

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

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The complex based on the cyclotron IC100 of the Laboratory of Nuclear Reactions (JINR, Dubna, Russia) 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 coordinates 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 few thousands square meters of track films with holes in the wide range of densities have been produced. The cyclotron based complex is capable to solve different kinds of scientific and applied problems as well.

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## INTRODUCTION

The Facility for nuclear filters production has been developed by Laboratory for Nuclear Reactions of JINR in 1985 [1]. Complex is based on the cyclotron IC100 [2]. The cyclotron has been designed to accelerate multi-charged ions from Carbon ( $^{12}\text{C}^{2+}$ ) to Argon ( $^{40}\text{Ar}^{7+}$ ). Beam energy is fixed to 1.2 MeV/A at 4<sup>th</sup> acceleration harmonic and to 0.6 MeV/A at 6<sup>th</sup> harmonic of RF. The internal PIG ion source was installed at IC100 which defines possible range of ions [3].



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

To improve performance and to realize industrial production of nuclear filters it was proposed to produce nuclear filters using film irradiation by more heavy ions [4].

## CYCLOTRON UPGRADE

In 2003-2006 the applied research facility has been 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 Ion Source [5]. Cyclotron commissioning and first

beam tests have been done using  $^{86}\text{Kr}^{15+}$  and  $^{132}\text{Xe}^{23+}$  ions. The extracted beam current has exceeds 2  $\mu\text{A}$ . Ions of Ar, Fe, I, W and other elements were accelerated and extracted from the cyclotron (Tabl.1).

*Table 1. Ions accelerated at IC100*

Element	Ion	A/Z	Current $\mu\text{A}$
Neon	$^{22}\text{Ne}^{4+}$	5,5	0,7
Argon	$^{40}\text{Ar}^{7+}$	5,714	2,5
Iron	$^{56}\text{Fe}^{10+}$	5,6	0,5
Krypton	$^{86}\text{Kr}^{15+}$	5,733	2
Iodine	$^{127}\text{I}^{22+}$	5,773	0,25
Xenon	$^{132}\text{Xe}^{23+}$	5,739	1,2
Xenon	$^{132}\text{Xe}^{24+}$	5,5	0,6
Tungsten	$^{182}\text{W}^{32+}$	5,6875	0,015
Tungsten	$^{184}\text{W}^{31+}$	5,9355	0,035
Tungsten	$^{184}\text{W}^{32+}$	5,75	0,017

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

The position and the shape of central region electrodes was 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 special shape. The field deviation from isochronous profile was reduced to an acceptable level and imperfection 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 in three times. The specialized beam channel and equipment for film irra-

diation as well as box for applied research were designed and assembled at IC100. Two coordinates beam scanning system provides homogenous 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).

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	5,545,95
RF harmonic	4	4
Ion energy, MeV	1...1,25	0,9...1,1
Field, kGs	18,8...20,1	17,8419,3
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	45455
Beam emittance (4RMS)	$250\pi$	$\sim 250\pi$
AM separation, $\pi$ mm-mr		
Inj.line Accept, $\pi$ mm-mr	$225\pi$	$\sim 220\pi$
$^{86}\text{Kr}^{15+}$ beam intensity	$\sim 10^{12} \text{ p}^{-1}$ (2.5 $\mu\text{A}$ )	$8 \cdot 10^{11} \text{ p}^{-1}$ (2 $\mu\text{A}$ )
$^{132}\text{Xe}^{23+}$ beam intensity	$2.6 \cdot 10^{11} \text{ p}^{-1}$ (1 $\mu\text{A}$ )	$3 \cdot 10^{11} \text{ p}^{-1}$ (1.2 $\mu\text{A}$ )
holes density uniformity multiple irradiation	$\pm 10\%$	$\pm 10\%$ $\pm 3\%$
Long term beam stability	$\pm 10\%$	$\pm 4...10\%$
Total beam transmission	8%	7%

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

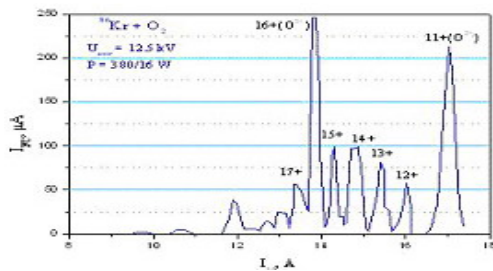


Fig.2. Kr spectrum from DECRIS-SC. Extraction voltage 12.5 kV. SRF power is 380 W

Beam current of injected ions exceeds 60  $\mu\text{A}$  for  $^{86}\text{Kr}^{15+}$  and 30  $\mu\text{A}$  for  $^{132}\text{Xe}^{23+}$  (Fig.2). 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  $250\pi$  mm-mr 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 kGs). Isochronous field profile has been formed by shaping of sectors and by using of plate shims. There are no trim coils in IC100. 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.

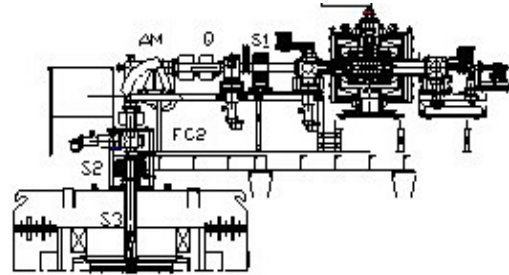


Fig.3. Axial injection channel (length  $\approx 5$  m)

DECRIS – superconducting ECR Ion source;

□ – analyzing magnet; S1, S2, S3 – focusing solenoids; Q – correction quads; FC2 – Faraday cup

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. Distance between wires was decreased from 8 to 4 mm in order to provide homogenous electric field distribution. With Buncher on ion current is increased in three times which is close to designed values.

**Beam measurements.** IC100 accelerated beam energy is fixed at  $\sim 1$  MeV/A [8]. A/Z range of ions and RF frequency might be slightly varied (Tabl.2). Beam current distribution of  $\text{Ar}^{7+}$ ,  $\text{Kr}^{15+}$  and  $\text{Xe}^{32+}$  ions during acceleration in the IC100 is presented in Fig.4. The RF phase selection of ions takes place up to  $\sim 150$  mm. RF capture efficiency of DC beam (Buncher is off) is close to 10% of injected current which is close to  $40^\circ$  RF phase band. With Buncher on RF acceptance of IC100 cyclotron is increased in three times up to 30% [9]. Resonance (Garren-Smith) curves were measured to control beam phase motion inside 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.

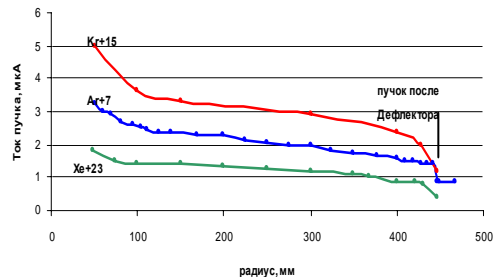


Fig.4. Beam current distribution during acceleration of Ar, Kr, and Xe ions

**Cyclotron Vacuum system** consists of two sets of Cryo- and turbo-pumps. Cyclotron operates at vacuum level of  $10^{-8}$  Torr. Acceleration efficiency due to vacuum losses inside the cyclotron (from  $\sim 150$  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).

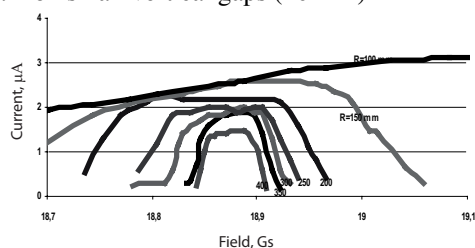


Fig.5. Resonance curves of  $^{86}\text{Kr}^{15+}$ . Plato is symmetrical at all radii

Ions of  $^{184}\text{W}^{32+}$  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 hexacarbonyl tungsten powder  $\text{W}(\text{CO})_6$  sublimation has been used for ion production in ECR source [11]. For production of Fe ions vapors of metallotzen  $\text{Fe}(\text{C}_5\text{H}_5)_2$  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  $^{56}\text{Fe}^{10+}$  ions is almost 0.5 µA ( $3 \cdot 10^{11}$  pps).

**Extraction system** of IC100 consists from an Electrostatic Deflector and two magnetic channels. Deflector is located at free valley. The first channel is installed in the free space between sectors. Second channel MC2 of  $20 \times 10$  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 channels. 70% of beam passes Deflector. Total extraction efficiency of beam is almost 50%. Extracted beam shape after second channel is  $5 \times 4$  mm (Fig.6).



Fig.6. Foto of extracted beam of  $^{86}\text{Kr}^{15+}$  after magnetic channel. Distance between wires is 5 mm

**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  $300 \times 200$  mm<sup>2</sup> 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 Membrans (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 repetition rate of 100 Hz. Special attention was paid to symmetry of beam current on both sides of film. Production cycle usually takes about 2-4 hours because of the film rotation speed is 5 to 10 cm·c<sup>-1</sup>. Beam current is stabilized by tuning of injection line solenoid S1 as well as by changing of buncher voltage and power of ECR source. Long term stability of beam current is better than  $\pm 5\%$  providing the automatic 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.

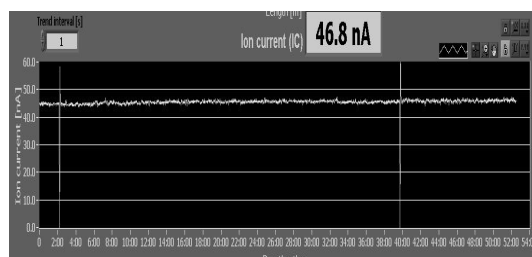


Fig.7. Long term stability of  $^{132}\text{Xe}^{23+}$  beam. Current was measured on target. Irradiation period one hour

**TM channel.** Differential pumping system along beam channel of 10 m length separates cyclotron volume from irradiation chamber and consists of 4 turbo-pumps and two for-vacuum lines (Fig.8).



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

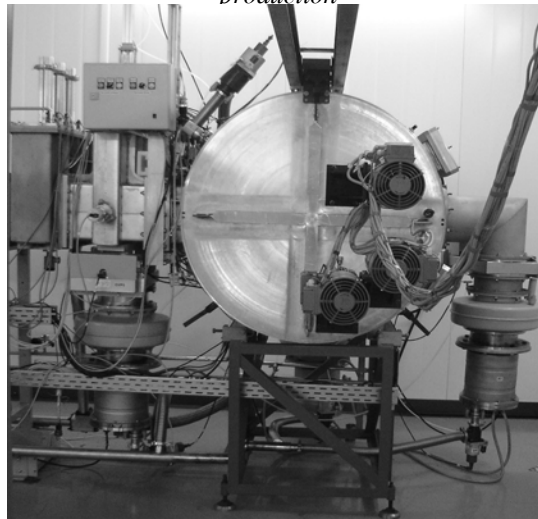


Fig.9. Chamber for TM production

Film rewinding chamber and three high speed turbo-pumps 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.

### CONCLUSIONS

Intense beams of 1 MeV/A heavy ions of Ne, Ar, Fe, Kr, Xe, I, W elements have been successfully accelerated at IC100 cyclotron. Parameters of irradiated crystals have been studied. Industrial production of different kinds of polymer films was performed and few tens of thousands of square meter of TM was produced in the wide range of hole densities – from  $5 \cdot 10^5$  to  $3 \cdot 10^8$  cm<sup>-2</sup>. 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 attention is paid 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. Authors are greatly appreciate to LNR staff and all people who helps to upgrade facility performance.

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### УСКОРИТЕЛЬНЫЙ КОМПЛЕКС ДЛЯ ПРОИЗВОДСТВА ЯДЕРНЫХ ФИЛЬТРОВ И ПРОВЕДЕНИЯ НАУЧНО-ПРИКЛАДНЫХ ИССЛЕДОВАНИЙ НА БАЗЕ ЦИКЛОТРОНА ИЦ100

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На циклотронном комплексе ИЦ100 Лаборатории ядерных реакций ОИЯИ (г. Дубна, Россия) 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. Были получены интенсивные пучки тяжелых ионов Ne, Ar, Fe, Kr, Xe, I, W с энергией около 1 МэВ/нукл. Был проведен 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.

### ПРИСКОРЮВАЛЬНИЙ КОМПЛЕКС ДЛЯ ВИРОБНИЦТВА ЯДЕРНИХ ФІЛЬТРІВ І ПРОВЕДЕННЯ НАУКОВО-ПРИКЛАДНИХ ДОСЛІДЖЕНЬ НА БАЗІ ЦИКЛОТРОНУ ІЦ100

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На циклотронному комплексі ІЦ100 Лабораторії ядерних реакцій ОІЯД (м. Дубна, Росія) реалізовано промислове виготовлення ядерних фільтрів. У результаті проведення повної модернізації циклотрон був оснащений надпровідним ЕЦР-джерелом і системою зовнішньої аксіальної інжекції пучка. Імплантаційний комплекс був обладнаний спеціалізованим каналом транспортування з системою сканування пучка і установкою для опромінення полімерних плівок. Були отримані інтенсивні пучки важких іонів Ne, Ar, Fe, Kr, Xe, I, W з енергією біля 1 МеВ/нукл. Був проведений ряд наукових досліджень по вивченню властивостей опромінених кристалів, проведено опромінення різних полімерних плівок, виготовлено кілька тисяч квадратних метрів трекових мембран у широкому діапазоні змін щільності отворів. Циклотронний комплекс здатний також вирішувати і інші науково-прикладні завдання.