ACCELERATOR COMPLEX BASED ON DC-60 CYCLOTRON

M. Zdorovets#, I. Ivanov, M. Koloberdin, S. Kozin, V. Alexandrenko, E. Sambaev, A.Kurakhmedov, A. Ryskulov, Institute of Nuclear Physics, Astana, Kazakhstan

Abstract

DC-60 heavy ion accelerator [1], put into operation in 2006, according to its specifications - spectrum, charge and energy of accelerated ions, has the high scientific, technological and educational potential. The highest possible universality both by spectrum of accelerated ions and acceleration energy and regimes was built in DC-60 heavy ion accelerator designing. The new interdisciplinary research complex based on DC-60 cyclotron makes it possible to create a highly-developed scientific-technological and educational environment in the new capital of Kazakhstan. This article is a review of the DC-60 heavy ion accelerator and the works carried out based on the cyclotron.

INTRODUCTION

DC-60 accelerator is a dual cyclotron, which is capable of charged particles acceleration up to kinetic energies in MeV/nucleon, expressed in the following relation: $E = 60(z_i/A)^2$, where z_i - accelerated ion charge, A - atomic weight of ion. Relation (z_i/A) in formula must be within the following limits: $(z_i/A) = (1/6 \div 1/12)$, that impose constraints on charge of accelerated ions.

Prototypes ECR heavy-ion source are sources DECRIS-2 and DECRIS-3 [2] which is used in the DC-60 accelerator. On the "ECR - surface" is used magnetic field configuration «minimum B» for the plasma confinement and electronic heating. This configuration is obtained as a result of the superposition of an axial field of magnetic mirror and a radial field of a sextupole magnet. Two single coils with an iron yoke form an axial magnetic field, and the radial magnetic field is created by an NdFeB permanent sextupole of a magnet.

The operating frequency of UHF the ECR generator is 14 GHz. The flash chamber of source is insulation meant for a voltage up to 25 kV. The extraction of ions is performed two elements Plasma electrode and the mobile extraction electrode.

For the beam transport from the ECR ion source to the cyclotron created a powerful system of axial injection of beam, which is consisting of:

- focusing element;
- energy-analysing magnet;
- detecting of elements;
- bunchers;
- vacuum pumps;
- electrostatic inflectors.

The entrapment of phase to accelerate in the center of the cyclotron is 30° ÷ 35°. This means that no more than 10% of ion of the desired charge will be involved in the acceleration process. To increase efficiency the entrapment of the beam by axial injection systems is installed the bancher with a sine wave, which includes the beam particles in the desired range of phases and increases the capture coefficient to 30÷50 %. Turn of the beam from the vertical axial injection channel in the median plane of the cyclotron using the electrostatic spiral of inflector.

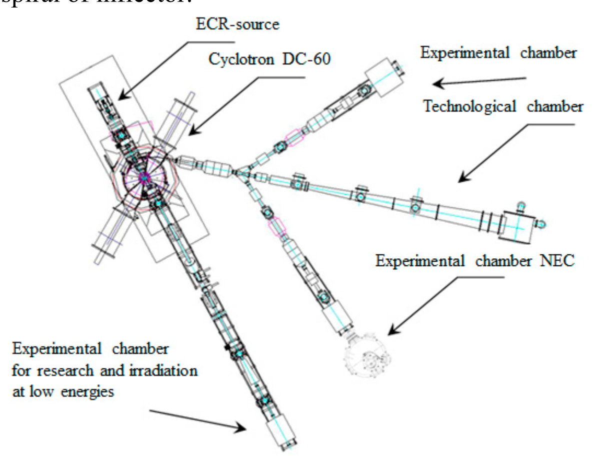

Figure 1: The scheme of the DC-60 accelerator complex.

The upper energy of the accelerated ions is 1.75 MeV/nucleon. The variation of the energy of ions in the range from 0.35 to 1.75 MeV/nucleon is provided by changes in the charge of the accelerated particles and magnetic field of the cyclotron.

High frequency system has a variation of the frequency in the band 12 - 18 MHz and provides the acceleration of ions on harmonics 4 and 6.

The electrostatic deflector with the electric field strength of 75 kV/cm is used for the beam extraction from the cyclotron which located in the cavity of the magnet. The beam transport channels from the cyclotron to the target chamber include the standard system focusing and rotation of the accelerated ions. Thus, range of ions accelerated on DC-60 cyclotron is ^{6}Li to ^{132}Xe, variation of ion energy is over the range 0.35 to 1.75 MeV/nucleon.

CYCLOTRON OPERATION

Since 2006 to 2014 many experimental works in the domain of nuclear and atomic physics, radiation physics of solid and nanotechnology have been carried out at the DC-60 cyclotron. The data of beam time in a period of 2006 - 2014 of operation of the accelerator is shown in Fig. 2.

#mzdorovets@gmail.com

ISBN 978-3-95450-170-0

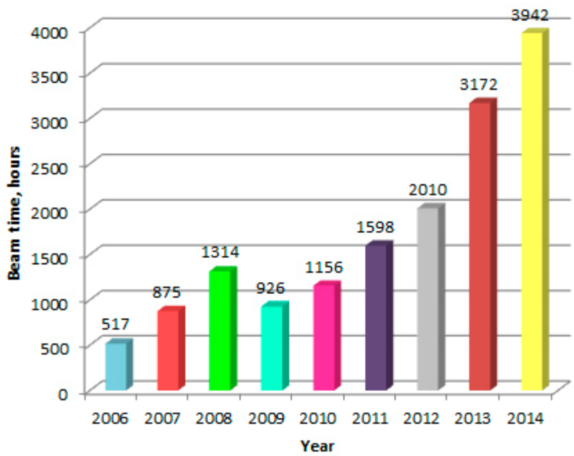

Figure 2: Total cyclotron beam time in the years 2006 - 2014.

As seen in Figure 2, there is an increase of the cyclotron beam time year by year, and in 2014 the work of the cyclotron is started its maximum. At the same time, about a third of the time is accounted for by the production of track membranes.

Over the last eight years of operation of DC-60 heavy-ion accelerator which used-on of the modes of operational of ion ^{6,7}Li, ^{12}C, ^{13}C, ^{14}N, ^{16}O, ^{20}Ne, ^{32}S, ^{40}Ar, ^{84}Kr и ^{132}Xe in the energy range 0.35 - 1.75 MeV/nucleon. For every the acceleration performance characteristic and resonance curves, radial beam profiles which carried out to optimize each system cyclotron [3] were measured. This work is carried out in the section "Fine-tuning technology of new ions in the DC-60 accelerator" of the program "Implementation of comprehensive research investigation in physics, chemistry, biology and advanced technologies on the basis of a heavy ion DC-60 accelerator", financed from the republican budget.

In 2014 work to the production lithium ions in the ECR source and further acceleration of ions on a cyclotron successfully completed. After the development of the technology of producing ions from solids using gateway solids feed to the ECR source, opens the possibility of using a number of prospective (not accelerated earlier) ion beams, such as ^{11}B, ^{40}Ca, ^{48}Ti, ^{56}Fe, ^{58}Ni, ^{98}Mo, etc.

Table 1 shows the main modes of operation of the accelerator and received the beam current of accelerated ions on the ECR source and the current external beam of ions from the cyclotron in the transport channel. All modes of operation of the cyclotron shown in Table 1 were optimized for long and stable operation. These values are ion beam current at the ECR source and extracted from the cyclotron are not as big as possible. Of all the modes of the most-coveted the acceleration modes with the maximum possible of energy, is a 1.75 MeV/nucleon.

Table 1: Current characteristics of accelerated ion beams

Ion	A/Z	Energy, MeV/nucl.	Beam current ECR, μA	Extracted beam current, μA
$^{7}Li^{1+}$	7	1.32	110	2.2
$^{12}C^{1+}$	12	0.40	63	0.6
$^{12}C^{2+}$	6	1.00	147	1.7
$^{12}C^{2+}$	6	1.25	150	1.5
$^{12}C^{2+}$	6	1.50	170	2.1
$^{12}C^{2+}$	6	1.75	140	1.7
$^{13}C^{2+}$	6.5	1.25	18.1	0.7
$^{13}C^{2+}$	6.5	1.50	19.9	0.6
$^{13}C^{3+}$	4.3	1.75	16.3	0.5
$^{14}N^{2+}$	7	0.4	84	0.9
$^{14}N^{2+}$	7	1.0	134	1.5
$^{14}N^{3+}$	4.6	1.4	325	2.0
$^{14}N^{3+}$	4.6	1.5	320	2.7
$^{14}N^{3+}$	4.6	1.75	120	1.9
$^{16}O^{2+}$	8	1.0	90	1.08
$^{16}O^{3+}$	5.3	1.25	85	1.1
$^{16}O^{3+}$	5.3	1.4	112	0.9
$^{16}O^{3+}$	5.3	1.5	95	0.8
$^{16}O^{3+}$	5.3	1.75	86	1.1
$^{20}Ne^{3+}$	6.67	1.08	106.0	1.03
$^{20}Ne^{3+}$	6.67	1.4	95.8	1.56
$^{20}Ne^{4+}$	5	1.75	76.4	2.0
$^{32}Se^{6+}$	5.33	1.75	61.1	0.8
$^{40}Ar^{4+}$	10	0.48	44.6	0.67
$^{40}Ar^{4+}$	10	0.64	37.2	0.84
$^{40}Ar^{5+}$	8	0.58	24.2	0.4
$^{40}Ar^{7+}$	5.7	1.1	42.7	1.2
$^{40}Ar^{7+}$	5.7	1.75	45.1	1.0
$^{84}Kr^{9+}$	9.3	0.4	47.6	0.25
$^{84}Kr^{10+}$	8.4	0.7	49.8	0.4
$^{84}Kr^{12+}$	7	1	34.3	1.7
$^{84}Kr^{15+}$	5.6	1.4	26.2	1.9
$^{84}Kr^{15+}$	5.6	1.75	28.6	2.1
$^{132}Xe^{14+}$	9.42	0.6	11.8	0.14
$^{132}Xe^{15+}$	8.8	0.4	10.7	0.25
$^{132}Xe^{17+}$	7.7	1	21.2	0.40
$^{132}Xe^{20+}$	6.6	1.5	22.6	0.46
$^{132}Xe^{22+}$	6	1.75	16.5	0.32

When accelerating ions of xenon and krypton are received intense beams of ions on the ECR source and even more so after the acceleration and the output from the cyclotron is quite low is shown in Fig.2. In the design of accelerator has been paid a lot of attention averaging charging ion beams on the ECR source, and thus justifies the selection of the microwave generator at a resonant frequency of 14 GHz. The production high intensities of highly charged ions on the ECR source is required under current conditions of operation of the cyclotron. In 2015 it is planned to modernize the ECR source and replacement of a RF generator with frequency variation of 18 GHz, so on the DC-60 accelerator will be able to produce large

ISBN 978-3-95450-170-0

currents of highly charged ions without reducing a current ion beams with a smaller charger.

EXPERIMENTAL TASKS CARRIED OUT ON CYCLOTRON

A facility based on DC-60 cyclotron is fully debugged production irradiation of polymeric materials (PET) the films with thicknesses in the range of 12 - 23 microns to create a track-etched membranes with pore density of $5{\cdot}10^5$ to 10^9 cm^{-2} [4].

The investigation in the field of nuclear physics is carried out by measuring the elastic scattering cross section of light nuclei on nuclei 1-p shell near the Coulomb barrier [5, 6], measuring the output section of the characteristic X-ray emission in the interaction of heavy ions with atoms of the target [7], the measurement of the neutron yield in the interaction accelerated heavy ions of average energy with easy targets [8].

The investigation in the field of radiation physics of solids is carried out by measuring the effect of irradiation with charged particles of low and medium energy on the structure and physic-mechanical properties of the alloy with a shape memory effect, the investigation of resistance to radiation of a structural materials with protective coatings and working medium of a dosimetric instrument, the development of techniques of modeling the interaction of heavy ions at high energy with structural materials of space technology [9-14].

The research to test the modes of chemical etching of the polymer material, modification of membrane surfaces [15], creating a smart filter, template synthesis of highly ordered metallic nanostructures arrays et al are carried out in the area of track-etched membranes [16].

SUMMARY

A facility based on DC-60 cyclotron has been created for scientific and applied research, as well as for nanotechnologies application. During work from 2006 to 2014 beams of ^{6,7}Li, ^{12}C, ^{13}C, ^{14}N, ^{16}O, ^{20}Ne, ^{32}S, ^{40}Ar, ^{84}Kr и ^{132}Xe were accelerated in energy range from 0.35 to 1.75 MeV/nucleon. The beam parameters have been investigated, technological polymer film irradiation was provided and track membranes were fabricated.

With the implementing techniques of producing ions using the sluice feed solids in the ECR source significantly expand the range of accelerated ions. With an increase in the spectrum of the accelerated elements will increase the possibility of staging, find and solve new problems and experiments in the field of experimental nuclear physics, radiation physics of solids and various applications.

REFERENCES

[1] B. Gikal et al., DC60 heavy ion cyclotron complex: First beams and project parameters, Physical of particles and nuclei letters, V5(7), pp. 642-644.

[2] V. Kutner et al., Operation and Resent Development of ECR Ion Sources at the FLNR (JINR) Cyclotrons, Proceedings of 15th International Conference on Cyclotron and their Applications, Caen, France, (1998), pp. 405-408.

[3] Ivanov I.A. et al., Testing of the acceleration mode ^{132}Xe^{22+} ions with an energy of 1.75 MeV / nucl. at the DC-60 cyclotron, Bulletin of ENU, 97, pp. 189-196.

[4] Mashentseva A. et al., Osnovy membrannykh tekhnologiy. Polucheniye i issledovaniye svoystv trekovykh membrane, Astana: Master PO, 186 p.

[5] Burtebayev N. et al., Detailed study for 16O elastically scattered from ^{16}O at energies 20, 24 and 28 MeV, International Journal of Modern Physics E22 (8), 1350058.

[6] Gridnev K.A. et al., Investigating the ^{16}O + ^{12}C reaction over a wide range of energies, Bulletin of the Russian Academy of Sciences: Physics 75 (7), pp. 961-963.

[7] Gorlachev I. et al., X-ray production cross section for K-, L- and M-shell by 14 MeV and 19.6 MeV nitrogen, Nuclear Instruments and Methods in Physics Research B, Vol. 330, pp. 86-90.

[8] B. Gikal et al., Secondary fusion reactions in the bombardment of light-element targets with low-energy heavy ions, Physics of particles and nuclei letters, Vol. 11, № 4, pp. 462 – 466.

[9] Uglov V.V. et al., Stability of Ti-Zr-N coatings under Xe-ion irradiation, Source of the Document Surface and Coatings Technology 204 (12-13), pp. 2095-2098.

[10] Kislitsin S.B. et al., Blistering and α γ phase transitions at annealing of stainless steel C12Cr18Ni10Ti irradiated by low energy alpha-particles, Problems of Atomic Science and Technology (2), pp. 17-22.

[11] Russakova A. et al., Color center accumulation in LiF crystals under irradiation with MeV ions: Optical spectroscopy and modeling, Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms, 313, pp. 21-25.

[12] Dauletbekova A. et al., Color centers and nanodefects in LiF crystals irradiated with 150 MeV Kr ions, Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms 286, pp. 56-60.

[13] Dauletbekova A. et al., F center creation and aggregation in LiF crystals irradiated with 14N, 40Ar, and 84Kr ions, Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms 326, pp. 311-313.

[14] Li W. et al., Effect of orientation on ion track formation in apatite and zircon, American Mineralogist 99, Issue 5-6, pp. 1127-1132.

[15] Korolkov I.V. et al., The effect of oxidizing agents/systems on the properties on track-etched PET membranes, Polymer Degradation and Stability 107, pp. 150-157.

[16] Mashentseva A. et al., Synthesis, Structure, and Catalytic Activity of Au/Poly(ethylene terephthalate) Composites, Acta Physica Polonica A 125, Issue 6, pp. 1263-1266.

ISBN 978-3-95450-170-0