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THE JINR U-400 ISOCHRONOUS HEAVY ION CYCLOTRON

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Abstract

The main data on the 4-meter isochronous cyclotron (the U-400) currently under construction at the Joint Institute for Nuclear Research at Dubna are presented. The accelerator is designed to produce intense heavy-ion beams with a maximum energy $E = 725\ q^2/A$ MeV and an intensity of $10^{14} - 10^{11}$ part/s in a wide range of elements through xenon ($3 \leq A/q \leq 12$). A brief description of the design features and parameters of the facility is given.

The U-400 Isochronous Heavy Ion Cyclotron currently under construction at the JINR Laboratory of Nuclear Reactions is a development of the multiply-charged ion-acceleration technique used at this Laboratory.[1,2] In comparison with the two accelerators operated at the Laboratory, the new cyclotron will open up wider possibilities for solving some fundamental and applied problems of modern physics.

The Laboratory's principal accelerator, the U-300, is a classical cyclotron with a pole diameter of 310 cm, which is used to carry out numerous experiments in different fields of nuclear physics. This cyclotron provides the acceleration of $^{11}B^{2+}$, $^{12}C^{2+}$, $^{14}N^{2+}$, $^{15}N^{3+}$, $^{16,18}O^{3+}$, $^{20,22}Ne^{4+}$, $^{28}Si^{5+}$, $^{31}P^{5+}$ and $^{40}Ar^{6,7,8+}$ ions with the A/q parameter of 5 to 7, where A is the mass number and q is the charge of the ion accelerated. The energy of the accelerated ions is equal to $E = 250\ q^2/A$ MeV. An improvement made to the available multiply-charged ion source has furnished the acceleration of $^{48}Ca^{7+}$, $^{48,50}Ti^{7,8+}$, $^{51}V^{8+}$, $^{54}Cr^{8+}$, $^{56,58}Fe^{9+}$ and $^{64,66,68}Zn^{10+}$ ions with intensities of about $10^{11} - 10^{12}$ part/s to an energy above the Coulomb barrier.

The other accelerator, the U-200 Isochronous Heavy Ion Cyclotron with a pole diameter of 200 cm has been in operation since 1968. At this cyclotron, the ion energy is defined by the expression $E = 156\ q^2/A$ MeV.

By using the tandem system of the U-300 and U-200 Cyclotrons we succeeded in producing germanium, krypton, and xenon beams with an energy of 7.5 MeV/nucl. and an intensity of about 5×10^{10} part/s.

During the recent years the Laboratory of Nuclear Reactions Cyclotrons has been operated under critical conditions, being incapable of accelerating heavier ions and producing higher beam intensities. Therefore it was decided to make a 4-meter cyclotron similar to the 2-meter isochronous cyclotron. Primarily it was intended to construct a cyclotron with a pole diameter of 400 cm by modifying the existing U-300 Cyclotron. In particular, it was supposed to increase the pole diameter, introduce the azimuthal variation of the magnetic field, and increase its induction to 2 T. However, the extensive experimental program of the Laboratory on the synthesis and investigation of new elements has not allowed us to shut down the U-300 Cyclotron for reconstruction. Ultimately it was decided to construct the U-400 Cyclotron by making use of the main units manufactured for the U-300, such as electromagnet pole tips, the vacuum chamber, sectors, rf resonators, etc. Other units including the electromagnet had to be manufactured anew. The electromagnet of the U-400 is similar to that of the U-300.

The 1770 ton electromagnet yoke (Fig. 1) of the proposed cyclotron is made of separate steel sheets and assembled directly in the cyclotron hall. The diameter of the electromagnet poles and the pole tips serve as the top and bottom walls of the vacuum chamber and are equal to 400 cm. The gap between the pole tips is 30 cm. The acceleration full radius is 180 cm. The main coil of the electromagnet contains twice 224 windings of aluminum conductor with a 53 x 53 mm^2 square cross section and an inner channel 34 mm in diam. for water cooling. With an excitation current of 2200-2500 A in the coil the magnetic field is equal to 2.15 T in the center. The stability of the current in the main coils is 5×10^{-5}.

The azimuthal variation of the magnetic field is furnished by four pairs of spiral sectors with a sector angle of 45°. The maximum spiral angle is 30°. (A variant for straight sectors is also available). The sectors are mounted on the pole tips on shims with a 1.8 cm gap and their height can be varied from 9.5 cm in the center to 11 cm on the periphery. Thus the hill and valley gaps are equal to 4.4 - 7.4 cm and 30 cm, respectively.

An isochronous magnetic field is provided by varying the height of the sectors and by using ten pairs of circular trim coils placed in the gap between the sectors and the pole tips. Each trim coil consists of three turns of water-cooled copper conductor. The insulation of the winding is furnished by glass fiber filled with an epoxy compound.

The azimuthal harmonics of the magnetic field are adjusted by coils mounted in two valleys.

The measurements of the magnetic field of the U-400 have been carried out using a model half its full size. With a magnetic field of 2.15 T in the magnet center, the measured radial distribution of the magnetic field deviates from the field required for the isochronous acceleration of ions to an energy of 10 MeV/nucl. by not more than 0.005 T. In this case the magnetic field flutter determined by the expression $\langle B^2\rangle - \langle B\rangle^2/\langle B\rangle^2$ is 0.055. A magnetic field of 1.8 T provides the isochronous acceleration of ions to an energy of 50-60 MeV/nucl., thus leading to a flutter of 0.10. At the end of 1976, the mounting of the body of the electromagnet together with the main coils and power supply units was completed. At present, mechanical and electrical tests of the magnet and preparation for magnetic measurements are underway.

The rf system of the U-400 Cyclotron consists of two independent dee systems (Figs. 1,2), each being designed to include a resonant cavity with an inner diameter of 140 cm and a length of 480 cm, a rod with an outer diameter of 42 cm, and a dee with an angle of 45^o. The dees are positioned in the opposite valleys of the magnet gap.

The frequency range of the rf system is 6 to 12 mHz, which provides the possibility of accelerating ions with A/q ranging from 3 to 12 on the first-fifth harmonics of the accelerating voltage. The frequency adjustment is provided by moving the shorting bar of the rf system.

At the U-400 Cyclotron there will be an arc-discharge ion source with radial ion extraction, i.e., the same type of ion source as that employed successfully at the existing accelerators of the Laboratory (Fig. 2). The ion source is inserted through an axial hole 20 cm in diameter in the magnet yoke and pole tip and is removable without disturbing the vacuum. In the future it is intended to use an external type of ion source.

A high vacuum is required to decrease beam losses during acceleration. The vacuum needed to reduce these losses to 30% is estimated to be 1×10^{-6} Torr. It is supposed to produce such a vacuum by seven diffusion pumps of the BA-8-7 type, connected in series with booster pumps of the BH-3 type, a total pumping rate being 28000 l/s (Fig. 2). The results of testing the vacuum chamber and the rf system have confirmed that it is possible to produce a pressure of below 1×10^{-6}. Subsequently it is supposed to combine the cryogenic and diffusion pumping to obtain a pressure of 3×10^{-7} Torr. To improve the vacuum in the central part of the vacuum chamber an additional pumping through the lower vertical hole available in the electromagnet is possible.

The assembly and mounting of the main units of the U-400 and production of an internal beam are planned for the end of 1977.

The beam extraction method by stripping, developed and used at the U-200 cyclotron, will also be employed at the U-400. The main idea of this method is that after passing through a thin stripping foil placed on the boundary between the valley and the hill, the ions add charges, change their trajectories, and escape from the vacuum chamber. A peculiar feature of this method is that behind the stripping foil one deals with ions of equal energies but different charges. This implies that simultaneously with the most intense ion beam with charge q_{eff}, ions with charges $q = q_{eff} \pm \Delta q$ can be extracted in two symmetric directions. To provide a possibility of using several beams at the same time one should separate spatially the beams of ions with different charges. The calculation suggests that ions with different charges can be separated provided that $(q_1/q_2) \cdot (\Delta q/q_{eff}) \geq 0.01$. For instance, in the case of $^{56}Fe^{7+}$ ions one can in principle use three different ion beams with charges 23, 24 and 25 (Δq=1) and nearly equal intensities. The total intensity of all the beams will be close to 90% of the internal beam intensity (Fig. 3).

Thin 40-60 $\mu g/cm^2$ carbon foils will be used as stripping targets. A special sluice for inserting the stripper into the vacuum chamber without disturbing the vacuum and a remote control of the stripper are foreseen.

The ion beams will be extracted from the U-400 cyclotron chamber in two opposite directions (Fig. 4), up to three beams with charges differing by one or two units (depending on the type of the particle). The external beams will be divided by a system of septum magnets. This will provide a possibility of performing experiments on several external beams simultaneously. A peculiar feature of the beam-transport system is the beam layout in two planes. This is due to the fact that the median plane of the U-400 magnet lies 4 meters above the floor of the experimental hall. At a level of 1.3 m, it is intended to work with bulky experimental equipment such as a magnetic spectrograph to study multinucleon transfer reactions, a versatile electromagnetic isotope separator, a separator of nuclear reaction products, etc. (Fig. 4). The lowering of the beam will be achieved by two magnets with BR = 1.2 Tm and a deflection angle of 90^o. The magnets are put one under the other in such a manner that the direction of the beam coming out of the upper magnet coincides with the vertical axis of the rotation of the lower magnet. Thus the lower magnet combines the functions of both the deflecting and commuting magnets and permits the switching of the beam from one experimental setup to another.

The total number of the beam channels is 12. At the U-400 Cyclotron, a great variety of ions with the A/q values mentioned will be accelerated. The main range of the ion mass numbers is $20 \leq A \leq 140$ (A/q = 9-11). In addition, in some experiments there will be a possibility of accelerating ions of adjacent mass numbers, e.g., $12 \leq A < 20$ (A/q = 3-4) and $140 < A \leq 240$ (A/q = 19-26). The ions of the main range are supposed to be accelerated to an energy of about 10 MeV/nucl. determined by the expression $E = 725\ q^2/A$ MeV. Relatively light ions such as carbon to neon may be accelerated to an energy of 50-60 MeV/nucl.

The beam intensities at an ion energy of 10 MeV/nucl. will be 10^{14} - 10^{13} part/s at $20 \leq A < 80$ and 10^{12} - 10^{11} part/s at $80 < A \leq 140$. The main parameters of the U-400 Cyclotron are listed in the table to follow.

TABLE I.

Magnet yoke weight	1770 ton
Pole diameter	400 cm
Full radius	180 cm
Gap between the poles	30 cm
Number of windings in the main coil	224 x 2
Current	2200-2500 A
Magnetic field in the center	2.15 T
Sector number	4
Sector angle	45°
Hill gap	4.4 - 7.4 cm
Valley gap	30 cm
Magnetic field flutter	0.055
Dee number	2
Dees angle	45°
Frequency range of rf system	6-12 mHz
Range of the A/q values	3-12
Number of harmonics of the accelerating field	1-5
Pressure of residual gas in the vacuum chamber	1×10^{-6} to 3×10^{-7} Torr
Pumping rate	28000 l/s
The beam extraction is performed by ion stripping.	
Beam extraction coefficient	30-90%
Thickness of carbon foil stripper	40-60 $\mu g/cm^2$
Radial emittance of external beams	80 mm mrad
Vertical emittance of external beams	40 mm mrad
Channel number	12
Ion energy	725 q^2/A,MeV

References

1. G. N. Flerov, I. A. Shelayev, V. S. Alfeyev, S. I. Kozlov, I. V. Kolesov, R. Ts. Oganessian, V. N. Pokrovsky, K. I. Syomin, A. N. Filipson, V. A. Chugreyev. Proc. the 4th All-Union Meeting on Charged-Particle Accelerators, 1975, Nauka, v. II, pp. 9-12.

2. G. N. Flerov. Proc. Int. School-Seminar on Reactions of Heavy Ions with Nuclei and Synthesis of New Elements, 1975, Dubna, D7-9734, 1976.

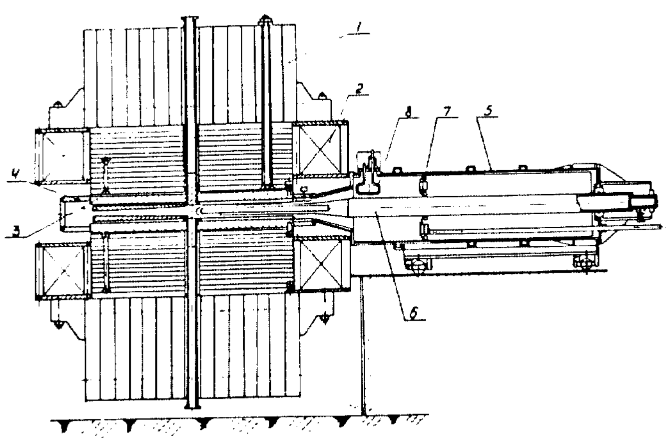

Fig. 1. Sectional view of the U-400 Cyclotron:
1 - electromagnet yoke;
2 - main excitation coils;
3 - vacuum chamber top and sector;
4 - vacuum chamber;
5 - the rf cavity; 7 - shorting bar;
6 - rod with a dee; 8 - coupling loop.

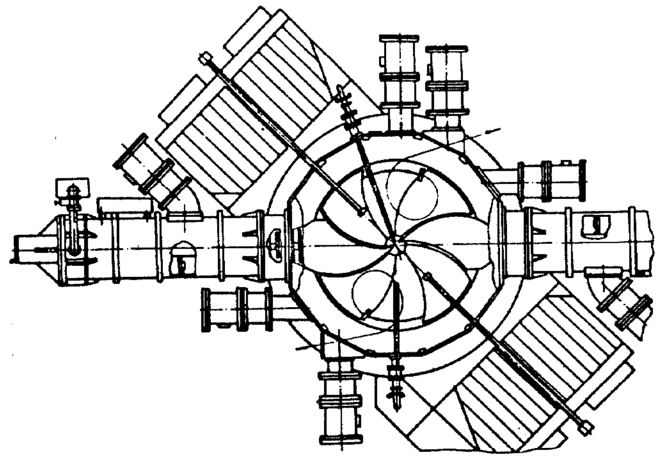

Fig. 2. Schematic diagram of the U-400

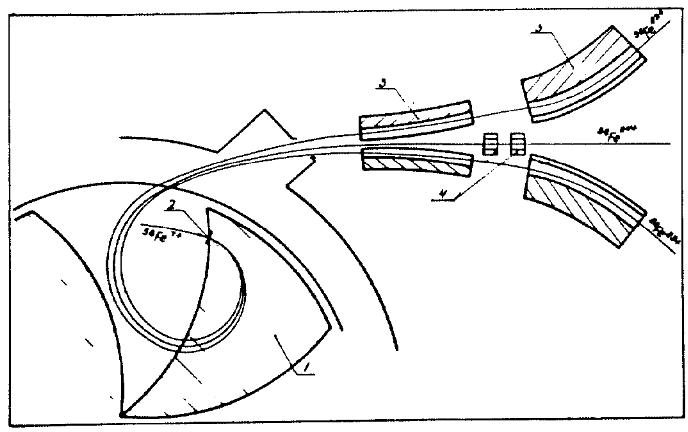

Fig. 3. The beam extraction and separation systems for the ^{56}Fe ions:
1 - sector;
2 - stripping foil;
3 - septum magnets;
4 - electromagnetic lenses.

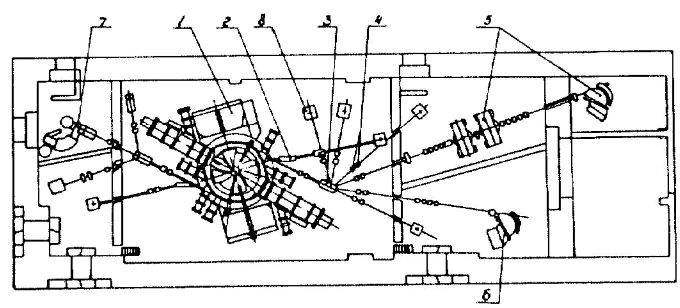

Fig. 4. The U-400 site and beam layout:
1 - the U-400 Cyclotron;
2 - septum magnet;
3 - the magnet lowering the beam level;
4 - electromagnetic lenses;
5 - reaction product separator;
6 - magnetic spectrograph;
7 - versatile electromagnetic isotope separator;
8 - beam line.