Письма в ЭЧАЯ. 2008. Т. 5, № 7(149). С. 140–147

IC100 CYCLOTRON–BASED FACILITY FOR PRODUCTION OF NUCLEAR FILTERS AS WELL AS FOR SCIENTIFIC AND APPLIED RESEARCH

B. Gikal, S. Dmitriev, G. Gulbekian, P. Apel', V. Bashevoi, S. Bogomolov, O. Borisov, V. Buzmakov, A. Cherevatenko, A. Efremov, I. Ivanenko, O. Ivanov, N. Kazarinov, M. Khabarov, I. Kolesov, V. Mironov, A. Papash, S. Pashchenko, V. Skuratov, A. Tikhomirov, N. Jazvitsky

Joint Institute for Nuclear Research, Dubna

The complex based on the IC100 cyclotron of the Flerov Laboratory of Nuclear Reactions (JINR, Dubna) provides industrial fabrication of nuclear filters. During modernization the cyclotron was equipped with superconducting ECR ion source and axial injection system. The specialized beam channel with two-coordinate scanning system and equipment for irradiation of polymer films has been installed in the implantation part of the complex. High-intensity heavy-ion beams of Ne, Ar, Fe, Kr, Xe, I, W have been accelerated to 1 MeV/nucleon energy. The investigation of irradiated crystals features, irradiation of different polymer films have been provided. Also a few thousand square meters of track films with holes in a wide range of densities have been produced. The cyclotron-based complex is capable of solving different kinds of scientific and applied problems as well.

На циклотронном комплексе ИЦ-100 Лаборатории ядерных реакций им. Г. Н. Флерова ОИЯИ (г. Дубна) реализовано промышленное изготовление ядерных фильтров. В результате проведения полной модернизации циклотрон был оснащен сверхпроводящим ЭЦР-источником и системой внешней аксиальной инжекции пучка. Имплантационный комплекс был оборудован специализированным каналом транспортировки с системой сканирования пучка и установкой для облучения полимерных пленок. Получены интенсивные пучки тяжелых ионов Ne, Ar, Fe, Kr, Xe, I, W с энергией около 1 МэВ/нуклон. Выполнен ряд научных исследований по изучению свойств облученных кристаллов, проведено облучение различных полимерных пленок, изготовлено несколько тысяч квадратных метров трековых мембран в широком диапазоне изменения плотности отверстий. Циклотронный комплекс способен также решать и другие научно-прикладные задачи.

PACS: 29.20.dg

INTRODUCTION

The facility for nuclear filter production was developed by the Flerov Laboratory of Nuclear Reactions of JINR in 1985 [1]. The complex is based on the IC100 cyclotron [2]. The cyclotron has been designed to accelerate multi-charged ions from carbon ($^{12}C^{2+}$) to argon ($^{40}Ar^{7+}$). Beam energy is fixed to 1.2 MeV/A at 4th acceleration harmonic and

Fig. 1. IC100 cyclotron. Shown are the SC ECR source, injection line, magnet and resonance cavity

to 0.6 MeV/A at 6th harmonic of RF. The internal PIG ion source was installed at IC100 which defines possible range of ions [3]. To improve performance and to realize industrial production of nuclear filters, it was proposed to produce nuclear filters using film irradiation with heavier ions [4].

CYCLOTRON UPGRADE

In 2003–2006 the applied research facility was equipped with superconducting ECR ion source and axial injection system (Fig. 1). High-intensity beams of high-charge state ions of heavy element are supplied from the ion source [5]. The cyclotron commissioning and first beam tests have been done using $^{86}\mathrm{Kr}^{15+}$ and $^{132}\mathrm{Xe}^{23+}$ ions. The extracted beam current exceeds 2 μA. Ions of Ar, Fe, I, W, and other elements were accelerated and extracted from the cyclotron (Table 1).

During the commission period, an original design has been tailored to improve cyclotron performance. In addition to focusing elements in the injection line a third solenoid was installed at a distance of $\sim$600 mm from the cyclotron median plane and acceptance of vertical part of injection line was increased.

The position and the shape of central region electrodes were rearranged and optimized in order to improve efficiency of ion acceleration at first turns. The electrostatic deflector and two magnetic channels were installed in the IC100 in order to extract beam. Distortions of magnetic field caused by passive iron channels have been compensated by shimming plates of

Table 1. **Ions accelerated at IC100**

Element	Ion	A/Z	Current, μA
Neon	$^{22}Ne^{4+}$	5.5	0.7
Argon	$^{40}Ar^{7+}$	5.714	2.5
Iron	$^{56}Fe^{10+}$	5.6	0.5
Krypton	$^{86}Kr^{15+}$	5.733	2
Iodine	$^{127}I^{22+}$	5.773	0.25
Xenon	$^{132}Xe^{23+}$	5.739	1.2
Xenon	$^{132}Xe^{24+}$	5.5	0.6
Tungsten	$^{182}W^{32+}$	5.6875	0.015
Tungsten	$^{184}W^{31+}$	5.9355	0.035
Tungsten	$^{184}W^{32+}$	5.75	0.017

special shape. The field deviation from isochronous profile was reduced to an acceptable level and imperfection of first harmonic was suppressed to few Gauss. The beam centering was improved. Independent RF power supply of each resonator from two RF generators essentially improves cyclotron tuning and provides guarantee of long-term beam stability on target. With new 3/2$\beta\lambda$ drift buncher beam current was increased three times. The specialized beam channel and equipment for film irradiation, as well as box for applied research, were designed and assembled at IC100. Two-coordinate beam scanning system provides homogeneous ion implantation into large surface polymer films [6]. Comprehensive measurements of beam parameters were performed and influence of different factors on beam quality has been investigated. IC100 operating parameters are close to designed values (Table 2).

Superconducting ECR ion source was designed for SRF frequency range up to 24 GHz and axial magnetic field up to 30 kG [4, 5]. 18 GHz SRF generator of 1 kW power is employed at IC100 DECRIS-SC.

Table 2. **IC100 parameters**

Parameter	Designed	Realized
Accelerated ions	Ar, Kr, Xe	Ne, Ar, Fe, Kr, I, Xe, W
A/Z range	5.3–6.0	5.54–5.95
RF harmonic	4	4
Ion energy, MeV	1–1.25	0.9–1.1
Field, kG	18.8–20.1	17.84–19.3
RF frequency, MHz	20.4–20.9	19.8–20.6
Injection voltage, kV	12.5	14–15
Injection vacuum, Torr	$5{\cdot}10^{-7}$	$1.5{\cdot}10^{-7}$
Cyclotron vacuum, Torr	$5{\cdot}10^{-7}$	$5{\cdot}10^{-8}$
RF dee voltage, kV	50	55; 45
Beam emittance (4RMS)		
AM separation, mm·mrad	250π	$\sim 250\pi$
Inj. line accept, mm·mrad	225π	$\sim 220\pi$
$^{86}Kr^{15+}$ beam intensity	$\sim 10^{12}$ s^{-1} (2.5 μA)	$8{\cdot}10^{11}$ s^{-1} (2 μA)
$^{132}Xe^{23+}$ beam intensity	$2.6{\cdot}10^{11}$ s^{-1} (1 μA)	$3{\cdot}10^{11}$ s^{-1} (1.2 μA)
Holes density uniformity		
multiple irradiation, %	± 10	$\pm 10 \pm 3$
Long term beam stability, %	± 10	$\pm 4{-}10$
Total beam transmission, %	8	7

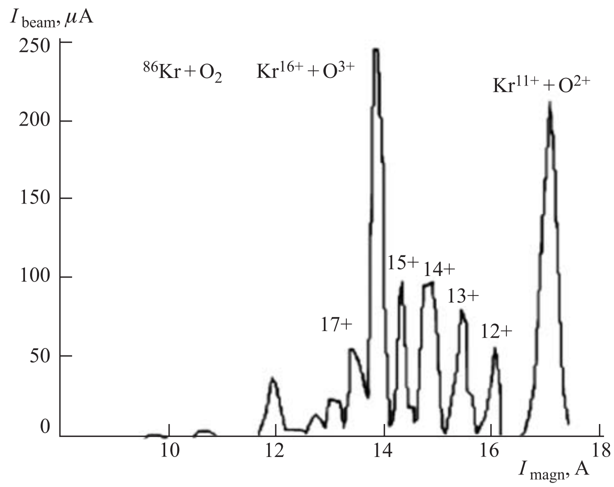

Fig. 2. Kr spectrum from DECRIS-SC. Extraction voltage is 12.5 kV. SRF power is 380 W

Beam current of injected ions exceeds 60 μA for ^{86}Kr^{15+} and 30 μA for ^{132}Xe^{23+} (Fig. 2). The source produces high charge states of very heavy ions. Wide range variation of beam current is routine procedure for DECRIS-SC.

The axial injection line is accomplished with three focusing solenoids S1–S2–S3, single quad lens Q, analyzing magnet AM and correction magnets (Fig. 3) [7]. With S3 solenoid, acceptance of injection channel was upgraded to 250 πmm·mrad and beam is focused at the inflector entrance to 8 mm spot.

The gap between sectors in the cyclotron was reduced to 20 mm in order to provide high-level magnetic field (19 kG). Isochronous field profile has been formed by shaping sectors and by using plate shims. There are no trim coils in IC100. The central region was modified and dee-ground gaps were reduced to 7 mm in order to improve beam focusing in axial direction and to increase RF acceptance.

Drift 3/2$\beta\lambda$ grid buncher has been tested at IC100. To minimize transit time effects, the gap between grid electrodes has been reduced to 3 mm. The distance between wires was decreased from 8 to 4 mm in order to provide homogeneous electric field distribution. With buncher on, ion current is increased three times, which is close to designed values.

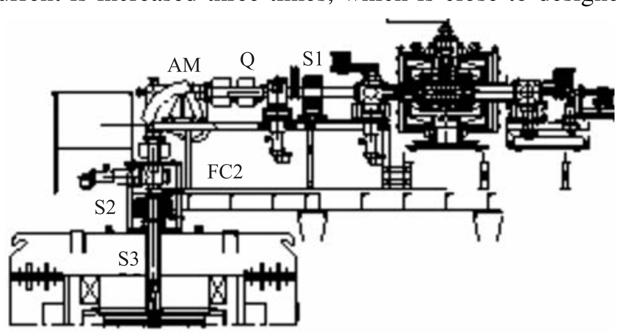

Fig. 3. Axial injection channel (length ≈5 m). DECRIS — superconducting ECR ion source; AM — analyzing magnet; S1, S2, S3 — focusing solenoids; Q — correction quads; FC2 — Faraday cup

Beam Measurements. IC100 accelerated beam energy is fixed at ∼1 MeV/A [8]. A/Z range of ions and RF frequency might be slightly varied (Table 2). Beam current distribution of Ar^{7+}, Kr^{15+} and Xe^{32+} ions during acceleration in the IC100 is presented in Fig. 4. The RF phase selection of ions takes place up to ∼150 mm. RF capture efficiency of DC beam (buncher is off) is close to 10% of injected current, which is close to 40° RF phase band. With buncher on, RF acceptance of IC100 cyclotron is increased three times, up to 30% [9]. Resonance (Garren–Smith) curves were measured to control beam phase motion inside the cyclotron (Fig. 5). Symmetry position of resonance curves at all radii, as well as for extracted beam, provides experimental evidence of good quality field profile.

Cyclotron Vacuum System consists of two sets of cryo- and turbopumps. The cyclotron operates at vacuum level of 10^{-8} Torr. Acceleration efficiency due to vacuum losses inside the cyclotron (from ∼150 to 400 mm radii) is in complete agreement with preliminary computer simulations and it is about 60–70% for all ions [10]. The slope of beam current distribution curves is similar for all ions and does not depend on ion charge (Fig. 4). There are no significant vacuum losses in the IC100 cyclotron due to gas stripping of heavy ions. Slight decline of ion current is caused by aperture losses of beam on small vertical gaps (20 mm).

Ions of $^{184}W^{32+}$ have been accelerated and delivered to the target. Beam current of W ions on the target exceeds 17 nA ($3{\cdot}10^9$ pps). Technology of composite hexa-carbonyl tungsten powder $W(CO)_6$ sublimation has been used for ion production in ECR source [11]. For production of Fe ions, vapors of metallotzen $Fe(C_5H_5)_2$ composite unit have been injected into the discharge chamber of ECR source. Injected current of Fe ions of +9, +10, +11 charge states is equal to 3–5 μA. Extracted beam of $^{56}Fe^{10+}$ ions is almost 0.5 μA ($3{\cdot}10^{11}$ pps).

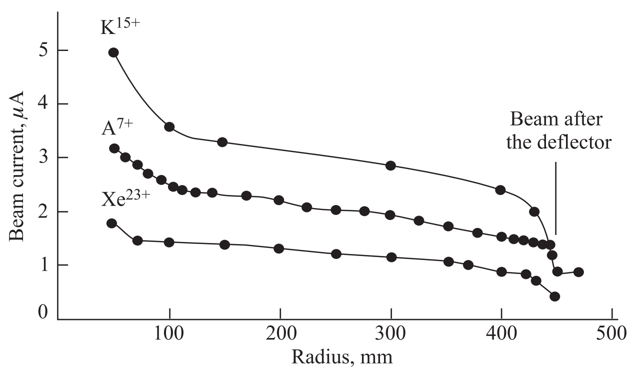

Fig. 4. Beam current distribution during acceleration of Ar, Kr, and Xe ions

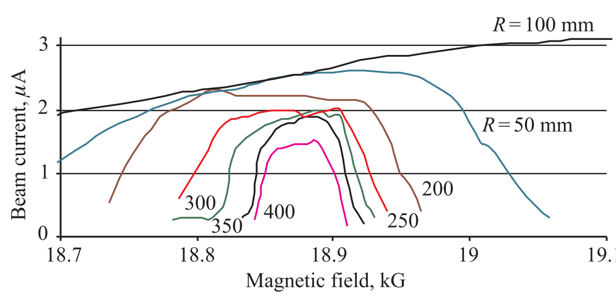

Fig. 5. Resonance curves of $^{86}Kr^{15+}$. Plato is symmetrical at all radii

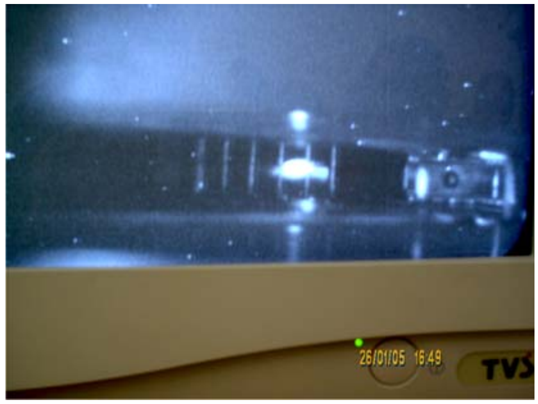

Fig. 6. Photo of the extracted beam of $^{86}Kr^{15+}$ after magnetic channel. The distance between wires is 5 mm

Extraction System of IC100 consists of an electrostatic deflector and two magnetic channels. The deflector is located at free valley. The first channel is installed in the free space between sectors. The second channel MC2 of 20×10 mm aperture is located in the field region with high azimuth gradient. To provide smooth compensation of gradient fields along the beam trajectory, the MC2 was divided in 5 sections with different local gradients. Drop of average field in the acceleration region caused by iron channels has been reduced to an acceptable level by special shim plates installed in the valley between the channels. Seventy percent of beam passes the deflector. Total extraction efficiency of beam is almost 50%. Extracted beam shape after the second channel is 5×4 mm (Fig. 6).

Beam Diagnostics and Current Stability. Special measures have been made to improve long-term stability of beam and to provide uniform distribution of beam current on 300×200 mm target area. Two RF generators are used for independent feed of two RF resonators. Back loop phase stability system ensures precise tuning of RF phase and amplitude on both dees independently. Beam line multi-wire probe with 90% transparency, Faraday cups located on both sides of radiation area, the central collector intercepting part of beam were employed for on-line beam diagnostics during films irradiation. Faraday cup in the beam line and other elements are used for current calibration.

For production of nuclear tracking membranes (TM), the film is moving in the vertical direction. Beam is focused in elongated ellipse in vertical direction and spread out in horizontal direction by scanning magnets with a repetition rate of 100 Hz. Special attention was paid to symmetry of beam current on both sides of the film. Production cycle usually takes about 2–4 h because the film rotation speed is 5 to 10 cm$\cdot c^{-1}$. Beam current is stabilized by tuning injection line solenoid S1, as well as by changing buncher voltage and power of ECR source. Long-term stability of beam current is better than $\pm 5\%$ providing the automatic

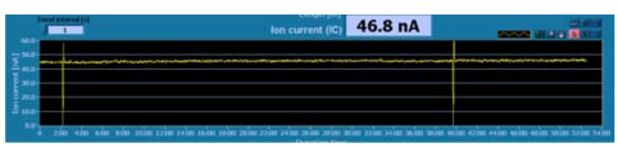

Fig. 7. Long-term stability of $^{132}Xe^{23+}$ beam. Current was measured on target. Irradiation period 1 h

Fig. 8. Beam delivery line to device for polymer film production

Fig. 9. Chamber for TM production

tuning system is on (Fig. 7). To guarantee high uniform hole density distribution, as well as to reduce influence of sparks in the cyclotron, the film is irradiated two times.

TM Channel. Differential pumping system along beam channel of 10 m length separates the cyclotron volume from the irradiation chamber and consists of four turbopumps and two for-vacuum lines (Fig. 8). Film rewinding chamber and three high-speed turbopumps are shown in Fig. 9. Cryogenic panel system of 50,000 l/s pumping speed for water vapors will provide high vacuum even with heavy gas load during fast film rotation.

CONCLUSION

Intense beams of 1 MeV/A heavy ions of Ne, Ar, Fe, Kr, Xe, I, W have been successfully accelerated at the IC100 cyclotron. Parameters of irradiated crystals have been studied.

Industrial production of different kinds of polymer films was performed and a few tens of thousands of square meters of TM was produced in the wide range of hole densities — from $5\cdot10^5$ to $3\cdot10^8$ cm^{-2}. The IC100 cyclotron–based facility is well fitted to solve other scientific and applied research programs including nanotechnologies. Modification and improvement of different subsystems is under way. Special efforts are made to expand range of accelerated ions, to increase beam intensity, to upgrade beam diagnostics, automatic control system, to improve beam stability, to modify vacuum system of radiation channel, etc.

The authors are greatful to FLNR staff and all people who help to upgrade the facility performance.

REFERENCES

1. *Gikal B. et al.* JINR, P9-86-305. Dubna, 1986.
2. *Gulbekian G. et al.* JINR, P9-86-785. Dubna, 1986.
3. *Andrijanov A. et al.* JINR Preprint P9-85-598. Dubna, 1985.
4. *Gikal B. et al.* Modernization of Cyclotron Implant Facility IC100. JINR Preprint E9-2003-121. Dubna, 2003.
5. *Efremov A. et al.* Status of the Ion Source DECRIS-SC // Rev. Sci. Instr. 2006. V. 77, 03A320. P. 235–239.
6. *Gulbekian G. et al*. JINR Preprint P9-87-495. Dubna, 1987.
7. *Alexandrov A. et al.* Space Charge Dominated Beam // Proc. of the Workshop on Physics for Heavy Ion Fusion ECR Sources, RIKEN, Japan, 1998. P. 49.
8. *Gikal B. et al*. JINR Preprint P9-2002-240. Dubna, 2002.
9. *Gikal B. et al*. // Proc. of EPAC98, Sweden, 1998. P. 2199–2201.
10. *Tikhomirov A., Kováč P.* // J. Vacuum Technol. 1999. V. 52. P. 401.
11. *Nakagava T.* Production of Highly Charged Metal Ion Beams from Organic Metal Compounds at RIKEN 18 GHz ECRIS // Nucl. Instr. Meth. A. 1997. V. 396. P. 9–12.