105 CM HEAVY ION ISOCHRONOUS CYCLOTRON FOR APPLIED RESEARCH

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Abstract

The isochronous cyclotron IC-100 with a pole diameter of 105 cm is designed for applied research using heavy ion beams with energies ranging from 0.5 to 1 MeV/u. The present paper contains the results of experiments aimed at producing internal and external ion beams, as well as of the studies of the interactions of heavy ion beams from the IC-100 cyclotron with various polymers, metals and crystals.

Production of accelerated ion beams at the IC-100 cyclotron

A detailed description of the IC-100 cyclotron can be obtained from Ref. [1].

This Section gives the results of measurements using an accelerated ion beam. The main parameters of the units and systems of the IC-100 cyclotron are listed in table 1.

Table 1

Electromagnet weight	43 tons
Power consumption	90 kW
Average magnetic field	(18.3-20) kG
Extraction radius	46 cm
Number of sectors	4 (56° each)
Valley/hill gap	110/20 mm
Number of dees	2 (34° each)
Dee voltage (nominal)	50 kV
Dissipated RF power	10 kW
RF frequency range	(20.1-20.9) MHz
Harmonic mode	4,6
Limiting vacuum in the chamber (without ion source and without rf voltage on the dees)	7×10^{-7} torr
Operating vacuum (with beam)	$(5\text{-}8)\times10^{-6}$ torr

The relative intensities of the $^{22}Ne^{4+}$, $^{35}Cl^{4+}$ and $^{40}Ar^{7+}$ ion beams as functions of the radius are presented in fig. 1. All measurements were carried out

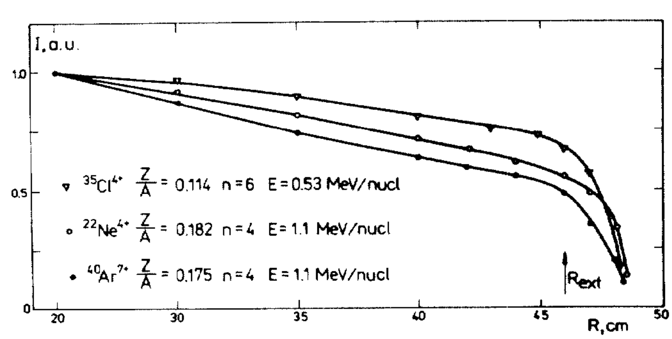

Fig. 1. The relative intensitites of the $^{22}Ne^{4+}$, $^{35}Cl^{4+}$, and $^{40}Ar^{7+}$ ion beams as functions of the acceleration radius.

in the range from R=20 cm to R_{max}, which corresponds to a sharp decrease in beam intensity. As is seen from the figure, the beam intensity varies slightly in going from R=20 cm to R=46 cm, and this is indicative of the absence of ion losses in the acceleration process as a result of phase shifts or the instability of betatron oscillations. The inconsiderable intensity decrease is due to ion loss as a result of charge exchange on the residual gas in the acceleration chamber. The intensity decrease is observed for R>46 cm, this being in good agreement with the radial distributions of the average magnetic field [2].

The measurements carried out using the $^{40}Ar^{7+}$ ion beam at several radii have shown that over the entire range of acceleration energies the beam passes in the median plane and has a cross section not exceeding half the hill and dee apertures. The radial size of the beam at final radii lies between 5 and 7 mm. The parameters of the ions accelerated at the cyclotron IC-100 are listed in table 2.

Table 2

Ion	$\frac{Z}{A}$	B,kG	f, MHz	n	E,MeV/nucl	I, s^{-1}
$^{11}B^{2+}$	0.182	18.9	20.9	4	1.2	$2\cdot10^{13}$
$^{12}C^{2+}$	0.167	19.8	20.2	4	1.1	$3\cdot10^{13}$
$^{16}O^{3+}$	0.187	18.3	20.9	4	1.2	$3\cdot10^{13}$
$^{22}Ne^{4+}$	0.182	18.9	20.9	4	1.2	$4\cdot10^{13}$
$^{23}Na^{4+}$	0.174	19.3	20.4	4	1.1	10^{12}
$^{35}Cl^{4+}$	0.114	19.5	20.4	6	0.5	$2\cdot10^{13}$
$^{40}Ar^{7+}$	0.175	19.1	20.4	4	1.1	$2\cdot10^{12}$
$^{56}Fe^{7+}$	0.125	18.3	20.9	6	0.5	10^{11}

Beam extraction system

The beam extraction from the cyclotron IC-100 was implemented in two ways: first, by using an electrostatic deflector and by charge exchange on a thin carbon boil. The use of the electrostatic method for beam extraction is illustrated in fig. 2. The deflector had an angle of 28° and a radial aperture of 10 mm. It is located in the valley whose axis is perpendicular to that of the resonance system of the cyclotron. The deflector has no water cooling because of a small dissipation of beam power on the grounded plate (not more than 10 W). The whole system is mounted on the flange of the vacuum chamber and this fact makes it possible to remove the deflector for examination. The optimization of the extraction conditions was implemented for the $^{40}Ar^{7+}$ ions accelerated to the full energy of 1.1 MeV/u. The maximum efficiency of passage through the deflector was 70%. The entire intensity of the deflected beam measured directly at the exit of the deflector (point 2 in fig. 2) lies within a circle 8 mm in diameter. For other ions accelerated to an energy of (0.5-1.2) MeV/u the extraction coefficient is equal to (60-65)%.

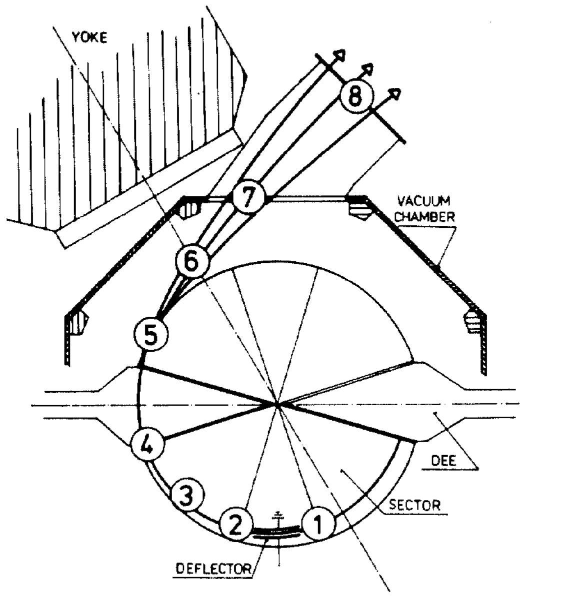

Fig. 2. Layout of the extraction system using the electrostatic method.

The solution of a number of applied problems (e.g. the production of nuclear membranes, ion implantation, etc.) require the irradiation of targets with widths of up to several tens of centimeters by ion beams of constant intensity. For this purpose rather sophisticated and bulky systems of scanning by means of electric and magnetic fields are used [3,4]. We have decided to use another method. As it can be seen from fig.2, after passing the deflector the beam traverses the distance between points 4 and 5 in the stray magnetic field of the cyclotron with a radial gradient of $\sim$5 kG/cm. The beam is influenced by the strong radially defocusing action of the field. At point 5 the beam has a horizontal dimension of 50-70 mm while its radial size is equal to 320 mm in the irradiation plane (point 8) at a distance of 0.5 m from the extraction flange of the vacuum chamber. The measurements carried out for the $^{16}O^{3+}$ and $^{40}Ar^{7+}$ ions have shown that for a beam having a size of 300 mm in the horizontal plane the distribution uniformity makes up (10-15)% whereas the vertical size of the beam does not exceed 20 mm.

At the IC-100 cyclotron studies were carried out to investigate and implement the possibility of ion extraction using the method of charge exchange on a thin foil. The extraction diagram is shown in fig. 3. The stripping method of beam extraction used at the IC-100 cyclotron has some specific features which impose some limitations on the initial conditions (small extraction radius, small valley angle and hill gap).

An additional limitation is the necessity that the slope of the external beam trajectory be 45° with respect to the position of the extraction flange. This slope corresponds to that of the trajectory of ions extracted using the electrostatic method. The mathematical simulation of the extraction by the charge-exchange method at the IC-100 has shown that ions with $q<1.85$ ($q = Z_2/Z_1$, where Z_1 and Z_2 are the ion charges before and after stripping, respectively) "perish" in the central region of the cyclotron as a result of the relatively large radius of their trajectory curvature in the given magnetic field. The trajectories of ions with $q>1.85$ and with the azimuthal position of the foil at $112° \leq \varphi_S \leq 119°$. At the same time, for $\varphi_S < 117°$ the trajectories of the ions that undergo charge exchange traverse the sector boundary at two points, the angles of entrance and exit from the sector being focusing ones in the radial direction and defocusing ones in the axial direction. This leads to a considerable increase

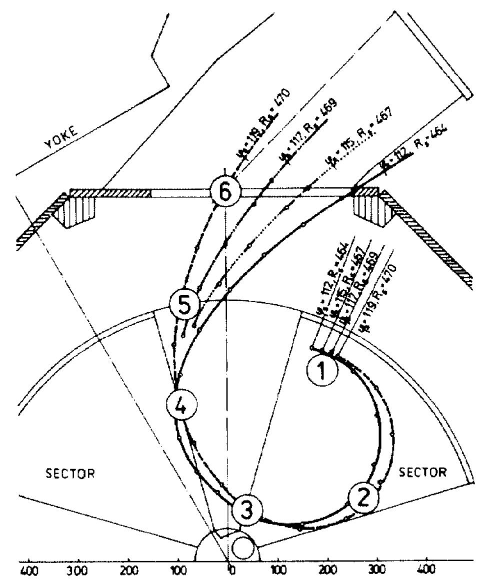

Fig.3. Schematic of ion extraction using the charge-exchange method.

in the axial size of the beam in the sector and to its loss. Thus the possible working range of the positions of the charge-exchange foil turns out to lie within $117° \leq \varphi_S \leq 119°$. As can be seen from fig.3, the slope of the extracted trajectory is equal to about 45° for φ_S=117°. This position of the foil was chosen to be operational. The charge-exchange extraction method was used in experiments on $^{12}C^{2+}$, $^{16}O^{3+}$, and $^{22}Ne^{4+}$ ion beams with a full energy of (1.1-1.2) MeV/u. The initial charge of these ions changes by a factor of 2 as a result of charge exchange. A graphite foil $\sim$ 50 μg/cm² thick was used as a charge exchange target. It was placed on a probe which could move in radial and azimuthal directions. The experimental value of the extraction coefficient was obtained to be (70-50)% for the above-mentioned ions. The cross section of the external beams lies within a circle 15 mm in diameter at a distance of 0.5 m from the extraction flange plane (point 6).

Use of heavy ion beams from the cyclotron IC-100 to the study the process of defect formation in condensed media

In the last decades the physics of radiation damages (PRD) and radiation materials science (RMS) have developed considerably as independent trends of research in solid state physics. Heavy ion beams, especially with energies of (1-2) MeV/u present a rather efficient instrument for these investigations. The $\sim$ 1 MeV/u $^{16}O^{3+}$, $^{22}Ne^{4+}$, and $^{40}Ar^{7+}$ ion beams from the IC-100 cyclotron were used to carry out a large series of the studies of radiation damages in crystals and in metals. As a result, by measuring microhardness the radiational strengthening of nickel and vanadium was investigated and important results about the influence of the energy range of the primarily knocked-out atoms on the degree of the radiational strengthening of these metals have been obtained [5]. Studies were also carried out to investigate changes in the mechanical properties, in the dielectric and other constants in piezoelectric ZnO, $LiNbO_3$ (piezoelectric crystals are used in acoustic flaw detectors in modern nuclear reactors). It is shown that the properties of these crystals become better after irradiation as a result of the processes of radiation-stimulated diffusion [6].

The trends of the PRD and RMS are of great importance in solving applied problems by using interactions of heavy ion beams with polymers. Ion irradiation leads to the destruction of polymers which, after subsequent physico-chemical treatment, serve as a material for the production of nuclear membranes with unique properties and with strongly calibrated holes ranging from 10 nm to 10 μm in size. The IC-100 cyclotron provides the possibility of producing Ar ion beams with an energy of 1.1 MeV/u and with an intensity of 10^{12} pps. In addition, it is also capable of accelerating $^{35}Cl^{4+}$ ions with an intensity of 10^{13} pps to an energy of 0.5 MeV/u. The latter are used to make nuclear track membranes on the base of polyethylene terephthalate films 3, 5 and 10 μm thick [7].

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