HIMAC AND NEW FACIILITY DESIGN FOR WIDE SPREAD USE OF CARBON CANCER THERAPY

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Abstract

Since 1994, the clinical trial with HIMAC at National Institute of Radiological Sciences (NIRS) has been successfully progressed, and more than 1,800 patients have been treated with carbon ions. In 2003, as a result, the carbon-ion cancer therapy was approved as a highly advanced medical technology by the Japanese government. Based on the development of the accelerator and irradiation technologies for 10 years, we have proposed a wide spread use of carbon therapy facility. In this paper, we review the ten-years development of the HIMAC facility and report the conceptual design of the proposed facility.

INTRODUCTION

Heavy-ion beams are very suitable for treatment of deeply seated cancer because of excellent physical-dose distribution and high LET characteristic 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 290 MeV/n carbon beam, total number of patients treated at HIMAC exceeded 1,800 in this February. Typical treatment-example is shown in Fig. 1. Figure 2 shows the number of treated tumors up to August 2003. They distribute 18% on lungs, 16% on heads and necks, another 16% on prostates, 10% on bones and soft tissues, 9% on livers, 5% on uteruses and 26% on other sites. A local-control rate (2 years) is better than 70% for most of protocols, while the early side effects with grade 3 on the skin are only 3%.

At an early stage of the clinical trials, the number of fractional irradiations was typically 18 and the treatment required 6 weeks except for the extra time for diagnostics and treatment planning. The number of fractions, however, has been decreased for some protocols especially of lung and liver without increasing serious side effects. Typical number of fractions is as low as four for liver cancer. For the lung-cancer treatment, further, only one fractional irradiation has been tried since April 2003. Such decrease of fraction number can increase the number of treatments.

As a result of accumulating numbers of protocols, the carbon therapy at NIRS was approved as a highly advanced medical technology by the Japanese government. Such progress of the carbon-therapy with HIMAC has been supported by the high-reliability operation [2] and by the development of the beam delivery and accelerator technologies. Based on the development and the experience for ten-years at HIMAC, we have proposed a wide spread use of carbon-therapy facility.

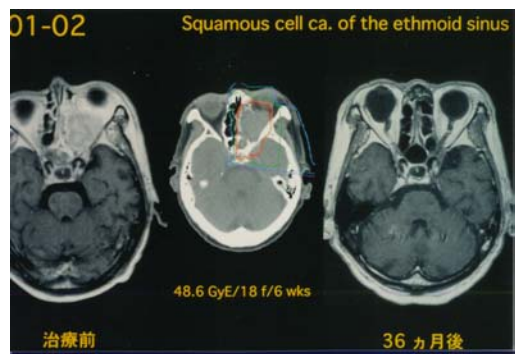

Figure 1: Typical example of treatment on Head & Neck. CT images from left are before treatment, treatment planning and 36 months after treatment, respectively.

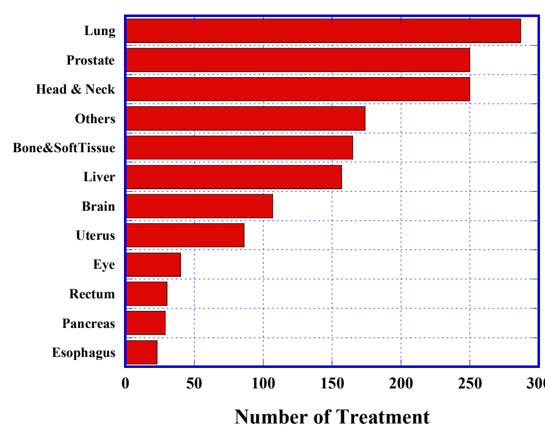

Figure 2: The number of tumors treated. The data are summarized from June 1994 to August 2003, and total number of treatment is 1601.

PROGRESS OF HIMAC

During ten years, we have carried out the developments and the researches in not only the ion therapy but also the related fields. Among of them, we describe the developments related directly to the therapy, here.

Irradiation gated with patient's respiration

Damage to normal tissues around tumor was inevitable in treatment of a tumor moving along with respiration of a patient. A respiration-gated irradiation system, therefore, which can respond quickly to irregular respiration, was developed [3]. In this system, the irradiation-gate signal is generated only when target is at the design position and the synchrotron can extract a beam. The beam is delivered by the RF-KO extraction method, according to the gate signal. This method has been applied to liver, lung and uterus cancers since February 1996. Figure 3 shows the view of irradiation gated with respiration.

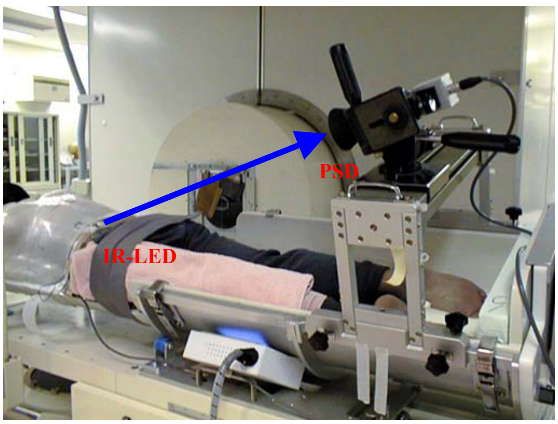

Figure 3: The view of irradiation gated with respiration using the horizontal irradiation port.

Layer-stacking irradiation method

In a conventional irradiation method, the fixed SOBP (Spread-Out Bragg Peak) produced by a ridge filter results in undesirable dosage to the normal tissue in front of target, because the width of an actual target varies within the irradiation field. In order to suppress the undesirable dosage, thus, the layer-stacking irradiation method was proposed [4], and the HIMAC irradiation system has been upgraded to put the technique including the treatment planning [5] into practice.

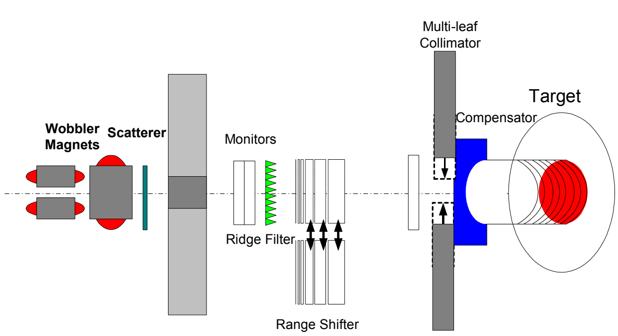

Figure 4: Schematic drawing of the layer-stacking irradiation method.

A schematic drawing of this method is shown in Fig. 4. This method is to conform a variable SOBP to a target volume by controlling dynamically the conventional beam-modifying devices. The small SOBP with several mm in WEL, which is produced by a single filter, is longitudinally scanned over the target volume in a stepwise manner. The target volume is longitudinally divided into slices, to each of which the small SOBP is conformed using the MLC (Multi Leaf Collimator) and the range shifter, and a variable SOBP coinciding to the target volume is to be formed. This method will be utilized routinely from the next fiscal year.

Spot scanning method

A spot-scanning as completely conformal irradiation method has been developed in the secondary beam line in order to accurately treat tumor adjoining critical organs [6]. A schematic drawing of the spot-scanning system at HIMAC is shown in Fig. 5. The spot-scanning method is realized such that it adopts spot beams whose dose distributions are 3D localized around their Bragg peak. The target volume is divided longitudinally into slices, and the range is adjusted to the depth of each slice by using the range shifter. For lateral scanning in each slice, the spot beams are scanned by the horizontal and vertical scanning magnets. The range is changed to the depth of next slice when the prescribed dose is reached, and the next lateral scanning starts. When the beam position should change for the next spot and for the next slice, the beam delivery is stopped within 1 ms by the RF-KO extraction method. A test result for irregular shaped target is shown also in Fig. 5. It is obviously shown that the measured dose distribution is consistent with the planned one.

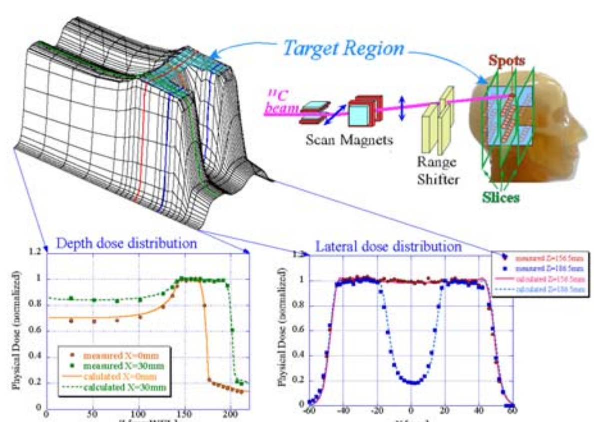

Figure 5: Schematic drawing of the spot-scanning system (Upper-right) and comparison between designed dose distribution and measured one. Lower-left: the depth dose distribution, Lower-right: the lateral one. Lines: designed ones. Symbols: measured one.

RF-KO slow-extraction method

At HIMAC, the RF-KO slow-extraction with AM and FM was developed [7]. An advantage of this method is quick response within 1 ms to a gate-signal of an extraction start/stop. Thus this method realized the irradiation gated with respiration. However, the method brought a huge ripple of the spill at the early stage. Thus the dual FM method and the separate function method were proposed toward the spot-scanning method, and it was verified that they were able to sufficiently suppress the spill ripple [8]. An AM function was optimised, further, in order to obtain a flat spill-structure [9]. Figure 6 shows the spill structure obtained by using the optimised AM function and the feedback method. Owing to the separate function method, further, it is clearly observed also that the ripple is suppressed sufficiently.

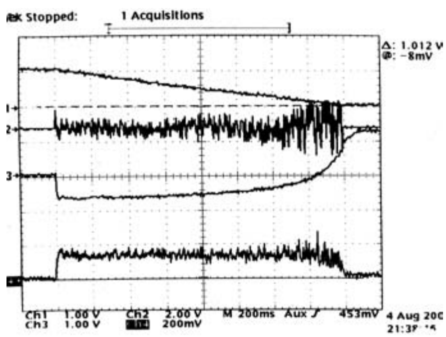

Figure 6: Flat spill structure by optimising AM function and feedback. Spill structure is the bottom trace in each figure.

DESIGN STUDY OF WIDE SPREAD USE FACILITY FOR CARBON THERAPY

Design Considerations and Specifications

Number of treatment room

The ratio of treatment frequency with the horizontal irradiation port (H-port) to that with the vertical one (V-port) is around 5:4. In addition, since the number of treatments per year should be more than 600 patients due to an economical reason, the facility needs three treatment rooms; (H-port), (V-port) and (H&V-port). The rooms are strongly required to be placed at the same floor for an efficient treatment.

Irradiation method

More than 30% at the ratio of the tumor treated with the irradiation gated with respiration. Thus the irradiation gated with patient's respiration and the layer-stacking irradiation method should be applied in order to sufficiently suppress the undesirable dose. The spot-scanning method has a potential to deliver completely conformal 3D dose distribution. However, it is difficult for the spot-scanning method to manage the dose distribution in the moving target with respiration.

Required residual range and beam energy

Figure 7 shows the histogram of the number of treatments on the residual range required. It is obviously found that the residual range of 250mm covers almost all patients. The residual range depends on not only the beam energy, but also the forming method of a lateral irradiation field and the irradiation-port length. Under using the spiral-wobbler method as is described in the section 3.2, an energy of carbon-ions should be more than 400 MeV/n corresponding to the 275 mm range in order to obtain the 250 mm residual-range. Thus the maximum energy is determined to be 400 MeV/n. Considering the treatment for eye melanoma, on the other hand, the minimum energy is to be 140 MeV/n.

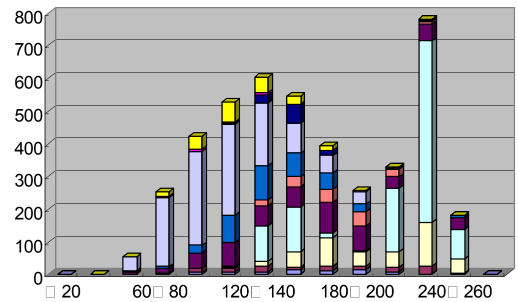

Figure 7: Histogram of the treatment number on required residual-range in mm.

Irradiation-field size and beam intensity

As can be seen in Fig. 8, the filed diameter of 150 mm covers treatments of more than 85%, and the SOBP size of 150 mm covers that more than 97%. The requirement for the beam intensity is estimated, thus, under the field diameter of 150 mm, the SOBP size of 100mm and the irradiation-dose rate of 2 Gy/min. The required intensity is to be $1.2 \cdot 10^9$ pps assuming the beam-utilization efficiency of 40%.

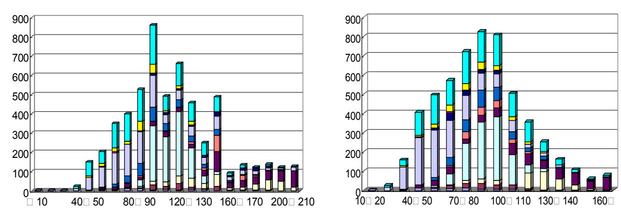

Figure 8: Histogram of the treatment number on field diameter in mm (Left) and that on SOBP in mm (Right).

Facility size

Downsizing the accelerator and beam delivery systems can reduce the cost, which naturally results in the small size of the facility. Thus the whole facility size is designed to be within 60 m × 50 m as the goal. For the purpose, both the irradiation-port length and the synchrotron radius should be limited to around half size in HIMAC, which are 5.5 m and 10m, respectively. Further, the injector linac cascade should be downsized within 6 m.

Conceptual Design of Facility

The proposed facility consists of two10GHz-ECR ion sources with permanent magnets, an injector linac cascade (RFQ+IH) with an energy of 4 MeV/n, a synchrotron ring with an energy range from 140 to 400 MeV/n and beam delivery systems with a spiral wobbler method. The image view of the proposed facility is shown in Fig. 9.

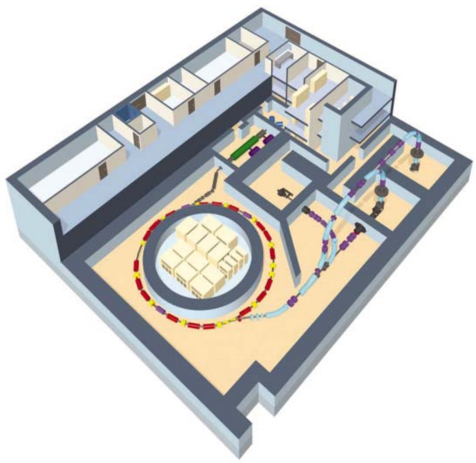

Figure 9: Image view of the proposed facility.

Beam Delivery System **[10]**

According to the design considerations, the beam delivery system should realize a residual range of 250 mm with a beam energy of 400 MeV/n and an irradiation-field radius of 220 mm at maximum, under the irradiation-port length of 5.5 m. For the purpose, a spiral-wobbler method has been proposed. In this method, the beam center at isocenter is moving on a spiral orbit by modulating the amplitude of the wobbler currents. As a result, this method can produce the uniform field even under the considerably small beam size compared with that in the conventional wobbler method. Since this method can use a relatively thin scatter, thus, this method brings a uniform lateral-dose distribution even under the above specification. This method can easily realize the irradiation gated with respiration, further, because only the total dose should be managed. In the present design, the angular and AM frequencies are to be 59 Hz and 23 Hz, respectively. The beam size at the isocenter is 25 mm at σ. A simulation result predicts the lateral-dose uniformity of less than ±3% in the irradiation-field size of 220 mm under a residual range of 250 mm for the 400 MeV/n carbon-beam.

As is shown in Fig 10, the irradiation port consists of beam monitors, wobbler magnets, a scatterer, ridge filter, range filter and collimator. Using the ridge filter, the SOBP size is changeable from 40 to 150 mm. The range shifter is installed to adjust the residual range in a patient. A MLC defines the irradiation field. A bolus can shape preciously the distal field. A secondary emission monitor as a main dose monitor is placed upstream of the wobble magnet to measure the total dosage. As a sub dose monitor, a parallel-plate ionization chamber is used at upstream of the multi-leaf collimator. A multi-segmented ionization chamber checks the field size and the dose uniformity. Finally, the system is designed to realize the layer-stacking irradiation.

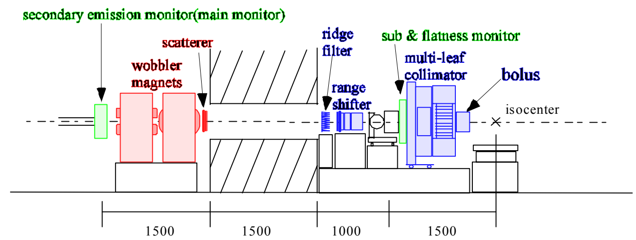

Figure 10: Layout of the beam delivery system.

Ion Source **[11,12]**

A compact 10GHz-ECR ion source, which uses permanent magnets for generating both of sextupole and mirror fields, has been developed for the proposed facility owing to its compactness and its easiness in operation and maintenance. Further, this source employs a travelling-wave amplifier with variable frequency fro 9 to 18 GHz, which can compensate a deviation from the magnetic field designed. As a result of the improvement for the first ECR ion source, an output current of C^{4+} ion was obtained at 300 eμA under a microwave power of 300 W, and it was verified that the intensity fluctuation was kept by less than 6% during 20 hrs. The second 10GHz-ECR ion source was designed to increase the extraction voltage to 60 kV in order to sufficiently reduce a space charge effect in a low-energy transport line. It was already confirmed that the source can supply 500 eμA of C^{4+} beam under an extraction voltage of 40 kV.

Injector linac cascade **[13]**

The injector system comprises RFQ and Interdigital H-mode (IH) linacs. The layout of the linac cascade is shown in Fig. 11. The injection energy will be 8 keV/n. With the RFQ linac, the C^{4+} beam is bunched and accelerated to 600 keV/n. Then emittances of the extracted beam are matched with a short section consisting of a quadrupole triplet installed between the RFQ and IH linacs. The bunched and matched beam is accelerated up to 4 MeV/n with the IH linac. Finally, C^{4+} ions are fully stripped by a thin foil, and fully stripped carbon ions are injected to the synchrotron ring.

For the RFQ linac, the conventional four-vane structure will be used. By using the operation frequency of 200 MHz, a length and diameter of the cavity are approximately 2 m and 0.3 m, respectively. The IH linac operated with 200 MHz will be used for the second injector because of its compactness. For the transverse focusing of the beam, the Alternating-Phase-Focusing (APF) method will be employed. Since both transverse and longitudinal focusing is provided just with the rf-acceleration field for the APF method, no additional focusing elements inside of the cavity is needed. Therefore, downsizing of the cavity as well as the high acceleration rate can be accomplished. According to the current design, the length and diameter of the cavity will be approximately 3 m and 0.3 m, respectively.

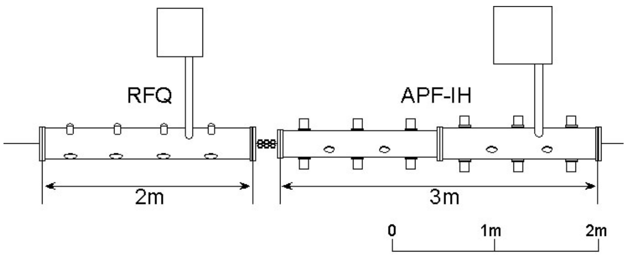

Figure 11: Layout of the RFQ and APF-IH linacs.

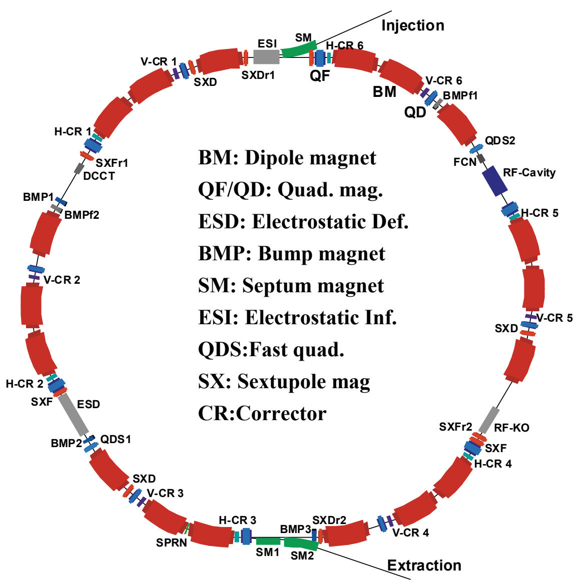

Figure 12: Layout of the synchrotron ring.

***Synchrotron* [14]**

The synchrotron is designed to accelerate a C^{6+} beam from 4 to 400 MeV/n at maximum. The FODO lattice structure is chosen, because this simple structure can increase the dipole-magnet filling factor while keeping the small beam size. The cell number is to be 6, considering the phase-advance per cell and the third-order slow-extraction. The extraction system should employ the RF-KO extraction for the layer-stacking method and the irradiation gated with respiration. The ring structure is shown in Fig. 12. This lattice is a FODO missing magnet design, while each cell contains three dipole magnets having rectangular shape and two quadrupole magnets (QF and QD). The ring circumference is 61.5 m, and the dipole-magnet filling factor of 43 % is achieved. (Qx/Qy) = (1.70/3.13) and (1.70/1.85) are candidates as working point considering the resonance lines and space charge effect. The horizontal and vertical acceptances are 240 and 30 πmm·mrad after the COD correction, respectively, while those of the injection beam of 10 πmm·mrad. An rf-voltage of 2 kV is required under a ramping speed of 2.7 T/s and a dilution factor of 1.2, which gives a maximum bucket height of ±0.4% in $\Delta p/p$.

Assuming an output current of 200 eμA from the ion source and a gain of 20 by multiturn injection, a delivered intensity is estimated to be $2\cdot10^9$ pps at maximum. It is noted that the efficiencies in each process are taken account into the estimation.

SUMMARY

During ten-years of clinical trials with HIMAC, both the beam delivery method and the accelerator technology have been much improved at HIMAC. It has brought a good result of the clinical trial and resulted in rapidly growing interest in the carbon therapy. Nowadays, there are several candidates for the carbon therapy in Japan. Therefore, NIRS has proposed a new facility for wide spread use of carbon cancer therapy. An R&D for the proposed facility will start from the next April.

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REFERENCES

[1] Y. Hirao, *et al.*, Nucl. Phys. **A538** (1992) 541c-550c.
[2] E. Takada, *et al.*, in this conference.
[3] S. Minohaya, *et al.*, Int. J. Radiat. Oncol. Bio. Phys. **47**(4) 1097-1103.
[4] Y. Futami, *et al.*, Nucl. Instrum. Meth. **A430** (1999) 143-153.
[5] N. Kanematsu, *et al.*, Med. Phys. **29**, 2823-2829 (2002).
[6] E. Urakabe, *et al.*, Jpn. J. Appl. Phys. **40**, 2540-2548 (2001).
[7] K. Noda, *et al.*, Nucl. Instrum. Meth. **A374** (1996) 269-277.
[8] K. Noda, *et al.*, Nucl. Instrum. Meth. **A492** (2002) 269-277.
[9] T. Furukawa, *et al.*, “Global Spill Control in RF-knockout Slow-Extraction” Nucl. Instrum. Meth. A in press.
[10] M. Komori, *et al.*, “Design of Compact Irradiation Port for Raiotherapy Facility”, in this conference.
[11] M. Muramatsu, *et al.*, Rev. Sci. Instr. 71, 984 (2000).
[12] M. Muramatsu, *et al.*, “Compact ECR Ion Source with Permanent Magnets for Carbon Therapy”, Rev. Sci. Instr. in press.
[13] Y. Iwata, *et al.*, “Beam Dynamics of Alternating-Phase-Focusing Linacs for Medical Accelerators”, in this conference.
[14] T. Furukawa, *et al.*, “Design of Synchrotron at NIRS for Carbon Therapy Facility”, in this conference.