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NOVEL APPROACH TO DESIGN OF THE COMPACT PROTON SYNCHROTRON MAGNETIC LATTICE

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Abstract

A compact proton synchrotron for cancer therapy has been developed. The proposed magnetic lattice includes short dipole magnets with opposite direction of the field. The lattice optical functions are close to the usual for weak-focusing synchrotrons. At the same time, it allows achieve value of momentum compaction factor less than unity, and thereby avoid intensity limitations due to longitudinal instabilities. Multiturn injection and resonance extraction description finalizes the presented design of compact proton synchrotron.

INTRODUCTION

Every year new facilities for hadron therapy are commissioning worldwide. In the market, several companies supply turnkey solutions based on cyclotrons and synchrotrons. Various research groups develop new conceptions, and optimize traditional design.

Last years, an interest in the compact single room proton therapy systems has grown significantly in the cancer treatment community. It is the cost effective solution for small hospitals to be involved into the proton therapy. First single room proton therapy facility supplied by Mevion Medical Systems shown successful results of operation [1, 2]. Now most manufacturers propose single room modifications of supplied equipment. Two of them, HITACHI and PROTOM developed compact particle therapy systems based on synchrotrons [3, 4]. These accelerators have diverse conceptions and significantly different parameters.

The presented article describes the results of an attempt to find an optimal design of compact proton synchrotron. The main idea is that optimum should be between the systems mentioned above and should incorporate merits of both.

MAGNETIC LATTICE

Lattice with non-gradient bending magnets and edge focusing is the most compact. Such lattice was used in the facility developed in BINP [5]. An imperfection of the system was the low intensity of proton beam about of $5 \cdot 10^8$ particles per cycle. The intensity limitation was caused by longitudinal negative mass instability at injection energy and small vertical aperture [6]. The main reason of instability growth is the large value of momentum compaction factor $\alpha > 1$. Instability can be suppressed by beam energy spread but for intensity about of 10^{10} protons, the required energy spread is larger than achievable energy acceptance of synchrotron.

Installation of one quadrupole lens per cell moves optics to the normal regime. Maximal values of ß-functions are increased significantly, so vertical aperture shall be enlarged accordingly when transverse acceptance saving. Note that value of momentum compaction factor should be small enough to avoid transition crossing in the treatment energy range. It is the traditional lattice design, but disadvantages of this solution are high costs and energy consumption.

Further increasing of quadrupoles number can provide good enough optics. However, additional quadrupoles enhance free space problem and impede injection and extraction.

Application of field gradient bending magnets provides useful design, also. However, a limitation of field value leads to enlarging of synchrotron dimensions.

Therefore, the weak focusing lattice with non-gradient bending magnets is most simple and cost effective. The negative mass regime problem or in other words the problem of additional horizontal focusing shall be solved. Bending magnets edges determine vertical focusing and fix it. So, the bending angle is an operating parameter only. The bending angle is increased up to more than 360º for achieving of required values of horizontal tune, momentum compaction and transition energy. Finally, for closing reference orbit magnetic field in part of magnets shall be reversed. It is a simple solution which is used sometime in storage rings for high energy physics. After optimization the novel compact lattice for proton synchrotron was developed.

SYNCHROTRON DESIGN

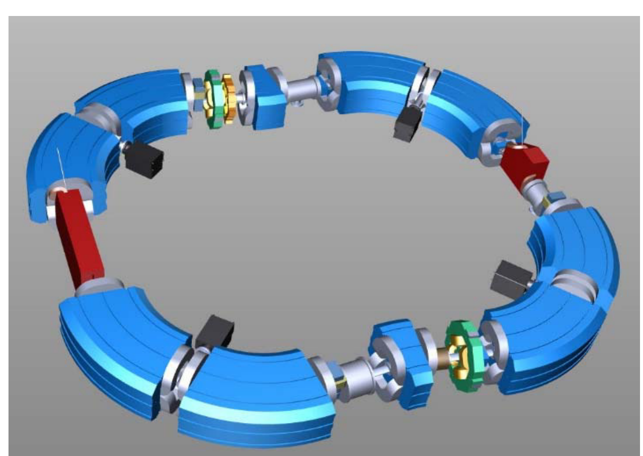

Figure 1: 3-D model of the synchrotron.

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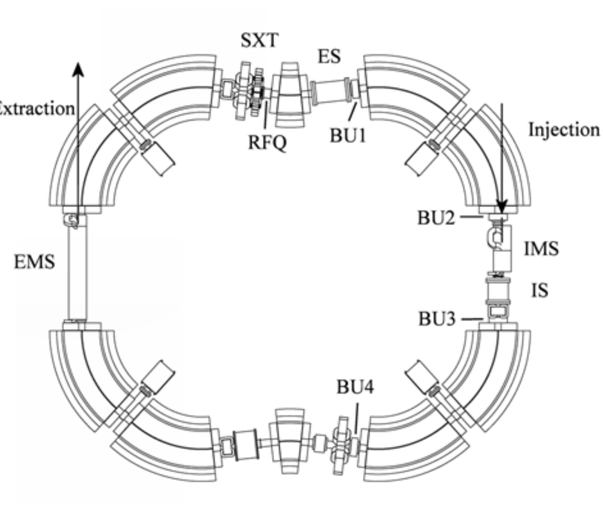

Figure 2: Preliminary layout of the synchrotron.

Preliminary 3D model and layout of synchrotron are presented in Figs. 1, 2 accordingly. Main parameters of synchrotron are listed in Table 1.

Synchrotron lattice consists of four 96° quadrants, two reverse 12° bending magnets, and straight sections (two sections with length of 150 cm and four sections with length of 80 cm). Every quadrant includes two 48° bending magnets and short straight parts with length of 25 cm. The short straight parts are used for beam position monitors and pumping out ports installation. The quadrant dividing is motivated by simplification of laminated bending magnets design. Moreover, installation of vacuum pumps in the middle of quadrant leads to smooth pressure distribution. In the long straights correction magnets, elements of injection/extraction, RF cavity, and diagnostics equipment are installed. The optical functions of the synchrotron are presented in Fig.3.

Table 1: Main Parameters of Synchrotron

Parameter	Value
Particles	p
Injection energy	3.5 MeV
Extraction energy	70 – 230 MeV
Circumference	16.1 m
Repetition rate	1 Hz
Betatron tunes ν_x/ν_y	1.29/0.9
Momentum compaction α	0.617
Transition energy γ_{tr}	1.273
Max β – functions x/y	2.5/3.4 m
Max dispersion	2.1 m
Chromaticity x/y	-0.35/-0.54
Regular vacuum chamber	Elliptical, 82 x 32.7 mm
Working aperture x/y	60 x 30 mm
Acceptance x/y	35.6/ 7.7 cm·mrad
Momentum acceptance	±1.5%
Orbit dimensions	500 x 435 cm
Injection	multiturn
Extraction	resonance

The working point is chosen by follow reasons:

i) The horizontal tune should be close to n/4 for multi-turn injection high efficiency;

ii) The horizontal tune should be not far from n/3 for easy detuning at resonance extraction;

iii) The footprint due to space charge tune shift shouldn't be crossed by low order machine and sum resonances.

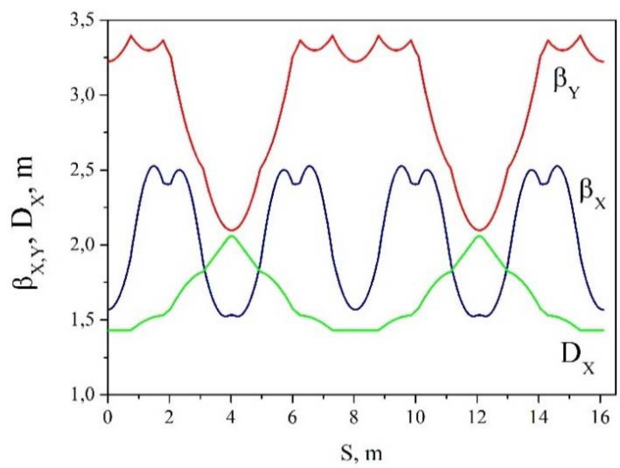

Figure 3: Optical functions of the synchrotron.

All bending magnets with maximal field 1.86 T supplied in series. The curved yokes of H-type magnets will be assembled from two half-cores and two water cooled saddle type excitation coils. The magnetic field simulations was made using MERMAID code. The model and results of the simulation are presented in Fig. 4. The generation of high magnetic field with acceptable losses requires fool filling of coil window. Moreover, few turns are inserted into the magnet gap.

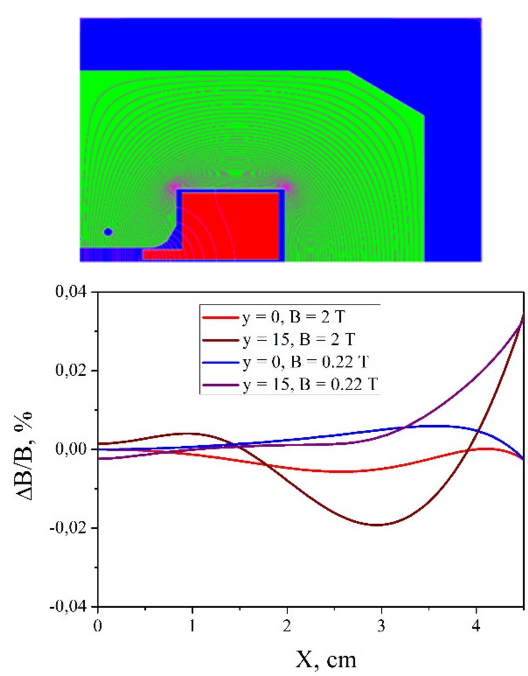

Figure 4: The design of the bending magnet (top), and field quality at different currents (bottom).

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INJECTION AND EXTRACTION

RFQ linear accelerator with energy of 3.5 MeV is proposed as an injector. Commercially available RFQ provides current up to 3 mA with pulse duration up to 350 μs. Injected beam has transverse emittance about of 5 mm·mrad and momentum spread of ±0.75 %.

For accumulation of protons in the synchrotron, the multi-turn injection is proposed. Before the moment of injection, bump magnets (BU1 - BU4) shift locally the reference orbit close to the septum. The bump magnets are supplied with a pulse current with duration up to 350 μs and injection process is realized at the linear falling part of the field.

Two septums are used at injection. The first one is Lambertson type septum (IMS) with field of 0.6 T and bending angle about of 1050 mrad has thickness of septum about 6 mm. The second one is the bending electrostatic septum (IS) with deflection angle of 70 mrad and thin foil with thickness of 0.1 mm. The injection scheme is presented in Fig.5.

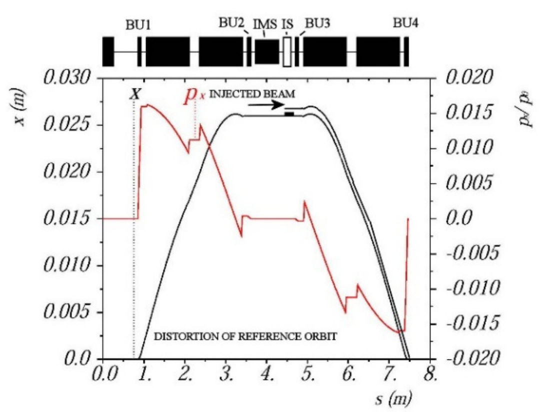

Figure 5: The local distortion bump and the orbit for injection.

The feature of proposed injection is accumulation of protons with small momentum spread and betatron oscillations amplitudes only. Other particles any case will be lost due to aperture limitations, injection mismatches and a space charge. Simple simulations of injection was made for preliminary calculation of efficiency. As it shown at Fig.6, the efficiency of injection decreases with time from 35 % for 20 μs down to 12 % for 350 μs.

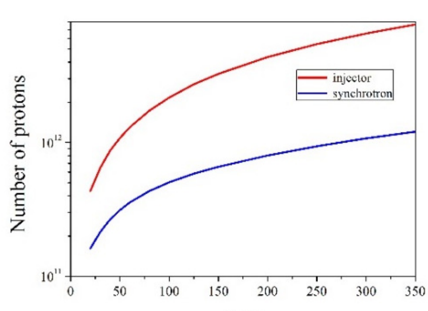

Figure 6: Number of protons generated by injector (red line) and stored into synchrotron (blue line) versus time.

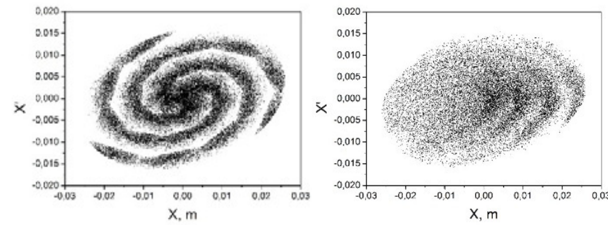

Figure 7: The phase space mapping for beam without (left) and with energy spread (right). The injection time is 20 μs.

The typical horizontal phase space mapping for beams with different value of momentum spread is presented at Fig.7.

The RF knockout scheme is proposed for slow beam extraction [7, 8]. Extracted particles income to the electrostatic septum with foil thickness of 0.1 mm, and horizontally kicked to the aperture of extraction Lambertson magnet with vertical bending angle 474 mrad and effective septum thickness of 6 mm. The results of preliminary extraction simulation are shown at Fig.8. The extracted protons are driven by transverse RF kicks from stable beam core through separatrix to unstable region.

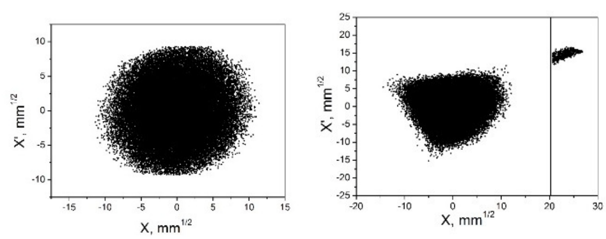

Figure 8: The normalized horizontal phase space at septum azimuth during extraction, with amplitude modulation by random noise (all extracted particles are shown in picture).

CONCLUSION

The novel design of compact proton synchrotron is proposed. It includes short bending magnets with reverse field. Such design prevents longitudinal instability growth that is typical for weak focusing accelerators. The development will be continued for optimization of working point, injection and extraction efficiency.

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