STATUS OF CYCLOTRON DESIGN IN THE EFREMOV INSTITUTE

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The status, main technical parameters and brief description of new types of cyclotrons for applied purposes designed in the institute over 1993-1995 are given. The results of external beam injection systems studies are described. The aspects of up-dating of a small size MGC-20 series accelerator are discussed.

1. Introduction

In the Efremov Institute are being continued works on creation of new cyclotrons of applied application. During 1993-1995 years were developed two cyclotrons RIC-10 and C-35, and also technical project of modernization serial MGC-20 cyclotron.

RIC-10 cyclotron is intended for application in centers of positron emission tomography. The cyclotron will be employed for production of positron emitting isotopes of carbon-11, nitrogen-13, oxygen-15 and fluorine-18 types. Enriched targets, containing carbon-13, nitrogen-15 and hydrogen-18 are expected to be used, thus aiiowing to obtain sufficient yield of radioisotopes at low final energy (around 10 MeV) and beam current up to 50 mkA [1].

Hydrogen ions are supposed to be accelerated on the cyclotron and extracted onto targets, joined directly to a vacuum chamber of an accelerator. Beam is extracted by stripping of negative ions on thin carbon foils with an efficiency of 100%, thus providing greater safety for personnel.

Seven samples of MGC-20 cyclotron are working in different countries. Now eighth sample has been worked out for Egypt and being under assembling. Such multi-pupose machines continue to interest customers. Large range of energy change (5-20Z ^{2}/A MeV) and ion types allows to use MGC-20 cyclotron for nuclear physics experiments, activating analysis of materials, medical isotope production. Now modernization of MGC-20 cyclotron is produced for increasing of energy up to 22-24 Z^2/A Mev. Then further possibilities of cyclotron short-lived isotope production will arise. For example isotopes ^{123}J, ^{67}Ga, ^{111}Jn, ^{52} Fe, ^{43} K and so on may be worked out.

The C-35 cyclotron can be widely applied for production of radioisotopes in industry and medicine. This machine offers the following features : compact magnet and resonance system, possibility of energy variation from 15 to 35 MeV, low activation of the cyclotron elements (providing an easy access to the machine already in about an hour after its switching off), simultaneous extraction of two beams in opposite directions, high intensity of extracted beams, possibility of on-line maintenance of an external ion source, low power consumption, maintenance simplicity of the accelerator with a hydraulic jack available.

This cyclotron can be used for acceleration of hydrogen and deuterium negative ions. A system of external axial injection with a multipole ion source is applied. The source will provide the beam intensities up to 500 mkA for H ions and up to 100 mkA for D ions at the cyclotron outlet. The beams are extracted by means of electron stripping on a thin graphite foil. The extraction of beams in three directions but the most efficient is operation with two simultaneously extracted beams.

Main parameters of the RIC-10 and C-35 cyclotrons are given in Table 1.

2. General description of the RIC-10 cyclotron.

The RIC-10 cyclotron is an isochronous sector-focusing machine with fixed magnetic field and fixed frequency of a dee voltage. It is designed based on a compact magnet of shielding type with a pole diameter of 73 cm.

Magnetic field of the cyclotron is shaped by height profiling of sectors, without use of trim coils. An R.F. accelerating system provides an energy gain of approximately 100 KeV per a turn and, respectively, the total number of turns is not more than 110. A source of negative hydrogen ions with a "cold" cathode is axially introduced into the chamber through the hole in a pole in the upper part of the magnet.

Beam is the extracted into each of four targets by stripping of ions on a thin (40 mkg/cm) carbon foil. Simultaneous irradiation of two targets is provided. One stripping device comprises three foils manually placed into the working position without vacuum deterioration.

For easy maintenance the upper part of the magnet can be lifted through 50 cm by way of a hydraulic lift. This provides an easy access to the in-chamber components and targets.

For assembly a remotely-controlled two-electrode probe is provided. It can be moved from the final beam acceleration

radii. Under normal operating conditions of the cyclotron the above probe is replaced, for a small one with a limited range of movement in the zone of final acceleration radius.
Vacuum volume of the cyclotron comprises the vacuum chamber and coaxial cavities. It is pumped out by two vacuum diffusion pumps with water-cooled bafflers each with the pumping speed of 630 l/s for nitrogen and 2300 l/s for hydrogen. When 3 cm /min (40 cm .Torr/s) of hydrogen is supplied to the ion source and gas flow fom the surface of structural material of 5.10 $^{-1}$ cm^3. Torr/s, the pumping units provide an average operating pressure in the chamber of 5.10^{-6} Torr. The design beam losses due to the residual gas stripping are about 30%.

Table 1: Main parameters of RIC-10 and C-35 Cyclotrons.

	RIC-10	C-35
Beam: type of ions	H$^-$	H$^-$ D$^-$
Energy H$^-$, MeV	10	15-35
D$^-$, MeV	-	10-18
Current H$^-$, mkA	50	500
D$^-$, mkA	-	100
Magnet: pole diameter, cm	73	150
number of sectors	4	4
sector angle, degrees	45	45
gaps (hill/valley), cm	5/10	5/18
magnetic field (in the center),	1.48	1.34
supplied power, kW	22	22.5
weight, t	10	55
R.F. system: number of dees	2	2
dee angle, degrees	45	45
frequency , Mhz	45	40,7
harmonic mode	2	2.4
dee voltage, kV	35	50
generator output power, kW	9	35
Ion source: type	PIG	CUSP
current H-, mA	0.3	3
power, kW	up to 1.5	3
Power consumption, kW	55	120

The automatic control system switches on the off all cyclotron equipment, brings the preset operating conditions and controls the operation of all systems of the cyclotron. All cyclotron systems are controlled both manually (from racks and local panels) and remotely by a microcomputer (PC). Mainly, the cyclotron systems will be controlled by their own microprocessors, connected with the PC through a controller. An R.F. generator is controlled by a separate intellectual controller. The controllers are connected with the PC through the RS-232 interface. In addition to the standart PC keyboard a functional console is provided for the control of the cyclotron.
The cyclotron is equipped with a water cooling system, comprising a closed loop for water circulation with a plate-type heat exchanger. Pressure drop in the water cooling system is 4 kg/cm^2. Water flow rate is 50 l/s. Maximum temperature of cooling water is 25 degrees Celsius.
The general view of the RIC-10 cyclotron is presented in Fig.1. The upper part of the magnet with the axial ion source, installed on it, is removed. The largest vertical dimension of the cyclotron with the lifted upper beam is 2.8 m. A matching magnet, installed at the cyclotron beam outlet, serves for additional correction of the accelerated particle trajectories with the aim of their input separation applying electromagnetic elements standard for the Efremov Institute: quadrupoles, correcting and bending magnets.

3. General description of the C-35 cyclotron.

The general view of the cyclotron is given in Fig.2. A shielding-type, magnet is designed for the excitation of the constant magnetic field with an average induction of 1,34 T. The rated current in a magnet coil is 500 A, magnet outer diameter - 2.7 m, height, including a support, is 2.15 m, iron core mass - 49 tons. The upper part of the magnet can be raised through 0.8 m upward together wish the vacuum chamber cover, thus providing an easy access to in-chamber components.
Harmonic coils are located in the "valleys" of the magnet and gradient coils - on the sectors.

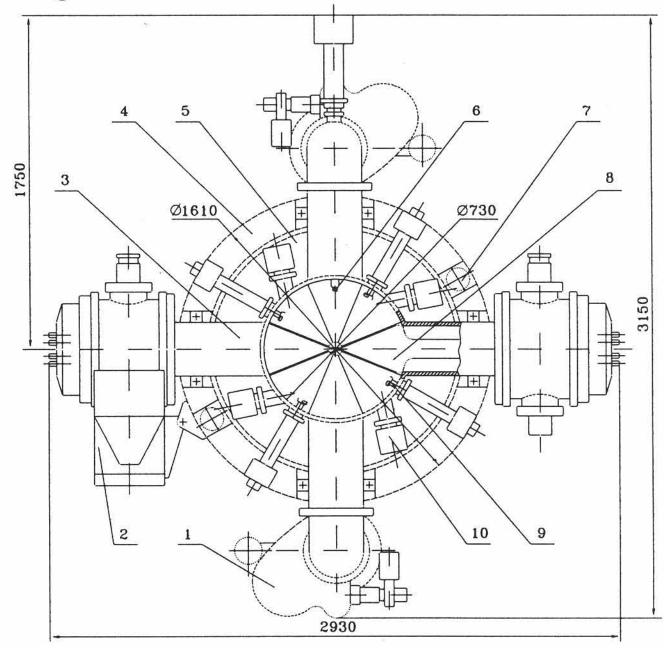

Fig. 1. Plan view of the RIC-10 cyclotron: 1. Diffusion pump. 2. RF generator. 3. Vacuum chamber. 4. Electromagnet. 5. Main coil. 6. Beam probe. 7. Hydraulic lift. 8. Dee. 9. Stripping foil. 10. Target

The vacuum chamber consists of covers (formed by the intermediate pole pieces) with the ring plates of non-magnetic steel welded to them and a ring-shaped casing, being simultaneously a part of the iron core. The vacuum chamber contains: an accelerating resonance system, gradient and harmonic coils, three beam extraction devices and inner probe.

A central conductor of the accelerating system comprises two 45 degree dees fastened to the stems of complicated shape and having a common part near to the short-circuiting flange. The vacuum chamber cladding, including vertical shields installed on it, serves as an outer conductor. Due to the double conductive coupling (a connecting plate between the dees and the common part of the dee stem), the accelerating system is a single resonator for which one RF-power input and one system for frequency automatic tuning are sufficient.

In such configuration the resonance system is totally located inside the magnet cavity, i.e. no special windows in the reverse iron core are needed. This circumstance improves the magnet performances and reduces the ionizing radiation intensity in the vicinity of the cyclorton. Other advantages of the accelerating system are mechanical rigidity of the central conductor and low linear density of RF-currents (not more than 20 A/cm at the rated amplitude of the dee voltage of 50 kV).

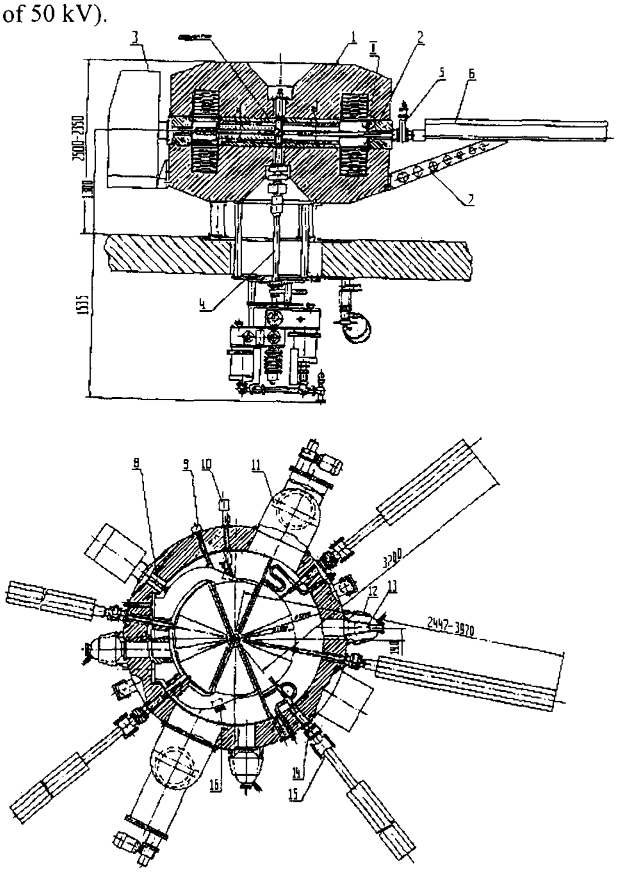

Fig. 2. Plan view of the C-35 cyclotron
1-magnet; 2- accelerating chamber; 3 - final stage; 4 - external injection system; 5 - vacuum valve; 6 - probe; 7 - supporting arm; 8 - power input; 9 - RF-probe; 10 - FAT trimmer; 11 - duct; 12 - matching magnet; 13 - vacuum chamber ; 14 - vacuum valve; 15 - beam extraction device; 16 - capacitor.

The RF-power supply system consists of a pilot generator, power amplifier, system for power transfer from the final stage generator to the dees, system for automatic stabilization of the dee RF-voltage amplitude and system for frequency automatic tuning.

Cryogenic pumps with a pumping capacity of 5000 l/s are used for high-vacuum pumping of the accelerating chamber. Computations of the beam losses due to residual gas atoms show that at a total pumping capacity not less than 5000 l/s the beam losses are not more than 3%. The working vacuum in the acceleration zone is assumed to be than 5×10^{-6} mm of Hg. For preliminary pumping out and regeneration of cryopumps we employed mechanical pumps with the pumping capacity of 16 l/s. One of them is used for pumping out the ion source volume, the second - for the part of the iron core from the emission hole diaphragm of the ion source to the cyclotron.

The axial injection system of the cyclotron incorporates a multipole ion source, chamber for differential pumping out with a vacuum valve and beam diagnostics, two correction magnets, solenoid lens, matching quadrupole doublet and helical electrostatic inflector. All magnetic elements of the ion-optical tract are designed on the basis of permanent magnets made of samarium-cobalt alloy. Beam energy H^- - 30 kV (D^- - 15 kV), tract length from the ion source to the cyclotron median plane - 1,8 m.

A helical electrostatic inflertor is employed for the beam bending from a vertical channel to the cyclotron. A collimating diaphragm, preventing particle deposition on the electrodes, is installed at the inflector inlet.

Thin graphite foils are used of the beam extraction from the cyclotron. The cyclotron is equipped with three beam extraction devices with a special mechanism for a used foil replacement. It should be noted that simultaneously a modification of cyclotron, providing beam acceleration and extraction in a plane perpendicular to the floor, was thoroughly studied. Similar layout is atteractive due to appreciably higher radiation safety of the cyclotron. The front part of the magnet is hinged, thus allowing easy opening of the vacuum chamber for access to the internal components of the cyclotron and target assemblies.

4. Conclusions.

At present, the manufacture of the RIC-10 cyclotron equipment is practically completed and it is under assembly. Shaping of magnetic field of the cyclotron is the primary task in the process of adjustment. The automatic field topography by means of a personal computer is constructed and adjusted.

Simultaneously with the manufacturing of the equipment of the RIC-10 systems were tried-out and optimized on an operating cyclotron of the MGC-20 type, in particular, the negative ion source with the "cold" cathode and the system for beam extraction by stripping on a thin foil, including foil fabrication technology. Results on measurements of vertical and horizontal emittances of the extracted beam of negative hydrogen ions are obtained. The intellectual controller for control of the R.F. generator is made and tested under operating conditions. All these activities are aimed at the hastening of the start-up of the RIC-10 cyclotron.

At present working drawings for the C-35 cyclotron are elaborated. The 1:2 scale model of the accelerating system is constructed. Computed and measured (greater than 1.5%) frequency values are in a satisfactory agreement taking into account the complicated configuration of the resonator.

An experimental multi-purpose stand is constructed at the Efremov Institute with the aim of testing and further optimization of the systems for beam external injector, at the first stage of the C-35 cyclotron. The stand comprises: ion source; two vacuum chambers; ion tube; beam diagnostic; elements of the ion-optical system; beam diagnostic chamber at the tract outlet; power supply, control and measuring systems; two turbomolecular pumps; forevacuum line. For primary formation of a negative ion beam we use a multipole source[2]. Its gas- discharge chamber consists of an anode, cathode, plasma electrode and a magnetic filter. A cylindrical part of the anode made of oxygen-free copper has the inner diameter of 75 mm and length of 100 mm. The cooled anode contains twelve raw of SmCo magnets (six in each raw) designed for generating the "cusp" magnetic field. The magnetic filter is galvanically coupled with the anode. The cathode unit, channel for hydrogen supply and leads of the cooled magnetic filter are mounted on the gas-discharge chamber back cover. A bias potential relative to the anode can be applied to the plasma electrode. A working gas is supplied to the discharge chamber through the anode back cover using a special system based on a piezoceramic regulator with a feedback, intended for supply of smoothly regulated amount of gas. Ion selection from plasma, their separation from electrons, beam focusing and acceleration up to the final energy of 30 keV are performed in a five-electrode axially-symmetric, made as an accelerating tube with channels for electrodes cooling.

At tests the emission hole of the source was 2 mm. A discharge in the source was initiated at a voltage of 360-400 V. Hydrogen pressure in the gas discharge chamber did not exceed $8x10^{-3}$ Torr in the course of preliminary experiments. At the discharge current of 4 A, discharge voltage of 160 V, extraction voltage of 3,8 kV, acceleration voltage of 30 kV we produced a 300 mkA H^- ion beam, focused up to 3 mm in diamemer at the 320 mm distance from the emission hole. The preliminary experiments showed the proper choice of the source design .

The ion-optical systems parameters were chosen by the results of the code, developed at the Efremov Institute and realizing the envelope method. By the computational results a version comprising a solenoid lens and matching quadrupole doublet was taken as a reference one. It offers a sufficient flexibility and allows to match the beam and the inflector at an appreciable deviation of the beam parameters from the nominal at the source outlet.

At present the manufacture and assembly of the stand equipment are finished. Working vacuum is obtained and the preliminary tests of the multipole ion source are carried out. Power supply, control and measuring systems are under adjustment. In the nearest future we plan to continue the tests of the ion source with the aim to obtain the required beam parameters. Later elements of the ion-optical systems will be tested for experimental optimization of their characteristics.

5. References

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