CONCEPTUAL STUDY OF PULSE HIGH FIELD COMPACT PROTON SYNCHROTRON FOR MEDICAL USE

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Abstract

Feasibility is studied about a compact 200 MeV proton synchrotron using very high field (4 T), short pulse (3.5 ms) bending magnet for proton therapy system. The lattice design, injection and extraction, RF acceleration and dynamic aperture are discussed.

1 INTRODUCTION

Radiation therapy using high energy proton or carbon has been proved to be a very effective method of cancer treatment. For the spread of this effective therapy system, compact and low cost accelerators are strongly required. A challenging idea of proton synchrotron using pulse high field (5 T) magnet was proposed by BINP [1], and a joint study of Frascati and BINP proposed a more feasible design using 4 T pulse magnet [2]. Endo K. et al. (KEK) have proposed a design using more relaxed bending field of 3 T for the realization of a very small proton and carbon synchrotron [3]. The authors have studied the feasibility of 4 T magnet synchrotron, and have shown that improvement of magnet shape can reduce higher order components of magnetic field, and can increase the dynamic aperture considerably [4,5].

This paper reports the further study of the feasibility and a revised design of 4 T proton synchrotron, using an improved design of bending magnet [6].

2 LATTICE DESIGN

2.1 Lattice and main parameters

Major parameters of this revised design study are listed in Table 1. Figure 1 shows the lattice layout. As medical accelerators require the simplicity of adjustment and operation, the authors adopted the lattice formed by four bending magnets with bending radius 0.54 m and edge angle 4.5 deg. Therefore, the problem of the miss of tracking between bending and quadrupole fields is avoided. Two quadrupole magnets are prepared for tune survey and changing of operation point during development step. Two sextupole magnets are also equipped for the decrease of the effect of unexpected sextupole field. Although, tune shift due to natural chromaticity is sufficiently small, and chromaticity correction is unnecessary. A bump magnet and a fast kicker are set on the same straight section. Injection and extraction septums of Lambertson type are located on the opposing straight section. Injection and extraction are performed in vertical direction. Two RF cavities are equipped, considering the required high gap voltage.

Table 1: Major parameters

Item	Value
Extraction energy, T_{ext}	200 MeV (644 MeV/c)
Injection energy, T_{inj}	3 MeV (75.1 MeV/c)
Circumference, C	6.193 m
Average radius, R	0.986 m
Bending radius, ρ	0.54 m
Bending field, B	0.42 - 4 T
Gap height / width	0.052 / 0.020 m
Bending angle	90 deg
Edge angle	4.5 deg
Acceleration time	3.5 ms
Transition gamma, γ_{tr}	1.283 (265 MeV)
Betatron tune, ν_H / ν_V	1.38 3 / 0.429
Betatron function (Max.), β_H / β_V	1.20 / 2.34 m/rad
Dispersion (Max.), η_H / η_V	1.07 / 0 m
Natural chromaticity, ξ_H / ξ_V	-0.148 / 0.125
RF frequency, f_{RF}	3.86 – 27.4 MHz
Max. RF gap voltage, V_{max}	8.4 kV
Accumulated protons, N	1.3×10^{10}
Repetition rate	2 pulse/s

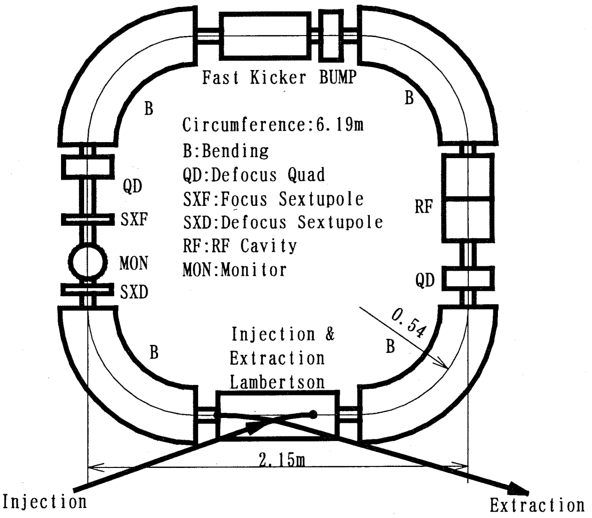

Figure 1: Lattice layout

2.2 Operation point and lattice functions

Figure 2 shows operation points for various edge angles. Adopted operation point is the center of a stable region with edge angle of 4.5 deg and horizontal and vertical tune of (ν_H, ν_V)=(1.383,0.429). Betatron functions and dispersion of this operation point are shown by Figure 3. Lattice related calculation was performed using "MAD".

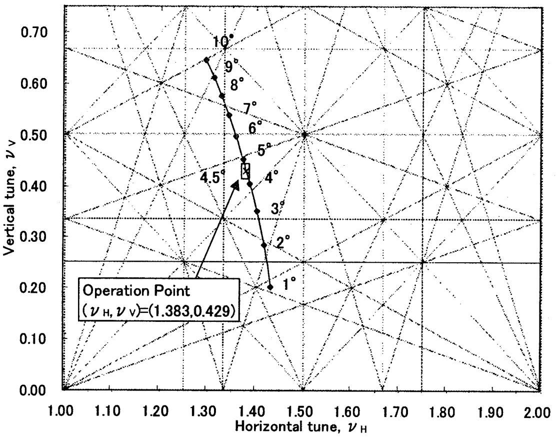

Figure 2. Operation points for various edge angles

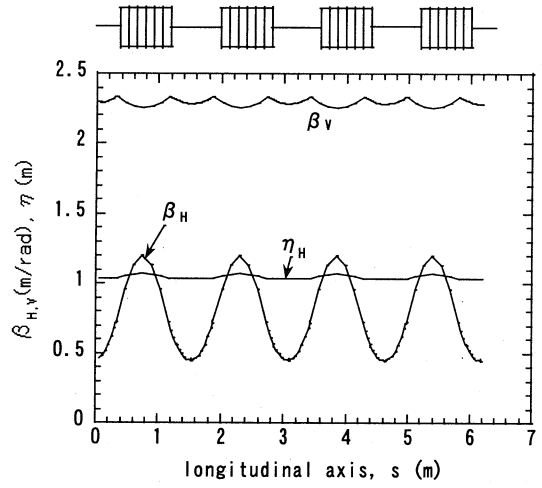

Figure 3: Lattice functions

3 INJECTION AND EXTRACTION

3.1 Injection and accumulated particles

A 3-MeV RFQ (e.g. AccSys Co. Type PL-3i, ϵ_N (normalised) = 0.8π mm-mrad, $\triangle p/p=\pm 0.6\%$, I=15 mA, pulse duration 10-300 μs) seems suitable for the injector, due to its high current and reasonable cost. As momentum spread for effective injection is less than ±0.1% as mentioned later, the estimated effective current is reduced to 2.4 mA for gaussian distribution of momentum. In order to reduce the activation of synchrotron, an energy analysing system is desirable. Using multiturn stacking injection in the vertical direction, the radius of accumulated beam is estimated as shown in Table 2. Assuming that first 4 turn vertical injection is effective, horizontal and vertical normalised emittance of circulating beam can be estimated as 0.8π and 3.2π mm-mrad, respectively. Momentum spread of circulating beam at injection and extraction is assumed to be ±0.1% and ±0.2%, respectively. The value ±0.2% was estimated by RF bucket height as mentioned later. It must be noted that the increase of horizontal radius due to dispersion is kept small by reducing effective momentum spread of the beam from injection system. Rotation error 0.5 mrad and the relative error of field strength 1x10^{-3} of bending magnets cause horizontal and vertical closed orbit distortions (COD) of 0.4 and 0.8 mm, respectively. The symbol "$\triangle$B" denotes the orbit shift of 0.54 mm/turn caused by the rapid increase of bending field during injection. Beam radius will be increased by the shift of 2 turns between 4 turns of injection.

Table 2: Beam envelope (radius, mm)

Factor / Direction	**Emittance**	**Dispersion**	**COD**	**$\triangle$B**	**Total**
	3-200 MeV	3-200 MeV	3-200 MeV	3-200 MeV	3-200 MeV
Horizontal	3.5-1.2	1.2–2.1	0.4	1.1-0	6.2-3.7 (w_H)
Vertical	9.7-3.3	0	0.8	0	10.5-4.1 (w_V)

Number of accumulated protons N is limited by allowable space charge tune shift estimated by the following equation for the elliptic cross-section beam.

$$\Delta \nu_{sc\,H,V} = (R/\nu_{H,V})\, N\, r_p / \{ F_B \pi w_{H,V}(w_H+w_V) \beta^2 \gamma^3 \} .$$

Where, bunching factor F_B =0.42, classical radius of proton r_p=1.535x10^{-18} m, horizontal and vertical beam radius $w_{H,V}$ of Table 2, and relativistic values β and γ are used. Considering the contingency for the unexpected tune migration, a conservatively small value 0.03 is set as the limit of space charge tune shift. Due to the smaller betatron tune, vertical tune shift limits N as 1.3x10^{10}, and corresponding tune shift is estimated as ($\Delta \nu_{sc\,H}$, $\Delta \nu_{sc\,V}$) =(0.016, 0.03), as shown by the rectangle in Figure 2. Two pulse per second operation will fulfil the requirement 2.0x10^{10} proton/s of typical proton therapy systems.

3.2 Extraction

Due to the very short pulse operation, only fast extraction is possible. Because of the vertical tune of 0.429, the accelerated beam is efficiently kicked in vertical direction. Though one turn extraction is most efficient, it is impractical, because of the comparative values of revolution time 36.6 ns and ordinary switching time 30 ns of kicker power supply. For the extraction under the tight space and the large magnetic rigidity, a Lambertson type septum magnet with bending field of 1 T will be one of few practical options. Therefore, thickness of septum will not be less than 1 mm. Vertically extracted beam is bent outward in the horizontal plane with the radius of 2.14 m. In addition to the effect of bump magnet, kicker should move the beam 10 mm at the extraction point with the kick angle of 8.5 mrad. Assuming a travelling wave type magnet, kicker parameters can be estimated as listed in Table 3. As estimated current rising time ~50 ns (sum of switching time and filling time) is smaller than the time for 2 circulation, two turn extraction might be possible, and the expected extraction efficiency will be 85 %.

Table 3: Kicker parameters

Item	Value
Length	0.35 m
Magnetic field	0.052 T
Filling time	17.5 ns
Charging voltage	62.5 kV
Magnet current amplitude	2.5 kA

4 BEAM ACCELERATION

4.1 RF acceleration

The RF gap voltage V kV is estimated by, $V\sin\varphi_s = C\rho dB/dt$, where $B=B_0 \sin(\pi t/2\tau_0)$ with $B_0 = 4$ T and $\tau_0 = 3.5$ ms, and φ_s is the acceleration phase. For keeping RF gap voltage within moderate value, acceleration phase at the starting of RF acceleration is set to be 45 deg with gap voltage of 8.4 keV. The RF control scenario will be to keep the bucket area in ($\Delta E/\Omega$ - φ) phase space during acceleration constant, where $\Omega = 2\pi f_{RF}$. The RF bucket area $A(\Gamma(t))$, can be estimated by,

$$A(\Gamma(t)) = \alpha(\Gamma(t))(16\beta/\Omega)((eV)E/(-2\pi\eta))^{1/2},\ \eta = 1/\gamma_t^{\,2} - 1/\gamma^2.$$

Moving bucket factor $\alpha(\Gamma(t)) = A(\varphi_s(t))/A(0)$ can be approximated as $\alpha(\Gamma(t)) = (1 - \Gamma(t)^{0.79})^{1.27}$ [7], with $\Gamma(t) = \sin\varphi_s(t)$. Using the initial conditions V=8.4 kV and $\varphi_s = 45$ deg, gap voltage and acceleration phase are obtained as shown in Figure 4. Energy deviation during acceleration is less than the bucket height $(\Delta E)_{max}$, in (ΔE - φ) phase space, which is estimated by,

$$(\Delta E)_{max} = \beta\{[(eV)E_s/\pi\eta] \vert (\pi - 2\varphi_s)\sin\varphi_s - 2\cos\varphi_s \vert\}^{1/2}.$$

Using $\Delta p/p = \beta^{-2}\Delta E/E$, this gives the estimation of the maximum possible momentum dispersion $(\Delta p/p)_{max}$ during acceleration. At the extraction energy, it will be estimated as 0.2% with the gap voltage of 0.45 kV and acceleration phase of 30 deg. Time evolution of momentum dispersion at the starting of acceleration needs further study.

4.2 Dynamic aperture

The authors proposed an improved design of a pulse magnet with relative Fourier coefficient of sextupole component less than 3×10^{-4} [5,6]. Using sextupole and decapole components, dynamic apertures for various energy levels during acceleration are obtained as shown in Figure 5. Comparison with estimated beam radius shows that enough dynamic apertures are kept during acceleration. Simulation was performed using "SixTrack".

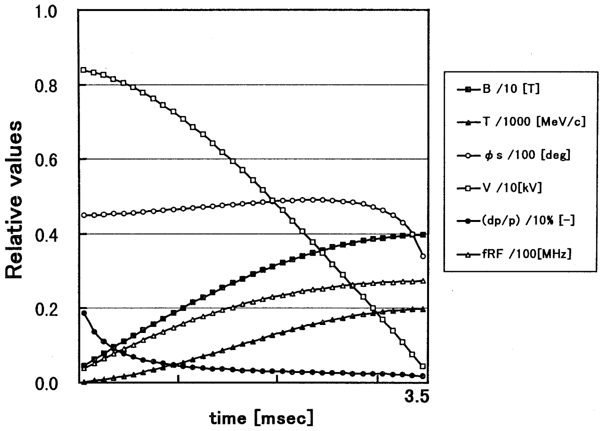

Figure 4: RF parameters during acceleration

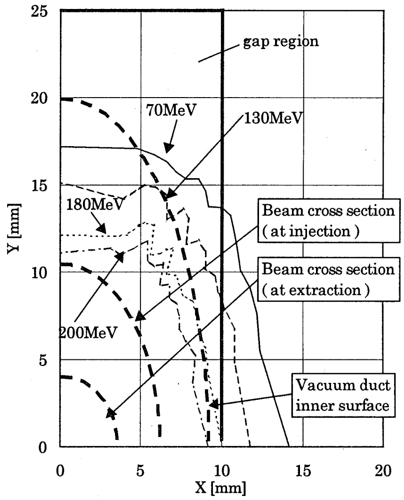

Figure 5: Comparison of dynamic aperture

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