Status Report on HIMAC

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Abstract

The NIRS heavy-ion two-synchrotron medical facility, HIMAC, has been commissioned from the end of 1993 after the success of beam tuning of the entire accelerator system in a short term. About 7 months after the beginning of the synchrotron beam tuning, HIMAC delivered the beam for a clinical trial to the first patient on 21 June, 1993, following 4 months of preparatory experiments. One ring is operated to supply fully stripped C ions at an energy of 290 MeV/u to a therapy room for a clinical trial and preparatory experiments. The other ring is operated at several energies in order to investigate further precise tuning of beam and machine. Ion species being accelerated so far are He and C. The intensity of the beam circulating in the rings is well controlled in a wide range from $5x10^2$ to $1x10^{10}$ ppp because the synchrotron can accelerate the beam stably without a beam feedback signal.

1. Introduction

Heavy-Ion Medical Accelerator in Chiba (HIMAC) at National Institute of Radiological Sciences (NIRS) is a heavy-ion two-synchrotron facility dedicated to medical use such as cancer therapy. HIMAC is designed to meet medical requirements[1] based on in-house experiences and the research of biological effectiveness and clinical trials at LBL. Ion species range from He to Ar. Acceleration energy varies from 100 to 800 MeV/u. Intensity of the beam extracted slowly from the synchrotron is, for example, $3x10^8$ pps of fully stripped Ne ions at 600 MeV/u for a spill length of 400 ms at a repetition rate of 1/2 Hz.

Figure 1 shows a bird's eye view of the HIMAC facility together with photographs of typical elements of each accelerator system. A main accelerator consists of two identical synchrotron rings installed at upper and lower underground floors of the building. An injector accelerator consists of a cascade of linacs, RFQ and Alvarez, preceded by two kinds of ion sources, ECR and PIG. A high-energy beam transport system consists of vertical and horizontal beam lines which deliver the beam from the upper and lower rings to three therapy rooms and experimental irradiation rooms for basic researches of various fields. One of therapy rooms is equipped with both vertical and horizontal irradiation ports, while the others are with vertical or horizontal, respectively.

2. Commissioning and Status

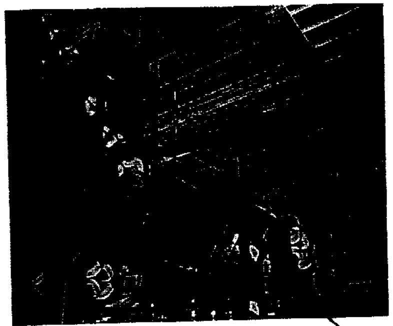
The injector linac has been operated with various ion species since the first beam of singly charged He ions was successfully accelerated at 6 MeV/u in the end of March, 1993[2]. After the accurate alignment of ring magnets etc., baking of vacuum chambers, and fine tuning of power supplies during the summer, 1993, a beam tuning of two rings was started for doubly charged He ions in the middle of November. In less than a month, the beam was slowly extracted from the both rings at 230 MeV/u with a spill length of more than 300 ms successfully at a repetition rate of 1/2 Hz. Performance of a high-energy beam transport system was confirmed to be satisfactory in excellent agreement with calculated optics parameters.

As soon as the accelerator system has been commissioned after the approval in radiation safety inspection, a new beam of fully stripped C ions has been accelerated at a new energy of 290 MeV/u. The beam is chosen for the first clinical trial of cancer therapy of head and neck because the radiological characteristics is close to the known modality. By using the beam supplied from the lower ring weekdays from 12:00 to 20:00 o'clock, preparatory experiments of physics, biology, and medicine have been extensively carried out toward the first clinical trial. The final testing and tuning of the irradiation systems have also been carried out in this period. On the other hand, the upper ring has been operated to study further tuning such as a new energy, a ripple reduction, and a new approach controlling the slow extraction process.

Because the stable acceleration can be achieved without a beam feedback of a phase and a radial position which controls a frequency of the rf accelerating voltage, the intensity can be reduced as small as $5x10^2$ ppp while the maximum intensity is $1x10^{10}$ ppp of He ions. Recently, new energies of 430, 600, and 100 MeV/u are achieved.

3. Operating Parameters and Tuning

The injector linac is operated at a repetition rate of 2 Hz to supply the beam to two rings and a room for medium-energy experiments. Two rings are operated 180-degrees out of phase at the same repetition rate of 1/2 Hz. In this section, operating parameters and routine tuning are briefly described for C ions at 290 MeV/u as a typical example.



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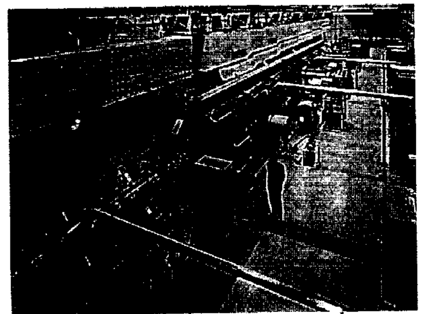

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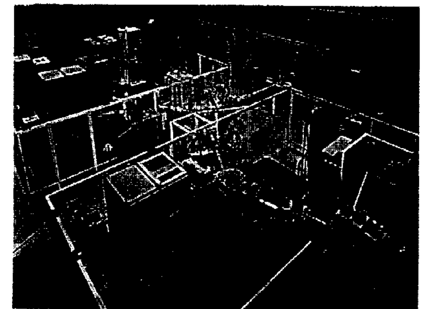

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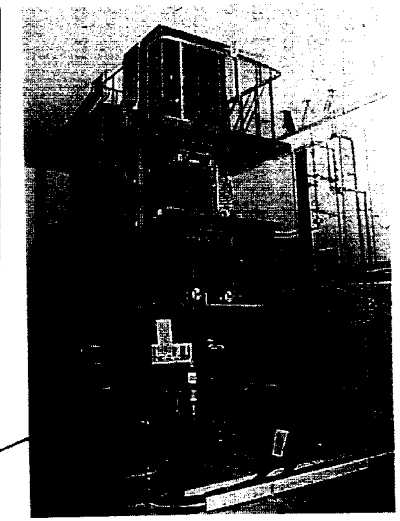

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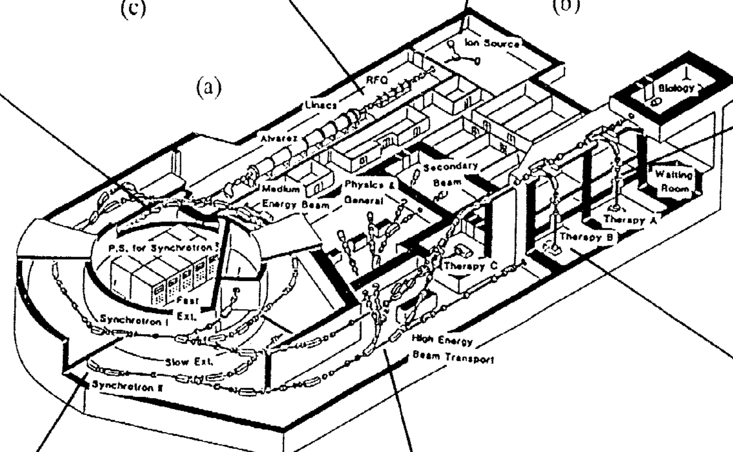
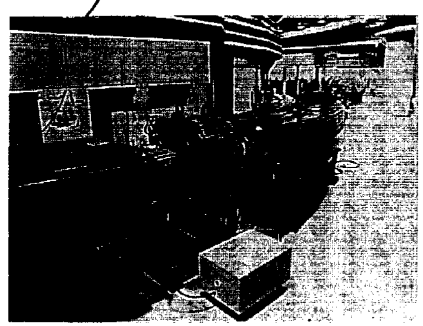


(a)

Fig. 1 Schematic bird's eye view and recent photographs of the HIMAC facility
(a) Schematic bird's eye view
(b) Ion sources:
ECR(front) & PIG(rear)
(c) Injector linac cascade:
RFQ(front) & Alvarez(rear)
(d) Injection beam line:
Switching mag. for both rings
(c) Lower synchrotron:
BM, QM, etc.
(f) High-energy beam lines:
Horizontal beam lines
(g) Irradiation device:
Wobbler mag. of vertical line
(h) Therapy room:
Positioning table with vertical & horizontal ports



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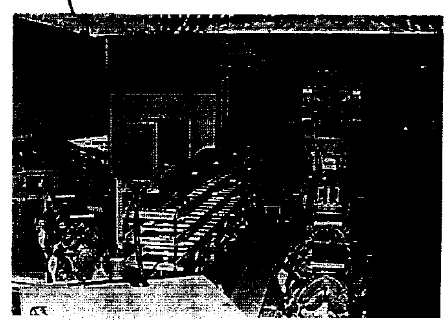

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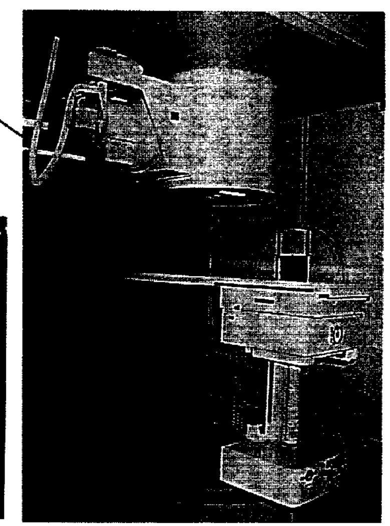

(h)

3.1. Injector

The ECR source is used to produce C^{4+} ions because of a long life and is operated with a microwave of 10 GHz at a repetition rate of 2 Hz and a pulse width of 3 ms.

The RFQ linac accelerates the beam from 8 to 800 keV/u and the Alvarez linac from 0.8 to 6 MeV/u. The both linacs are pulse-operated at the same radio-frequency of 100 MHz with pulse widths of 0.6 ms at RFQ and 1 ms at Alvarez, respectively. RFQ is excited by a final rf power amplifier with a peak power of 35 kW. Alvarez is divided into three independent tanks and each tank is excited by each final rf power amplifier with a peak power of about 200 kW each.

A charge stripper producing the fully stripped C ions is furnished at the exit of Alvarez. The debuncher rf cavity is equipped at a midway of the injection beam transport line to synchrotrons in order to improve the momentum spread. It is pulse-operated at 100 MHz and is excited by a final rf power amplifier with a peak power of 3kW.

3.2. Synchrotron

A trapezoidal waveform of excitation current of a series of twelve dipole magnets and a field monitoring magnet of each ring at a repetition rate of 1/2 Hz includes four periods: an 80 ms flat bottom, a 680 ms upward slope, a 400 ms flat top, and a 640 ms downward slope, all of which are smoothly connected by additional 50 ms periods each other. The minimum and maximum current is 138 and 1040 A, respectively. Likewise, focusing and defocusing quadrupole magnets are excited by same waveforms with the minimum and maximum current of 80 and 610 A, respectively.

A repetitive control is applied to a power supply of each main magnet independently in order to realize an accurate waveform for each one. This control results in precise tracking among excitations of three kinds of main magnets, and seems rather stable.

Injection beam channel consists of a dc-operated septum magnet and an electrostatic inflector with a thin septum electrode. A multi-turn injection of the linac beam is carried out within the flat bottom by four fast bump magnets being pulse-operated at a decay time of 0.2 ms.

An rf capture starts at 2 ms after the multi-turn injection and completes when the rf accelerating voltage is gradually raised up to 6 kV during a period of 10 ms. In the middle of the rf capture, the beam feedback loop of a phase and a radial position starts automatically when a signal level of the bunched beam reaches at the given value for the feedback. However, the feedback is not mandatory in the recent operation because of stable beam acceleration.

The rf accelerating voltage is kept constant at 6 kV until the end of the flat top. The rf acceleration automatically starts at the beginning of a smooth connection between the flat bottom and the upward slope. A direct digital synthesizer type master oscillator dictates the accelerating frequency. A long search coil equipped at a gap of the field monitoring dipole magnet detects a field change and generates clock pulse at 0.2 Gauss increase or decrease. The synthesizer is controlled by means of an address register for a memory module with triggering of the field clock[3].

At the flat top, a slow extraction due to the third-integer resonance at a horizontal tune value of 11/3 is carried out by changing the focusing quadrupole current for more than 300 ms. A difference of current between the beginning and the end of the flat top is about 0.9 A. A separatrix and a bump orbit are generated by two sets of two sextuple magnets and four bump magnets, respectively, both of which are excited during the flat top only.

The extraction beam channel consists of two-stage electrostatic deflectors with a thin septum electrode and two-stage dc-operated septum magnets. A high voltage of the first deflector is varied from 62 to 30 kV during the flat top in order to decrease a horizontal movement of the beam direction due to a separatrix motion.

A set of six sextuple magnets is excited by a trapezoidal waveform to correct a chromaticity with the minimum and maximum current of 3.4 and 20 A, respectively.

3.3. Routine Tuning

Operating parameters are stored and re-loaded as a data file of the computer control system. When the computer receives operator's instruction to start the machine operation, it automatically sets the operating value of all magnets after initialization in which a full excitation of all magnets is repeated several times to reproduce the previous magnetic field well.

Ion sources, by nature, usually meet a problem of reproducibility especially for intensity and emittance of ion beam. As a routine tuning of the ECR source itself, a gas flow rate and a microwave power are adjusted to optimize both the intensity and the emittance. Focusing elements of a low-energy beam transport line are tuned in order to reproduce the previous profile at the entrance of RFQ. Focusing elements of a medium-energy beam transport line are cooperated to give the same profile and axis as before at a focus point of the entrance of an injection beam transport line to the ring.

Steering magnets between the focus point to the septum magnet of the ring injection beam channel are tuned if necessary while no quadrupole magnets are tuned usually. A high voltage of the electrostatic inflector is finally tuned to obtain the same beam profile and axis as before at the exit of the electrostatic inflector and to obtain the intense beam circulating in the ring during the multi-turn injection.

The injection energy is monitored by a momentum analyzing magnet system equipped at a beam transport line to a room for medium-energy experiments. The analyzing system is preceded by a pulse-operated switching magnet and has a high resolution of 5×10^{-4} in comparison with a longitudinal acceptance of the synchrotrons. When the energy deviation is observed, an rf phase of the final rf power amplifier of the third Alvarez tank is tuned. After this tuning, a current of the main magnets of the rings is no longer tuned at the flat bottom.

In recent routine operation, no further tuning on the synchrotrons is done although steering and quadrupole magnets of the high-energy beam transport lines are occasionally tuned. The beam profile observed at the end of the high-energy beam transport line is well reproduced as before and the accelerator system is running all day long for the preparatory experiments as it is.

3.4. Tools for Waveform Adjustment

It is essential for a beam tuning at a new energy to generate an accurate current waveform of each magnet and device operating parameters which give a nice performance of tracking and working points such as a tune value.

Three kinds of generation methods are prepared in the design stage. The first one is based on the field measurement data of magnets and a theoretical tune value of beam orbit computation. The second and third ones are to modify a waveform partly and to shift a waveform along the time axis as a whole, respectively. Such modification and shift are carried out by operators through a graphic CRT display in order to obtain a high performance of tracking and working point of tune value experimentally.

During the first beam tuning, the first method was necessarily applied. It was known that the waveform was insufficient in both tracking and tune value. The second method was then applied to modify current values at both the flat bottom and the flat top. This improved the tune value but was still insufficient for tracking.

The fourth method has been developed with help of a temporarily storing function of a waveform in a temporary file of the computer. The current waveform of the dipole magnets is once stored in the file. It is then transferred to the graphic display for editing a waveform of the quadrupole magnets. It is further modified by the second method at both the flat bottom and the flat top. The fourth one results in improving tracking so much.

4. BEAM PERFORMANCE

It is pointed out from the beam operation that the linac beam shows better performance of emittance and momentum spread than design values which are estimated on the assumption of errors associating with fabrication, assembly, and operating stability. Because the linac is manufactured in less than a tolerance, the normalized emittance is better by a factor of 4 at 0.7 π mm•mrad and a momentum spread is better by a factor of 3 at ± 0.1 %.

The maximum peak current of C^{6+} ions delivered from the linac to the rings is 450 μA while the intensity injected to the rings is usually controlled at about a third of the maximum by a set of mesh attenuators and beam slits.

A beam transmission efficiency of low-energy, medium-energy, and high-energy beam transport lines is about 90 % or more as expected in the design stage. An efficiency of the cascade of linacs is about 85 % as expected, too. An overall efficiency of the rings from injection to extraction is estimated at 13 % for a decay time constant of 200 μs of fast bump magnets. An efficiency of the slow extraction is then estimated from both intensities observed at injection and extraction beam channels with help of a beam signal waveform observed by an electrostatic beam monitor in the ring. The efficiency of the slow extraction is about 70 % when an efficiency of the multi-turn injection is assumed to be 40 % and an efficiency of the acceleration observed from the beam waveform is about 60 %.

Intensity decrease in the ring occurs mainly during a smooth connection between the flat bottom and the upward slope. A space charge effect is considered to occur from the fact that the intensity of the circulating beam decreases much when the intensity of the injected beam is higher than 300 μA of He^{2+} ions.

Beam profiles observed at several measuring points of the accelerator system are satisfactory as expected in the design stage. Typical of horizontal and vertical beam size is 10 mm each at the end of the high-energy beam transport line as expected.

The beam extracted slowly from the ring has a worse vertical emittance than a value predicted by adiabatic damping by a factor of 6. This emittance growth is supposed to arise from a coupling between horizontal and vertical tunes and it will be studied further.

A ripple of the extracted beam seems to be a mixture of 50 Hz and 100 Hz components. Such a ripple is considered to come from a current ripple of the focusing quadrupole magnets because the extraction based on the third integer resonance is very sensitive to the fluctuation of tune value.

Horizontal and vertical tune values at the flat bottom and the flat top are experimentally set in view of tracking, chromaticity, and a tune shift due to space charge effect. Because chromaticity plays a role of decreasing a tune shift due to momentum spread, it is corrected to improve a beam loss while it occurs still during a smooth connection between the flat bottom and the upward slope.

5. FURTHER BEAM INVESTIGATION

One of subjects is to make a height of intensity envelope of the extracted beam more constant with time during all the extraction period by a feedback. An intensity signal of the beam observed by a thin plastic scintillator equipped at a mid-way of a high-energy beam transport line is fedback to an active filter of the power supply of the main focusing quadrupole magnets. This feedback works surely well and it will be installed for actual operation.

Another subject is to decrease the intensity ripple of the extracted beam. The ripple of 50 Hz and 100 Hz should be decreased by the same feedback as described above. However, the operation test of the feedback shows ineffective results to both frequencies. A ripple compensator, which is a signal generator producing a mixture of several harmonics, is prepared in order to investigate a response of the ripple through the active filter. This method can be effective to decrease the ripple occasionally but needs more study.

A new approach is to control the slow extraction process by means of an rf knock-out for the tune measurement. Preliminary results show that the rf knock-out voltage with an appropriate bandwidth around a resonant frequency is able to extract the beam slowly through the third-integer resonance while the separatrix is fixed during the extraction period[4]. Beam performance seems to be high because of less ripple and better emittance than those of an ordinary slow extraction. This method is promising to produce the beam synchronized to breathing of a patient because rf voltage can be turned on and off immediately.

In addition to these subjects, an acceleration of different ion species at upper and lower rings is under investigation by means of alternate acceleration of different ion species by the linac due to two kinds of ion sources.

6. PERFORMANCE OF SYNCHROTRON ELEMENTS

The synchrotrons are running well due to a high performance of all the synchrotron elements. In this section, a performance of a power supply[5] and an electrostatic beam monitor are briefly described as typical examples of such a high performance.

6.1. Power Supply

In the case of the dipole magnet power supply whose maximum rating is 2,260 A, a static filter is installed while no active filter. A voltage ripple is measured and a current ripple is then estimated to be 4×10^{-5} in a peak to peak value at a current of 1,045 A and 5×10^{-4} at 137 A. In spite of no active filter, a remarkably low ripple is realized. In the case of the quadrupole magnet power supply whose maximum rating is 1,360 A, active filters being of reactor transformer type are equipped at both positive and negative outputs in addition to a static filter. The current ripple is estimated to be about 6×10^{-6} in a peak to peak value at a current of 615 A and 6×10^{-5} at 85 A.

6.2. Electrostatic Beam Monitor

Two electrostatic beam monitors which generate beam signals to control the rf accelerating voltage through a beam feedback loop are equipped at both ends of the rf accelerating cavity in order to improve a signal to noise ratio by combination of two signals from the two monitors.

When the rf cavity is powered at an rf accelerating voltage of 6kV, the beam signal is contaminated at a gain range of 70 dB by rf noise because of a leakage of rf power through wiring of ferrite bias current.

On the other hand, when the rf cavity is not powered during the multi-turn injection, the beam monitor can work at a gain range of 100 dB and can detect the increase of intensity of the circulating beam during the multi-turn injection period of 0.2 ms. This nice performance was helpful for observation of the efficiency during the multi-turn injection especially for the first beam tuning of the rings.

7. SUMMARY

Performance of HIMAC in first year of operation can be characterized by the following: the successful first beam tuning achieved in a short term, the stability shown in routine operation and in no-feedback operation, the capability to tune new ion species and energy almost instantaneously, and last but not least, the successful first clinical trial on schedule. These are attributed to not only an excellent linac elements resulting in a high beam performance but also excellent synchrotron elements resulting in high accuracy, small ripple, and low noise. The entire HIMAC facility is thus featured by a high performance of reproducibility and stability.

A future plan is under investigation in taking full advantage of two-ring structure in addition to extension of the HIMAC capability such as an acceleration of heavier ions than Ar. A function of storage ring will be added to the lower ring. This project will include a construction of electron cooling devices, a junction beam transport line between the upper and lower rings, a fast extraction channel of the upper ring, a fast injection channel of the lower ring, a secondary particle production target, and so on. HIMAC will then supply a positron emitting radioisotope beam with a short life to a therapy room for simultaneous treatments and diagnosis.

8. ACKNOWLEDGEMENTS

There were so many works for construction of the entire HIMAC facility. In order to satisfy the specification, many persons have made extensive efforts toward the completion in 1993 since the design stage in 1987. Staffs and guest scientists of the Institute and engineers of many companies, especially of Mitsubishi Electric Corporation, Sumitomo Heavy Industries, Ltd., Hitachi, Ltd., and Toshiba Corporation are gratefully acknowledged. We would like to thank crews of Accelerator Engineering Corporation established at the end of 1992 for skillful operation of the HIMAC facility.

9. REFERENCES

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