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DEVELOPMENT OF ACCELERATION TECHNIQUE FOR HADRON THERAPY IN JINR

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Abstract

Development of accelerators for hadron therapy is one of JINR activities in the field of acceleration technique. The JINR-IBA collaboration has developed and constructed the C235-V3 cyclotron for Dimitrovgrad hospital center of the proton therapy. Proton transmission in C235-V3 from radius 0.3m to 1.03 m is 72% without beam cutting diaphragms, the extraction efficiency is 62%. The cyclotron was delivered in this center in 2012.

The project of the medical carbon synchrotron together with superconducting gantry was developed in JINR. Carbon ion beams are effectively used for cancer treatment. The PET is the most effective way of tumor diagnostics. The radioactive carbon ion beam could allow both these advantages to be combined. JINR-NIRS collaboration develops formation of a primary radioactive ion beam for the scanning radiation and on line PET diagnostic.

A superconducting cyclotron C400 was designed by the IBA-JINR collaboration. This cyclotron will be used for therapy with proton, helium and carbon ions.

PROTON CYCLOTRON C235-V3

The JINR-IBA collaboration has developed and constructed the C235-V3 proton cyclotron for Dimitrovgrad hospital proton center. The C235–V3 cyclotron, superior in its parameters to the IBA C235 medical proton cyclotron, has been designed and manufactured by the JINR-IBA collaboration. This cyclotron is a substantially modified version of the IBA C235 cyclotron.

Modification of the extraction system is the main aim of the new C235-V3 cyclotron [1-2]. The main feature of the cyclotron extraction system is a rather small gap (9 mm) between the sectors in this area. The septum surface consists of several parts of circumferences of different radii. The septum thickness is linearly increased from 0.1 mm at the entrance to 3 mm at the exit. The proton extraction losses considerably depend on the septum geometry. In the septum geometry proposed by JINR, where the minimum of the septum thickness is placed at a distance of 10 cm from the entrance, the losses were reduced from 25% to 8%. Together with the optimization of the deflector entrance and exit positions it leads to an increase in the extraction efficiency to 80%. The new extraction system was constructed and tested at the IBA C235 cyclotron. The experimentally measured extraction efficiency was improved from 60% for the old system to 77% for the new one.

Figure 1: Cyclotron C235-V3 in JINR engineering center.

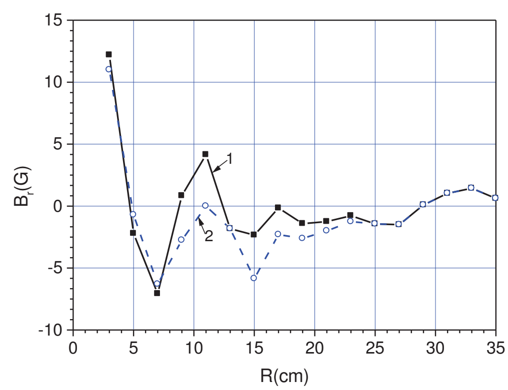

Figure 2: Distribution of average radial component in cyclotron median plane at shim thickness 2 mm (curve 1) and shim thickness 1.7 mm (curve 2).

Another difference in the structure of the magnetic field for the C235–V3 cyclotron compared to an IBA C235 serial cyclotron is related to the value of the radial component of magnetic field in the median plane, bump parameters, and the minimal value of the vertical betatron frequency in the central area of the cyclotron.

The bump of magnetic field B_z in the center is used in many cyclotrons for axial focusing during the first turns, when the B_z variation is low. When the decreasing field of the bump passes to the increasing isochronous one, the dip in the axial betatron frequency Q_z could appear. In the C235-V3, Q_z decreases at a radius of 10 cm down to ~0.04–0.05.

The presence in the area of the Q_z minimum of the mean radial component of the magnetic field B_r with a

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level of 5 G and gradient of 5 G/cm in the median plane results in the transformation of coherent motion of the center of gravity of the beam in this area into the noncoherent oscillations of individual particles and coherent oscillations of the center of gravity. The simulated axial r.m.s. (±2σ) size (Fig.3) is equal to 6 mm at B_r=0, it increases up to 12 mm at B_r corresponded to shimm thickness of 2mm (Fig.2) and 8 mm at optimized shimm thickness of 1.7 mm. In the C235-V3, the B_r component was optimized using the establish of shim correctors at the sectors.

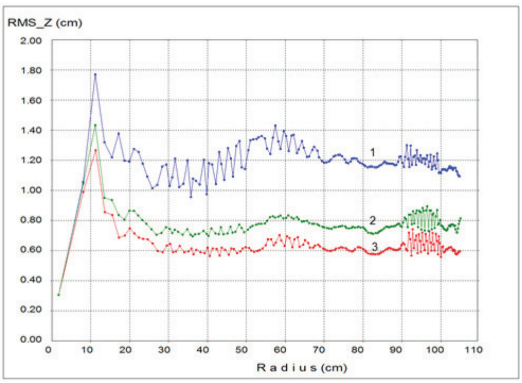

Figure 3: Simulated dependence of axial r.m.s. (±2σ) size on radius: curve 1 at B_r (curve 1in Fig.2), curve 2 at B_r (curve 2 in Fig.2), curve 3 at B_r=0.

In experiment, the r.m.s. vertical size of the beam (2σ) (Fig.4) at the radii of 15–20 cm is ~17–18 mm and becomes comparable with the vertical aperture of the accelerator of 20 mm determined by the interdee gap.

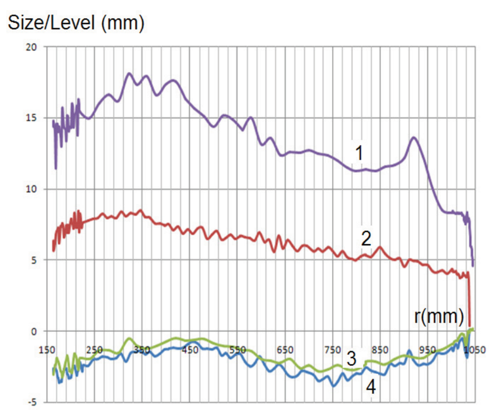

Figure 4: Experimental dependence of axial r.m.s. size (1, 2) and beam center gravity (3, 4) on radius 1, 3 – before magnet field optimization, 2, 4 after optimization.

During the further acceleration of protons in the area of large radii, where the aperture of the accelerator decreases, the appearance of the radial field in the median plane leads to beam losses because of the large amplitude of noncoherent oscillations occurring in the central area of the accelerator.

After shimm optimization, the axial size of the proton beam at radii of 15–20 cm was reduced by a factor of two and was ~7–8 mm (Fig. 4). This led to the efficiency of acceleration in the C235–V3 cyclotron being increased to 72% without the establishment of restrictive diaphragms.

SUPERCONDUCTING SYNCHROTRON FOR CARBON THERAPY

A project of the medical superconducting synchrotron (Fig.5) dedicated for the carbon therapy has been designed in JINR [3]. The basis of this medical accelerator is the superconducting JINR synchrotron – Nuclotron. The Nuclotron type straight dipole magnets were adopted for the optic of the medical synchrotron and beam delivery system. The superconducting magnets permit to reduce the accelerator electrical consumption, the size and weight of the accelerator and the carbon gantry.

The superconducting electron string ion source is planed to use for $^{12}C^{4+}$ injection in the carbon linac. The compact IH linac will apply as synchrotron injector.

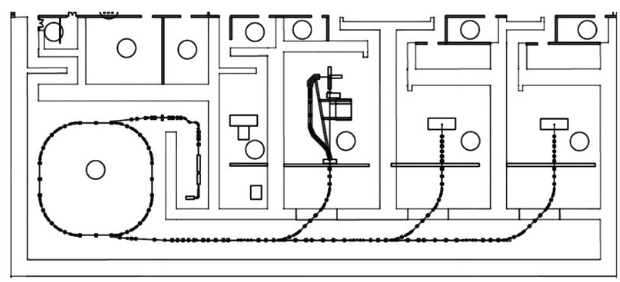

Figure 5: Layout of the carbon therapy hospital center on the basis of superconducting synchrotron.

The FODO structure is more preferable for injection and extraction schemes and corrections of the closed orbit distortions. The synchrotron magnetic system [3] consists of 4 superperiods, which involves 8 straight dipole magnets, 8 quadrupole lenses and multipole correctors. The maximum magnetic field in dipole magnets corresponds to 1.8 T. The multiturn injection is realized at fulfilling of the horizontal acceptance during 10-15 ion turns. The stored beam intensity is equal to 10^{10} ions C^{6+} per pulse. The working point corresponds to betatron tunes $Q_{x,z}$ ≈3.25. Nonlinear 3 order resonance $3Q_x$=10 is used for slow beam extraction. The intensity of extracted beam is equal to 10^9 pps.

One important feature of this project is related to the application of superconducting gantry. The superconducting magnets of low aperture (about 120 mm) are used in the gantry. The gantry consists of two 67.5° and one 90^0 bending sections, each including similar dipole magnets.

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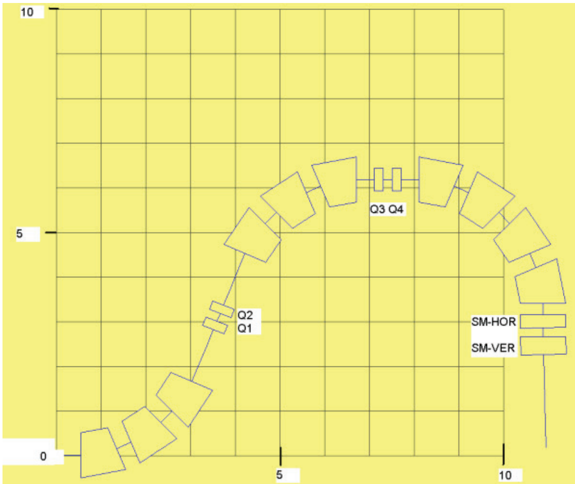

Figure 6: Layout of the JINR superconducting carbon ion gantry.

FORMATION OF PRIMARY RADIOACTIVE CARBON ION BEAMS

Accelerated ion beams of the positron-emitting ^{11}C isotope (half-lifetime is about 20 min) were first used at NIRS-HIMAC for cancer therapy applications. The use of the ^{11}C ion beam could allow both these advantages to be combined because this beam could be simultaneously used both for cancer treatment and for on-line positron emission tomography. Verification of the radiation dose in the tumor target will be carried out simultaneously with cancer treatment.

In the ISOLDE scheme the ^{11}C isotope is produced through the nuclear reaction ^{14}N $(p,\alpha)^{11}C$ in the target chamber filled with N_2 gas. The nitrogen gas target also contains 5% of H_2 to produce $^{11}CH_4$ molecules. The Electron String Ion Source [4] is one of the promising ion sources for generation of the positron-emitting $^{11}C^{4+}$ ion beam at the intensity of $6{\cdot}10^9$ pps. The charge capacitance of the Krion-2 ion trap is $6{\cdot}10^{10}$ elementary charges. As was shown experimentally [4], adjusting the electron energy, injection time, and time of ion confinement, one can get up to 50 % of C^{4+} in the total ion beam pulse extracted from the source. So, the existing ion source Krion-2 could produce around $2{\cdot}10^9$ C^{4+} particles per pulse at an optimized ion conversion efficiency. The maximum number of C^{4+} ions produced per pulse in Krion-2 corresponds to $4{\cdot}10^9$. The further increase of ion intensity in Krion-2 is restricted by electron string capacity at magnetic field 3T. The developed in JINR new ESIS Krion-5T with magnetic field 5-6T will produce $6{\cdot}10^9$ $^{11}C^{4+}$ ions per pulse.

The radioactive carbon beams are planed to use for the HIMAC raster scanning irradiation. According to the this therapy requirements, the ion source should produce C^{4+} ion beams with the intensity of $6{\cdot}10^9$ particles per pulse and pulse width of 0.1 ms. The project number of ions produced in the ring per injection-extraction cycle and applied for the scanning irradiation corresponds to $2{\cdot}10^9$ particles. Maximum number of extracted ions is equal 10^8 pps at HIMAC raster scanning.

SUPERCONDUCTING CYCLOTRON C400 APPLIED FOR CARBON THERAPY

Carbon therapy is the most effective method to treat the resistant tumors. A compact superconducting isochronous cyclotron C400 was designed by JINR-IBA collaboration [5]. 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 H_2^+ ions will be accelerated to the energy 265 MeV/amu and protons will be extracted by stripping.

Three external ion sources will be mounted on the switching magnet on the injection line.

The design of the C400 magnetic system was based on its main characteristics: four-fold symmetry and spiral sectors; deep-valley concept with RF cavities placed in the valleys; elliptical pole gap is 120 mm at the center decreasing to 12 mm at extraction; accelerate up to 10 mm from the pole edge to facilitate extraction; pole radius is 187 cm; hill field is 4.5 T, valley field is 2.45 T; magnetic induction inside yoke is less 2-2.2 T; the magnet weight is 700 tons and the magnet yoke diameter is 6.6 m; the main coil current is 1.2 MA. The optimized sector geometry provides vertical focusing Q_z~0.4 in the extraction region.

Extraction of protons is supposed to be done by means of the stripping foil. It is possible to extract the carbon beam by means of one electrostatic deflector (which is located in valley between sectors) with a 150 kV/cm field inside. The extraction efficiency was estimated as 73% for the septum with increased (0.1 – 2) mm thickness along its length**.** The extraction of the carbon and proton beams was realized by the separate channels. Both beams have a spot with $\sigma_{x,y}$<1 mm at this point. Transverse emittances are equal to 10 π mm·mrad and 4π mm·mrad for the extracted carbon beam.

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