PARAMETERS, PRESENT STATE AND APPLICATION PERSPECTIVES OF THE U-250 CYCLOTRON

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ABSTRACT

Design features of the basic elements of the U-250 multipurpose isochronous cyclotron – magnetic structure, ion source, vacuum and RF systems, beam extraction and beam transport systems – are described.

Possibilities for further sophistication of cyclotron design and those for further extension of mass over charge state ratio range of accelerated ions along with increasing their attainable energies using new type ion sources have been analysed.

1. INTRODUCTION

Modern cyclotrons, first of all isochronous ones, enable beams of accelerated ions to be obtained in a wide range of atomic masses and energies. In constructing the multipurpose U-250 cyclotron the most optimal approaches have been used which stemmed from experience gained at the Laboratory of Nuclear Reactions of JINR in designing, manufacturing and heavy ion accelerating on the U-200 and U-400 cyclotrons.

Designing and manufacturing of the U-250 cyclotron is carried out at the NIIEFA. The isochronous cyclotron U-250 is intended for accelerating ions with $A/Z = 2 \div 6$ to the energy over Coulomb barrier and those with $A/Z \leq 10$ to energies 1 to 2 MeV/amu. Maximum attainable energy of accelerated ions will comprise 204 Z^2/A. Beam energies and intensities for the U-250 are presented in Table 1. This cyclotron is planned to be installed at the Institute of Nuclear Physics in Tashkent (Republic of Uzbekistan). Given below is a description of the U-250 design features and a review of the scope of the applied and fundamental research planned.

2. DESIGN FEATURES OF THE U-250

The main problems related to the development of heavy ion cyclotrons are: necessity of controlled field – frequency variation in a wide range, utilization of acceleration modes based on integer harmonics keeping acceleration conditions and orbit centering satisfied for all the set of ion species; obtaining and maintaining of operational vacuum in the particle acceleration zone.

Configuration of the accelerator has been chosen to be typical for cyclotrons developed at the NIIEFA: H-shaped electromagnet, vacuum chamber between poles is to be constituent part of the magnetic structure; double Δ shaped resonance system with panel frequency tuning, axial introduction of the internal ion source.

The main parameters of the U-250 are given in Table 2, the lay-out of the cyclotron facility equipment is shown in Fig. 1.

3. MAGNETIC STRUCTURE

Magnetic structure of the cyclotron involves H-shaped electromagnet, two 100 mm thick pole disks which are parts of the vacuum chamber lids, four pairs of pole sectors, two main magnetizing coils and correcting windings.

Electromagnet consisting of upper and lower girders, two uprights and two conical cores made of armco-type steel, girders and uprights being of welded structure made of 30 mm thick sheets, and core's disks and sectors being made of forged pieces.

The heaviest bulk unit of the electromagnet weighs not more than 30 tonnes. Sectors providing magnetic field azimuthal variation have straight edges and angular extension of 45°.

With two main magnetizing coils of 170 turns each the current is 900 A, cooling water consumption flux is 60 litres/min. Seven groups of correcting coils positioned in the valleys are intended for correction azimuthal magnetic field lower harmonics and regulation of the radial field profile for obtaining isochronic dependence.

4. VACUUM

Vacuum chamber of dismountable structure consists of two soldered hexagonal covers and six uprights between the latters. Side walls of the chamber made of non-ferric steel have holes for joining resonance system, vacuum pumps, three diagnostic probes and beam extraction system. Internal surface of the chamber at points where piston rods and resonance system dees are mounted are plated with copper sheets with water cooling tubes soldered to them.

Total volume of the chamber and both resonance systems amounts to 8.5 m^3, total released gas flux involving properties of used construction materials being estimated to be $5 \cdot 10^{-4}$ m^3 Pa/sec. (It does not include the ion source gas flux.)

Taking into account heavy ion charge exchange cross section in the residual gas, operational pressure in acceleration area is estimated to be in the $(5 \div 10) \cdot 10^{-5}$ Pa limits depending on the type of ions accelerated.

Calculation of spatial pressure distribution was carried out under the assumption that incoming gas flux from the source of light ions comprised 3 cm^3/min with that for heavy ions 0.3 cm^3/min, pumping out rate for all the system being assumed to be 12 m^3/sec. Under these assumptions acceleration of light ions will occur practically without losses and those for 8-fold charged state argon and krypton will amount up to 35% and 60%, respectively. The above pumping out rate can be provided by commercial diffusion oil pumps. Two pumps of 5 m^3/sec pumping speed connected directly to the vacuum chamber and two pumps of 1 m^3/sec pumping speed connected to resonance system. Two additional "getter" pumps of 2 m^3/sec pumping speed can be installed on the vacuum chamber by design in order to pump out active gas.

It should be noted that the small gaps of the electromagnet and the use of internal source with gas release can cause serious difficulties in obtaining proper vacuum.

5. ACCELERATION AND RF SYSTEM

Acceleration of a given set of ion species on the U-250 requires controlled variation of the accelerating frequency within 8 to 19 MHz range. In the cyclotron an acceleration system has been designed which involves two identical resonance systems with 42° angular extension dees positioned in diametrically opposite valleys. Each resonance system consists of the resonator tank, dee rod frequency tuning panel operating automatically, adjusting device and an automatically frequency tuning trimmer. The whole resonance system is mounted on a movable cart on rails providing convenience for dismounting, repairing and assembling.

Resonator tank has 1.5 × 1.2 m rectangular cross section and length of 2 m. It is made of bimetal steel-copper that simplifies the construction and reduces gas releasing surface area. Stiffening hollow ribs are soldered to the external sides of the tank's wall which serve at the same time as channels for cooling water. The hole in the side wall of the tank covered with removable copper bars is intended for panel mounting followed by joining vacuum pump.

One end of the dee rod of rectangular cross section is attached to the movable flank of adjusting device placed at the rear wall of resonator tank, the other end being attached to the dee.

Possibility of dee tuning relative to both dee rods and (together with dee rod) resonance system tank is provided.

Frequency variation is accomplished by changing the gap between dee rod and movable panels. Each panel consists of three parts attached to the tank and linked with each other with flexible copper contacts. Each link consists of stiffened soldered carcas and cooled copper cladding. The estimated RF losses at dee voltage amplitude of 75 kV and frequency of 19 MHz amount to 73 kW, maximum linear current density on contacts not exceeding 60 A/cm.

Autonomically excited RF generator is assembled by conventional configuration: commercial frequency synthesizer-aperiodic amplifier of 40 W, power-amplifier with distributed parameters of 2.5 kW power on each of the two tracts and 2 final cascades with maximum power of 100 kW each.

Final stage of the generator is located closely to the resonator tank; RF power supply is accomplished by means of conductive connection mode.

6. ION SOURCE

In order to obtain a set of ion species required two types of ion sources are assumed to be used. For acceleration of H, D and helium ions an ordinary conventional source with (pening) discharge will be used and for injection of heavy ions a compact multicharge-state ion source will be installed which is similar to that developed at the LNR of JINR with arc discharge and open magnetic trap.

For centering initial orbits and attaining required ion beam intensities puller will be able to be shifted on the pulling out dee and on the ion source tip. Shifting will be accomplished remotely without damaging vacuum.

Note that today's progress in generation of multicharged ions based on RF heating, ECR, laser sputtering of the working agent allows hope for obtaining highly charged ions and arranging external injection of particles into the U-250.

7. BEAM EXTRACTION SYSTEM

Beam extraction from the U-250 cyclotron will be mainly accomplished by their stripping on the carbon foils. This method is the most effective for relatively light ions (extraction coefficient is close to 100%) since it enables one to decrease considerably induced activity level inside the accelerator thus essentially improving its operation reliability and maintenance conditions. Along with stripping, the method of electrostatic deflector and passive magnetic channel are presumed in those modes of heavy ion acceleration when stripping method cannot provide high extraction efficiency and quality of the extracted beam.

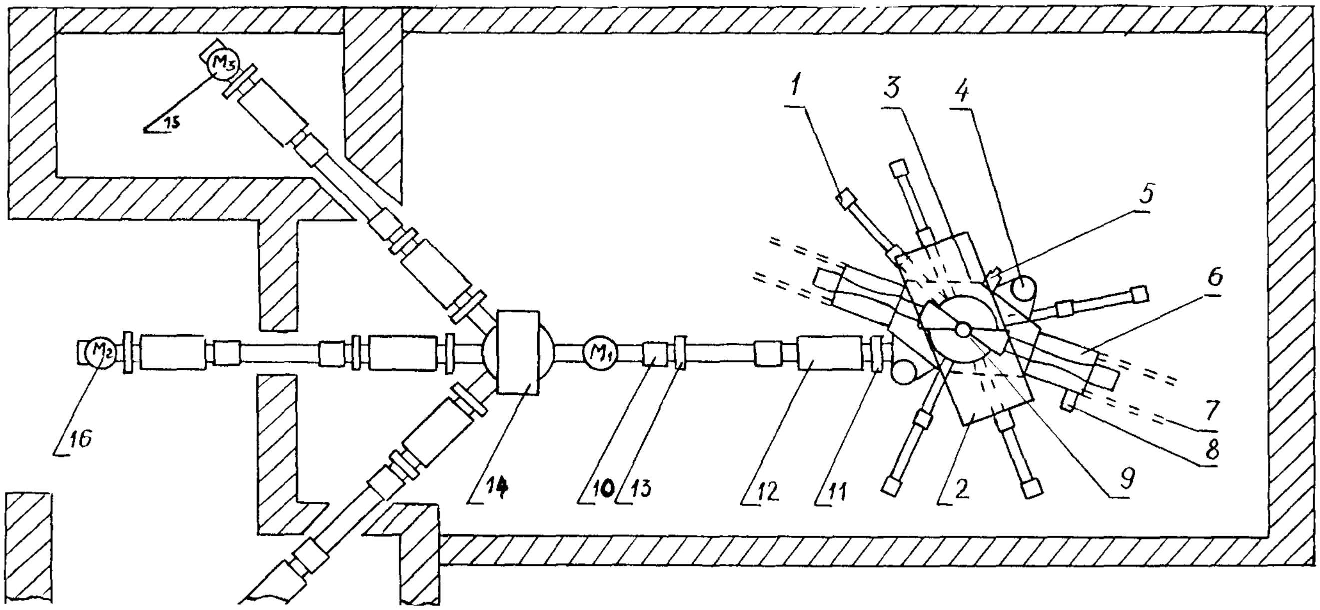

Fig. 1. Lay-out of the cyclotron facilities: 1 – probes; 2 – main magnet; 3 – vacuum chamber; 4 – deflector; 5 – chamber pumps; 6 – resonance system; 7 – final cascade of the RF generator; 8 – ion source; 9 – correcting magnet; 10 – electromagnetic lenses; 11 – diagnostic system; 12 – beam port pumps; 13 – chamber for isotope production; 14 – bending magnet; 15 – chamber for basic research; 16 – chamber for applied researches.

Table 1. Beam parameters of the U-250

Type of ions	Energy, $\frac{Mev}{nucl}$	Total energy, Mev	Beam current, μA	Extraction efficiency, %
Protons p (under acceleration of $^2H^{1+}$)	41.5	41.5	800	100
Deutrons d (under acceleration of $^2D^{1+}$	12.5	25	500	100
Deutrons d (under acceleration of DH^{1+}	22.5	45	500	100
$^4He^{1+}$	12.5	50	500	100
$^3He^{1+}$	22.5	68	500	100
$^{12}C^{3+}$	12.5	152	50–70	100
$^{14}N^{3+}$	9.4	132	70–100	80
$^{16}O^{4+}$	12.5	203	50–60	100
$^{20}Ne^{5+}$	12.5	254	10–20	60
$^{40}Ar^{7+}$	6.2	248	5–10	50
$^{40}Ar^{8+}$	8.2	328	1–2	60–65
$^{48}Ca^{8+}$	5.7	340	1	40
$^{56}Fe^{6+}$	2.3	131	10	30
$^{58}Ni^{6+}$	2.2	127	10	30
$^{84}Kr^{8+}$	1.9	155	4–6	25

Table 2. The main parameters of the U-250.

1. Magnetic structure	
Diameter of the main magnet	
yoke, cm	270
pole, cm	250
average field strength, T	1.9
gaps between poles	
between hills, mm	26–46
between valleys, mm	150
Power:	
main coil, kW	165
additional coil, kW	35
Weight (steel), tons	385
Weight (aluminium coil), tons	5.4
2. RF system	
Number of dees	2
Dee angular extension, °	42
Beam-limiting aperture, cm	2.5
Frequency range, MHz	8–19
Operation harmonics	1, 2, 3, 4
Dee voltage, kV	75
RF power, kW	150
3. Cyclotron	
Total dimensions, m	7×10×4
Total weight, tons	420
Total power, kW	800

8. BEAM TRANSPORT SYSTEM

The lay-out of the main technological areas of the cyclotron facility is shown in Fig. 1. The beam of accelerated ions is ejected into beam port through a 130 mm aperture and focused by a pair of quadrupole lenses and enters either the target chamber M1 or the tuning magnet. After the magnet the beam is transported to experimental chambers M2, M3. Conventional quadrupole lenses are used as focusing elements in the beam line. For extracted beam tuning standard type magnets are utilized.

Beam tuning and transporting system enables one without noticeable losses in intensity to have accelerated ion beam currents at the target site up to several hundred microamperes, angular divergence and energy spread not exeeding 0.3 and 1%, respectively. Beam parameter control is carried out by beam profile transducer.

In a working state vacuum (up to 10^{-4} Pa) in the beam port is provided by vacuum pumps with polyfenilethyr for oil-free pumping out.

The main chamber (M1) and chambers M2 and M3 (for fundamental research in nuclear physics and research in applied nuclear physics, respectively) are heavily shielded to provide radiation protection of the personnel when experiments are carried out with light ions at beam current values up to 800 μA. The experimental areas have been laid out in such a way that there is always possibility to carry out maintenance, check-up and adjusting operations at any experimental site.

Isotope production on an external beam considerably simplifies a number of problems related to target cooling in the main chamber.

At present works on production isotopes, such as ^{131}I and ^{57}Co, for example, are carried out at INP using the research reactor and the U-150 cyclotron.

With the U-250 accelerator put into operation it becomes possible to produce short-lived ^{123}I. ^{123}I has considerable advantages: it gives less patient radioactivity dose and provides better contrastivity of the radiograms.

Preliminary estimates suggest that using the U-250 cyclotron facilities such large amount of ^{123}I can be obtained which is enough for medical examination of several thousand patients yearly. ^{123}I is also applicable for examining kidneys, thyroid glands, for diagnosing cancer at its initial stage, for examining risk (suspected) groups. Using the same facilities ^{201}Tl isotope which nowadays is succesfully applied for early diagnostics of infarcts and for other medical purposes can also be produced.

Besides isotope production, the U-250 accelerator facilities allow us to carry out neutron activation analysis, study the effect of neutron irradiation on materials, simulate radiation produced defects in solids used in nuclear power plants, monitor new technological processes in electronic industry, conduct research in metallurgy, etc.

In addition to applied research listed above, the very same facilities open new vistas for developing research in nuclear physics in the following lines:

Nuclear structure studies using in-beam nuclear spectroscopy methods. Accelerated heavy ions are a unique means for populating highly excited high spin states of nuclei – residual reaction products – which, as a rule, lie far away from β-stability line.

The determination of spin-parities of nuclear excited states, their maximum energies and spin values along with transition probabilities can elucidate behaviour of the nucleus at high rotation rates which attained in heavy ion induced reactions, in particular, the changes of its shape, moment of inertia and other parameters caused by the response of nuclear matter to the extreme external perturbation exerted by heavy projectile.

Nuclear reaction mechanism studies. The distinctive feature of heavy ion induced reaction is its new mechanism called deep inelastic process. It is intermediate between reaction proceeding through compound nucleus stage and that of direct interaction. Deep inelastic processes are specified by the formation of binuclear systems, by intensive kinetic energy dissipation over different degrees of freedom. Multinucleon transfer reaction is of similar nature. Nuclear reaction time delay studies along with those of reaction product angular distributions can yield detailed information on the reaction mechanism and the behaviour of nuclear matter in such strong perturbations.

Studies of atomic phenomena in heavy ion collisions. Time-dependent Coulomb field of colliding ions causes an essential shift of atomic levels and restructuring of electronic configurations from states in isolated atoms to those of molecular orbitals. Dynamical Coulomb field induced restructuring of electrons is accompanied by mutual inner shells ionization of colliding ions, the ionization probability being dependent on the combination of atomic numbers and on the energy of collision. The determination of ionization probabilities gives information on the average field value at any moment, the latter quantity being significant for studies of ions collision dynamics. Results of this kind of experiment are widely used in studying reaction time delays, ion interaction with matter, activation analysis, etc.

As mentioned above, the project can be subjected to further upgrading in respect to expanding the range of atomic masses of accelerated ions and attainable energies of acceleration ion using new types of ion sources.

But solving these problems requires great technical and intellectual efforts and proper high expenditures. The way out of the situation could be found in collaboration – pulling efforts of all groups interested in the project.

9. REFERENCES

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