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PRODUCTION OF 70 MeV PROTON BEAM IN A SUPERCONDUCTING CYCLOTRON

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Abstract

Production of 70 MeV proton beams with help of a cyclotron-type facility is one of highly requested tasks presently. Such beams are used for medical applications including direct tumor irradiation and also for production of medical isotopes. The applications mentioned above dictate corresponding requirements imposed on the beam quality and intensity. For proton therapy treatment it is sufficient to have 300 to 600 nA output beam current with rather strict tolerance on the transverse beam quality. On the other hand, for the isotope production the major requirement is high enough beam intensity (hundreds μA) with less demanding beam quality. Nowadays, for production of the proton beams in the energy range considered cyclotrons with resistive coil weighting ~140 to 200 t are mostly used. In these cyclotrons two extraction methods – with electrostatic deflector and with stripping foils – can provide somewhat different quality of the output beam. In given report a possibility of using a superconducting cyclotron instead of room-temperature one is considered. To this end, acceleration of various ions was investigated with analysis of the main facility parameters and resulting output beams.

INTRODUCTION

Nowadays, the majority of cyclotrons intended for production of proton beams with energy about 70 MeV have rather low magnetic field in range of 1 to1.4 T [1-2]. As a result, the facility has footprint of 4 to 6 m and weight above 140 t. Application of higher level of magnetic field for such machines based on superconductive technology permits designing of accelerator with substantially lower size and weight. But application of high magnetic fields introduces some limitations in the cyclotron design. For example, acceleration of H^- ions in the selected energy range becomes practically impossible in high magnetic field due to massive particle losses by Lorentz stripping. On contrary, in room-temperature machines acceleration of H^- ions are widely used that provides a highly effective particle extraction near 100% by stripping foils with a possibility of some energy variation of the output beam. So, in the superconducting cyclotrons either protons or H_2^+ ions can be used for acceleration. The latter has a strong enough coupling of outside electron with the nucleon to stay stable even in considered high magnetic field of the facility. In case of protons an application of an electrostatic deflector for particles extraction leads to somewhat lower extraction efficiency and fixed energy of the output beam. On the other hand, for extraction of accelerated H_2^+ ions a stripping foil can be used. This will increase the output proton beam intensity twice compared to the internal H_2^+ beam current: each H_2^+ ion generates 2 protons downstream the stripping foil. The price in this case would be essentially bigger size of the facility compared to the cyclotron for proton acceleration with the same central magnetic field.

The goal of present work is investigation of various variants of superconducting cyclotrons for production of proton with output energy about 70 MeV in terms of their main technical parameters and extracted beam characteristics. Comparison of obtained parameters with that for existing commercial cyclotrons is also included. The highly realistic computer modelling of the proposed accelerators was performed with usage of spatial distributions of the facility electromagnetic fields and careful beam dynamics analysis.

PROTON CYCLOTRON

The 70 MeV cyclotron for acceleration of ions with charge to mass ratio 1 has K-value 70 MeV. So, in the paper we adopt K70 as a name for the machine. For protons the main limitation for the magnetic field level relates to the possibility of the practical realization of the machine central region. Calculations show that for magnetic field above 2.9 T it will be highly problematic to design the required center structure since it is almost impossible to install the spiral inflector infrastructure in the region: there is no room for potential connections to the inflector electrodes. The inflector diameter together with its RF shield is less than 25 mm for 2.9 T central magnetic field. The cyclotron magnetic system has 4-fold structure based on spiral sectors (Fig. 1). The valley axial gap 450 mm permits placement of 2 spiral RF cavities operating on the 2nd harmonic with frequency 88 MHz. The peak dee voltage of 30 kV is limited by consumption power in the system. The axial gap between the sectors reduces from 30 mm in the central region to 22 mm at the final radius. Parameters of the superconducting coil and required space around it for placement of the cryostat were selected looking at similar configurations of the successfully operating cyclotrons. The engineering current density in the coil is 75 A/mm^2 as result of this approach. The obtained eventually magnetic field distribution provides a sufficient axial focusing of the beam with axial betatron frequency being above 0.2 in the whole radial range (but the very center). The resulting diameter of the cyclotron is less than 2 m and its weight ~18 t.

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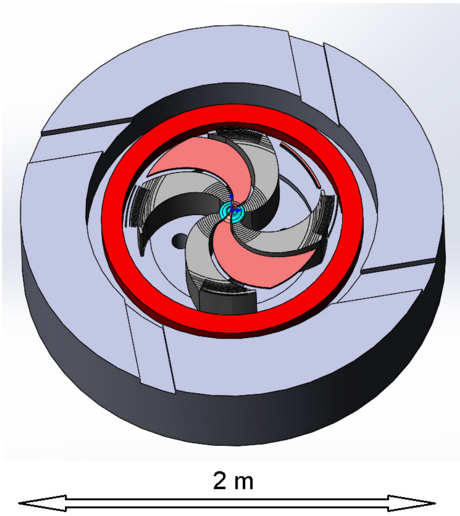

Figure 1: Cyclotron magnetic system.

The central region design permits both external and internal ion source applications. To change the mode of the operation the only dee tips should be replaced. The spiral inflector and internal PIG ion source are inserted axially to the working positions. The corresponding opening in the magnet return yoke and the pole are foreseen for both regimes. More detailed investigation of the beam dynamics was performed for operation with the internal ion source.

The central region design provides high efficiency of the beam transmission about 30% and good centering of the accelerated particle orbits with the amplitudes of the radial betatron oscillation being on average less than 1 mm in the whole working radial range. The cyclotron extraction system consists of electrostatic deflector with 110 kV/cm field strength and two passive magnetic channels. The first magnetic harmonic introduced by the channels will be compensated by corresponding magnetic elements installed just opposite the channels azimuthally. Besides the septum and anti-septum, the magnetic channels have also a set of the shimming plates to minimize the field perturbation in the region of the final internal orbits of the accelerated particles.

The beam extraction efficiency about 60% was obtained by the simulations. In compliance with the purpose of the study the only main characteristics of the cyclotron were defined for comparison to other designs without detailed optimization of the extraction system. The beam quality of 14 π·mm·mrad (horizontal emittance) and 1 π·mm·mrad (axial emittance) were obtained for the extracted beam. Despite of very small size of the spiral inflector (Fig. 2), the preliminary analysis shows that it is possible to converge to the technically realized construction of the unit. Installing a buncher to the axial injection line it is possible to reach about 30% beam transmission efficiency through the central region after carefully matching of the beam emittance to the acceptance of the cyclotron. Given adopted limitation on the beam loss power to be below 1 kW [3] and optimistic extraction efficiency of ~87%, the internal beam intensity should be below 120 μA, i.e., extracted beam current will be 100 μA. The extraction efficiency about 90% could be obtained using a set of phase slits in the central region. In the internal ion source regime, the beam intensity at injection can exceed 60 μA. Extracted beam current in this case can reach ~14 μA.

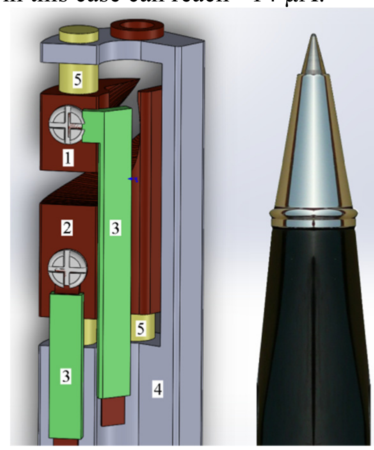

Figure 2: Structure of spiral inflector: 1 – upper electrode, 2 – lower electrode, 3 – potential connections, 4 – electrode fixation, 5 – ceramic isolators.

H_2^+ CYCLOTRON

As an example of H_2^+ accelerator for obtaining 70 MeV proton beam the superconducting cyclotron K280 [4] can be considered. The facility is planned as an injector of carbon beam to hadron therapy complex [5]. The cyclotron has 3-fold magnetic structure with the central magnetic field of 2.64 T (Fig. 3). All valleys are occupied by the spiral cavities operating on 3rd RF harmonics with frequency 60.8 MHz and peak voltage 90 kV. The cyclotron has uniform 52 mm gap between the sectors, which is sufficient for placement all elements of the extraction system. The engineering current density in the coil is selected to be 70 A/mm^2. Diameter of the cyclotron is 3m and its magnet weight is ~70 t.

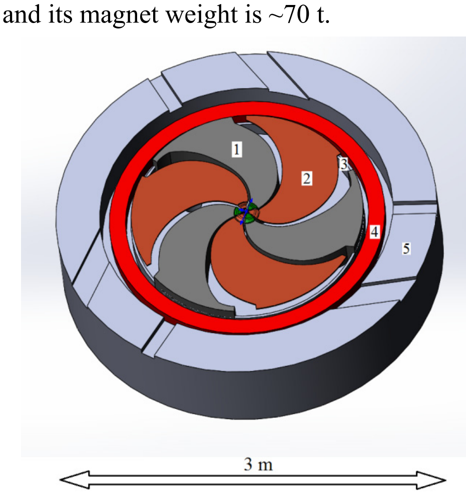

Figure 3: Cyclotron K280: 1 – sector, 2 – dee, 3 – valley shim, 4 – coil, 5 – yoke.

As an external ion source, ECRIS SUPERNANOGAN [6] can be used for production H_2^+ ions with intensity above 1 emA at maximal extraction voltage of 30 kV. The ion source is placed 3 m above the cyclotron median plane.

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The main magnet fringe field is sufficiently small at the position of the source. The designed low energy beam transport line (LEBT) connects the source with the cyclotron. After passing through the horizontal section of the LEBT, where the analyzing magnet focuses ions in both transverse directions, the beam enters the axial injection line. The beam intensity in the LEBT can be measured by a Faraday cup, and the beam adjustment can be performed by the electrostatic steerer. There are also three room-temperature 200-mm solenoids for transverse focusing of the beam. The axial magnetic field produced by the cyclotron magnet in the injection line is rather high, leading to strong over-focusing of the particles. This induces large angular spread in the beam. The effect can be mitigated with the help of the solenoid closest to the main magnet. The solenoid field direction is opposite to that of the cyclotron. In the line the sine-wave buncher ensures longitudinal focusing of the injected beam.

The tune diagram shows that there is no crossing of dangerous resonances in the acceleration range except the very last turns, where the following resonances occur: parametric resonance (*2Qz=1)* and coupling resonances of the third and fourth order (*Qr-2Qz=0, 2Qr+2Qz=3, 2Qr-2Qz=1*).

The central region structure was carefully optimized to provide the best axial focusing and centering of the initial turns in the cyclotron. The spiral inflector design with its RF shielding allows sufficient space for the inflector potential leads. In compliance with the transverse size of the beam the inflector aperture was chosen to be 4 mm. The electrical radius of the inflector is 20 mm for potential at the electrodes of ±6 kV. The magnetic radius of the inflector is 13.4 mm. The inflector itself moves into the cyclotron axially to its working position inside the RF shielding attached to the dummy dees. There is a possibility of rotating the inflector inside the RF shield by several degrees for better matching of the injected beam to the central region acceptance. In the central region there are several posts attached to the dees and dummy-dees to provide sufficient scraping of the so-called "tails" from the injected beam distribution over its cross section and, simultaneously, to increase the rigidity of the unit structure (Fig. 4). The axial aperture available for the beam passage is 6 mm on initial turns.

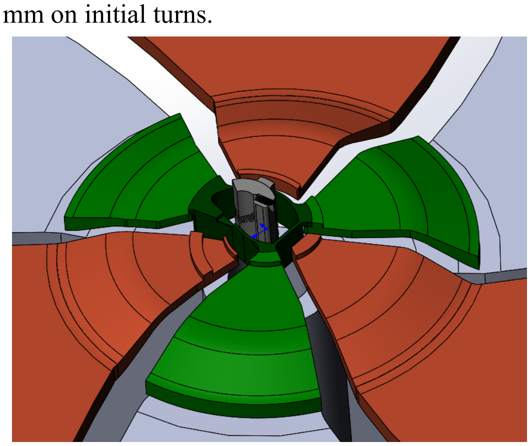

Figure 4: Central region structure of the K280 cyclotron.

The high-efficiency extraction of the proton beam can be obtained by stripping the H_2^+ ions on the foil placed inside the vacuum chamber of the accelerator. The method permits varying the output beam energy in a limited range. Calculation the energy variation by changing the stripping foil position shows a drastic difference in the trajectories corresponding to various energies with no point in the cyclotron magnet yoke where these tracks belonging to different energies converge. For example, protons of relatively low energy of 35-40 MeV make two turns in the vacuum chamber, and their trajectories in the magnet yoke are fairly separated from the corresponding paths of protons with higher energy, namely, 60-70 MeV (Fig. 5). Also, strong dependence of the beam axial envelope on the stripping foil position takes place. This effect limits the permissible energy variation of extracted protons by above mentioned 60-70 MeV range.

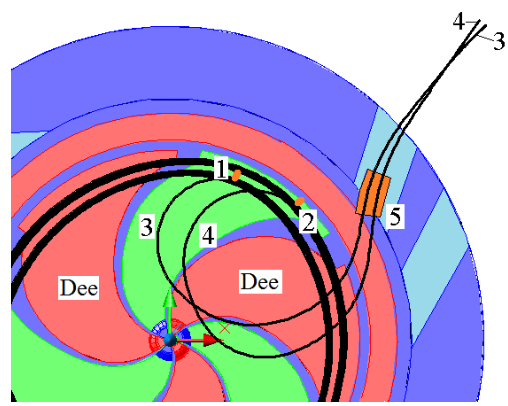

Figure 5: Extraction protons from K280 by stripping foil: 1 – the foil location for extraction of 60 MeV protons, 2 – the foil location for extraction of 70 MeV protons, 3 – trajectory of 60 MeV protons, 4 – trajectory of 70 MeV protons, 5 – bending magnet for steering proton beams with output energy in the range 60-70 MeV.

3D simulation of the proton extraction by stripping H_2^+ ions shows that the axial size of the H_2^+ beam on the stripping foil reaches ~6 mm. The axial focusing of the proton beam downstream the stripping foil is not sufficient. As a result, the axial envelope of the proton beam increases drastically to 30-50 mm at the exit of the magnet yoke (Fig. 6), the main reason for that being the axial over-focusing near the main coil. The improvement can come from installation of a combined-function-dipole in the yoke outlet window. In addition to the increased axial focusing, the dipole can provide also converging of 60 to 70 MeV proton paths to a common switching magnet for their transport downstream a single versatile set of the beam lines. Calculations show that the extraction efficiency by the stripping reaches ~95% in this case. Given the ion source H_2^+ ions intensity of 1 mA and accelerated particle current of 440 μA upstream the stripping foil, the output proton beam current can reach ~800 μA. Calculated horizontal and axial emittances of the output beam are 30 and 20 π·mm·mrad correspondingly with energy spread of ±0.67%.

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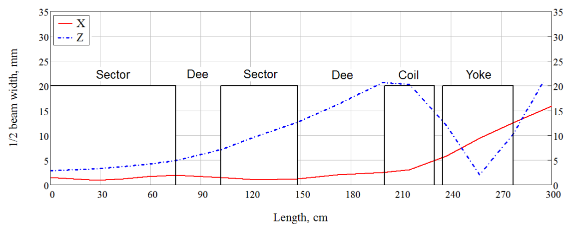
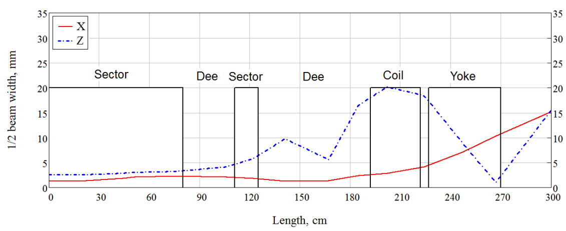


a)



b)

Figure 6: Extracted beam envelopes with energy of 70-MeV (a) and 60-MeV protons (b).

CONCLUSIONS

Application of high magnetic fields in a superconducting cyclotron for final energy of 70 MeV does not permit acceleration of H^- ions. So, protons or H_2^+ ions can be used instead. Selection the proton as an accelerated particle has some disadvantages (no possibility of the output energy variation, lower extraction efficiency) compared to H^- acceleration variant. But the size and weight of the proton superconducting cyclotron are smaller by 2-3 times and by 7-10 times correspondingly (Table 1). Also, the proton cyclotron can provide a good quality of the output beam, which is in compliance with its possible medical application. A superconducting cyclotron for H_2^+ ions acceleration with K-value of 280 MeV is 4 times heavier compared to corresponding superconducting proton cyclotron at the same energy of the output beam. But even in this case the cyclotron is by several times lighter than a room-temperature machine for the same application. Also, usage of the stripping foil for beam extraction will ensure a number of positive features mentioned in the text of the paper. Besides, the K280-variant of the cyclotron can be designed with 4-sectors magnetic structure with even higher magnetic field. This will reduce the size of the machine even more. Another optimization would be a decreasing the acceleration voltage leading to lower RF consumption power. Application of 2 instead of 3 dees also can be considered to make the design simpler and more reliable. All calculations conducted for the design of the cyclotrons were performed for realistic configurations that were as much as possible close to the existing and successfully operational facilities. In this context it is worthwhile to mention selection of moderate engineering current density in the main coil of the cyclotron magnet, assignment of sufficient space for cryostat and extraction system elements et al.

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Table 1: Summary Table of Parameters

Description	**K70**	**K280**	**IBA Cyclone 70**	**BEST 70**	**NIIEFA C80**
Ion	p	H_2^+	H^-	H^-	H^-
Energy, MeV	70	60-70	30-70	35-70	40-80
Beam intensity, μA	100	800	750	700	200
Injection type	Cusp/PIG	ECR	Cusp	Cusp	Cusp
Dimensions: D×H, m	2.0/1.0	3.0/1.4	4.0/3.8	4.5/1.7	5.7/2.6/3.4
Weight, t	18	70	140	195	250
Central magnetic field, T	2.89	2.64	1.0	0.95	1.35
Extraction type	ESD	Stripping	Stripping	Stripping	Stripping
RF voltage	30	90	50	70	60
Country	Russia	Russia	Belgium	Canada	Russia