RING CYCLOTRON FOR THE PROTON THERAPY

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Abstract

The ring sector cyclotron is one of possible basic accelerators to be used in the centers for proton therapy. In our report we present the main parameters of an RC-18/210 ring cyclotron, which uses a CC-18/9 cyclotron as an injector. A layout of the equipment of the center is suggested including separate shielded rooms equipped with gantries for the cancer treatment.

INTRODUCTION

Nowadays great interest is expressed in the use of high-energy beams of accelerated protons for the cancer treatment. The advantage of the accelerated beams of protons in comparison with photon or electron beams are an increased ionization loss at the end of the ion's track (the Bragg peak) and sharp reduce of the radiation in the transverse cross-cut. These specific features of the proton beams allow the effect of irradiation to be many times concentrated on a malignant tumour with a minimum influence on surrounding tissues.

In our report we have considered a possibility of using a ring sector cyclotron for the beam therapy. This machine is distinguished with acceleration of high beam currents, which widens possibilities of its using in nuclear medicine.

REASONS FOR CHOICE OF THE ACCELERATOR TYPE

The medical and technical requirements for the proton beams to be used for the beam therapy are sufficiently precisely specified; these are as follows:

- The proton beam energy is to be varied in the 70-230 MeV range. The beam energy determines the depth of the Bragg peak maximum. The energy spread in the beam is set in accordance with the size of the tumour along the beam axis in terms of FWHM (full width half amplitude); it can be several percent. The aforementioned energy of accelerated protons can be obtained only on large-scale accelerators of high cost.
- The beam current is to be 10^{11}-10^{12} particles/sec. In this case the radiation treatment lasts for several minutes.
- The accelerator should be equipped with a system for the beam transport to several separated shielded rooms fitted out with a gantry.
- The size of the output beam should be varied from narrow, of diameter 4-10 mm, up to wide, 30×30 cm^2 in size. The beam should have sharp reduce of the radiation in the transverse direction.

Table 1 presents the advantages and drawbacks of different types of accelerators, which can produce the beams with parameters required for the proton therapy.

The suggested ring cyclotron is distinguished with a possibility of accelerating high beam currents. Being the basic accelerator of the proton therapy center, this machine will satisfy not only the needs of the proton therapy but it will also provide the production of a wide spectrum of radioactive isotopes and generation of intensive flows of neutrons for various purposes, the neutron therapy included.

Table 1: Accelerators used for the proton therapy

Type of accelerator	Advantages	Drawbacks	Notes
Synchro-cyclotron (phasotron)	Acceleration of ions from zero energy to the maximum	Limited beam current. Fixed energy	In some centers old operating phasotrons are used
Proton synchrotron	Variable energy	Need for injector. Limited beam current.	In some centers new synchrotrons are used
Isochronous cyclotron	Acceleration of ions from zero energy to the maximum	Fixed energy	The IBA cyclotron Cyclone-235 is commercially available
Linear accelerator	Possibility of accelerating high beam currents	Fixed energy	High cost compared with other types of accelerators
Ring cyclotron	Possibility of accelerating high beam currents	Need for injector	Ring cyclotrons are used in South African Republic, Japan and Switzerland.

Note: isochronous cyclotrons allow the beam energy to be varied; however in this case their cost will increase significantly.

The ion-optical beam properties of all the accelerators given in Table 1 are practically similar; therefore the beam transport system (the gantry included) does not depend on the chosen type of the machine and can be delivered separately from the accelerator. In the D.V. Efremov Institute (NIIEFA) much work on calculating and manufacturing the equipment for beam transport channels is carried out; and in this connection the aforementioned circumstance is very important for us. This equipment includes the following: a lens quadrupole, bending and analyzing magnets, beam position and beam profile probes, Faraday cups, targets of various types and vacuum equipment. The cost of the beam transport system can be up to 25-30% of the total cost of the processing equipment of the system.

THE RC-18/210 RING CYCLOTRON

We consider the ring cyclotron with a fixed energy of protons, which allows sector magnets with a minimum gap (approximately 1.5 cm) to be used. The isochronous magnetic field is formed by varying the vertical gap and the angular width of the sector magnets. Trimming coils are not used for this purpose. The RF system of the cyclotron comprises two resonators with high Q-factor. Operating frequency has only one fixed meaning. This is the most economic version of the accelerator from the viewpoint of expenditures for its construction and operation. In principle, a ring cyclotron provides a possibility of energy variation. However, this will require the variation of the accelerating voltage frequency and the radial dependence of the average magnetic field at different levels of the magnet excitation, which will make the machine more sophisticated and expensive.

High intensity of the beam produced at the ring cyclotron allows the energy to be varied owing to its partial absorption by calibrated foils at the output of the accelerator [1, 2]. The analyzing magnet installed behind the foil serves to select a part of the beam, which meets the energy and energy spread requirements for therapy. Simultaneously the analyzing magnet filters protons from the accompanying gamma and neutron background.

A cyclotron CC-18/9 is used as an injector for the ring cyclotron. If the proton therapy center is equipped with a home-made system for radioisotope diagnostics [3], the aforementioned cyclotron-injector will be the second CC-18/9 machine in this center. Two available similar cyclotrons will increase significantly the reliability of works on production of isotopes for diagnostics and the reliability of the cancer treatment.

At the orbit of the ring cyclotron the average magnetic field is equal to the half of the average magnetic field of the cyclotron-injector. In this case at equal operating frequencies of the RF systems of the cyclotrons, the acceleration in the ring cyclotron occurs at the 4^{th} harmonic mode. In the cyclotron-injector the acceleration occurs at the 2^{nd} harmonic.

A schematic of the ring cyclotron is shown in Figure 1. Mass, size and energy consumption of the ring cyclotron will decrease due to chosen sufficiently high energy of the injected protons and refusal from final energy variation. The total mass of the ring cyclotron is about 500 t, and the electric power consumption will not exceed 400 kW.

In Table 2 and, Table 3 are given the design parameters of the main units of the cyclotron CC-18/9 and the ring cyclotron RC-18/210 with an energy of 210 MeV and a beam current of up to 50 μA.

The beam extraction system consists of an electrostatic deflector, a septum-magnet and a bending magnet. The extraction efficiency is more than 95-99%.

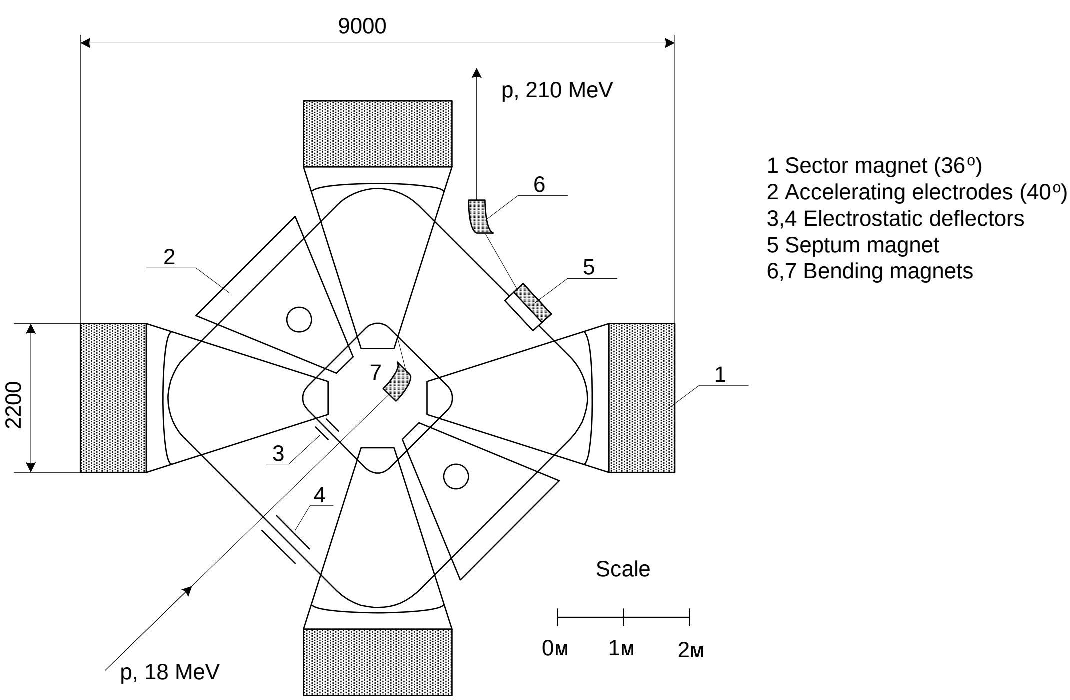

Figure 1: The RC-18/210 ring cyclotron

Table 2: The CC-18/9 cyclotron-injector parameters

Proton beam energy, MeV	18
Beam current, μA	0…100
Magnetic field induction (in the center), T	1.25
Accelerating voltage frequency, MHz	38.2
Accelerating voltage harmonic mode	2
Final radius of acceleration, cm	50
Extraction efficiency (foil stripping), %	~100
Energy spread, FWHM, %	1.0

Table 3: The RC-18/210 ring cyclotron parameters

Proton beam energy, MeV	210
Beam current, μA	50
Sector magnets	
- Number of magnets	4
- Magnet anglular width, degrees	36
- Maximum induction, T	1.9
- Average induction at Rk, T	0.76
- Gap (min), cm	1.5
- Mass (120 × 4), T	480
- Power consumption (20 × 40), kW	80
RadioFrequency System	
- Number of cavities	2
- Cavity angle, degrees	40
- Accelerating voltage, kV	150
- Operating frequency, MHz	38.2
- Harmonic mode	4
- Power consumption (60 × 2), kW	120
Orbit parameters	
- Injection radius, cm	
of sector magnet	105
between magnets	87.5
- Extraction radius, cm	
of sector magnet	325
between magnets	265
- Focusing frequency	
vertical	1.3-1.08
radial	1.02-1.21
- Orbit separation, cm	
under injection	1.65
under extraction	0.16

BEAM THERAPY CENTER

Figure 2 shows a supposed layout for the equipment of the beam therapy center. All the equipment of the 210 MeV ring cyclotron, including the beamlines for the beam transport to four separated shielded rooms, 2-m thick concrete walls and labyrinths, is located in the building with a total area of 2500 m^2 approximately.

The cyclotron-injector is housed in a separate cyclotron hall-1. When the cyclotron-injector is not used for the radiation treatment it can be used for production of ultra short-lived and short-lived radionuclides. The set of these radionuclides includes practically all radioisotopes used for diagnostics and the contact beam therapy.

Cyclotron hall -2 houses the RC-18/210 cyclotron, a special device to vary the beam energy (by means of its absorption with foils), analyzing and bending magnets, lens quadrupoles, beam probes and vacuum equipment (not shown on the scheme). The energy absorber allows the beam energy to be reduced and the necessary energy spread to be set [2, 4]. For this purpose rotating foils of variable thickness are used. Then a beam of low intensity (0.1 μA) with specified characteristics is directed to one of the shielded rooms (3, 5 or 6) equipped with the gantry to carry out radiation treatment. It is reasonable to make a separated passage from these shielded rooms to the medical department where patients are prepared for the treatment.

Room 4 is intended for the treatment with a beam of high intensity (up to 20-40 μA) and with an energy of 210 MeV (the beam power is more than 8 kW). In this room the works can be carried out on generation of intensive neutron flows for research, the neutron therapy and for production of a wide set of rare or long-lived radionuclides (for example, positron generator Sr-82/Rb-82 m, as well as Se-73, Fe-52, At-211, Ac-225, etc.).

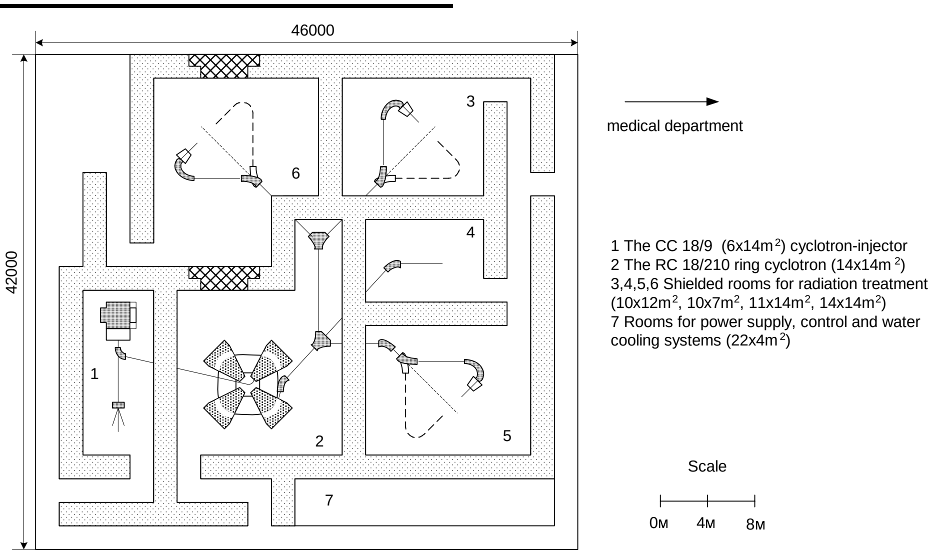

Figure 2: The system for proton therapy. Layout of the equipment.

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