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TRICYC.
TRItron-Based Analog of CYClone
(Proposal)

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TRICYC. Аналог CYClone на базе TRItron
(Предложение)

Предлагается разработка ускорительного комплекса TRICYC для производства медицинских изотопов и для других прикладных целей. Основной установкой комплекса является ускоритель типа TRITRON, обладающий рядом достоинств, позволяющих ему конкурировать с работающими в настоящее время циклотронами аналогичного назначения.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

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We propose an accelerator complex TRICYC for production of medical isotopes and for other applied purposes. The basic facility of the complex is a TRITRON type accelerator, which has advantages that make him competitive with currently operating cyclotrons designed for similar purposes.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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Introduction

In this paper we propose an accelerator complex TRICYC for production of medical isotopes and for other applied purposes. The basic facility of the complex is a TRITRON type accelerator [1], which, in our opinion, has advantage that makes him competitive with currently operating cyclotrons designed for similar purposes, e.g. Cyclone-30 (Belgium) [2] and TR-30 (Canada) [3].

Layout of the complex

In Fig. 1 there is a general view of the basic TRITRON type accelerator, which is described, for example, in ref. [1]. It is a separated orbit cyclotron. The beam bending is done by means of superconducting "window frame" type magnets and focusing by means of alternative gradients of the magnetic field of magnets along the spiral path of particles. The magnets are united into 12 flat sectors; between them there are superconducting cavities or probes to measure the position of the beam.

It is proposed to use a superconducting linear accelerator with spatially uniform RF focusing (RFQ linac) as an injector for the basic accelerator. A facility of this type is believed to be the proper one for providing the necessary level of injected beam intensity and energy at minimum operation costs. To guide the RFQ linac beam from the injector to the main accelerator, one can use a conventional particle transport line consisting of bending magnets and magnetic focusing elements.

Reasons for choosing parameters

The requirement is to develop a proton accelerator of maximum energy about 35 MeV and total extraction current not less than 0.5 mA at 100% efficiency of beam extraction. The energy consumption of the facility must be less than that of cyclotrons in operation - CYCLONE-30 and TR-30.

The TRICYC parameters were chosen on the basis of the experimental and calculated characteristics of the accelerator TRITRON [1], [4],[5], which is planned to be in operation in 1994. That is why the TRITRON data are used in table 1 and in the calculation. Estimating new parameters, we tried to keep them as close to TRITRON ones as possible. The best credibility and reliability of the results achieved was ensured by making the most of the experience gained in construction of TRITRON.

The following requirements were taken into consideration in studying various aspects of the accelerator: reliability of the structure, high assurance of achieving the design parameters, a possibility of being controlled by the minimum of medium-skilled personnel, highly computerised monitoring of the accelerator operation, the smallest possible costs and the shortest possible construction time.

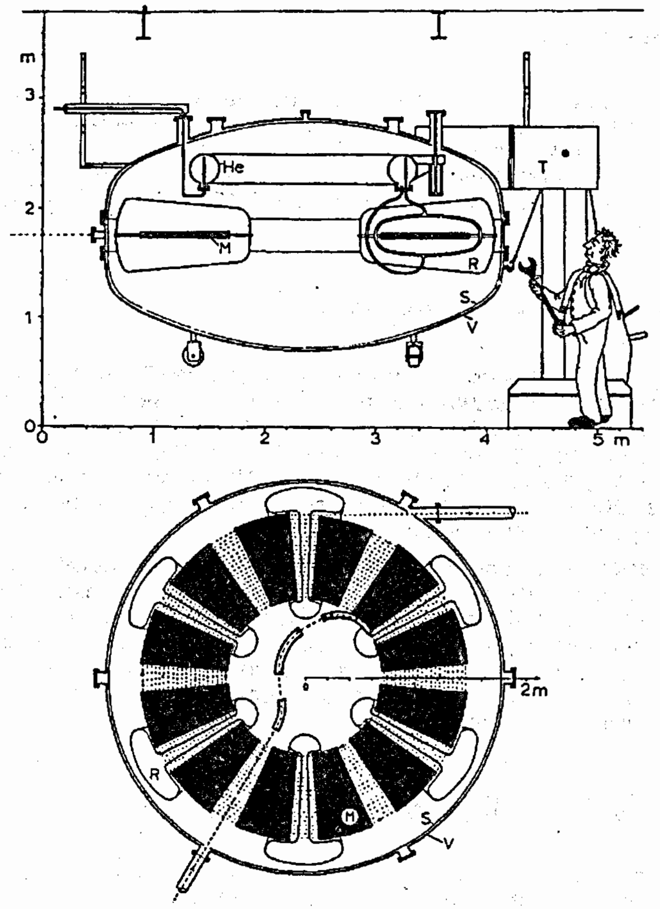

Fig. 1. General view of the basic accelerator. M: sector magnet; R: RF cavity; V: vacuum chamber; S: 80K shield against beam; HE: helium vessel; T: supporting column.

Beam intensity

The difference between the TRICYC and TRITRON parameters arose from a significant increase in the accelerated beam intensity from 1.4 to 1000 μA. The possibility of having larger intensities (up to 10 mA) and accelerated proton energies (up to 500 MeV) was indicated with the relevant calculations in ref. [1].

A higher intensity of TRICYC as compared with TRITRON requires a higher power of the RF system. Since the maximum beam power will not exceed ~50 kW, the power of each of 6 RF generators must be about 15 kW instead of 0.3 kW at TRITRON [6].

Beam aperture

According to [1], total beam losses must not exceed 10 W or 10^{-4} in relative units to avoid the shift of superconducting elements to the normal state and a too high level of induced radioactivity. In this connection it is necessary to increase the aperture of magnetic channels. For the given level of particle losses the geometric aperture must be as large as at least 4 root-mean-square dimensions of the beam, the particle density distribution in the beam being supposed to obey the normal law. Assuming that TRICYC allows transverse focusing of particles as in TRITRON (the same frequencies of free oscillation, see table 1) and that the normalised emittance of the beam extracted from the RFQ linac is equal to the emittance in TRITRON, we obtain the magnetic channel aperture not less than 20 mm. It is taken into account that the zone of finite radii is most critical one from the point of view of dissipated beam power. It should be mentioned for comparison that the beam aperture in the magnetic channels of TRITRON is 11 mm.

Assuming also that the radial dimension of the current layer is 3 mm and the protective copper shield is 2 mm thick, as it is in TRITRON, we obtain the spacing between orbits about 55-60 mm. In this case we assume that the magnetic induction in the return part of the magnetic channel core must be below the saturation level of the steel used for it.

Using the design and dimensions of RF cavities from TRITRON, we find that the number of turns in the accelerator for the interorbit spacing obtained must be about 14 instead of 20 as in TRITRON. Correspondingly, the energy gain per turn and the maximum amplitude of the RF voltage will increase while its distribution along the radius remains the same (the cavity design is the same as in TRITRON).

TABLE 1. Comparison of CYCLONE-30, TR-30 and TRICYC parameters

PARAMETERS	CYCLONE-30	TR-30	TRICYC
BEAM			
particles accelerated	H - ions	H - ions	protons
extracted beam energy (MeV)	15÷30	15-30	14.6-42.2
max. intensity (μA)	500	300	1000
max. power in beam (kW)	7.5÷15	4.5÷9	42
revolution frequency (MHz)	16.375	18.25	5.666÷9.444
radial oscillation frequency Qr	1.04÷1.06	-	1.5 ÷1.7
axial oscillation frequency Qz	0.54÷0.63	-	1.1 ÷ 1.7
longit. oscil. frequency Qs	0	0	~0.3
number of turns	176	-	14
particle loss at accelerator (%)	2	5	0.01

INJECTION			
source	multicusp	multicusp	RFQ-linac
injected beam energy (MeV)	0.028	0.025	3.1÷ 8.7
injection current (mA)	2	7	1
emittance (norm.) (π.mm.mrad)	0.84	0.34	9
1st turn radius (cm)	3	-	64
heat load on cryosystem (W)	-	-	40
total el. power demand (kW)	5.5	3.7	71
BEAM EXTRACTION			
technique	stripping	stripping	acceleration
extraction radius (cm)	70	65	142
orbit separation (mm)	-	-	60
extraction efficiency (%)	~ 100	~ 100	100
MAGNET STRUCTURE			
beam aperture (mm)	-	-	20
field in "hill" (T)	1.7	1.9	0.6 ÷1.0
field in "valley" (T)	0.12	0.55	$0.5 \cdot 10^{-4}$
number of sectors	4	4	12
sector angle (°)	54÷58	38	20
gap between poles (cm)	3	4	3.1
sector shim height (cm)	40	5	6
pole diameter (cm)	148	152	296
mass of iron (t)	45	46	2.16
ampere-turns per pole (MA-t.)	-	0.0375	0.218
coil current (A)	-	-	1400
inductance (H)	-	-	0.238
current density (A/mm^2)	-	-	600
power in current coils (kW)	7.2	-	0.012
total heat inleakage due to contacts between coil sections (W)	-	-	12
RF SYSTEM			
number of dees (cavities)	2	2	6
voltage at a dee (kV)	50	50	300÷750
energy gain per revolution (MeV)	0.17	-	2 ÷ 3
harmonic number	4	4	30÷18
frequency (MHz)	65.5	73	170
dissip. RF power (kW)	30	28	-
beam power (kW)	-	-	42
heat load on cryosystem (W)	-	-	54
weight of all dees (cavit.) (t)	-	-	3
CYCLOTRON DIMENSIONS			
diameter (cm)	268	230	360
height (cm)	157	126	210
total weight (t)	45	46	10
POWER DEMAND			
at maximum beam power (kW)	< 90	-	180
efficiency of complex (%)	17	-	23

Longitudinal motion of particles

Further estimation of the TRICYC parameters was based on the requirements of longitudinal motion in this accelerator. In so doing, the theory outlined in ref. [5] was used.

To optimise the installation parameters for having the given range of the final beam energy, we employed the ratio "h" of the particle revolution frequency to the RF frequency. For each value of "h" it was necessary to ensure longitudinal stability, i.e. to keep the equilibrium phase "φ" values for a central particle (a particle that follows a spiral path with zero amplitudes of free radial oscillation [5]) within the range $0 < \varphi < \pi/2$ during the whole process of acceleration. In Fig. 2b there is "φ" as a function of the radius for the acceleration mode chosen. Particle phases are seen to be in the range between 45 and 70 degrees during acceleration. In this case the maximum RF amplitude was as high as 750 kV instead of 500 kV as in TRITRON. Yet, this value of the amplitude is still within the range of experimental values obtained for TRITRON cavities [1]. Other parameters obtained in calculation of the longitudinal beam motion are given in table 1.

The extracted beam energy may stepwise vary within the range given in table 1 owing to higher RF harmonic mode of acceleration with the corresponding decrease in the amplitude of the accelerating voltage. The indicated particle energy range is larger than in prototype accelerators CYCLONE-30 and TR-30. Besides, owing to a strong longitudinal focusing of particles the harmonic number can be sufficiently large, which ensures a small step in varying the final energy. Since the basic accelerator allows approximately a 5-fold increase in the energy injected, one must ensure the corresponding change in the output energy of the injector when varying the final energy of the complex.

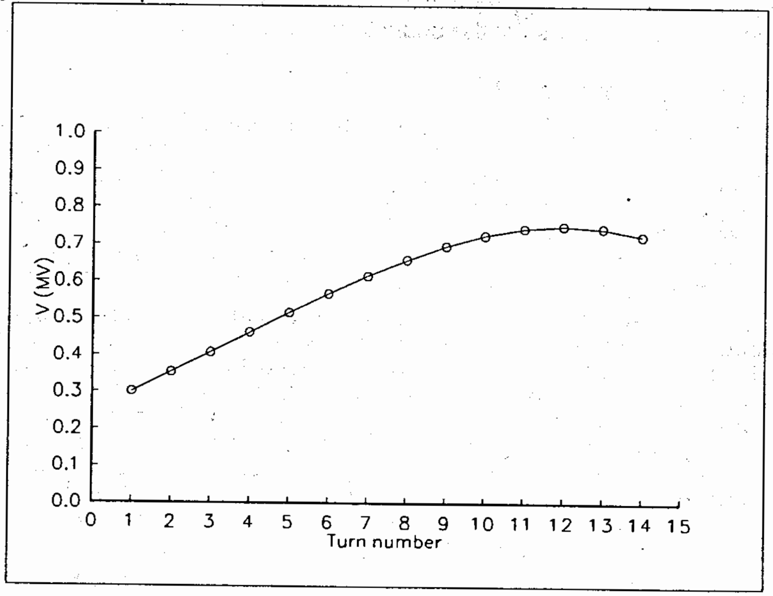

Fig. 2a. RF voltage amplitude as a function of turns.

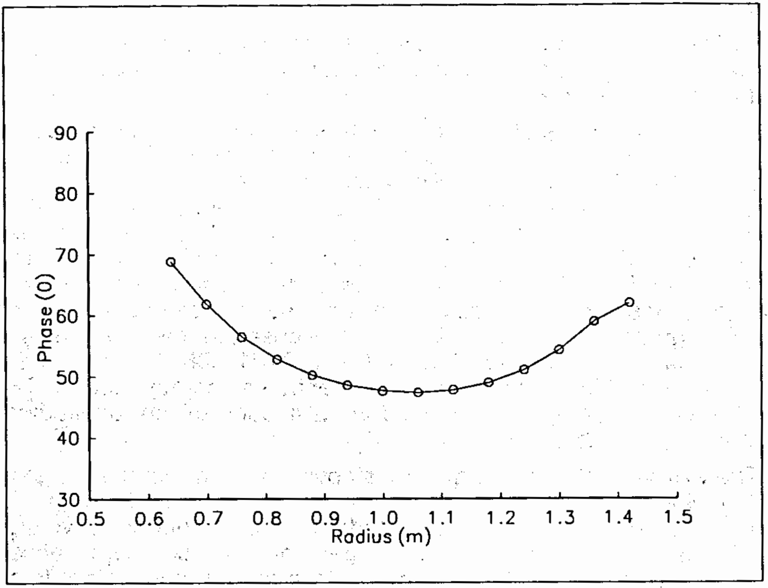

Fig. 2b. Central particle phase as a function of the radius.

At the given harmonic number the smooth variation of energy between energy levels is effected by controllable longitudinal coherent oscillations of particles. To use this energy variation technique one must choose the different initial energy and RF phase of the beam to be injected.

Power consumption

As mentioned above, a key problem to be solved in designing the complex is to minimise its power demand involving the power transferred from the RF system to the beam and the power of a cryogenic system, which is necessary because of heat load produced by the superconducting magnet, RF system and RFQ injector when the complex is in operation. The transitional process of cooling the accelerator systems from room temperature to helium temperature with the corresponding power consumption is not considered here.

We have all the necessary data to estimate the power consumption of an accelerator in operation. The maximum power in the beam is known (see table 1). The necessary maximum RF amplitude has been discussed above. The experimental data on TRITRON cavities (Fig. 8 in ref. [1]) yield the heat load per cavity below 9 W, which is larger than heat dissipation in TRITRON (6 W) owing to a higher amplitude of the accelerating voltage in TRICYC. Of course, the amplitude and the dissipated power per cavity could be reduced by increasing the number of cavities. However, the gain in efficiency will not be large enough to justify hindering the access to systems by installing cavities in previously vacant gaps between magnet ridges.

It was also pointed out in ref. [1] that total heat released in"warm" jumpers between neighbouring SC coils (the main source of power dissipation in the magnet system) does not exceed 1 W per each of 12 magnetic sectors at the coil current 1800 A. As to the RFQ injector, the total heat load on the cryogenic system from this machine is expected to be below 40 W. Using the known empirical relation describing the necessary power consumption per 1 W of heat load in a 1 kW cryosystem, we obtain estimates of power consumption for the complex in operation. The main results of this estimation are shown in table 1. Most of the power consumption is seen to be connected with power dissipation in RF cavities.

Transverse motion of particles

Using the earlier obtained parameters, one can make a quasiperiodical focusing structure of accelerator turns whose main function, besides forming a spiral path of the central particle, is to ensure the necessary transverse focusing of a beam with free oscillation frequencies close to the ones in TRITRON. Fig. 3 shows the calculation results for frequencies and envelopes (beta-functions) of the beam in the above-mentioned structure. The results were obtained by means of the known programme MAD [7]. Comparison with the data of ref. [8] shows that the task we set is fulfilled. Thus, the above estimations, which concern the aperture required for guiding a beam of the given emittance with tolerable losses and involve the values of free oscillation frequencies in TRITRON, are well substantiated.

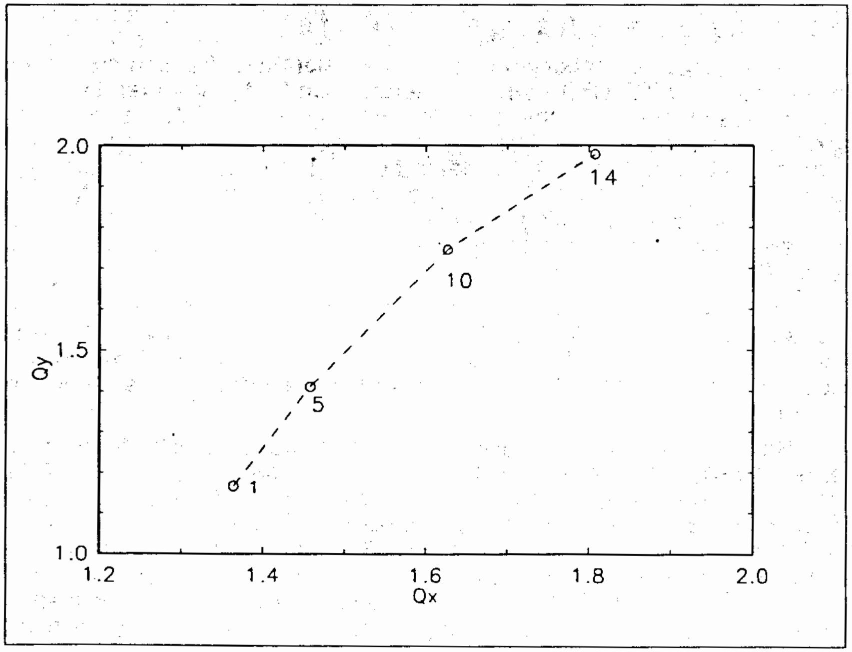

Fig.3a. Free oscillation frequencies of particles.

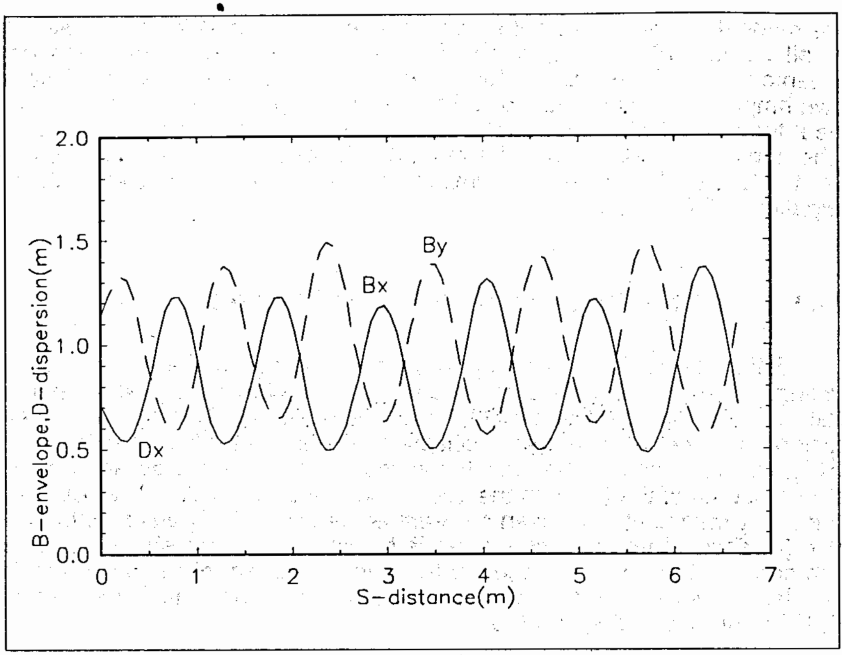

Fig.3b. Beta-functions and dispersion of the 1-st turn.

Beam space charge effects

The analysis of stability problems in acceleration of a high-current (about 10 mA) beam in a TRITRON type accelerator can be found in ref. [1]. Our task is much easier because the particle intensity in TRICYC is an order of magnitude lower. As is known, in acceleration of charged particles electromagnetic self-fields of the beam occur. They consist of beam fields in free space and fields of induced sources in the environment around the beam (e.g. walls of the accelerating chamber). These fields act on the accelerated beam, and their action is not always favourable as far as the particle stability is concerned.

As shown in [1], there is no problem of resistive transverse instability of the beam in a TRITRON type accelerator even for the intensity of 10 mA owing to high conductivity of the accelerating copper chamber and extremely short acceleration time (about 14turns multiplied by a period of revolution equal to1.5μc)

Shifts of transverse oscillation frequencies arise mainly from the beam charge field without allowance for the walls. Estimations based on ref. [9] show that even at the injection energy of 3 MeV the shift of transverse oscillation frequencies does not exceed 0.02 for the beam current of 1 mA. In this case the rms dimensions of the beam increase only by 0.07 mm. Thus, no noticeable effect on the particle dynamics is expected. Besides, as pointed out above, the motion of particles in TRICYC is only slightly sensitive to resonances of transverse oscillations, and even larger frequency shifts are not a matter of concern.

A high amplitude of the accelerating voltage in TRICYC is responsible for an unusually high frequency of longitudinal oscillations of particles. As a result, shifts of longitudinal oscillation frequencies caused by the space charge produce little effect on the phase stability of the beam.

Injector

As follows from the aforesaid, a superconducting linear accelerator is proposed to be an injector in order to reduce the power consumption. At present there is no suitable machine in operation. The best progress was achieved in development of superconducting linacs with electrostatic accelerators as boosters [10]. A 9-MeV machine of this type is about 3 m long and consumes about 40 W at the helium temperature. The cost of an accelerator like this is about US$1,000,000. However, these machines require beam injection at the particle to light velocity ratio β equal to about 0.05÷0.06. The preinjector could be an RFQ type (warm) linear accelerator. One of these machines is described in ref. [11]. It is a high-current (up to 2 mA) accelerator of energy 0.138 MeV (β=0.02), 138 cm long, with power consumption (from the mains) 22 kW.

One must conform the parameters of the injector with the separated orbit cyclotron in the normalised emittance, intensity, energy range and time structure.

Analysis of parameters

The basic parameters of the accelerator, obtained on the basis of the above estimations, are listed in table 1. The characteristics of the prototype cyclotrons in operation are also given for comparison. It is seen from table 1 that dimensions of TRICYC are about 1.5 times larger than those of the prototype accelerators.

The level of the magnetic field is such that the "warm" version of the system is possible. Yet, the maximum permissible current density in magnet coils at the given orbit separation is limited in this case. That is why superconducting magnets must be used.

The RF system and the RFQ injector are also made superconducting to provide increased energy gain for particles.

In connection with the aforesaid power is saved during the operation of the complex: the efficiency of the machine with 2 times higher extracted beam intensity and a slightly higher particle energy is somewhat higher than that of the prototype cyclotrons.

Naturally, there is no problem in achieving a 100% efficiency for injection and extraction of a high-current beam since the machine is based on the principle of separated orbit acceleration. Thus, one doesn't need to accelerate H- ions that are less handy for injection than protons and which are subject to electric dissociation in the magnetic field and to disintegration in the residual gas in the course of acceleration.

Besides, all advantages of TRITRON over a cyclotron are realised here [5]:

- strong transverse focusing;

- particle stability unaffected by resonance crossing as it occurs very fast, without distortion of the beam quality;

- strong longitudinal focusing of the beam and absence of typical negative cyclotron features, such as growing particle energy spread, increase in the effective phase volume, etc.

The expected beam intensity can be 2 or more times higher than in the prototype accelerators owing to stronger transverse and longitudinal focusing of particles.

Like TRITRON, this machine is in principle capable of accelerating not only protons but also other particles in a large range of charge-to-mass ratios (Q/A). For example, deuterons and other particles with Q/A = 0.5 can be accelerated.

The TRITRON principle allows significant advantages: compared with the prototypes, the weight of the magnet decreases by a factor of about 20;and the total weight of the machine, by a factor of about 4; the accelerator consists of identical modules relatively small in size.

An especially interesting feature of this accelerator is its potential capability of increasing the proton energy to 70 MeV within its proposed dimensions owing to an increase in the RF amplitude. This possibility was indicated in ref. [1]. As is known, in the Canadian project they considered a possibility of increasing energy to the limit mentioned in order to use the machine for production of isotopes through some nuclear reactions and for therapeutic irradiation of ocular melanoma [12]. According to tentative estimations, the size of the magnet in this case would be 4 m, the diameter of a pole 2.8 m, the weight 125 t. A similar machine was considered in ref. [13]. The TRITRON type accelerator is seen to surpass the above-mentioned machines in the parameters.

Feasibility of the machine

As mentioned earlier, substantiation of the TRICYC parameters was largely based on the experience of developing the accelerator TRITRON, which is now at the start-up stage and for basic systems of which the design parameters have been really attained. In this sense feasibility of TRICYC is beyond any doubt. Nevertheless, one should indicate some difficulties that may arise in implementation of this proposal.

The construction costs of the complex seem to be larger than for cyclotrons operating in Belgium and Canada because the structure of the machine is more complicated and the type of accelerator considered is non-traditional and novel.

There could be difficulties during the operation of the complex: superconducting coils and cavities imply continuous and long-time (2-3 months) operation under operator's control. The regular operation of prototype accelerators does not require the presence of personnel.

Conclusions

The accelerator design proposed has the following advantages over the existing ones:

- the intensity of the extracted beam is twice as high; with its proper distribution it is equivalent to operation with two beams;

- operation both with protons and deuterons is possible;

- power input per beam power unity is slightly lower;

- 100% beam extraction is inherent in the accelerator design as it is based on separated orbits. There is no charge exchange target, which is indispensable in H- and D- ion accelerators;

- the weight of the complex is lower;

- energy can be increased to 70 MeV by increasing the amplitude of the accelerating voltage;

A current disadvantage of the accelerator can be high technology required, which results in more numerous personnel at the initial stage of its operation: the accelerator is intended for use in industrially developed countries.

Acknowledgements

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