THE PRESENT STATUS OF THE U-400 ISOCHRONOUS CYCLOTRON

B.N.Gikal, G.G.Gulbekyan, V.B.Kutner

Joint Institute for Nuclear Research, Dubna, U.S.S.R.

1. Introduction. - The development of heavy ion physics at the Laboratory of Nuclear Reactions is closely related to the construction and development of accelerators providing intense ion beams within a wide range of masses and energies.

There are a cyclic implanter, the U-200, the U-300 and the U-400 cyclotrons.

Presently a cyclotron system consisting of the U-400 and the U-400M cyclotrons is being constructed at the Laboratory. The tandem system is designed for the acceleration of ^{12}C - ^{238}U ions to energies of 120-20 MeV/nucleon[1].

In contrast to the majority of the facilities under construction in the world, the U-400 and the U-400M are capable of autonomous operation. In this case the cyclotrons can accelerate ions of elements belonging to the first half of the Periodic Table. To produce still heavier ions it is necessary to use the tandem system.

At the beginning of 1989 the classical cyclotron U-300 was shut down for reconstruction into the U-400M cyclotron[2].

A system for the axial injection of ions was constructed for the U-200 cyclotron and tested with a $^{4}He^{1+}$ beam. The efficiency of beam transportation from the source to the final acceleration radius was 8-10% for I_{inj} 500 μA, 6% for I_{inj} = = 1 mA. Presently an external high-current injector is being developed on the basis of a PIG-type ion source.

2. The U-400 cyclotron. - The first beam was produced at the U-400 cyclotron at the end of 1978. Last year this accelerator was in operation for 5200 hrs, the rest of time was divided between the installation of new equipment and the preventive inspection and maintenance of its units. The operation time of the accelerator was used in the following way:

- 3650 hrs - irradiation of targets;
- 270 hrs - preparation of physical facilities;
- 430 hrs - investigations in the field of the accelerator technique;
- 850 hrs - accelerator preparation and mode optimization.

Until presently, the ions of elements from ^{10}B to ^{132}Xe with the mass-to-charge ratio of 5-12 have been accelerated at the U-400 cyclotron. The necessary increase of the magnetic field along the radius for different A/Z values is provided mostly by a difference in the excitation levels of the main coil (fig. 1). This enables one to have a low-powered correction system consisting of 10 radial and 4 azimuthal coils. Usually, only 2-4 of them are used during experiments.

Basic cyclotron parameters are presented in Table I.

The cyclotron is capable of irradiating physical targets both inside the accelerator chamber and in the 12 channels positioned at 3 levels (fig. 2). Beam extraction in two directions ("A" and "B") is performed through charge exchange.

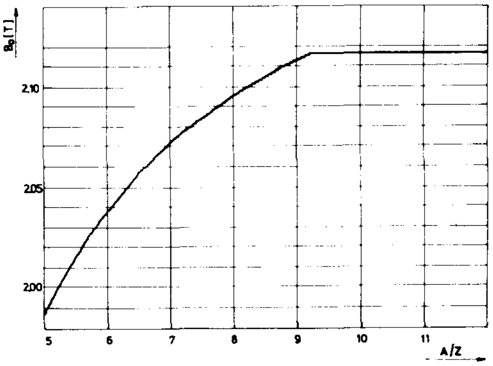

Fig. 1 - The dependence of the magnetic field at the centre of the cyclotron on the mass-to-charge ratio of the accelerated ion

TABLE I

The mass/charge ratio of accelerated ions -	5-12
Magnetic field -	19.87 - 21.17 kG
Frequency of the HF generator -	5.4 - 12.2 MHz
Harmonic mode -	2
Vacuum in the cyclotron chamber -	1×10^{-6} - 5×10^{-7} Torr
Emittance of the external beam: horizontal -	40 mm·mrad
vertical -	16 mm·mrad

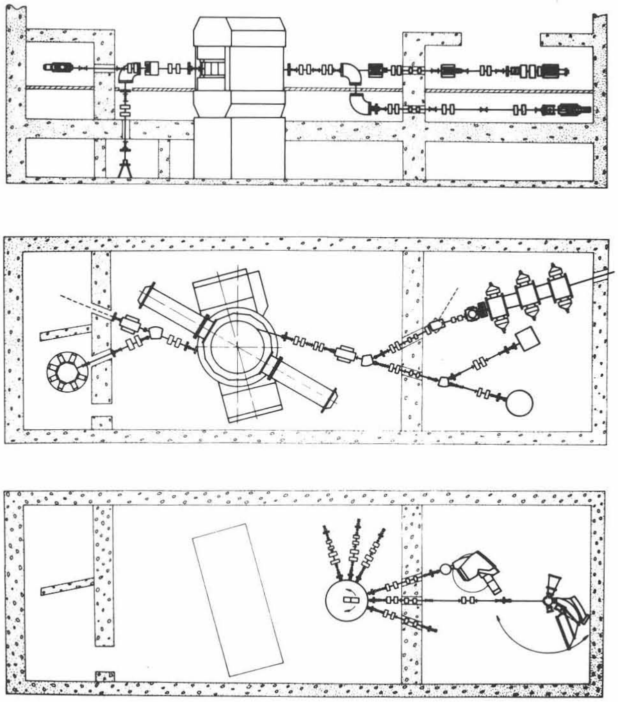

Fig. 2 - The lay-out of the U-400 ion guides location

3. Beams of the U-400 cyclotron. - The spectrum of ions accelerated at the cyclotron has been determined by the demands of physical experiments. A high-current internal PIG-type source allowed one to obtain ion beams of both gaseous and solid materials.

The ions accelerated include ions of rare isotopes such as ^{18}O, ^{58}Fe, ^{64}Cu, ^{70}Zn, etc. The high degree of sample enrichment has permitted the beam intensity at the level of the basic isotopes.

Ion beam extraction in both directions is performed via charge exchange on thin graphite foils of 40-200 μg.s^{-2} thickness$^{5)}$. On passing the extraction foil the charge increases 2.5 - 4.5 times.

The extraction coefficient is practically determined by the charge distribution and makes up 30-100%. The maximum beam intensity is limited by the thermal durability of the extraction foil and is 7×10^{12} pps for Ar, 1-1.5$\times10^{13}$ pps for light ions of oxygen and neon. Under these conditions the foil lifetime is about 24 hrs$^{6)}$.

Table II presents the parameters of the ions accelerated at the U-400. The energy of ions and the maximum intensity are indicated for the internal beam. The energy of the external beam is determined by the characteristics of the extraction system. The beam intensity depends on one of the factors: the extraction coefficient, the durability of the extraction foil, limitations due to biological shielding. It should be noted that for some ions ($^{40}\mathrm{Ar}^{4+}$, $^{48}\mathrm{Ti}^{5+}$, $^{55}\mathrm{Mn}^{6+}$, $^{56}\mathrm{Fe}^{6+}$, $^{51}\mathrm{V}^{5+}$) the intensities of internal beams listed in the table have been obtained only after prolonged irradiation. At the beginning of the irradiation the cycle intensity is several times smaller (fig. 3). The gradual increase in intensity is associated with the step-by-step optimization of the ion source which is necessary for obtaining a concrete ion charge state and for the better adjustment of the accelerator itself.

The energy of the external beam depends on the dynamics of the beam after passage through the stripping foil. This dynamics depends mainly on the ratio of charges before (Z_1) and after (Z_2) charge exchange. For each charge exchange coefficient (Z_2/Z_1) there is a definite range of foil

TABLE II

Ion	Internal beam		External beam			
	E (MeV/nucl)	I (c^{-1})	E (MeV/nucl)			I (c^{-1})
			III	II	I	
$^{11}\mathrm{B}^{2+}$	18.0	$2\ 10^{12}$	9.0	12.0	18.0	$2\ 10^{12}$
$^{14}\mathrm{N}^{2+}$	12.6	$2\ 10^{14}$	7.0	9.5	--	$1.5\ 10^{13}$
$^{15}\mathrm{N}^{2+}$	8.4	$2\ 10^{14}$				
$^{16}\mathrm{O}^{2+}$	7.9	$3\ 10^{14}$	6.0	8.8	--	$1.5\ 10^{13}$
$^{18}\mathrm{O}^{3+}$	17.5	$4\ 10^{13}$	7.0	10.0	16.2	$1.5\ 10^{13}$
$^{20}\mathrm{Ne}^{2+}$	5.3	$2\ 10^{14}$	4.2	5.6	--	$1\ 10^{13}$
$^{20}\mathrm{Ne}^{3+}$	13.4	$2\ 10^{14}$	7.5	10.0	14.5	$1\ 10^{13}$
$^{20}\mathrm{Ne}^{4+}$	20.0	$2\ 10^{12}$	10.	14.3	21.6	$2\ 10^{12}$
$^{22}\mathrm{Ne}^{3+}$	13.0	$2\ 10^{14}$	6.2	8.4	12.1	$1\ 10^{13}$
$^{27}\mathrm{Al}^{3+}$	6.1	$5\ 10^{13}$				
$^{31}\mathrm{P}^{4+}$	7.4	$1\ 10^{13}$				
$^{40}\mathrm{Ar}^{4+}$	5.3	$1.5\ 10^{14}$	3.8	5.3	--	$7\ 10^{12}$
$^{40}\mathrm{Ar}^{5+}$	7.9	$9\ 10^{13}$	5.0	7.0	--	$7\ 10^{12}$
$^{40}\mathrm{Ar}^{6+}$	13.4	$3\ 10^{12}$	6.5	9.3	14.0	$1\ 10^{12}$
$^{48}\mathrm{Ti}^{5+}$	5.6	$4\ 10^{13}$	4.1	5.5	--	$7\ 10^{12}$
$^{49}\mathrm{Ti}^{5+}$	5.4	$2\ 10^{13}$				
$^{50}\mathrm{Ti}^{5+}$	5.0	$1\ 10^{13}$				
$^{51}\mathrm{V}^{5+}$	5.5	$5\ 10^{13}$				
$^{52}\mathrm{Cr}^{6+}$	6.8	$5\ 10^{12}$	4.4	6.4	--	$2\ 10^{12}$
$^{53}\mathrm{Cr}^{5+}$	5.3	$1\ 10^{13}$				
$^{54}\mathrm{Cr}^{5+}$	5.3	$1\ 10^{13}$				
$^{55}\mathrm{Mn}^{6+}$	5.5	$6\ 10^{13}$	4.2	6.0	--	$6\ 10^{12}$
$^{56}\mathrm{Fe}^{6+}$	5.3	$3\ 10^{13}$	4.2	5.7	--	$6\ 10^{12}$
$^{58}\mathrm{Fe}^{6+}$	5.3	$2\ 10^{13}$	3.8	5.3	--	$3\ 10^{12}$
$^{58}\mathrm{Ni}^{6+}$	5.2	$1\ 10^{13}$	4.0	5.4	--	$3\ 10^{12}$
$^{64}\mathrm{Ni}^{6+}$	5.3	$1\ 10^{13}$				
$^{64}\mathrm{Zn}^{7+}$	6.2	$1\ 10^{12}$				
$^{70}\mathrm{Zn}^{8+}$	5.2	$4\ 10^{11}$				
$^{76}\mathrm{Ge}^{8+}$	5.3	$2\ 10^{12}$				
$^{84}\mathrm{Kr}^{9+}$	6.0	$5\ 10^{11}$				
$^{90}\mathrm{Zr}^{11+}$	9.0	$1\ 10^{11}$				
$^{129}\mathrm{Xe}^{12+}$	4.6	$5\ 10^{9}$				
$^{129}\mathrm{Xe}^{11+}$	3.8	$5\ 10^{9}$	2.3	3.3	--	$1.5\ 10^{9}$

I - one-turn extraction
II - two-turn extraction
III - three-turn extraction

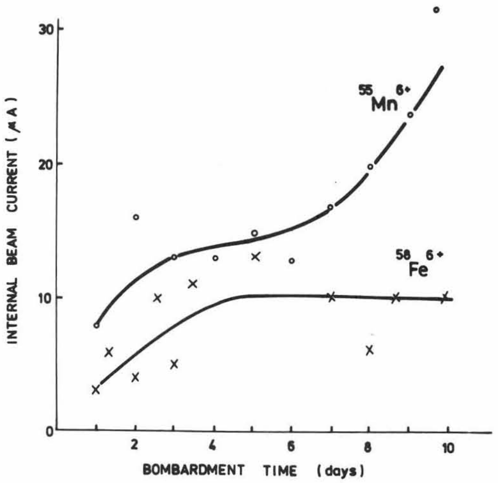

Fig. 3 - The time dependence of the intensity of $^{55}Mn^{6+}$ and $^{58}Fe^{6+}$ beams during the irradiation cycle

positions along the radius at which the maximum extraction efficiency is provided. One-, two- and three-turn extractions from the U-400 cyclotron have been performed. The extraction mode depends on the number of beam turns on the sector-valley boundary after passing through the extraction foil but before entering the ion guide.

Switching from one extraction mode to another changes the ion energy substantially (by 30-40%). In each extraction mode it is possible to change the energy smoothly within a narrow range (±5%) by means of radial and azimuthal foil movement. In some cases one can expand the regulated range by means of a transfer from one extracted ion charge to another one.

An example of the ion charge spectrum after passing through a $^{59}Co^{5+}$ extraction foil and the possible regulation of the extraction beam energy are presented in figs. 4 and 5. Similar dependences have been established for several dozens of ions. The general view of the possible variants of beam extraction from the U-400 cyclotron is given in fig. 6. The presented experimental data correspond to the mechanism of extraction in the "A" direction.

The scale of foil movement is presented in fig. 7. Beam extraction in the "B" direction is analogous to that in the "A" direction. Both mechanisms have a chamber for changing the foil without vacuum leakage in the cyclotron chamber.

It is possible to change the extraction foil without breaking the vacuum in the cyclotron chamber.

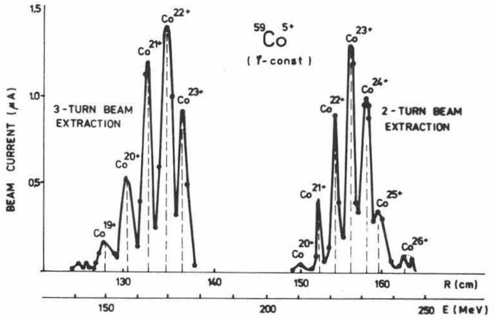

Fig. 4 - Typical dependence of the external beam intensity on the radial position of the extraction foil at a fixed azimuth

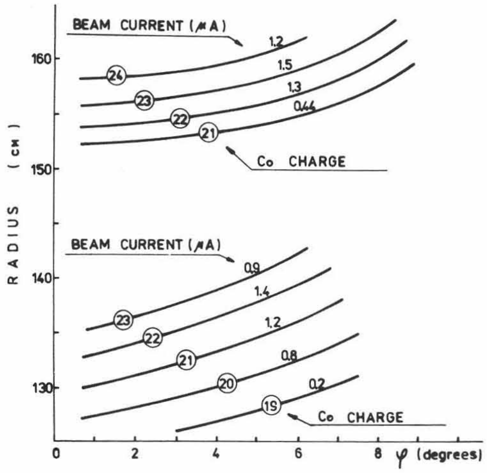

Fig. 5 - Foil position over the radius and azimuth during the extraction of a Co beam

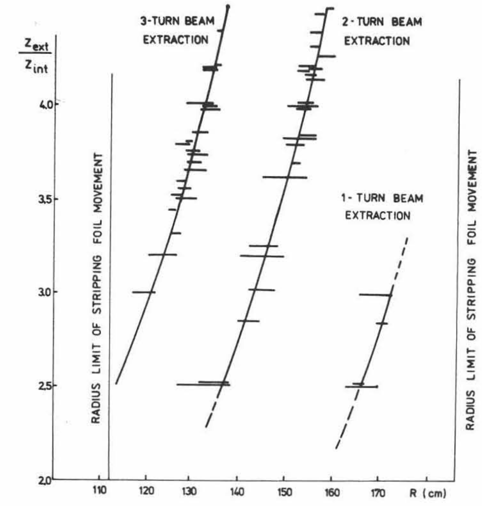

Fig. 6 - Experimental dependence of the extraction radius on the charge exchange factor

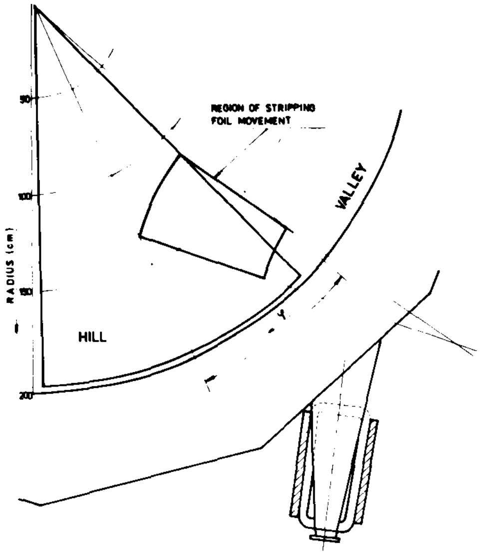

Fig. 7 - The region of foil movement

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