Status of HIMAC Construction at NIRS-JAPAN

M.Kanazawa, H.Ogawa, S.Yamada, Y.Sato, K.Sato, A.Itano, M.Kumada, K.Noda, T.Kohno, E.Takada, M.Sudou, A.Kitagawa, K.Kawachi, M.Endo, T.Kanai, F.Soga, S.Minohara, and Y.Hirao,

National Institute of Radiological Sciences, Division of Accelerator Research, 4-9-1 Anagawa, Chiba 260, JAPAN

Abstract

A heavy ion synchrotron facility dedicated to the medical use, HIMAC (Heavy ion medical accelerator in Chiba), is now under construction. This report describes the accelerator system and its present status of construction.

1 Introduction

The HIMAC project was approved in 1987, which is a heavy ion accelerator facility for cancer treatments. The ion species required for clinical treatment range from He to Ar. To have a range of 30 cm in human body for silicon ion, the maximum beam energy is 800 MeV/u. Requirement of beam intensity is determined to 5 Gy/min so that the one irradiation can be completed with a few tens of seconds. Irradiation facility comprizes three treatment rooms and other experimental rooms. One of the treatment rooms is equipped with both horizontal and vertical beam courses. Other two rooms are equipped with one beam course (horizontal or vertical).

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	0.6πmm · mmrad(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 impedence	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 magnets	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)
	Repetition 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 temperature	200 °C
	Average pressure	1×10^{-9} torr
	Pumps	Sputter ion pumps Ti getter pumps Turbo molecular pumps
Extraction system	Type	Slow (1/3 resonance)
	Length of spill	up to 400 ms (slow)

The main parameters of the accelerator complex are listed in Table 1. This report focuses recent progress of HIMAC accelerator construction, and we refer Ref.1 for further description of the design concept of the HIMAC.

2 Ion Source

The performance test of the PIG ion source[2] has been carried out since 1987, and almost finished now with good results which satisfy the requirement on the beam intensity from He to Ar. The pulsed operation with low duty have been found effective both to increase the intensity of highly charged ion and to make the life time of the ion source long. The life time is determined by that of a filament and is more than one week.

The ECR ion source[3] has two solenoid coils and NdFe permanent magnets to generate mirror and sextupole field, respectively. The plasma chamber is fed with microwave source of 10 GHz, 2.5kW. Preliminary results of beam test shows that the obtained intensity exceeded the required value for He, N, and Ne. Further beam test will be continued with new plasma chamber to increase the beam intensity of highly charged ion.

3 Injector Linac

In the injector system, both RFQ and Alvarez linacs have been tested with high power successfully. As shown in Fig.1 the whole system of the Alvarez linac was tested at Niihama works of Sumitomo Heavy Industries Ltd. The all parts of the control system are also completed including a software of a man-machine interface.

3.1 RFQ linac

The RFQ linac is of a four vane type and divided into four tanks. A longitudinal and a transverse field distribution are tuned with side tuners. After tuning, the field uniformity was obtained within a deviation of 2% azimuthally and 3.3% longitudinally. The measured Q-value was 11800 which is 67% of the calculated value with superfish program. The peak rf power of 300 kW can be fed to the cavity, which is enough to accelerate the ions of charge to mass ratio of higher than 1/7. The maximum surface field on the vane top is estimated to be 200 kV/cm (1.8 Kilpatrick) with above peak rf power. The high power operation with repetition rate of 3 Hz and duty factor of 0.3 % has been performed without any trouble.

3.2 Alvarez linac

An Alvarez tank is separated into three independent rf cavities so that an rf power required for each cavity does not become too high. The peak rf power is estimated to be about 3 MW in total with 70 % Q value of the calculated value including stem losses. The maximum surface field is 128 kV/cm (1.1 Kilpatrick), resulting in an average axial field of about 2 MV/m.

The third cavity has been fabricated in advance and measured rf property. The measured Q value was 81

% of the calculated value and the deviation of the field distribution is measured as less than 2%. RF power of 1.5 MW for the tank has been obtained from the final stage amplifier and the operation with this rf power has been stable. The amplitude stability of 10^{-3} and a phase stability of 1 degree have been obtained during 400μ s which is long enough for multi-turn injection to the synchrotron.

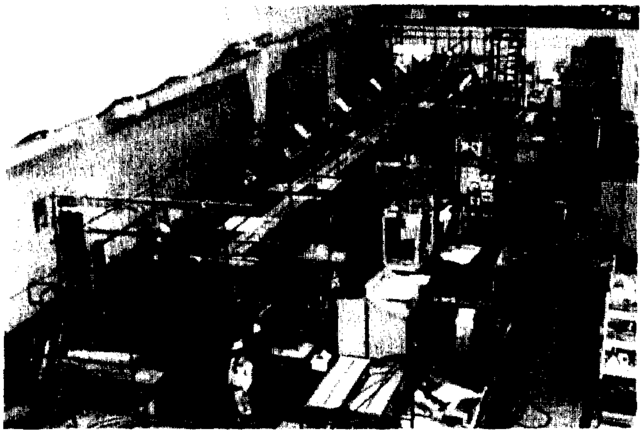

Fig.1. An overview of the Alvarez linac assembled and tested at Niihama works, Sumitomo Heavy Industries, Ltd. Three sets of the high power amplifiers can be seen at the right of the tank.

3.3 Debuncher

A 100 MHz debuncher cavity is introduced to suppress the momentum spread of the beam. An rf voltage of 300 kV (for q/A=1/4) rotates the beam bunch in a longitudinal phase space, and reduces the energy spread of 1.2% to a satisfactory value of 0.11%. An error of relative phases in the acceleration field among Alvarez tanks affects most seriously on the energy spread, which will increase the energy spread from 0.11% to 0.2% in the simulation[4] with a relative phase error of 1 degree.

4 Synchrotron

Two synchrotrons with the same lattice, which are installed in the upper and lower underground floors, are operated independently each other except the alternate pulse operation. The output energy of each ring must be variable in a wide range from 100 to 800 MeV/u. The upper ring provides the beam for a vertical course and the lower ring provides the beam for a horizontal course or vertical course.

4.1 Magnets

The bending magnets are of sector type with demountable pole end pieces at both ends to adjust the integrated field strength of each magnet. The first bending magnet has been fabricated and its magnetic field distributions have been measured[5] with a Hall probe as shown in Fig.2. The measured radial field distributions show the nice flatness in a required horizontal aperture of 110 mm and the required field range from 0.1 to 1.5 T. At present, fabrication of all bending magnets is in progress. The quadrupole magnets have also demountable pole end pieces, whose shape can be adjusted to obtain the flat field gradient in the wide aperture of 115mm. The first quadrupole magnet has been fabricated and various measurements have been made. A measured distributions of field gradient show that the punched pole cross section satisfies the specification on the field gradient. At present, steel punching for all quadrupole magnets are being made. Other magnets such as sextupole magnets, steering magnets, bump magnets, and septum magnets are under fabrication.

Fig.2. Photograph of the Dipole Magnet.

4.2 Power supplies

A power supply for the bending magnets has thyristor rectifiers of 24 pulses, which consist of 8 blocks of 6 pulse thyristor bridges working in converter-inverter mode. Two power supplies for the focusing and defocusing quadrupole magnets have thyristor rectifiers of 24 pulses, whose thyristor bridges working in converter mode. The reactive power is compensated by 12 pulse thyristor controlled reactors (TCR) equipped in parallel with a set of capacitors. The voltage variation of the primary ac line can be compensated with this TCR. These power supplies and TCR are controlled digitally by 16kW pattern memory driven with clock pulse of 1200 Hz, which is phase-locked to 50 Hz of ac power line. A feed forward loop by the use of the computer will realize precise tracking of the current pattern. The current pattern starts from the same phase of the ac power line to make the feed forward loop effective. These power supplies are under construction now.

4.3 RF acceleration system

One set of RF acceleration system has been constructed in advance to prove that the our design is correct and a constructed system works well. After the tests of each element, we have performed operation as a total system. In the high power test, the rf frequency has been swept in 0.7 sec from 1 to 8 MHz with acceleration voltage of 6 kV. The shunt impedance is about constant of 320 Ω with rf acceleration voltage of 6 kV though it is 550 Ω at 1 MHz in low power operation. When the cavity frequency has been increased slowly, we have encountered the parasitic resonance which destroyed the grounding capacitors of ferrite bias windings. Further tests will be made to increase the acceleration voltage.

The monitors of beam phase and position are used to control the acceleration frequency. The fundamental frequency component of the beam signal is processed by heterodyne technique in the monitor electronics. This allows good signal to noise ratio with required lowest beam intensity of 10^7 ppp. To control the acceleration frequency stably, digital feedback control system with a digital synthesizer (STEL-1375a) has been developed. The control system has been tested with two steps. In the first step, the feed back loop, which locks the rf frequency in the circulating beam bunch, has been tested with a simulator circuit of the synchrotron oscillation. From this experiment, it has been found that the feed back loop had fast response to damp the synchrotron oscillation. In the second step the beam test[6] of the control system has been performed in collaboration with INS, Univ. of Tokyo. In this beam test, we could accelerate He ion from 10 MeV/u to 160 MeV/u at a low intensity of 8×10^6 ppp successfully.

4.4 Control system

Configuration of the control system for the synchrotron rings has been fixed.[7]

Major feature includes:

1) A VAX cluster will be used for man-machine interfacing and for supervising various subsystems via Ether net.
2) Output pattern of main dipole magnets and other power supplies will be controlled via VME board CPU and memory module where PDOS real time system will be installed.
3) Also Toshiba-G200E will be employed for controlling the RF system and the transport-line magnets etc.

4.5 Injection and extraction

A multiturn injection method is adopted to increase the beam current in the ring. The duration of bump orbit to inject the beam is adjustable between 80 and 240 μ depending on the beam emittance from the linac. This period determines the maximum effective turn number, which will range from 10 to 30 turns.

Slow beam extraction is adopted by the use of the third order resonance of 11/3. To prevent the leakage of electric field of the electrostatic deflector, tungsten plate of 0.3mm thick is used. There are two septum magnets after the electrostatic deflector, and the both magnets are equipped outside the vacuum chamber to remove the source of outgas.

4.6 Vacuum system

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. The arrangement of sputter ion pumps, titanium getter pumps and turbo-molecular pumps has been fixed. All the vacuum chamber of the rings are bakable up to 200 ℃. In order to decrease eddy current on the vacuum chamber in the bending magnet gap, the chambers are made of SUS-316L of 0.3 mm thick reinforced by ribs with a pitch of 20mm. Direct heating with dc current in this thin chamber has been tested and the temperature of 200 ℃ on the surface has been obtained with low current of 260 A. The other vacuum chambers are heated with the insulated heaters attached on the surface of the chambers.

5 Beam delivery

The vertical beam line can transport the beams with the energy of up to 600 MeV/u from the upper and lower synchrotrons, and the horizontal beam line can transport the beams with the energy of up to 800 MeV/u from the lower synchrotron. A junction beam line is prepared to transport the horizontal beam into the vertical beam line. To get an efficient usage of treatment rooms, it is necessary to switch the beam quickly from one course to an other, keeping the reproducibility of the beam position within 2.5mm at the isocenter. To measure the beam profile, multi wire chamber with Ar+CO_2 gas has been made and tested with proton beam at NIRS.

6 Treatment equipment

The scanning magnets and their power supplies have been made. It has a sinusoidal current shape of 57 Hz. This frequency is different from the frequency of ac power line (50Hz) to avoid possible deviation from uniform beam distribution by beam modulation. The design of a multi-leaf collimator has been fixed and its performance will be tested with heavy ion beam in LBL.

7 Building

The shape of the building has appeared over the ground level, and the civil-engineering works is at its final stage. Utilities such as power lines, cooling water pipes, air conditioner units are now being installed. Installation of the injector system is just going to start this month.

8 Acknowledgment

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