THE FOCUSING STRUCTURE OF THE PRAGUE PROTON SYNCHROTRON FOR HADRON THERAPY

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Abstract

This paper reports a lattice design of a dedicated proton synchrotron for hadron therapy. This synchrotron, named as a Prague Medical Synchrotron (PRAMES), will be used as a kernel of an accelerator complex of a Prague Oncological Hospital (Czech Republic). The synchrotron will be able to accelerate high-intensity proton beam of $6.25 \cdot 10^{10}$ protons per pulse till the energy of 60÷220 MeV with the 1 Hz repetition rate. The active scanning of tumours is assumed. To satisfy this requirement, the slow (third-order) extraction scheme is analysed. The single turn injection of the proton beam is utilised to get the trapped proton beam with small transverse emittance on the injection energy of 12 MeV. The developed focusing structure of the ring has two superperiods with two long straight sections to install the injection, acceleration and extraction systems. Each period is composed of two achromatic cells to provide, first of all, a high efficiency of the slow extraction. The cell consists of two rectangular dipole magnets with the 45 degree bending angle and 22.5 degree edge angle at both ends, and a triplet of quadrupole lenses. To adjust the working point to the slow extraction, an additional quadrupole triplet in the superperiod is utilised. The output horizontal and vertical tunes are 2.666 and 1.8, respectively. The slow extraction scheme of the accelerated proton beam is discussed in the paper.

1 INTRODUCTION

A good clinical experience with proton-beam radiotherapy has stimulated the interest in designing and constructing dedicated hospital-based machines for this purpose. Reliability and simplicity without loosing the required parameters of the machine, should be considered, first of all, to design this accelerator. The technological and economic requirements for these machines are of great importance for an industrial approach. A synchrotron meets the machine requirements better than a linear accelerator or a cyclotron [1]. The dedicated proton synchrotron is built in the Loma Linda University Medical Center (USA). There are several projects offered in different countries (USA, Japan, Italy, China). Most of the proposed medical synchrotrons are based on the weak-focusing structure to get a compact design.

Specifications for such a machine are not hard but a consensus is necessary on several key requirements [2]. Extraction energy of the proton beam should be from 60 MeV till 220 MeV with the energy variability less than 0.4 MeV to treat the cancer at different depth. The average beam current should be, at least, 10 nA for reasonably short treatment periods of time. The injection energy may be small. The minimum value of this energy can be estimated using the Laslett tune shift. But the accelerator complex for cancer therapy should be able to produce the short-lived radiopharmaceuticals for the proton emission tomography (PET). Then it is necessary to find some compromise between an injection energy and cost of the injector. A low current injector can be accommodated by using multiturn injection but this additional complexity should be avoided in a medical accelerator. The single-turn injection is chosen.

The transverse emittance and momentum spread should be as small as possible. Real normalised transverse emittance for the proton linear accelerator is equal to 0.6π µm.rad, then one can assume the normalised emittance of the trapped beam of 1π µm.rad and the momentum spread of ± 0.003 on the injection energy.

The PRAMES has been designed to accelerate the 12 MeV high-intensity proton beam from a RFQ/DTL linac to the maximum output energy of 220 MeV. To satisfy the requirements of the slow extraction, the focusing structure of the dedicated proton synchrotron for the cancer therapy is proposed. The lattice design is based on the achromatic cells with conventional warm dipole magnets. The repetition rate is chosen of 1 Hz to have a sufficient time duration for the slow extraction. Using the active scanning of the tumour with protons for a single spill, the tumour will get at least $5 \cdot 10^{10}$ protons per pulse. The spill time could be till 250 ms. The slow extraction using the third-order radial resonance determines the working point position. The strong-focusing lattice has been analysed to get good controlled transverse dimensions of the proton beam.

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2 PRAMES LATTICE DESIGN

The general layout of the PRAMES lattice is shown in Figure 1.

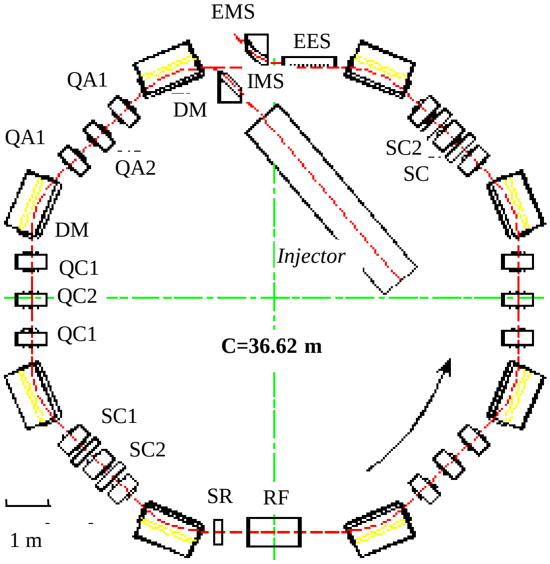

Figure 1: General layout of the ring of the PRAMES.

The main parameters of the PRAMES are listed in Table 1.

Table 1

Output kinetic energy (MeV)	60 ÷ 220
Energy variability (MeV)	< 0.4
Energy variability accuracy (MeV)	< ± 0.35
Average current (nA): patient / acceleration	7.8 / 10
Repetition rate (Hz)	1
Norm. transverse emittance(π.µm)	1
Number protons per pulse: patient (active scanning) acceleration	$4.8 \cdot 10^{10}$ $6.25 \cdot 10^{10}$

The developed focusing structure of the ring has a race-track configuration with two long straight sections to install the injection, acceleration and extraction systems. To minimise the β-function and the dispersion function, the double bend achromat with the focusing triplet (QA1-QA2-QA1) is utilised. The dipole magnets (DM) are the rectangular magnets with the bending angle of 45°. To minimise the coil current, the maximum magnetic field is equal to 1.2 T. The working point position can be optimised by the adjusting triplet of the quadrupole lenses (QC1-QC2-QC1). The lattice of the synchrotron has two sorts of the sextupole lenses. The sextupoles in the arcs with a finite dispersion are grouped into two families (SC1, SC2). They only influence on the chromaticity. The sextupole lens (SR) in the non-dispersion straight section influences only on the beam behaviour near the third-order resonance line.

The lattice parameters are listed in Table 2. The focusing structure of the ring is calculated using the MAD and the AGILE programs.

Table 2

Main parameters of the Prague proton synchrotron

I. Proton Beam Properties (round beam)	Proton Energy (MeV)	
	12	220
Momentum (MeV/c)	150.535	679.123
Rigidity (Tm)	0.502	2.265
Acc. Emittance (π µm)	6.232	1.381
Energy spread	±0.003	±0.0014
Orbit Period (µsec)	0.77	0.208
Incoh.Vt. Tune Shift @ $6.25 \cdot 10^{10}$ protons	-0.052	-0.009
II. Lattice Parameters		
Circumference (m)	36.62	
Dipole magnet field (T): min / max	0.26599 / 1.2	
Straight Section (m)	3.5	
Bending Radius (m)	1.88768	
Effective Length of the dipole magnet (m)	1.4825	
Dipole Edge Angle (deg)	22.5	
Number of Quadrupoles: achromatic + adjusting	12 + 6	
Max.Quad.Strength (m^{-2})	5.0	
Betatron tune on the extraction: ν_x / ν_z	2.666 / 1.8	
β-functions (220MeV) β_x (m) : max / avegare β_z (m) : max / average	 7.089 / 3.037 8.46 / 3.6297	
Dispersion (m): max / av	1.026 / 0.3337	
Chromaticity (ξ_x , ξ_z) natural corrected	 -4.977 , -3.627 -4.981 , -3.609	
Transition energy	5.562	
Working region H/V,mm	80 / 55	

The magnet field uniformity in the dipole magnet of the ring should be less than $5 \cdot 10^{-4}$. The vertical dimension of the working region is determined by the vertical beam size on the injection energy. But in a machine uisng a slow extraction, the good-field region required for the extraction becomes the important characteristics in the horizontal plane. The “stable” region during extraction will occupy the same horizontal space at all energies. Then the horizontal “good” field region should be the same for both - the injection and extraction energies. The horizontal size of the working region is equal to 80 mm for the electrostatic septum (EES) described below.

3 RESONANCE EXTRACTION

The tumour is treated with the spatial definition of a voxel (e.g. 5×5×2 mm^3). The spill must be uniform. It requires a relatively long, high-quality spill. The extracted beam should have the same extraction trajectory amd momentum spread throughout the spill time. To avoid losses of the particles in the extraction elements, the achromatic cells are used for the focusing structure design.

The amplitude selection method is chosen from possible extraction techniques. This classic method needs the minimum of equipment. The spill can be switched on and off using special quadrupoles. The developed focusing structure of the synchrotron has two families of the adjusting quadrupole lenses to lead the working point on the different extraction energy to the resonance line $8\nu_x=3$ (Figure 2).

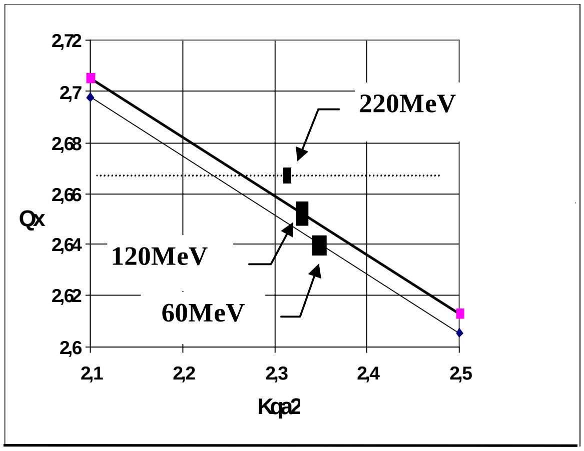

Figure 2: Variation of the horizontal betatron tune for different kinetic energy to lead to the third-order resonance line $3Q_x=8$. The strength of the second (focusing) quadrupole lense is fixed (Kqa1=-1.28957 m^{-2}).

To ensure transverse stability for the extracted beam, the chromaticity of the lattice should be negative. The natural chromaticities of the proposed structure are -4.977 (horizontal) and -3.627 (vertical). Correction of the chomaticity is determined by the extracted beam quality.

The third-order resonance is driven by a sextupole perturbation of the resonance sextupole lense (SR) installed in the zero-dispersion long drift space. The effective length of the sextupole lenses is equal to 15 cm. The normalized strength of the resonance sextupole is equal to 12.8 m$^{(-1/2)}$.

Two families of the sextupole lenses (SC1, SC2) are placed in the non-zero dispersion arcs of the ring to correct the chromaticity and escape the angular dispersion of the extracted particles with different momentum

The normalized strength of the sextupoles are less than 0.1 m$^{(-1/2)}$. The corrected chromaticities of the proposed structure are -4.981 (horizontal) and -3.609 (vertical). The horizontal phase space of the extracted beam is presented in Figure 3. The kinetic energy of the proton is equal to 220 MeV with the relative momentum spread of ± 0.0014. Calculation of the slow extraction is performed using the AGILE program.

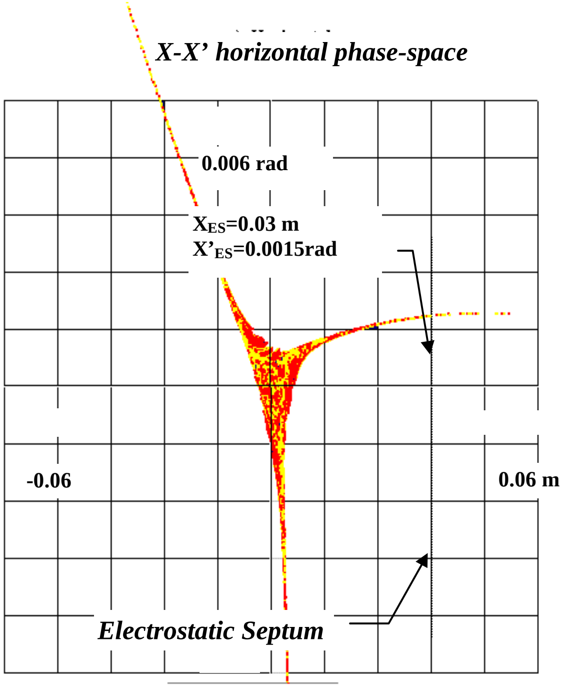

Figure 3: The horizontal phase-space for the third-order resonance extarction of the accelerated particles (on the entrance into the electrostatic septum).

A high efficiency (98%) of the extracted particles is an important requirement for this machine. Then the elements of the extraction channel are the electrostatic (EES) and magnetic septa (EMS). The both elements are located in the zero-dispersion long drift space. The electrostatic septum has to be designed with the 0.05 mm wire diameter. The distance between the circulating beam and the wires of the electrostatic septum is assumed to be more than 25 mm. The gap between the plates of the septum is equal to 10 mm. The length is equal to 1200 mm. The applied voltage is 40 kV. The developed focusing structure of the ring allows to provide a sufficient deviation of the extracted beam from the circulating one to install the first magnetic septum with the blade thickness about 10 mm.

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