COMMISSIONING AND PERFORMANCE OF THE HIMAC MEDICAL ACCELERATOR

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Heavy ions show the excellent dose concentration especially at a position located deep in a human body. This character of heavy ions are well suited for the medical treatment of the cancer. A heavy ion synchrotron complex, HIMAC, has been constructed at NIRS for this purpose. The HIMAC accelerator consists of an injector linac, a couple of synchrotron rings, long and complicated beam transport lines, three treatment rooms and four experimental rooms. The maximum energy of the synchrotron is determined so that the residual range of silicon ions exceeds 30 cm in water. The clinical trials of the cancer treatment started on June 21 using a 290 MeV/u carbon beam, and 21 patients were treated by the end of February 1995.

1. INTRODUCTION

During the last 19 years, clinical trials have been carried out at NIRS with fast neutrons and protons as well as conventional X-rays and gamma rays. Based on the long experience of radiotherapy, NIRS decided to construct a heavy ion accelerator, HIMAC, for medical use[1],[2]. The main reason to adopt heavy ion therapy is the excellent dose localization both in transverse and longitudinal directions. In the longitudinal dose distribution, a very sharp Bragg peak is observed around the end point of heavy ions as shown in Fig. 1. Such a distribution is much more effective in the treatment of deeply seated tumors than exponentially decreasing dose distribution of X and γ rays. High relative biological effectiveness (RBE) of heavy ions at the Bragg peak is expected to be efficacious even on the radio-resistive tumors. Another high LET characteristics, a low oxygen enhancement ratio (OER), seems also very attractive. These characteristics of heavy ions were shown to be very effective in medical treatment by clinical trials at LBL[3].

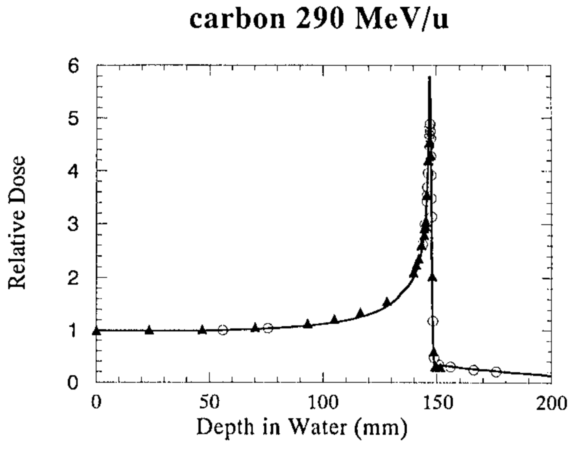

Fig. 1: A typical example of dose distribution of heavy ions in water.

The HIMAC project was approved in 1987 as one of the major project of “Comprehensive 10 year Strategy for Cancer Control” promoted by Japanese government since 1984. The construction of the injector started in the same fiscal year of 1987. The maximum energy of HIMAC is designed to be 800 MeV/u for light ions with $q/A = 1/2$ so that silicon ions reach 30 cm deep in a human body. Ion species of He, C, Ne, Si *etc.* are required for the clinical treatment. In the facility, there are three treatment rooms one of which has both vertical and horizontal beam lines. The other two treatment rooms are equipped with a vertical and a horizontal beam lines, respectively.

The beam tests of the accelerator started in November 1993 and the basic experiments for cancer treatments was begun in February 1994. The first clinical irradiation was carried out on June 21 and the treatment was successfully completed for three patients in August 1994. The patients have cancer cells in the head or the neck. It takes about 90 seconds for a single fractional treatment with 290 MeV/u carbon beam, while the precise patient-fixing procedure requires about 20 minuets. Three treatments per week and total of 18 treatments for each patient were planned to destroy perfectly tumor cells. The interim report of the heavy ion treatment for the first three patients shows excellent results just as expected. Radiation damage on the inside surface of the mouth seems very small in spite of the perfect damage of tumors.

Table 1: Requirements for the HIMAC beam

Ion species	^{4}He to ^{40}Ar
Maximum energy	800 MeV/u (q/A=1/2)
Minimum energy	100 MeV/u
Beam intensity*	1.2×10^{10} pps for ^{4}He
	2.0×10^{9} ^{12}C
	8.5×10^{8} ^{20}Ne
	4.5×10^{8} ^{28}Si
	2.7×10^{8} ^{40}Ar
Beam duration	400 ms (typical)
Repetition rate	1/2 Hz for each ring
Beam emittance	10 π mm mrad
Momentum spread	< ±0.2%
Field size	22 cm (Max. diameter)
Dose uniformity	±2%
Maximum range	30 cm
Dose rate	5 Gy/min. (Max.)

*Extracted beam intensity per ring.

In the second series of the clinical trials, heavy ion therapy was applied to cancers at the head or neck, the lungs and the central nerve system. Eighteen patients were treated in the second series extended to the end of February 1995. In the third series of the trials, much more patients will be treated with other types of cancers, for examples, the uterus, the liver, the prostate *etc*.

2. HIMAC FACILITY

The medical requirements for the output beam properties of HIMAC are summarized in table 1. The minimum output energy is required because of the treatment of superficial cancers. A cutaway view of the facility is shown in Fig. 2. As shown in the figure, the upper ring provides a vertical beam (600 MeV/u max.) to the treatment rooms A and B, and a horizontal beam with the same energy to the experimental room for biology. The extracted beam from the lower ring (800 MeV/u max.), on the other hand, goes horizontally to the treatment rooms B and C, and experimental room for physics and general purposes. Since a branch of the lower high energy beam transport (HEBT) line merges into the upper HEBT line, the output beam of the lower synchrotron can be provided vertically to the treatment rooms A and B. In order to get a high efficiency of the treatment room usage, it is required to switch the accelerated beam from one treatment room to the other room within 5 minuets. The reproducibility of the beam position should be better than ±2.5 mm at the isocenter. Such precise beam positioning is realized with a special sequence in the switching magnet excitation. An energy change of the synchrotron is also required once in a day to select the optimum residual range for different patients. After changing the beam energy, the dose uniformity in the irradiation field will be checked, whereas no such check is scheduled after the beam course switching.

There are two other experimental rooms for the medium energy (6 MeV/u) experiments and for the secondary beam experiments. A beam line for generating the radioactive beam will be installed in near future. Positron emitters, such as ^{11}C, will be effective in checking the irradiated area.

In the following subsections, brief descriptions are given for major components of HIMAC.

A. Ion Sources

We have two types of ion sources: a PIG and an ECR sources. A PIG source is a hot cathode type and operated in a very short pulse with a relatively long time interval. Such an operation mode increases appreciably an arc impedance resulting in a high arc voltage. The performance of the PIG source is excellent including the lifetime of the source[4].

An ECR source is a single stage type and energized with a 10 GHz microwave source of 2 kW max. The source is equipped with a sextupole permanent magnet of 9 kG at a pole tip.[5] The output beam intensities and emittance are satisfactory for the treatments. Since the ECR source is very stable and easy to operate, the ECR source is preferable in the daily operation for the clinical treatment.

Both sources are installed independently on high voltage decks of 60 kV max. and provide ions with 8 keV/u to the next acceleration stage.

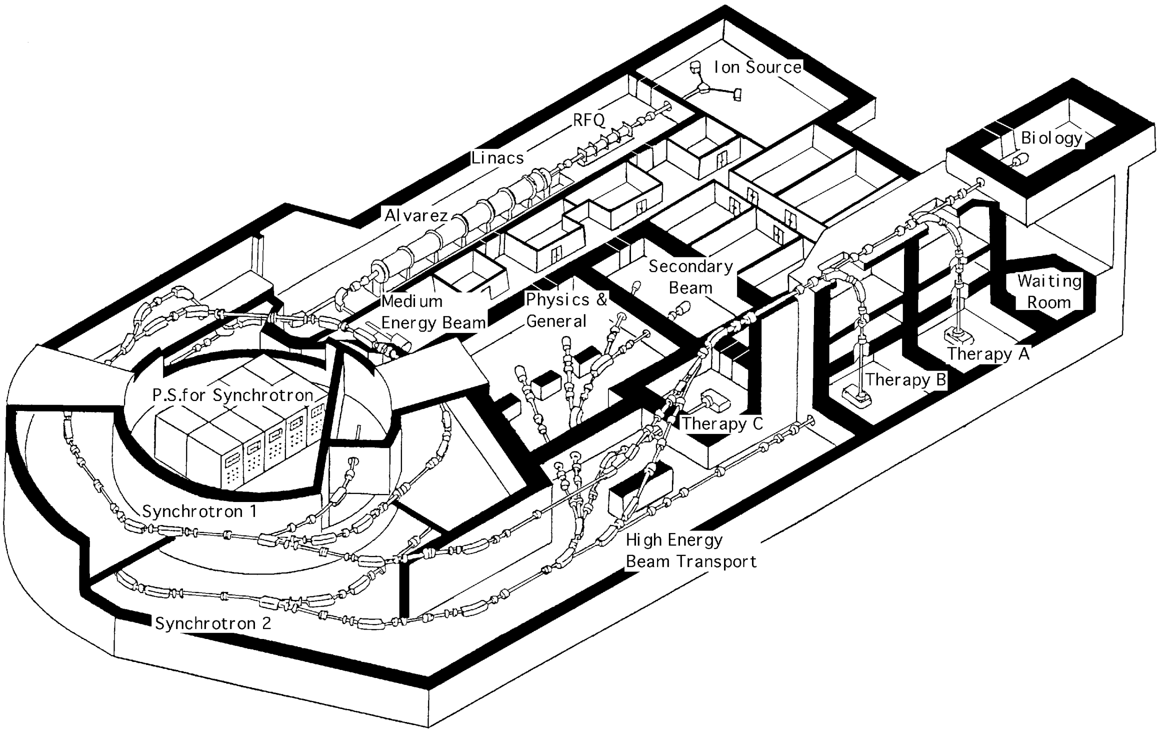

Fig. 2: A Bird’s eye view of the HIMAC facility.

B. Linacs

The injector consists of a 100 MHz RFQ, an Alvarez linac, a debuncher to reduce the momentum spread of the output beam, and beam transport lines connecting them[6].

An RFQ linac accelerates heavy ions with $q/A \geq 1/7$ from 8 keV/u to 800 keV/u. The RFQ is a conventional four vane type and has a vane length of 7.2 m. Since the vane length is very long comparing with the tank diameter, a filed distribution must be carefully tuned along longitudinal direction. About 40 side tuners are introduced for this purpose and realize very small field error of 4.9% and 2.6% for longitudinal and transverse directions, respectively. An acceptance and anaccelerating rate are 0.6 π mm¥mrad (normalized) and 0.76 MV/m, respectively.

The RFQ is followed by an Alvarez type linac (DTL) operated with the same frequency of 100 MHz. Both linacs are operated with a very low duty factor of 0.3% at maximum. The transverse phase space matching between the RFQ and the DTL is accomplished with a quadrupole magnet quadruplet installed in a 1.9 m long beam transport line. The DTL tank is 24 m long and separated into three independent rf cavities. The diameter of the cavities is about 2 m and change from one cavity to the next in order to obtain reasonable values for transit time factors. Since a transverse emittance of the output beam from the RFQ is thoroughly small, a FODO type focusing sequence is adopted for Q-magnets in the drift tubes. The magnets have laminated cores and are excited with the same flat-top-duty of 0.3% max.

At the output end of the DTL, a 100 μg/cm^2 thick carbon stripping foil is inserted to improve a charge to mass ratio of the ions. Only one stripping stage is adopted at a relatively high ion energy of 6 MeV/u because of the reliability of the system and of advantages for future expansion to the acceleration of heavier ions.

C. Synchrotrons

The main accelerator of HIMAC consists of two independent synchrotron rings with the same circumference of 130 m. The two ring structure of the synchrotron makes it possible to provide a treatment room simultaneously with a horizontal and a vertical beams having different energies. As a future extension, two stage acceleration of the heavier ions is planned.

A pulse magnet located in a MEBT line between the linac and the synchrotron switches the output beam from the injector to the upper and lower synchrotron rings. The two synchrotron rings are operated independently from each other except that the magnets must be excited 180° out of phase. The synchrotron is a separated function type with a FODO type focusing structure. The ring consists of 12 unit cells, whereas the superperiodicity of the ring is 6. A bending angle and a radius of the sector type dipole magnet are 30° and 6.5 m, respectively. The dipole field changes from 0.11 T at injection energy to 1.5 T at maximum with a ramping rate of 2 T/s (max). The effective length of the dipole magnets are adjusted by shimming cores at both ends of the pole tips. Design value of the betatron tunes are 3.75 and 3.25 for horizontal and vertical directions, respectively. The actual values, however, are chosen typically at 3.68 and 3.13 in a daily operation.

A current pattern of the synchrotron magnets is controlled with digital processors and a repetition rate can be varied from 0.3 to 1.5 Hz. A typical operation pattern is 200 ms for a flat base, 700 ms for rise and falling time and 400 ms for a flat top. A multiturn injection scheme is adopted to increase the circulating beam current by a factor of 20 and a third order resonant extraction scheme is employed to realize a rather long beam duration of 400 ms.

The rf system is required to cover a wide frequency range from 1 to 8 MHz. The maximum acceleration voltage is estimated to be 10 kV for ions with a charge to mass ratio of 1/2. A fully digital control system (sampling rate of 500 kHz) is adopted for the feed back loop of the phase and the beam position. The rf frequency essentially varies with a B-clock pulse generated at every 0.2 G change in bending field. Feed back loops of a phase and a beam position are adopted to adjust the frequency. The whole control system works very well and even a very low intensity beam of a few hundred particles per second can be stably accelerated without $\Delta\phi$ and Δr feedback loops.

D. Irradiation apparatus

In order to realize a large and uniform irradiation field, a wobbler scanning method is adopted. As shown in Fig. 3, a pair of wobbling magnets is installed in the beam line to make a circular trajectory at the isocenter. A scatterer with a proper thickness is used to smooth out the transverse dose distribution. Other important elements of the irradiation apparatus are a ridge filter and a range shifter. The ridge filter has a profile like a saw-tooth and broaden the momentum

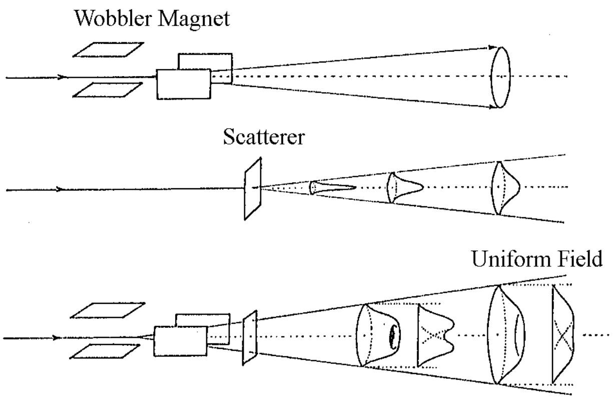

Fig. 3: A schematic explanation for field broadening with a pair of wobbling magnets.

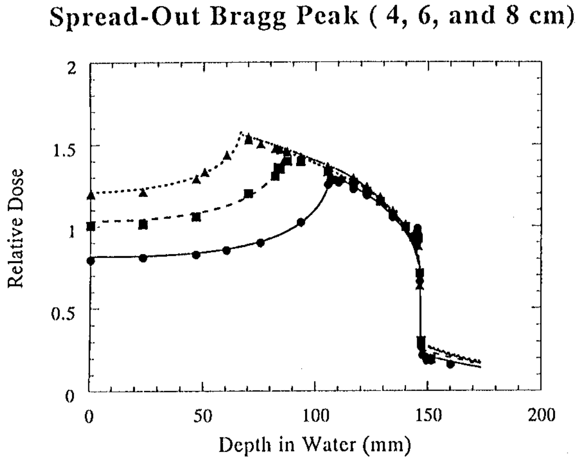

Fig. 4: Examples of physical dose distribution of the spreaded out Bragg peak.

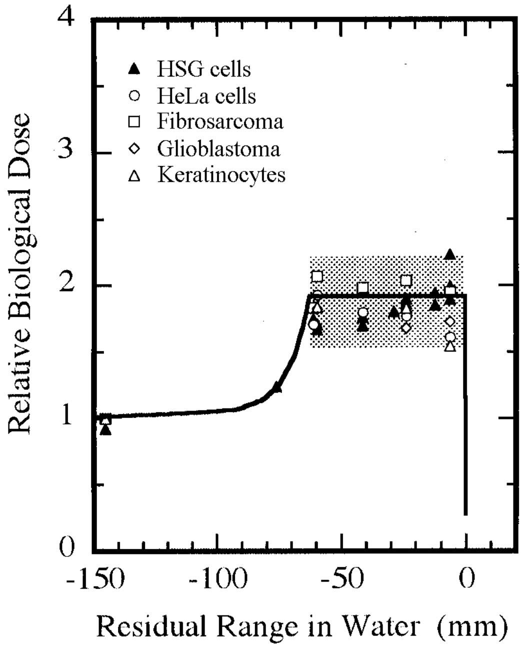

Fig. 5: An example of the biological dose distribution for a spreaded out Bragg peak.

spread of the ions through it. The ion beam with large momentum spread results in a spreaded out Bragg peak, which is necessary in a treatment of large size of tumors. Examples of the spreaded out dose distribution with the ridge filters are shown in Fig. 4. An example of the biological dose distribution for a spreaded out Bragg peak is also shown in Fig. 6 together with typical results of biological experiments. The range shifter, on the other hand, is made of plastic plate and changes the effective energy on a patient.

3. BEAM PERFORMANCE

The first beam from the injector has been obtained in late March 1993 with singly charged He ions. Beam tests have been begun for dual synchrotron rings in November 1993 with doubly charged He ions. The ions were accelerated to 230 MeV/u with a repetition rate of 1/2 Hz for each ring. Tests of the slow extraction from both rings were successfully completed in December and the extracted beams were transported to three treatment rooms within a few days. The length of the extracted beam spill was typically 300 ms. After careful tuning of the whole system including the measurements of biomedical effects of the carbon ions, clinical trials of the heavy ion cancer therapy started in late June 1994 with 290 MeV/u carbon beam.

In Fig. 6, an example of oscilloscope signals is given for a bending magnet excitation pattern (top), a pulse magnet for beam extraction (2nd), beam signal in the synchrotron ring (3rd) and the extracted beam signal (bottom). In the signal of the extracted beam, the very big intensity fluctuation can be observed. This fluctuation is due mainly to a current ripple of the synchrotron magnets, since no feedback system works to stabilize the extracted beam intensity. High frequency components of the beam ripple are suppressed appreciably after careful tuning of the synchrotron magnet power supplies. At the flat top, voltage ripples of the power supplies of Q_F and bending magnets are kept extremely low values of less than 1×10^{-6} and 1×10^{-5} , respectively (50 Hz). A beam ripple, however, remains at high level. The fluctuation of the bending filed may affects on the beam ripple through the sextupole magnets for chromaticity correction. By reducing the sextupole filed, satisfactory beam spill is obtained as shown in Fig. 7.

Stability and reproducibility of the whole accelerator system are excellent. Even in the early stage of the accelerator operation, it takes only 3 hours to get the accelerated beam in a treatment room. Most part of the tuning time are spent in tuning of the ion source and LEBT elements.

4. FUTURE DEVELOPMENTS

This facility is open for many researchers who are interested in the heavy ion science as well as heavy ion therapy. The accelerator is required to accelerate heavier ions with a variety of energies and with high quality. In order to meet these demands, third ion source of 18 GHz ECR source is now under developments. Ions from these three ion sources will be accelerated simultaneously with so called time sharing acceleration scheme and delivered to a medium energy experimental room, the upper synchrotron ring and the lower synchrotron ring.

A secondary beam will be available within a few years to investigate the possibility of precise check of the ion stopping position in a human body. The positron emitters, such as ^{11}C, are considered to be effective for this purpose. The beam course will be open for other scientific fields.

Further sophisticated irradiation schemes, such as a spot scanning method or a three dimensional irradiation method, are also important in improving the effectiveness of the heavy ion therapy. An irradiation treatment synchronized with human breathing is our first target to reduce the unwanted irradiation to the normal cells around the tumor. The treatment will be realized with a quick response of the rf-knockout beam extraction from the synchrotron ring[7].

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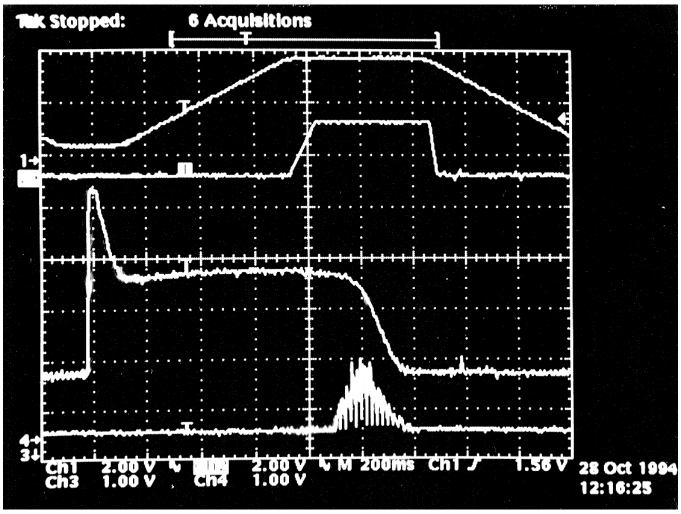

Fig. 6: A typical oscilloscope view of the synchrotron acceleration cycle: An excitation pattern of the synchrotron magnet (top), a bump field (2nd), a beam signal in the ring (3rd) and an extracted beam signal (bottom).

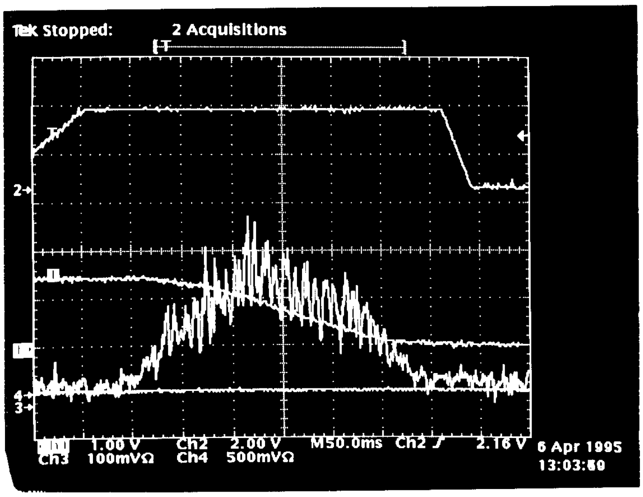

Fig. 7: An example of the beam spill from the synchrotron (bottom) together with a circulating current (middle) and a waveform of the bump magnet (top).