PROPOSAL FOR CARBON-BEAM FACILITY FOR THE CANCER THERAPY IN JAPAN

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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 1,900 patients were already 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 ten-years, we propose a carbon-therapy facility. This paper reports the conceptual design of the facility.

INTRODUCTION

At HIMAC [1], since the first clinical trial on three patients in June 1994, total number of treated patients exceeded 1,900 in this June. As a result of the clinical trial, a local tumor-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. However, the number of fractions has been decreased for some protocols. Typical number of fractions is as low as four for liver cancer. For the lung-cancer treatment, in particular, only one fractional irradiation has been carried out since April 2003. The one-fraction treatment brings surprisingly the low total dose by half compared with the large number of fractions, and 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 propose a carbon-beam facility for cancer therapy.

DESIGN STUDY

Design Considerations and Specifications

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

The irradiation gated with patient's respiration [3] and the layer-stacking irradiation method [4,5] should be applied in order to sufficiently suppress undesirable dose. Although the scanning method [6] has a potential to deliver completely conformal 3D dose distribution, it is difficult to control preciously the dose distribution in the moving target with respiration.

Figure 1 shows a histogram for the number of treatments on the residual range required for 10-years treatment. It is obviously found that the residual range of 250mm covers almost of all patients. The residual range depends not only on the beam energy, but also on the irradiation method. Using the spiral-wobbler method [7], the carbon energy is estimated to be 400 MeV/n in order to obtain the residual range of 250 mm. For the treatment for eye melanoma, on the other hand, the minimum energy is to be 140 MeV/n.

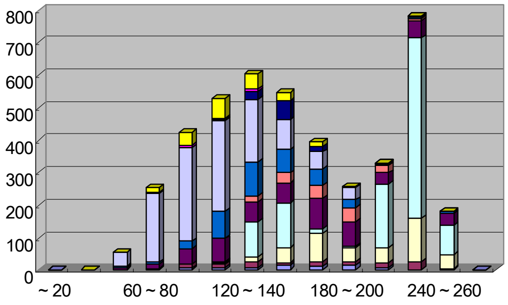

Fig. 1: Histogram of the treatment number on required residual-range in mm.

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As can be seen in Fig. 2, the irradiation-filed diameter of 220 mm covers treatments of more than 85%, and the SOBP size of 150 mm covers that more than 97%. Thus the requirement for the beam intensity is estimated to be $1.2 \cdot 10^9$ pps assuming the beam-utilization efficiency of 40%, under the field diameter of 150 mm, the SOBP size of 150mm and the dose rate of 2 Gy/min.

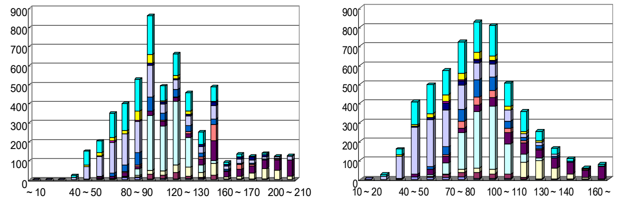

Fig. 2: Histogram of the treatment number on field diameter in mm (Left) and that on SOBP in mm (Right).

Downsizing the accelerator and beam delivery systems can naturally reduce the construction cost. 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. Further, the injector-linac cascade should also be downsized.

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 layout of the proposed facility is shown in Fig. 3.

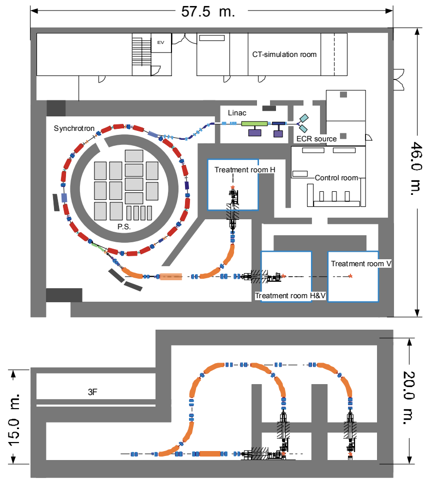

Fig. 3: Layout of the proposed facility.

Beam Delivery System [8]

According to the design considerations, the beam delivery system should realize a residual range of 250 mm with the carbon 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 is moving on a spiral orbit by the amplitude modulation of the wobbler currents. This method can produce the uniform field even under the small beam size compared with that in the conventional wobbler one, because of using a relatively thin scatter. 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. By simulation, it is verified from Fig. 5 that the dose distribution is to be uniform after one-second irradiation.

As is shown in Fig 5, the irradiation port consists of beam monitors, spiral-wobbler magnets, a scatterer, ridge filter, range filter and collimator. The ridge filter is designed to change the SOBP size from 40 to 150 mm. The range shifter is installed to adjust preciously the residual range in a patient. The multi-leaf and bolus collimators define preciously the lateral irradiation field and the distal one, respectively. A secondary emission monitor as a main dose monitor is placed upstream of the wobble magnets 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.

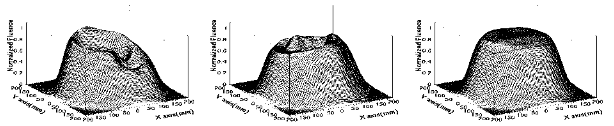

Fig. 4: Simulation result of dose distribution at isocenter by spiral wobbler. After an irradiation is started, 0.1s (Left), 0.2 s (Middle) and 1.0 s (Right).

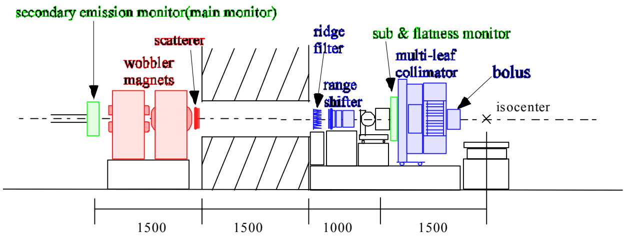

Fig. 5: Layout of the beam delivery system.

Ion Source [9]

A compact 10GHz-ECR ion source, which utilizes permanent magnets for generating both of the 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 from 9 to 18 GHz, which can compensate a deviation from the magnetic field designed. As a result of the improvement, an output current of C^{4+} ion was obtained at 300 eμA under a microwave power of 300 W and the extraction voltage of 25 keV. It was also verified that the intensity fluctuation was kept by less than 6% during 20 hrs operation.

Injector linac cascade [10]

The injector system comprises RFQ and Interdigital H-mode (IH) linacs. The layout of the linac cascade is shown in Fig. 6. The injection energy is 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 beam from the RFQ is accelerated up to 4 MeV/n with the IH linac. Finally, C^{4+} ions are fully stripped by a thin foil.

For the RFQ linac, the conventional four-vane structure will be used. Using the operation frequency of 200 MHz, a length and diameter of the cavity are approximately 2 m and 0.3 m, respectively. For the transverse focusing of the beam, the Alternating-Phase-Focusing (APF) method will be employed in the IH linac. Since both transverse and longitudinal focusing are 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 present design, the length and diameter of the cavity will be approximately 3 m and 0.3 m, respectively.

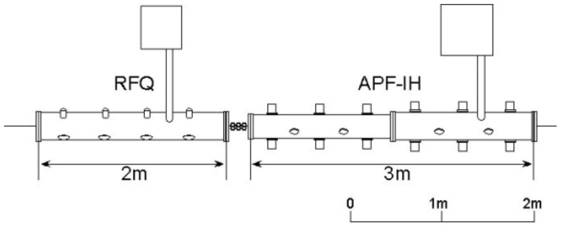

Fig. 6: Layout of the RFQ and APF-IH linacs.

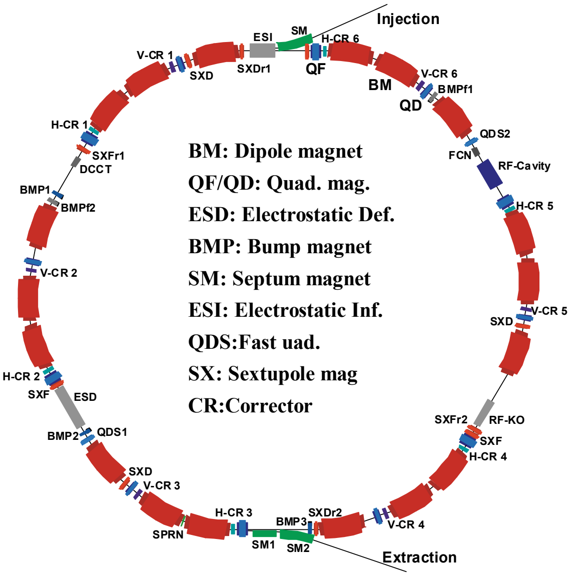

Fig. 7: Layout of the synchrotron ring.

Synchrotron [11]

The synchrotron is designed to accelerate C^{6+} beam from 4 to 400 MeV/n. The betatron-phase advance in one cell is designed to be around 90 degree for the injection and extraction systems. The cell number is to be 6 by considering the third-order slow-extraction with the horizontal tune of 5/3. The extraction method should employ the RF-KO extraction [12] for the irradiation gated with respiration. The ring structure is shown in Fig. 6. This lattice is a FODO missing magnet design, while each cell contains three dipole magnets having rectangular shape and two quadrupole magnets (QF/QD). The ring circumference is 61.5 m, and the dipole-magnet filling factor of 43 % is achieved. (Qx/Qy) = (1.70/1.13) 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 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, the multiturn-injection gain of 20 and the repetition frequency of 0.5 Hz, a delivered intensity is estimated to be $2 \cdot 10^9$ pps.

SUMMARY

During ten-years of clinical trials with HIMAC, both the beam delivery method and the accelerator technology have been significantly improved. It has brought the 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 carbon-beam facility for cancer therapy. An R&D for the proposed facility started from this April.

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