: $^1H^+$, $^2H^+$, and $^3H^+$. The height of the $^1H^+$ (proton) peak is 40 pA, the molecular ion peak $^2H^+$ is 200 pA, and the $^3H^+$ ion peak is 130 pA. Thus, the proton ratio in the beam is approximately 10%.

The low RF power of the source (< 10 W) accounts for the small proton ratio. Despite this, the ion source produces about 400 nA of proton current at a total beam current of 4 μA.

3.3. AXIAL ION ENERGY SPREAD

Ion energy spread of the source was measured using a retarding field energy analyzer (RFEA) [8, 9]. The analyzer consists of three flat parallel grids with 80% transparency, spaced 2 mm apart. The first and third grids are held at zero potential, while a positive retarding potential is applied to the middle grid relative to the accelerating voltage. The collector is made of copper, has a diameter of 25 mm, and is positioned 30 mm from the third grid. The analyzer is enclosed in a stainless steel cylinder with a diameter of 45 mm and a length of 50 mm. Beam energy analysis was conducted by varying the retarding potential in the range of 0…100 V and measuring the resulting collector current I_c. The current I_c was measured using a ”Keithley 6485” picoammeter and recorded on a computer.

The collector current I_c depends on the retarding potential U_r applied to the second grid. The ion energy distribution function (IEDF), $f(E)$, is proportional to the first derivative of the collector current I_c [8]: $f(E) \propto -dI_c/dU_r$. The ion energy spread ΔE is defined as the full width of the distribution function at half maximum (FWHM).

Energy spread measurements were conducted for different extraction U_{ext} and acceleration voltage U_{acc}. Fig. 2 illustrates the result of measurements at U_{ext}=200 V, U_{acc}=1 kV and p=3 Pa.

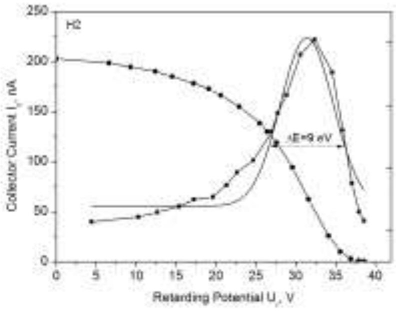

Fig. 2. Collector current (points) and its derivative (squares) vs retarding voltage U_r. The solid curve is a Gaussian fit

The dependence of the collector current I_c on a retarding potential U_r is shown by the points. The line with squares is the derivative of the collector current with a negative sign ($-dI/dU$). This curve is proportional to IEDF and is fitted with Gaussian function (solid curve). The FWHM of Gaussian function determines the ion energy spread, which is equal to ΔE=9 eV.

Measurements showed that at low extraction and acceleration voltage (U_{ext} =30 V, U_{acc}=0.5 kV), the ion energy spread is ΔE=8 eV and rises with increasing voltages. At high voltages (U_{ext} =240 V, U_{acc}=6 kV) the ion energy spread reaches ΔE=16 eV.

It was also observed that, at the same extraction U_{ext} and acceleration voltages U_{acc}, the energy spread increases as the gas pressure p decreases.

In general, the energy spread tends to grow with an increase in extracted current, remaining within the range of ΔE =8…16 eV.

3.4. BEAM EMITTANCE

The emittance of the RF source was measured using an electrostatic scanner, the design and operation of which are described in [10]. The scanner consists of two parallel deflecting plates, where a sawtooth electric voltage is applied, as well as input and output slits and a Faraday cup to measure the ion current that passes through both slits. A stepper motor moves the scanner in the transverse beam vertical *x*-direction. The plates are 120 mm long in the longitudinal direction, with a 10 mm gap between them. The widths of the input and output slits is 200 μm. The scanner was positioned 40 mm from the RF source, with its movement along the *x*-coordinate ranging from 0 to 14 mm in 100 μm steps. The voltage applied to the electrostatic plates varied from -200 V to +200 V in 2 V steps.

Beam emittance measurement were carried out in the regime of maximum extracted ion current (U_{ext} = 250 V, U_{acc} = 7 kV, $p \leq$ 1 Pa). The geometric emittance, that encloses 90% of the total beam current, is ε_{90}= 9.8 π·mm·mrad, while the rms emittance is ε_{rms}=2.2 mm·mrad. The normalized emittance is ε_N =0.037 π·mm·mrad. The energy-normalized emittance of the source equals 0.8 π·mm·mrad·$(\mathrm{MeV})^{1/2}$ and is 1.5 times smaller than the emittance of the RF ion source from “High Voltage” company [11].

4. CONCLUSIONS

A compact nuclear microprobe requires an ion source capable of generating a stable proton ($^1H^+$) beam with a current up to 10 nA and an energy spread of approximately 10 eV. To meet these requirements, a low power inductive RF ion source has been developed. The source parameters are as follows: RF power <10 W, frequency is 45 MHz, ion current ≤ 4 μA, beam current stability over time < 1%, and a proton content is about 10%.

The source is simple in design and does not contain incandescent cathodes that could sputter and contaminate the internal surface of the source. The low RF power (< 10 W) facilitates the operating temperature conditions of the source and minimizes high-frequency electromagnetic interference with electronic measuring equipment. Moreover, the reduced RF power, combined with measures to minimize RF pickup on the extraction and acceleration power supplies, allows for a significant reduction in the ion energy spread, bringing it down to an acceptable range of 8-16 eV. The normalized emittance is ε_N =0.037 π·mm·mrad and the energy-normalized emittance equals 0.8 π·mm·mrad·$(\mathrm{MeV})^{1/2}$.

Based on these parameters, it can be concluded that this source is suitable for use in the injector of the compact nuclear microprobe at the IAP NAS of Ukraine.

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