DEDICATED DC-110 HEAVY ION CYCLOTRON FOR INDUSTRIAL PRODUCTION OF TRACK MEMBRANES

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Abstract

In the Laboratory of nuclear reactions JINR dedicated accelerator complex on the basis of the heavy ion cyclotron DC-110 for the industrial track membrane production has been developed and created. The isochronous cyclotron DC-110 accelerates the ions Ar, Kr and Xe with a fixed energy of 2.5 MeV/nucleon and intensity of 10-15 μA. The cyclotron is equipped with ECR ion source - DECRIS-5 (18 GHz) and axial injection system. The pole diameter of the magnet is 2m. Isochronous magnetic field formed by shimming sectors on the level of 1.67 T. Accelerated ions $^{40}Ar^{6+}$, $^{86}Kr^{13+}$, $^{132}Xe^{20+}$ have close mass-to-charge ratio, which allows changing particles without changing the operation mode of the cyclotron. Accelerator complex DC-110 is capable of producing up to 2 million square meters of track membranes per the year.

INTRODUCTION

A series of heavy-ion accelerators for applied purposes have been developed and created at the Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research. The IC-100 cyclotron was put into operation in 1985 and upgraded in 200-2002 [1,2]. In 2004-2006 the DC-60 cyclotron was created for the Interdisciplinary Research Center of the Gumilev Eurasian National University (Astana, Kazakhstan) [3,4]. The accelerator beams are successfully used for solid state physics research, and track membrane production. Based on the technological solutions and experience of operating the IC-100 and DC-60 accelerators there has been developed the project of the DC-110 cyclotron [5,6]. The accelerator complex produces intense Ar, Kr, and Xe ion beams with a fixed 2.5 MeV/nucleon energy, which allows the production of track membranes on the basis of up to 30 μm thick polymer films.

The accelerator complex includes:
- the DC-110 cyclotron,
- ECR ion source and axial beam injection system,
- accelerated beam transport channel equipped with technological equipment for irradiating the polymer film,
- vacuum system,
- electrical supply and control system,
- cooling system.

The accelerator is furnished with one polymer film irradiation channel. The possibility of installing a switching magnet and assembly of a second channel is provided for increasing the productivity of the equipment by simultaneous irradiation of film on one channel and preparing for installation on the other.

The cyclotron magnet has a 2m pole diameter. The ions being accelerated are $^{40}Ar^{6+}$, $^{86}Kr^{13+}$ и $^{132}Xe^{20+}$ with close mass-to-charge ratios of 6.667, 6.615, and 6.600, which allows realizing an acceleration regime practically at a fixed frequency of the accelerating system and fixed magnetic field.

The DC-110 accelerator does not provide for ion energy variation and changes in the mass-to-charge ratio of accelerated particles. This concept is characterized by increased reliability and by simplicity of controlling the complex.

ION SOURCE

The 18 GHz DECRIS-5 ion source was developed on the basis of sources of the DECRIS-4 (14 GHz) series with copper windings created at LNR (JINR, Dubna) [7] by intensifying the magnetic structure and changing to a new type of microwave oscillator. The DECRIS-5 ion source created for industrial application is characterized by increased reliability.

To ensure the design parameters of the beams accelerated on the DC-110, the ion source should generate intensities of $^{40}Ar^{6+}$, $^{86}Kr^{13+}$ and $^{132}Xe^{20+}$ ion beams of not less than 85μA, 150 μA and 150 μA, respectively. After assembling the ECR source and axial injection system, thorough adjustment of all systems of the source and axial injection channel was carried out. Beams of Ar, Kr, and Xe ions were produced from the source. The possibility of producing maximum Ar, Kr, and Xe ion beam intensity was investigated, the results are given in Table 1.

Table 1. Maximum ion beam intensities obtained from DECRIS-5 source in μA (Z - ion charge).

Z	8+	9+	11+	15+	18+	19+	20+
Ar	1200	750	300				
Kr				325	182	120	70
Xe							220

BEAM AXIAL INJECTION SYSTEM

For transporting the ion beam of the ECR source to the center of the cyclotron, beam axial injection system is used, which is composed of:
- 3 focusing elements, 2 correcting elements,
- analyzing magnet,
- diagnostic elements of the injected beam,

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- linear buncher located 2450 mm away from median,
- sinusoidal buncher located 800 mm away from median plane,
- vacuum system based on turbomolecular pumps and cryogenic pumps,
- electrostatic inflector located in the center of the cyclotron for deflecting the injected beam from the vertical channel into the cyclotron median plane.

The 20 kV injection voltage was selected for the optimal conditions of beam dynamics in the cyclotron center.

CYCLOTRON MAGNETIC STRUCTURE

The DC-110 magnetic structure is created on the basis of an electromagnet with a 2m pole diameter.
The use of radial correction coils is not provided for in the DC-110 cyclotron; the isochronous magnetic field is formed by iron structure. Azimuthal correction coils are installed in the valleys of the cyclotron for correcting the first harmonic.

In the working gap of the magnet there are four pairs of sectors with straight boundaries fastened at the magnet's pole. Each sector is equipped with lateral detachable shims. Azimuthal or vertical processing of the lateral sector shims was used for correcting the magnetic field when forming the isochronous acceleration conditions and also for compensating the effect of the magnetic channel used for focusing the beam in the cyclotron's beam extraction system. A compensating channel identical in design to the main channel is installed in the cyclotron centrally-symmetrically to the focusing magnetic channel for suppressing odd harmonics of the magnetic field. The main parameters of the magnet of the DC-110 cyclotron are given in Table 2.

Table 2. Main parameters of DC-110 cyclotron magnet.

Pole diameter, [mm]	2000
Number of sector pairs	4
Angular length of sector (helicity)	52^{o} (0^{o})
Number of radial correction coils	0
Number of sets of azimuthal correction coils	2
Electromagnet weight [tons]	250
Isochronous magnetic field at center, T	1.67

RADIO FREQUENCY SYSTEM OF CYCLOTRON

A resonance system consisting of the following components is used in the DC-110 isochronous cyclotron for producing a dee-accelerating voltage:

- two quarter-wave coaxial resonators, which are stainless-steel tanks plated inside with copper,
- two copper dees with an angular span of 40°,

The characteristics of the RF system are given in Table 3.

Table 3. General characteristics of RF system.

Resonance frequency of resonators	7.494 - 7.806 MHz
Acceleration harmonic	2
Dee voltage	55 kV
Maximum power of RF generator	20 kW

BEAM EXTRACTION

An electrostatic system based on a deflector with a 50–60 kV/cm and focusing magnetic channel is used at the DC-110 cyclotron for extracting accelerated beam. The deflector is located in the valley. A passive magnetic channel is used in the cyclotron chamber for focusing the beam during extraction.

BEAM CHANNELS FOR IRRADIATION OF POLYMER MATERIALS

The DC-110 cyclotron complex (Fig.1) has one channel for transporting accelerated ion beams with the possibility of installing a switching magnet and assembling a second channel.

The horizontal heavy ion beam scanning system is created on the basis of a magnet supplied by a sawtooth current. Vertical scanning is accomplished by an electrostatic deflector with a sawtooth voltage of 15 kV. The scanning system provides irradiation of a 600×200 mm^2 stationary target with uniformity not worse than ±10% and irradiation of a moving film up to 600 mm wide at a speed from 0.05 to 1 m/s.

Figure 1: DC-110 cyclotron.

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CYCLOTRON OPERATING REGIMES AND ACCELERATED IONS

To accelerate $^{40}Ar^{6+}$, $^{86}Kr^{13+}$, $^{132}Xe^{20+}$ ions have a small difference in the mass-to-charge ratio (6.667, 6.615, and 6.600), it was decided to use an acceleration regime with a fixed magnetic field. The frequency of the accelerating system should be changed in conformity with Table 4.

Table 4. Optimal frequency values of RF system (F_{RF}) and magnetic field (B_0) .

Ion	A/Z	B_0, T	F_{RF}, MHz	Frequency difference, kHz
$^{40}Ar^{6+}$	6.6667	1.6612	7.653	23
$^{86}Kr^{13+}$	6.6154	1.6612	7.712	-18
$^{132}Xe^{20+}$	6.6000	1.6612	7.730	0

The acceleration regime indicated in Table 6 doesn't require a change in any parameters of the accelerator systems when changing the type of ions being accelerated except for tuning the frequency of the resonance system.

The phase acceptance of the DC-110 cyclotron is about 30°; a beam bunching system is used for increasing capture efficiency of the injected beam into acceleration. The efficiency of capturing the beam into acceleration and the coefficient of the beam intensity increase compared to the unbunched beam are shown in Table 5.

An increase of the capture coefficient to 48% at a low injected beam intensity of 6 μA, is related not only to a decrease of the space charge effect in the beam but mainly to a decrease of beam emittance at a low intensity from the ion source.

Table 5. Capture coefficient of injected beam into acceleration in different regimes.

I_{inj}, μA	Capture coefficient into acceleration in %			
	without bunching	Lin-on. Sin-off.	Sin-on. Lin-off.	Sin+Lin – on.
6	9.3	23.2	25.8	48.2
18.4	8.7	15.6	25.0	38.0
49	9.1	15.7	25.7	36.7
103	8.7	14.1	24.8	34.0

The main tuning of the DC-110 cyclotron to achieve the design parameters was done with the use of a $^{86}Kr^{13+}$ ion beam. During accelerator tuning, a regime was found with a high beam transmission coefficient from the ion source to the polymer film irradiation device at an injected beam intensity close to the maximum, 150 μA.

In a working regime, the pressure in the cyclotron chamber as at the moment of commissioning was $2.4{\cdot}10^{7}$ Torr (without the beam, $1.7{\cdot}10^{-7}$ Torr). Losses of $^{86}Kr^{13+}$ ions during acceleration from radius 140 mm to radius 890 mm were about 37% both in the case of a bunched beam and in the case of disconnected bunchers, of which vacuum losses amount to about 30%. In 2013 as a result of vacuum training of the cyclotron chamber internal surfaces there was achieved a pressure of $\sim 1{\cdot}10^{-7}$ Torr in the acceleration mode. Vacuum losses in this case decreased by a half.

Works on creating the DC-110 cyclotron complex began in August 2009. In 2012, assembly and adjustment of the cyclotron equipment were carried out in the building of the BETA research and industrial complex and beams of accelerated Ar, Kr, and Xe ions were obtained.

Table 6 presents design and experimentally obtained parameters of ion beams after the completion of commissioning. There was carried out the irradiation of a polymer film of 12μm thickness with ions of Kr. The non-uniformity of pore density in the manufactured track membranes was better than ±10%.

Table 6. Ion beam parameters of the DC-110 cyclotron.

Ion	ECR beam intensity, μA	Extracted beam intensity, μA		Ion energy, MeV/nucleon
		design	obtained	
$^{40}Ar^{6+}$	94	6	13	2.5
$^{86}Kr^{13+}$	150	13	14.5	2.5
$^{132}Xe^{20+}$	190	10	10.9	2.5

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