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Lattice Design of a Proton Synchrotron for Medical Use

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A proton synchrotron dedicated to medical use with the maximum energy of 250MeV has been designed. A quadratic Chasman–Green lattice is adopted among several lattices. It is chosen from the point of view of making beam size, dispersion and machine dimensions to be small.

KEY WORD : Synchrotron/Proton Therapy/Medical Use

1. INTRODUCTION

It is known that a proton beam with intermediate energy (70～250MeV) has good effects for cancer control, due to its notable dose localization according to the Bragg peak. Among several types of proton accelerators, a synchrotron is preferable because it can produce proton beams with various energies, which is convenient for the flexibility of cancer therapy.

In practice, a compact proton synchrotron with the maximum energy of 250MeV dedicated to medical use has already been constructed and utilized for clinical treatment at Loma Linda University in U.S.A.[1] and another dedicated synchrotron with the maximum energy of 230MeV is proposed by University of Tsukuba[2].

At Kyoto University, a preliminary proposal[3][4] of proton synchrotron which utilizes its proton linac as an injector has been made. As a prototype machine for medical use and machine study, the synchrotron should be compact so as to be constructed in a hospital, but some straight sections left for further extensions are also desirable. In addition, its aperture should be compact in order to reduce the magnet dimensions for the economy of total cost.

Considering these design requirements, the authors compared three typical lattices, and chose Chasman–Green like lattice with quadratic shape as the candidate lattice.

The candidate lattice is a Chasman–Green type lattice with four–fold symmetry which can also realize two–fold symmetric doubly achromatic straight sections. Proton beams from RFQ linac are injected through an electrostatic septum and accelerated by a ferrite loaded untuned rf cavity.

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2. LATTICE CONSIDERATION

As a proton synchrotron for medical use needs a straight section for beam extraction in addition to an injection section, lattices of few straight sections such as a racetrack or triangular type, which are sometimes adopted for compact ring for synchrotron radiation, are not convenient for our prototype machine. On the other hand, the lattice should be simple from the point of view of saving space and construction cost. Considering these requirements, we compared following three typical types of lattices ; A : a simple FODO lattice with 90 deg sector bending magnets, B : a racetrack type simple Chasman–Green lattice, and C : a quadratic Chasman–Green like lattice with doublet of 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 superperiodicity of 2 (abbreviated as CG–mode) are calculated. Figures 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.

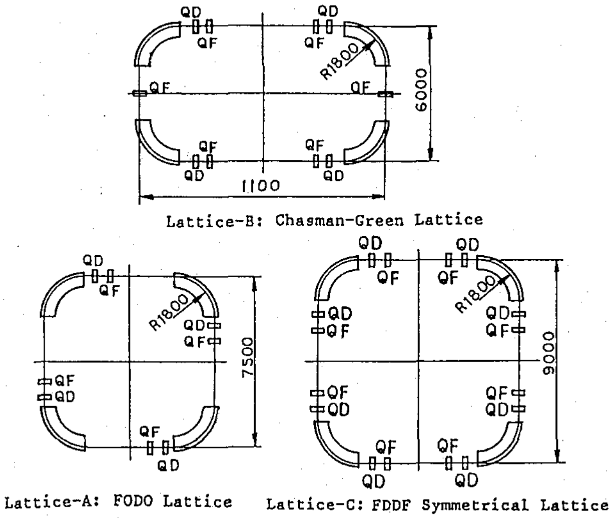


Fig. 1. Schematic layouts of considered lattices.

Table 1. Comparison of Lattice Type

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	(H)	3.40 [m]	5.26 [m]	3.34 [m]	3.26 [m]
Function	(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]

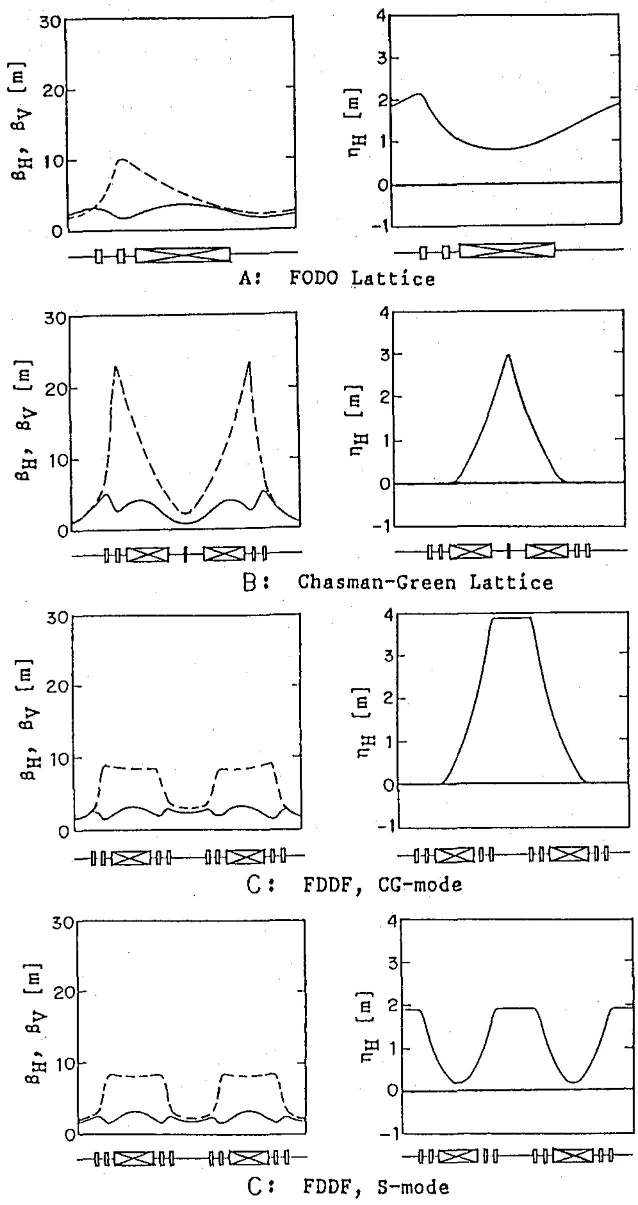


Fig. 2. Betatron functions and dispersion functions. (Solid line: horizontal, dash line: vertical)

From comparison of beta and dispersion functions of these three lattice types shown in Fig. 2, it is known that (1) a simple FODO lattice A is an acceptable lattice from the point of view of the balance of beam size and dispersion function, (2) a simple Chasman–Green lattice B is not preferable because the maximum value of dispersion function is rather large and (3) a Chasman–Green like lattice C which uses doublets of quadrupole magnets has also acceptable beta and dispersion functions (S–mode), and can make doubly 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 proton beams more effectively than the focusing magnets of simple Chasman–Green lattice B.

At present, lattice C has been chosen as the candidate lattice. It is preferable as a prototype lattice, because it can realize doubly achromatic sections. Before final decision of the lattice, detailed design of injection and extraction systems is needed.

3. LATTICE DESCRIPTION AND MACHINE PARAMETERS

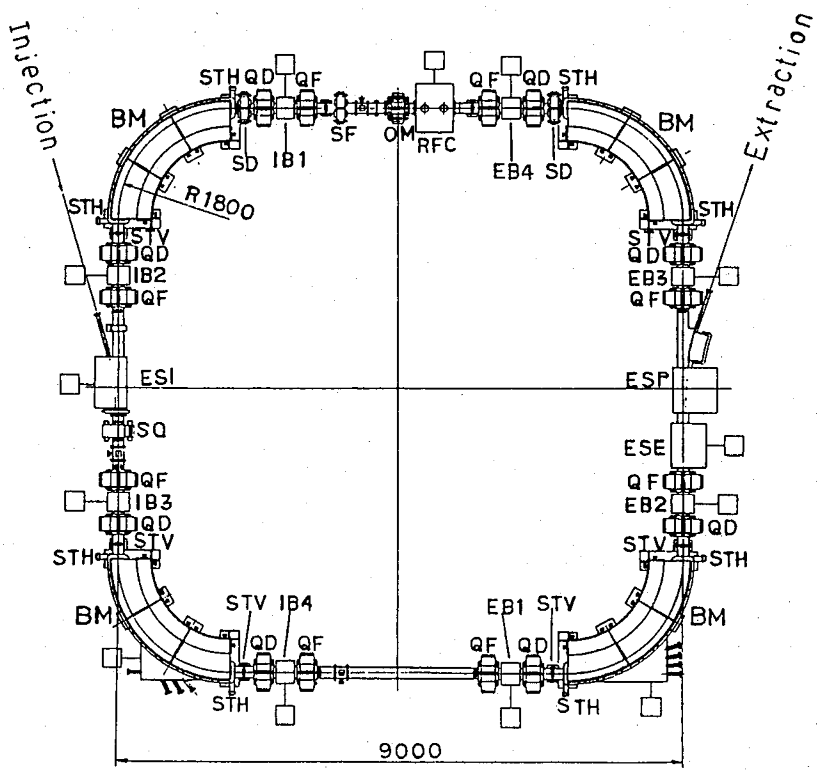
As the basic design requirement for the medical proton synchrotron, we set the maximum energy of 250MeV (Momentum : 729MeV/c) and averaged proton beam current more than 10 nA. Compromising the demands of compactness with requirement of flexibility as a prototype research machine, we set radius of curvature and magnetic field of bending magnets (BM) to be moderate values of 1.8m and 1.35T, respectively. Detailed lattice layout is shown in Fig. 3 and its lattice and machine parameters are listed in Tables 2 and 3. The lattice has a quadratic shape with four 90 deg sector bending magnets. Sector magnets have the following advantages, in comparison with rectangular magnets. Proton orbits are not affected so much in case they deviate from the design orbit. The effect of fringing field of bending magnets can be compensated and controlled only by horizontal steering magnets. So 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.

Doublets of quadrupole magnets (QF, QD) are located on both ends of every straight section, and following 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 beta and dispersion functions in horizontal direction are satisfactorily small. For S–mode they are 3.34m and 1.87m, respectively and 3.26m and 3.92m, respectively for CG–mode.

Considering the requirements for small beta functions and high efficiency for 4 turn injection, betatron tunes (ν_H, ν_V) are set as (2.2, 1.15), and this operation point is shown in necktie diagrams (*i. e.* stable regions) of Fig. 4. Transition momenta 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 (250MeV).

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 functions in horizontal and vertical directions is large enough. Considering this condition, three sextupole magnets are located at the places shown in Fig. 3.

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, a straight section is left for additional devices.



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. Main Parameters of Medical Proton Synchrotron

Energy Region	
Injection	7 [MeV] (114.8 [MeV/c])
Extraction	70~250 [MeV] (729.1 [MeV/c])
Repetition Rate	0.25 [Hz]
Circumference	32.9 [m]
Focusing Structure	FDBDF
Length of Long Straight Section	5.4 [m]
Number of Betatron Oscillations	
Horizontal Direction	2.20
Vertical Direction	1.15
Transition Momentum	3.7 [GeV/c] : S-mode
	2.5 [GeV/c] : CG-mode
Bending Magnet (Without Edge Focusing)	
Radius of Curvature	1.8 [m]
Length along the beam orbit	2.827 [m]
Bending Angle	90 [deg]
Field Strength	
Maximum (at 250 [MeV])	1.35 [T]
Injection (at 7 [MeV])	0.21 [T]
Quadrupole Magnet	
Length	0.2 [m]
Maximum Field Gradient (F/D)	8.35/−7.30 [T/m] : S-mode
	9.52/−8.16 [T/m] : CG-mode
	7.10/−6.32 [T/m]
RF Acceleration System	
Frequency Range	1.107~5.589 [MHz]
Cavity Type	Ferrite Loaded Untuned Quarter Wave Coaxial Cavity
Energy Gain	67 [eV]
Peak RF Voltage	374 [V]
Acceleration Time	1.0 [sec]
Scheme of Extraction	1/3 Resonance
Beam Intensity	1.2×10^{11} ppp

Table 3. Machine Parameters

Operation Mode		S-mode	CG-mode
Betatron Tune	(H/V)	2.20/1.15	2.20/1.15
Betatron Function	(H)	1.70~3.19 [m]	1.46~3.13 [m]
	(V)	2.42~8.72 [m]	1.89~9.20 [m]
Dispersion Function	(H)	0.21~1.87 [m]	0.00~3.92 [m]
Momentum Compaction		0.0605	0.125
Transition Momentum		3.70 [GeV/c]	2.49 [GeV/c]
Chromaticity	(H)	−1.546	−1.380
	(V)	−3.650	−3.22

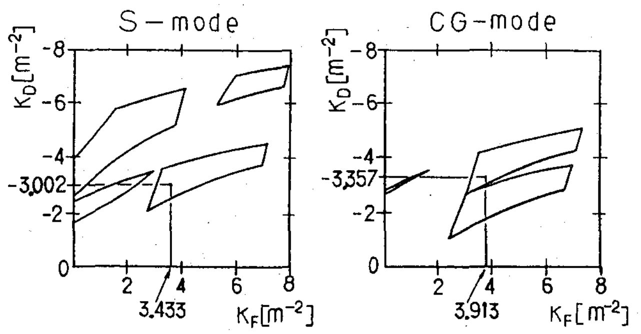


Fig. 4. Necktie diagram.

4. INJECTION AND EXTRACTION

4.1 INJECTION

The synchrotron utilizes the liner accelerator, which is under operation at Institute for Chemical Research, Kyoto University, as its injector. It consists of an RFQ and a drift–tube linac of Alvarez type operated at the frequency of 433MHz and accelerates proton up to 7 MeV. Detailed description of the linac is presented in Ref. 5.

The accelerated beam is deflected horizontally at the angle of 15 deg by an electrostatic septum and injected into the bump orbit of the synchrotron. The injection point is located at the center of the straight section. Because the injected beam is expected to have enough current, 4 turn injection scheme can be used. The designed injection orbit is shown in Fig. 5.

In order to realize high injection efficiency, an electrostatic septum with an electrode whose length and thickness are 700mm and 0.1mm, respectively, is utilized. Required electric field is 5.2×10^6V/m and the corresponding gap voltage is 77kV for gap width of 15mm.

Bump orbit of which distance from central orbit is 46mm at injection point will be formed by four bump magnets. The magnetic field falls down from 0.045T to 0T in 40μsec. Because of its quick response time, ferrite will be used for magnet core material. Parameters of the

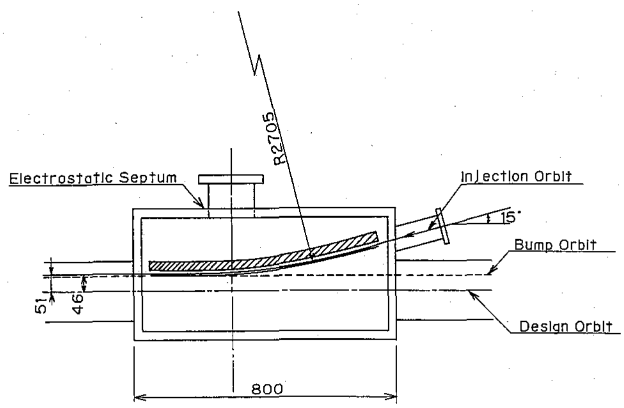


Fig. 5. Injection orbit.

Table 4. Parameters of Injection System

Bump Magnet	
Number of Magnets	4
Length	200 [mm]
Bending Angle	16.9/21.0 [deg] : S–mode
	16.3/23.7 [deg] : CG–mode
Gap Height	70 [mm]
Field Strength (Maximum)	0.0454 [T]
Electrostatic Septum	
Number	1
Length	700 [mm]
Bending Angle	15 [deg]
Thickness of Septum	0.1∼5 [mm]
Gap width of Electrode	15 [mm]
Electric Field	5.16×10^{6} [V/m]
Gap Voltage	77.4 [KV]

injection system are summarized in Table 4.

4.2 EXTRACTION

The accelerated beam is slowly extracted with a third order resonance. The operation point is brought to the resonance by the tuning of the magnetic field of quadrupole magnets. At extraction point located at a straight section of the synchrotron, beams are extracted by the electrostatic septum and succeeding magnetic septums. The designed extraction orbit is shown in Fig. 6.

The deflection angle of the electrostatic septum is 0.615 deg. To increase efficiency of extraction, foil type septum with 0.1mm thickness and 600mm length will be used and required electric field is 8.0×10^{6}V/m. Then extracted beam is further bent by the first and second magnetic septums with deflection angles of 4.385 deg and 15 deg, respectively.

Bump orbit of which distance from the central orbit is 40mm at extraction point will be formed by four bump magnets. Because it takes few hundreds msec for full extraction, the

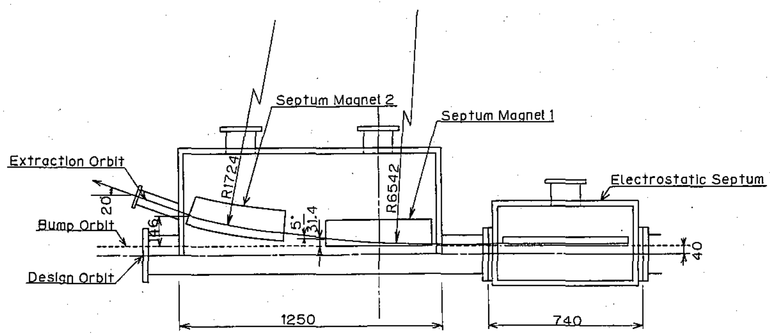


Fig. 6. Extraction orbit.

Table 5. Parameters of Extraction System

Bump Magnet	
Number of Magnets	4
Length	200 [mm]
Bending Angle	14.6/18.2 [deg] : S–mode
	14.1/20.6 [deg] : CG–mode
Gap Height	70 [mm]
Magnetic Field (Maximum)	0.251 [T]
Electrostatic Septum	
Number	1
Length	600 [mm]
Bending Angle	0.615 [deg]
Thickness of Septum	0.1 [mm]
Gap width of Electrode	10 [mm]
Electric Field	8.0×10^{6} [V/m]
Gap Voltage	80.0 [KV]
Septum Magnet 1	
Number	1
Type	Rectangular
Length	500 [mm]
Bending Angle	4.3853 [deg]
Gap Height	40 [mm]
Gap Width	50 [mm]
Magnetic Field	0.3718 [T]
Septum Magnet 2	
Number	1
Tyme	Sector
Length	450 [mm]
Bending Angle	15.0 [deg]
Gap Height	40 [mm]
Gap Width	50 [mm]
Magnetic Field	1.411 [T]

flat top of 1 sec is required for the main magnets in order to attain the duration of extraction of 0.5sec. Parameters of extraction system are summarized in Table 5.

5. RADIO FREQUENCY ACCELERATION

5.1 ACCELERATION PARAMETERS

The parameters of rf acceleration are given in Table 6. Proton beams injected into the synchrotron at the energy of 7MeV are accelerated to 250MeV by the rf acceleration system. The revolution frequency varies from 1.107MHz to 5.589MHz. Considering permeability of

Table 6. Parameters of RF Acceleration

Beam Intensity	1.2×10^{11} [ppp]
Acceleration Period	1 [sec]
Energy Range	7~250 [MeV]
Harmonic Number	1
RF Frequency	1.107~5.589 [MHz]
Acceleration Voltage	374~240 [V]
Acceleration Phase	10.3~15.4 [deg]

ferrite and the use of conventional rf devices in this frequency range, harmonic number is set to be unity. The required acceleration voltage of 134V is obtained by the equation

$$V\sin\phi_s = C\rho\ \mathrm{d}B/\mathrm{d}t,$$

where V, C, ϕ_s and $\mathrm{d}B/\mathrm{d}t$ are required voltage, circumference of the ring, synchronous phase and rate of magnetic field increase, respectively. The optimum injection voltage (V_{inj}) is given as follows[6]

$$V_{inj}=\pi h\,|\,\eta\,|\,E\beta^2\,(\Delta P/P)/(2e),$$

where h, E, β and $\Delta P/P$ are harmonic number, total energy of the injected beam, velocity ratio with the light and fractional momentum spread, respectively and η is the frequency dispersion defined by $1/\gamma_t^2-1/\gamma^2$.

Assuming the momentum spread of 0.3%, the optimum acceleration voltage at the injection stage is 177V. During acceleration, the acceleration voltage and its phase are changed keeping the rf bucket area to be constant without losing captured proton beam. The calculated acceleration voltage and its phase are shown in Fig. 7. In order to control the acceleration voltage and its phase, rf control system shown in Fig. 8 was designed. The

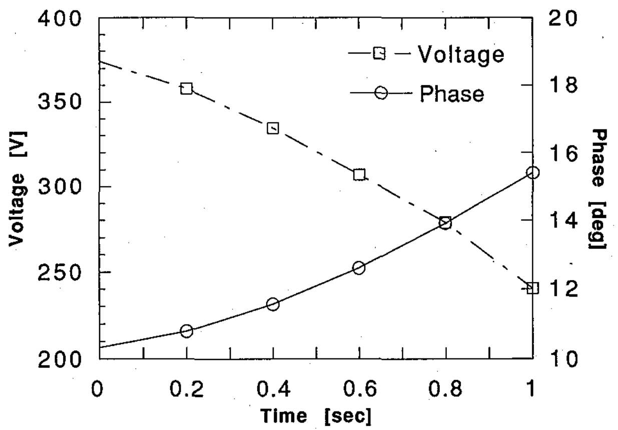


Fig. 7. Acceleration voltage and phase.

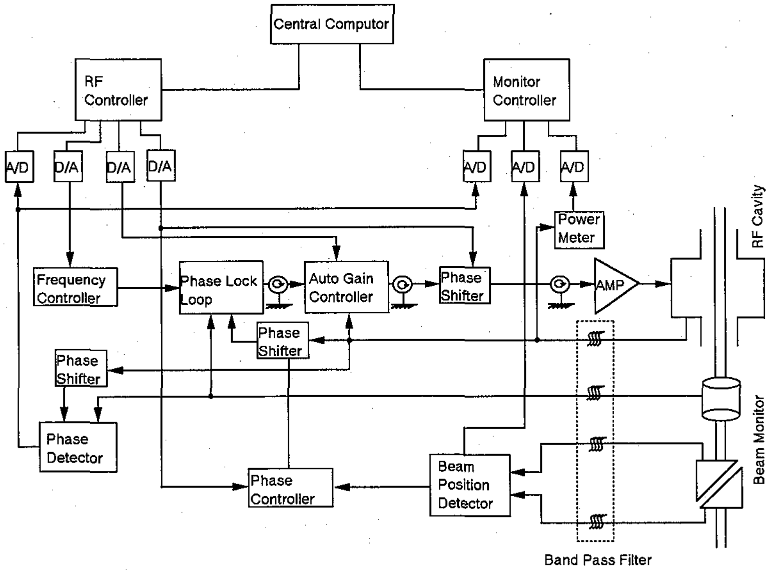


Fig. 8. RF control system.

acceleration rf signal is picked up from and tuned with circulating beam by phase lock loop (PLL).

5.2 ACCELERATION CAVITY

In order to make a compact acceleration cavity and to realize wide operation frequency range, a ferrite loaded untuned cavity is to be used. For providing high impedance for wide frequency range, the ferrite with low Q and high permeability as Ni–Zn is used for the cavity.

Because untuned cavity has no capability of frequency tuning, the external resistance is used to provide flat impedance for wide frequency range by reducing effective Q value. And an external capacitance is used to set the resonant frequency at the center of operation range. From the point of view of reducing the required rf power, wider ferrite is preferable. Therefore, the thickness of ferrite should be as large as possible in the limited space. To achieve required acceleration voltage of 400V with the commercial solid state amplifier (1 KW), shunt resistance is set to be 100Ω. In Fig. 9, cavity impedance and its phase are shown.

The cavity has been designed to be simple and free of maintenance. The schematic view of the designed cavity is shown in Fig. 10 and its specifications are summarized in Table 7. The basic design of the cavity is based on that of Loma Linda University[7].

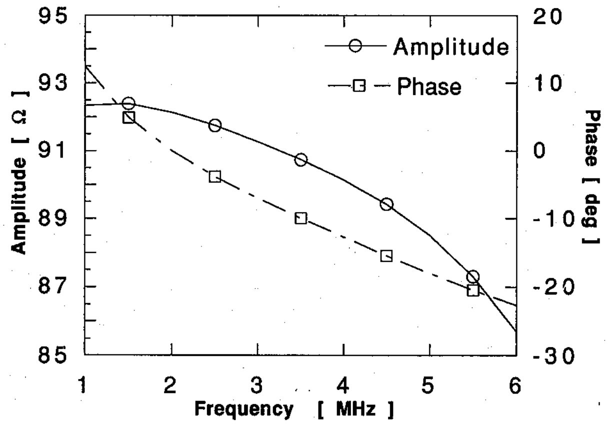


Fig. 9. Cavity impedance and phase.

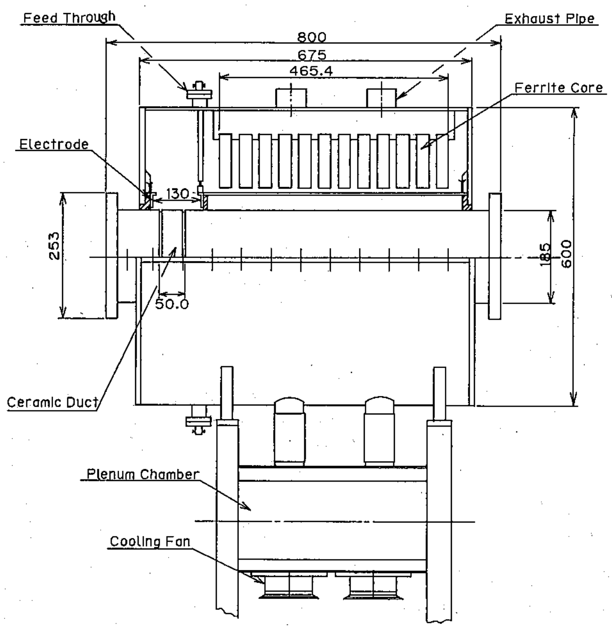


Fig. 10. Schematic view of a acceleration cavity.

Table 7. Specifications of Acceleration Cavity

Cavity Type	Ferrite Loaded Untuned Quarter Wave Length Coaxial Cavity
Cavity Length	675 [mm]
Ferrite Material	Ni–Zn
Number of ferrite cores	12
Ferrite Size	$^{\phi ex}500\times{}^{\phi in}280\times25.4$ [mm]
Cooling	Air Cooling

6. MAGNETS DESIGN

6.1 BENDING MAGNETS

In order to realize a compact lattice, the bending radius and the magnetic field are set to be 1.8m and 1.35T, respectively. Sector type magnets, of which bending angle are 90 deg will be used to eliminate the loss of the aperture of the magnet caused by the sagitta of the beam. These magnets are made of laminated iron core for the transient operation and the C type cross section is adopted considering the convenience of beam monitoring and evacuation. The shape of bending magnet is shown in Fig. 11.

In order to realize the good field region within an aperture of $|x| \leqq 90$mm, $|y| \leqq 35$ mm, pole width of 300mm and pole–edge shims for fine field tuning are required. Edge shape with Rogowscki curve[8] will be used for keeping constant field distribution during acceleration.

The required magnetomotive force is 8.3×10^4A • turn. To keep the current below 3000 A, number of turns per pole is set to be 24 turn/pole. Major specifications of bending magnets are shown in Table 8.

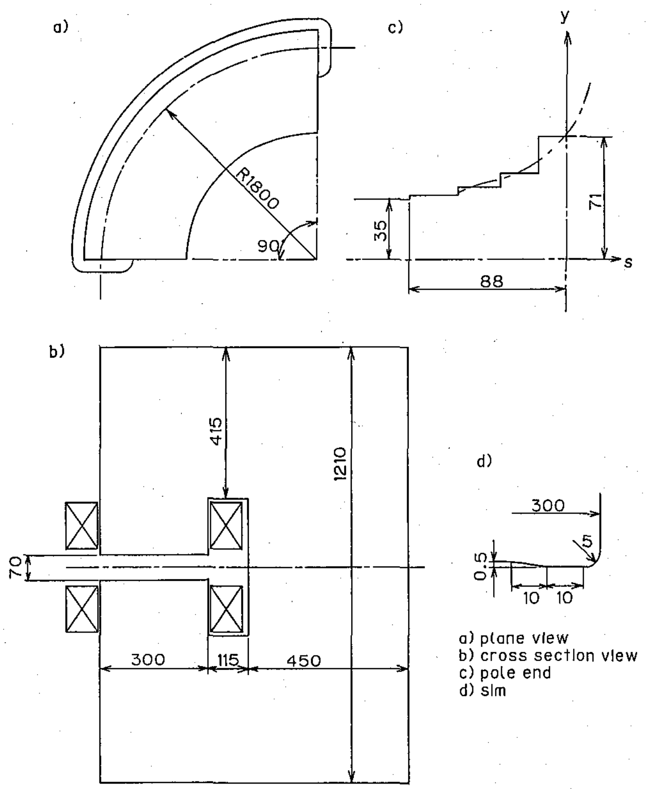


Fig. 11. Shape of bending magnet.

Table 8. Specifications of Bending Magnets

Number of Magnets	4
Bending Radius	1.8 [m]
Bending Angle	90 [deg]
Gap Height	70 [mm]
Pole Width	300 [mm]
Magnetic Field (Maximum)	1.35 [T]
Magnetomotive Force (Maximum)	8.28×10^4 [A • turn]
Coil Resistance	25.5 [mΩ]
Coil Inductance	39.2 [mH]
Weight	20 [ton]

6.2 QUADRUPOLE MAGNETS

The shape of quadrupole magnets is shown in Fig. 12. Required maximum K value is 3.91m^{-2} which corresponds field gradient of 9.52T/m.

The bore radius is 75mm. The pole shape is made with a hyperbolic curve which is connected to its tangential lines at both sides in order to increase good field region. The pole gap is 150mm. Required magnetomotive force per pole is 2.34×10^4A • turn. Major specifications

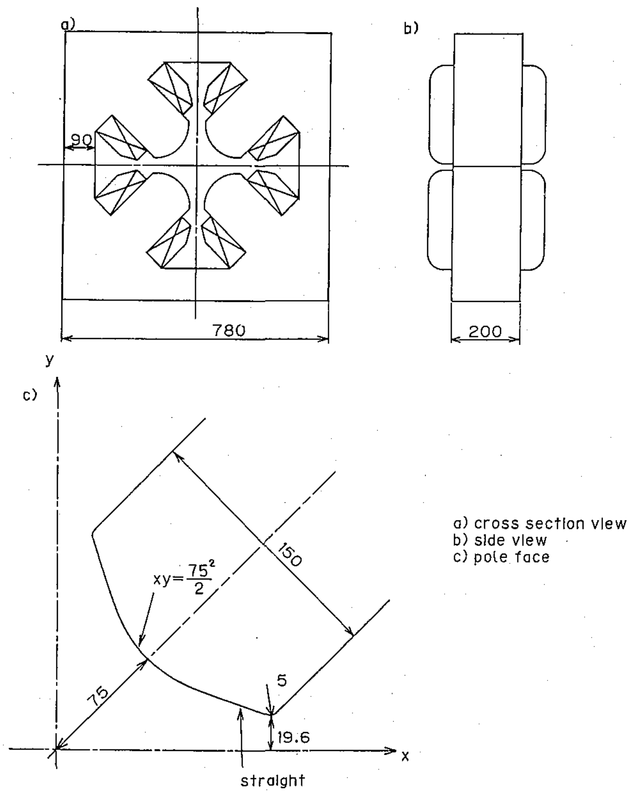


Fig. 12. Shape of quadrupole magnet.

Table 9. Specifications of Quadrupole Magnets

Number of Magnets	8 : QF
	8 : QD
Length	0.2 [m]
Bore Radius	75 [mm]
Pole Width	150 [mm]
K Value	3.43 [m^{-2}]/−3.00 [m^{-2}] : S–mode
	3.91 [m^{-2}]/−3.36 [m^{-2}] : CG–mode
	2.92 [m^{-2}]−2.60 [m^{-2}]
Field Gradient (Maximum)	9.52 [T/m]
Magnetomotive Force (Maximum)	2.34×10^4 [A • turn/pole]
Coil Resistance	78.7 [mΩ]
Coil Inductance	48.4 [mH]
Weight	1 [ton]

of quadrupole magnets are summarized in Table 9.

6.3 SEXTUPOLE MAGNETS

The shape of sextupole magnets is shown in Fig. 13. Sextupole magnets will be used not only for correction of the chromaticity but also as perturbation for slow extraction. In order to correct chromaticity, at least a pair of sextupole magnets are needed, but for reducing the powers two SD and one SF magnets are used. Maximum K′ value is 42.92m $^{-2}$ which corresponds to B″ of 104T/m^2. Required magnetomotive force per pole is 5.8×10^3A • turn. Major specifications of sextupole magnets are summarized in Table 10.

Table 10. Specifications of Sextupole Magnets

Number of Magnets	1 : SF
	2 : SD
Length	0.1 [m]
Bore Radius	75 [mm]
Pole Width	75 [mm]
K Value	42.5 [m^{-3}]/−33.6 [m^{-3}] : S–mode
	18.7 [m^{-3}]/−12.8 [m^{-3}] : CG–mode
Field Gradient (Maximum)	104 [T/m^2]
Magnetomotive Force (Maximum)	5.8×10^3 [A • turn/pole]
Coil Resistance	475 [mΩ]
Coil Inductance	73.3 [mH]
Weight	450 [kg]

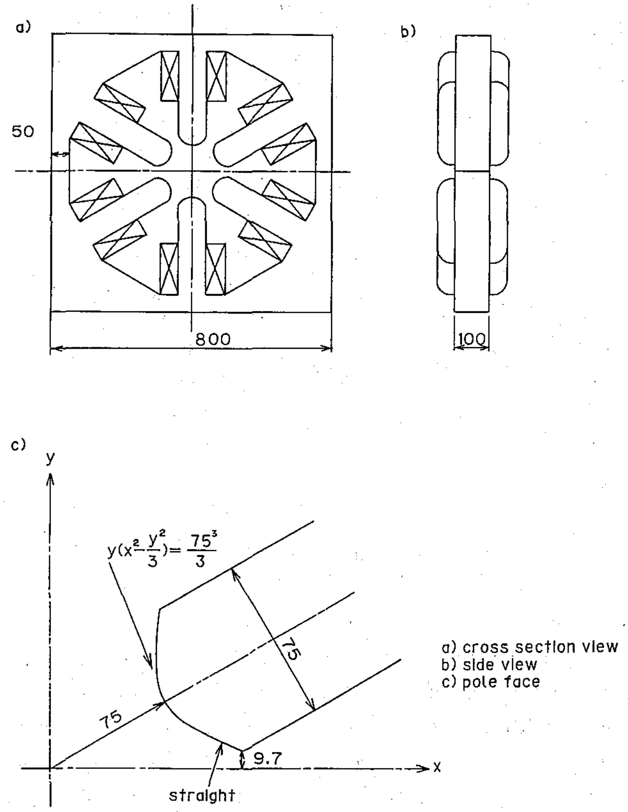


Fig. 13. Shape of sextupole magnet.

7. CONTROL SYSTEM

7.1 OVERVIEW OF CONTROL SYSTEM

For the control system of medical accelerator, it is required to be highly reliable and persistent for a long use. As it is also required that the system can be operated with few operators and little assistance from machine specialist, the control and monitoring are performed mainly with computers. Back–up system is prepared for system trouble of each sub–system. The block diagram of the control system is shown in Fig. 14. The control system consists of the main system and sub–systems. Each system has its own work stations which are linked by the local network (Ethernet). Total information about facility and patients are processed by the server type computer. The injector, synchrotron and beam transport control systems are located in the accelerator control room. Beam radiation, utility and back–up control systems are located in the radiation control room.

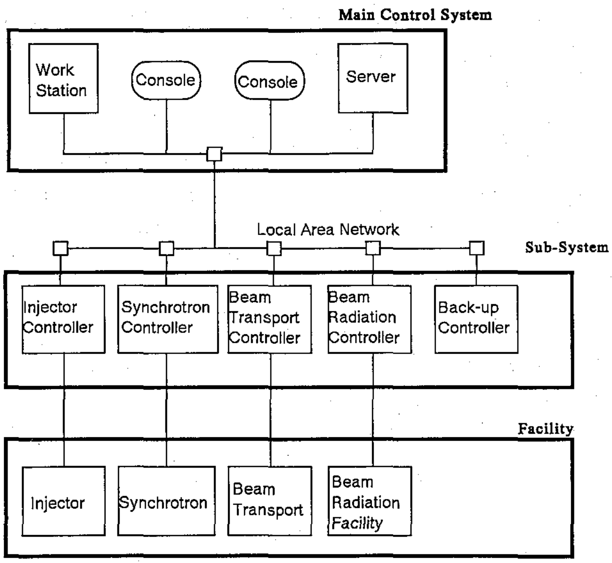


Fig. 14. Block diagram of the control system.

7.2 CONTROL SYSTEM FOR SYNCHROTRON

The block diagram of the control system for synchrotron is shown in Fig. 15. The work station is used for the total control of the synchrotron and two terminals are prepared for monitoring, testing and maintenance. Components grouped as magnets, rf and beam monitors are supervised by each computers. Work station, terminal and single computers are linked by

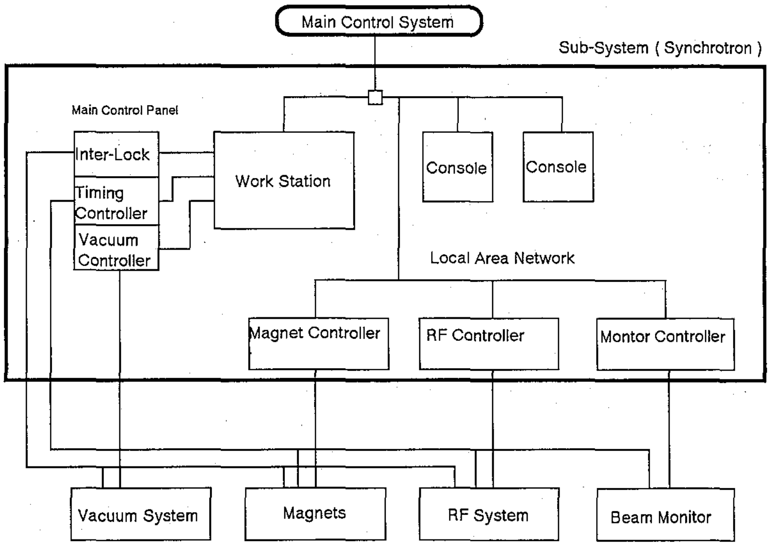


Fig. 15. Block diagram of the control system for synchrotron.

local network. For timing, vacuum and interlock control systems, the sequence control system will be used for reliable operation. These sequencer are located at the central control panel.

7.3 SOFTWARE

The software required for medical use should be satisfied accuracy, high efficiency and especially user–friendly interface which can be used by people not trained for computer or accelerator operation. To reach these goals, software with the following functions must be developed.

(1) graphic user interface based on the window system
(2) real time database that can be used in network environment
(3) on line help
(4) high management capability of utility like pointing device or high defined graphic device

8. CONCLUSION

The proton synchrotron dedicated to medical use has been designed. As our candidate, a Chasman–Green like lattice with quadratic shape which can meet the demand of compactness and good beam quality is adopted. In addition to basic study of a lattice, design study of main devices of the synchrotron has been already carried out. Although further studies are needed for detailed design such as beam injection and extraction, the study of main items is already finished and it is ready for construction.

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