# A CONTINUOUSLY OPERATED 70mA, 50keV PROTON SOURCE FOR PLASMA DIAGNOSTIC AND OTHER APPLICATIONS

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*A radio-frequency ion source has been developed in the Budker Institute of Nuclear Physics, Novosibirsk. Ion source is designed to operate in cw mode with beam modulation. The ion source works with hydrogen at 50kV producing an ion beam current of up to 70mA. 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.*

*This paper describes the experimental results obtained during the ion source testing. Ion source can be applied in many areas including plasma diagnostic, accelerator technique, ion implantation, etc.*

## I. 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 10s. Recently, a radio-frequency proton source (Fig.1) was developed for cw operation with beam modulation.

### I.A. Plasma emitter

In the ion source, plasma is produced by an inductively driven RF discharge with a frequency of 4.6MHz. The plasma is generated with six turns external RF antenna *9* inside a ceramic cylinder *7* with inner diameter of 80mm and length of 96mm. Permanent magnets are installed in the rear flange of the discharge chamber. Inside of the ceramic chamber a Faraday shield (FS) *8* is installed. It is made as copper cylinder with 1mm thick wall, which has axial slits. The ceramic chamber is vacuum sealed at both ends with indium. All internal metal surfaces of the plasma chamber including Faraday shield are covered by thin ceramic layer to reduce molecules production via recombination at the surface[5].

Hydrogen gas is puffed into the discharge chamber using an electromagnetic valve *4* through a micro-channel inside the triggering device *6*. The discharge is initiated by applying a high voltage pulse between two electrodes separated by a ceramic tube. A short spark is generated at the tube end and thrown out into the plasma chamber.

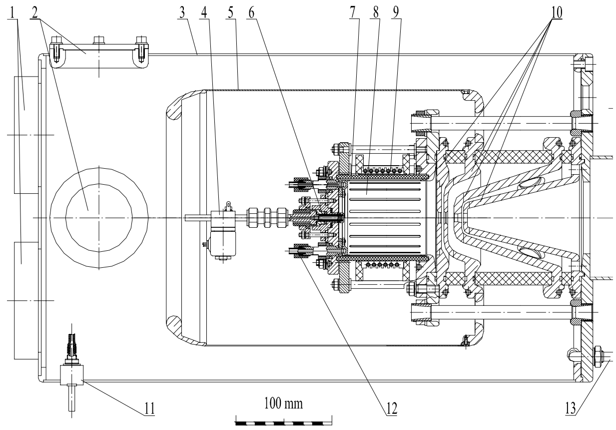


Fig. 1. Ion source: 1 - fans, 2 - flanges for input cables, 3 - metal case, 4 - gas valve, 5 - electrostatic shield, 6 - triggering unit, 7 - ceramic chamber, 8 - Faraday shield, 9 - antenna, 10 - ion optical system, 11 - gas feed, 12 - Faraday shield cooling manifold, 13 - cooling manifold.

The RF power required to produce a beam with ion current of 70mA was about 1.8kW. 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 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 is 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 FS 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 500W. 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 box should be less than 750W to avoid development of critical thermo mechanical stresses and damages. In the experiments, the plasma box was operated under smaller loads with 25% duty factor, which corresponded to average power of about 450W.

### I.B. Ion-optical system

The plasma source is connected to an electrostatic accelerator (Fig.2). Three cylindrical ceramic insulators *6* 20, 80 and 10mm in height are used for mounting of the four electrodes of the ion optical system (IOS): plasma electrode *1*, extracting *2*, accelerating *3* and grounded *4*. The central part of the electrodes has inserts made of molybdenum. Molybdenum parts are soldered to the massive copper holders with water cooled channels *8* at periphery. The water channels are made of copper tube and soldered to the holders. Electrodes and ceramic insulators are assembled in stack and clasped by using impregnated epoxy studs *5*. The holders have the holes *7* for pumping.

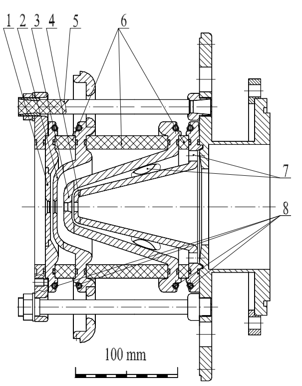


Fig.2. The 50kV electrostatic accelerator.

The IOS is designed to operate continuously. Numerical simulations of the electrode thermal stresses and deformations under the expected heat loads were carried out using the ANSYS workbench.

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 addition to the power released by secondary particles during beam formation, the plasma electrode is heated by the plasma discharge. This power is about 270W for the plasma discharge operated continuously with maximum power. Power of 35W (1% of the beam power) is dissipated at the edge of the hole. The maximum calculated temperature at the edge of the hole is then about 97ºC. This value is admissible for cw mode of the beam formation. According to our simulations, the maximum temperature of the extraction, acceleration, grounded electrodes is in the range of 62÷67ºC.

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 0.03mm. Simulated deformations of the other electrodes are also found to be negligibly small.

The ion optical system was optimized using the 2D PBGUNS™ code[10] to achieve an angular spread of the beam less than 10mrad. Plasma emitter parameters were taken to be $kT_e$ = 8eV, the initial ion drift energy 10eV, and $kT_i$ =2 eV, and the total current at the extraction plane is about 100mA. The proton fraction was set to 100%. The correction on the beam specie mix can be 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 beamlet geometry, the electrode potentials and ion trajectories in the optimized version of the ion optical system is show in Fig.3.

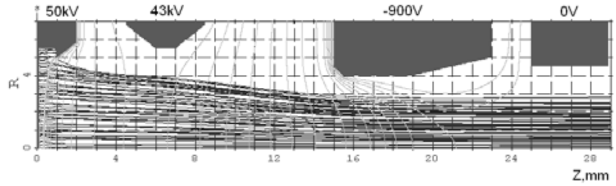


Fig.3. Electrode configuration, ion trajectories and equipotentials in the ion optical system.

The diameter of holes in the plasma, extracting, accelerating and grounded electrodes is 10mm, 11mm, 8mm and 9mm, correspondingly. The gaps between the plasma, extracting, accelerating, and grounded electrodes are 2.5, 6.5 and 2 mm, correspondingly.

Angular divergence of the beam was calculated as a function of the beam current for different potential of the extracting electrode. Minimum of the angular divergence was about 9mrad.

## II. EXPERIMENTAL RESULTS

The ion source was tested with beam extraction of up to 73mA current at 50keV energy operating up to 1s without modulation and in the various regimes of modulation. Intervals between 1s pulses were about 3min determined by 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. An angular divergence of the beam was 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 (Fig.4).

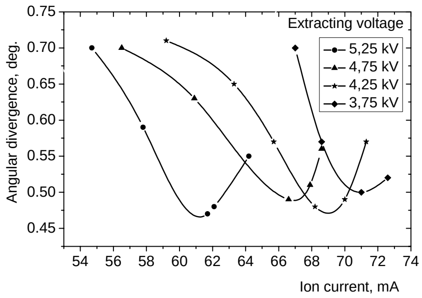


Fig.4. Angular divergence of the beam as a function of the beam current for different extraction voltages.

The beam current was varied from 55 to 73mA and extracting voltage varied in the range 3.75÷5.25kV. Minimum of beam divergence corresponded to an angle of <0.5° in wide range of extracting voltages in agreement with the simulations. With decrease of the extracting voltage below 4.2kV optimum beam current with minimum divergence increased up to 73mA.

Extracted ion hydrogen beam comprised protons and molecular ions $H_2^+$ and $H_3^+$. To determine the beam composition, the Doppler shifted $H_\alpha$ radiation of hydrogen atoms was measured with Ocean Optics HR2000 spectrometer. Atomic hydrogen with full energy *E*, fractional energies *E*/2 and *E*/3 appeared from dissociation and neutralization processes of the beam ions at hydrogen gas flowing out from the ion source. The ion beam composition was derived from the optical measurements using the procedure described in paper[11].

Measurement of the beam composition was also used to adjust gas flow for higher proton fraction. Fig.5 shows the beam composition as a function of gas flow rate for the fixed extracted beam current of 65mA. The proton fraction increased from 55 to 60% with increase of the gas flow from 0.15 to 0.3 Torr·l/s. Optimal gas flow was about 0.33 Torr·l/s.

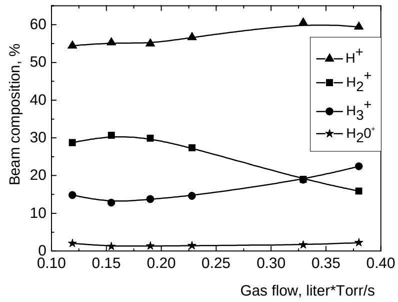


Fig.5. Beam composition as a function of gas flow.

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 50Hz and 25% duty cycle during 3min 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°. After dismount of the plasma box its internal surface was inspected. No visible damages on the internal surfaces were found.

## ACKNOWLEDGMENTS

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