HIMAC PROJECT AT NIRS-JAPAN

Y. Hirao, H. Ogawa, S. Yamada, Y. Sato, T. Yamada, K. Sato, A. Itano, M. Kanazawa, K. Noda, K. Kawachi, M. Endo, T. Kanai, T. Kohno, M. Sudou, S. Minohara, A. Kitagawa, F. Soga*, S. Watanabe*, E. Takada**, K. Endo***, M. Kumada***, and T. Matsumoto****
National Institute of Radiological Sciences
4-9-1, Anagawa, Chiba-shi, 260, Japan

A heavy ion synchrotron complex for medical use is being constructed at Chiba, Japan. General feature and present status of this project are described.

Introduction

An original idea of the HIMAC (Heavy Ion Medical Accelerator in Chiba) Project was proposed at the High LET Radiotherapy Division in the US-Japan Cooperative Cancer Research Program in 1979 at Kyoto, Japan. In 1983, the Japanese government decided to promote the 10 year strategy for cancer initiative. The HIMAC Project has also been proceeding along it, towards the end of the program. It was approved in 1987 and is expected to complete and to start the first clinical trial in 1993.

The superiority of heavy ion therapy has been demonstrated through radiological experiments and clinical trials at Lawrence Berkeley Laboratory so far. Based on their results of heavy ion therapy and of neutron and proton therapies at NIRS, the HIMAC project has been proposed in years.

In the proposed facility, the maximum output energy should be 800MeV/u for silicon ions in order to realize a residual range of 30cm in human body. Such a high energy beam is also effective to produce radioactive beam of high quality for diagnosis and/or treatment. The area of beam irradiation must be enlarged to cover homogeneously whole area to be treated. The maximum diameter of the irradiation field is chosen at 22cm. Beam intensity should be sufficient to give a dose of 5Gy into the irradiation field within an allowed time duration of several to a few tens of seconds. For therapeutic purpose, vertical beam is indispensable requirement. The main parameters of the accelerator complex are listed in Table I.

Table I
HIMAC parameters

Ion source	Type	PIG & ECR
	Ion species	from ^{4}He to ^{40}Ar
	q/A	> 1/7
Injector	Frequency	100 MHz
	Repetition rate	3 Hz Max.
	Duty factor	0.3% Max.
	Acceptance	0.6 π mm·mrad (normalized)
RFQ linac	Input/Output energy	8 / 800 keV/u
	Vane length	7.3 m
	Cavity diameter	0.6 m
	Surface field	205 kV/cm (1.8 Kilpatrick)
	Peak rf power	260 kW (70% Q)
Alvarez linac	Input/Output energy	0.8 / 6.0 MeV/u
	Total length	24 m (3 rf cavities)
	Cavity diameter	2.20/2.18/2.16 m
	Average field	1.8/2.2/2.2 MV/m
	Shunt impedance	34 - 47 MΩ/m (effective)
	Surface field	150 kV/cm (1.3 Kilpatric)
	Peak rf power	770/820/760 kW
	Focusing sequence	FODO (6.8 kG/cm Max.)
Synchrotron (for one ring)	Output energy	100 - 800 MeV/u (q/A = 1/2)
	Average diameter	41 m (12 cells, 6 s-periods)
	Focusing sequence	FODO
	Betatron tunes (H/V)	3.75 / 3.25
	No. of dipole magnet	12 (3.4 m each)
	Dipole field	0.11 (Min.) / 1.5 (Max.) T
	No. of Q magnets	24 (0.4 m each)
	Quadrupole field	0.51 (Min.) / 7.0 (Max.) T/m
	Long straight sect.	12 (5.0 m each)
	Repetetion rate	1/2 Hz
	Rise/flat-top time	0.7 / 0.5 s
Acceleration system	No. of cavities	1 (one more is forseen)
	Frequency range	1.0 - 7.9 MHz (harmonic 4)
	Acceleration voltage	11 kV peak at 1 MHz
	RF power input	30 kW peak at 6 MHz
Vacuum system	Material of chamber	SUS-316 L (0.3 mm thick)
	Baking tempereture	200 °C
	Average pressure	1 × 10^{-9} torr
	Pumps	Sputter ion pumps
		Ti getter pumps
		Turbo molecular pumps
Extraction system	Type	Fast & slow (1/3 resonance)
	Length of spill	up to 400 ms (slow)

Ion Source

Two types of ion sources are prepared for the injector system: a PIG and an ECR sources. The PIG source is used mainly for lighter ions, whereas the ECR source is expected to improve heavier ion capabilities of HIMAC. The ion source system is to cover at least from He to Ar. The injection energy to the linac is 8keV/u, and is realized by putting the sources on the high voltage platforms of maximum 60kV.

The PIG source is of a hot cathode type. The pulse operation of the system is expected to be effective for increasing both intensity and lifetime. The preliminary results show that the extracted beam intensities exceed the required values except for Si.

The plasma chamber of the ECR sourc is fed with a microwave source of 10GHz, 2.5kW. Two solenoids with return yokes generate axial magnetic field, whereas radial sextupole field is produced with NdFe permanent magnet installed outside the vacuum chamber.

Injector Linac

The injector system is composed of an RFQ and an Alverez linacs, as shown in Fig.1. The output energies of the linacs are 0.8 and 6MeV/u, respectively. The injector is designed to accelerate heavy ions with a charge to mass ratio of higher than 1/7. The maximum repetition rate and duty factor are 3Hz and 0.3%, respectively.

The structure of the RFQ linac is of four vane type with single loop rf coupler. The total length of the vanes and the cavity diameter are about 7 and 0.6m, respectively. The entire cavity including the vanes themselves is divided into four sections. The peak rf power of ~300 kW, 100MHz is fed to the cavity through the single loop coupler. The maximum surface field on the vane top is ~200kV/cm (1.8 Kilpatrick).

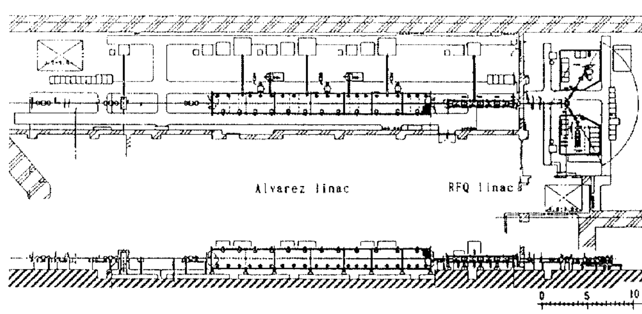

Fig.1. Layout of injector linac system including ion sources.

The operation frequency of the Alvarez linac is 100MHz as same as of the RFQ linac. A pulsed quadrupole magnet is equipped in every second drift tube, and a FODO type focusing sequence of quadrupole lenses is adopted. A transverse acceptance is 2.8π mm·mrad (normalized) with the highest field gradient of 6kG/cm and large enough to accept the output beam of 0.8π mm·mrad (normalized) from the RFQ. The peak rf power is estimated to be about 3.0MW in total. A diameter and a length of the linac cavity are about 2 and 24m, respectively. The cavity is separated into three sections and

Guest scientists: * from INS, Univ. Tokyo, ** Fac. Sci. Univ. Tokyo, *** KEK, **** Dokkyou Univ. Med. School rf power of about 1MW is fed to each of them through a loop coupler. The average axial fields of the sections are 1.8, 2.2 and 2.2MV/m, respectively. Following the Alvarez linacs, an equipment of charge exchange with a $100\mu g/cm^2$ thick carbon foil is installed. Manufacturing of all parts of the injector system including the ion sources is proceeding as in the Fig.2, which shows the third section of the Alvarez.

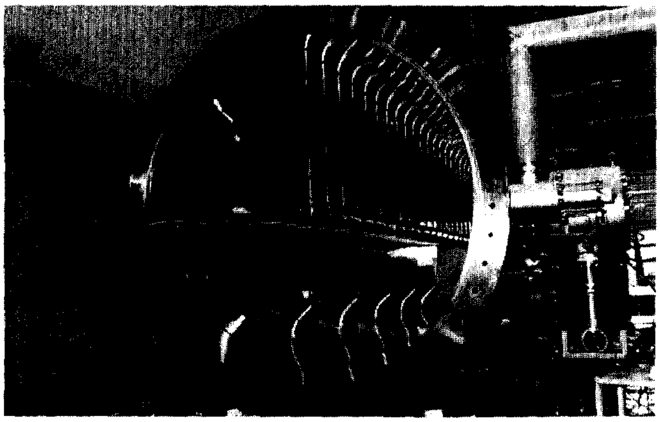

Fig.2. Inside view of the third section of Alvarez linac, seen from low-energy side.

Synchrotron

The synchrotron consists of two rings, which are installed in the upper and lower floors and are operated independently of each other except the alternate injection and excitation. The output energy of each ring must be variable in a wide range from 100 to 800MeV/u. The two ring structure of the synchrotron is expected to make the operation mode much more flexible. The synchrotron can provide horizontal and vertical beams simultaneously at different energies for the two beam treatment or for two different treatments. In the future extension, two stage acceleration of the heavier ions will be possible. It will be also feasible that one of the rings is used as a storage ring, aiming at the treatment and diagnosis with radioactive beams and/or a single shot beam.

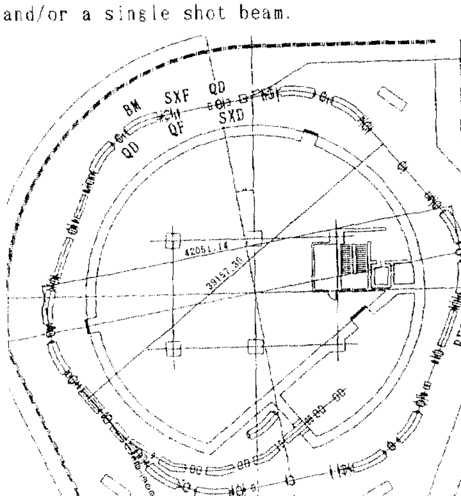

Fig.3. Layout of the upper ring of synchrotron, lower one is almost the same.

The layout of the upper ring is shown in Fig.3. The rings are of a separated function type with a standard FODO focusing sequence. An average diameter of the rings is about 41m. The maximum magnetic rigidity is 9.75Tm. The bending magnets are of sector type and have the maximum field of 1.5T. The quadrupole magnets have the maximum field gradient of 7.4T/m. The closed orbit distortion and the chromaticity are dynamically corrected with a set of steering magnets and with a set of sextupole magnets, respectively. A multiturn beam injection scheme is adopted to increase the beam current by ten times. The horizontal and vertical acceptances of the rings are 30π and 3π mm·mrad in normalized values, respectively.

Two kinds of extraction modes, fast and slow extraction, are prepared for the upper ring, while only slow one for the lower ring. The extraction septum magnets for both modes are installed in the same long straight section in the upper ring. The slowly extracted beam is directed to the outside of the rings, whereas the pulsed beam is extracted to the inside. The slow extraction scheme uses a third order resonance. Beam spill time is to be longer than 400ms at 600MeV/u.

For each of two rings, a current source for the bending magnets of the maximum current of 2100A is composed of four sets of high power thyristor rectifier blocks working in 24 phases followed by a filter circuit. Two 24-phase thyristor current sources of the maximum current of 1600A are prepared for focusing and defocusing quadrupole magnets. The reactive power is dynamically compensated by 12-pulse thyristor controlled reactor (TCR) equipped parallel with a set of capacitors. These sources and TCR are controlled digitally by a computer. A feed-forward loop by the use of the computer will realize precise tracking of the current pattern. The repetition rate of pulse operation of them is varied in a range of 0.3-1.5Hz depending on extraction energies of the two rings. In a proposed current waveform, at 0.5Hz, a rising time and flat top time are 0.7 and 0.5s, respectively. The maximum value of the time derivative of the bending field is about 2T/s.

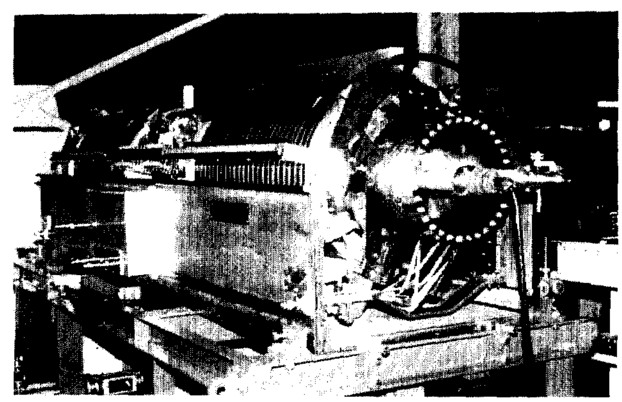

Fig.4. Rf acceleration cavity with a pair of $\lambda/4$ resonators. Upper and side covers are removed.

The rf acceleration system has to have a wide frequency range from 1.0 to 7.8MHz, where a harmonic number of 4 is chosen. The cavity, installed in each ring, consists of a pair of ferrite loaded $\lambda/4$ resonators as shown in Fig.4 and generates an acceleration voltage of 11kV. The cavity is powered by a single tetrode of the final rf power amplifier.

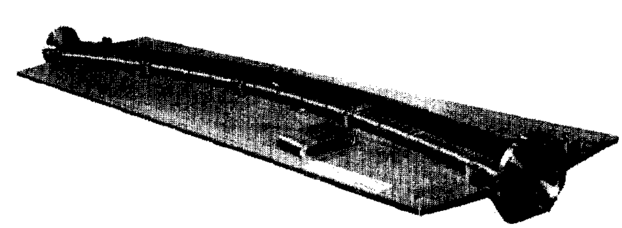

Fig.5. One section of vacuum chamber installed inside the bending magnets, made of 0.3mm thick SUS-316L reinforced by ribs.

The maximum rf output power is 30kW. The system is operated with feed-back loops in order to lock the rf frequency in the circulating beam bunches and to position the beam correctly, respectively.

An average vacuum pressure of an order of 10^{-9} Torr is necessary to accelerate fully stripped ions with a negligible amount of beam loss. A combination of sputter ion pumps, titanium getter pumps and turbo-molecular pumps is chosen to realize such a pressure. All the vacuum chambers of the rings are bakable up to 200℃. The chambers installed inside the bending magnets are made of SUS-316L of 0.3mm thick reinforced by ribs to suppress the unwanted effects of eddy current due to varying magnetic field, as shown in Fig.5.

Beam Delivery System

The total layout of the beam delivery system is shown in Fig.6. The system consists of the vertical beam line which guides the beams up to 600MeV/u from the upper synchrotron ring and the horizontal beam line which guides the beams up to 800MeV/u from the lower one. A junction beam line is prepared to guide the horizontal beams into the vertical beam line. Two vertical treatment courses one of which reaches to the same isocenter of one of the horizontal one and biological irradiation course are prepared in the vertical beam line. The horizontal beam line has two horizontal treatment courses and two experimental rooms, one for physics and general, and another for secondary beam experiments. To get an efficient usage of treatment courses, it is necessary to switch beams rapidly from one course to the other within 5 minutes, keeping the reproducibility of the beam position within ±2.5mm at the isocenter.

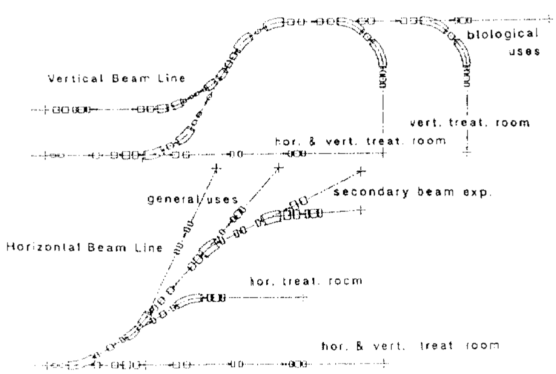

Fig.6. Total layout of horizontal and vertical beam delivery system.

Concerning the secondary beam courses for the development of diagnostic and therapeutic applications of radioactive beams, the momentum spread of ions is expected to be ±0.2% with analyzing magnets and a wedge degrader. The vertical beam line is also usable for the therapeutic applications of radioactive beams. The produced radioactive beams are transported to a vertical treatment course, and the precise stopping point of the beams in a patient's body is measured, and then, the treatment is carried out by stable ion beams having the same range as the radioactive beams.

Treatment devices

The medical requirement on the beam has a considerably unique feature, such as a broad and uniform beam, and specially modulated range distribution. To meet the required specifications, each treatment course comprises a scatterer, a pair of scanning magnets, a range shifter, a ridge filter, a multileaf collimator and several beam monitoring devices, as shown in Fig.7.

In case of heavy ion treatment, it is very important to set up a patient with regard to the delivered beam center and beam shape. The patient positioning system consists of a laser pointer, a digital X-ray TV, an X-ray CT, a treatment couch, a compensator holder and patient immobilization aids. The treatment couch is automatically controlled by the patient positioning computer linked to image verification devices.

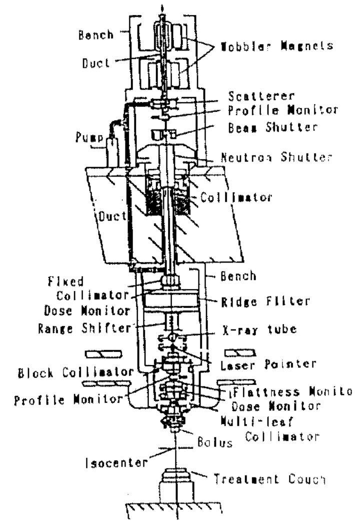

Fig.7. Typical set of treatment devices, in the vertical beam course.

The treatment planning is supported by a computer which has a compatible software with the patient's position image data. The main activity of the treatment planning system is the simulation of iso-effect dose distribution for heavy ion treatment, which takes into account inhomogeneous electron density and biological response factors in the body.

These treatment facilities are necessary to meet the specification of three dimensionally conformed (3D) irradiation, in order to prove that heavy ion therapy could be markedly better than the best use of other radiation therapies.

Building

The height of the building of HIMAC facility reaches to about 30m because of the necessity of vertical beam. Considering such a height and radiation shielding, more than half of the building is constructed under the ground level.

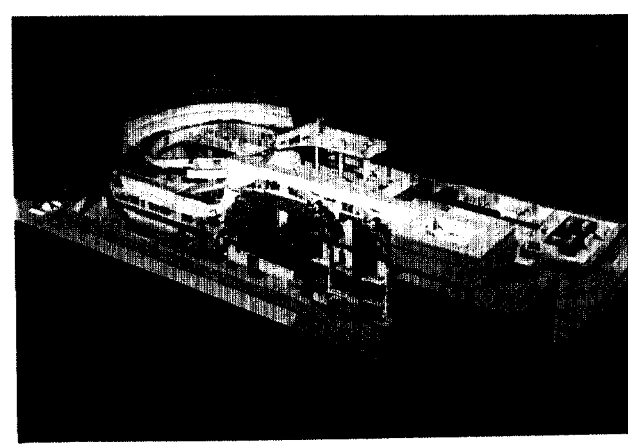

Fig.8. 1/100 scaled model of the total facility.

Acknowledgment

The authors have cooperated with many accelerator staffs of various laboratories as well as of NIRS, and also of industrial companies. The authors would express sincere thanks to the physicists, engineers and radiotherapists of domestic and foreign laboratories, especially of LBL, GSI and LNS, for their very helpful suggestions and valuable informations.