DESIGN STUDY OF PROTON SYNCHROTRONS FOR MEDICAL USE AT KYOTO UNIVERSITY

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ABSTRACT

A proton synchrotron dedicated to medical use with the maximum energy of 250 [MeV] has been designed. The present lattice was adopted after comparison of three typical lattice types from the point of view of making small beam size and dispersion. This paper describes the outline of the design and its major specifications.

INTRODUCTION

For the purpose of cancer therapy, a proton beam with the intermediate energy (70 ~ 250 [MeV]) has advantages of good dose localization due to the Bragg peak, and lower cost for construction. Among several types of such proton accelerators, a proton synchrotron is promising because of its capability of various energy operation and lower cost compared with a proton linac. In fact, a compact proton synchrotron with the maximum energy of 250 [MeV] dedicated to medical use has already been constructed and utilized for clinical treatment at Loma Linda university[1] and another dedicated synchrotron with the maximum energy of 230 [MeV] is proposed at University of Tsukuba[2].

At Kyoto University, a preliminary proposal[3] of proton synchrotron which utilizes its proton linac as the injector has been made. As a prototype machine for medical use and machine study, the synchrotron should be compact so as it can be constructed in a hospital, but some straight sections left for further extensions are also desirable. In addition, its emittance should be as small as possible in order to reduce extracted beam size and magnet dimensions for the economy of total system cost.

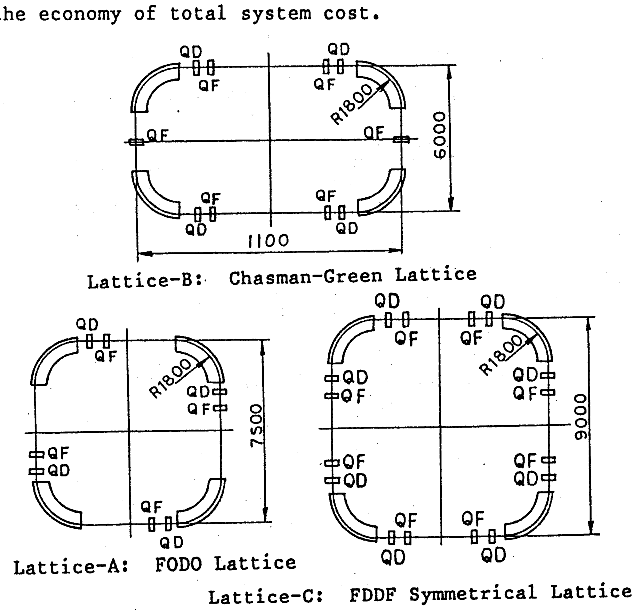


Fig. 1 Schematic layouts of considered lattices

Considering these design requirements, the authors compared three, typical lattices, and chose square, Chasman-Green like lattice as the candidate lattice.

LATTICE CONSIDERATION

As a medical use proton synchrotron needs an additional straight section for beam extraction besides an injection section, lattice layout of few straight sections as racetrack or triangular type, which are sometimes adopted for compact SR rings, are not convenient for our prototype machine design. On the other hand, the lattice layout should be simple

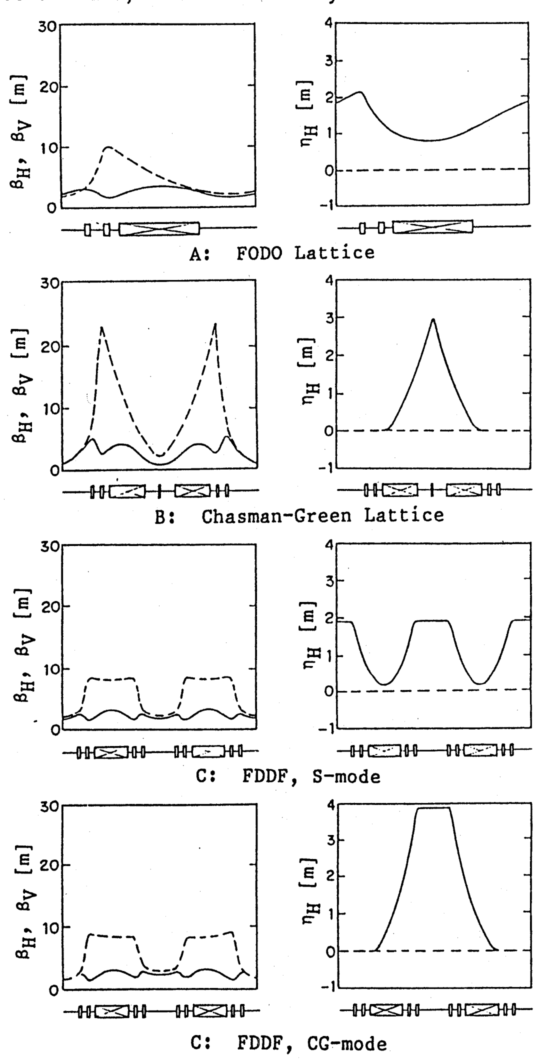


Fig. 2 Betatron functions and Dispersion functions (——: Horizontal, ----: Vertical)

Table 1
Comparison of lattice types

Type	A	B	C(S-mode)	C(CG-mode)
Lattice Description	FODO	Chasman-Green	Symmetrical	Chasman-Green
Layout	Square	Racetrack	Square	Square
Super period	4	2	4	2
Betatron tune (H/V)	1.85/ 1.20	2.20/ 1.15	2.20/ 1.15	2.20/ 1.15
Max. betatron function (H)	3.40[m]	5.26[m]	3.34[m]	3.26[m]
(V)	10.4[m]	26.0[m]	8.72[m]	9.20[m]
Max. dispersion function (H)	1.87[m]	2.93[m]	1.87[m]	3.92[m]

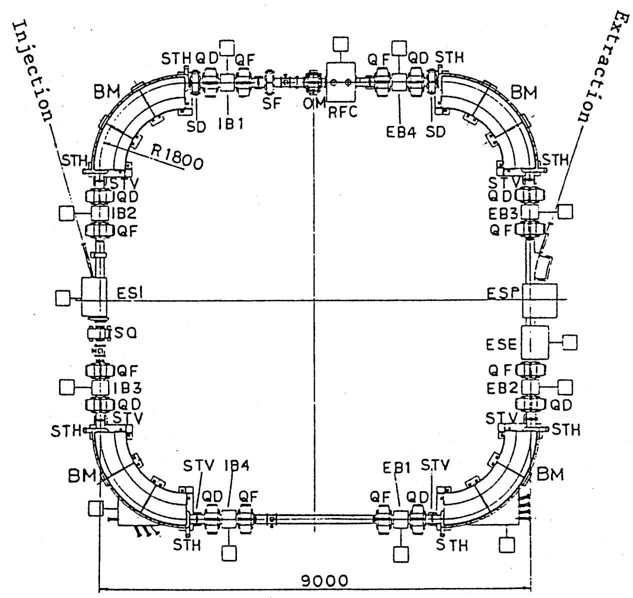
from the point of view of saving space and construction cost. Considering these requirements, we compared following three typical types of lattice: (A) a simple FODO lattice with 90 [deg] sector bending magnets, (B) a racetrack type simple Chasman-Green lattice, and (C) a square Chasman-Green like lattice with doublet quadrupole magnets at both ends of each straight section. For this lattice, a symmetrical mode with the superperiodicity of 4 (abbreviated as S-mode) and a Chasman-Green mode with the superperiodicity of 2 (abbreviated as CG-mode) are calculated. Figs 1 and 2 show basic layouts and the beta and dispersion functions of these three lattices respectively. Their typical parameters are listed in Table 1.

Comparing beta and dispersion functions of the three lattice types shown in Fig. 2, it is known that (1) simple FODO lattice A is an acceptable lattice from the point of view of the balance of beam size and dispersion function, and (2) simple Chasman-Green lattice B is not preferable because the maximum value of dispersion function is rather large. (3) Chasman-Green like lattice C which uses doublets of quadrupole magnets has also acceptable beta and dispersion functions (S-mode), and can make double achromatic straight sections with moderate maximum dispersion (CG-mode). Qualitatively, this is due to the fact that pairs of doublet quadrupole magnets of lattice C control more effectively than the focusing quadrupole magnets at the middle points of bending magnets of simple Chasman-Green lattice B.

For this time, lattice C has been chosen as the candidate lattice because it is preferable as a lattice of a prototype apparatus in the point that it can realize double achromatic sections. The lattice will be finally fixed after detailed design and estimation of injection and extraction systems.

LATTICE DESCRIPTION AND MACHINE PARAMETERS

As the basic design requirement for a medical proton synchrotron, the authors set extraction energy of 250 [MeV] (momentum: 729 [MeV/c]) and averaged proton beam current more than 10 [nA]. Compromising the demands of compactness as a prototype research machine, we set radius and magnetic field of bending magnets (BM) as moderate values of 1.8[m] and 1.35[T] respectively. Detailed lattice layout is shown in Fig. 3 and its lattice and machine parameters are listed in Tables 2 and 3. The lattice is a square type, with four 90 [deg] sector bending magnets. Sector magnets have such an advantage to rectangular magnets as proton orbits are affected with smaller changes in case they deviate from the design orbit. The effect of fringing field of bending magnets is compensated and controlled by horizontal steering magnets (STH) attached to both sides of bending magnets. Two sets of steering magnets (STH, STV) are located on both ends of each straight section in order to control both position and direction of the beam orbit.



BM	Bending Magnet
QF/QD	Quadrupole Magnet
SF/SD	Sextupole Magnet
STH/STV	Steering Magnet (Horizontal/Vertical)
SQ	Skew Q Magnet
OM	Octupole Magnet
IB	Injection Bump Magnet
EB	Extraction Bump Magnet
ESI/ESE	Electric Septum (Injection/Extraction)
ESP	Extraction Septum Magnet
RFC	RF-Cavity

Fig. 3 Layout of Proton Synchrotron

Table 2
Proton synchrotron parameters

Lattice	
Injection energy	7 [MeV] (114.8 [MeV/c])
Extraction energy	250 [MeV] (729.1 [MeV/c])
Focusing sequence	FDDF
Layout type	Square (9×9[m])
Superperiodicity	S-mode : 4
	CG-mode : 2
Circumference	32.91[m]
Average diameter	5.24[m]
Betatron tunes (H/V)	2.20/1.15
No. of bending magnet	4 (90 [deg], sector type)
Bending field	1.35[T]
No. of Q magnets	16 (0.2[m] each)
Quadrupole field (F/D)	S-mode 8.35/-7.30 [T/m]
	CG-mode 9.52/-8.19 [T/m]
	7.10/-6.32 [T/m]
Long straight section	2.70[m] (effective)
Repetition cycle	1 [Hz]
Acceleration system	
Type of cavity	Nonresonant
Load material	Ferrite
Harmonic number	1
Frequency range	1.106 ~ 5.588 [MHz]
Acceleration voltage (max)	392[V]

Table 3
Machine parameters

Operation mode		S-mode	CG-mode
Betatron tunes	(H/V)	2.20/1.15	2.20/1.15
Betatron function	(H)	1.70 ~ 3.34	1.46 ~ 3.26
	(V)	2.42 ~ 8.72	1.89 ~ 9.20
Dispersion function	(H)	0.15 ~ 1.87	0.00 ~ 3.92
Momentum compaction		0.0606	0.125
Transition momentum		3.70 [GeV/c]	2.49 [GeV/c]
Chromaticity	(H)	-0.633	-0.651
	(V)	-1.714	-1.758

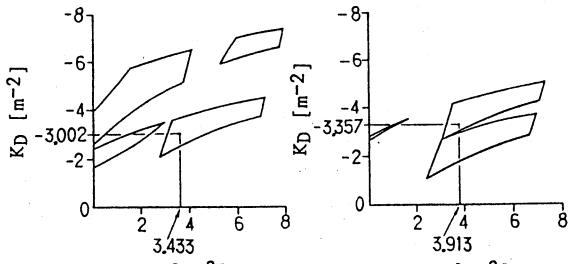


Fig. 4 Necktie diagram

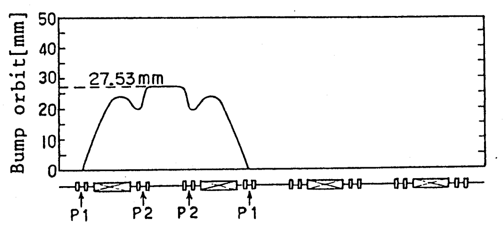


Fig. 5 Bump orbit of S-mode (Almost the same for CG-mode)

Doublets of quadrupole magnets (QF, QD) are located on both ends of every straight section, and two operation modes are considered as mentioned above: (1) symmetrical mode of superperiodicity 4 (S-mode) and (2) Chasman-Green mode of superperiodicity 2 (CG-mode). Maximum β_x and dispersion of 3.34[m] and 1.87[m] for S-mode and 3.26[m] and 3.92[m] for CG-mode are satisfactorily small.

Considering the requirement for small beta functions and high efficiency for 4 turn injection, betatron tunes (ν_x, ν_y) are set as (2.2.1.15), and this operation point is shown in necktie diagrams (i.e. stable regions) of Fig. 4. Transition momentums of 3.7 [GeV/c] for S-mode and 2.5 [GeV/c] for CG-mode are higher enough than maximum operation momentum of 0.73 [GeV/c] (250 [MeV]).

In order to compensate natural chromaticity efficiently, a pair of sextupole magnets (SF, SD) should be located at two points where the difference between $\beta_{x1}\beta_{y2}$ and $\beta_{x2}\beta_{y1}$ is large enough, and these pints are a pair of (1) each point on the edges of bending magnets and (2) each of the center points of straight sections, from the distribution of β_x and β_y and symmetry of the lattice (cf. Fig. 2). Considering the restraint of practical lattice layout, three sextupole magnets are located as Fig. 3. As the defocusing sextupole magnet is too long to be located between a pair of quadrupole magnets, it is divided into two magnets located at equivalently the same points considering lattice symmetry.

In addition, a skew quadrupole magnet (SQ) and an octupole magnet (OM) are prepared for further beam correction. As the machine is a prototype and may be used for machine research as well as the fundamental study for medical irradiation, straight sections has spaces for additional devices.

INJECTION, EXTRACTION, AND BEAM CURRENT

Injection and extraction bump orbits are made by the groups of four bump magnets (IB1~4 for injection and EB1~4 for extraction) located at the middle points of each four pairs of doublet quadrupole magnets on both ends of straight sections. As shown by Fig. 5, bump orbits are symmetrically controlled and deviate from the design orbit only in the region of four bump magnets. Therefore injection and extraction bump orbits can be controlled independently.

Injection proton beam is generated by an RFQ and a drift tube linac, and injection energy is set as 7 [MeV]. Injected beam is leaded to the injection bump orbit by a static electric septum for injection [ESI] with the length of 0.6[m] and an electric field of 80 [keV/cm]. As proton current of injected beam can be expected to be high enough, 4 turns injection is planned. As there is no effective radiation damping and therefore no self-consistent mechanism of deciding the emittance of the beam circulating in a proton synchrotron, we assume the horizontal and vertical natural emittances of accumulated proton beam to be 15π [mm·mrad] and 1.5π [mm·mrad] respectively, considering the design parameters of Loma Linda synchrotron.

Using this horizontal emittance and taking closed orbit distortion (COD) into account, maximum half beam size (1σ) in the horizontal direction has the maximum values of 24 [mm] for 7 [MeV] and 12 [mm] for 250 [MeV] at bending magnet sections. Injection and extraction orbits and cross-section of vacuum ducts are determined considering these parameters.

Number of stored protons, for the designed horizontal and vertical emittances mentioned above, is restricted by space charge effect and is estimated as $8.8 \cdot 10^{11}$. Assuming fast extraction of 1 [Hz], averaged extracted beam current is 19 [nA]. In practice, a presonance, slow extraction is planned and the averaged current will be anticipated to be a little smaller. Full energy beam is extracted by an electrostatic septum (ESE) and two septum magnets for extraction (ESP1,2).

RADIO FREQUENCY ACCELERATION

Proton revolution frequency varies from 1.107 [MHz] (7 [MeV]: injection state) to 5.589 [MHz] (250 [MeV]: extraction state). A nonresonant accelerating cavity loaded with ferrite is used, and maximum gap voltage for acceleration is 392[V] assuming 0.5 [sec] linear acceleration. Harmonic number h is set to be 1. As error of accelerating RF frequency causes deviation of orbits, accelerating frequency must be adjusted to revolution frequency to the order less than 10^{-6}. Considering the demands of accurate RF control which must be valid even in transition region (in spite that this does not occur in this synchrotron design), RF signal for acceleration is picked up from circulating beam itself using PLL (Phase Lock Loop) technique some milliseconds after the injection, while a programmed RF signal is used before such a timing.

SUMMARY AND DISCUSSION

A prototype proton syncrotron for medical use has been designed. The candidate lattice is a square, Chasman-Green type lattice, using doublet quadrupole magnets on both ends of each straight section. As, its basic design has been made, design of injection, extraction, and beam transport and irradiation systems is needed. In addition, research and development of detailed components and RF control system is planned in order to realize the synchrotron.

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