IC-100 Accelerator Complex for Scientific and Applied Research


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Abstract—Industrial production of nuclear filters has been implemented at the IC-100 cyclotron complex of the Laboratory of Nuclear Reactions at the Joint Institute for Nuclear Research. After the complete upgrade, the cyclotron was equipped with the superconducting ECR ion source and the system of external axial beam injection. The implantation complex was equipped with the special transportation channel with the beam scanning system and the setup for irradiation of polymer films. Intense beams of heavy ions Ne, Ar, Fe, Kr, Xe, I, and W with an energy of ~1 MeV/nucleon were obtained. The properties of irradiated crystals were studied, different polymer films were irradiated, and several thousands of square meters of track membranes with pore densities varying in a wide range were produced. Other scientific and applied problems can be solved at the cyclotron complex.

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INTRODUCTION

In 1985, at the Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research, the IC-100 cyclic implanter of heavy ions was developed [1, 2]. The cyclotron was designated for acceleration of ions from 12C²⁺ to 40Ar⁷⁺ with a fixed energy of ~1.2 MeV/nucleon for acceleration at the fourth harmonic of the high voltage system and ~0.6 MeV/nucleon for acceleration at the sixth harmonic. The internal ion source of PIG type was used at the accelerator; this source completely determined the mass range of accelerated ions [3]. For more efficient application of the complex and for implementation of industrial production of nuclear filters, it was proposed to switch to irradiation of films by heavier ions [3].

In the course of the upgrade performed in 2003–2005, the IC-100 implantion complex was equipped with the system of external axial beam injection into the cyclotron (Fig. 1a) and the superconducting ion source based on the electron cyclotron resonance (ECR) (Fig. 1b). This provided a possibility of obtaining intense beams of highly charged ions of xenon, iodine, krypton, argon, and other heavy elements of the Periodic Table [4]. The launching and the adjustment of systems of the IC-100 cyclotron was performed using 86Kr¹⁵⁺ and 132Xe²³⁺ beams. The intensity of accelerated and extracted beams is ~2 μA.

40Ar⁷⁺ beams with a current of more than 2 μA, 56Fe¹⁰⁺ with a current 0.3 μA, 127I²²⁺ with a current up to 0.25 μA, 132Xe²⁴⁺ with a current 0.6 μA, 182W³²⁺ with a current ~0.015 μA, and so on (see Table 3) were also accelerated.

In the course of commissioning, the scheme of the beam injection channel from the ECR source to the input of the central region of the cyclotron was changed. In addition to two focusing solenoids, the third short focus solenoid was mounted at a distance of about 60 cm from the median plane of the cyclotron which provided a possibility of a considerable increase in the acceptance of the vertical part of the injection channel.

The spiral inflector is mounted at the center of the cyclotron. The position and the shape of the electrodes in the central region are optimized for obtaining the optimal acceleration of ions at first turns.

The electrostatic deflector and two focusing magnetic channels are used for ion extraction from IC-100.

The additional shimming of the poles of the cyclotron compensated the distortions of the magnetic field caused by the installation of the passive focusing magnetic channels, which provided a possibility of concentrating the beam and decreasing the dip in the average magnetic field.

The specialized beam transportation channel with the setup for irradiation of the polymer film and the box for investigations with heavy ion beams were also created. The system of beam scanning in two planes [7] providing homogeneous implantation of ions on a large area of the target (Fig. 2) was mounted in the transportation line of the extracted beam. The installation of two RF generators with a separate power supply for each resonator provided a possibility of cardinal improvement of the cyclotron tuning and ensuring long-term stability of the beam current.
Experimental measurements of the beam properties were performed, and the factors influencing the quality and intensity of extracted ions were determined. The tests and the analysis of the beam parameters provided a possibility of diagnosing and solving the problems related to the homogeneity of the film irradiation, the long-term beam stability, and reaching the parameters of the setup close to the design values. The comparison of the design and the obtained values of the parameters is given in Table 1.

1. ECR SOURCE

The IC-100 cyclotron was designed for acceleration of multicharged ions in the range $A/Z = 5.3–6.0$, which imposed strict constraints on obtaining intense beams of highly charged ions of heavy elements. For this purpose, the superconducting ECR source was developed at the Laboratory of Nuclear Reactions together with researchers of the Laboratory of High Energies of the Joint Institute for Nuclear Research. The level of the axial field in the source was up to 3 T, and the frequency of RF heating was 18 GHz [3, 4]. The DECRIS-SC superconducting ion source demonstrated high efficiency and reliability in operation. The spectra of krypton and xenon ions are shown in Figs. 3 and 4. The current of the krypton and xenon ion beams was measured in the focal plane of the analyzing magnet (Fig. 5). After separation and collimation of the injected beam on the diaphragm with a 20-mm diameter, the current of the beam of $^{86}$Kr$^{15+}$ ions was 60–70 $\mu$A, and that of $^{132}$Xe$^{23+}$ ions was 25 $\mu$A (see Table 2) for optimized accelerator tuning to the target. These values are close to the design values of the intensity of these ions from the ECR source (see Table 1). The ion source has considerable margins with respect to intensity of injected beams of heavy ions and provides a possibility of regulating the beam current on the target in a wide range. The ECR source is controlled from the control panel of the IC-100 cyclotron (see Fig. 29).

2. AXIAL INJECTION CHANNEL

The schematic diagram of the axial injection channel of the IC-100 cyclotron is shown in Fig. 5. The main ion optical elements of the channel are the focusing solenoids, the correcting quadrupole lens, the analyzing magnet, and the correcting dipole magnets. In the course of tuning of the accelerator, the conditions of the beam passage along the injection channel of IC-100, depending on different factors, were studied experimentally and compared with the results of computer simulation (Fig. 6). The simulation was performed using the program library for calculation of the dynamics of multicomponent intense ion beams [8]. The inflector was represented as the collimator with a hole diameter of 8 mm.

The results of computer simulation are shown in the form of particle trajectories (Fig. 6a) and beam envelopes along the injection line from the output of the ECR source to the input of the inflector (Figs. 6b, 6c). Two transportation schemes were analyzed: the scheme with two focusing solenoids and that with three focusing solenoids. The third focusing element was mounted for beam matching at the input of the inflector. The ion intensity distribution in the injection channel is shown in Fig. 6d. The mean square emittance (4 RMS) of the $^{86}$Kr$^{15+}$ ions beam after separation in the analyzing magnet is $\varepsilon \approx 250\pi$ mm mrad ($\varepsilon_{\text{norm}} \approx 0.8\pi$ mm mrad) [3], which is somewhat higher than the transmission capacity of the vertical part of the external injection line of IC-100. The acceptance of the channel in the operation mode with two solenoids is $A \approx 150\pi$ mm mrad ($A_{\text{norm}} \approx 0.5\pi$ mm mrad) for the 8 mm input dia-