CONSTRUCTION OF GATCHINA ISOCHRONOUS CYCLOTRON

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1. Introduction

A synchrocyclotron [1] which accelerates protons up to 1 GeV at beam intensity of 1 μA is in operation at Petersburg Nuclear Physics Institute. The accelerator is applied for studies in physics of elementary particles, nuclear physics as well as for proton therapy and radioisotope production for medicine, *etc*. For increasing radioisotope production, for organization of the ocular melanoma irradiation facility as well as for extending the traditional studies of short-lived isotopes it was decided to build a 75–80 MeV H^- ion accelerator with beam current of 100 μA [2, 3].

Energy of 75–80 MeV and possibility to regulate it are necessary for production of high quality radioisotopes using reactions unattainable at lower energies. The Gatchina isochronous cyclotron (GIC) may be used to produce large quantities of isotopes such as ^{18}F, ^{43}K, ^{52}Fe, ^{67}Ga, ^{77}Br, ^{111}In, ^{123}I, ^{201}Tl *etc*, which could not be obtained with a help of nuclear reactors. Shown in Table 1 are isotopes with their half-life times, the demand of thirty St. Petersburg radiological hospitals per year, the accelerator time for production, and the cost of some radioisotopes.

Table 1

Radioisotopes for medical applications

Isotope	$T_{1/2}$	Demand for 10^3 MBk/year	Accelerator time consumption in hours/year	Cost of radioisotopes (1000 $)
^{18}F	1.8 h	$(20–40)\cdot 10^3$	200–400	
^{43}K	22 h	400–800	200–400	
^{52}Fe	8 h	40–80	3060	
^{67}Ga	3.3 d	300	70	348
^{111}In	2.8 d	860	450	2084
^{123}I	13 h	900	22	
^{201}Tl	3 d	700	95	970
^{77}Br	56 h	230	124	

Realization of this project should allow providing the demand on short-lived radiopharmaceutical preparates for hospitals of the North West part of Russia. The cost of the produced isotopes is so high that it is able to justify the expenditure on cyclotron construction during in a few years.

Another perspective direction of activity can be the organization of the ocular melanoma irradiation facility at the new cyclotron. For example, the cost of the melanoma treatment at the PSI 72 MeV cyclotron is millions dollars per year.

Also the possibility of using the cyclotron like powerful external injector for the synchrocyclotron was considered [4].

2. General description

To minimize the expenditures while designing the cyclotron, an attempt was made to use at most the existing synchrocyclotron infrastructure, *i.e.* the building, the bridge crane for 30 tones, the electric power, water cooling, ventilation systems, *etc.* The iron yoke of the synchrocyclotron model magnet is used for a magnet system. Table 2 and Fig. 1 show the main cyclotron parameters. The plain view of its arrangement in the experimental hall of the synchrocyclotron is given in Fig. 2.

Probably, the energy of 75–80 MeV is nearly the maximum possible one for H^- isochronous cyclotron with the solid magnet pole diameter of 2 m. The H^- ions acceleration enables to perform smooth energy regulation of the extracted beam. The intensity of 100 μA is necessary for isotope production and is limited both with an ion source and the chamber activation.

Table 2

Gatchina cyclotron parameters

MAGNET	Pole diameter	2.05 m
	Valley gap (max.)	386 mm
	Hill (min.)	146 mm
	Number of sectors	4
	Spiral angle (max.)	65°
	Isochronous field in the center	1.352 T
	Flutter (max.)	0.02
	Extraction radius	0.40–0.90 m
	Ampere-turns	3.4×10^5
	Power	120 kW
	Weight	250 t
RF SYSTEM	Frequency	41.2 MHz
	Voltage	60 kV
	Harmonic	*2*
	RF Power	2×40 kW
VACUUM	Pressure	$10^{-7}(N_2)$, $10^{-6}\,(H_2)$ mbar
	2 Cryo-pumps	2×5000 l/s
	Cryo-panels with liquid N_2	$S = 0.3$ m^2
SOURCES	External: Surface-plasma, stationary source; multi-pole source	
	Voltage	20 kV
EXTRACTION	Energy	45–80 MeV
	Method	Stripping

The vertical focusing at the final radii has been achieved due to spiral angle $\gamma \sim 65°$. Another way, *e.g.* the flutter enlargement at a given average field, would lead to a hill field growth and H^- ion losses as a result of dissociation in magnetic field.

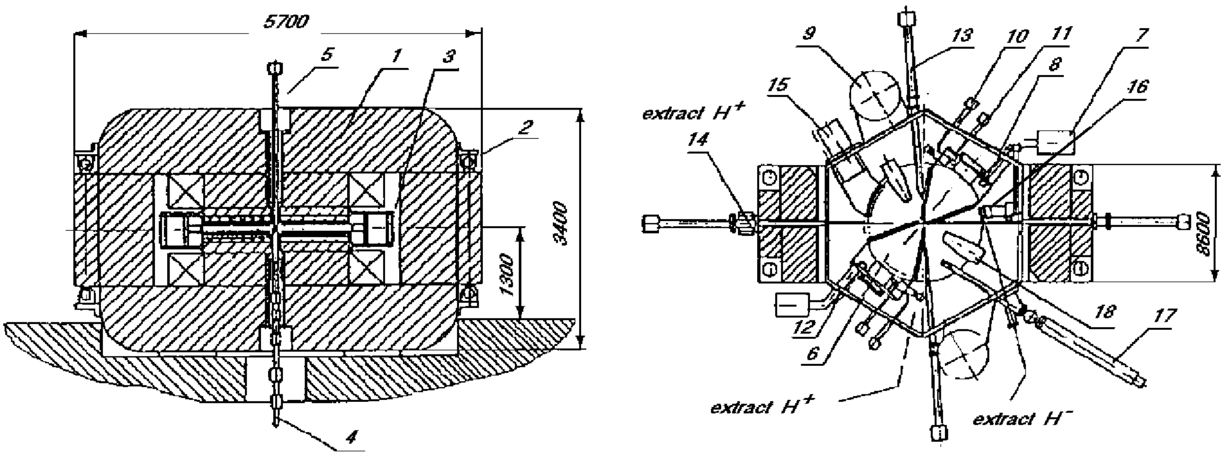

Fig. 1. General view of cyclotron. 1 – electromagnet; 2 – hydraulic jack; 3 – vacuum chamber; 4 – external injection system; 5 – axial injection deflector; 6 – resonance system (dee); 7 – final cascade of RF generator; 8 – RF power input; 9 – vacuum pump; 10 – tuning capacitor; 11 – trimmer of automatic frequency tuning; 12 – RF probe; 13 – diagnostics probe; 14 – septum protection foil; 15 – extraction system deflector; 16 – magnetic channel; 17 – stripping device; 18 – cryo-panel

The accelerating chamber has an unusual design. The magnet pole tips and the harmonic coils are located outside the vacuum chamber. The chamber from stainless steel having relatively thin lids and being large in size is mechanically attached to a pole tips that provides relative rigidity under the action of the atmospheric pressure. The chamber frame of hexagonal shape is welded of nonmagnetic stainless steel. The chamber walls are made of duraluminum. The two of them that face the yoke side are undetachable. In the region of a resonance system, the chamber lids are covered by copper sheets with the tubes to let the cooling water through.

Due to the large recharge H^- cross section, a high vacuum is required. The load on pumping means originates from an external ion source, gas desorbtion from the surface and leakages. Estimations show that in order to obtain 10^{-7} mbar for air and 10^{-6} mbar for hydrogen it is necessary to provide the following pumping speeds: 10 m^3/s (H_2), 25 m^3/s (H_2O) 10 m^3/s (CO_2 and N_2) and 5 m^3/s (hydrocarbon). Now our efforts are concentrated on external source and the axial injection system by using a spiral inflector. High vacuum system consists of two pumps with pumping speed 5000 l/s each and two turbo-molecular pumps on 3000 l/s and 1000 l/s on the injection beam line.

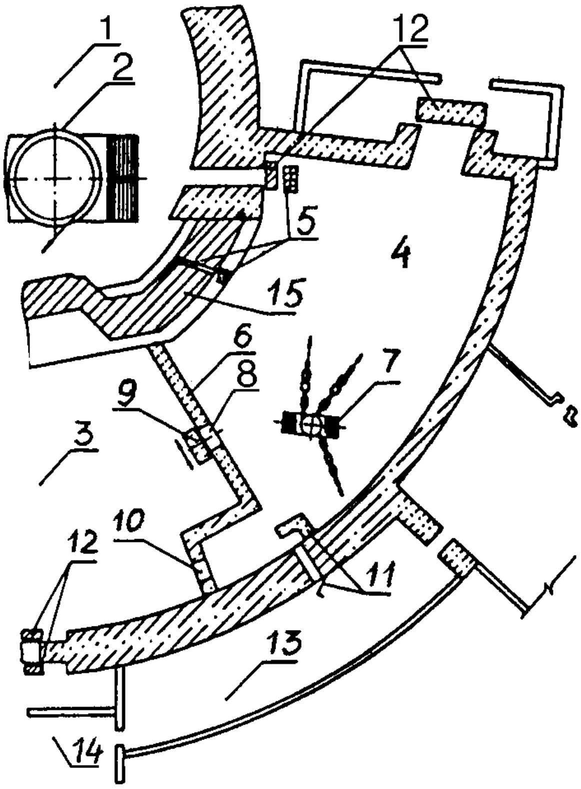

Fig. 2. Scheme of cyclotron arrangement. 1 – hall of synchrocyclotron; 2 – synchrocyclotron; 3 – experimental hall; 4 – cyclotron hall; 5 – additional shielding; 6 – wall separating the cyclotron hall; 7 – cyclotron; 8 – opening for crane passage closed by a wheeled block; 9 – new shielding door; 10 – crane cargo opening; 11 – cyclotron hall entrance; 12 – shielding doors; 13 – control hall; 14 – laboratories; 15 – shielding wall from iron blocks

3. Researches and development

A new cyclotron construction assumes some researches and development work have to be done. The specific magnetic structure has to be developed. There have to be developed the acceleration system operating at the second harmonic of the ion revolution, the axial injection system with the central inflection and beam optics, the H^- ion source, *etc.*

3.1. Design and modeling the magnet and magnetic structure

Magnetic field requirements. The cyclotron magnetic field of the conventional isochronous cyclotron must meet some requirements. The magnetic rigidity on the final orbit must achieve $B \cdot r = 13.2$ kGs·m that corresponds to the 80 MeV energy. For isochronism the 8.5% increasing of the azimuthally averaged magnetic field from the centre to the final orbit has to be provided. The azimuthal variation of the magnetic field must provide for z focusing and a permissible value of vertical oscillation frequency ν_z. A room has been left for the high frequency system, and the gap between shims should be more than 140–150 mm. But for H^- cyclotron there is an additional and essential requirement related with confining the electromagnetic dissociation of H^- ions by the limit of 5%.

A rich variety of schemes for the magnetic field azimuthal variation is used for the isochronous cyclotrons: separated magnet structures, the straight wedge sectors, sectors with low spirality and high spirality, shims with wedges as an Archimedes spiral. The challenge was to select the magnetic structure optimal for our case. There are two main problems connected with designing the magnetic field of the isochronous H^- cyclotron. The first one is the selection of the magnetic structure, which provides the maximal energy of the accelerated H^- ions for a given magnet under the condition that beam losses are lower than 5%. The second problem is the determination of the pole tips geometry that provides the selected field distribution.

H^- dissociation in the magnet field of cyclotron. The careful analysis of H^- dissociation data in a magnetic field of the cyclotron was carried out. As a result of the analysis, it was found out that there is a discrepancy in published data concerning parameters of dissociation. The dissociation parameter data presented in the well known monograph edited by B.P.Murin lead to underestimation of H^- losses in dissociation. Most authentic parameters are given in papers of G.M.Stinson *et al.* and R.T.Lee [5].

H^- losses and selection of the magnetic structure. The H^- losses due to electromagnetic dissociation are defined by the ion energy and magnetic field. In our case the final radius of the acceleration is fixed and the averaged magnetic field on the final radius is defined by the final energy. In this case the maximum field in cyclotron can be reduced only using the magnetic structure with low magnetic field in the hill. The needed focusing can be provided using a high value of the spiral angle. Two alternative versions of the magnetic structure have been examined. The first one had on the final radius flutter $F = 0.04$, spiral angle $\gamma = 55^\circ$, harmonic amplitude $A_4 = 4.15$ kGs and the second structure has $F = 0.025$, $\gamma = 65^\circ$, $A_4 = 3.28$ kGs. The both modifications provide almost the same net axial focusing and are distinguished by the field in the hill region. The second version with low flutter and high spiral angle was selected for Gatchina cyclotron because of the lower (5%) beam losses [6].

The magnet design and optimization. Next problem is connected with the determination of the pole tips shape, which provide the needed magnetic field distribution. For today there are no calculation methods to define the pole tips geometry, which provide a given distribution of the magnetic field. For that reason, designing was made frequently on precedent or by using the trial and error method. In the last few decades great progress has been made when computer codes such as 2D code POISSON and commercial 3D code TOSCA appeared. But even application of 3D program TOSCA does not result in the automatic decision of a problem because of the complicated 3D pole tip geometry, the time consuming calculations and, as a result, impossibility to examine the great number of variants. In our case the basic parameters of the magnet structure, hill and valley gaps and sector spirality have been selected by using 2D POISSON calculation and the real 3D magnetic field has been examined on the small scale models. At first the opportunity of replacement of a conic pole of the synchrocyclotron model magnet with 1.5 m diameter by cylindrical poles with 2 m diameter has been established. At the next stage the magnetic circuit of cyclotron was optimized [7]. In Fig. 3 the general view of a quarter of reconstructed magnet and magnet SP-72 are presented. The modification of SP-72 has allowed to eliminate the iron saturation in the yoke, to decrease a current in a magnet down to 800 A and to reduce power consumption down to 120 kW. On the base of the 2D calculation the hill and valley gaps have been selected. With this aim in mind, a set of the axially symmetric magnets with the ring shims have been calculated with averaged gaps $2g_0$ = 260, 300 and 360 mm and with the corresponding set of excitation currents which provided the same isochronous magnetic field $<B(r)>$ and 80 MeV energy at a radius $R_f \sim 0.9$ m. From these calculations it was estimated also that a shim of 1 cm thickness corresponds to the field ~ 1 kGs at the last ring. As a result, for a variation of magnetic field from hill to valley to be 8 kGs, gaps of hills and valleys are chosen to be 150 mm and 380 mm, respectively. The final shim profile is shown in Figs. 4a, b.

Flutter as a parameter having been determined by the azimuthally field distribution cannot be exactly calculated by 2D code. Nevertheless it was developed an approximate method of flutter estimation by the representation azimuthally edge effect by the radial one for the straight sectors [8, 9].

The representation of the flutter dependence on radius by using the dimensionless parameter X, where $X = r/Ng_h$, is to best advantage and in particular has clearly demonstrated the radius where flutter focusing becomes inefficient. According to the result of calculation, the flutter focusing is effective if X is equal or more than 0.5 or when $r \leq g_h$.

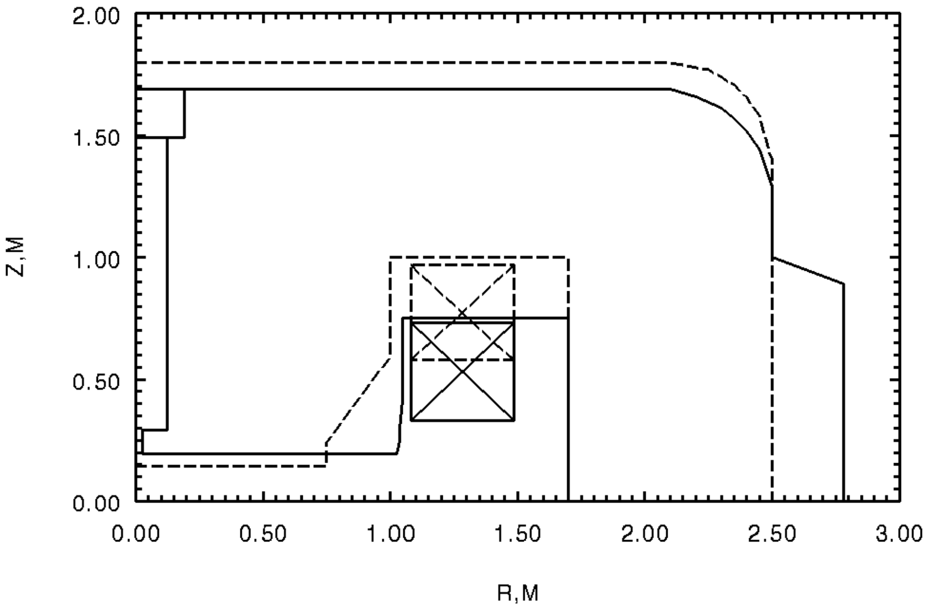

Fig. 3. The contours of the isochronous cyclotron and SP-72 magnets are presented. Dotted line is a contour of the initial magnet SP-72 and solid line is a result of the reconstruction

Effect of spiral pole tips. Spiraling of pole tips introduces an alternating gradient component that increases the net focusing. The effective value of the flutter in such a case is multiplied by the factor $S(r, \gamma) = 1 + 2\tan^2\gamma(r)$. However the flutter falling as the spiral is introduced because the distance between the sectors along the perpendicular to the median sector line is reduced what is the same as decreasing the structure period. The effect of the flutter falling can be obtained from the data if instead of X one introduces an effective value $X_{\text{eff}} = X{\cdot}\cos\gamma$. The overall effect of the spiraling can be expressed by the parameter which is a product of two multiplicands: flutter $F(r)$ and $S(r,\gamma)$. When $X_{\text{eff}} < 0.5$, the flutter is drastically decreased and it can cause the reduction of focusing. The ultimate spiral angle for the given value of X parameter can be found as a root of the equation

$$U(X,\gamma) = (F(X{\cdot}\cos\gamma) \,/\, F(X)) \cdot (1 + 2\tan^2\gamma) - 1 = 0.$$

In our case the spiraling is ineffective at radii smaller than 15 cm, so it is reasonable to use the high spiral angle only for radii $r > 35$ cm.

In this connection, at small radii it is reasonable to use direct sectors. On the basis of the analysis of the large number of variants, for Gatchina cyclotron the structure with minimally possible flutter and maximal spiral at the large radii and direct sectors in the central area was chosen.

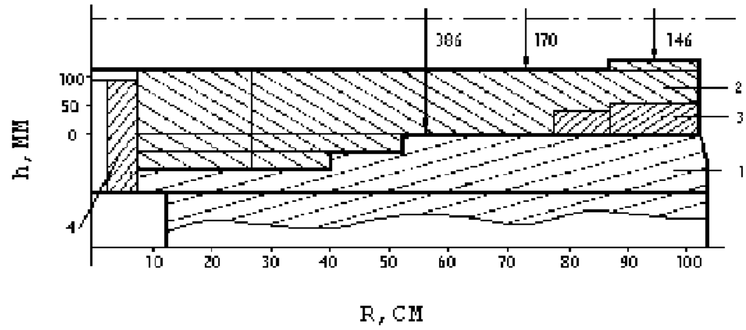

Fig. 4a. Side view of the hill and valley: 1– pole tip; 2 – sector; 3 – valleys shims; 4 – central plug

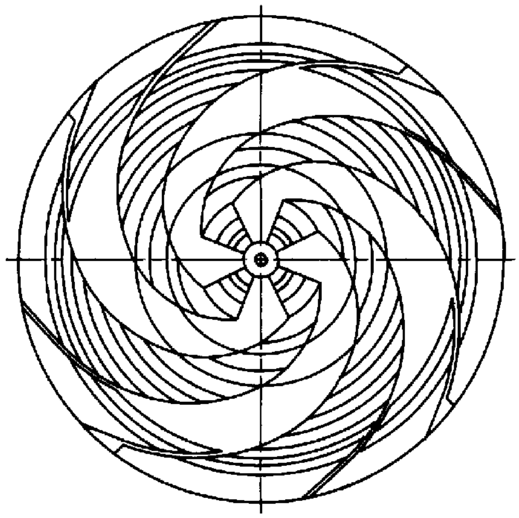

Fig. 4b. Plane view of the pole tip

Model measurements. The calculations using above mentioned methodology allow to choose the basic parameters of the magnetic structure. The detailed 3D field distribution has been examined on the models with the scales $k_1 = 1.33$ and $k_2 = 8$ and with the spiral angles $\gamma = 55°$ and $\gamma = 65°$, respectively. The model measurements have confirmed the basic results of the calculation and have allowed to receive complete 3D magnetic field distribution. In addition, the effect of the discrepancy between magnetic and geometrical spiral angle, which reaches 4° at $\gamma = 65°$ that corresponds to 30% focusing reduction, has been examined. The effect should be taken into account when designing the magnet. On the basis of the calculations and model measurements the standard magnet SP-72 was reconstructed and pole tips were manufactured [11].

3.2. Design of the acceleration system

The magnet parameters have to be considered as basic data for designing an acceleration system: the isochronous frequency of the particle revolution is equal to 20.6 MHz, the magnet radius is 1 m and the hill gap is 140 mm. An energy gain per turn has to be 200 keV/turn in order to reach the final energy of 80 MeV on 400 turns and to restrict the H^- losses by 5%. A high energy gain per turn provides the acceptable tolerance for the average magnetic field isochronism also. After examination alternative versions, two-dee scheme operating on the second harmonic of ion revolution with frequency f_0 = 41.2 MHz has been chosen [12]. This option has advantages of low radio frequency power dissipation and makes room in the vacuum chamber for probes and an extraction system. The accelerating system consists of two quarter-wavelength resonators excited in phase. The resonator dees are bridged in the centre as shown in Fig. 5. As far as the resonator length is less than $\lambda/4$ = 1.8 m, the acceleration system can be disposed entirely within a vacuum chamber. The resonator geometry is chosen on the basis of an approximate analysis for the purpose of minimization RF losses for the given frequency and energy gain per turn. As a result of optimization, the dee angle is chosen to be α = 60° and the resonator parameter stem length and the resonator half-height have to be nearly equal.

The next problem after the selection of a base line configuration is connected with the tuning of the resonator on the given frequency. An exact calculation for the determination the stem length S_L is very complicated due to irregular shape of the resonator, that is why approximate calculations were used. In these calculations the resonator was represented as a sequence of transmission lines having different characteristic impedances Z_i. As a result, the calculated resonance frequency agrees within 6% with experimental data obtained at a model. To define more exactly the calculation results, models of the acceleration system (AS) were built.

The models were made of two-side copper-clad plastic, usually used for printed-circuit boards. One side of the covering was used as a current conductive surface, and the other was used for soldering the stiffening plates. This made possible to manufacture large surfaces of plastic plates of 2 mm thickness. The models were made knockdown. The knockdown design of the model enables modifications of the AS geometry and permits to investigate alternative versions of AS. On the models there was determined the resonator geometry that provided the necessary resonance frequency with an accuracy better than 0.5%. The detuning of the resonator under the variation of its geometric parameters was measured. Also measured were the voltage decrease along the dee from the central region to the final radius (~ 12%), the tuning range of the capacitor (~ 2%) and of the fine trimmer (~ 0.3%), the influence of the high frequency probes and power input. The experimentally measured results were differing from calculated ones by 5−15% and resonance frequency – by 6%.

AS parameters are as follows: dee aperture a = 30 mm, dee-ground liner gap C = 33 mm, dee radius R = 1 m, dee angle α = 60°, accelerating gap d = 20 mm. The resonator box: height h = 466 mm, width b = 1060 mm, stem width b' = 430 mm, stem length S_1 = 210 mm. Electric parameters: energy gain per turn w = 200 keV, dee voltage amplitude U = 61 kV, dee voltage decrease 12%, quality factor Q = 3400, dee RF losses $P = 2 \times 5.6$ kW, box RF losses P = 41.6 kW.

The master oscillator tuned on the frequency of 41.2 MHz excites the 15 kW preamplifier which push-pull output is connected with two 40 kW power amplifiers, each placed in the chamber vicinity. Commercial produced broadcasting transmitter “Molnija” was used as the master oscillator and preamplifier was reconstructed and retuned on higher frequency. The output of preamplifier *via* two fidder lines is switched onto two final cascades. Each of resonance subsystems is inductively coupled *via* a loop with the output cascades, thus forming their resonance anode contours. The power supply rectifier is of 10 kV and 160 kW. Automatic amplitude friequency and phase control systems as well as a break-down protection system are envisaged.

3.3. Source and injection

The cyclotron design envisages the application of internal and external sources. An internal source (Penning type with a filament thermal cathode, an anode and a cathode reflector) has been considered to be a source for the accelerator operation at the initial stage. But at present time our efforts are concentrated on the external sources.

An external source has a number of advantages. Primarily, there is no gas leakage into the chamber and it gives an advantage in decreasing of H^- losses and chamber activation. Several types of external sources have been considered. The well developed in Russia source is a surface-plasma one designed in Novosibirsk and applied at Moscow Meson Factory [13]. The source operates in a pulse mode with a single pulse of 1 ms duration, duty factor of 10 and a pulse current up to 10 mA. The test facility is now built for experiments with a surface plasma H^- source. A specimen of the source (a gas-discharge cell, assembled together with small pole tips, an extracting electrode, and an electromagnetic feeding valve on high voltage insulators) were made at INI (Moscow). The test facility is comprised of a vacuum chamber with over-all dimensions 50×50×50 cm^3, a pump system, a hydrogen gas-discharge pulse feeding valve, and power supply generators of discharge current pulses and high voltage extraction pulses. The source is installed as a unit in the gap of a small electromagnet mounted in the vacuum volume. Water-cooling coils of electromagnet are placed into vacuum-tight shells [14].

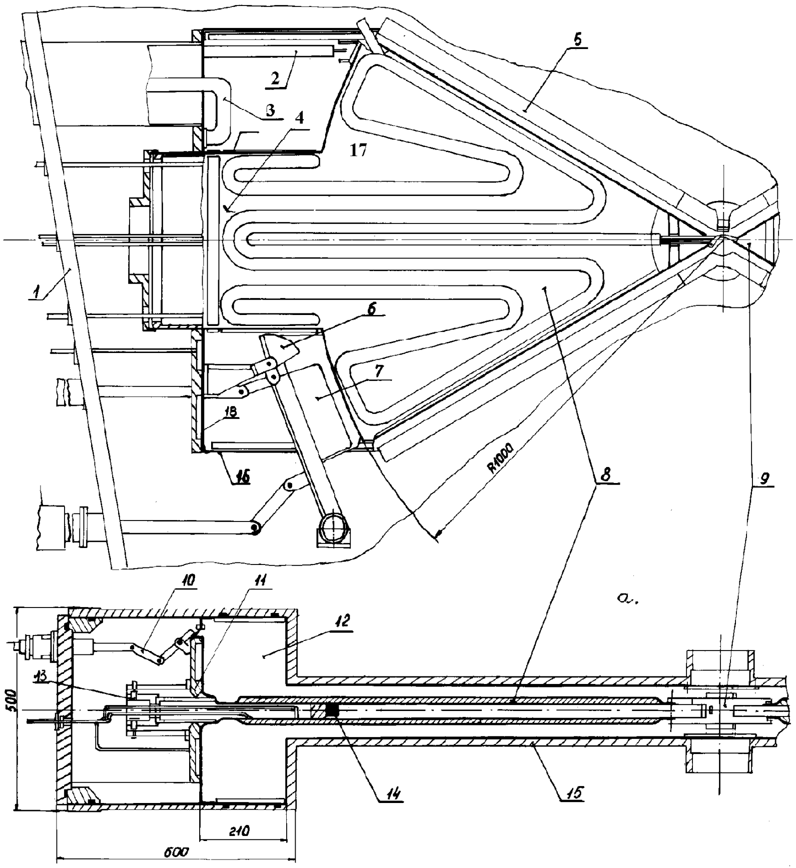

Fig. 5. Design of the acceleration system for GIC. 1 – side wall of vacuum chamber; 2 – RF probe; 3 – RF power input; 4 – Stem; 5 – dummy-dee; 6 – fine trimmer; 7 – tuning capacitor; 8 – dee; 9 – removable shorting jumper; 10 – clamping contact; 11 – base plate; 12 – resonator box; 13 – positioning device; 14 – buffle; 15 – vacuum chamber lid; 16 – side plates; 17 – plates for the primary frequency tuning; 18 – shorting plate

Nowadays the comprehensive tests and setting-up work are in progress. The features of the gas-discharge in the different modes of operation are investigated. The first H^- ion beam with 0.3 mA intensity is generated. There is a good reason to believe that this type of source can be used for an external injection into the isochronous cyclotron. As far as the pulsed mode operation does not correspond to the continuous mode of the cyclotron operation, a version of a surface plasma source with continuous operation is under consideration.

The most successful external H^- source developed in West countries is a volume-plasma or multicusp source. In our laboratory, a test stand of the axial injection system with the multicusp source is built. A specimen of the source with multicusp magnetic field is constructed at the Efremov Institute.

The vacuum part of the stand consists of two cubic chambers connected by a pipe of 2 m length and 80 mm in diameter. Each of chambers has up to five coupling flanges for vacuum pumps, a source and devices for the beam indication. The diffusion pump BA-5-4 with pumping speed of 1200 l/s and the turbo-molecular pump TMH-1000 are used for stand pumping. The power supplies consist of the arc supply

(100 A, 150 V), filament heater supply (300 A), plasma electrode supply (100 A, 5 V), and extractor lens supply (50 kV, 50 mA). All supplies are at 20 kV voltage relative to the ground. At the present, the stand is in operation and the filament form and gas discharge regime optimization are in progress.

To inject H^- ions into the cyclotron, an axial injection channel has been designed. This channel happens to be an universal one for two types of sources. It consists of two magnetic lenses and focusing solenoid. It assumes the spiral deflector to be used to deflect the beam in the median plane.

3.4. Radiation problems and shielding

The problem of the radiation safety is of critical importance for the H^- cyclotron design. At H^- acceleration there are irremovable losses of H^-, which are recharged to H^0, and the resulting neutral hydrogen atoms follow strait trajectories stopping in the vacuum chamber. At the cyclotron designing it is proposed to restrict the beam losses by 5% of the internal beam. The radiation problem can be divided into two: one problem is the induced radioactivity and the second is the biological protection.

A problem of the induced radioactivity was taken into account at designing all components of the cyclotron, in particular all iron and copper have been avoided from median plane and carbon and aluminum have been preferred, the probe flanges are avoided from median plane also. The vacuum chamber is well protected by the neutral beam buffles made of 50×50 mm^2 carbon bars. The buffles are reducing the dose power by 2 times when the chamber is made of Al and by 5 times when it is of stainless steel. The estimations show that at 10% beam loss (10 μA beam loss) the γ dose power is 0.1 rad/hour at 1 hour after "end of beam" at 1 m distance. At the maintenance time, the irradiated buffles have to be taken out of the chamber. The estimations show that the magnet coil insulation provides at least 10 operation years and the rubber vacuum chamber gaskets have to be replaced after one year operation period [15].

The cyclotron is installed in the experimental hall of the operating synchrocyclotron in the unused for experiments part of the hall. The shielding wall for protection against the synchrocyclotron radiation is constructed. The shielding wall provides the sufficient protection if either meson beams are extracted to the main experimental hall or the beam loss of the primary proton beam is less than 1% (10^{10} s^{-1}), that is the standard requirement for the proton beam transportation through the experimental hall. At the first stage, variants of the cyclotron installation in the special hangar with a knock down shielding construction were considered. The variant of the cyclotron installation in the existing experimental hall allows to reduce expenditure on the shielding as far as high effective synchrocyclotron shielding walls are used and an existing infrastructure of the synchrocyclotron (electric power supply, water cooling system, crane on 30 t) also can be used.

The shielding wall dimensions 1.2 m for thickness and 4.6 m for the height [16] have been defined after the model experiment in the experimental hall. As far as the total height of experimental hall is 12.5 m, there is a clearance in 5 m to allow the use of the crane both in the experimental as well as in the cyclotron areas. The constructed shielding wall gives opportunity to work at the cyclotron area when the synchrocyclotron is in operation. The scattering radiation above the wall barrier gives the most important contribution to the summary dose. Additional shielding efforts are foreseen to improve the situation.

4. Status of the cyclotron project

In parallel with the research, the development work of the civil-engineering design has been launched. To the present time the detailed design and the drawing for manufacturing of the main cyclotron components are accomplished including magnet, radio frequency system, vacuum chamber, beam diagnostic probes, axial injection system *etc.* The basic civil works are finished. The cyclotron magnet is installed in the experimental hall of the operating synchrocyclotron. A shielding wall for the protection against radiation of synchrocyclotron beams allowing work in the cyclotron hall is constructed. The installation of cyclotron in a part of existing hall has allowed to use an existing synchrocyclotron infrastructure: a building, electric power supply, water-cooling, crane on 30 t and to reduce to minimum expenditures on the construction of the biological protection. To the present time the rules of accession to the cyclotron hall are established on the basis of the dosimeter measurements in the real situation.

On the basis of the above mentioned investigation the commercially produced magnet SP-72 with a pole of 1.5 m was reconstructed in the cyclotron magnet with a pole diameter of 2 m. As a result of the magnetic circuit optimization it was possible to lower considerably a working current, to reduce the maximal field in the magnet yoke from 31 kGs up to 23 kGs and to lower capacity of the power supply to 120 kW that makes possible to reduce the cyclotron operation expenditures. The new coils of a magnet are made. The magnet is mounted on the specially constructed basement; the electric power supply and water cooling systems are submitted. The updated commercial power supply source IST-1000 was used as a source of a stabilized current. It was possible to build in the IST-1000 the second power supply for the median plane coil on 500 A and 13 V. The personal computer is used to control the magnet current. The pole tips with spiral sectors are manufactured and installed in the gap. 32 harmonic coils are manufactured, and power supplies for each coil on maximal current 20 A and voltage 5−10 V are developed and mounted in one rack.

The upper part of the magnet has to be lifted using the hydraulic lifting system to do modification of the shim profile under the magnetic field measurement and correction. The initial project of a hydro-system was corrected for simplification and reducing expenditures of manufacturing at the expense of using hydraulic jacks available at the laboratory. A new hydraulic station is assembled and a mechanical part of the lifting system is manufactured.

The computer controlled automatic system for the magnetic measurements is developed [17]. The magnetic field is measured by Hall probes, accuracy of the probe adjustment in the measurement point is 0.1 mm, accuracy of measurement – 10^{-4}. The first obtained results allow to conclude that a magnetization curve, a value of the ampere-turns, flutter and spirality coincide with those obtained on models. Now the laborious work on forming the isochronous magnetic field and corrections of the local nonuniformities are necessary.

Manufacturing of major components of an acceleration system is in progress. The master oscillator and preamplifier on 41.2 MHz and 15 kW “Molnija” is in running order, two power amplifiers on 40 kW are assembled. In the present period their adjustment and test are in progress. The developed anode rectifier on 150 kW and 10 kV is in process of manufacturing. A dee manufacturing method suitable for the laboratory conditions has been developed. The working model of all acceleration system including a preamplifier “Molnija”, power amplifiers and dees are supposed to be developed to tune up the components coupling in the high power conditions.

Two test facilities for H^- source are in operation: one test facility is for the surface-plasma source and the other is for the multicusp-source. The test facility for the multicusp-source supposed to be the test bench for the axial injection beam line with the long vacuum tube, pumping system, diagnostic equipment and focusing solenoids.

An assortment of the computer codes has been developed for the beam dynamics and optics calculations in the isochronous cyclotron. The first one is meant for the calculations of the static equilibrium orbits, betatron oscillation frequencies, isochronism and *etc*. [18]. The second code is dedicated for the modeling of the particles acceleration from the central region up to extraction [19], and “ORBITA-1” code is dedicated for the beam optics calculations in the stripper extraction system [20]. The comprehensive computer calculations are in progress for optimization of central optics and axial injection taking into account 3D electric field distribution.

At this stage, we are going to concentrate our efforts on the magnetic measurements and field corrections, the tuning-up and test of acceleration system, test and tuning-up the H^- sources and axial injection system.

5. Conclusions

A design and construction of 80 MeV H^- ion cyclotron with intensity of 100 μA is in progress at Petersburg Nuclear Physics Institute without State financing. The cyclotron is to be used both for medical purposes (radio pharmaceutical production) and for the investigation in nuclear physics, solid state physics *etc*, traditional for PNPI. According to approximate estimations, the cost of radioactive isotopes demands for St. Petersburg medical centres is more than 3 M$ per year. According to newspaper information, Russia buys the medical radioactive isotopes on 50 M$ per year. There is also information on 108 M$ funding the similar isochronous cyclotron project on 72 MeV for Slovakia. For this reason the realization of Gatchina isochronous cyclotron project is of high priority task for PNPI and the North West region of Russia.

To the present time, the detailed design and the drawing for manufacturing the main components are accomplished. The research and development works required for the design and creation of such an unique device are successfully performed. The basic civil works are finished, including the magnet basement, shielding wall, *etc.* The magnet is manufactured and installed in the experimental hall of the operating synchrocyclotron. The magnetic measurements are in progress. The manufacturing of major components of an acceleration system is in progress. The working model of all acceleration systems supposed to be developed. The test facilities for the tune-up of the H^- source and for the axial injection are in operations. To the present time, about 75% of work on the cyclotron creation in the minimal complete set (only accelerator without transport beam line , isotope production targets, isotope separator equipment) is executed.

At the same time, a number of works are stopped now because of absence of financing. First of all it is industry and commercially produced equipment: manufacturing of vacuum chamber, pumping system, H^- source, isotope production target and separators.

In order to finish project and to put new cyclotron into operation, a financing on 1–5 M$ is required depending on equipment complete.

The cyclotron design has been performed by Accelerator Division of PNPI in collaboration with the D.V.Efremov Scientific Research Institute of Electrophysical Apparatus.

At the present time, R&D and engineering work is performed by the staff of Accelerator Division of PNPI. The main coordinators and group leaders are **N.K.Abrossimov, S.A.Artamonov, V.A.Eliseev, A.V.Zubarev, E.M.Ivanov, V.S.Ivanov, Yu.T.Mironov, G.F.Mikheev, A.S.Pokrovskii, G.A.Riabov, V.A.Smolin, I.A.Petrov, B.B.Tokarev.**

References

[1] N.K.Abrossimov *et al.*, “Present Status of 1 GeV Synchrocyclotron in Gatchina”, in *Proceedings of the 7th All-Union Confe-Conference on Charged Particle Accelerators, Dubna, Russia, 14–16 October 1980* (Dubna, 1981), v. **2**, p. 75.

[2] N.K.Abrossimov, S.A.Artamonov, P.V.Bogdanov, V.A.Volchenkov, A.A.Vorobiev, S.P.Dmitriev, V.A.Eliseev, B.D.Ershov, V.S.Kuligin, E.M.Ivanov, Yu.T.Mironov, G.F.Mikheev, V.G.Mudrolyubov, A.S.Pokrovskii, G.A.Riabov, V.A.Smolin, G.L.Sokolov, Yu.I.Stogov, A.P.Strokach, V.P.Fominenko, and P.V.Chervyakov. “Gatchina Isochronous Cyclotron”, in *Proceedings of 13th International Conference on Cyclotrons and Their Applications, Vancouver, Canada, 6–10 July 1992* (World Scientific Publishing Co., Singapore, 1993), p. 58.

[3] N.K.Abrossimov, S.A.Artamonov, P.V.Bogdanov, V.A.Volchenkov, A.A.Vorobiev, S.P.Dmitriev, V.A.Eliseev, B.D.Ershov, V.S.Kuligin, E.M.Ivanov, Yu.T.Mironov, G.F.Mikheev, V.G.Mudrolyubov, A.S.Pokrovskii, G.A.Riabov, V.A.Smolin, G.L.Sokolov, Yu.I.Stogov, A.P.Strokach, V.P.Fominenko, and P.V.Chervyakov. “Gatchina Isochronous Cyclotron of H^- ions”, in *Proceeding of 13th Workshop on Charged Particle Accelerators, Dubna, Russia, 13–15 October 1992* (Dubna, 1993), v. **2**, p. 205.

[4] N.K.Abrossimov, S.P.Dmitriev, V.A.Eliseev, G.F.Mikheev, and G.A.Riabov. ”Feasibility Study of H^0 Injection in LNPI Synchrocyclotron.”, Gatchina, Soviet Union, 6 November 1986, p. 1, unpublished (in Russian).

[5] G.M.Stinson *et al.,* Nucl. Instr. Meth. **74**, 331 (1969); R.T.Lee, TRI-DW-89-32, TRIUMF, Canada, 1995, 12 p.

[6] N.K.Abrossimov, S.A.Artamonov, V.A.Eliseev, and G.A.Riabov. “H^- Ions Losses due to Electro-Magnetic Dissociation and their Effect on the Selection of the Magnetic Structure of the Isochronous Cyclotrons”, in *Proceedings of 15th Workshop on Charged Particle Accelerators, Protvino, Russia, 22–24 October 1996* (Protvino, 1996), v. **2**, p. 244.

[7] N.K.Abrossimov, S.A.Artamonov, V.A.Eliseev, and G.A.Riabov. “The Magnet and Magnetic Structure. Design of the 80 MeV H^- Isochronous Cyclotron. Part 1. Special Feature and Design” , Preprint PNPI-2085, Gatchina, 1995. 25 p.

[8] N.K.Abrossimov, S.A.Artamonov, V.A.Eliseev, and G.A.Riabov. “Design and Optimization of the Magnetand Magnetic Structure for the 80 MeV H^- Isochronous Cyclotron”, in *Proceedings of 2nd International Workshop on Beam Dynamicand Optimi-Optimization, St-Petersburg, Russia, 4–8 July 1995,* p. 7.

[9] N.K.Abrossimov, S.A.Artamonov, V.A.Eliseev, and G.A.Riabov.”Design and Modelling of the Spiral Structure for 80 MeV H^- Cyclotron”, in *Proceedings of 15th International Conference on Cyclotrons and Their Applications, Caen, France, 1998,* p. 518.

[10] N.K.Abrossimov, S.A.Artamonov, V.A.Eliseev, and G.A.Riabov.”The Magnet and Magnetic Structure Design of the 80 MeV H^- Isochronous Cyclotron. Part 2. Model Investigation”, Preprint PNPI-2285, Gatchina, 1998. 32 p.

[11] N.K.Abrossimov, S.A.Artamonov, V.A.Eliseev, and G.A.Riabov. ”Design and Optimization of the Magnet and Magnetic Structure for 80 MeV H^- Isochronous Cyclotron”, in *Proceedings of 6th European Particle Accelerator Conference, Stockholm, Sweden, 22–26 June 1998*, p. 1928.

[12] S.P.Dmitriev, G.F.Mikheev, G.A.Riabov, and V.P.Fominenko."Design of the Acceleration System for 80 MeV H^- Isochronous Cyclotron in Gatchina", in *Proceedings of 14th Workshop on Charged Particle Accelerators, Protvino, Russia, 25-27 October 1994* (Protvino, 1994), v. **3**, p. 112.
[13] Yu.I.Belchenko *et al*., in *Proceedings of the 13th International Conference on High Energy Particle Accelerators, Novosibirsk, Russia, 7−11 August 1986* (Novosibirsk, Publishing House "Nauka", Siberian Division, 1987), v. **2**, p. 276.
[14] V.S.Ivanov, O.I.Kashtanova, G.A.Riabov, V.A.Smolin, and B.B.Tokarev. "The Test Facility for the H^- Ion Surface Plasma Source for Gatchina Isochronous Cyclotron", PNPI Research Report 1996−1997, Gatchina, 1998, p. 360.
[15] Yu.T.Mironov and G.A.Riabov, "Radiation Problem of the Gatchina Isochronous H^- Cyclotron", PNPI Research Report 1992−1993, Gatchina, 1994, p. 245.
[16] N.K.Abrossimov, Yu.T.Mironov, and G.A.Riabov. "Shielding of the Gatchina Isochronous H^- Cyclotron", PNPI Research Report 1992−1993, Gatchina, 1994, p. 242.
[17] V.A.Eliseev, J.A.Kassman, I.A.Krasnoschokova, V.V.Marchenkov, G.A.Riabov, and V.N.Slyusur. "The Field Mapping System for the Isochronous Cyclotron at Gatchina", PNPI Research Report 1994−1995, Gatchina, 1996, p. 278.
[18] S.A.Artamonov and S.Yu.Kuznetsov. "Optimization of the Isochronous Magnetic Field in Accelerators with Azimuthal Variation", in *Proceedings of 2nd International Workshop on Beam Dynamic and Optimization, St. Petersburg, Russia, 4–8 July 1995,* p. 53.
[19] S.A.Artamonov and S.Yu.Kuznetsov. "The Modern Program of Particle Dynamics Simulation in Accelerators with Azymuthally Varying Magnetic Field", in *Proceedings of 2nd International Workshop on Beam Dynamic and Optimization, St-Petersburg, Russia, 4–8 July 1995,* p. 46.
[20] G.A.Riabov and V.A.Volchenkov. "Calculation of Beam Optics in Magnetic Field of Isochronous Cyclotron", PNPI Research Report 1996−1997, Gatchina, 1998, p. 365.