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HIMAC PROJECT AT NIRS

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ABSTRACT

A heavy ion synchrotron complex dedicated to the medical use, HIMAC (Heavy Ion Medical Accelerator in Chiba), has been proposed by NIRS. This paper describes the brief review of the design study of HIMAC. The acceleator complex consists of an injector linac, two heavy ion synchrotron rings and a high energy beam delivery system. Four irradiation rooms are prepared for the medical treatment. Two of the rooms are equipped with both of horizontal and vertical beam courses. Extra four experimental rooms will be available for radiological, biomedical and other related subjects.

A part of the NIRS proposal has been approved by the government and the construction of the injector system will be begun in this fiscal year. The preparatory experiments for the cancer treatment are scheduled in 1992 and the clinical trial is expected to start in 1993.

INTRODUCTION

The radiological effects of heavy ions on organic cells are well suited for medical treatment of the cancer. The formation of the Bragg peak in a human body is one of the most remarkable properties of heavy ions. In the very sharp peak, heavy ions loss most of their kinetic energies resulting the high LET characteristics localized both in transverse and longitudinal directions. The degree of the dose localization is far superior to those of the neutrons and photons. The oxygen enhancement ratio (OER), which is defined as a ratio of doses required to kill the hypoxic and aerated cells, is close to unity in the vicinity of the Bragg peak. The low value of the OER is very much desired to realize homogeneous effects on a tumor which tends to be hypoxic in the central region. The superiority of heavy ion therapy is well demonstrated through radiological experiments and clinical trials at Lawrence Berkeley Laboratory, USA. As a further expansion of the long experience on proton and neutron radiotherapies, NIRS has decided to construct a heavy ion synchrotron facility dedicated to the medical use.[1]

In the proposed therapy, an output energy should be higher than 800 MeV/u for Si ions in order to realize a residual range of 30 cm in a human body. The high output energy of the accelerator is also very effective to produce the radioactive beams of high quality for the treatment and/or the diagnostics. The area of the heavy ion irradiation must be enlarged to cover the whole area to be treated. The maximum diameter of the irradiation field is chosen to be 22 cm.

The major requirements for the HIMAC facility are summarized in Table 1, and the main parameters of the accelerator complex are listed in Table 2. A layout of the HIMAC facility is shown in Fig.1.

ION SOURCE

Two types of ion sources are prepared for the accelerator: a PIG and an ECR sources. The PIG source will be used mainly for light ions, whereas the ECR source is expected to improve drastically heavy ion capabilities of HIMAC. The ion sources are required to produce heavy ions ranging from He to Ar. For typical ions, the source intensities are listed in Table 3 together with the intensities at each stage of the acceleration. Both types of the ion sources will be installed on a high voltage station of about 50 kV, and the remote control of the source parameters is possible from the earth potential. The output beam energy is 8 keV/u.

The PIG source is of a hot cathode type and the magnetic field of 7 kG is chosen. The magnet gap and the maximum extraction voltage are 20 cm and 35 kV, respectively. A test stand of the PIG source has been constructed and beam tests are now in progress. The pulse operation of the ion source, including the gas feeding system, is expected to be very effective for increasing the beam intensity and the source liftime and is the major subject of the tests.

A plasma chamber of the ECR source consists of two stages, both of which are fed by 10 GHz microwave power with a sigle source of 2.5 kW. Three independent coils with return yokes generate axial magnetic field, whereas the radially sextupole field is produced by $SmCo_5$ permanent magnet installed in the vacuum chamber. The bore diameter of the multipole magnet is 10 cm, and the extraction voltage is about 20 kV. In this summer, the R&D of the ECR source has been started in cooperation with the accelerator people of INS, University of Tokyo. The first beam test of the source is scheduled at the end of this fiscal year.

INJECTOR LINAC

The injector system of HIMAC is composed of an RFQ and Alvarez linacs. The operation frequency of the injector is chosen to be 100 MHz in order to ensure the sufficient focusing strength. The output energies of the linacs are respectively 0.8 and 6 MeV/u. The injector is designed to accelerate heavy ions with a charge to mass

Table 1
Requirements for HIMAC facility

Ion species:	from ^{4}He to ^{40}Ar
Maximum energy:	800 Mev/u for q/A = 1/2
Minimum energy:	100 MeV/u for q/A = 1/2
Intensity per ring*:	1.2×10^{10} pps for ^{4}He Ions
	2.0×10^{9} ^{12}C
	3.4×10^{8} ^{20}Ne
	4.5×10^{7} ^{28}Si
	2.7×10^{7} ^{40}Ar
Beam duration:	400 ms
Repetition rate:	1/2 Hz for each ring
Beam emittance:	10π mm·mrad (unnormalized value)
Momentum spread:	< ± 0.2%
Irradiation facility	
Treatment rooms:	2 (Horizontal beam only)
	2 (Horizontal & Vertical beams)
Experimental rooms:	4
Beam characteristics	
Field size:	22 cm diameter
Dose uniformity:	±2% over entire field
Maximum range:	30 cm
Dose rate:	500 rad/min (5 Gy/min)
Field broadning:	Wobbler scanning method

* Extracted beam intensity

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ratio of larger than 1/7. The maximum repetition rate and the rf duty factor are 3 Hz and 0.3%, respectively.

The RFQ linac is of four vane type. The length of the vanes and the cavity diameter are about 7 and 0.6 m, respectively. The entire cavity, including the vanes themselves, is divided into four sections. The mechanical setting of the vanes will be performed in a section independently from the other sections. Through the setting procedure, an error of the capacitance distribution due to the vane misalignment is longitudinally smoothed out, resulting the relatively small deviation of the intervane voltage. The peak rf power of about 300 kW is fed to the cavity through a single loop coupler. The maximum surface field on the vane top is about 200 kV/cm (1.8 Kilpatrick), which is well below the experimentally confirmed value at this frequency.[2] The transverse acceptance of the linac is 0.6 π mm·mrad in a normalized value. A fast bunching method[2] is adopted in the beam

Table 2
HIMAC parameters

Ion source	
Type	PIG & ECR
Ion species	from ^4He 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	FFDD (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	2
Frequency range	1.0 - 7.5 MHz (harmonic 4)
Acceleration voltage	6 kV per cavity (peak)
RF power input	15 kW per cavity (peak)
Vacuum system	
Material of chamber	SUS-316LN (3 mm thick)
Baking tempereture	200 °C
Average pressure	1×10^{-8} 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)

Table 3
Beam intensity schedule for typical ions

Ion species	C^{6+}	Ne^{10+}	Si^{14+}
Intensity on target (pps)	1.8×10^8	3.1×10^7	4.0×10^6
Treatment delivery transmission		0.1	
Beam transport transmission		0.9	
Extracted intensity (pps)	2.0×10^9	3.4×10^8	4.5×10^7
Synchrotron repetion rate (Hz)		0.5	
Extraction efficiency		0.8	
Acceleration efficiency		0.9	
RF capture efficiency		0.8	
Circulating ion intensity (ppp)	6.9×10^9	1.2×10^9	1.6×10^8
Injection efficiency		0.5	
Injection interval (μs)		76.8	
Injected ion intensity (pps)	1.8×10^{14}	3.1×10^{13}	4.1×10^{12}
Injected ion current (eμA)	170	49	9.1
Beam transport transmission		0.75	
Stripper efficiency	0.93 (2+→6+)	0.67 (3+→10+)	0.52 (4+→14+)
Alvarez linac transmission		0.9	
RFQ linac transmission		0.8	
Beam transport transmission		0.7	
Source electrical current (eμA)	160	58	13
Ions from source	C^{2+}	Ne^{3+}	Si^{4+}

dynamics design and a transmission efficiency is calculated to be about 90%. The RFQ linac is essentially a copy of TALL[3] developed at INS, University of Tokyo.

A drift tube of the Alvarez type linac is equipped with a pulsed quadrupole magnet. A FFDD type focusing sequence of quadrupole lenses is adopted to suppress a required field gradient. A transverse acceptance of the linac is 5.8 π mm·mrad with the highest field gradient of 6.8 kG/cm and large enough to accept the output beam from the RFQ. An effective shunt impedance of the linac cells ranges from 34 to 47 MΩ/m (80% of calculated value) and the peak rf power is estimated to be about 2.4 MW in total. A diameter and a length of the linac are respectively about 2 and 24 m. The linac is separated into three cavities to each of which an rf power of about 1 MW is fed through a loop coupler. The average axial fields of the cavities are 1.8, 2.2 and 2.2 MV/m, respectively. After the Alvarez linac, the heavy ions are charge stripped with a 100 μg/cm^2 thick carbon foil.

SYNCHROTRON

The HIMAC synchrotron consists of two rings, which are installed in the different floors and operated essentially independent of each other. The two ring structure of the synchrotron is expected to make the operation mode much more flexible. The synchrotron can provide the horizontal and vertical heavy ion beams simultaneously for the different treatment rooms. The treatment with multiple beams is also acceptable. In the future extension, two stage acceleration of the heavier ions will be possible. It is also possible in the future that one of the synchrotron ring is used as a storage ring, aiming the treatment and diagnostics with radio active beams and/or a single shot beam.

The synchrotron is a separated function type with a standard FODO type focusing sequence. The numbers of unit cells and superperiods are 12 and 6, respectively. A diameter of the synchrotron is about 41 m. The maximum magnetic regidity of the synchrotron magnets is 9.75 Tm. A multiturn beam injection scheme is adopted to increase the beam current by ten times. The horizontal and vertical acceptances of the synchrotron ring are respectively 30 and 3 π mm·mrad in normalized values. A set of steering magnets and beam position monitors is installed in the ring for the correction of the closed orbit distortion at the injection energy. A set of sextupole magnets is also prepared for the chromaticity correction.

The output energy of the synchrotron must be variable in a wide range from 100 to 800 MeV/u for Si ions. Two extraction modes are prepared: a fast and a slow extraction modes. The extraction septum magnets for those modes are installed in the same long straight section. The slowly extracted beam is directed to the outside of the ring, whereas the pulsed beam is extracted to the inside. The slow extraction scheme will use a third order resonance, and the beam spill time will be longer than 400 ms at 600 MeV/u.

A current source for the bending magnets consists of four sets of 12 phase rectifiers followed by a filter circuit. High power thyristor blocks are adopted in the rectifiers and controlled digitally by a computer. A "feed forward loop" with the computer will realize the precise tracking of the current pattern. Two similar current sources are prepared for focusing and defocusing quadrupole magnets. In a proposed current waveform, a flat top and a rising time are about 0.5 and 0.7 s, respectively. The maximum value of the time derivative of the bending field is about 2 T/s.

An rf system of the synchrotron must have a wide frequency range from 1.0 to 7.5 MHz, where a harmonic number is chosen to be 4. An rf station consists of a pair of ferrite loaded $\lambda/4$ cavities, and can generate a voltage of up to 6 kV. The input power for the cavity is about 15 kW. A couple of the rf stations are installed in a ring. The stations are operated with a feed back loop in order to lock the rf frequency with the circulating beam bunches. The signal of the beam position monitor is also fed back to the frequency control circuit. A feed forward technique of the beam position signals developed at BEVALAC[4] is considered to be very effective in the acceleration of heavy ions, and may be adopted by the system.

An averaged vacuum pressure of an order of 10^{-8} torr is enough to accelerate fully stripped ions with a negligible amount of the beam loss. A combination of a sputter ion pump, a titanium getter pump and a turbo molecular pump may be the best choice to realize such a pressure. The vacuum chamber of the synchrotron ring is bakable up to 200 °C. A metal gasket will be used as a standard vacuum seal. The chamber is made of 3 mm thick SUS-316LN in order to suppress the unwanted effects of the eddy current due to the varying magnetic fields.

BEAM DELIVERY SYSTEM

A beam delivery system of HIMAC is required to provide heavy ion beams into four different treatment rooms in a very short time of about 5 min. The beam switching is performed only by exciting or deexciting a switching magnet. The high reproducibility of the magnetic field in the switching magnet may be obtained with the specially programmed sequence of the magnet excitation. The residual field, on the other hand, can be compensated with a small current source prepared for this purpose. The position error of only 2.5 mm will be allowed at the target position.

A requirement of the simultaneous irradiation of heavy ion beams makes the beam delivery system very complicated and relatively large. This system is designed to accept an attempt of the medical diagnostics with radioactive beams.

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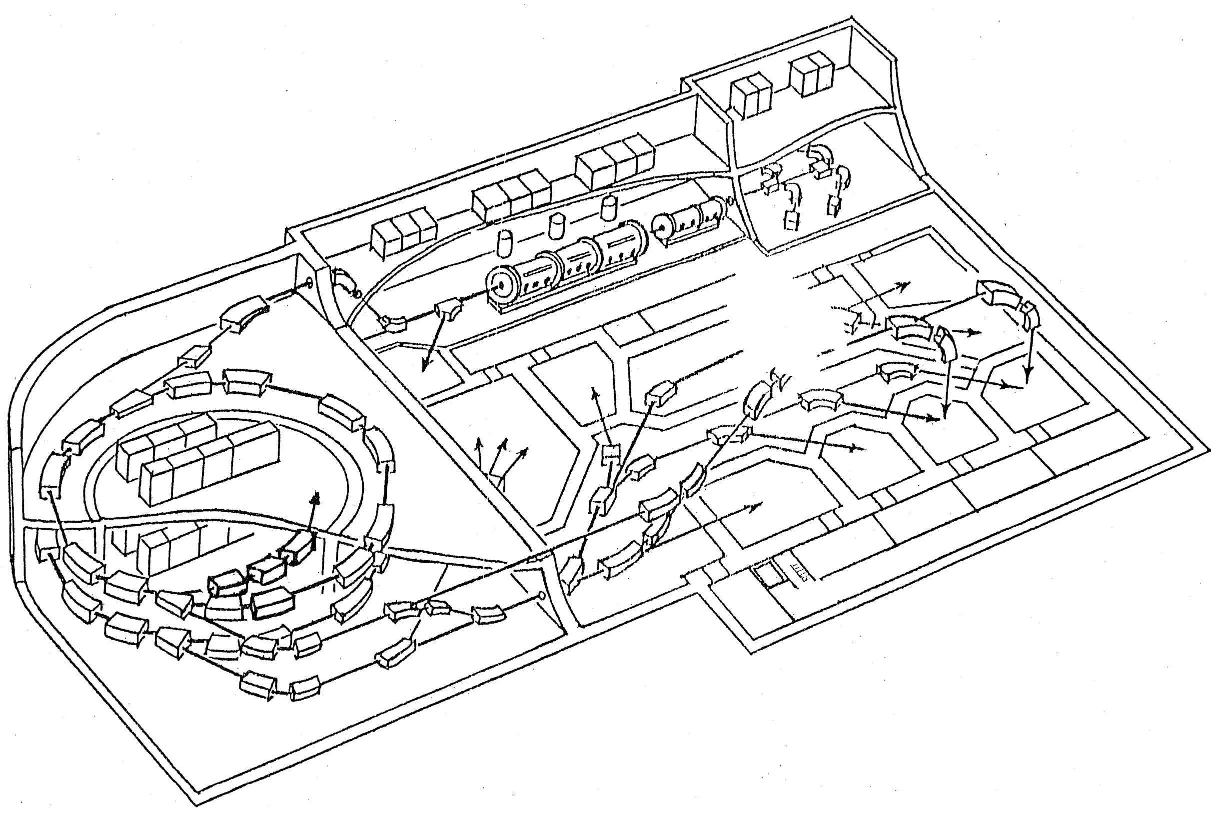

Fig.1 A bird's eye view of the NIRS heavy ion facility HIMAC.