CENTERS OF HADRON THERAPY ON THE BASIS OF CYCLOTRONS

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Abstract

Hadron therapy hospital centers have become wide spread in the world during the last decade. These centers were created mainly on basis of the cycling accelerators such as cyclotrons and synchrotrons. Now there are several proposals of the proton centers on the basis of linear accelerators. In this report we discuss features, advantages and disadvantages of hadron therapy centers on the basis of cyclotron equipment. Both proton and carbon therapy techniques are considered in this report.

It is proposed to construct a cyclotron-based proton therapy center in Dubna. The medical cyclotron for this center is to be constructed by JINR-IBA collaboration this year. The cyclotron beam test experiments are plan for 2009. After that the medical cyclotron could be used for the Dubna hospital center and contribute to promoting the proton therapy in the future Russian centers.

INTRODUCTION

There are about 2.3 million of tumor patients in Russia and 450 thousand of new patients appeared every year. The hadron therapy can be considerably effective for treating 50 thousand cancer patients per year in Russia. The existing Russian research centers of proton therapy provide cancer treatment only for 1 % of patients to whom this treatment is recommended.

Dubna is one of the leading proton therapy research centers of the in Russia. The modern technique of 3D conformal proton radiotherapy was first effectuated in Russia in this center, and now it is effectively used in regular treatment sessions. A special Medico-Technical Complex was created at JINR on the basis of the synchrocyclotron (phasotron) used for proton treatment. About 100 patients undergo a course of fractionated treatment here every year.

At present JINR in cooperation with Belgium firm IBA develops a dedicated medical cyclotron applied for the proton therapy. It is planned to complete its construction this year and to carry out beam tests in 2009. After that the accelerator could be installed in the Dubna hospital centre of proton therapy. The project of the Dubna center involves 3 treatment rooms with one gantry system. The design treatment capability of the center is 1000 patients per year.

The JINR-IBA collaboration designed the C 400 superconducting cyclotron for the carbon therapy and IBA starts its construction. This first medical carbon cyclotron will be installed within the framework of the Archade project in Caen (France).

JINR MEDICO-TECHNICAL COMPLEX

The pioneering proton therapy researches began at JINR in 1967 [1]. The JINR Medico-Technical Complex (MTC) consists of 7 rooms, where proton, pion and neutron beams are used [1]. The research synchrocyclotron (Fig.1) with the proton energy of 660 MeV and current of 3 μA is used for medical applications. About 580 patients were treated at the JINR MTC by the proton beams. During the last years around 100 patients per year got the proton treatment there. The methodic of 3 D conformal proton radiotherapy was effectuated there, when the irradiated dose distribution coincidents with the tumor target shape with an accuracy of 1 mm [1]. This required solving the following tasks: formation and monitoring of proton beams with required parameters; development of the computer codes and a technique, for construction of individual collimators and boluses; development of a system for immobilization of the patient and verification of its position relative to the proton beam. The equipment used for 3D conformal therapy in room 1 is presented in Fig.2.

Fig. 1 JINR synchrocyclotron applied for proton therapy.

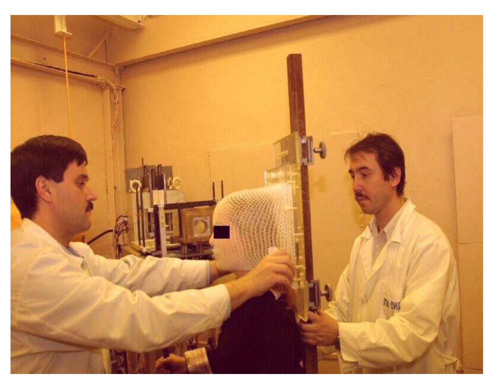


Fig.2 Room 1 of the JINR Medico-Technical Complex used for 3 D conformal proton therapy.

Unique x-ray and proton tomographs were constructed for on-line diagnostics and verification of the patient's position relative to the proton beam.

A special radiological department of the Dubna hospital was established to provide proton treatment on the basis of the JINR synchrocyclotron. The number of patients treated in this department per year is restricted by nonspecialized proton synchrocyclotron. To reach the proton treatment of 1000 patients per year, the project of the Dubna hospital center of the proton therapy on the basis of a specialized medical cyclotron was proposed.

PROTON MEDICAL BEAMS

Protons have excellent physical properties for radiation therapy which permit one to control very precisely the shape of the dose distribution inside the patient's body. The dose delivered by a proton beam is well localized in space, not only in the lateral direction, but also very precisely in depth, due to the presence of the characteristic Bragg peak. The energy of the proton beam can be so chosen such that protons penetrate to the correct depth for each tumor. By adding the Bragg peak of successively lower energies and intensities, a spread-out Bragg peak (SOBP) can be generated which has uniform dose distribution over the entire depth of the tumour (so-called passive spreading technique or technique of double scattering). Parameters of medical proton beams are given in Table 1.

Table 1. Parameters of proton medical beams

Parameter	Value
Maximal energy, MeV	230-250
Depth of penetration, mm	30
Beam intensity in cancer treatment, p/s	$5\cdot10^9$
Dose rate, Gy/l/min	2
Irradiation dose, Gy/fraction	2
Number of fractions	20-30
Treatment time, min	2
Homogeneity of irradiation dose, %	±2,5
Maximal treatment volume in passive scanning, l	7,5
Maximal treatment volume in active scanning, l	2
Spot size of pencil beam, mm	3
Maximal scanning size on tumor, cm	20·20

The passive double scattering technique permits to realize 3D conformal proton radiotherapy which provides good coincidence of the dose distribution with tumor volume. The beam utilization efficiency is about 40% at the passive double scattering treatment.

Ideally, one would like to deposit the dose only inside the target volume. To reduce the dose burden outside the target volume and give more dose to the target, the proton beam must be applied to the patient from many directions using a proton rotating gantry.

The best way of delivering a conformal dose to a tumor is thus to change, during the treatment the energy of the beam and, with magnets placed upstream, its direction, all at the same time. These sophisticated active scanning systems are effectively used in cancer treatment together with the passive spreading technique. There are two strategies of active magnetic beam scanning: the raster scan and the spot scan. The active scanning methods are based on energy and intensity variation within the treatment time. The new technique allows to deliver dose with variable modulation and with a complete three-dimensional conformation to the tumor volume. The beam utilization efficiency is increased to 75% by application of the active scanning scheme. The passive and active scanning schemes can be used both with the cyclotrons and synchrotrons (Table 2).

Table 2 Parameters of medical proton cyclotrons and synchrotrons

Parameter	Cyclotron	Synchrotron
Energy of extracted particles	fixed	variable
Energy variation rate, MeV/s	15	4
Energy spread, %	0,5	0,1
Stability of energy, %	0,1	0,1
Maximal beam current, nA	300	15
Current modulation time, ms	1	1
Extraction efficiency, %	60-80	90
Beam utilization, %	50	>50
Working cycle, %	100	70
Emittance of extracted beam, π·mm·mrad	5-10	2-3
Diameter of accelerator, m	4-5	7-12
Weight, t	200-250	20-30

The proton energy can be natural vary in synchrotrons due to variation of the acceleration ramping time. The energy of the extracted beam in cyclotron is fixed. However the fast proton energy variation is easily performed during active cancer treatment by using a wedge degrader. The beam intensity variation at active scanning is one of key parameters at Pencil Beam

Scanning (PBS) and Intensity Modulated Proton Therapy (IMPT).

CYCLOTRON CENTERS OF PROTON THERAPY

There are 22 centers of proton therapy in the world now. More than 47.5 thousand patients were treated by proton therapy during the last 50 years, 60 % of them were treated over the last 10 years and 90% of all patients are now treated in the hospital-based facilities.

Advantages of the medical proton cyclotron (Fig. 3) are simplicity, reliability, small size, and most importantly, the ability to modulate rapidly and accurately the proton beam current (Fig.4). The current modulation of the extracted proton beam at a frequency up to 1 kHz is most advantageous with PBS at IMPT [2].

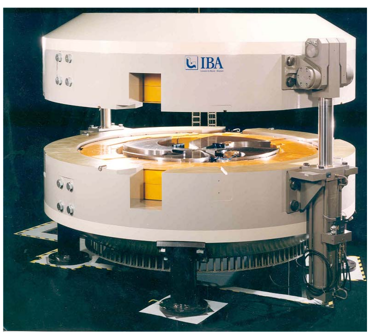


Fig. 3 C235 IBA cyclotron for proton therapy.

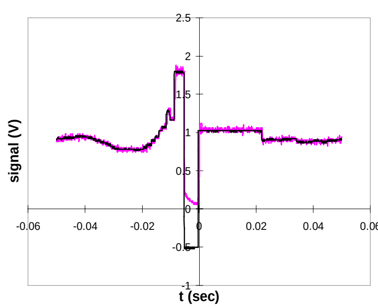


Fig.4 Beam intensity variation at the IBA C235 proton cyclotron [2].

The recently developed RF-knockout extraction technique used in the medical synchrotrons provides beam intensity modulation in the 1 kHz range [3]. However, the spill ripple is around ±10% in this case.

The gantry (Fig. 5) is one of important parts of the equipment for modern hospital centers of proton therapy. The parameters of the extracted beams obtained from the cyclotron and the synchrotron are rather different. The cyclotron proton beam has a circular beam profile at the gantry isocenter with Gaussian distribution in both vertical and horizontal directions [4]. The slow beam extraction method used in synchrotrons, however, can not deliver a beam with the Gaussian distribution in the horizontal phase space. Further, its vertical emittance is normally different from horizontal one.

Fig. 5 IBA proton gantry

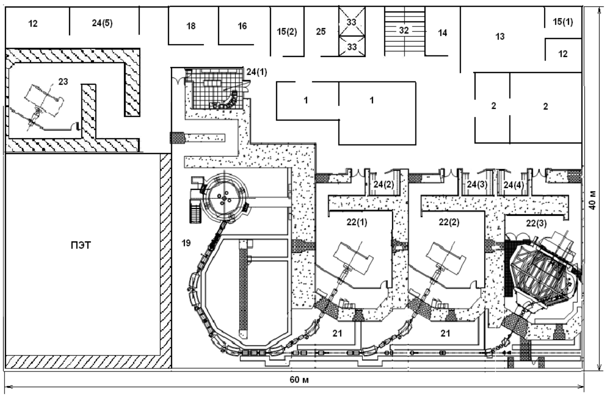
However, in a rotating gantry the horizontal and vertical profiles of the beam at the isocenter should not have correlations between the gantry rotation angles. A special rotator section should be installed in the synchrotron beam transfer line to avoid correlation between the beam shape and the gantry rotation angles [5]. This section rotates the beam on half of the gantry rotation angle.

Fig.6 PSI new superconducting proton medical cyclotron constructed by Accel.

The active spot PBS technique was developed at the PSI cyclotron medical complex [6]. The new medical supeconducting cyclotron of this complex is shown in Fig.6. The typical required beam intensity for a cancer target at the irradiation dose of 1 Gy and the target volume of 1 l during 1 min is 0.2 nA [6]. The spot PBS is carried out in time by the fast kicker; in horizontal direction by the sweeping magnet; in vertical direction by the patient table motion and in z-direction by the range shifter [6]. The grid size at the PSI spot scanning is 5 mm, time required for proton energy variation is 150 ms to provide one grid step shift in z-direction [6].

DUBNA CYCLOTRON CENTER OF PROTON THERAPY

The project of the Dubna Center of Radiation Medicine (CRM) involves the cyclotron center of proton therapy, the PET center, the department of conventional radiotherapy based on the electron linac, the diagnostic department, and the proton therapy clinic. The accelerator equipment of this center is shown in Fig. 7.



Fig,7 Layout of the of the accelerator equipment of the Dubna CRM.

The proton therapy center has 3 treatment rooms, one with the gantry and two with the fixed beams. About 1000 patients per year will be treated there.

The medical cyclotron for this center is simulated by the JINR-IBA collaboration. This cyclotron design is a modified version of IBA C235 cyclotron [2] (Table 3). The goal is to modify the sectors spiral angle (R>80 cm, Fig.8-Fig9) for improving of the cyclotron working diagram.

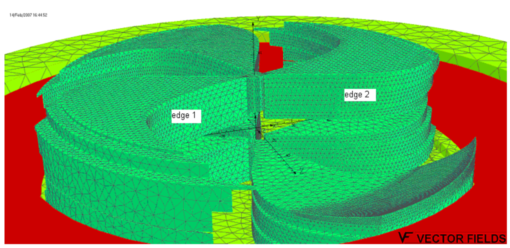


Fig.8 Simulation of the magnetic field.

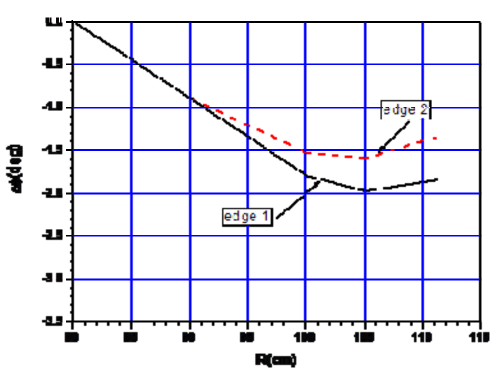


Fig. 9 Final spiral angle modification .

The simulations of proton beam extraction are presented in Fig. 11.

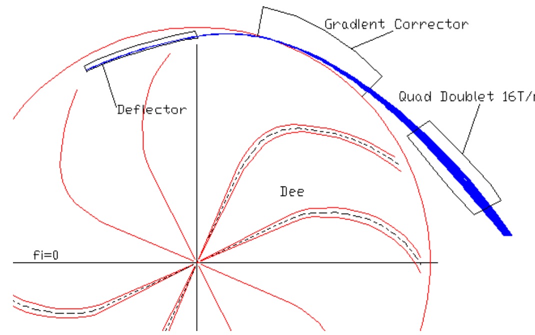


Fig. 10 Simulation of proton beam extraction by electrostatic deflector .

Table 3 Parameters of the modified C235 isochronous proton cyclotron.

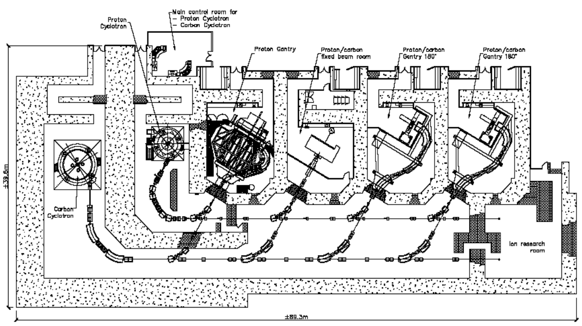
General parameters	Value
Proton energy, MeV	235
Internal current, nA	300
Beam emittances, π·mm·mrad	12/11
Magnetic field (min/max) T	0.9/2.9
Number of sectors	4
Magnet diameter, m	4.3
Radius of beam extraction, m	1,08
Valley depth, cm	60
RF frequency, MHz	106.1
Operation	4 harmonic
Dee voltage, (min/max) kV	60/130
Ion source	PIG, internal
Electrostatic deflector field, kV/cm	170
Extraction efficiency, %	60
Power, kW	446
Weight, t	220

CYCLOTRON CENTERS OF CARBON THERAPY

Carbon therapy is the most effective method to treat the resistant tumors. The cyclotron center of carbon therapy was recently proposed by IBA [2]. The center consists of a carbon cyclotron, a proton cyclotron, two carbon superconducting gantries, proton gantry and a medical room with a fixed beam (Fig. 11) [2]. A compact superconducting isochronous cyclotron C400 was designed by JINR-IBA collaboration [7-9]. This cyclotron will be used for radiotherapy with protons, helium and carbon ions. The $^{12}C^{6+}$ and $^{4}He^{2+}$ ions will be accelerated to the energy of 400 MeV/amu and extracted by electrostatic deflector, H_2^+ ions will be accelerated to the energy 265 MeV/amu and protons will be extracted by stripping [7-9]. The magnet yoke has a diameter of 6.6 m. The total weight of the magnet is about 700 t. The main coil current is 1.2 MA. Superconducting coils will be enclosed in a cryostat, all other parts are warm.

The beam will be accelerated at the fourth harmonic of the revolution frequency, i.e. at 75 MHz. It will be obtained through two cavities placed in the opposite valleys. The dee voltage increases from 80 kV at the center to 170 kV in the extraction region.

Three external ion sources will be mounted on the switching magnet on the injection line located below of the cyclotron. The $^{12}C^{6+}$ ions are produced by a high performance ECR at the injection current of 3 μA. The alphas are produced by the other ECR source, while H_2^+ are produced by a multicusp ion source. All species have a Q/M ratio of 1/2.



Fig,11 Layout of the accelerator equipment in IBA cyclotron center of carbon therapy [2].

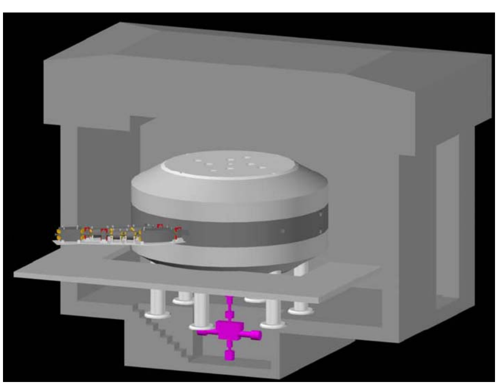


Fig. 12 Layout of the C400 carbon cyclotron [7-9].

FORMATION OF PRIMARY RADIOACTIVE CARBON ION BEAMS

Beams of accelerated ^{12}C ions are efficiently used for cancer treatment. On the other hand, positron–emission tomography (PET) is the most effective way of tumor diagnosis. The ^{11}C ion beam could allow both these advantages to be combined because it could be used both for the cancer treatment and for the on-line positron emission tomography [10]. Formation of a primary radioactive $^{11}C^{6+}$ ion beam with the intensity of 10^{10}-10^{11} pps from the ion source in continues or pulse mode allows cancer treatment and on-line dose verification [11].

^{11}C isotopes are produced at the nuclear reaction $^{14}N(p,\alpha)^{11}C$ in the target chamber filled with N_2 gas irradiated by a proton beam [10]. If the target chamber also contains about 5% of H_2, methane molecules $^{11}CH_4$ are produced in the target volume [11]. Radioactive methane is separated from N_2 and H_2 [10] and then is loading into the ion source [11]. The measured conversion efficiencies of methane molecules to carbon ions in the JINR Electron String Ion Source (ESIS) is rather high, 12-15 % for C^{6+} ion beams [11]. This conversion efficiency permits obtaining primary radioactive $^{11}C^{6+}$ beams at the ion source intensity of 10^{10} -10^{11} pps and performing cancer treatment and on-line dose verification.

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