A CYCLOTRON COMPLEX FOR ACCELERATING MULTICHARGED IONS UP TO RELATIVISTIC ENERGIES

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1. SUMMARY

The accelerating complex for the production of the multicharged ion beams up to uranium with a final energy of 300 MeV/amu is described. It is supposed to use a Wideroe type accelerator at the first stage of acceleration (up to 0.59 MeV/amu), a conventional isochronous cyclotron at the second stage (up to 10 MeV/amu), and an isochronous cyclotron with superconducting magnet coils at the final stage. Such a structure of the accelerating complex provides high beam intensity at the full energy of 300 MeV/amu (about 10^{13} particles per second for uranium), and the intermediate energy of 10 MeV/amu (about 10^{14} particles per second for uranium). Some preliminary parameters of the accelerator are presented.

2. INTRODUCTION

A special interest in relativistic nuclear physics using multicharged ions of a wide mass range has resulted in the development and construction of quite a number of accelerator facilities for energies of 6 to 8 MeV/nucleon to relativistic energies from 2 to 10 GeV/nucleon[1, 2, 3].

In the region of energies near the Coulomb barrier (up to 10 MeV/nucleon) cyclotron and linear accelerators are used equally successfully as accelerator facilities.

For energies of 2-10 GeV/nucleon, as a rule, use is made of earlier constructed proton synchrotrons after the proper conversion of r.f. range and the improvement of vacuum conditions permitting a lengthly (seconds) process of acceleration without changing the ion charge[4].

The transition from the continuous or quasi-continuous beam of multicharged ions (in cyclotron or linear accelerators) to the pulsed mode (in synchrotrons) reduced beam intensity by about three or four orders of magnitude. This is determined by the ratio of injection time to the full cycle of the magnetic field. Since the time of multiturn injection cannot be longer than 100 μsec, and the full cycle of the magnetic field is measured in seconds or tenths of seconds, the above-mentioned factor of reduction is characteristic of all synchrotrons, even without taking into account vacuum losses. For the case of single-turn injection in synchrotrons the intensity may be reduced additionally by two orders of magnitude.

Despite the above-said reduction of multicharged ion intensity in accelerating in the synchrotron mode at energies of 2-10 GeV/nucleon, this mode seems most reasonable at the present state of accelerator technique, since the full radius (R) at tolerable magnetic inductions amounts to some tens of meters:

$$\xi \bar{R}\bar{B} = \frac{\sqrt{2W_n E_{op} + W_n^2}}{ec} , \qquad [1]$$

where $\xi = q/A$, q being an ion charge, W_n is the energy per nucleon. From expression [1] it follows that the magnetic rigidity $\bar{B}\bar{R}$ for the energy of 10 GeV/nucleon and $\xi = 0.5$ is 73 T-m.

For a linear accelerator with constant energy gain per charge U_0, one needs the length

$$L = W_n/U_0 \qquad [2]$$

to attain an energy per nucleon W_n.

For the practical value $U_0 \simeq 1$-3 MeV/m with $\xi < 0.5$, the length of the linear accelerator is greater than 10 km.

However, in the region of intermediate energies of 300-400 MeV/nucleon the acceleration of multicharged ions in the synchrotron mode is not optimal, since for this energy range cyclic accelerators can be developed which are acceptable in size and which operate in the continuous mode. In particular, by using superconducting magnets having a field strength of 4-5 T, it is possible to develop a cyclotron which can operate in the continuous mode, the energy being 300-400 MeV/nucleon with a mean acceleration radius not larger than 4-4.5 m. The limit densities of the beam charge (κ) for identical beams (emittance, energy) are related as follows:

$$\frac{\kappa_c}{\kappa_s} = \frac{Q_c}{Q_s}\frac{\bar{R}_s^2}{\bar{R}_c^2} \qquad [3]$$

where Q_c and Q_s are proper free oscillation frequencies.

From relation [3] it follows that even for weak-focusing cyclotrons ($Q_c < 1$) a permissible density of the charge is several times larger than the synchrotron one.

Thus, taking into consideration the absence of a macro duty cycle which results in the intensity increase by about three orders of magnitude, as well as a larger beam density limit, it has to be accepted that the cyclotron with superconducting coils for accelerating heavy ions up to uranium (about 300 MeV/nucleon) has considerable advantages.

At present the cyclotron complex intensity limitation is determined by the possibilities of ion sources which, however, at low ionization can provide currents up to tens of mA. To increase the ion charge state during acceleration, a properly developed (theoretically and experimentally) mechanism of stripping on solid-state and gaseous targets can be applied[5].

The authors assumed these considerations as the basis of the proposed multicharged ion cyclotron complex.

3. PRODUCTION OF IONS OF HIGH CHARGE STATE

Sources of multicharged ions available at present, such as the Penning source (PIG)[6], the electron-cyclotron resonance (ECR)[7], or the electron beam ion source (EBIS)[8], provide a relatively high ion charge state (up to q = 13-14). However, the yield of multicharged ions is rapidly decreased with increasing charge state. Thus, e.g., for the PIG source the percentage of ions of the given charge is greatly reduced, approximately as 2^q with the maximum yield of ions of charge 5-7. For the HF source of the electron cyclotron resonance type and the EBIS source the maximum ion yield can be shifted up by 2-4 charges. However, for any further increase of charge the yield is sharply reduced.

The ionization factor $n_e\tau$, where n_e is the density of the ionizing electron current and τ is the time of ion confinement in the electron flux[9], serves as the basic characteristic determining the ion yield.

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The limit values of the ionization factor for various types of sources are presented in Table 1.

Table 1

Ion source	$n_e \tau$
PIG	7.10^{16} cm^{-2}
ECR	10^{18} cm^{-2}
"KRION"	2.10^{19} cm^{-2}
Target (solid or gaseous)	6.10^{23} Z/A sd

d *is the target thickness (cm)*
s *is the target density (g/cm^3)*
Z, A *are the charge and the number of nucleons of the target-nucleus.*

It follows from Table 1 that the ionization factor of the solid-state (or gaseous) target is practically out of reach for the continuous sources, the difference being two to three orders of magnitude. Pulsed sources can approach stripping targets in efficiency. However, they are not applicable for cyclotron modes of acceleration.

The average charge (q) for various ions in passing through a solid-target is shown in Fig. 1.

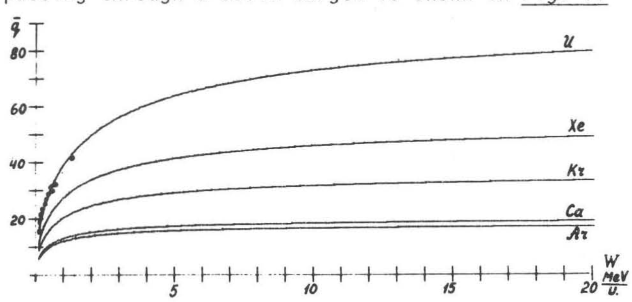

Fig. 1. The energy - average charge dependence in the use of a solid stripper.

This charge is determined by the following formulas[10]:

$$\frac{q}{Z_0} = [1 + (v/3.6 \cdot 10^8 Z_0^{0.45})^{-1.667}]^{-0.6} \qquad [4]$$

$$v = c\sqrt{1 - (1 + W_n/E_{op})^{-2}}$$

The available experimental points[5,10] plotted on the graphs show a possible use of calculated data in designing.

The widths of the beam charge distribution and the relative amount of ions of the equilibrium charge after passing through the target are equal, respectively, to:

$$d = \tfrac{1}{2}\sqrt{q[1-(\frac{q}{Z_0})^{1.667}]}\ ,$$

$$\varepsilon = \frac{1}{d\sqrt{2\pi}} \int_{-\frac{1}{2}}^{+\frac{1}{2}} \exp[\frac{(Z-q)^2}{2d^2}]\, dZ\ . \qquad [5]$$

The values of these physical quantities for two stages of stripping are presented in Table 2.

Table 2

Ion	q_1	d_1	ε_1	q_2	d_2	ε_2	$\varepsilon_1 \cdot \varepsilon_2$
U	34	2.62	0.15	73	2.42	0.17	0.025
Xe	23	2.33	0.17	46	3.08	0.13	0.022
Kr	18	2.04	0.19	32	2.53	0.16	0.03
Ar	10	1.25	0.31	17	0.62	0.58	0.18

It follows from Table 2 that the intensity of the beam with equilibrium charge (q) is about 30% for light ions and is decreased down to about 15% for heavy ions up to U.

In order to obtain the equilibrium charge of ions the target thicknesses are within[11] 10-100 μg/cm^2 with $\beta < 0.1$, which allows one to apply both solid-state (10-40 μg/cm^2) and gaseous targets (about 100 μg/cm^2). The energy loss as well as the increase of beam emittance in passing through such thicknesses is negligibly small.

At present, the functioning sources make it possible to obtain low charge states with the intensity exceeding 10^{14} p/sec (U^{+7} with the intensity of 7×10^{14} p/sec)[12]. After passing twice through a target (solid-state or gaseous) the decrease of intensity on the basis of the above-mentioned calculations does not exceed a factor of 50--i.e., ion intensity with the maximal charge at the output of the accelerator complex will be 10^{13} sec^{-1}.

Note that the method of obtaining the ions of heavy elements with intermediate acceleration and restripping has been selected for the project of accelerating uranium in the "SUPERHILAC". U^{+7} is obtained from the source, then a section of the Wideroe accelerator is employed to produce an energy gain from 12 to 113 keV/n. After stripping, U^{+11} ions are injected into the SUPERHILAC. The intensity gain for U^{+11} is about 100[12].

Thus, the scheme of producing ions of high charge state with intermediate acceleration and further stripping on the target has some advantages compared to ionization up to a high charge state directly in the ion source.

4. ACCELERATING COMPLEX FOR MULTICHARGED IONS

The minimal energy of accelerated ion must exceed the Coulomb barrier for all the elements of the Periodic Table. Numerically this value is within 6-10 MeV/nucleon.

The energy of 10 MeV/nucleon, determining the level of the first stage of acceleration, along with nuclear physics requirements is determined by the conditions of the secondary ionization of the ion which for the further cyclotron acceleration must be close to the maximum one ($q \lesssim Z$). Thus, the optimum scheme of the cyclotron complex for ion acceleration up to uranium must include the following facilities:

a) a source of ions of low charge state to obtain a highly intensive primary beam,

b) a linear accelerating system providing the necessary energy per nucleon to obtain (after the first stripping) the equilibrium charge sufficient for the acceleration in the cyclotron to 10 MeV/nucleon. In the given case this energy has been chosen to be 0.59 MeV/nucleon,

c) a cyclotron for the first stage of acceleration,

d) a cyclotron for the second stage of acceleration permitting one to obtain an energy of 300 MeV/nucleon for all ions.

The schematic view of this complex is shown in Fig. 2.

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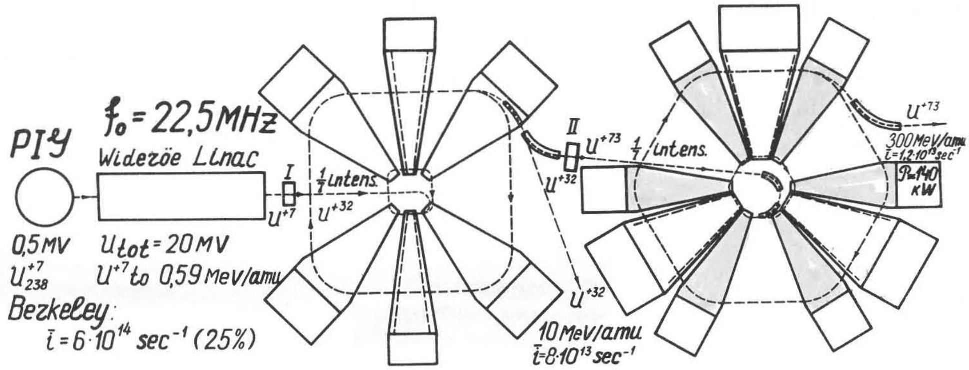

Fig. 2. Schematic view of the accelerating complex.

Any continuous or quasi-continuous source providing average ion current of about 1 mA can be used as an ion source. Such currents are not difficult for the known ion sources. In particular, the popular PIG source fully satisfies this requirement. The source is set up on the pre-injector platform of 0.5 MV potential providing an initial energy of U^{+7} equal to 14.7 keV/nucleon.

A linear accelerator of Wideroe type is the most desireable injector for the cyclotron. Its accelerating system is best suited for continuous and quasi-continuous modes (about 25-30%) at frequencies of 20 to 30 MHz. The first two sections of the Wideroe accelerator in the UNILAC accelerating complex can serve as a prototype of such an accelerator. Based on the characteristics of these sections one can give an approximate estimate of the parameters of the linear accelerator-injector. These parameters are presented in Table 3.

Table 3

Parameters of the linear accelerator	Value
1. Ion energy variations in acceleration (keV/amu)	15 - 590
2. Ion velocity variations (%)	0.56 - 3.54
3. Accelerating system frequency (MHz)	22.5
4. Average voltage over the gaps of drift tubes (kV/cm)	60
5. Shunting resistance (Ω/m)	50 - 60
6. R.F. losses in the macropulse (MW)	0.4 - 0.6
7. Length (m)	12 - 15
8. Summed effective voltage (MV)	20
9. Macro duty factor (%)	25 - 100
10. Normalized emittance (cm × mrad)	0.1 - 0.17
11. Equilibrium phase	-30°

The magnetic parts of this complex, as follows from Fig. 2, consist of sector magnets which with straight edges ensure the required strong focusing of ions in the given energy range. Such isochronous cyclotrons as VICKSI (K = 120), GANIL (K = 400), and Oak Ridge (K = 440), which are under construction at present[2,14], are prototypes of the first stage accelerator.

Recently a number of projects of isochronous cyclotrons using superconducting coils have been developed (e.g. Michigan, Chalk River[15]). In these accelerators the field variation in the median plane is achieved by means of sector shims on the cylindrical pole of the pill-box shaped magnet with a pair of concentric superconducting coils. The accepted magnetic systems provide weak focusing in the axial direction.

The proposed magnetic system of the second stage of acceleration is shown in Fig. 3.

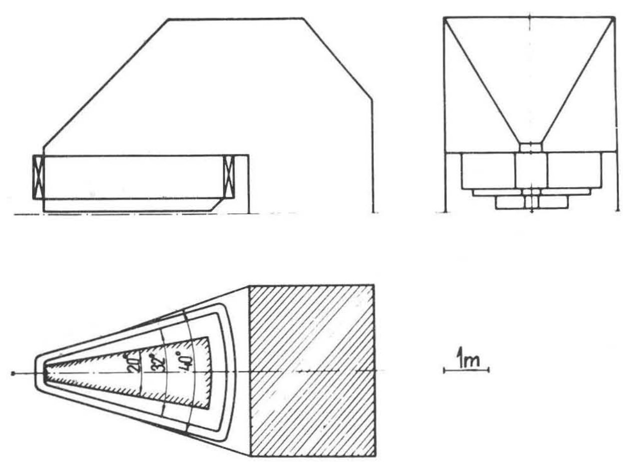

Fig. 3. The magnetic sector of the second cyclotron.

This system consists of 6 sector magnets, in contrast to the above-mentioned ones, and it provides strong focusing of the beam in both directions. The angular width of the pole tip, equal to 20°, has been taken proceeding from the requirements of both magnetic (flutter, average field) and r.f. (acceleration multiplicity) accelerator systems.

Based on the published data on designed and functioning superconducting coils at constant currents, the current density averaged over the coil section, including the vacuum coating, can be 25 A/mm^2 [15]. In this case the transverse dimensions of the coil are about 20 × 80 cm^2. The coils can be made of a conductor of 2 × 3.5 mm^2 cross-section, containing 300 superconducting NbTi-50 wires with a current limit of about 2.3 kA. The magnet coil of the CERN bubble chamber[16] is an example of this solution.

The shaping of the average magnetic field can be provided by profiling the gap and by shims on the edge

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surfaces of the pole magnet. The parameters (presented in Table 4) of sector magnets must be improved in detailed designing and modelling of sector magnets both for the first and second stages.

Table 4

[Basic magnet parameters for two acceleration stages]

Parameters of the sector magnet	I stage	II stage
1. Number of sectors	4	6
2. Initial radius (cm)	75	75
3. Full radius (cm)	460	440
4. Angular width of the pole (degrees)	28	20
5. Interpolar gap (cm)	8	10
6. Induction over the sector (T)	1.7 - 1.9	4.5 - 5.0
7. Magnet height (cm)	600	800
8. Magnet width in the yoke (cm)	240	370
9. Magnet length (cm)	700	700
10. Weight of a single sector (t)	500	1000
11. Ampere-turns per sector	$250 \cdot 10^3$	$8 \cdot 10^6$
12. Power supply (kW)	125	--
13. Energy stored per sector (MJ)	--	20

The r.f. accelerating system of cyclotrons must provide about 1 MeV/turn energy gain of accelerated particles per unit charge at radii from about 0.9 to 4.3 m. The r.f. system consisting of two (in the first cyclotron) and three (in the second one) cavities with Δ - shaped dees as accelerating electrodes is optimum in the case under consideration.

The magnetic system of the second accelerator (six sectors of 20° angular width in the median plane) makes it possible to locate accelerating electrodes of only 30° angular width in the intersector region. The maximum energy is gained in the electrode with harmonic number N = 6 (N = r.f./orbit frequency), but it must be restricted to N = 3. Hence the energy gain is limited to 0.707 of the maximum one. The working frequency is 22.5 MHz in this case. This frequency corresponds to N = 14 in the first accelerator. To achieve maximum energy gain the angular width of the accelerating electrode must be about 13°.

Both in the first and the second accelerators, the range of working radii is about a quarter of the wave length of the accelerating voltage. This makes it necessary to use a half-wave resonant system with vertical resonant lines. In order to avoid considerable changes along the accelerating edge and to reduce r.f. losses, the resonant line must have a radial width comparable with radial dimensions of the Δ - electrode.

The r.f. losses in cavities are determined to a considerable extent by the capacity between Δ - electrode and the external electrode. Therefore, it is necessary to make it as small as possible.

In the first accelerator the distance between the magnets is such that the accelerating gap can be formed by the edge of the Δ - electrode and the protrusions of the external walls of the cavity (Fig. 4). If one assumes that for the accelerating voltage of 250 kV amplitude, the minimum accelerating gap (R_{min}) is 5 cm (the transit time factor is F = 0.98), the width of the central electrode of the line is 2 m, and the gap in the line is 0.7 m, the resonant length of the line (each half) is 2.2 m, and the power loss in the lines is about 40 kW.

In the cavities of the second accelerator it is reasonable to profile the external electrode in agreement with the vertical profile of the magnet and make the width of the internal electrode variable (Fig. 5) to reduce the power losses. The resonant length of the line and the summed power losses will be about 2.2 m and 80 kW, respectively. The power loss in the Δ - electrodes will be about 1 kW for the first accelerator and about 2 kW for the second one.

Efficient operation of a heavy ion accelerator, consisting of cascaded stages and ion transport which must be carefully matched to each other, can only be achieved with a sophisticated control system. A great deal of experience with such systems has been gained at high energy proton synchrotrons (CERN, FNAL, IHEP, etc.). At such accelerator complexes, also consisting of several acceleration stages (pre-injector, linear accelerator, booster, the basic synchrotron), systems of hierarchical controls were developed with the extensive use of computers as accumulators of information about operation modes of all accelerator systems both for detailed analysis of all mode peculiarities and for the automatic control of the basic synchrotron systems. As experience has shown, the development of such systems with two and three-stage structure is reasonable. The control systems of separate acceleration stages and of some important accelerator units employ

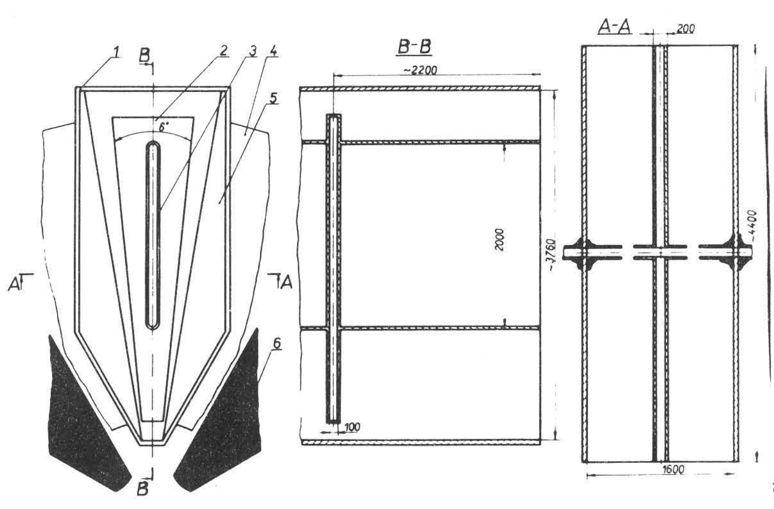

Fig. 4. The r.f. resonator of the first cyclotron:
1) external wall
2) Δ - electrode
3) resonant line
4) accelerating chamber
5) the lug of the external wall for shaping the accelerating field
6) magnet sector.

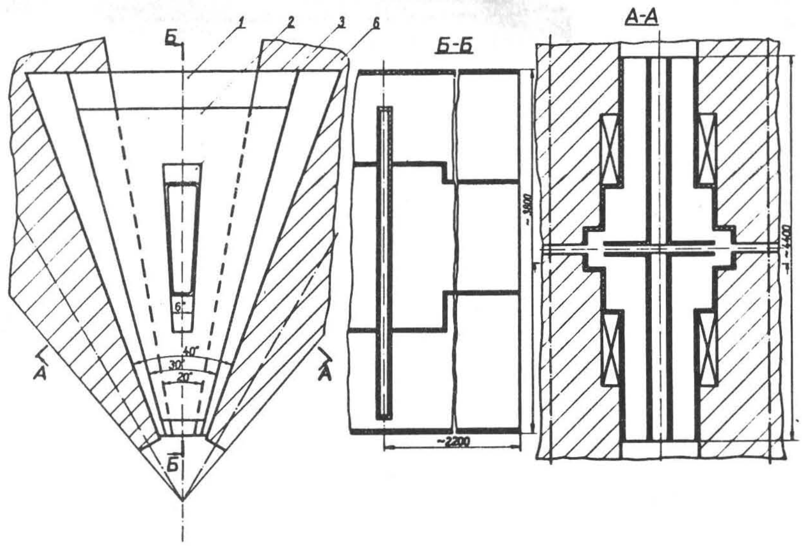

Fig. 5. R.f. resonator of the second cyclotron (see notations of Fig. 4).

autonomous computers of fairly low power. The whole acceleration complex is controlled from a central panel by a powerful computer equipped with displays and communication lines with all the subsystems of the lower level. The heavy ion accelerator complex includes some "standard" devices widely used in experimental physics laboratories. Control devices for ion sources, pre-injectors, linear accelerators, and isochronous cyclotrons are now in common use. Thus, the problem of developing the complex control system can be based on available experience and seems quite possible. The equipment necessary for implementing such a system is available now. Small and medium size computers of the third generation such as EC-computers meet the present day requirements. The CAMAC standard allows one to build flexible systems of computer communication with signal probes and executive units based on standard commercial electronic units. This considerably reduces the time of development and construction both of separate subsystems and of the whole control complex. Recently the elements of the fourth generation (microprocessors, integral cells of memory, etc.) have appeared. This fact results in a further reduction of volume and the cost of all the basic control units.

The basic parameters of two-cascade heavy ion cyclotron acceleration are presented in Table 5.

As follows from Table 5, the system of beam extraction from the first accelerator is easily implemented by means of known types of iron-current channels[18] whose septum is 4-6 mm. With a radial separation of 2.6 cm and emittances of the internal beam not larger than ~π cm mrad, complete separation of orbits at the full radius occurs. The extraction efficiency is about 100%. For the second stage of acceleration it is necessary to increase closed orbit separation about 10-20 times. This is achieved by closed orbit expansion at full radius with a 5 - 10% decrease of the main harmonic variation[19].

The vacuum system has no special requirements due to the small number of turns in acceleration (70 and 980). Charge exchange effects will be negligibly small with a vacuum chamber pressure of 10^{-7} Torr.

The optical beam properties for the linear accelerator and the first cyclotron as well as for the first and second cyclotrons are matched by means of quadrupole lenses and bending magnets. There is an analysing magnet between the first and second cyclotrons. It separates ions with non-resonant charge to permit clean operation.

The above-mentioned parameters of the heavy ion accelerating complex will be specified in further detailed development of and modelling of separate complex systems. Nevertheless, at the first stage of designing one can already see the real possibility for implementation of the complete system.

Table 5

Parameter	1st cyclotron	2nd cyclotron
1. Injection radius (m)	1.04	0.93
2. Beam extraction radius (m)	4.3	4.15
3. Average strength of the magnetic field at injection	0.784	1.60
4. Average field strength at full radius (T)	0.792	2.11
5. Acceleration frequency (MHz)	22.5	22.5
6. Acceleration harmonic number	14	3
7. Energy gain per turn (MeV/charge)	1.0	1.0
8. Radial separation in the beam extraction region (cm)	2.4	0.13
9. Final energy per nucleon (MeV/nucleon)	10	300
10. Injection energy per nucleon (MeV/nucleon)	0.59	10
11. Maximum ratio A/q	7.4	3.26
12. Product of harmonic number and number of turns	980	2940
13. Charge and intensity of ions (particles/sec)		
a) uranium	32; 10^{14}	73; 4.10^{13}
b) xenon	23	46
c) crypton	18	32
d) argon	10; 10^{15}	17; 3.10^{14}

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