Beam-Delivery Systems

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Abstract

A particle therapy facility consists of three main equipment components: an accelerator, a beam transport system, and a treatment delivery system. In the beam-delivery system the narrow beam from the accelerator is tailored to suit the lesion being treated. The requirements of beam depend on details of the beam-delivery system used. Both passive and active beam-delivery systems are employed to deliver the required dose to the target. In this chapter, both delivery system and the accelerator for heavy ions are introduced.

Keywords

Beam delivery • Dose conformation

7.1 Passive Delivery System

7.1.1 Basic Principles of Passive Delivery

A high-energy beam accelerated by an accelerator is delivered through a beam transport system to a treatment delivery system. The narrow pristine beam extracted from the accelerator, and sometimes called a "pencil beam," is not suitable for use in treatment except for the beam-scanning method. The passive irradiation system expands "the pencil beam" and tailors the expanded beam to meet clinical requirements of a higher-dose delivery in a target tumor within a patient with lower-dose irradiation to normal tissue. This method is called "passive beam delivery," sometimes classified as "broad-beam method." We describe the details of the passive beam delivery with the beam-delivery systems of HIMAC.

7.1.2 Passive Beam-Delivery Systems of HIMAC

HIMAC has three treatment rooms which have the passive beam-delivery systems. Treatment rooms A, B, and C are equipped with vertical, vertical and horizontal, and horizontal beam courses, respectively. Figure 7.1 shows the beam-delivery systems of treatment room B of the HIMAC [1, 2]. Both beam ports have the almost same structure, but the horizontal beam course is slightly longer than the vertical one. Beam transport lines deliver the pencil beam and focus the beam on the isocenter without momentum dispersion.

The method mainly used to widening the pencil carbon beam uniformly in the lateral direction is a wobbler-scattering method. The wobbler-scatterer method generates a uniform irradiation field using a combination of a wobbler magnet system and a scatterer system. The wobbler magnet system is a pair of bending magnets which are installed so that the directions of their magnetic fields are mutually orthogonal. By applying alternating currents to the two magnets which are out of phase with each other by 90°, the pencil beam delivered from the accelerator is rotated in a circular pattern as shown in Fig. 7.2b. The radius of the circle can be changed by varying the effective current supplied to the wobbler magnet system. The wobbler magnets of HIMAC beam-delivery systems are located 11.7 m upstream from the isocenter of

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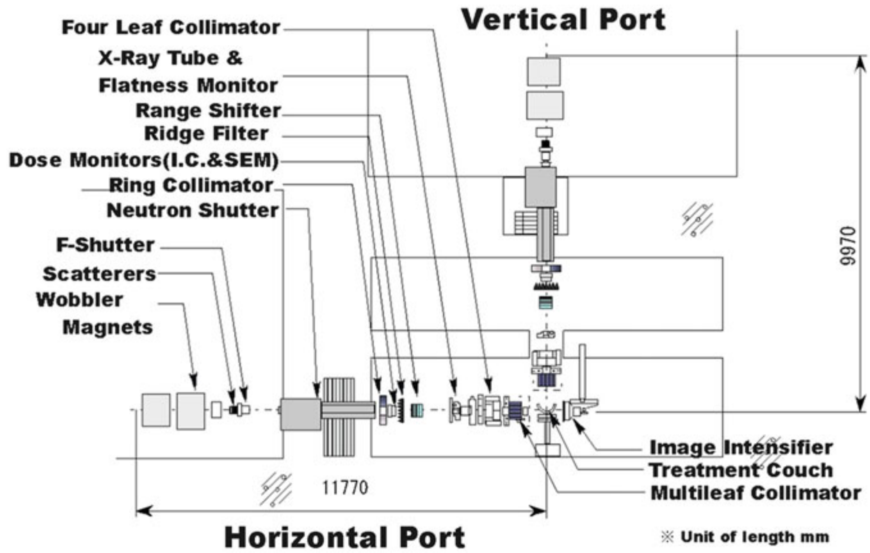

Fig. 7.1 Beam-delivery systems of treatment room B of HIMAC. The horizontal beam port and vertical beam port which have a common isocenter are shown. Both beam ports have the same configuration

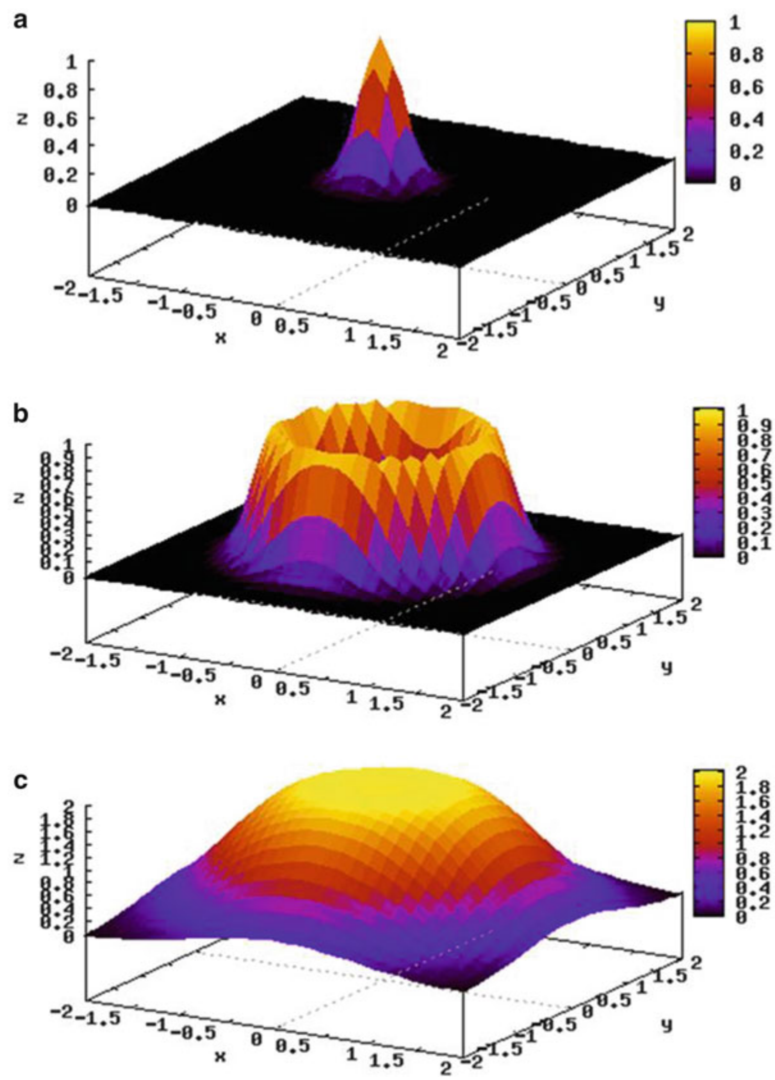

Fig. 7.2 Uniform broad beam generated by the wobbler-scattering method. (**a**) A pencil beam delivered from an accelerator source, (**b**) a beam rotated by wobbler magnets, and (**c**) a beam broadened by a scattering system placed downstream from the wobbler magnet system

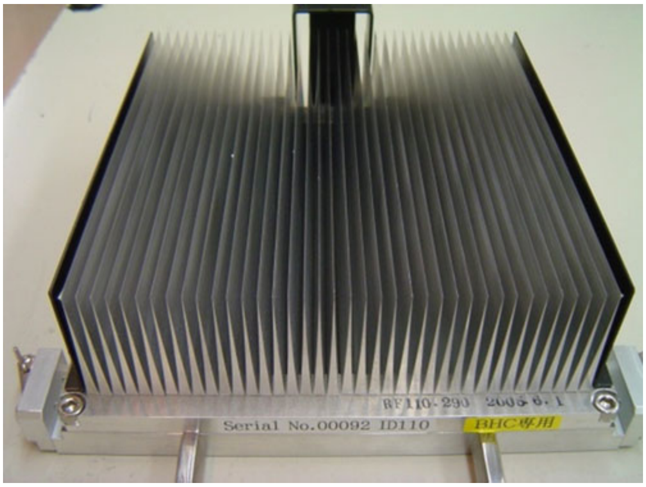

Fig. 7.3 Ridge filter

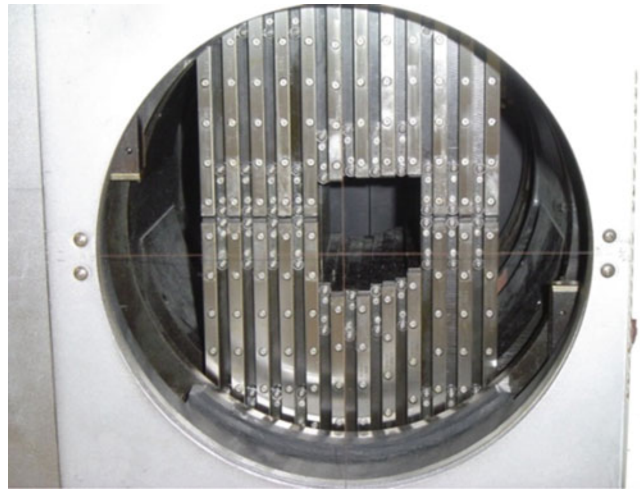

Fig. 7.4 Multi-leaf collimator (MLC)

the horizontal beam course and 9.9 m from the isocenter of the vertical beam course. Each magnet has an effective magnetic length of 660.1 mm and its pole gap is 110 mm. Both magnets can be excited at 1,200 A at the maximum.

The annular beam is broadened by the scatterer system placed downstream from the wobbler magnet system (Fig. 7.2c). As the scatter system, a binary scatter system is often used. It has several scatterer boards and each differs in thickness from the neighbor board by a factor of two. The total thickness can be changed by selecting a binary combination of scatterer boards. The scatterer system of HIMAC contains seven metal sheets, each of which is plunged into the beam course by an actuator.

By tuning the currents to the wobbler magnets and the thickness of the scatterer it is relatively easy to make different uniform irradiation fields with different sizes. The irradiation field made by the wobbler-scatterer method is not susceptible to the variation in the beam position at the entrance of the irradiation system. Meanwhile, it has a periodic time structure corresponding to the frequency of the alternating current.

Uniform broadening of a beam in the depth direction corresponds to producing a spread-out Bragg peak (SOBP). An SOBP is formed by superposing many monoenergetic Bragg peaks. In other words, the SOBP is made to respond to the energy modulation of a monoenergetic beam. There are two main ways of modulating the beam energy and superimposing Bragg peaks: one uses a ridge filter device and the other a rotating range modulator. The ridge filter device is used for the beam-delivery system using the wobbler-scatterer method.

The ridge filter device is composed of many uniform bar-ridges, manufactured with highly precise processing technology, which are set parallel to each other on one plane as shown in Fig. 7.3. Ridge filter devices, corresponding to different SOBP widths, are often prepared for a high-energy beam and a low-energy beam. Since the cross-sectional shape for the bar-ridge determines the change of thickness, appropriate design of the bar-ridge allows delivery of a homogeneous biological dose to the target region. In the case of a carbon beam, the SOBP is composed of a range of LET components with different weighting factors at each depth. The survival rate under a mixed LET radiation field was experimentally proved to be described by a formalism proposed in the theory of dual radiation action on the basis of the linear-quadratic (LQ) model [3].

After broadening of a beam in the lateral and depth directions, the beam is cut to the shape of the target tumor projected in the beam's eye view. A patient collimator, a multi-leaf collimator (MLC) device or their combination is used for the two-dimensional cutting of a uniform beam. The patient collimator is a block that has a tumor projection-shaped aperture. The block is thicker than the maximum range of the beam and is often made of brass, which is easy to cut by a wire-electrical discharge machine. Although the patient collimator needs to be manufactured for each irradiation direction, it reduces blurring of the lateral dose distribution because the patient collimator can be placed near the body surface of the patient.

The MLC is a device that has many pairs of thin leaves. These leaves are shifted to suitable positions to make a tumor projection-shaped aperture. Use of an MLC device has the advantages of increased speed and reduced costs for treatment preparation because no individual patient collimators need to be manufactured. In some situations the MLC device cannot be moved close to the body surface of a patient due to its size and blurring of the lateral dose; then distribution is not necessarily small.

Figure 7.4 shows the MLC used at the horizontal beam port of HIMAC beam-delivery systems. The MLC consists of 23 pairs of 6.5 mm thick iron plates with 0.25 mm spacing. The leaf with thickness of 140 mm in the beam direction

Fig. 7.5 Manufacture of patient compensators by machining center

has a tongue-and-groove structure except the central leaf to reduce the interleaf dose-leakage. The central leaf has the tongue structure on both sides. The leaf moves at a maximum speed of 80 mm/s and stops at a position with less than ±0.5 mm precision.

The final step in the broad-beam method is the adjustment and conformation to the target in the depth direction using a range shifter (RSF) device and a patient compensator (bolus).

The RSF is composed of several energy absorbers having different thicknesses and the total thickness of the system can be changed by selecting suitable absorbers. The RSF of HIMAC systems consists of ten polymethyl methacrylate (PMMA) plates of various thicknesses. Combinations of plates result in thicknesses from 0.25 to 255.75 mm in a binary manner.

A patient compensator is a block that has an engraved depression in the shape of the depth direction of the target tumor volume. The block is often made of high-density polyethylene which is easy to engrave and is a low-atomic-number material for reduced scattering of the beam. Patient compensators, like patient collimators, also need to be manufactured for each irradiation direction. Figure 7.5 shows the manufacture of patient compensators by a machining center.

The dose control of irradiation with the passive beam method is performed by each individual irradiation. As well as a conventional X-ray irradiation system, the treatment delivery system with carbon beams requires two independent monitor systems to ensure safe and reliable irradiation.

Each treatment delivery system of HIMAC has two identical parallel-plate ionization chambers (IC; aperture diameter about 20 cm). They are filled with atmospheric air and operated by applying +2,000 V. Each IC consists of three cathodes and two anodes that are staggered with the gap of 5 mm. There used to be other monitors, an ionization chamber and a secondary emission monitor (SEM), to have redundancy by using different types of monitors. They were, however, replaced with the present ICs after the high reliability of ICs in practical use was confirmed [3]. One of the ICs works as the main monitor and the other works as the auxiliary monitor. A beam shutter is interlocked to the beam monitors and is closed when the measured dose value reaches the prescribed value. The auxiliary monitor also closes the beam shutter when the measured dose value reaches the value that is larger than the prescribed value by 5 %.

7.1.3 Layer-Stacking Method

In the broad-beam method, with arrange modulator, a constant SOBP over the field area results in an undesirable dose to the normal tissue proximal to the target [3, 4]). Therefore, in order to avoid unwanted doses, a layer-stacking method was developed. The layer-stacking method is a way of stacking many mini SOBPs along the depth direction and changing apertures of the MLC as if drawing the lineation of the cross-sectional surface of the target tumor volume as shown in Fig. 7.6.

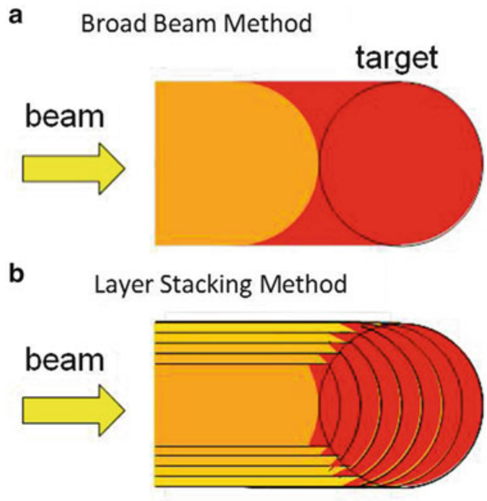

Fig. 7.6 Layer-stacking method. (**a**) Because the broad-beam method makes the fixed SOBP irradiation field, the high-dose region exists outside the tumor target. (**b**) The layer-stacking method can change SOBP according to the shape of the target and reduce the high-dose region outside the tumor target

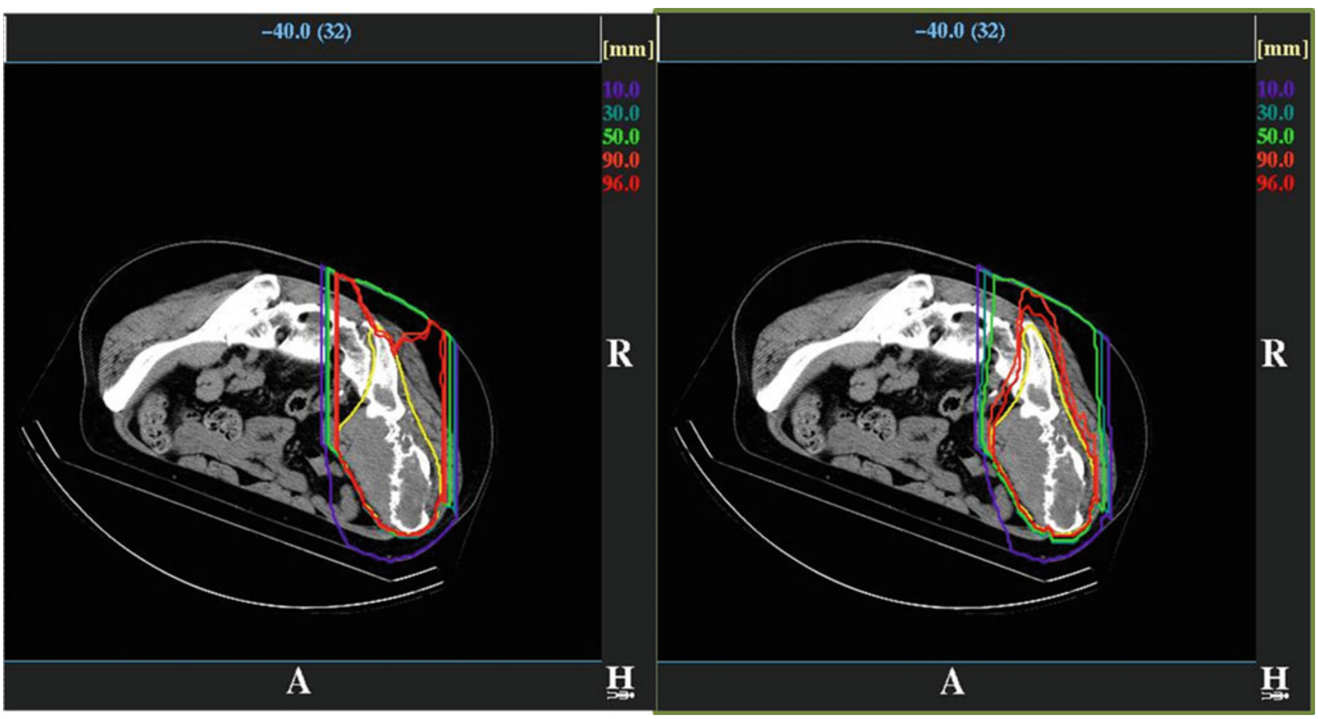

Fig. 7.7 Example of dose distribution planed to the tumor in the bone and soft tissue region by the broad-beam method (*left*) and the layer-stacking method (*right*)

At HIMAC the layer-stacking method has been used for carbon-ion radiotherapy (C-ion RT) since 2005. A thin-layer irradiation field with a mini SOBP (about 10 mm) is longitudinally swept step by step with changing thickness of a range shifter from the distal end of the target volume to the shallowest end. The mini SOBP is produced with a thin ridge filter. At each step, the radiation field shaped by the MLC changes to conform the contour of the target at each slice. Once the described dose is delivered to the slice volume, beam extraction is quickly cut off and the MLC and the range shifter are set to the next slice, and this sequence is repeated to the last slice. To accomplish the irradiation in clinically acceptable time, quick responses of the MLC motion, of the range shifter motion, and of the beam on/off are essential. Figure 7.7 shows an example of dose distributions of tissues during treatment planning. The left one is of tissues by the ordinary broad-beam method, and the right one by the layer-stacking method. The dose to the normal tissue proximal to the target is remarkably reduced by the layer-stacking method. Among the merits of this method are not only the improved dose distributions, but also that they are achieved with the same devices as the passive treatment delivery system.

7.2 Scanning Delivery System

7.2.1 Overview and Basic Principles of Scanning Delivery

In order to achieve the required dose distribution, the treatment planning system (TPS) for the scanning delivery optimizes and outputs the particles numbers (weight) for each irradiation point (spot) in the target volume. Figure 7.8 shows an example of the optimized weight maps. It is required to the scanning delivery system to realize required particle distribution safely. Thus, the scanning delivery system controls the beam position three-dimensionally by magnetic deflection for transverse and by changing energy for longitudinal. The schematic of the scanning delivery is shown in Fig. 7.9. To realize desired field as calculated by the TPS, we must control the fluence of each spot to keep it as close as possible to the prescribed fluence in the TPS, because errors in the irradiation disturb the uniformity. There are several kinds of errors in the irradiation that commonly occur, such as size and position of the pencil beam and resolution of the monitor, making the uniformity of the irradiated dose distribution worse than that in the TPS.

7.2.2 Transverse Beam-Scanning Methods

There are several scanning methods to deliver the required fluence maps, while it is common to scan the beam by the magnetic deflection. Three scanning methods, as schematically shown in Fig. 7.10 and summarized in Table 7.1, are well known as follows: (1) spot scanning, (2) raster scanning, and (3) continuous raster scanning. (1) Spot scanning and (2) raster scanning are sometimes called “discrete spot scanning” and “continuous spot scanning,” because both of them employ the spot by spot control of the magnet. In spot scanning irradiation, the beam supply is turned off just after the counter reaches the preset value of each spot. Thus, exposure during the transition between spots is zero, although leakage after the beam is turned off is unavoidable. In raster-scanning irradiation, when the preset count is delivered to a raster point, the beam position is shifted to the next raster point without turning the beam off, within each iso-energy slice. Meanwhile, when the slice needs to be shifted or all irradiation is finished, it is necessary to turn off the beam. Continuous raster scanning is similar to raster scanning as far as beam-on/beam-off operations are concerned. The scanning magnets are operated according to the preset current pattern for each iso-energy slice. In this method, it is

Fig. 7.8 Example of optimized weight map

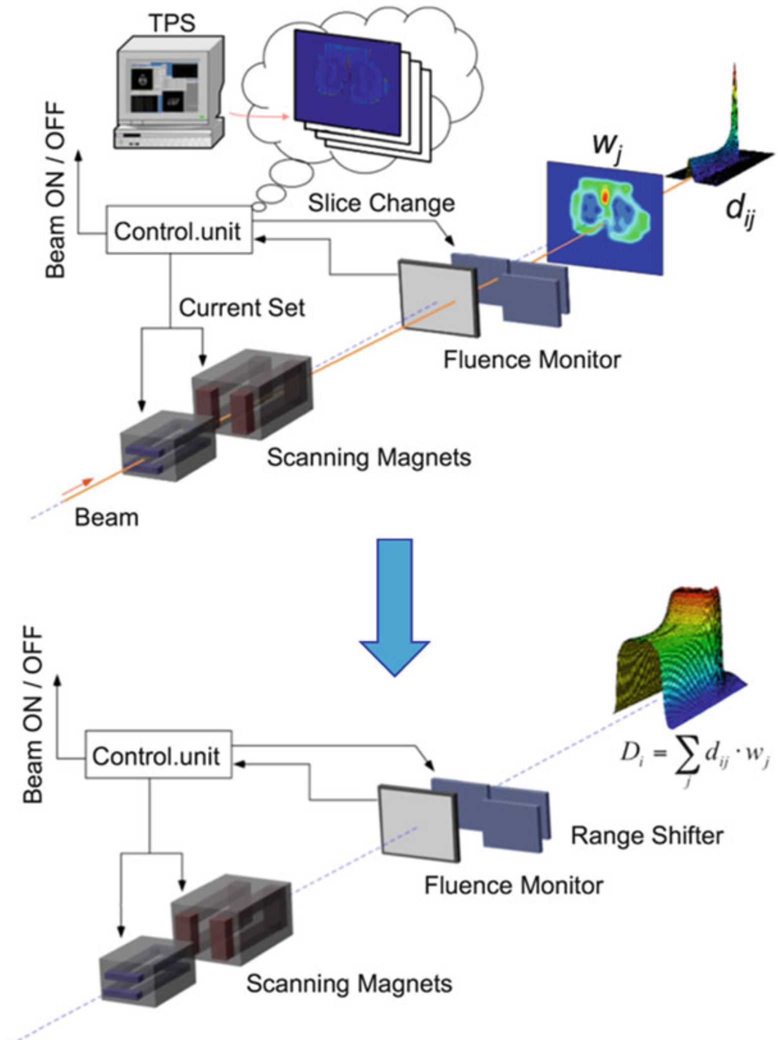

Fig. 7.9 Schematic of dose conformation by scanning delivery

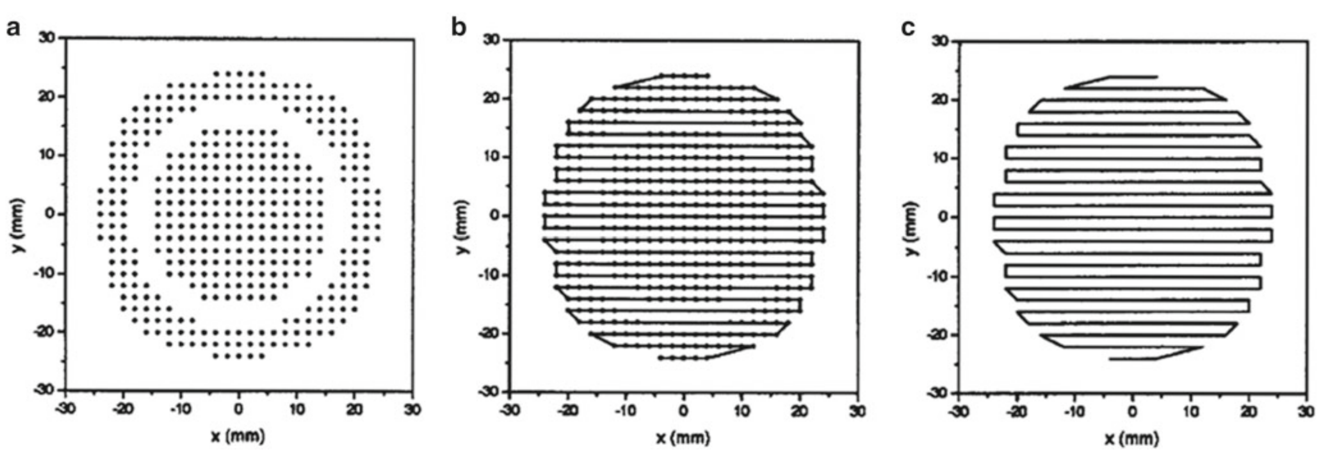

Fig. 7.10 Comparison of transverse beam-scanning methods

Table 7.1 Comparison of transverse scanning methods

	Spot scanning	Raster scanning	Continuous raster scanning
Magnet control	Stepwise	Stepwise	Continuous
Dose control	Spot by spot, discrete	Spot by spot, continuous	Continuous
Optimization	Discrete	Discrete	Continuous
Unavoidable exposure	Limited by beam-off time	Limited by scan speed	None

necessary to apply a different optimization procedure, in which a discrete weight map is interpolated and iteratively optimized to obtain a continuous weight map.

7.2.3 Depth-Scanning Methods

The depth scanning, i.e., shifting the Bragg-peak position in the target, can be realized by changing the beam energy. Two popular depth-scanning techniques are (1) range shifter scanning and (2) energy scanning. Recently, an alternative technique combining the range shifter scanning and the energy scanning, (3) hybrid depth scanning, is proposed. These three scanning methods are schematically shown in Fig. 7.11. In the range shifter scanning, the energy absorber, which consists of plastic plates, is used to shift the Bragg-peak depth. The commissioning and the control of this method are easier than others. Further, the irradiation time can be shortened compared with other method, because it takes only few hundred milliseconds to insert/remove the plates. However, the range shifter plates may broaden the spot size of the beam on a target and produce secondary fragments. On the other hand, in the energy scanning, the Bragg-peak depth can be controlled by directly changing the beam energy from the accelerator. Thus, this method does not employ the range shifter plates. However, this method needs relatively longer time for energy variation and for the commissioning. Further, the fine adjustment of the Bragg-peak position is required, because the energy step from the accelerator is usually discrete. In order to overcome these problems, the hybrid depth-scanning method was developed. In this method, coarse tuning of the beam range is provided by the accelerator, while fine tuning is provided by the range shifter plates. The hybrid depth scanning can provide dose distributions with steeper lateral dose falloffs and higher peak-to-plateau ratio compared to the range shifter scanning and comparable to the energy scanning. Thus, the hybrid depth-scanning method is routinely used at NIRS-HIMAC since 2012.

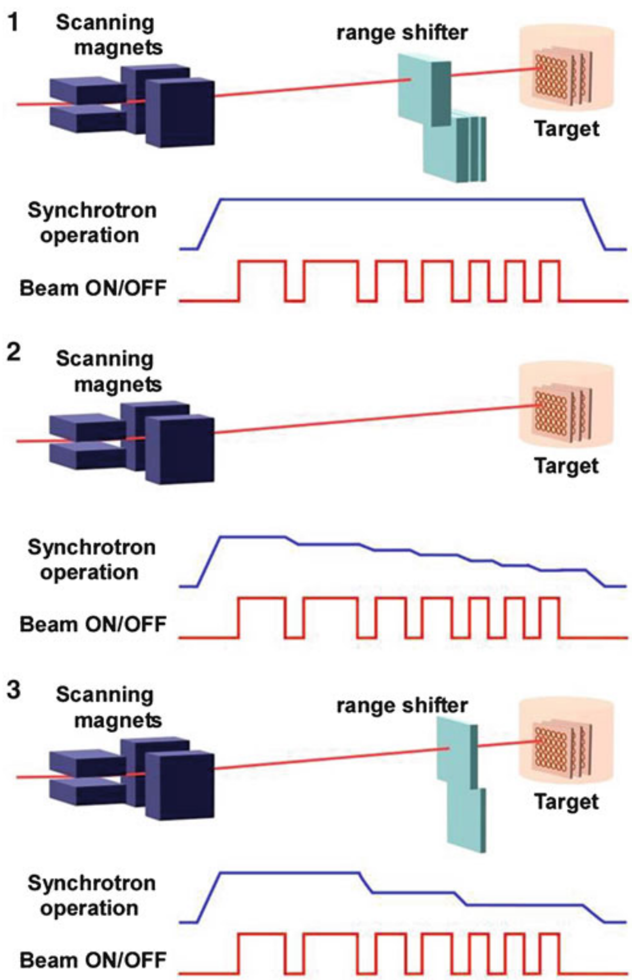

Fig. 7.11 Schematic of depth-scanning methods, from the upper (*1*) range shifter scanning, (*2*) energy scanning, and (*3*) hybrid depth scanning

7.2.4 Control System and Beam Monitoring

While the advantage of the scanning delivery is its flexibility for dose conformation, the implementation of quick and reliable beam control and monitoring are required because the beam properties from the accelerator directly affect the dose distribution compared to the passive delivery. Further, sufficient safety features should be implemented. For this purpose, two flux monitors and one or two beam position monitors are employed in the scanning delivery system. The safety interlock features for errors of the beam flux, position, and size should be implemented including the watchdog and the monitoring of each device. Since these undesirable errors deteriorate the dose distribution, the beam should be turned off as quickly as possible after their detection. Example of control system configuration is shown in Fig. 7.12.

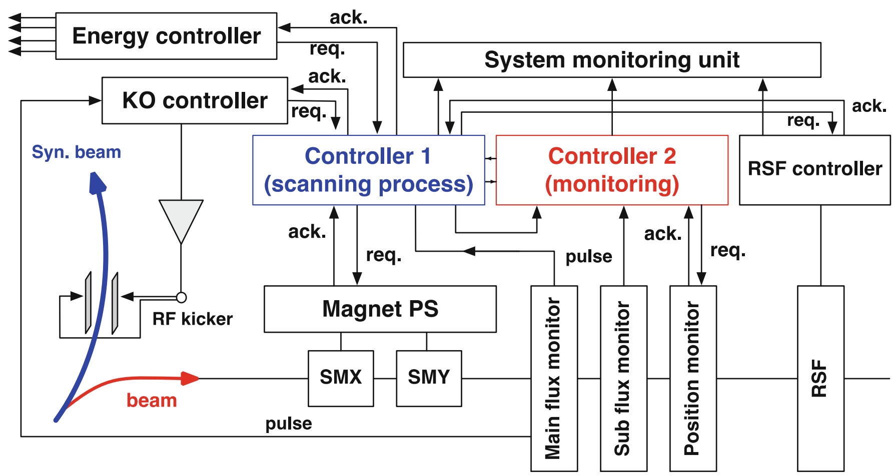

Fig. 7.12 Schematic of control system for NIRS scanning system

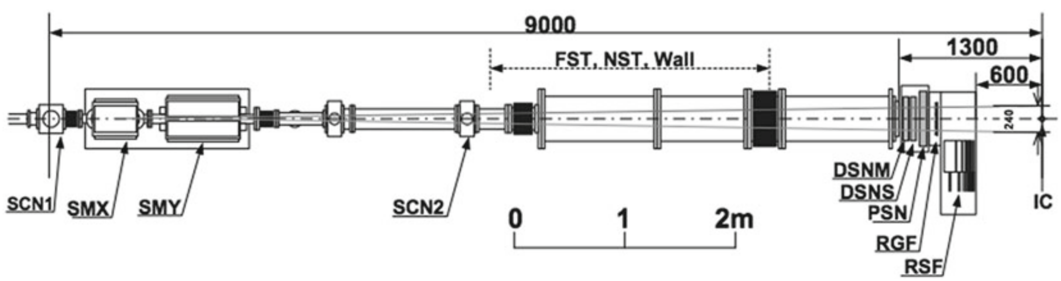

Fig. 7.13 Layout of NIRS scanning system

7.2.5 System Configuration Example: NIRS Scanning System

Layout of the fast scanning system is shown in Fig. 7.13. It consists of the scanning magnets (SMX and SMY), main and sub flux monitors (DSNM and DSNS), position monitor (PSN), mini ridge filter (RGF), and range shifter (RSF). To achieve the fast beam scanning at the isocenter, the distances from SMX and SMY to the isocenter are designed to be 8.4 and 7.6 m, respectively. The vacuum window is made of 0.1 mm thick Kapton and located 1.3 m upstream from the isocenter. Beam monitors, RGF, and RSF are installed downstream of the vacuum window. The primary beam shutter (FST) and the neutron shutter (NST) are placed in the middle of the irradiation port (indicated by the dotted arrow in Fig. 7.13).

The basic parameters of the NIRS scanning system are described as follows. To obtain the range of more than 300 mm, the maximum energy is chosen as 430 MeV/u. The required field size is 220 × 220 mm^2 for the transverse directions with a 150 mm length for the longitudinal direction. This covers most of the target that are treated by the existing passive irradiation system at the HIMAC. Under these conditions, the new system must be as fast as possible to treat the moving target with rescanning. Based on the conceptual design study, the system was designed so as to provide a modulated dose delivery with beam-scanning velocities of 100 and 50 mm/ms at the isocenter. These scanning velocities enable us to achieve the fastest irradiation time of around 40 ms for an example uniform 2D field having a 102 × 102 mm^2 size with spot spacing of 3 mm. To fulfill these requirements, we made strong efforts to develop (1) the fast scanning magnet and its power supply, (2) the high-speed control system, and (3) the beam monitoring. As a result of the development, the NIRS system took only 20 s to deliver the physical dose of 1 Gy to a spherical target having a diameter of 60 mm with eight rescans. In this irradiation, the average of the spot-staying time was considerably reduced to 154 μs, while the minimum staying time was 30 μs.

7.3 Heavy-Ion Accelerators

7.3.1 Overview of Heavy-Ion Accelerators

To treat a deeply seated tumor in a patient using carbon ions, ions have to be accelerated up to 430 MeV/u. A speed of carbon ions at this energy is roughly 73 % of the light speed,

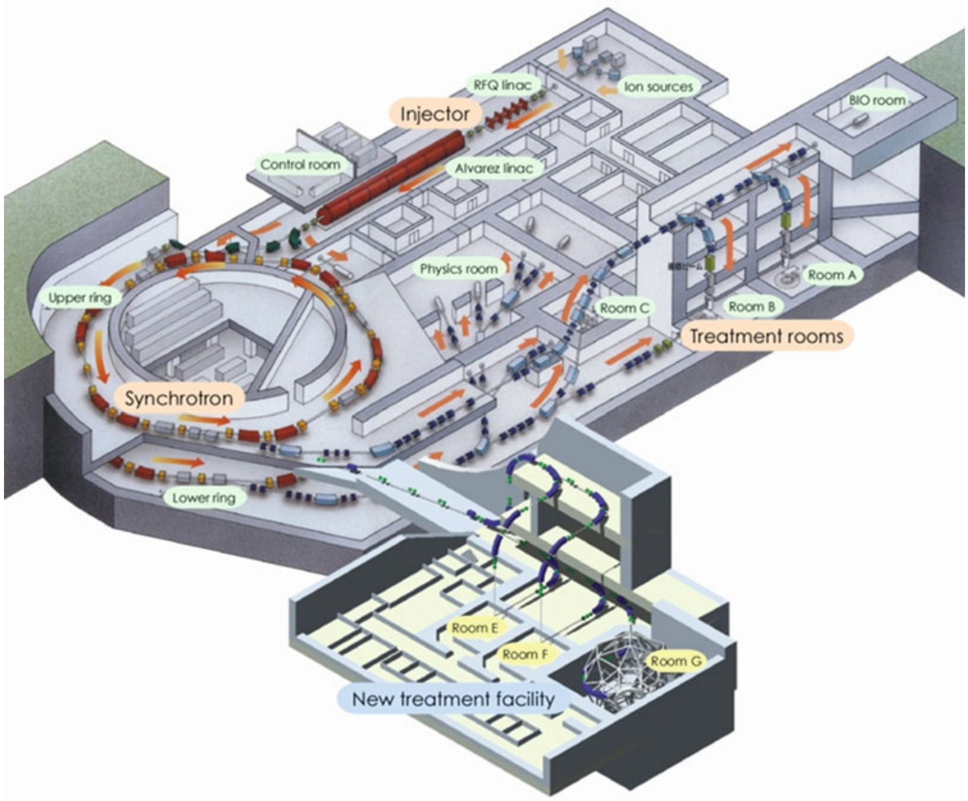

Fig. 7.14 Bird's-eye view of the HIMAC

and a corresponding residual range in a patient is approximately 30 cm, which may cover most of tumor sites. To accelerate carbon ions to the required energy, heavy-ion accelerators, such as synchrotrons or cyclotrons, are used. For proton radiotherapy, cyclotrons are commonly used, because cyclotrons can generally provide higher beam intensity, as compared with that of synchrotrons. However, only synchrotrons are presently employed for C-ion RT, because synchrotrons can change energy of output beams directly from accelerators, and control intensity of extracted beam. These features of synchrotrons are preferable for ion radiotherapy and further quite attractive for the scanning beam delivery, since a quality of treatment beam is quite important to control dose distributions.

A bird's-eye view of the HIMAC accelerator complex is shown in Fig. 7.14 [5]. The accelerator part of the HIMAC complex consists of three ion sources: a linear-accelerator cascade and two synchrotron rings. The ion source produces carbon ions of C^{2+}, and they are transported and injected to the linear-accelerator cascade. A linear accelerator, abbreviated as "linac," refers to a device that accelerates ions along a linear path. The linear-accelerator cascade of the HIMAC complex consists of a radio-frequency-quadrupole (RFQ) linac and an Alvarez drift-tube linac (DTL) and can accelerate ions up to 6 MeV/u having a charge-to-mass ratio of A/Z = 7.

The ions, as accelerated with the linear-accelerator cascade, are then injected and accelerated with the synchrotron rings. When energy of ions reaches to those, required for treatment beams, the circulating beam in the ring is slowly extracted from the ring by using an RF-knockout (RF-KO) slow-extraction method [6] and is delivered to a beam-delivery system, as described in the preceding sections. For a reliable and stable dose management in ion radiotherapy, the extracted beam should have characteristics, such as a sufficiently long duration, low fluctuation in the time structure, and quick beam on/off for gated irradiation to moving targets, such as lung or liver tumor, which is called "respiratory-gated irradiation"; the heavy-ion accelerators for ion radiotherapy must be designed so as to satisfy those requirements.

7.3.2 Multiple-Energy Operation

In raster-scanning irradiation, a target is directly irradiated with high-energy heavy ions. The position of the focused beam on a target is controlled by the fast horizontal and vertical scanning magnets. To control the depth dose distribution, energy degraders, such as range shifters, consisting of PMMA plates having various thicknesses, are used in the

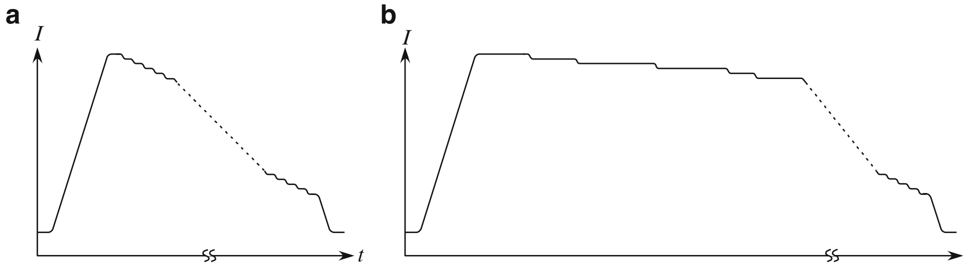

Fig. 7.15 Schematic drawing of synchrotron pattern for multiple-energy operation. (**b**) The same pattern as (**a**), but with the extended flattops. The beam is extracted from the synchrotron ring during these extended flattops

present irradiation system with broad-beam irradiation. However, these range shifters may broaden the spot size of the beam on a target and concurrently produce secondary fragments, which could adversely affect the depth dose distribution. Since focused beams are used to irradiate a target in the raster-scanning irradiation method, it is preferable to change the beam energy directly by the accelerators, instead of using such energy degraders.

To change the energy of the beam, as provided by the synchrotron ring, a multiple-energy operation with extended flattops is developed [7]. The proposed operation enables us to provide heavy ions having various energies in a single synchrotron cycle, namely, the beam energy would be successively changed within a single synchrotron pulse by an energy step, corresponding to a water range of 2 mm. With this operation, the beam range could be controlled without using any energy degraders, such as the range shifters, and hence an excellent depth dose distribution could be obtained.

The multiple-energy operation employs operation patterns having a stepwise flattop, as schematically shown in Fig. 7.15a. With these operation patterns, the heavy ions injected in the ring are initially accelerated to the maximum energy and then successively decelerated to lower energies. Although the stepwise pattern only has short flattops, where the beam can be extracted from the ring, we can extend the flattop and extract the beam during the extended flattop. Having consecutively extended the flattops, as illustrated in Fig. 7.15b, the beams having various energies can be extracted from the ring within a single synchrotron cycle, and hence the total irradiation time can be considerably reduced.

To prove the principle of multiple-energy operation with extended flattops, beam acceleration and extraction using the stepwise operation pattern was performed. The pattern has 11 short flattops, corresponding to beam energies of 430, 400, 380, 350, 320, 290, 260, 230, 200, 170, and 140 MeV/u. A similar pattern was prepared for other devices, such as the main quadrupole and sextupole magnets, the RF-acceleration cavity, and the beam-extraction devices in the extraction channel. By using the prepared operation pattern, the beam will be first accelerated to 430 MeV/u and then consecutively decelerated down to 140 MeV/u at an energy step of 20 or 30 MeV/u. Results of the beam test are shown in Fig. 7.16. Beams having 11 different energies were successively extracted from the synchrotron ring. The multiple-energy operation using this pattern was successfully commissioned and has been used for scanning treatments since FY 2012 [8].

7.3.3 Intensity Control

In ion radiotherapy, intensity control of treatment beams, as well as fast on/off switching and stability in position and intensity of beams, is quite important. Thus, the RF-KO slow-extraction method has been used to meet these requirements of treatment beams. In this method, the beam is diffused by the transverse RF field. When the frequency of which has frequency modulation (FM) that is matched with betatron motion, the beam is excited by the third-order resonance and hence extracted from a synchrotron ring. The control of the transverse RF field is responsible for beam-on/beam-off switching.

Since beam intensity has to be controlled during irradiation a slice by a slice for a 3D-scanning irradiation method gated with patient's respiration, beam intensity has to be dynamically changed and precisely controlled. To satisfy these requirements, an intensity-modulation system was developed [9]. In the system, beam intensity is monitored with a flux monitor, installed at exit of a beam nozzle. Information on the beam intensity is fed into a feedback control system and used to control RF amplitude for the RF-KO beam-extraction system.

An example of intensity-modulation tests is shown in Fig. 7.17. In the tests, a beam having 350 MeV/u was used, and beam intensity, as extracted from the synchrotron ring, is modulated 1 to 30. As can be seen in the figure, beam intensity is well control as expected.

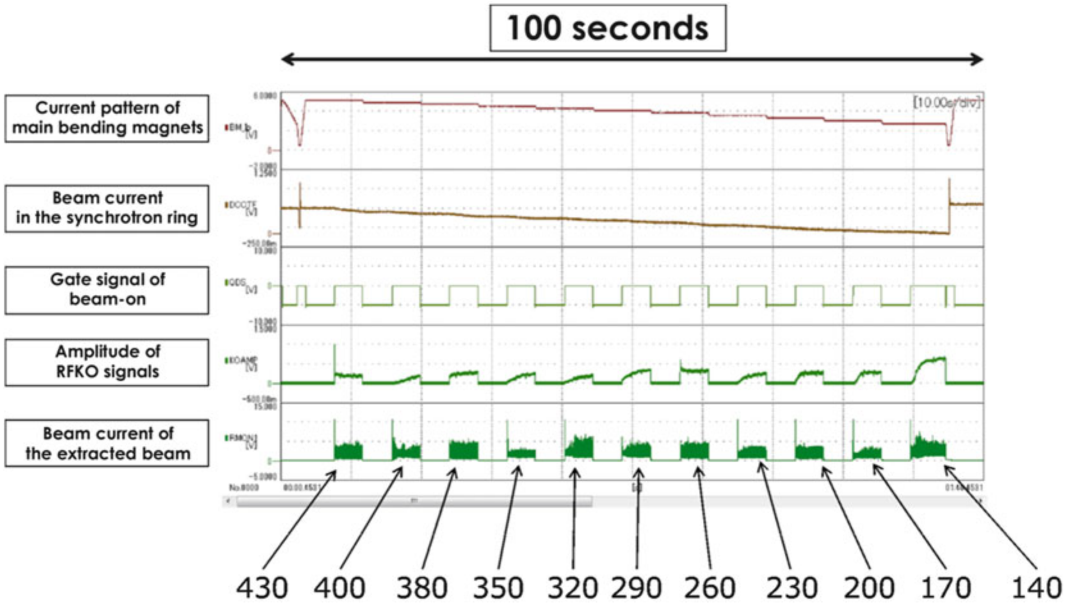

Fig. 7.16 Example of the beam acceleration test using the 11-flattop operation pattern. Beams having 11 different energies were successively extracted from the synchrotron ring

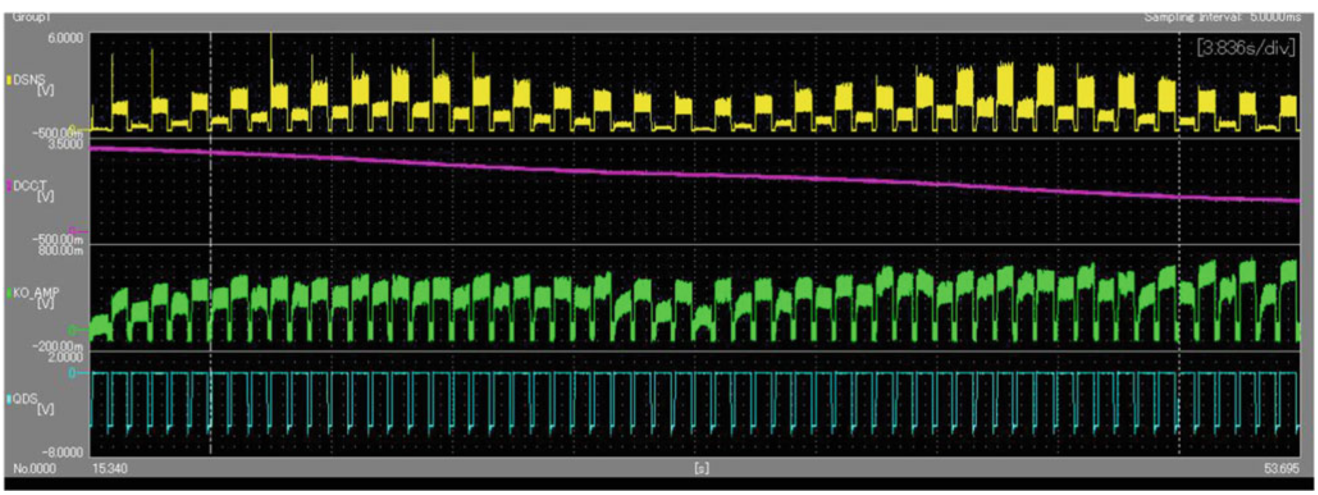

Fig. 7.17 Example of intensity-modulation tests using carbon beams of 350 MeV/u. Measured intensity of an extracted beam (*yellow*), beam current of a circulating beam (*pink*), an amplitude of RF-KO signal (*green*), and applied current for sextupole magnet in the ring (*blue*) are shown

References

1. Minohara S, Fukuda S, et al. Recent innovations in carbon-ion radiotherapy. J Radiat Res. 2010;51:385–92.
2. Torikoshi M, et al. Irradiation system for HIMAC. J Radiat Res. 2007;48(Suppl A):A15–25.
3. Kanai T, Sudo M, Matsufuji N, Futami Y. Initial recombination in a parallel-plate ionization chamber exposed to heavy ions. Phys Med Biol. 1998;43:3549–58.
4. Kanematsu N, Endo M, Futami Y, et al. Treatment planning for the layer-stacking irradiation system for three-dimensional conformal heavy-ion radiotherapy. Med Phys. 2002;29:2823–9.
5. Hirao Y, et al. Annual report HIMAC. National Institute of Radiological Sciences:NIRS-M-89/HIMAC-001; 1992.
6. Tomizawa M, et al. Slow beam extraction at TARN II: Nucl Instr Method. 1993;A326:399.
7. Iwata Y, et al. Multiple–energy operation with extended flattops at HIMAC: Nucl Instr Method. 2010;A624:33.
8. Mizushima K, et al. Proceeding of particle accelerator society Japan FRUH09; 2012.
9. Mizushima K, et al. The HIMAC Beam-intensity control system for heavy-ion scanning: Proceeding of international particle accelerator conference (IPAC); 2011. pp. 3592–3594.