New Accelerator Facility for Carbon-Ion Cancer-Therapy

Koji NODA1*, Takuji FURUKAWA1, Takashi FUJISAWA1, Yoshiyuki IWATA1, Tatsuaki KANAI1, Mitsutaka KANAZAWA1, Atushi KITAGAWA1, Masataka KOMORI1, Shinichi MINOHARA1, Takeshi MURAKAMI1, Masayuki MURAMATSU1, Shinji SATO1, Yuka TAKEI1, Mutsumi TASHIRO2, Masami TORIKOSHI1, Satoru YAMADA2 and Ken YUSA2

Compact Accelerator/Carbon-ion cancer therapy/Gated irradiation method/Raster scanning/Rotating gantry.

The first clinical trial with carbon beams generated from HIMAC was conducted in June 1994. The total number of patients treated as of December 2006 was in excess of 3,000. In view of the significant growth in the number of protocols, the Japanese government gave its approval for carbon-ion therapy at NIRS as an advanced medical technology in 2003. The impressive advances of carbon-ion therapy using HIMAC have been supported by high-reliability operation and by advanced developments of beam-delivery and accelerator technologies. Based on our ten years of experience with HIMAC, we recently proposed a new accelerator facility for cancer therapy with carbon ions for widespread use in Japan. The key technologies of the accelerator and beam-delivery systems for this proposed facility have been under development since April 2004, with the main thrust being focused on downsizing the facility for cost reduction. Based on the design and R&D studies for the proposed facility, its construction was begun at Gunma University in April 2006. In addition, our future plans for HIMAC also include the design of a new treatment facility. The design work has already been initiated, and will lead to the further development of therapy using HIMAC. The following descriptions give a summary account of the new accelerator facility for cancer therapy with carbon ions and of the new treatment facility at HIMAC.

INTRODUCTION

Heavy-ion beams are very suitable for the treatment of deeply seated cancer because of an excellent physical-dose distribution and high-LET characteristics around the Bragg peak. Therefore, NIRS decided to carry out heavy-ion cancer therapy with HIMAC.1) Since the first clinical trial on three patients in June 1994 with a 290 MeV/n carbon beam, the total number of patients treated at HIMAC exceeded 3,000 in December 2006. At an early stage of the clinical trials, the number of fractional irradiations was typically 18, and the treatment required 6 weeks, besides the extra time needed for diagnostics and treatment planning. The number of fractions, however, has been decreased for some protocols, especially for the lung and liver cancer treatments, without encountering any serious side effects. Such a decrease in fraction number can increase the number of treatments. As a result of the accumulating numbers of protocols, carbon therapy at NIRS was approved as a highly advanced medical technology by the Japanese government. Such advances of carbon therapy with HIMAC have been supported by highly reliable operation2) and by the development of beam-delivery and accelerator technologies.3–5)

After the clinical trial at HIMAC was conducted, carbon-ion accelerator facilities for cancer therapy were proposed in the world. Among them, the PATRO project6) by Hyogo prefecture government has been conducted since 2001, and the HIT project7) in Heidelberg and the CNAO project8) in Milan have been progressed. Based on our ten-year experience at HIMAC, on the other hand, we proposed the development of a new accelerator facility for carbon-ion cancer-therapy for widespread use in Japan. The key technologies regarding the accelerator and beam-delivery systems for the new facility were developed from April 2004 to March 2006, with emphasis being place on a downsized facility so as to reduce the cost. As a result, the design of the new facility was completed, and the facility size was downsized. In particular, the size of the synchrotron could be downsized to 63 m of the...
circumference, which was smaller than those of the PATRO
design (93.6 m in 320 MeV/n) and the PIMMS design (77.6 m in 400 MeV/n), but was comparable with that of the HIT project. At Gunma University, therefore, in co-operation with NIRS, construction of the new carbon-ion facility was started in April 2006. The new facility consists of an accelerator complex, three treatment rooms and a CT-simulation room. The accelerator complex contains a compact ECR ion source, an injector linac cascade (RFQ + IH) with energy of 4 MeV/n, and a synchrotron ring with a maximum energy of 400 MeV/n. The beam-delivery system employs the spiral wobbler method, which mainly consists of wobbler magnets, a thin scatterer, a multi-leaf collimator, a range shifter, a ridge filter and two dose monitors. In this proposed facility, the spiral wobbler method can deliver a maximum irradiation field with a residual range of 250 mm, a diameter of 150 mm and a SOBP of 150 mm. Three treatment rooms, equipped with horizontal and/or vertical beam-delivery systems, are being prepared to handle the treatment of more than 600 patients per year. The area of this facility will be downsized to only around one-third compared with that of HIMAC.

A new treatment-facility project was also initiated in April 2006 for the purpose of further development of the therapy with HIMAC. This facility, which will be connected with the HIMAC accelerator, will consist of three treatment rooms: two rooms equipped with horizontal and vertical beam-delivery systems and one room with a rotating gantry. In the fixed beam-delivery system, a three-dimensional beam-scanning method will be employed with gated irradiation in order to increase the treatment accuracy; the irradiation field will be the same as that of HIMAC. Its energy will range from 140 to 430 MeV/n. According to the present design of the gantry system, a raster-scanning system with a broad beam will be installed, with the following main specifications: maximum energy of 400 MeV/n, lateral field of 150 mm × 150 mm, SOBP size ranging from 40 to 150 mm, and residual range of 250 mm at maximum.

Herein, we describe the design and R&D studies for the new carbon-therapy facility and the new treatment facility at HIMAC.

COMPACT CARBON THERAPY FACILITY

Design considerations
Residual range and beam energy

Figure 1 shows the statistics of the ten-year treatment period at HIMAC. It can be clearly seen in the figure that the residual range requires 250 mm to cover most of the patients. The residual range depends not only on the beam energy, but also on the forming method of a lateral irradiation field. When the range loss mainly due to scatterer can be suppressed to less than 25 mm, carbon ions with an energy of 400 MeV/n, corresponding to a 275-mm range in water, have a residual range of 250 mm. Thus, the maximum energy was determined to be 400 MeV/n. On the other hand, the minimum energy was determined to be 140 MeV/n for eye melanoma treatment.

Irradiation-field size and dose rate

As shown in Fig. 2, a field diameter of 220 mm and an SOBP of 150 mm can cover almost all types of patient treated at HIMAC. A larger field size of more than 200 mm has been required mainly for the treatment of oblong tumors. In such cases, it is important to maintain the field length rather than the diameter. The SOBP size should be changeable from 40 to 150 mm.

The irradiation-dose rate is required to be 5 GyE/min/l, the same as that at HIMAC. The dose rate corresponds to an intensity of 1.2×10⁹ pps, extracted from the synchrotron by assuming a beam-utilization efficiency of 30% at the beam-delivery system. According to the beam-intensity schedule for the compact facility, the synchrotron requires a C⁶⁺ intensity of more than 200 eμA from the injector linac cascade, and the ion source should provide a C⁶⁺ beam with an inten-
Irradiation method

Damage to normal tissues around the tumor is inevitable in the treatment of a tumor moving along with respiration. A respiration-gated irradiation system, therefore, that can respond quickly to irregular respiration, was developed.\textsuperscript{3} In this system, the irradiation-gate signal is generated only when the target is at the designed position and the synchrotron can extract a beam. Using the RF-KO extraction method,\textsuperscript{5} the beam is slowly extracted from the synchrotron according to the gate signal. This gated-irradiation method has been applied to liver, lung and uterus cancers since February 1996.

Table 1. Specifications of the new carbon-therapy facility.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion species</td>
<td>Carbon</td>
</tr>
<tr>
<td>Energy</td>
<td>140–400 MeV/n</td>
</tr>
<tr>
<td>Max. residual range</td>
<td>250 mm</td>
</tr>
<tr>
<td>SOBP</td>
<td>40–150 mm</td>
</tr>
<tr>
<td>Max. lateral-field size</td>
<td>220 mm φ</td>
</tr>
<tr>
<td>Max. dose rate</td>
<td>5 GyE/min/l</td>
</tr>
<tr>
<td>Beam intensity</td>
<td>1.2 $\times$ 10\textsuperscript{9} pps in front of beam-delivery system</td>
</tr>
<tr>
<td>Irradiation method</td>
<td>Gating/Layer stacking method</td>
</tr>
<tr>
<td>Number of treatment rooms</td>
<td>3 rooms, equipped with H&amp;V, H, V*</td>
</tr>
<tr>
<td>Number of treatments</td>
<td>&gt; 600 patients/year</td>
</tr>
</tbody>
</table>

\textsuperscript{3}H: Horizontal beam-delivery system, V: Vertical beam-delivery system.
duced by a ridge filter results in an undesirable dosage to the normal tissue in front of the target, because the width of an actual target varies within the irradiation field. In order to suppress such an undesirable dosage, the layer-stacking irradiation method was proposed, which has been applied to practical treatments. Since both of the irradiation methods mentioned above can considerably suppress an undesirable dose to normal tissue, it is planned to use them at the proposed facility as well.

**Number of treatment rooms**

The number of treatments per year needs to be more than 600 patients for economical reasons. Since the average number of fractions per treatment is 14 on average at HIMAC, the total irradiation number is estimated to be 9800/year for the treatment of 700 patients/year. Considering a single irradiation time of 25 min on average, including patient positioning, 3600 irradiations/year can be carried out in one treatment room under the following working schedule: 6 (hr/day) × 5 (days/week) × 48 (weeks/year). It should be noted that 2 hours are needed to prepare for the standup time of the whole system and QA/QC. From this, it is clear that the new facility requires three treatment rooms. Further, the ratio of the treatment frequency with the horizontal irradiation port (H-port) to that with the vertical one (V-port) is around 5:4. Therefore, the three treatment rooms should be equipped with H-port, V-port and H&V-ports.

The specifications of the proposed carbon-therapy facility are determined according to the design considerations mentioned above. The specification is summarized in Table 1.

**Design and R&D studies for the compact facility**

**Beam-delivery system**

A beam-delivery system was designed so as to obtain a residual range of 250 mm under a carbon energy of 400 MeV/n and an irradiation field of 220 mmφ. The layout of the system is shown in Fig. 3. This system consists of dose monitors, scanning magnets, a scatterer, a ridge filter, a range shifter and collimators. The ridge filter is designed to change the SOBP size from 40 to 150 mm. The range shifter is installed so as to precisely adjust the residual range in a patient. The multi-leaf and bolus collimators precisely define the lateral and distal irradiation fields, respectively.

![Fig. 3. Layout of the beam-delivery system for the compact carbon-therapy facility.](https://academic.oup.com/jrr/article-abstract/48/Suppl_A/A43/1053201/figs/3)

![Fig. 4. Lateral dose distributions after 1 min. of irradiation by (a) spiral wobbler and (b) raster-scanning method with a broad beam. In both figures, the solid lines and circles indicate calculations and measurements, respectively.](https://academic.oup.com/jrr/article-abstract/48/Suppl_A/A43/1053201/figs/4)
Since the multi-leaf collimator employs thin leaves with a thickness of less than 3 mm, a patient collimator is not required. The length of the beam-delivery system could be downsized to be 7.7 m, while that of HIMAC is longer than 10 m. The specifications of the beam-delivery system are summarized in Table 2.

Both the spiral-wobbler\textsuperscript{10} and raster scanning methods, using a relatively small broad beam, have been studied in a test-bench. As shown in Fig. 4, it was verified from the experiment that both methods could produce an irradiation field within a uniformity of ±2.5%.\textsuperscript{11} Further, both methods could easily realize irradiation gated with respiration and layer-stack irradiation, because only the total dose needs to be managed.

**Accelerator system**

**Injector system**

The compact injector system consists of a compact 10 GHz ECR ion-source\textsuperscript{12} and a linac cascade – an RFQ linac and an Alternating-Phase-Focused (APF) IH linac\textsuperscript{13} with the same operating frequency of 200 MHz. The output energy of the injector linac cascade is designed to be 4.0 MeV/n. The required intensity is 200 e μA in C\textsuperscript{6+} after a charge stripper.

A compact 10GHz-ECR ion source was developed for the compact injector system. It uses only permanent magnets to produce all of the required magnetic fields; sextupole and mirror fields allow us to design a considerably compact and cost-effective ion source. A traveling-wave-tube amplifier (TWT) with a maximum output of 300 W was employed to provide microwaves to the ECR zone. The TWT amplifier can be operated in a pulse mode in the frequency range from 8 to 10 GHz. It was verified that the compact ECR generates a C\textsuperscript{4+} beam with an intensity of 400 e μA under an extraction voltage of 30 kV, which is larger than the beam intensity of 260 e μA required from an intensity schedule so as to deliver 5 GyE/min/l to a patient.

For the cavity of the RFQ linac, we employed a conventional four-vane structure, because the technology of this structure is well established. Concerning the injection and extraction energies, we put constraints mainly on making the cavity compact. To design a compact cavity, a lower injection energy would be preferable, because it would make the buncher section shorter in the RFQ linac. However, a higher injection energy, which would make the extraction voltage in the ECR ion source higher, is advantageous to obtain a higher beam current from the ECR ion source. As a compromise, we designed an injection energy of 10 keV/n. The

**Table 2.** Specifications of the beam-delivery system.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam-wobbling radius A’ at I. C.</td>
<td>160 mm at σ = 25 mm, 207 mm at σ = 48.5 mm</td>
</tr>
<tr>
<td>Max. wobbling angle and frequency: X/Y Angle</td>
<td>27.4/29.4 mrad, Frequency: 59/23 Hz</td>
</tr>
<tr>
<td>Dose monitor</td>
<td>SEM for both main and sub monitor</td>
</tr>
<tr>
<td>Scatterer</td>
<td>0.1–3.2 mm Pb</td>
</tr>
<tr>
<td>Ridge filter</td>
<td>14 bar-ridge filters made of Al, corresponding to SOBP size</td>
</tr>
<tr>
<td>Range shifter</td>
<td>Binary type: 0.1, 1.0, 2.0, 4.0, 8.0, 16.0, 32.0, 64.0, 128 mmWEL</td>
</tr>
<tr>
<td>Flatness monitor</td>
<td>31 segmented ionization chambers</td>
</tr>
</tbody>
</table>

\*A = R + 2 σ; A beam-wobbling radius, R required lateral-field radius, σ one standard deviation of beam size.

**Fig. 5.** Experimental setup for the compact injector system.

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The cavity length would not exceed around 2.5 m, mostly because of manufacturing reasons as well as compactness. The required RF power is 120 kW, and the maximum width of the output RF pulse is 1.0 ms with a repetition rate of 4.0 Hz.

The IH cavity is known to provide a higher shunt impedance than that of conventional structures, such as Alvarez DTL. Moreover, using the APF method for IH-DTL allowed us to employ a rather high operating frequency, and hence to design a compact cavity. Although APF IH-DTL has such attractive features, it has never been practically used until now. The reason is that the electromagnetic (EM) field could not be calculated with the existing two-dimensional field solvers, and therefore lengthy and costly model studies would be required to determine the final structure of the cavity. With the recent developments of three-dimensional field solvers, the EM field in the IH cavity can be directly calculated. To verify the accuracy of the solver, we constructed a model cavity of APF IH-DTL. Measurements of the electric field distribution could be reproduced well with that calculated with the solver.

Based on the model cavity, the design of the high-power cavity of APF IH-DTL was completed in March 2006. As shown in Fig. 5, the APF IH-DTL was installed in conjunction with the compact ECR ion source and the RFQ linac. After installation, beam-acceleration tests of the entire injector system were carried out. Carbon ions were accelerated to 0.61 MeV/n by the RFQ linac and were injected to APF IH-DTL. As a result of the experiment, it was found that C^4+ ions could be successfully accelerated up to 4.0 MeV/n. As shown in Fig. 6, the average value and width of the energy distribution were measured to be E_{ave} = 4.0 MeV/u and ΔE/E = ± 0.4%, respectively. The beam intensity of accelerated C^4+ ions from APF IH-DTL was measured to be 390 eμA, twice as much as that required for treatments. The beam transmission of the entire injector system, including LEBT, RFQ linac and APF IH-DTL, was as high as 79%. Considering the known transmission of theLEBT and the RFQ linac, the transmission through APF IH-DTL was estimated to be almost 100%. Further, the normalized 90% emittance was also measured to be 1.0 π mm-mrad, slightly higher than the design value. These successful results of the acceleration tests have proven the excellent performance of the proposed compact injector system.

**Synchrotron**

A design study and R&D work on the proposed synchrotron were carried out in order to reduce the synchrotron size while keeping the required performance. The synchrotron was designed to accelerate a C^6+ beam from 4 to 400 MeV/n. The injection system employs multi-turn injection to increase the intensity. Because of the quick response to beam on/off, the RF-KO slow-extraction method is applicable to both irradiation gated with respiration and layer-stacking irradiation. The layout of the synchrotron is shown in Fig. 7. The lattice structure employed a FODO missing magnet design, while each cell contains three dipole magnets and two kinds of quadrupole magnets (QF/QD). As a result, the ring circumference could be considerably reduced to around 63 m, compared with half of the HIMAC synchrotron.

The resonance characteristics were investigated at the HIMAC synchrotron by means of a tune survey (Qx = 3.68~3.75, Qy = 3.0~3.5) with a high-intensity beam, in order to reduce the beam loss due to the space-charge effect. The integer resonance (Qy = 3) makes the beam loss large, even when correcting the COD (Closed Orbit Distortion). The working point is close to the integer resonance through the incoherent tune-shift under a high ion density after bunching. We thus changed the vertical tune from 3.13 to 3.23. Since the effect of the 3rd-order coupling resonance (Qx + 2Qy = 10) is not negligible, however, we tested the resonance correction by using four sextupole magnets. After the correction, the beam lifetime was increased by more than 5 times under (Qx,Qy) = (3.74, 3.23). Thus, the operation point of the compact synchrotron is set to be (Qx, Qy) = (1.74,1.23) at the injection stage, while avoiding a few sector resonances. Further, correction sextupole magnets for the resonance of Qx + 2Qy = 4 will be installed.

While the RF-knockout slow-extraction method has been routinely used for therapy at the HIMAC synchrotron, we have developed this extraction technique and transport of the extracted beam to improve beam performance. The time structure of the extracted beam has a critical impact on treatment, because any spill ripple will disturb dose uniformity. Thus, the time-structure control method was investigated. Both the microscopic structure (kHz-order) and the global one (Hz-order) were successfully controlled. These techniques will be applied at the proposed facility. For controlling the beam size, on the other hand, a measurement
method of the outgoing separatrix was proposed and verified.\textsuperscript{22)} Based on this measurement, the transport optics of the extracted beam were redesigned. This technique allows us to control the beam size precisely, as predicted. Based on this result, thus, we can optimize the aperture of the transport line and the specifications of the magnets with a sufficient margin.

An un-tuned RF-cavity, having a Co-based amorphous core, has been developed so as to make multi-harmonics operation possible for reducing the longitudinal space-charge effect.\textsuperscript{23)} The RF-cavity has the great advantage of using a transistor amplifier instead of a final RF amplifier with a tetrode tube, even with an output voltage of 4 kV. This RF-cavity was installed in the HIMAC synchrotron, and a beam test was successfully carried out.

In gated irradiation, a part of an accelerated beam frequently remains, producing a large amount of neutrons. However, the proposed synchrotron can decelerate the remaining beam to an injection-energy level, which brings about a considerable reduction in the thickness of the radiation-shielding wall, making the facility building cost more economical. The HIMAC synchrotron has been equipped with both B+ and B- clocks in order to make acceleration stable, even when the dipole field fluctuates due to current ringing. By utilizing this technique, therefore, it is easy for the proposed synchrotron to decelerate the remaining beam.

The vacuum system is designed so that the pressure is less than $1 \times 10^{-6}$ Pa on average, in order to keep a survival rate of more than 99%. The main vacuum pump is an SIP (Sputter Ion Pump) with a pumping speed of 360 l/s; fifteen SIPs are distributed around the ring. On the other hand, the roughing pump is TMP (turbo molecular pump) with 300 l/s; three TMPs are distributed around the ring. For differential pumping, two SIPs are installed at the end of the beam-injection line and the exit of the ring, respectively.

A COD correction is carried out in both the horizontal and vertical directions by using 6 correctors in each direction. The specifications of corrector are determined so as to correct the COD by assuming perturbations, such as the alignment error and the field error of the magnets. The corrector consists of a correction magnet and electrostatic position pick-up monitor; they are distributed near to the QF/QD for the horizontal/vertical COD correction. The chromaticity is also corrected by sextupole magnets. The sextupole field inside the dipole magnet is changed according to the excitation level, and the sextupole field produced by the eddy-current effect in the vacuum chamber inside the dipole magnet. It is noted that the effect is not negligible, even for a vacuum-chamber thickness of 0.3 mm. The sextupole field for the correction should be dynamically changed. Three sextupole magnets are prepared for a chromaticity correction in the horizontal and vertical directions, respectively.

The specifications of the proposed accelerator complex are summarized in Table 3.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
\textbf{Component} & \textbf{Specification} & \textbf{Description} & \textbf{Remarks} \\
\hline
\hline
\end{tabular}
\end{table}
Table 3. Specification of the proposed accelerator system.

1. Injector system

1-1. ECR ion source
- Outer dia.:320 mm, Length:295 mm
- Material of mirror and sextupole magnet: NdFeB
- Field strength of mirror magnet: 0.59T at extraction, 0.87T at gas injection, 0.25T at min.
- Field strength of sextupole magnet: 1.1 T on the surface of the chamber, Length 105 mm, Bore dia. 58 mm
- Microwave: Freq.: 8–10 GHz, Max. power: 300 W
- Beam current: 350 eμA of C4+ at extraction voltage of 30 kV

1–2 RFQ
- Four vane type
  - Injection/Extraction energy: 10 keV/n
  - Operation frequency/RF power: 200 MHz / 120 kW at 60% of Qc
  - Charge-to-mass ratio: ≤1/3
  - Size: Tank dia.:407.0 mm, Length: 2480.4 mm
  - Measured transmission: 81%

1–3 APF-IH
- Injection/Extraction energy: 608 keV/n/4.0 MeV/n
- Operation frequency/RF power: 200 MHz/360 kW at 60% of Qc
- Charge-to-mass ratio: ≤ 1/3
- Size: Tank dia.:400.0–440.0 mm, Length: 3437.4 mm
- Measured transmission: 95%
- Measured emittance and energy spread: 1.1 π mm·mrad (normalized), ΔE/E = ± 0.4%

2. Synchrotron
- FODO type
  - Injection / Extraction energy: Injection: 4.0 MeV/n, Extraction: 140–400 MeV/n
  - Circumference: 63 m
  - Injection / Extraction method: Multi-turn injection / RF-Ko slow extraction
  - Working point: (Qx, Qy) = (1.74, 1.23) at Inj. and Accel., (168, 1.23) at Extraction
  - Acceptance: (Ax, Ay) = (240, 30) π mm·mrad
  - Chromaticity: (Hori./ Vert.) = (–0.60 / –1.52)
  - Momentum compaction factor: 0.32–0.34
  - Operation cycle: < 0.5 Hz
  - Acceleration frequency: 0.90–6.97 at harmonic number of 2
  - Max. acceleration voltage: 2.0 kV
  - Vacuum system: Ave. pressure < 1 × 10⁻⁶ Pa, Effective pumping speed: 41.8 l/s/m

3. Beam transport system*
- Bending magnet
- Field strength: 0.82–1.48 T, Number: 11
- Quadrupole magnet
- Field strength: 10.6–19.1 T/m, Number: 20
- Tolerance of beam-axis displacement: ± 1 mm
- Vacuum system
- Ave. pressure < 5 × 10⁻⁴ Pa, Effective pumping speed: 6.7 l/s/m

*All of the magnets are made of laminated Si-steel of 0.5 mm in thickness for a fast field change within 1 min.
Application of other ion species for treatment

When a medical doctor requires cancer therapy by using other ion species, such as oxygen and proton ion, the following scheme is applicable in the proposed facility. Concerning oxygen therapy, the ECR ion source can produce an O$^{5+}$ beam current of more than 210 eμA, and the beam can be accelerated up to 4.0 MeV/n when the linac’s voltage can be increased by only 5%. This voltage is out of the specification, but it is possible, because of the design tolerance. Both the acceleration in the proposed synchrotron and the beam delivery are almost the same as that in carbon therapy. Since the residual range is reduced to around 190 mm, however, a part of the treatments will be limited. Further, the delivered beam intensity is decreased due to a lower current of O$^{5+}$ ion produced by the ion source and a lower stripping-efficiency from O$^{5+}$ to the fully stripped oxygen-ion than those of the carbon ion. However, since the LET of the oxygen ion is higher than that of the carbon ion, the irradiation time is almost comparable to that of the carbon therapy. Concerning proton therapy, the proposed injector system can also accelerate H$_2^+$ or H$_3^+$ produced by the ECR ion source up to 4 MeV/n. These beams are dissociated to a proton beam by a charge stripper located just after the APF-IH linac. The proton beam is injected to the synchrotron and accelerated to the final energy. This technique has been utilized at HIMAC and PATRO. The accelerated proton beam can be transported to the beam-delivery system for cancer treatment. In proton therapy according to the above scheme, however, we should check whether the parameters of the beam-delivery system are optimized or not.

Facility layout

Based on the design of the compact facility, Gunma University has been constructing a new carbon-therapy facility since April 2006. An image view of this facility is shown in Fig. 8. The facility size, including a fourth room for the development of a new treatment method, diagnosis rooms, lobby, staff rooms and control room, is designed to be 48 m $\times$ 70 m $\times$ 20 m.

NEW TREATMENT FACILITY AT HIMAC

A design study and R&D work on a new treatment facility with HIMAC has just been initiated, in order to the further development of carbon-ion therapy. The new treatment facility employs a fixed beam-delivery system and a rotating-gantry system. After completing the new treatment facility, the new facility will gradually increase the number at treatments. After almost of all the treatments will be carried out in the new facility, the present treatment rooms at HIMAC will be improved so as to apply a new irradiation method and/or to apply other ion species to the treatments.

Fixed-beam delivery system

In the new treatment facility, a repainting raster-scanning method with respiration-gated irradiation has been studied to achieve high accuracy, even in the treatment of tumors moving with breathing. This method will also be applied to increase the irradiation accuracy also in the treatment of head and neck tumors. With the present design, the fixed-beam delivery system will give a lateral field size of ±150 mm and a distal field size of 150 mm at maximum, using a carbon beam with an energy range from 140 to 430 MeV/n. Figure 9 shows the layout of the fixed-beam delivery system. The system consists of a pair of scanning magnets, dose monitors, a ridge filter and a range shifter. The beam-movement speed by the slow scanner is designed to be 5–10 mm/ms, while the faster one is 100 mm/ms. Two dose monitors, which are parallel-plate ionization chambers with an effective area of 250 mm$^2$, are prepared for dose management. The beam position and size are monitored by the multi-wire proportional counter. Considering the slice thickness, including target movement, the Bragg peak is slightly spread out by the ridge filter. The range shifter is utilized to change the slice in the target. Thus the range shifter should be as close as possible to the iso-center in order to avoid any beam-size change by multiple scattering through the range shifter. At present, raster-scanning with a pencil beam has been studied using the intensity modulation and the spill control.

Rotating gantry system

The rotating gantry has been conceptually designed so as to permit easy “on-demand treatment”, such as one-day treatment for a lung cancer. The specifications of the present design of the gantry are as follows: maximum beam energy of 400 MeV/n, lateral field of 150 mm $\times$ 150 mm in square, maximum SOBP size of 150 mm and maximum residual range of 250 mm. The rotating gantry employs raster scanning with a broad beam to produce a uniform irradiation field in the lateral direction. The broad-beam scanning method is chosen to avoid any rotation-angle dependence of the...
beam size due to X-Y coupling. Because of employing a broad beam, the gantry needs a scatterer, two dose monitors, a ridge filter, a multi-leaf collimator and a bolus collimator, as well as the conventional wobbler method. The effective length from scanner to iso-center should be as short as possible in order to achieve a downsized gantry. Thus, the final dipole magnet, having a bending angle of 90 degree, is utilized as one of the scanning magnets, in order to extend a source-to-surface distance as long as possible. Thus, a vacuum duct in the gap of the final bending magnet should not

![Fig. 9. Layout of the raster-scanning irradiation system.](image)

**Fig. 10.** (a) Layout of the rotating gantry, (b) irradiation port of the gantry in the present design: Scat, scatter; IC dose monitors; RGF, Ridge filter; UM, dose-distribution uniformity monitor.

<table>
<thead>
<tr>
<th>Specification of the rotating gantry.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gantry type</strong></td>
</tr>
<tr>
<td><strong>Max. energy</strong></td>
</tr>
<tr>
<td><strong>Irradiation method</strong></td>
</tr>
<tr>
<td><strong>Lateral field size / SOBP / Range</strong></td>
</tr>
<tr>
<td><strong>Length of irradiation port</strong></td>
</tr>
<tr>
<td><strong>Scanning frequency</strong></td>
</tr>
<tr>
<td><strong>Scanning angle</strong></td>
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<tr>
<td><strong>Transport</strong></td>
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<tr>
<td><strong>Field strength of bending magnet</strong></td>
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<tr>
<td><strong>Displacement of iso-center</strong></td>
</tr>
<tr>
<td><strong>Size and weight</strong></td>
</tr>
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</table>
be installed in order to avoid the eddy-current effect. In this design, the beam size is broadened due to multiple scattering through the air. However, the gap size of the magnet is almost the same as that in passing through the vacuum, because of eliminating the vacuum duct. The pole width of the final dipole magnet is designed by considering the energy-loss, multiple scattering through air and beam-center displacement due to scanning. The maximum strength of the leading field is designed to be 1.8 T, further, in order to downsize the gantry. As a result of the mechanical design, the gantry weight is around 300 tons and the maximum diameter is around 14 m. The maximum displacement of the iso-center is reduced to less than 0.7 mm under any rotation angle. The layout of the gantry is shown in Fig. 10. The specifications of the gantry are summarized in Table 4.

**Facility layout**

The new treatment facility is connected with the HIMAC accelerator complex and has three treatment rooms. Two of them are equipped with both horizontal and vertical beam-delivery systems and one is equipped with a rotating gantry. A schematic view of the new facility with HIMAC is shown in Fig. 11.

**SUMMARY**

We have designed a compact carbon-therapy facility for widespread use in Japan, and R&D studies have been carried out for the development of key technologies. Based on design and R&D studies, Gunma University has been constructing a compact carbon-therapy facility, in co-operation with NIRS, since April 2006. In addition, as a five-year project at HIMAC, a new treatment facility has been designed for the further development of heavy-ion therapy.

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**REFERENCES**


