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HEAVY ION MEDICAL ACCELERATOR IN CHIBA(HIMAC)

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Abstract HIMAC at NIRS is a heavy-ion synchrotron complex dedicated to the medical use. It consists of an injector system, a two-synchrotron ring system, a high-energy beam delivery system, and an irradiation system. Heavy ions such as He, C, Ne, Si, and Ar are accelerated in an energy range of 100-800 MeV/u and are delivered to six irradiation rooms as vertical and/or horizontal beams.

INTRODUCTION

It has been indicated that radiation therapy with heavy ions significantly improve the local tumor control due to the better physical and biological dose distribution in comparison with radiations of photons, protons, and neutrons. The aim of the HIMAC project is to establish the therapeutic advantages of high-energy heavy-ion beams as a high LET(Linear Energy Transfer) radiation and to develope further radiological applications.

The project was approved by the Japanese government in 1987, the entire HIMAC facility is expected to complete in 1993, and clinical trials will start in early 1994.

The HIMAC accelerator complex has been investigated to satisfy the radiation oncological requirements for heavy ions.[1] Three-dimensionally conformed irradiation achieved by a sophisticated system is required for heavy-ion treatment. The capability of both vertical and horizontal beams having different energies are essential for highly-controlled dose distribution. The capability of radioactive beams is also required for the developement of

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diagnosis and therapeutic applications.

A flexible accelerator complex consisting of two heavy-ion synchrotron rings which are preceded by heavy-ion linacs and are followed separately by vertical and horizontal beam transport lines is the most suitable choice to satisfy these requirements. This accelerator complex could allow future extensions by the best use of a feature of the two-ring structure.

Accelerated ion species range from He to Ar and their energies vary from 100 to 800 MeV/u. The beam duration slowly extracted from each synchrotron ring is to be longer than 400 ms so as to precisely control the irradiated dose. The beam intensity will realize a dose rate of about 2 Gy/min. in the maximum irradiation field size of 22 cm in diameter.

HIMAC FACILITY

The accelerator complex is roughly divided into an injector system, a two-synchrotron ring system, a high-energy beam delivery system, and an irradiation system. A bird's-eye view of the HIMAC facility is shown in Fig. 1, the main parameters of the HIMAC accelerators are summarized in Tables I and II, and the beam intensity schedule for typical ions is listed in Table III.

Two kinds of ion sources will be provided: a PIG and an ECR sources.

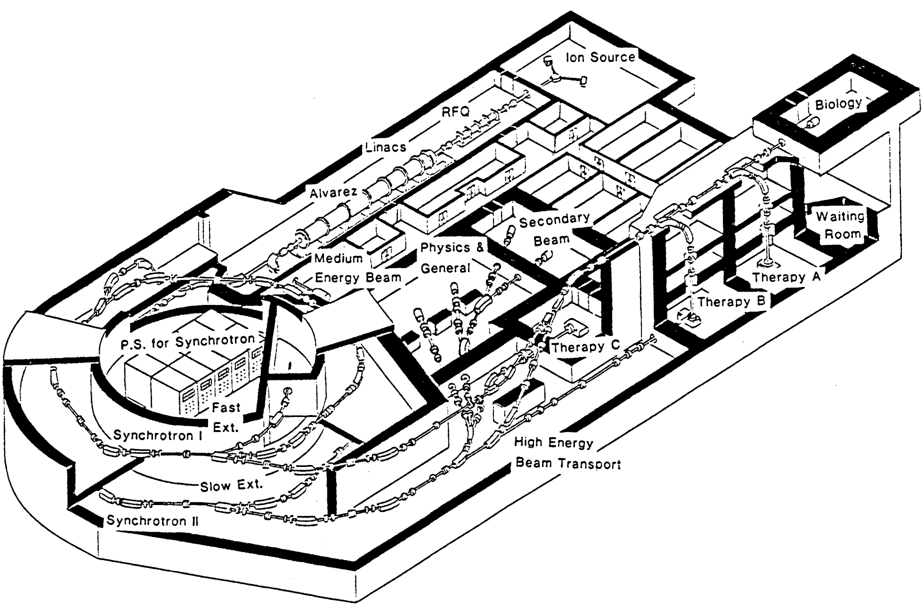

FIGURE 1 A bird's-eye view of the entire HIMAC facility

Specification of injector linacs is based on well-established performance of the PIG source, which is suitable for lighter ions. The ECR source is expected to improve heavier ion capability of HIMAC. Both sources are located independently on the high voltage platforms and the ions from the sources are injected into a linac system through a low-energy beam transport line (LEBT).

The injector system consists of an RFQ linac followed by an Alvarez linac. The operating frequency of both linacs is chosen at a rather low value of 100 MHz in order to give sufficient focusing strength. A charge stripper is installed only at the output end of the Alvarez linac considering the reliability of the stripper system.

The output energy of 6 MeV/u of the Alvarez linac is adopted so that fully stripped Si ions are produced in a reasonable fraction with the charge

TABLE I HIMAC accelerator parameters: Injector system

Ion sources	
Type	PIG & ECR
Ion species	He - Ar
q/A	$>1/7$
High voltage	60 kV Max. (on different platforms)
Low-energy beam transport line (LEBT)	
Length	7 m
Switching magnet	DC operation
Injector system	
Frequency	100 MHz
Repetition rate	3 Hz Max.
Duty factor	0.3% Max.
Acceptance	0.6π mm·mrad (normalized)
q/A	$>1/7$
RFQ linac	
Input/Output energy	8/800 keV/u
Structure	Four-vane type separated into 4 sections
Vane length	7.3 m
Cavity diameter	0.6 m
Max. surface field	205 kV/cm (1.8 Kilpatrick)
Peak rf power	260 kW (70% Q)
No. of final rf amp.	1
Alvarez linac	
Input/Output energy	0.8/6.0 MeV/u
Structure	3 independent rf cavities
Total length	24 m
Cavity diameter	2.20/2.18/2.16 m
No. of drift tubes	106 in total
Focusing sequence	FODO (Q-mag. in every 2nd tubes)
Average axial field	1.8/2.1/2.1 MV/m
Shunt impedance	31-47 MΩ/m (effective)
Max. surface field	150 kV/cm (1.3 Kilpatrick)
Peak rf power	1.02/0.95/0.89 MW (85% Q)
No. of final rf amp.	3 (peak output of 1.2 MW each)

TABLE II HIMAC accelerator parameters: Two-synchrotron ring system

Medium-energy beam transport line (MEBT)	
Charge stripper	Output end of the Alvarez linac
q/A after stripping	>1/4 at 6 MeV/u
Debuncher cavity	100 MHz
Two-synchrotron ring system (for one ring)	
Output energy	100-800 MeV/u for q/A=1/2 ions
Average diameter	41.3 m (circumference 130 m)
Maximum rigidity	9.73 Tm
Acceptance (H/V)	30/3 π mm·mrad (normalized)
Excitation of two rings	180° out of phase
Repetition rate	0.3-1.5 Hz
Typical repetition rate	1/2 Hz at 600 MeV/u
Rise/Flat-top period	0.7/0.5 s typical at 1/2 Hz
Bending field ramp rate	2 T/s Max.
Magnet lattice	
Focusing sequence	FODO (12 cells, 6 super-periods)
Betatron tunes (H/V)	3.75/3.25
No. of dipole magnets	12 (sector type, 3.4 m long)
Dipole field (Min./Max.)	0.11/1.5 T
Bending radius	6.5 m
No. of Q magnets	24 (0.4 m long)
Q-field (Min./Max.)	0.4/7.4 T/m
Power supplies for bending magnets	
Type	4 sets of 6-phase thyrisitor rectifier blocks (24 phases)
Reproducibility	1×10^{-4} at the max. current
Stability (goal)	2×10^{-5} at the max. current
Reactive power compensator	
Type	2 sets of 6-phase thyristor controlled reactors (12 phases)
Correction	
COD (horizontal only)	12 steering magnets
Chromaticity	12 sextupole magnets
Acceleration system	
No. of rf cavities	1 (2.5 m long, ferrite-loaded)
Frequency range	1-8 MHz (harmonic 4)
Acceleration voltage	11 kV peak at 1 MHz
Rf power loss	25 kW peak at 6 MHz
Momentum acceptance	±0.2% of the extracted beam
Vacuum system	
Average pressure	1×10^{-8} Torr
Baking temperature	200℃
Material of chamber	SUS-316L
Bending magnet chamber	0.3 mm thick stiffened by ribs
Multi-turn injection system	
Effective turn number	10-30
Injection period	80-240 μs
Slow extraction system	
Slow extraction scheme	3rd order resonance
Beam duration	400 ms typical at 1/2 Hz
Beam emittance (H/V)	10/10 π mm·mrad Max. (unnormalized)
Fast extraction system (the upper ring only)	
No. of fast kicker magnets	7 (0.3 m long)

stripper. For future extension of HIMAC to accelerate heavier ions, a space for an additional linac up to 8 MeV/u is prepared.

A debuncher cavity will be introduced in a medium-energy beam transport line (MEBT) in order to improve the momentum spread of the linac beam.

The beam from the injector is switched by a switching magnet of the MEBT and is alternately injected into two synchrotron rings installed on the different floors of the building.

Structures of two rings are almost identical to each other and are of separated function type. Two rings are alternately excited and accelerate heavy ions to different energies which range from 100 to 800 MeV/u for heavy ions with a charge to mass ratio of 1/2. The repetition rate varies from 0.3 to 1.5 Hz depending on the energy.

Each beam slowly extracted from the upper or the lower rings is delivered to a vertical or a horizontal high-energy beam transport lines (HEBT).

On the other hand, a fast extracted beam from the upper ring will be used for experiments and will be injected into the lower one: a junction beam transport line from the upper one to the lower one is foreseen.

Six irradiation rooms associated with the HEBT system consist of three treatment rooms and the rooms for physics and general-purpose experiments, secondary-beam experiments, and biological experiments. One of three treat-

TABLE III Beam intensity schedule for typical ions

Particle species	C	Ne	Si
Ions from ion sources	C^{2+}	Ne^{3+}	Si^{4+}
Source electrical current (eμA)	160	58	13
LEBT transmission		0.7	
RFQ linac transmission		0.8	
Alvarez linac transmission		0.9	
Stripper efficiency	0.93	0.67	0.52
Ions after stripping	C^{6+}	Ne^{10+}	Si^{14+}
MEBT transmission		0.75	
Injected ion current (eμA)	170	49	9.1
Injected ion intensity (pps)	1.8×10^{14}	3.1×10^{13}	4.1×10^{12}
Injection interval (μs)		76.8	
Injection efficiency		0.5	
Circulating ion intensity (ppp)	6.9×10^{9}	1.2×10^{9}	1.6×10^{8}
Rf capture efficiency		0.8	
Acceleration efficiency		0.9	
Slow extraction efficiency		0.8	
Synchrotron repetition (Hz)		0.5	
Extracted intensity (pps)	2.0×10^{9}	3.4×10^{8}	4.5×10^{7}
HEBT transmission		0.9	
Irradiation transmission		0.1	
Intensity on target (pps)	1.8×10^{8}	3.1×10^{7}	4.0×10^{6}

ment rooms is equipped with both courses for vertical and horizontal beams, and the other two are equipped with a course for a vertical or a horizontal beams, respectively. All courses will be equipped with irradiation devices consisting of wobbler scanning magnets, a scatterer, a range shifter, a ridge filter, a multi-leaf collimator, etc.

A supplementary junction beam transport line of the HEBT system is prepared to join the horizontal beam with the vertical one.

For secondary-beam experiments, a target will be placed in front of the secondary-beam production room and the desired ions, for example, ^{19}Ne and ^{10}C, are separated with analyzing magnets of the horizontal HEBT system.

Two more irradiation rooms are prepared for the fast extracted beam experiments from the upper ring and for medium-energy beam experiments from the Alvarez linac, respectively.

DISCUSSION

The HIMAC accelerator complex has been designed not only to satisfy the radiation oncological requirements but also to allow future extension.

The accelerator complex is featured by the two-ring structure which simultaneously provides both vertical and horizontal beams having different energies for two-beam treatment or two different treatments. Future extension will be due to this feature. Two-stage cascade acceleration of heavier ions will be possible. It will be also possible that the lower ring will be used as a storage ring, allowing the treatment and diagnosis with radioactive beams and/or a single shot beam of stable isotopes.

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