ACCELERATION TECHNIQUE DEVELOPED AT JINR FOR HADRON THERAPY

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Abstract

The JINR activities are aimed on the construction of accelerators for proton and carbon ion therapy. JINR-IBA have developed and constructed the proton cyclotron C235-V3. The cyclotron will be delivered in the first Russian hospital center of the proton therapy in Dimitrovgrad in 2012.

The project of the medical carbon synchrotron was developed in JINR. The project goal is accumulation of the superconducting Nuclotron technology at construction of the medical carbon synchrotron. Accelerated ^{12}C ion beams are effectively used for cancer treatment.

The PET is the most effective way of tumor diagnostics. The intensive radioactive ^{11}C ion beam could allow both these advantages to be combined. JINR-NIRS collaboration develops formation of a primary radioactive ion beam at intensity on the tumor target of 10^8 pps for the scanning radiation.

A superconducting cyclotron C400 has been designed by the IBA-JINR collaboration. This cyclotron will be used for radiotherapy with proton, helium and carbon ions. Its construction was started in 2010 within the framework of the Archarde project (France).

The interaction between delta electrons and DNA molecules is one of the important processes in the hadron therapy. The formation of low energy electrons and DNA ions are presented for the KEK electrostatic storage ring with the electron target developed by JINR-NIRS collaboration.

PROTON CYCLOTRON C235-V3

The JINR-IBA collaboration has developed and constructed the C 235-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.

One of the nearest goals is to modify the sector spiral angle at R>80 cm for improving the cyclotron working diagram and reducing of coherent beam losses at acceleration. The coherent beam displacement z from the median plane is defined by the vertical betatron tune Q_z: $z \propto Q_z^{-2}$. At $Q_z \cong 0.2$ the coherent beam displacement corresponds to 7 mm and at the free axial oscillation amplitude of 2-3 mm can cause beam losses due to reduction of the sector gap in the C235 cyclotron. An increase of the vertical betatron tune from $Q_z \cong 0.2$-0.25 to $Q_z \cong 0.4$ in C235-V3 permits the coherent losses at proton acceleration to be reduced by a factor of 3-4.

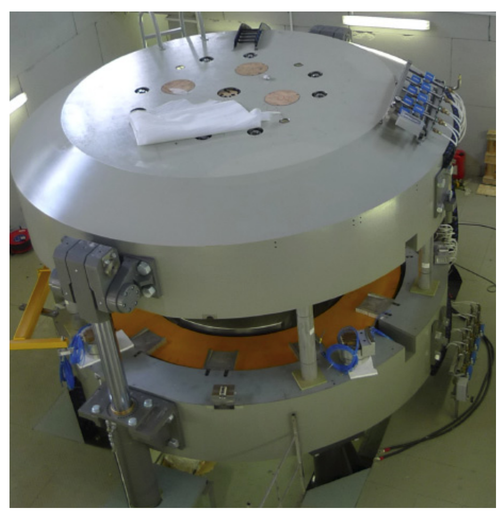

Figure 1: Cyclotron C235-V3 in JINR engineering center.

SUPERCONDUCTING SYNCHROTRON FOR CARBON THERAPY

A project of the medical superconducting synchrotron (Fig. 2) dedicated for the carbon therapy has been designed in JINR [3]. The basis of this medical accelerator is the superconducting JINR synchrotron – Nuclotron [4]. The Nuclotron type straight dipole magnets [4] were adopted for the optic of the medical synchrotron and beam delivery system. The

ISBN 978-3-95450-125-0

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.

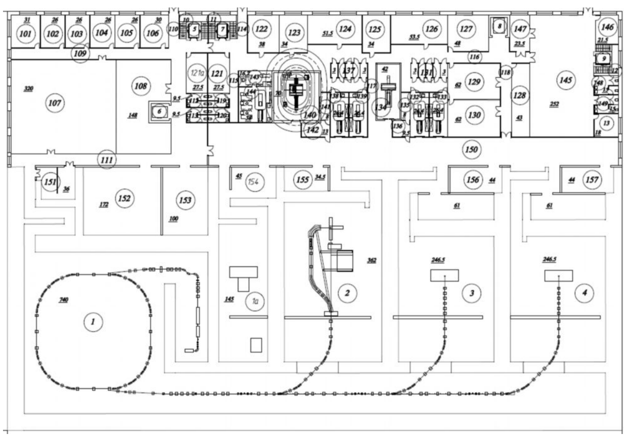

Figure 2: Layout of the carbon therapy hospital center on the basis of superconducting synchrotron.

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 $Q_{x,z} \approx 3.25$. Nonlinear 3 order resonance $3Q_x=10$ is used for slow beam extraction. The intensity of extracted beam is equal to 10^9 pps.

The beam delivery system [3] consists of following sections: the extraction section; the foil section provided equal beam emittances in both transverse planes; the accommodation section; the section for beam delivery in the cabin; the section of beam transportation between the medical cabins; the isocentric gantry; the channel with fixed beam position cabin. The beam delivery system should provide the fixed transverse beam sizes in the gantry isocenter. These sizes do not depend on the gantry rotation angle, the extracted ion energy, emittance of the extracted carbon ion beam.

The extracted carbon beam has non symmetric horizontal and vertical emittances, the vertical emittance is few times larger horizontal one. A special scattering foil is installed in the beam delivery system to provide both equal horizontal and vertical beam emittances. The accommodation section is used to provide same optical beam characteristic in the vertical and horizontal directions at exit. It accommodates the beam optic to the gantry for any its rotation angles. The section for beam delivery in cabin consists of the chopper, the achromatic bend and 2 triplets. The chopper involves 4 dipole magnets. The beam is pick-upped by an absorber trap, when dipoles switch off. The beam is transported in the channel when magnets switch on. The section of beam transportation between cabins has the horizontal betatron phase shift 2π and vertical one π. The optic of the isocentric gantry is achromatic at beam transportation to the tumour target. The gantry optic provides equal horizontal and vertical beta functions and zero alpha-function on the tumor target. The parameters of gantry optic is adjusted to obtain the equal vertical and horizontal beta and alpha functions at the gantry entrance at variation of extracted beam emittances and sizes.

The JINR-IBA collaboration develops superconducting cyclotron C400 and carbon gantry in frame work of Archade project [5]. This gantry is planed to use in JINR carbon synchrotron complex. The gantry provides rotation around the patient on an angle $0\text{-}180^0$. The positioner also rotates together with patient on an angle $180^0\text{-}360^0$. The main gantry superconducting dipole magnet has aperture 20×20 cm at magnetic field homogeneity of 10^{-4}. The magnetic field rate corresponds to 1 T/min. The magnet is cooled by 4 He-free criocoolers. The distance from dipole magnet exit to isocenter corresponds 2 m.

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 [6] 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 [6], 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.

ISBN 978-3-95450-125-0

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.

SUPECONDUCTING 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 $^{12}C^{6+}$ ions are produced by a high performance ECR at the injection current of 3 μA.

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 sectors have following parameters: the initial spiral law with parameter Nλ=77 cm with increasing spiral angle to the final radius with parameter Nλ~55 cm; the sectors azimuth width is varying from 25º in the cyclotron center to 45º at the sectors edge; axial profile is the ellipse with 60/1874 mm semi-axis, at the final radii the ellipse axial profile is cut by the planes at the distance z= ± 6 mm. 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 was found that 265 MeV is the energy of protons for 2-turns extraction..

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. Septum of the deflector was located at the radius 179.7 cm for tracking simulation. 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. It is possible to align both beams into one direction just before the energy degrader. 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.

FORMATION AND INTERACTION OF ELECTRONS AND BIOMOLECULAR IONS IN ELECTROSTATIC STORAGE RING

The basis of hadron therapy is the modifying action of carbon ion or proton beams on biological structures. In the case of carbon therapy, ions cause double strand DNA breaks due to direct ionization, and delta electrons produced in this case result in the DNA ionization along their trajectories. Most delta electrons have energy under 30 eV; ions and protons produce about 10^5 secondary electrons. Below we discuss the results of experiments related to the interaction between low energy electrons and bimolecular ions produced in the KEK electrostatic storage ring [7]. The KEK electrostatic ring with a perimeter of 8.1 m was first used to store different bimolecular ions, including ions of DNA molecules with a mass of up to 60000 u. The maximum ion energy is 30 keV/Z. A special electron target was developed for investigating the interaction between low energy electrons and biomolecular ions in the electrostatic storage ring in the framework of the JINR–NIRS-KEK collaboration [7]. The maximum energy of the target electrons is 100 eV, the maximum electron current is equal to 2 mA, and the length of the electron–ion interaction region is equal to 20 cm.

The cross section of the interaction between target electrons and ions of DNA molecules (oligonucleotide d(AAA)) has a maximum for a relative electron and ion energy of 4.5 eV. The peak in the cross section of the electron interaction with DNA ions is determined by the contribution of sugar–phosphate breaks and dissociative recombination and electron capture dissociation.

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ISBN 978-3-95450-125-0