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Feasibility study of a cyclotron complex for hadron therapy

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A B S T R A C T

An accelerator complex for hadron therapy based on a chain of cyclotrons is under development at JINR (Dubna, Russia), and the corresponding conceptual design is under preparation. The complex mainly consists of two superconducting cyclotrons. The first accelerator is a compact cyclotron used as an injector to the main accelerator, which is a six-fold separated sector machine. The facility is intended for generation of protons and carbon beams. The H_2^+ and $^{12}C^{6+}$ ions from the corresponding ECR ion sources are accelerated in the injector-cyclotron up to the output energy of 70 MeV/u. Then, the H_2^+ ions are extracted from the injector by a stripping foil, and the resulting proton beam with the energy of 70 MeV is used for medical purposes. After acceleration in the main cyclotron, the carbon beam can be either used directly for therapy or introduced to the main cyclotron for obtaining the final energy of 400 MeV/u. The basic requirements to the project are the following: compliance to medical requirements, compact size, feasible design, and high reliability of all systems of the complex. The advantages of the dual cyclotron design can help reaching these goals. The initial calculations show that this design is technically feasible with acceptable beam dynamics. The accelerator complex with a relatively compact size can be a good solution for medical applications. The basic parameters of the facility and detailed investigation of the magnetic system and beam dynamics are described.

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1. Introduction

Development of accelerators for producing carbon beams with the energy of 400–450 MeV/u for hadron therapy appears to be an increasingly important issue nowadays. The existing facilities for this purpose are mainly based on synchrotrons. It seems interesting to use isochronous cyclotrons instead, as is the case in proton therapy. However, the so far developed designs of compact superconducting cyclotrons have some disadvantages in addition to their advantages [1]. An alternative solution can be a facility based on a separated sector cyclotron justified in [2]. According to this reference, an attractive characteristic of this dual cyclotron solution is the option of a two-phase realization, since the high-energy carbon option can be added later, but in the first phase and already from the start of the project "low-energy" carbon-based particle therapy can be employed, together with the full spectrum of proton energies using acceleration of H_2^+ ions in the same machine. The design of this facility should comply with a number of conditions. First, the size and weight of the main accelerator must be as small as possible, which makes it expedient to use the highest possible magnetic field. Second, the injection energy should be low enough for the injector-cyclotron to be of reasonable size. Third, the

magnetic system design should be feasible, that is, the parameters of the superconducting coil (engineering current density, acting forces, etc.) should be adequate and the space between the sectors should be large enough to accommodate accelerating elements, beam injection system, etc. A separate task is to develop the magnet of the main machine such that it will maintain isochronism of the magnetic field and particle focusing along with a minimum number of resonance crossings by the beam during acceleration. Our proposal, which meets all the above-mentioned requirements, is an acceleration setup (Fig. 1) consisting of a compact injector-cyclotron (K280) and the main separated-sector cyclotron (K1600). Both cyclotrons are superconducting.

The proposed acceleration cascade having an external size of about 15 m is smaller than the synchrotron-based facilities for hadron therapy and has typical advantages of a cyclotron. Besides, building a synchrotron does not allow the phased approach. For comparison, below are the sizes of some similar facilities based on synchrotrons:

- HIT (Heidelberg, Germany) [3], final beam energy 430 MeV/u, size (with injector) ~40 m;
- CNAO (Pavia, Italy) [4], final beam energy 400 MeV/u, size (with injector) ~24 m;

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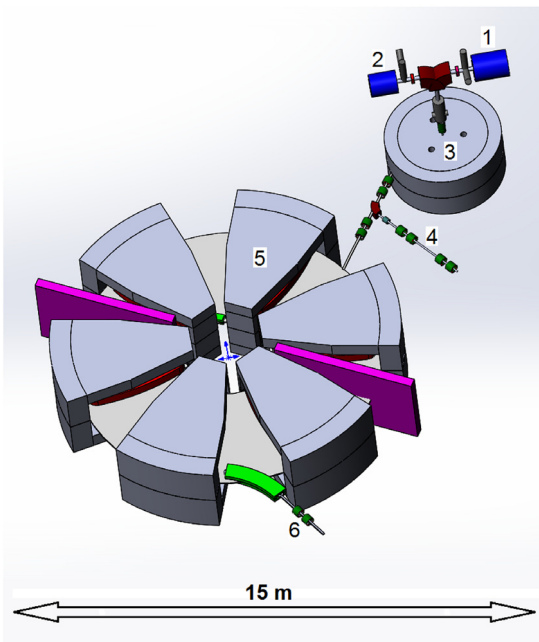 *E-mail address:* vsmirnov@jinr.ru (V. Smirnov).

Fig. 1. Acceleration complex layout: 1-^{12}C^{6+} ECR, 2-H$_2^+$ ECR, 3-K280, 4-medium energy beam transport line (proton and carbon 70 MeV/u), 5-K1600, 6-high energy beam transport line (carbon 400 MeV/u).

- HIMM (Lanzhou, China) [5], final beam energy 400 MeV/u, size (with injector) ~27 m.

The preliminary results on the project are presented in [6] and [7]. The latest developments in the facility design are described in the following sections.

2. The injector-cyclotron

The carbon injection energy to K1600 is chosen to be 70 MeV/u because the K280 with this final energy can be also used as a stand-by facility for medical applications having in mind a possibility of H$_2^+$ ions acceleration in addition to carbon ions. In the H$_2^+$ regime magnetic field of the cyclotron should be slightly corrected by dedicated trim coils foreseen in the accelerator design similar to that described in [8]. A spiral inflector, which will be used in the central region of the cyclotron for beam injection, has the same structure for both carbon and hydrogen ions, since their charge-to-mass ratios are almost identical. Subsequent stripping of H$_2^+$ ions allows obtaining protons with energy suitable for treating eye melanomas and skin cancer, or producing radioisotopes. A compact superconducting cyclotron seems to be the most optimal option for this machine. The magnetic rigidity of 70-MeV/u ^{12}C^{6+} ions is about that of 250-MeV protons. So, the injector design can be based on the proven technology that is used in modern accelerator setups [9–12]. Some technical solutions of these machines are applicable to the K280. The use of external ion sources limits the central magnetic field to a maximum of 3.0 T due to injection through the spiral inflector. Another constraint comes from the necessity of having the same acceleration frequency in the injector and in the K1600. This also influences the choice of the central magnetic field in the K280. Considering the above said, two variants of the injector design are initially investigated: a four-fold magnetic structure with the 1.98 T central field and a three-fold magnet with the 2.64 T central field. The central field level is defined by the choice of the RF harmonic mode of the accelerator – four or three – to provide the required frequency of the acceleration system in accordance with the K1600 acceleration frequency (synchronization). Both cases imply placement of spiral dees
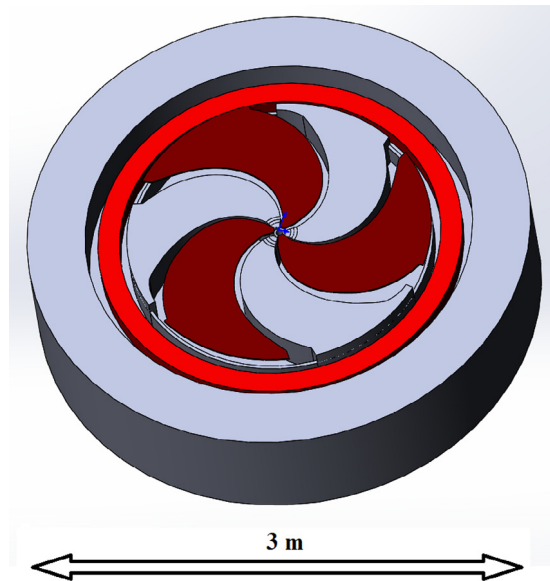

Fig. 2. K280 layout.

in all valleys of the magnetic structure to ensure maximal energy gain per turn. The four-fold structure has the highest energy gain per turn leading to more efficient particle extraction from the cyclotron vacuum chamber. An advantage of the three-fold structure is a higher magnetic field that allows a more compact and lighter magnet. This is why the three-fold option was selected as a baseline for the injector-cyclotron (Fig. 2). The field index has a moderate value at the final radius, and there is no problem with obtaining a sufficient magnetic flutter for the axial focusing of accelerated particles. This permits a sufficiently large axial air gap between the spiral sectors for the extraction system elements to be placed in this gap (Table 1). Considering the above said, the expected beam extraction efficiency of 80% can be achieved rather easily. The required spirality of the magnetic sectors at the final radius is below 55° to provide the axial betatron frequency near 0.3. The radial betatron frequency is below 1.2 at the selected final energy of the beam. This prevents crossing a dangerous resonance $2Qr = 3$, which normally limits the final energy in a cyclotron with the three-fold magnetic structure.

The SUPERNANOGAN 14.5 GHz ECR PANTECHNIK [13] based on permanent magnets is considered as the ^{12}C^{6+} ion source for the cyclotron. The available intensity of the ions from this source is 2.5 µA at the maximal extraction voltage of 30 kV. The company can deliver the unit together with the beam transport system including the Einzel lens, the double focusing dipole, two steerers, slits, the beam profiler, the Faraday-cup, and the complete gas system. Similar to the carbon beam, H$_2^+$ ions can also be obtained from an ECR ion source.

3. Medium-energy beam transport

The purpose of the medium-energy beam transport (MEBT) line is to deliver the beam extracted from the K280 to the K1600 with the required beam quality. Currently, the system is at an early design stage, and its structure details are not fully defined yet. In the initial assumption, several duplets of magnetic quadruples, magnetic steerers, and a beam diagnostics system are considered. In the case of using beams, accelerated in the K280, directly for medical purpose, the corresponding bending magnet is switched on to divert ions in the dedicated beam line (see Fig. 1). The final decision on the MEBT structure will be taken after detailed simulation of the beam dynamics in the K280 and in the MEBT. For example, additional bending magnets could be installed in the MEBT to take into account the final relative position of the cyclotrons in the cascade.