THE PRESENT STATUS AND PERSPECTIVES OF DEVELOPMENT OF THE JINR LABORATORY OF NUCLEAR REACTIONS HEAVY ION ACCELERATORS

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Studies with heavy ion beams in wide ranges of masses (up to uranium) and energies offer wide possibilities for solving basic scientific and essential economical problems.

Heavy ion beams with energies up to 10 MeV/nucleon have been responsible for considerable progress in the fields of the synthesis of new elements, of nuclear fission (the shape isomerism phenomenon, delayed fission, the regularities of the spontaneous fission of the transfermium elements), in the studies of nuclear properties near the stability limit (delayed proton and α-particle emission, the stability of light neutron-rich nuclei) and of the mechanism of interactions of complex nuclei (the formation of compound nuclei with high angular momenta, nucleon transfer reactions, nuclear quasi-molecules, etc.). An increase in heavy ion energies (to ~100 MeV/nucleon) allows one to investigate the interactions of complex multi-nucleon systems in which there manifest themselves the collective effects due to the properties of nuclear matter, such as Coulomb and surface forces, compressibility and viscosity. Such reactions lead to new nuclei which can be in extreme conditions near the limit of nuclear stability. Hign-energy beams permit very important investigations in the field of atomic physics, in particular, the studies of the electron structure of highly-ionized atoms and of the chemical processes occurring in highly ionized media. Of extremely great interest is the possibility of testing the laws of quantum electrodynamics in very strong fields occuring in collision of two uranium nuclei. the use of heavy ions for solving scientific, technical and applied problems is also very promising. The solution of a large number of essential economical problems is associated with the studies of radiation effects on materials. Special mention should be made of such important problems as the rapid scale simulation of radiation damages in the structural materials used to build nuclear energy facilities, the deep layer-by-layer implantation of diverse ions to produce new materials for technology (superconductors, semiconducting materials, etc.). The studies aimed to produce microporous nuclear filters including those from polymer materials, capable of standing high temperatures and chemically active media are also important.)

Heavy ion beams open up wide possibilities for studying biological processes and for medical diagnostics by irradiating biological samples with the short-lived radioactive isotopes of carbon, nitrogen and oxygen.

The solution of the above problems is associated with the construction of powerful accelerator facilities designed for producing intense heavy ion beams over wide ranges of masses and energies. The JINR Laboratory of Nuclear Reactions has at its disposal the three heavy ion cyclotrons: U200, U300, and U400. In what follows we give the main characteristics and parameters of beams from these accelerators, as well as prospects for their further development.

The Cyclotron U300

The U300 3-meter classical cyclotron[1)] has been operated at the JINR Laboratory of Nuclear Reactions since 1961. It is capable of accelerating heavy ion to energies $E=250\ Z^2/A$ over a wide range of the A/Z ratios. For nuclear studies particles with energies of 5-10 MeV/nucleon ($A/Z = 4.7 - 7.2$) are accelerated on the fundamental harmonic of r.f. voltage ($n = 1$), whereas very heavy ions (Kr, Xe) with energies of 1-2 MeV/nucleon are accelerated on the third harmonic ($n = 3$) to solve numerous applied problems. The continuous improvements to the arc-type ion sources used at the U300 have resulted in the possibility of obtaining intense heavy ion beams from gaseous and solid substances.

Ion beam extraction was performed using an electrostatic deflector, the extraction efficiency being equal to 25-30%.

The horizontal and vertical emittances of the external beam are equal to 80 and 30 mm mrad, respectively, the energy resolution is about 0.5%. The beam lay-out system consists of 12 beam lines for installing experimental equipment.

The Cyclotron U200

The isochronous cyclotron U200 having a pole diameter of 200 cm, which began operation in 1968, accelerates ions with $2.8 \leqq A/Z \leqq 5$ (from deuterons to argon) to a maximum energy $E = 145\ Z^2/A\ \mathrm{MeV}^2$). The beam extraction for $A/Z \geqq 3.8$ is performed by ion stripping on a solid target (a graphite foil 40-60 g/cm^2 thick). The extraction efficiency is equal to 100 - 40% depending on the energy and type of the ions to be accelerated. The horizontal and vertical emittances of the external beam are equal to 70 and 30 mm.mrad respectively, the beam energy resolution being about 1%. A simple kinematic setup for moving the foil along the radius and the azimuth of the cyclotron permits the continuous change of external beam energy within 35% of the maximum one. The external beam is transported to an experimental hall via 4 beam lines.

The Cyclotron U400

On the basis of the experimental data obtained in the process of constructing and operating the U200 cyclotron, the four-meter isochronous cyclotron U400 was put into operation late in 1978 at the JINR Laboratory of Nuclear Reactions. The U400 cyclotron is designed to accelerate heavy ions with mass numbers 4 A 250 to energies from 35 to 1.8 MeV/nucleon.

The U400 magnetic structure consists of four pairs of sectors with straight boundaries and angles of 45°. The isochronous magnetic field of 19 - 21.4 KG (corresponding to flutter values of 0.11 - 0.06) is provided by iron shims placed on the surface of the sectors and by current correcting coils. Ten pairs of radial coils each contributing up to 50 G are located in a gap between the chamber lids and the sectors (4 pairs of coils are used to correct the median plane). the eight pairs of harmonic coils providing the correction of the first harmonic power is 850 kW, the power of the current coils is equal to 56 kW.

The r.f. system of the U400 cyclotron consists of two disconnected circuits, each of which has the from of a quarter-wave coaxial line short-circuited at one end and loaded with the capacity of the 42° dee at the other. The dees are located in two opposite valleys. The power of the r.f. generator providing 100 kV voltage on each dee is equal to 150 dW. The ion acceleration is performed on the 1st, 2nd, 3rd, and 4th harmonics. The variation of the frequency of the cyclotron r.f. system in the range 6 - 12 MHz is achieved by a moving short. Frequency adjustment within 3% is accomplished by trimmers.

In the cyclotron a modification of the multiply-charged ion source 3) using cathode sputtering of solid working material is used to produce metal ion beams 4).

To reduce gas load in the cyclotron centre the gas-discharge chamber of the ion source is hermetically sealed in the cathode and anticathode regions by ring insulators. The input introduction of the sputtered electrode to the discharge chamber is also sealed. The resultant double decrease in the consumption of the working gas supporting the discharge has led to a better vacuum in the U400 chamber and to a several times increase in the beam intensity at final radii.

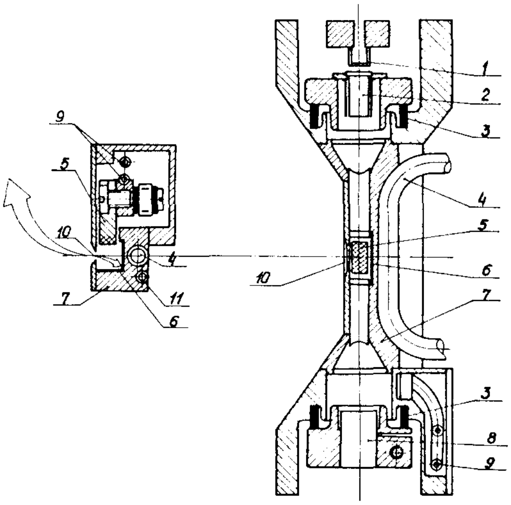

Fig. 1. The main elements of the ion source with the cathode sputtering of the working material designed for use at the U400 cyclotron. 1-filament, 2-cathode, 3- packing insulator, 4- discharge chamber cooling system, 5- sputtered electrode, 6- sputtered material collector, 7- discharge chamber, 8- anticathode, 9- sputtered electrode cooling system, 10- emission slit, 11- gas inlet.

In the case of using rare isotopes the reduction of solid working material consumption is extremely important. For this purpose the new modification of the ion source envisages the introduction of the sputtered electrode into the discharge chamber on the side of the centre of the first half turn of the ion beam trajectory. As a result, the uncontrolled sputtering of the electrode substance by returned ions is eliminated.

The consumption of solid working material in the ion source is reduced to the average amount of 15 mg/h at operation with metallic iron. A schematic view of the ion source is presented in Fig. 1.

The U400 vacuum volume consists of a chamber and two resonators and has an inner surface of 350 m^2. The working pressure (with beam) of 1 x 10^{-6} torr is provided by 5 oil diffusion pumps with nitrogen baffles, which have an overall pumping rate of 20000 l/s for N (100000 l/s for condensed components). The radial distribution of pressure with different amounts of the gas introduced into the ion source is presented in Fig. 2.

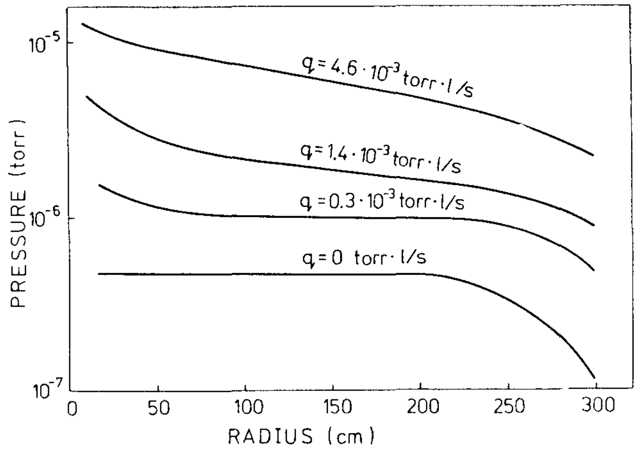

Fig. 2. The radial pressure distribution in the U400cyclotron with different amounts of gas supplied to the ion source.

The indicated value of working vacuum pressure provided 30% beam passage for the $14 \le A \le 84$ ions, this being determined by ion losses due to stripping by the residual gas. A further improvement to the vacuum is associated with decreasing the gas flow in the existing ion sources (or by the external injection of ions), as well as with the development of the distributed pumps.

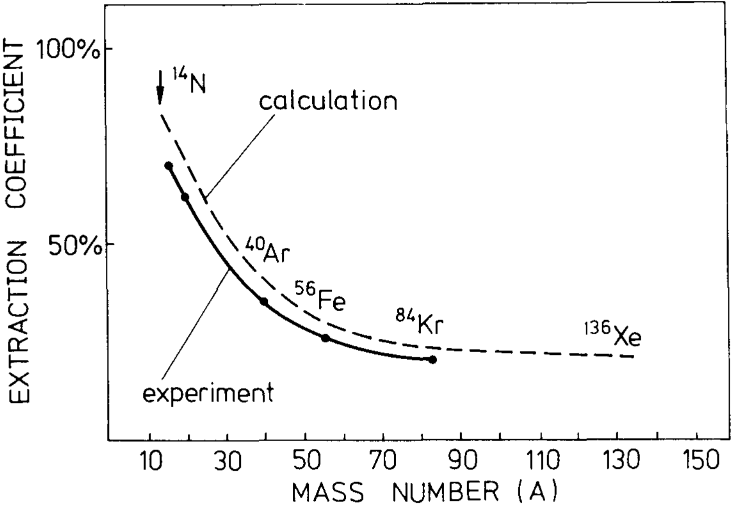

Fig. 3. The dependence of the extraction efficiency on the ion mass in the U400 cyclotron.

The ion beam extraction from the U400 cyclotron is accomplished by thin stripping foil with the possible variation of energy through the radial and azimuthal movement of the foil. Carbon foils (40 - 60) g/cm^2 thick are used as strippers. The lifetime of the foil is determined by the type and intensity of the incident ions. It is equal to (6-10) days for a $^{14}N^{2+}$ ion beam at an intensity of 6 x 10^{13} s^{-1}, while for a $^{55}Mr^{6+}$ ion beam with an intensity of 10^{13} s^{-1} it is equal to about 5 days. The extraction efficiency is determined by the value of the maximum effective charge after stripping. The extraction efficiency values for different ions are listed in Fig. 3. The external beam energy resolution is equal to 1%.

ION	E (MeV)	E (MeV/amu)	I_{int} (s^{-1})
$^{14}N^{2+}$	176	12,6	$2\cdot10^{14}$
$^{15}N^{2+}$	126	8,4	$3\cdot10^{14}$
$^{16}O^{2+}$	126	7,9	$3\cdot10^{14}$
$^{20}Ne^{3+}$	268	13,4	$2\cdot10^{14}$
$^{22}Ne^{3+}$	180	8,2	$2\cdot10^{14}$
$^{31}P^{4+}$	228	7,4	$1\cdot10^{13}$
$^{40}Ar^{4+}$	212	5,3	$1,5\cdot10^{14}$
$^{40}Ar^{5+}$	317	7,9	$9\cdot10^{13}$
$^{48}Ti^{5+}$	269	5,6	$4\cdot10^{13}$
$^{49}Ti^{5+}$	264	5,4	$2\cdot10^{13}$
$^{50}Ti^{5+}$	248	5,0	$1\cdot10^{13}$
$^{51}V^{5+}$	280	5,5	$5\cdot10^{13}$
$^{52}Cr^{6+}$	358	6,8	$5\cdot10^{12}$
$^{53}Cr^{5+}$	280	5,3	$1\cdot10^{13}$
$^{54}Cr^{5+}$	286	5,3	$1\cdot10^{13}$
$^{55}Mn^{6+}$	304	5,5	$6\cdot10^{13}$
$^{56}Fe^{6+}$	298	5,3	$3\cdot10^{13}$
$^{58}Fe^{6+}$	307	5,3	$2\cdot10^{13}$
$^{58}Ni^{6+}$	300	5,2	$1\cdot10^{13}$
$^{64}Ni^{6+}$	340	5,3	$1\cdot10^{13}$
$^{64}Zn^{7+}$	396	6,2	$1\cdot10^{12}$
$^{70}Zn^{8+}$	365	5,2	$4\cdot10^{11}$
$^{76}Ge^{8+}$	400	5,3	$2\cdot10^{12}$
$^{84}Kr^{9+}$	503	6,0	$5\cdot10^{11}$

The external beam transport system comprises 15 beam lines arranged at three levels. The beam transportation along 100 mm - diameter channels is performed by means of magnetic lenses with a maximum gradient of 600 G/cm and by 45° and 90° electromagnets with a 13 kG field.

The parameters of the ion beams from the U400 cyclotron are given in the Table. The indicated values of intensities correspond to the internal beams the energy of which was determined by the requirements of the physical experiment. the maximum intensities of the external beams were determined by the thermal stability of the stripping foil and ranged from 10^{14} to 5 x $10^{13}s^{-1}$ for N,O and Ne ions and from 10^{13} to 6 x 10^{12} s^{-1} for Ar, Ti, Mn, Cr, Fe and Ni ions. A comparison of the beam intensity values for the cyclotrons U200, U300 and U400 is given in Fig. 4. The general view of the U400 cyclotron is shown in Fig. 5.

A New Cyclotron Facility

The perspectives of further heavy ion physics research at the Laboratory of Nuclear Reactions are associated with the creation of a cyclotron complex designed to produce ions ranging from oxygen to uranium with energies of 120 - 20 MeV/ nucleon and intensities of 5 x 10^{12} -$10^{11}s^{-1}$. The complex will consist of the U400 as an injector and of the postaccelerator - the four-meter isochronous cyclotron U400M being constructed on the basis of the U300 cyclotron (Fig. 6). The ions accelerated in the injector cyclotron U400 are extracted from it by an electrostatic deflector, are transported to the U400M cyclotron via an ion line 120m long, and, after increasing their charge state by a factor of 5 - 8 during the passage through the thin foil, are injected onto an equilibrium orbit to be then accelerated to

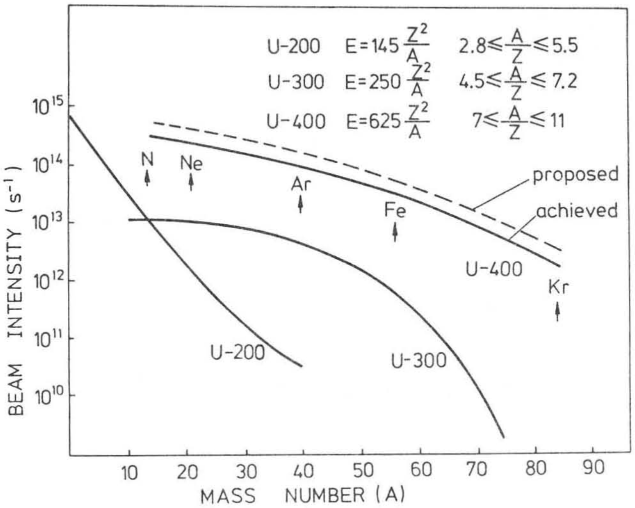

Fig. 4. The beam intensities produced by the JINR Laboratory of Nuclear Reactions cyclotrons.

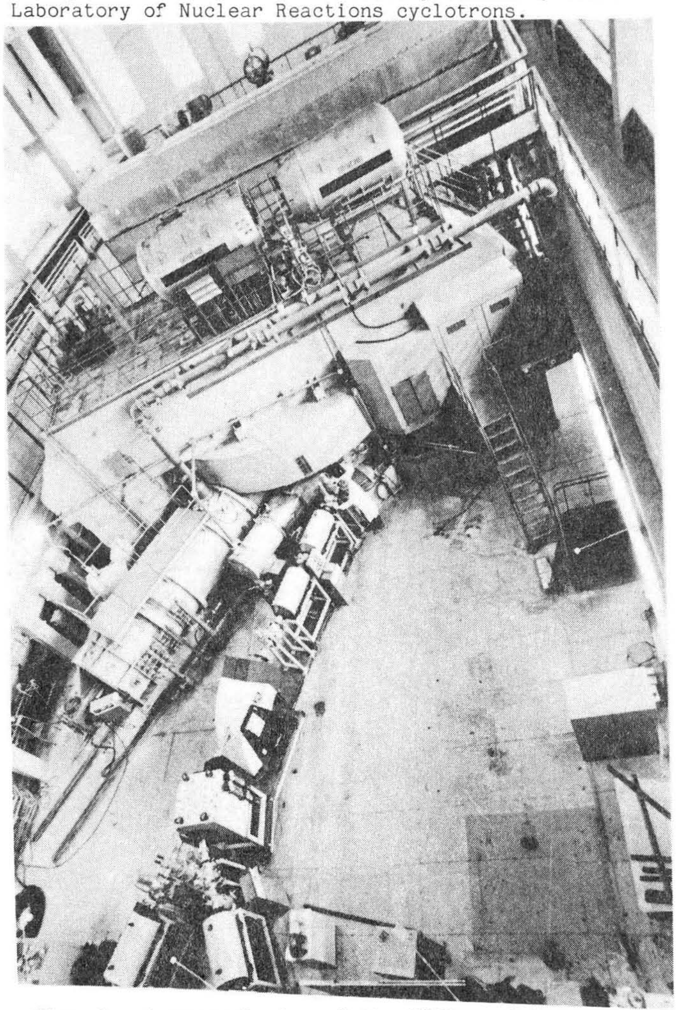

Fig. 5. A general view of the U400 cyclotron.

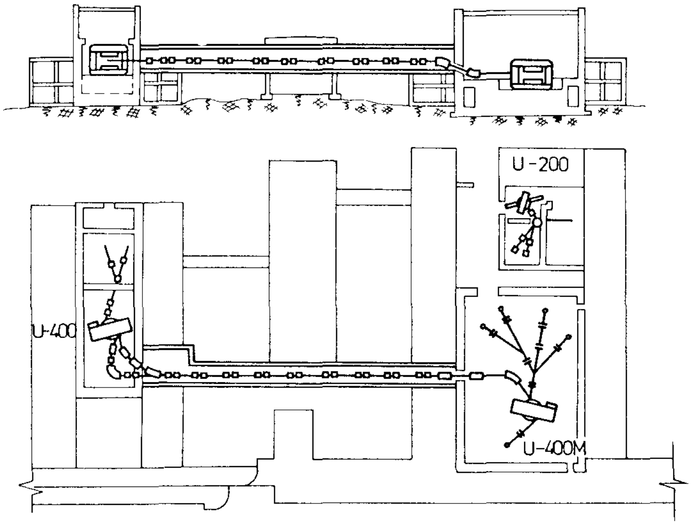

Fig. 6. A schematic view of the cyclotron complex U400 + U400M.

the final energy. For accelerating ions to the indicated energies the maximum parameter K = 0.48 $B_f \cdot R_f$ (B_f=20 kG, the average magnetic field, R_f = 1.75 m, the final radius of acceleration) is equal to 550 - 560.

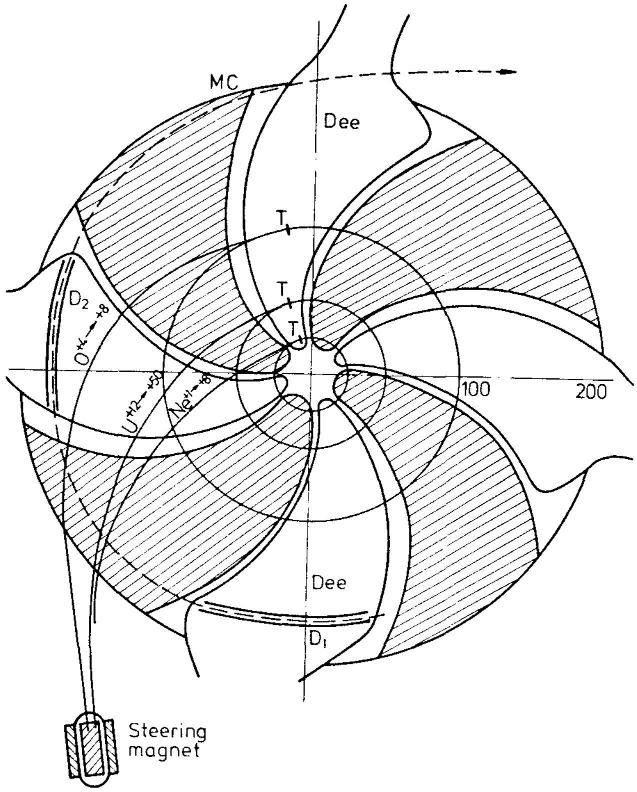

Fig. 7. A plan of the ion injection and extraction in the U400M cyclotron.

Ion focussing in the U400M accelerator is provided by four pairs of sectors with spiral angles of 40°.

The isochronous dependences of average magnetic fields upon the acceleration radius are provided, for ions with different A/Z ratios, by changing the gap between the sectors along the radius, and by the system of current correcting coils situated on the surface of the sectors.

The r.f. system of the U400M cyclotron consists of four dees with 42° angles, located in the valleys, and provides and accelerating voltage on the dees of up to 200 kV in the frequency range 15 - 25 MHz. The simplest way of ion injection into the cyclotron is the stripping of the injected ions in the region of the cyclotron centre. Therefore, ion beams will be extracted from the U400 cyclotron by electrostatic defector with an angle of 38° installed in the valleys. A three element magnetic channel will be used to focus the deflected ions. the ion beams extracted from the U400 cyclotron are transported via a 100 mm-diam beam line to the U400M accelerator. As the multiplicity of ion stripping by the thin foil varies over a wide range, the radius of the foil placed in the U400M centre is varied from 30 - 100cm (Fig. 7).

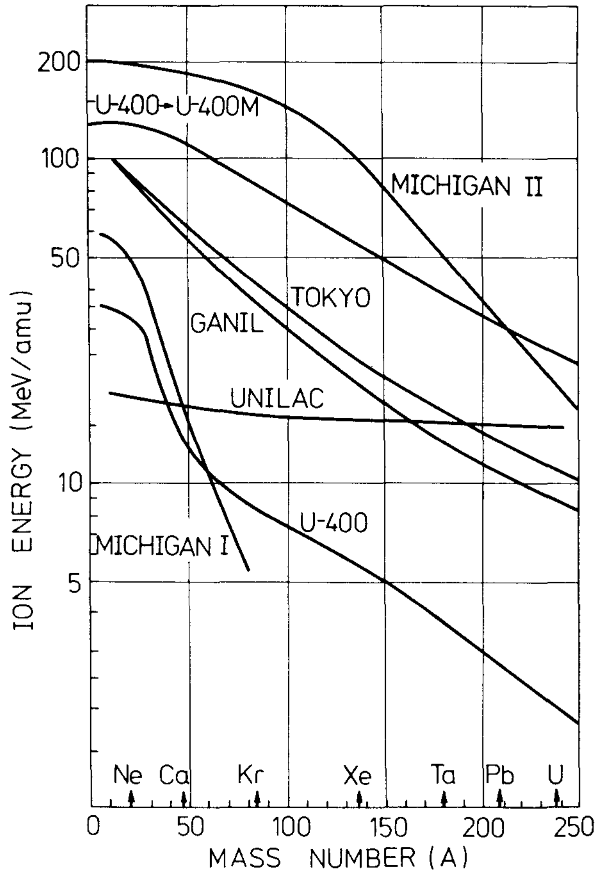

Fig. 8. The dependence of the ion kinetic energy on mass number for various accelerator complexes.

The accurate incidence of the injected ions on the foil and their matching to the equilibrium orbit will be achieved by using a steering magnet with a deflection angle of +/- 3°.

The evacuation of the U400M cyclotron to a pressure of 5×10^{-7} torr will be performed using five diffusion pumps with a total pumping rate of 5×10^{5} ls^{-1}

In Fig. 8 the characteristics of the future cyclotron complex are given in comparison with those of other heavy ion accelerators.

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References

1. I.A. Shelaev et al., Proc. of the VIh International Cyclotron Conf., New York, 1972, p. 232.

2. B.N. Gikal, et al., JINR 9-83-311, Dubna, 1983.

3. Yu.P. Tretyakov, et al., Proc. of the VIIth All-Union Meeting on Charged Particle Accelerators, Dubna, 1981, vol. 1, p. 81.

4. S.B. Bogomolov, et al., Proc. of the VIIIth Meeting on Charged Particle Accelerators, Dubna, 1983, vol. 1, p. 112.

5. Yu.Ts. Oganessian, et al., JINR 9-82-756, Dubna, 1982.