HIMAC SYNCHROTRON

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ABSTRACT

HIMAC(Heavy Ion Medical Accelerator in Chiba) is a first synchrotron accelerator facility for tumor therapy in a hospital environment in Japan. Major specifications of the synchrotron are described.

INTRODUCTION

The advantages of high energy beams of heavy ions for tumor therapy are the sharp dose concentration at Bragg peak both in longitudinal and transverse directions as well as their biological effectiveness. National institute of radiological sciences(NIRS) had proposed the construction of HIMAC facility for tumor therapy and biomedical research. Major accelerator requirements are summarized in Table 1. The intensities in it enable to finish one treatment within few minutes. Energy of 800Mev/u is required to provide a 30cm range in tissue for silicon beam. Simultaneous irradiation by horizontal and vertical beams with different energies is important for 3-dimensionally well controlled dose distribution.[1] These requirements are satisfied by an accelerator complex consisting of two heavy ion synchrotron rings which are preceded by linac[2] and are followed by independent vertical and horizontal beam transport lines[3]. Both rings are equipped with slow extraction channels. The upper ring has fast beam extraction channel for biological experiments.

A summary of the major parameters for the synchrotron is given in Table 2. Two rings are operated independently of each other except that the synchrotron magnets of each ring are excited 180° out of phase.

The construction started in 1987 and will continue until 1993. The clinical trial will start in 1994.

LATTICE ELEMENT

Synchrotron ring is of a separated function type with a strong FODO focusing structure. Schematic layout of the ring is shown in Fig. 1. Lattice functions are shown in Fig. 2 for one period of the lattice. A sector type magnet is chosen to suppress a change of betatron function with tune around the operation point.

A H-gap design of the dipole with saddle shape coil configulation is adopted to obtain a wide good field region. Plan view and cross section of the HIMAC dipole are shown in Fig.3. Specifications for the dipoles are given in Table 3. Table 4 and Fig. 4 show the specifications and the cross section of the quadrupole.

Pole end pieces made of glued stack of laminated silicon steel are attached to the magnet ends. This method facilitates a shimming control of the magnetic length by adding or omitting thin sheets between the poles and the end pieces.

Two families of 6 sextupoles are used to set the natural chromaticities (-3.90 H and -3.99 V) to zero at injection, acceleration and extraction. Correction of horizontal closed orbit distortion (COD) is achieved by 12 steering magnets and 12 position monitors. Residual COD after correction is estimated to be 4mm(3σ).

Beam apertures in magnetic elements at injection are shown in Table 5. Allowance for the closed orbit distortion is also taken into account(16mm H and 5.1mm V for 3σ). Useful beam apertures required for extraction are also shown.

INJECTION

Multiturn injection scehme is used to inject the beam from the linac. The injecting beam emittance of 1.5 π mm-mrad(normalized), ring aperture of 30π mm-mrad (normalized) and the estimated injection efficiency of 50% show that the real injected 40 turns during 160μs time interval give effective number of accepted turns of 20. A 0.7m-long, 35mm-thick septum magnet and a 0.7m-long electrostatic inflector(ESI) with field strengths of 0.5T and 66.7kV/cm respectively inject the 6MeV/u ions with q/A=0.25 into the ring. Four bump magnets distort the beam orbit around the ESI during injection.

Table 1.
HIMAC accelerator requirements.

Particle species	^{4}He to ^{28}Si, ^{40}Ar	
Maximum energy(Mev/u)	800 for q/A=0.5	
Minimum energy(Mev/u)	100	
Intensity of extracted beam (pps per ring)	$1.2x10^{10}$	He
	$2.0x10^{9}$	C
	$3.4x10^{8}$	Ne
	$4.5x10^{7}$	Si
	$2.7x10^{7}$	Ar
Beam spill length(ms)	400	
Repetition rate(Hz)	0.5 at 600Mev/u	
Extracted beam emittance(mm-mrad)	$\leqq 10\pi$	
Momentum spread(%)	$< \pm 0.2$	

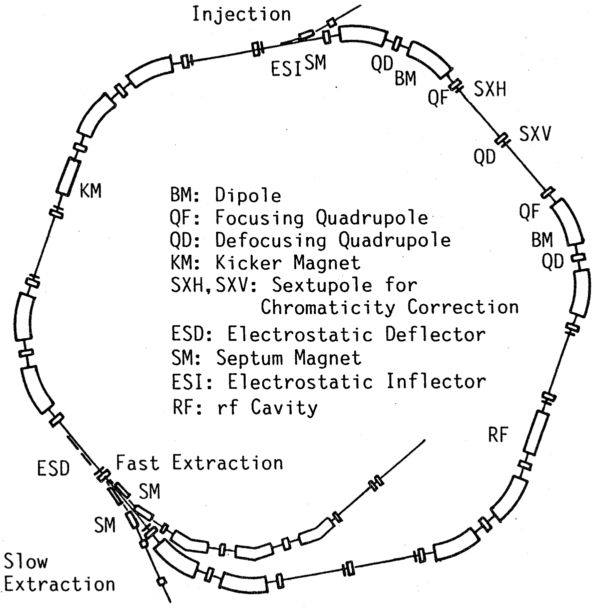

Fig. 1 Schematic Layout of HIMAC Synchrotron Ring.

Table 2.
Summary of major synchrotron parameters.

Maximum rigidity(T-m)	9.75
Injection energy(MeV/u)	6
Output energy(Mev/u)	100 - 800
Maximum intensity for light ions(ppp)	10^{11}
Repetition rate(Hz)	0.3 - 1.5
Injected emittance(π mm-mrad) Hor/Ver	264 / 26.4
Momentum spread after rf turn-on(%)	±0.7
Number of injected turns	40
q/A except Ar^{18+}	0.5
Vacuum(Torr)	5×10^{-9}
Lattice type	FODO
Circumference(m)	129.6
Periodicity	6
Cells per period	2
Long/Short straight section length(m)	5.0 / 0.8
Dipole field at full rigidity(T)	1.5
Quadrupole gradient at full rigidity(T/m)	7.4
Betatron tunes Q_x / Q_y	3.75 / 3.25
Radio-frequency range(MHz)	1 - 8
Harmonic number	4
Peak rf voltage(kV)	11
Cooling system heat load(MW)	5.4

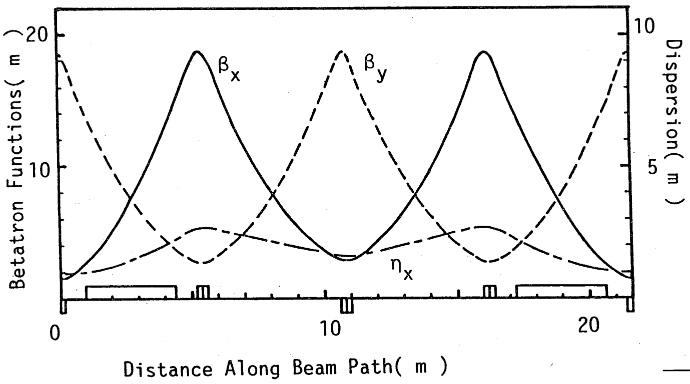

Fig. 2 Betatron and Dispersion Functions of HIMAC Synchrotron Lattice.

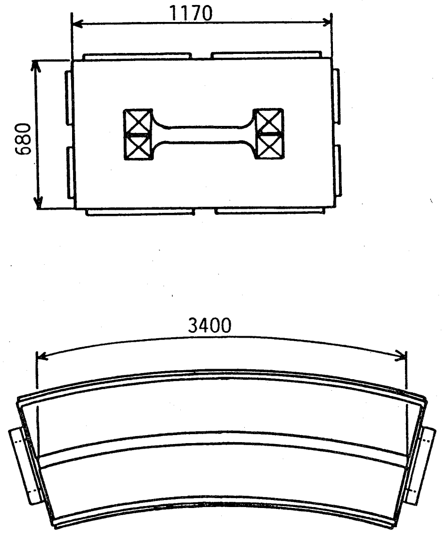

Fig. 3 HIMAC Dipole.

Table 3.
Specifications for the dipole magnets.

Number/ring	13*
Required field(T)	1.5
Magnet length(m)	3.4
Magnet type	Sector type
Good field region(mm) Hor/Ver	210 / 50
Vertical gap(mm)	66
Field flatness ΔB/B	$\pm2\times10^{-4}$
Bend angle(deg)	30
Field rise(T/s)	2
Magnet yoke Size(mm)	$1170^{w}\times680^{h}\times3400^{l}$
Material	Laminated silicon steel Nippon steel corp. 50A600
Lamination thickness(mm)	0.5
Number of coil-turns	40
Current(A)	2070
Magnet weight(ton)	24

*One dipole is used for on-line field measurements and a generation of B-clock for rf acceleration.

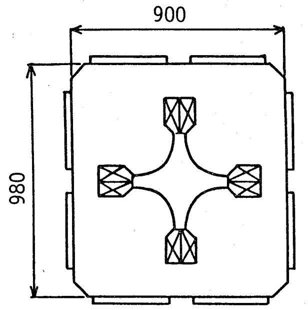

Fig. 4 HIMAC Quadrupole.

Table 4.
Specifications of quadrupole magnets.

Number/ring	24
Maximum field gradient(T/m)	7.4
Aperture diameter(mm)	ϕ192
Magnet length(m)	0.4
Good field region(mm) Hor/Ver	244 / 56
Gradient flatness ΔG/G	$\pm2\times10^{-3}$
Magnet yoke Size(mm)	$900^{w}\times980^{h}\times400^{l}$
Material	same as for dipoles
Number of coil-turns/pole	18
Current(A)	1570
Magnet weight(ton)	3.2

Table 5.
Injected/Useful beam aperture in dipole and quadrupole.

	Horizontal(mm)	Vertical(mm)
Dipoles	± 94/±105	±25
Focusing quadrupoles	±106/±122	±14
Defocusing quadrupoles	± 45/± 95	±28

SYNCHROTRON MAGNET POWER SUPPLY

The dipole magnets are powered by 2 sets of 24-phase thyristor controlled rectifiers. The 2 sets are operated in convertor-invertor mode at injection and flat-top. The quadrupole magnets are powered by one set of 24-phase thyristor controlled rectifier. The reactive power is compensated by 2 sets of 12-phase thyristor controlled reactor(TCR). A 1200Hz clock to control the power supply also serves as timing clock to generate the event signals of the whole synchrotron complex.

ACCELERATION

The rf voltage requirements are evaluated for a 0.7 second acceleration time up to 600MeV/u(dB/dt=2T/s) with a momentum spread of $\pm 0.3\%$ of injected beam from the linac and a filling factor of 0.8. The total energy gain per charge is about 1.7kV and the peak cavity voltage is 10kV for ions with q/Z=0.5 and 11kV for Ar^{18+}.

The rf cavity has a single gap structure which consists of a pair of ferrite loaded quarter-wave coaxial resonators coupled by a figure-of-eight configuration of ferrite bias windings. Fig.5 shows the cross sections and plan view of the rf cavity. Specifications of the rf cavity are summarised in Table 6.

The course patterns of rf frequency, voltage and ferrite bias current are generated by pattern memory modules. Event signals synchronized to the 1200Hz control clock of synchrotron magnet power supply initiate the capture, acceleration, flat-top and reset processes. Capture and flat-top event signals start the memory read-out by T-clock. The acceleration event signal starts the memory read-out by B-clock. Fine tuning is derived by signals from the beam-position and beam-phase monitors[4]. The beam monitor signals are buffered by FET amplifiers with 100kΩ input impedance. White noise level of the amplifier at input is $2nV_{rms}/\sqrt{Hz}$ with 100pF input capacitance. The beam monitor signals and the rf cavity voltages are processed by heterodyne frequency convertors. Double conversion with 50MHz and 455kHz intermediate frequencies(IF) are processed. Beam displacement and beam phase signals are obtained from 455kHz IF signals by amplitude-to-phase convertor and synchronous phase detector respectively. The fine tuning signals and the rf pattern data from the memory module are digitally summed and are transfered to a digital controlled phase continuous synthesizer with 51-58MHz output frequency. It is then converted to 1-8MHz rf frequency by heterodyne convertor and transfered to the rf power amplifier of the cavity.

SLOW EXTRACTION

A third-integer resonant extraction scheme is used to slowly extract the beams from the ring. A series of 4 bump magnets deform the closed orbit around the electrostatic deflector(ESD) and control the position in phase space of the separatrix dynamically during extraction. Two pairs of sextupoles and fast quadrupoles control the size of separatrix. Two succesive 1.3m-long, 70kV/cm ESDs give the 26mm turn separation at the entrance of the 1st septum magnet. Two magnetic septa are 1.2 and 1.0m-long with fields of 0.78 and 1.5T. The bend angles are 5.5° and 9.2° . The beam leaves the second magnetic septum 48cm apart from the central trajectory with angle of 15.85° . The magnets are outside of vacuum and can be operated at 100% duty factor.

FAST EXTRACTION

Fig.2 also shows the layout of the fast extraction system. The beam is extracted into the inside of the ring at the same straight section as for the slow extraction. A series of 5 bump magnets are used to distort the closed orbit at the septum magnet. A series of seven 0.36T, 0.3m-long fast kicker magnets located about 270° upstream in betatron phase are excited within 65ns. The beam separation at the entrance of the magnetic septum is 11mm.

VACUUM SYSTEM

Vacuum pressure of the ring is 5×10^{-9}Torr. Vacuum ducts, chambers and all components in the vacuum are bakable up to 200° C. 9 turbo molecular pumps, 25 sputter ion pumps and 25 titan getter pumps are distributed around the ring. The material of vacuum duct and chamber is SUS316L. The vacuum chambers in the dipole magnets are 0.3mm-thick stiffened by ribs.

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Table 6.
Specifications of the HIMAC rf cavity.

A pair of ferrite loaded quarter-wave coaxial resonators.	
Frequency range(MHz)	1 - 8
Harmonic number	4
Peak rf voltage(kV)	12
Total length(m)	2.77
Ferrite material	TDK SY6
Ferrite ring dimension(mm)	φ500xφ320x25
Number of ferrite rings	24x2
Bias current(A)	10 - 900
Number of bias windings	4
Vacuum duct diameter(mm)	φ190
Cooling water flow(l/min)	60
rf power amplifier tetrode	Eimac 4CW100000E

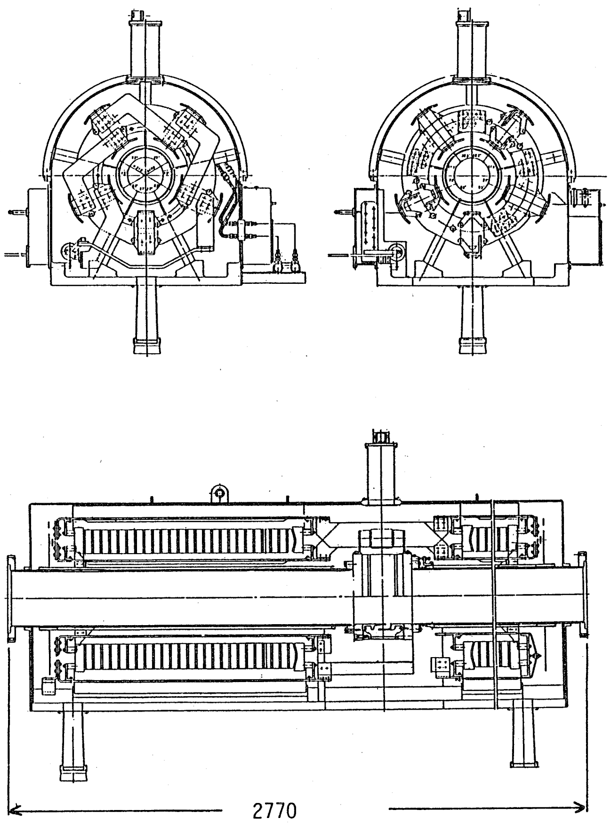

Fig.5 HIMAC rf Cavity.