

## RECENT PROGRESS AND FUTURE PLAN OF HEAVY-ION RADIOTHERAPY FACILITY, HIMAC

K. Noda, T. Furukawa, Y. Hara, T. Inaniwa, Y. Iwata, K. Katagiri, N. Kanematsu, A. Kitagawa, K. Mizushima, S. Mori, T. Murakami, M. Muramatsu, M. Nakao, A. Noda, S. Sato, T. Shirai, E. Takada, Y. Takei, National Institute of Radiological Sciences, Chiba, Japan

### Abstract

The carbon-ion radiotherapy (RT) with HIMAC has been conducted since 1994, and the accumulated treatment number exceeded 9,000 in May 2014. During the last two decades, NIRS has developed both the accelerator and beam-delivery technologies related to the carbon-ion RT, which has brought several carbon-ion RT facilities in Japan. At present, NIRS has developed a carbon-ion rotating gantry with the superconducting technology to be operated from 2016. As the future plan, NIRS has developed a direct acceleration system of positron-emission beams for verification on an irradiation field, and NIRS also just starts a design study of a superconducting synchrotron ring for carbon-ion RT.

### INTRODUCTION

Since 1994, NIRS has conducted the HIMAC facility [1] for both the cancer treatment and related studies by heavy-ions. NIRS has chosen a carbon-ion for the cancer treatment, based on the experience of the fast neutron RT. As the beam-delivery method, further, a single beam-wobbling method has been employed, because it is robust toward beam errors and offers easy dose management. The protocols were significantly increased after the development of the respiratory-gated irradiation [2]. In 2003, the Japanese government approved the carbon-ion RT with HIMAC as a highly advanced medical technology. Just after this approval, NIRS proposed a standard carbon-ion RT facility [3] in order to boost the carbon-ion RT in Japan through the reduction of the construction cost by downsizing the facility size. The fruits of this work were realized as a pilot facility in GHMC (Gunma university Hospital Medical Center), which has been successfully conducted since 2010.

NIRS, further, has been engaged in a “new treatment research project” [4] since 2006 for the further development of HIMAC treatments such as the “adaptive cancer radiotherapy” to accurately treat tumor even with changing both the tumor size and shapes during a treatment period. Since both the static and moving tumors should be treated in NIRS-HIMAC, The phase-controlled rescanning (PCR) method [5,6], based on a fast 3D scanning technology, has been developed to move toward the goal of adaptive cancer RT. In order to verify the developed technology through the clinical study, the new treatment research facility was constructed, as shown in Fig. 1. As the first stage, one of three treatment rooms has been opened since May 2011, utilizing an energy degrader for slice change for depth scanning in the 3D scanning. As the second stage since September 2012, both the first and

second rooms have been being operated with the hybrid depth scanning [7] with eleven energy steps of the HIMAC synchrotron toward more accurately treatment. In FY2013, operating two treatment rooms treated patients of 300 even under 3 hours operation a day, which result in increasing the total treatment number to 999 with HIMAC. In 2014, further, since the moving target treatment with the PCR method is scheduled in the new treatment research facility. After completing this clinical study, it is expected to be significantly increased the treatment number in the new treatment research facility. As the third stage, a compact carbon-ion rotating gantry has been developed in order to realize the intensity modulated carbon-ion RT (IMCT) combined with the 3D scanning for the more accurate and shorter-course treatments owing to the higher dose concentration. The rotating gantry will be installed to the third room.

As the future plan, NIRS has developed a direct acceleration system of positron-emission beams such as  $^{11}\text{C}$  and  $^{10}\text{C}$  for verification on an irradiation field, and NIRS also just starts a design study of a superconducting synchrotron ring for carbon-ion RT.

The recent progress and future plan of HIMAC for the heavy-ion cancer RT is reported.

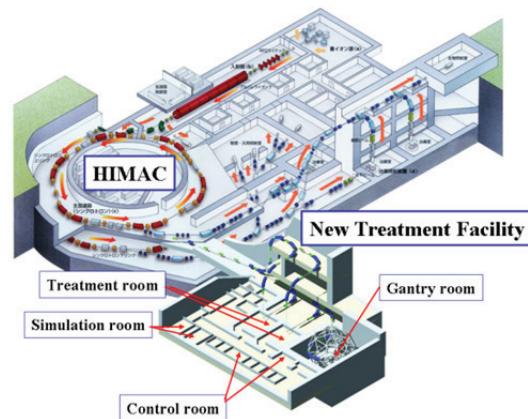


Figure 1: Bird's eye view of the present HIMAC.

### RECENT PROGRESS

#### Multiple Energy Operation for 3D Scanning

The PCR method as well as the conventional 3D scanning has essentially required a slice change for the depth scanning. During the first stage of HIMAC scanning treatment in 2011, the energy degrader, set just in front of a patient, has been utilized to change the slice,

because of saving the commissioning time of the HIMAC accelerator. It has been well known, however, that the variable energy operation by accelerator itself has great advantages over that by the energy degrader: keeping the spot size small and suppressing secondary neutron yield. Since the HIMAC synchrotron with one cycle operation can deliver enough high intensity of the carbon-ion beam for one-fraction irradiation with applying the 3D scanning, NIRS has developed the multiple-energy operation with one cycle of the HIMAC synchrotron. In this method, the energy of the extracted beam can be changed by step-wised energy pattern at the flattop of synchrotron operation. The duration of the flattop can be arbitrarily determined by a clock on/off in the flattop period, as shown in Fig. 2.

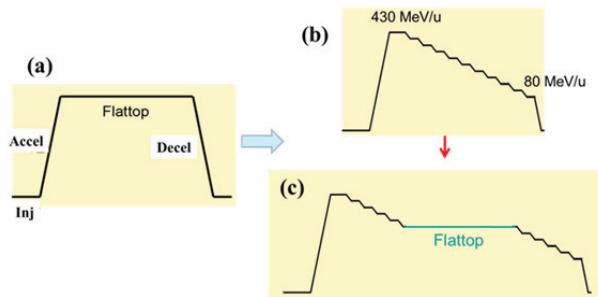


Figure 2. Schematic diagram of variable energy operation at HIMAC. (a) Conventional operation pattern, (b) Variable energy operation pattern and (c) Extended flattop with arbitrary energy by the clock on/off.

As the first step, an eleven-step energy operation from 430 to 140 MeV/n was developed [8], which has been routinely utilized for the hybrid depth scanning, since 2012. In the hybrid depth scanning, range of more than 3 cm is changed by the energy change with the synchrotron, while that of less than 3 cm by that with the thin energy degrader. As the second step, the 201-step energy pattern, which can change the energy ranging from 430 to 56 MeV/n, has been developed. The energy change in one step corresponds to a range shift of 2 or 3 mm, and it will take less than 100 ms for one slice change [8]. The bare tune in each energy level is designed so as to keep constant, while each separatrix size is increased with decreasing energy by changing the sextupole field of the separatrix exciter. Both the betatron tune and beam position changes during the multiple energy operation are adjusted with the design values. Figure 3 shows the tune variations in both the horizontal and vertical directions.

Further, a simulated irradiation on a prostate cancer that was treated with the hybrid depth scanning was carried out with 201-step multiple energy operation. As the result, it was verified that 201-step multiple energy operation can be well operated as same with the hybrid depth scanning. The 201-step multiple-energy operation will be applied to the clinical study from 2015.

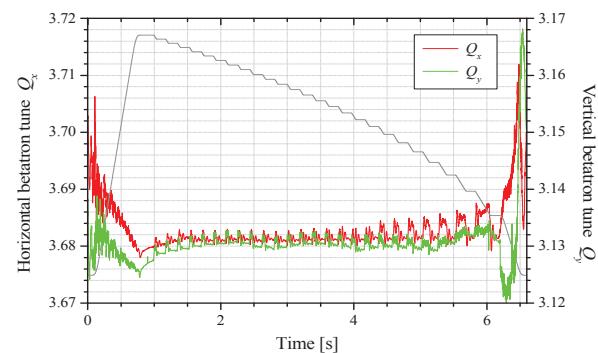


Figure 3: Tune variations during multiple energy operation.

### Superconducting Rotating Gantry

An isocentric superconducting rotating-gantry is being developed [9]. This rotating gantry is designed to transport carbon-ions having 430 MeV/n to an isocenter with irradiation angles of over  $\pm 180$  degrees, and is further capable of performing the fast 3D scanning with a scan size of approximately 20 cm square at the isocenter. Figure 4 shows a layout of the rotating gantry.

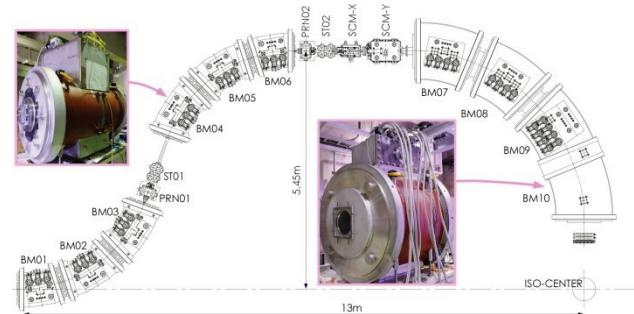


Figure 4: Layout of the superconducting rotating gantry.

The gantry consists of ten combined-function superconducting magnets, a pair of the scanning magnets, and two pairs of beam profile-monitor and steering magnets, allowing a compact geometry - the length and the radius of the gantry are approximately 13 and 5.5 m, respectively. Before manufacturing all magnets, the test superconducting magnet was designed and manufactured in order to verify a stability of a superconducting state under the mechanical rotation and vibrations on a rotating gantry and a stability of temperature under the fast slewing of the magnetic field to follow the multiple-energy operation. As the result of verification, no quench phenomenon was observed in each test. Following these tests, the magnetic-field measurements for both dipole and quadrupole fields are made in progress. It was verified that the overall results agreed with the calculated ones; however the precise analysis revealed that the dipole field, as provided by only exciting the dipole coil, has a slight quadrupole component. Owing to the small magnitude of this unexpected quadrupole component, this component can be adjusted the quadrupole coil.

In the 3D scanning with the rotating gantry, a delivered beam-spot size and beam distribution inside the spot at the isocenter should be kept constant independently of the rotating angle. Therefore, NIRS proposed the compensation method of the asymmetric phase-space distribution for a slowly extracted beam from the synchrotron [10], which utilizes a multiple scattering through a thin foil set in a position having an optimized beta function along a transport line before the gantry entrance. The proposed method is an essential technology for an efficient treatment through the 3D scanning with the rotating gantry. As an experiment result, it is found that the design parameters should be optimized with taking account of undesired multipole fields in the transport line as well as the extracted beam characteristics from the synchrotron. For the purpose, thus, a beam model is designed. The beam-model parameters are obtained by fitting with the measured beam-profile data. As the preliminary result is shown in Fig. 5, a spot size and profile can be fairly controlled by this method as almost expected.

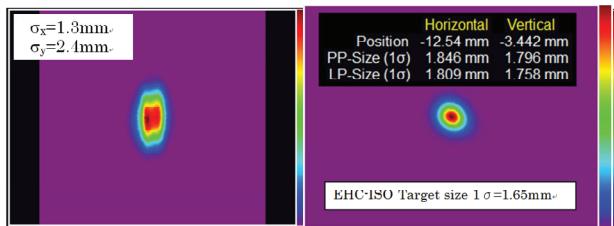


Figure 5: The change of the beam-profile at isocenter by the proposed method. Left: without scatterer, Right:with scatterer. Note that scales are different in each figure.

## FUTURE PLAN

### $^{11}\text{C}$ -ion Beam Production for on-Line Imaging

With on-line imaging by PET,  $^{11}\text{C}$ -ion beam is expected to allow for accurate control of the irradiation field during the 3D scanning. For this purpose, NIRS has proposed a method whereby  $^{11}\text{C}$  beams are produced by an ion source and subsequently accelerated for cancer treatment. In this method,  $^{11}\text{CH}_4$  molecules as ion-source gas should be produced and separated effectively from impurities. As a result of an investigation, it was found that by using a  $\text{NaBH}_4$  target for proton irradiation,  $^{11}\text{CH}_4$  molecules can be produced and extracted directly from the target box. It is expected that the number of collected volatile  $^{11}\text{CH}_4$  molecules exceeded the amount of molecules ( $10^{12}$ ) required for the ESI to produce  $10^{11} \text{ }^{11}\text{C}$  ions [11].

### Design Study of Superconducting Synchrotron

NIRS just starts a design study of a superconducting synchrotron ring for the further downsizing facility and saving the electric power. One of preliminary lattice-design results is shown in Fig. 6. The delivered energy of

carbon-ion ranges from 60 to 430 MeV/n and the circumference of around 20 m under around 5T.

This study will be progressed with developments of both the low and high temperature superconducting technologies, collaborating with the superconducting research groups in Japan,

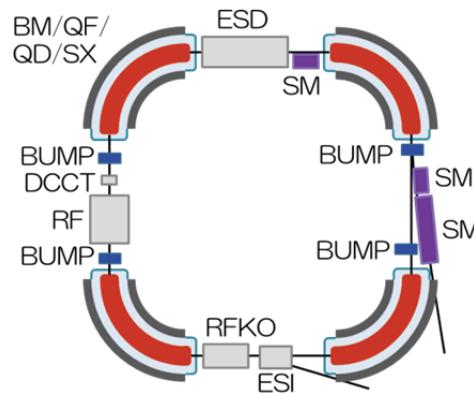


Figure 6: Design example of superconducting synchrotron.

## SUMMARY

More than 600 000 persons are diagnosed with cancer every year in Japan, and it is forecast that this number will continue to rise. In such a situation, following the GHMC facility as a pilot facility of standard version, Saga-HIMAT (Saga Heavy-Ion Medical Accelerator in Tosu) has been operated since August 2013, and i-ROCK (Ion-beam Radiation Oncology in Kanagawa cancer center) will be opened in 2015. They are constructed based on the development of both the accelerator and beam-delivery technologies by NIRS-HIMAC, which are also expected to boost applications of carbon-ion radiotherapy in Japan.

## REFERENCES

- [1] Y. Hirao *et al.*, Nucl. Phys. **A538** (1992) 541c.
- [2] S. Minohara *et al.*, Int. J. Rad. Oncol. Bio. Phys. **47**, 1097 (2000).
- [3] K. Noda *et al.*, J. Radiat. Res., **48** (2007) A43-A54.
- [4] K. Noda *et al.*, Nucl. Instrum. Meth. **B 266** (2008) 2182-2185.
- [5] T. Furukawa *et al.*, Med. Phys. **34**, 1085 (2007).
- [6] T. Furukawa *et al.*, Med. Phys. **37**, 4874 (2010).
- [7] T. Inaniwa *et al.*, Med. Phys., **39**, 2820 (2012).
- [8] Y. Iwata *et al.*, Nucl. Instrum. Meth A **624** (2010) 33.
- [9] Y. Iwata, *et al.*, Phys. Rev. ST Accel. Beams **15** (2012) 044701.
- [10] T. Furukawa and K. Noda, Nucl. Instrum. Meth A **565** (2006) 430.
- [11] K. Katagiri *et al.*, Rev. Sci. Instrum., **85**, 02C305-1-3, 2014.