FLNR HEAVY ION CYCLOTRONS FOR INVESTIGATION IN THE FIELD OF CONDENSED MATTER PHYSICS INDUSTRIAL APPLICATIONS

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Abstract

Applied research on heavy ion beams are carried out in many scientific centres of the world. Some of the developed technologies are successfully used in industry, for example, a well-known method of track membranes production using heavy ion beams, which as a rule have an energy from 1 to 3.5 MeV/nucleon. At FLNR several specialized accelerators have been created for this purpose.

Since 1983 a complex based on the IC-100 cyclotron for industrial manufacturing of track membranes operates at the JINR Flerov Laboratory of Nuclear Reactions (Dubna, Russia). The modernization in 2003 equipped the cyclotron with a superconducting ECR ion source as well as with an axial injection system. High intensity heavy ion beams of Ne, Ar, Fe, Kr, Xe, I, W have been accelerated to an energy of 1.2 MeV/nucleon.

The DC-60 cyclotron with smooth ion energy variation was designed by FLNR for the research center at L.N. Gumilev Euroasian State University in Astana (Kazakhstan). The cyclotron equipped with an ECR ion source accelerates ions from Carbon to Xenon. The energy of the extracted beams can be varied from 0.35 up to 1.7 MeV/nucleon.

In 2009-2010 a cyclotron complex for a wide spectrum of applied research in the field of nanotechnologies (template technologies, track membranes, surface modification, etc.) was designed at the Flerov Laboratory of Nuclear Reactions. This complex includes a specialized DC-110 cyclotron, which produces high intensity beams of accelerated Ar, Kr, and Xe ions with a fixed energy of 2.5MeV/nucleon. The DC-110 cyclotron is at the commissioning stage now.

The accelerated ion beams of U400 and U400M cyclotrons (FLNR) have been used for several years already by the Russian Space Agency (Roscosmos) for investigation of radiation resistance of electronic devices. For these experiments ions with atomic masses of 4÷209 and an energy of 3÷6 MeV/nucleon are used. Now a specialized channel and a facility for carrying out these investigations on the beams of ions with energies of 25-55 MeV/nucleon is being mounted.

IC-100 CYCLOTRON

In 1985, at the Laboratory of Nuclear Reactions of 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 $^{12}C^{2+}$ to $^{40}Ar^{7+}$ with a fixed energy of ~1.2 MeV/nucleon at acceleration at the fourth harmonic of the high voltage system and ~0.6 MeV/nucleon for acceleration at the sixth harmonic. A PIG type internal ion source was used at this accelerator; the mentioned source determined the mass range of accelerated ions. For more efficient application of the complex and for industrial production of track membranes, it was proposed to switch to irradiation of films with heavier ions [2].

In the course of the upgrade performed in 2003–2005, the IC-100 implantation complex was equipped with a system of beam axial injection from an external superconducting ECR ion source (Fig. 1). 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 were performed using $^{86}Kr^{15+}$ and $^{132}Xe^{23+}$ beams. The intensity of accelerated and extracted beams is ~2μA. $^{40}Ar^{7+}$ beams with a current of more than 2μA, $^{56}Fe^{10+}$ beams with a current of 0.3μA, $^{127}I^{22+}$ beams with a current of up to 0.25μA, $^{132}Xe^{24+}$ beams with a current of ~0.6μA, $^{182}W^{32+}$ beams with a current of ~0.015μA, and so on were also accelerated.

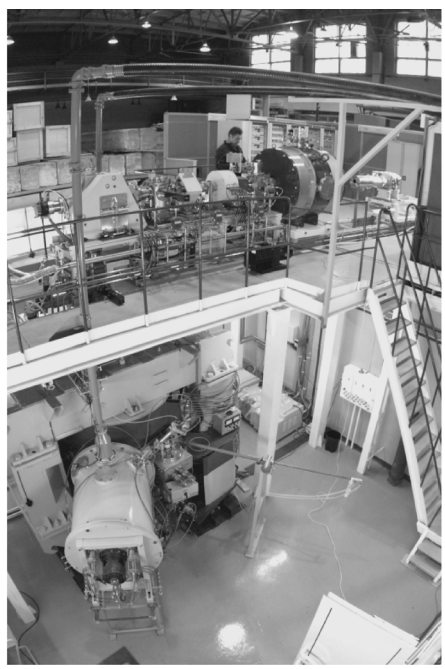

Figure 1: General view of the IC-100 cyclotron.

DC-60 CYCLOTRON

A specialized accelerating facility based on the DC-60 cyclotron was built by the Flerov Laboratory of Nuclear Reactions in collaboration with the Institute of Nuclear Physics (Almaty, Kazakhstan) for the Interdisciplinary Scientific Research Center of the Gumilev Eurasian

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National University (Astana, Kazakhstan). The facility, based on the heavy ion cyclotron DC-60, is capable of providing intense heavy ion beams ranging from Lithium to Xenon in the energy range of 0.35–1.7 MeV/nucleon. The facility is supplied with a (10–25)×Z kV (Z – the ion charge) low energy beam channel as well. Heavy ions are produced by the Electron Cyclotron Resonance Ion Source (ECR) (Fig. 2). The whole facility was designed, built, and put into operation over the period of 2004–2006 [3], [4]. Main parameters of the DC-60 cyclotron are shown in Table 1.

Table 1. Main parameters of DC-60

ION BEAM INJECTOR	**ECR ion source + axial injection system**
MAGNET	
Magnet pole diameter	1.62 m
Cyclotron magnetic field	1.45 T - main mode 1.25÷1.65 T - magnetic field variation
Weight of magnet	~ 100 tons
Magnet power	67 kW
Correction coils: - radial coils - azimuth coils Total power	 5 sets 2 sets 1 kW
RF SYSTEM	
- frequency - harmonic number - dee voltage - RF power	11.00 ÷ 17.5 MHz 4 and 6 50 kV 20 kW
Pressure in cyclotron vacuum chamber	$(1\div2)\cdot10^{-7}$ Torr
Main accelerated ion beam parameters	
Ions	**Li ÷ Xe**
Mass to charge ratio A/Z	6 ÷ 12
Accelerated ion energy	0.35 ÷ 1.7 MeV/nucleon
Beam intensity	$6\cdot10^{13}$ - $1\cdot10^{12}$ pps
Discrete ion energy change	Due to A/Z ratio
Smooth energy variation with respect to nominal one	-30 % / +20% Due to magnetic field variation
Low energy ion beam parameters	
Ions	**He ÷ Xe**
Mass to charge ratio (A/Z)	2 ÷ 20
Ion energy from ECR source	10 ÷ 20 keV/charge
Discrete ion energy change	Due to change of A/Z
Smooth ion energy variation	Due to extracted potential variation in ECR source

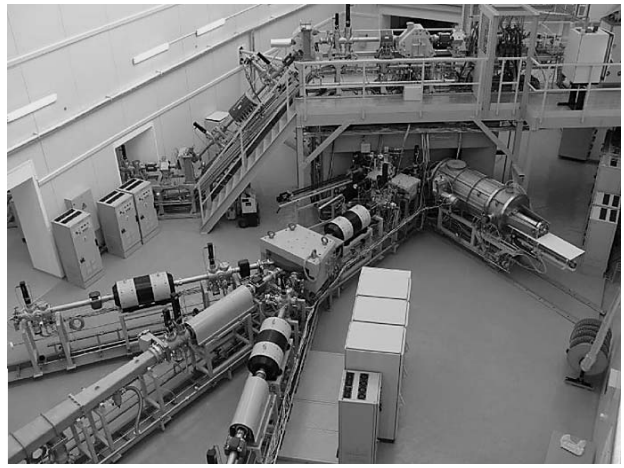

Figure 2: Photo of DC-60 cyclotron facility.

DC-110 CYCLOTRON

The project of the DC-110 cyclotron facility for applied research in nanotechnologies (track pore membranes, surface modification of materials etc) has been designed by the Flerov Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research (Dubna) [5]. The facility includes an isochronous cyclotron DC-110 for acceleration of intense Ar, Kr, Xe ion beams with a 2.5 MeV/nucleon fixed energy (Table 2). The cyclotron is equipped with a system of axial injection and with an 18 GHz ECR ion source. The cyclotron with a 2m diameter magnet pole creates in the working gap a magnetic field of 1.67 T. The RF system operates at a fixed frequency of 7.75MHz. The extraction system is equipped with an electrostatic deflector.

Ions of $^{40}Ar^{6+}$, $^{86}Kr^{13+}$ and $^{132}Xe^{20+}$ are chosen for acceleration in the cyclotron because they have a mass/charge ratio close to 6.667, 6.615 and 6.6 respectively. It allows realizing an acceleration mode on a practically fixed RF system frequency and with a fixed magnetic field level. Variation of ions energy and change of acceleration mode are not envisaged in this cyclotron. The cyclotron complex is equipped with two channels and two facilities for irradiation of polymeric films. The accelerator provides a possibility of preparing one of the facilities for irradiation while the second facility is being used for film irradiation. It raises considerably the efficiency of equipment. The DC-110 cyclotron is at the commissioning stage now (Figs. 3,4).

Table 2. Basic parameters of DC-110 cyclotron.

Accelerated ions	$^{40}Ar^{6+}$	$^{86}Kr^{13+}$	$^{132}Xe^{20+}$
Mass to charge ratio of accelerated ion, A/Z	6.667	6.615	6.6
Ions energy, MeV/n	2.52	2.52	2.52
Magnetic field, T	1.683	1.67	1.666
RF frequency	7.753	7.753	7.753

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Number of Acceleration Harmonic	2	2	2
Planned intensity of the extracted beams	12μA (2 pμA)	13 μA (1 pμA)	10 μA (0.5 pμA)

Figure 3: The DC-110 cyclotron.

Figure.4: The facility for irradiation of polimer films at the DC-110 cyclotron

SINGLE-EVENT EFFECTS (SEE) TESTING AT FLNR CYCLOTRONS

The Russian Space Agency (Roscosmos) carries out investigations of single-event effects (SEE) in electronic devices using ion beams of U400 and U400M cyclotrons of the Flerov Laboratory of Nuclear Reactions [6]. U400 cyclotron delivers beams of ions with atomic masses of 4÷209 at energies of 3÷29 MeV/nucleon [7]. U400M cyclotron [7] was intended for acceleration of ion beams in two modes:

- acceleration mode of high energy ions - 19–3 MeV/nucleon (mass to charge ratio of accelerated ions A/Z = 2.8 – 5),
- acceleration mode of low energy ions - 5–10 MeV/nucleon (mass to charge ratio of accelerated ions A/Z = 7– 10).

Both options are used for testing of electronic devices. A beam channel of low energy ions is now in operation (fig. 5). Ions of O, Ne, Ar, Fe, Kr, Xe, Bi with an energy of 3÷6 MeV/nucleon are available to users. At the end of 2012 the installation of the channel will be finished for testing at high energy ion beams. Beams of ions from C up to Xe with energies from 25 to 53 MeV/nucleon will be available for carrying out experiments.

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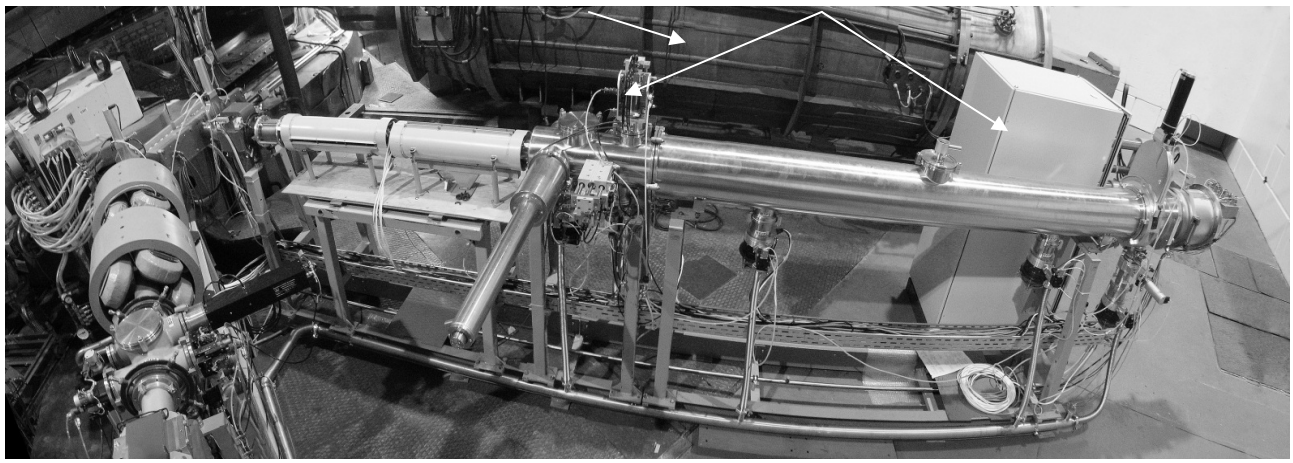

Fig. 5. General view of the ion beam transport line and experimental set up for SEE testing at U400M cyclotron.

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