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SINGLE APERTURE 70 mA, 50 keV RADIO-FREQUENCY  
PROTON SOURCE

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## Single aperture 70mA, 50 keV radio-frequency proton source

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### Abstract

A radio-frequency ion source has been developed in the BINP SB RAS. Ion source is designed to operate in cw mode with beam modulation. The ion source works with hydrogen at energy of 50 keV producing an ion beam current of up to 70 mA. The beam is extracted and accelerated by using a four electrode ion-optical system with single aperture. Initial beam diameter is 8 mm. The measured beam divergence is less than 0.5 deg. half angle. The paper describes the results of numerical simulations and experimental data obtained during the ion source testing.

### Одноапертурный 70 мА, 50 кэВ высокочастотный протонный источник

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### Аннотация

В ИЯФ СО РАН разработан высокочастотный ионный источник для работы в непрерывном режиме с модуляцией пучка. Ионный источник, работающий на водороде с энергией 50 кэВ, формирует пучок с ионным током до 70 мА. Пучок вытягивается и ускоряется четырех-электродной ионно-оптической системой с одной апертурой. Начальный диаметр пучка равен 8 мм. Измеренная расходимость пучка составляет менее 0.5 градусов. В работе описаны результаты численных расчетов и экспериментальные данные, полученные при испытаниях ионного источника.

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## 1. Introduction

Ion sources with proton beam current of about 100 mA have many applications in such areas as plasma diagnostic in magnetic fusion devices, accelerator technique, ion implantation, proton therapy, etc. In many of these applications the required beam energy is about 1 MeV or higher. For beam acceleration up to high energies without particles losses it has to have low enough divergence at the ion source output. The considered RF ion source would be appropriate for that producing a beam with ion current up to 70 mA, energy up to 50 keV, beam divergence less than 0.5 deg.

## 2. Ion source layout

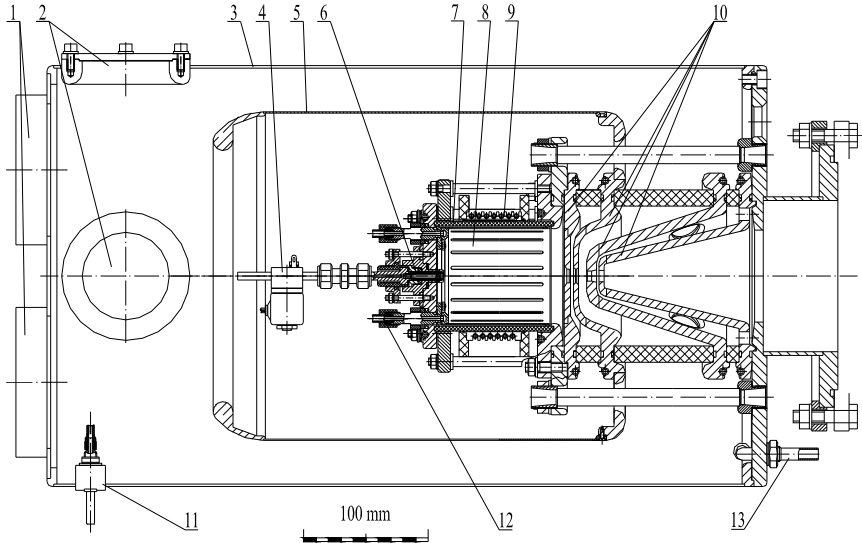
A number of the hydrogen beam injectors based on RF ion sources have been developed in Novosibirsk for plasma diagnostic and heating [1 – 4]. These injectors are capable of operating in a pulse mode with duration up to 10 s. Recently, a radio-frequency proton source (Fig. 1) was developed for cw operation with beam modulation.

### 2.1. Plasma emitter

In the ion source, plasma is produced by an inductively driven RF-discharge with a frequency of 4.6 MHz. The plasma is generated with external RF antenna inside a ceramic cylinder (7) with inner diameter of 80 mm and axial length of 96 mm. The antenna (9) is made of 4 mm diameter cooper tubing and has six turns wounded on a Teflon frame. It is connected to water manifold for cooling. Four permanent magnets are installed in the rear flange of the discharge chamber. The magnets are used to reduce plasma losses on the flange thus increasing overall energy efficiency of the discharge. Near the inner wall of the ceramic chamber a Faraday shield (8) is installed. It is made as oxygen free copper cylinder with 1mm thick wall, which has axial slits of 2.5 mm wide. Rear flange of Faraday shield has water channel for cooling and water manifolds (12). The ceramic plasma chamber is vacuum sealed at both ends with indium. All internal metal surfaces of the plasma chamber including Faraday shield, rear flange and plasma electrode are covered by thin ceramic layer to reduce molecules production at the surface [5].

Using an electromagnetic pulse valve hydrogen gas is puffed into the discharge chamber through a stainless steel tube with 0.125 mm i.d. and length of 40 mm placed in the triggering device (6). Tungsten 0.11 mm wire is inserted into the tube to reduce gas conductivity of the channel. The discharge is initiated by

applying a high voltage pulse of 6 kV (10 mks) between the triggering electrode placed inside ceramic tube and rear flange of the discharge chamber where the triggering device is mounted. Voltage is applied to the triggering device in 5 ms after the RF power on. A spark is generated at the end of ceramic tube and thrown out into the plasma chamber. Advantage of this type of ignition in comparison with tungsten filament is longer lifetime. The RF ion sources [2, 4] with the similar ignition unit operate reliably during many years.



*Fig. 1. RF ion source: 1 - electric fans, 2 - flanges for connecting RF and HV power cables, 3 - metal case, 4 - gas valve, 5 - internal electrostatic shield, 6 - triggering unit, 7 - ceramic discharge chamber, 8 - Faraday shield, 9 - RF antenna, 10 - ion optical system, 11 - gas feed, 12 - Faraday shield cooling manifold, 13 - grids cooling manifold.*

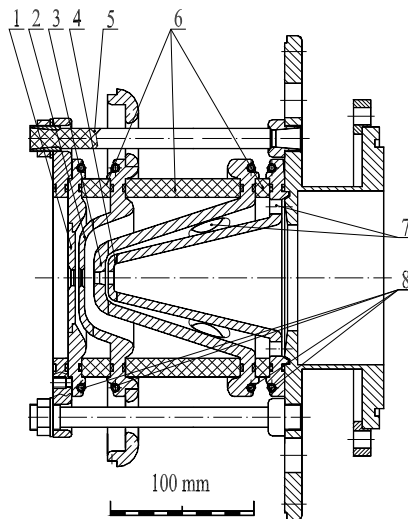
The RF power required to produce a beam with ion current of 70 mA was about 1.8 kW. Heat removal from plasma electrode and rear flange of the plasma box was sufficient to keep their temperature small enough during beam extraction. The Faraday shield was also intensively cooled by water flowing in the channels at its end. However, in the current design, water cooling is not sufficient to operate the ion source without modulation. So, it can operate only with modulation of the RF power and consequently with modulation of the beam. It means that in the intervals between beam extractions the RF power should be decreased down to a small level, which is only needed to sustain the discharge. In the other operational regime plasma discharge can be completely stopped between the beam pulses and

then re-excited with applying an RF power. Note, that the former regime corresponds to much less average RF power.

To estimate average power the temperature profile on the Faraday shield was calculated using the ANSYS workbench [6]. It was assumed that the power load is uniform inside plasma chamber and maximum temperature of the FS should be about 200°C. Under these assumptions, maximum acceptable average power dissipated on the internal surface of the FS was found to be about 500 W. Cooled end of the shield has temperature of 22°C, opposite one – 230°C. In the calculations only thermal conduction was considered. Plasma electrode and rear flange have total area two times smaller than the FS. It was assumed that average dissipated power in the plasma chamber should be less than 750 W to avoid damage. In the experiments, the plasma box was operated under smaller loads with 25% duty factor, which corresponded to about 450 W average power.

## 2.2. Ion-optical system

The plasma source is connected to an electrostatic accelerator (Fig. 2). Three cylindrical ceramic insulators (6) 20, 80 and 10 mm in height are used for mounting of the four electrodes of the ion optical system: plasma electrode (1), extracting (2), accelerating (3) and grounded (4) electrodes.



*Fig. 2. The 50 kV insulator unit and electrodes of the ion-optical system: 1 - plasma electrode, 2 - extraction electrode, 3 - acceleration electrode, 4 - grounded electrode, 5 - pull stud (insulator); 6 - ceramic spacers; 7 - holes for pumping, 8 - cooling water channels, water manifolds.*

The central part of the electrodes has inserts made of molybdenum. Molybdenum part is soldered to the massive copper holders with water cooled channels (6) at periphery. The water channels are made of copper tube of 4mm inner diameter and soldered to the holders. Electrodes and ceramic insulators are assembled in stack and clasped by using impregnated epoxy studs.

Ion optical system is designed to operate in a regime with continuously extracted beam. Numerical simulations of the electrode thermal stresses and deformations under the expected heat loads were carried out. The temperature profile and electrode thermo-mechanical deformations were calculated using the ANSYS workbench. It was suggested that the electrode temperature rise could be maximum 100°K in continuous mode of operation without modulation of the beam.

The temperature field developed on the heated electrodes during continuous operation and their deformations were simulated assuming that 1% of the beam power is dissipated in each electrode according [7 – 9] and to the results of our previous measurements. In the calculations, the temperature of the cooling channels is supposed to be 22°C. In addition to the power released by secondary particles during beam formation, the plasma electrode is heated by the discharge plasma. This power was about 270 W for the plasma discharge operated continuously with maximum power. Power of 35 W (1% of the beam power) is dissipated at the edge of the hole. The maximum calculated temperature at the edge of the hole then is about 97°C. This value is admissible for regime of the beam formation without modulation. According to our simulations, the maximum temperature of the extraction, acceleration, grounded electrodes is in the range of 62–67°C.

The calculated thermo-mechanical deformations of the electrodes are small enough and cannot change the gaps significantly. The plasma electrode deformation towards plasma chamber was estimated to be less than 0.03 mm. Simulated deformations of the extraction, acceleration and grounded electrodes are also found to be negligibly small.

The ion optical system was optimized using the 2D PBGUNS<sup>TM</sup> code [10] to achieve an angular spread of the beam less than 10 mrad. Plasma emitter parameters were taken to be  $kT_e = 8$  eV, the initial ion drift energy 10 eV, and  $kT_i = 2$  eV, and the total current at the extraction plane is about 100 mA. The proton fraction was set to 100%. The correction on the beam specie mix can be easily recalculated by taking an effective ion mass instead of proton mass. Qualitatively, presence of the molecular ions leads to a decrease of the current at minimum divergence.

The chosen beamlet geometry is shown in Fig. 3. Also the electrode potentials and ion trajectories in the optimized version of the ion optical system are shown in Fig. 4. The diameter of holes in the plasma and extracting electrodes is 10 mm and 11 mm, correspondingly. Accelerating and grounded electrodes have diameter of 8 mm and 9 mm, correspondingly. The gaps between the plasma, extraction, acceleration, and grounded electrodes are 2.5, 6.5, and 2 mm, correspondingly.

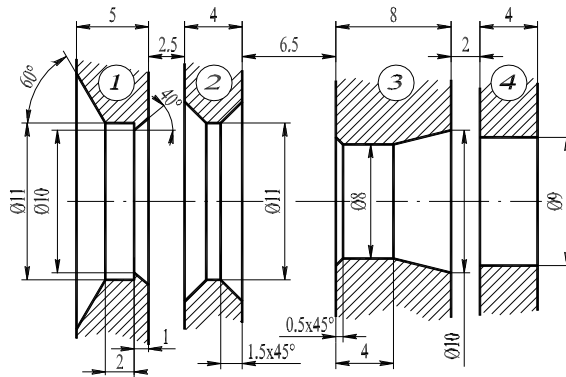


Fig. 3. Beamlet geometry: 1 – plasma electrode; 2 – extraction electrode; 3 – acceleration electrode; 4 – grounded electrode.

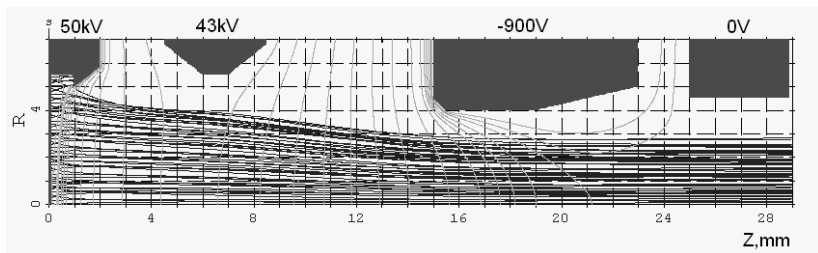


Fig. 4. Electrode configuration, ion trajectories and equipotentials in the ion optical system. The electrode potential relative to ground is given in the top.

Calculated emittance plot is shown in Fig. 5 at minimum of the beam divergence attained at the optimized current density and potentials on electrodes. The calculated rms normalized emittance is  $0.148 \pi \text{mm-mrad}$ .

Calculated angular divergence of the beam is shown in Fig. 6. It was calculated as a function of the beam current for different potential of the extracting electrode in percentages to the potential of the plasma electrode.

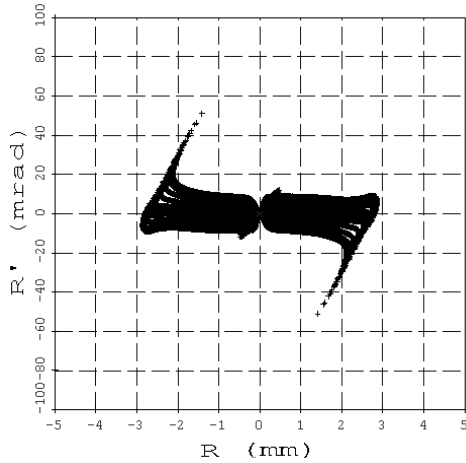


Fig. 5. Emittance plot.

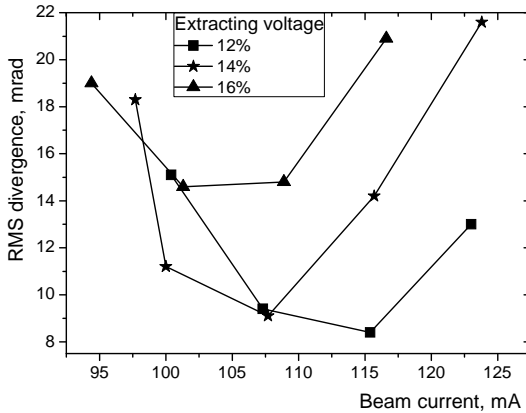


Fig. 6. Calculated RMS divergence of the beam vs beam current.

Minimum of the angular divergence was about 9 mrad. All numerical calculations were made with assumption that the beam contains 100% of protons. According to the spectroscopic measurements of beam composition protons make up about 60%, molecular ions  $H_2^+$  and  $H_3^+$  make up other 40% in about equal amounts. Corresponding recalculations with account of the mass of molecular ions result in reduction of the beam optimal current from 110 mA down to 94 mA.



### 3. Experimental results

The ion source has been tested with beam extraction of up to 73 mA current at 50 keV energy operating up to 1 sec without modulation and in the various regimes of modulation. Intervals between the 1s pulses were about 3 min and were determined by capacity of the existing high voltage power supply.

The beam profile was measured by an array of secondary emission detectors at the distance of 3.4 m downstream from the ion source. From this data, an angular divergence of the beam can be calculated as a ratio between beam radius at level  $1/e$  to the distance between the ion source and detectors. To identify a regime of operation with minimum beam size, an angular divergence as a function of the beam current for different extraction voltages was measured. The results of these measurements are summarized in Fig. 7. The beam current was varied from 55 to 73 mA and extracting voltage varied in the range  $3.75 \div 5.25$  kV. Minimum of beam divergence corresponded to an angle of  $<0.5^\circ$  in wide range of extracting voltages. With decrease of the extracting voltage below 4.2 kV optimum beam current with minimum divergence increased up to 73 mA. Beam divergence obtained from these data was 8 mrad in agreement with the simulations.

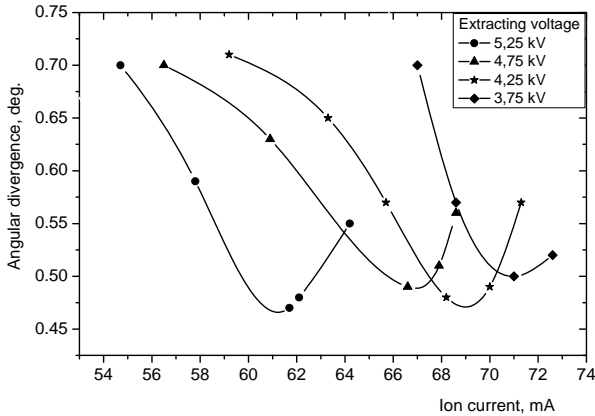


Fig. 7. Angular divergence of the beam as a function of the beam current for different extraction voltages.

Extracted ion hydrogen beam comprised protons  $H^+$  and molecular ions  $H_2^+$  and  $H_3^+$ . For calculation of the beam composition the Doppler shifted  $H_\alpha$  radiation of hydrogen atoms was measured. Atomic hydrogen with full energy  $E$ , energies  $E/2$  and  $E/3$  appeared from dissociation and neutralization processes of the beam ions coming through hydrogen gas flowing out from the ion source.

Ocean Optics HR2000 spectrometer was used for the measurements. Figure 8 shows the typical radiation spectrum  $H_\alpha$  of atomic hydrogen for the 50-keV beam. The spectrum was measured at an angle of  $55^\circ$  to the beam line. It contains five lines, which correspond to particles with different energies. The most intense (rightmost) line is the unshifted  $H_\alpha$  line of atomic hydrogen excited by the beam. Three lines on the left are due to fast hydrogen atoms with energies  $E$ ,  $E/2$ , and  $E/3$ . The line closest to the unshifted line is associated with hydrogen atoms with energy  $E/18$ , which result from dissociation of impurity water ions. The ion beam composition was derived from the optical measurements using the procedure described in [11].

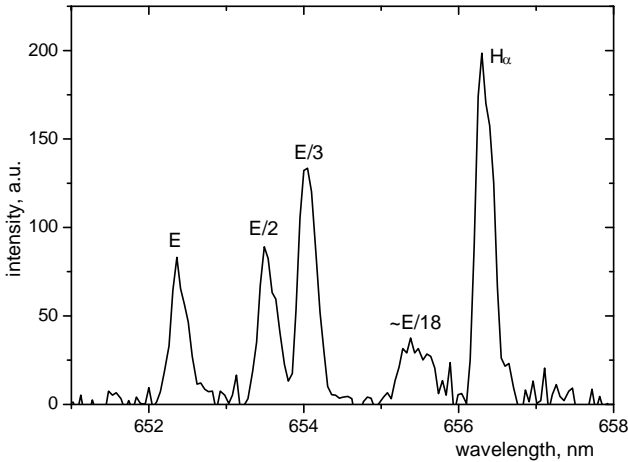
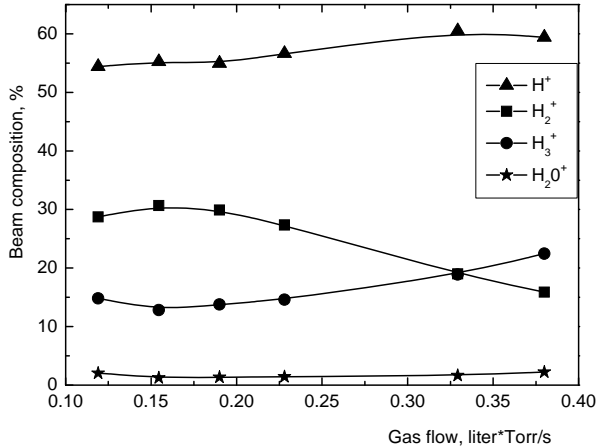


Fig. 8. Radiation spectrum  $H_\alpha$  of atomic hydrogen.

The spectrum shown in Fig. 8 corresponds to 62% of protons, 19.3%  $H_2^+$  ions and 17%  $H_3^+$  ions and 1.7% of  $H_2O^+$  ions in the extracted ion beam. For spectra measurement the ion source was operated with 1s long pulses.

Measurement of the beam composition was also used to adjust gas flow for higher proton fraction. Fig. 9 shows the beam composition as a function of gas flow for the fixed extracted beam current of 65 mA. Gas flow was controlled by MKS 1179A mass flow controller. The percentage of the proton increased from 55 to 60% as the gas flow increased two times from 0.15 to 0.3 Torr·l/s. Optimal gas flow was about 0.33 Torr·l/s.



*Fig. 9. Beam composition as a function of gas flow.*

Experiments with continuous operation of the plasma discharge were carried out in order to prove reliability of the plasma box. Plasma discharge was operated in the regime with frequency 50 Hz and 25% duty cycle during 3 min pulses without beam extraction. Between plasma pulses the ion beam was extracted and beam divergence was measured. The divergence stayed at the same level of about  $0.5^\circ$  that indicated stability of the plasma grid under power load from plasma.

After dismount of the plasma box from the ion optical system its internal surface was inspected. No visible damages on the surfaces of the Faraday screen, as well as the back flange and plasma grid were found.

## Acknowledgements

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