MULTIPLE-ENERGY OPERATION WITH QUASI-DC EXTENSION OF FLATTOPS AT HIMAC

Y. Iwata*, T. Furukawa, K. Mizushima, K. Noda, T. Shirai, E. Takeshita and E. Takada,
National Institute of Radiological Sciences (NIRS), 4-9-1 Anagawa, Inage, Chiba 263-8555, Japan.
T. Fujimoto, T. Kadowaki, Y. Sano and H. Uchiyama,
Accelerator Engineering Corporation (AEC), 3-8-5 Konakadai, Inage, Chiba 263-0043, Japan.

Abstract

Multiple-energy operation with quasi-DC extension of flattops is developed at the HIMAC. This operation uses synchrotron operation-patterns having a stepwise flattop. With these patterns, the beam would be first accelerated to the maximum energy, and then successively decelerated to the lower energies. Having extended the flattops and extracted the beam during these flattops, heavy ions having various energies can be provided within a single synchrotron cycle. Since the extraction energy can be quickly changed by the accelerator itself, no energy degrader will be required to control a depth dose-distribution. Having applied this multiple-energy operation to our fast raster-scanning irradiation, we can considerably reduce the total irradiation time and obtain an excellent depth dose-distribution. The beam acceleration and extraction tests using this operation were made. Successful results of the tests proved the effectiveness of this multiple-energy operation.

INTRODUCTION

A heavy-ion cancer therapy using Heavy-Ion Medical Accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences (NIRS) has been carried out since June 1994[1]. The successful results of the therapy led us to construct a new treatment facility[2]. The new treatment facility equips with three treatment rooms; two of them have both horizontal and vertical fixed-irradiation-ports, and the other is a rotating gantry port. For all the ports, the three-dimensional raster-scanning irradiation method with pencil beam will be employed[3].

In the present irradiation system at the HIMAC, a range shifter, consisted of PMMA plates having various thicknesses, is used to degrade the beam energy and to control the depth dose-distribution. Since focused pencil beams will be used in the raster-scanning irradiation, this range shifter may broaden the spot size of the beam on the target, and also produce secondary fragments, which would adversely affect the depth dose-distribution. Therefore, it is preferable to change the beam energy directly by the accelerators, instead of using the range shifter.

To change the beam energy, as extracted from the synchrotron ring, we propose the multiple-energy operation with quasi-DC extension of flattops. The proposed operation enables us to provide heavy ions having variable energies within a single synchrotron-cycle; namely, the beam energy would be successively changed more than hundred times within a single synchrotron-pulse by an energy step, corresponding to a water range of 2 mm. With this operation, the beam range would be controlled without using energy degraders, such as the range shifter, and hence an excellent depth dose-distribution could be obtained. In this paper, a method of the multiple-energy operation as well as the results of beam acceleration and extraction tests is presented.

MULTIPLE-ENERGY OPERATION

In the present operation of the synchrotrons, one cycle of a beam injection, acceleration and extraction is made every 3.3 s. Within the cycle, the beam would be extracted at the certain energy during approximately 2 s on the flattop of a synchrotron pattern. While, the proposed multiple-energy operation uses operation patterns of the synchrotron having a stepwise flattop as schematically shown in Figure 1. The pattern in the figure represents a current pattern for the main bending or quadrupole magnets in the synchrotron ring. The difference of the currents between the neighbouring short flattops is designed to provide the difference in a range of 2 mm in water. As the treatment starts, the stepwise pattern would be latched at the certain flattop of the corresponding energy, as requested by the irradiation control-system, and the quasi-DC extension of flattops initiates as illustrated on the bottom of Figure 1.

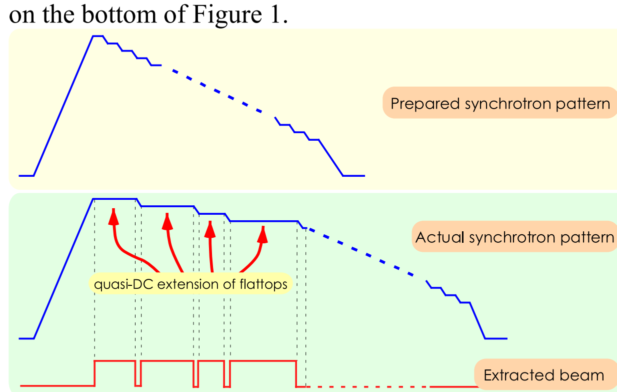

Figure 1: A schematic drawing of an operation pattern for the synchrotron ring. The operation pattern has a stepwise flattop; each flattop can be extended, and the beam could be extracted from the synchrotron ring during any of these flattops.

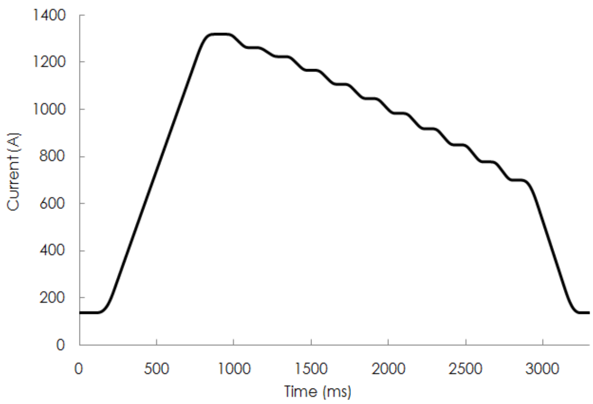

Figure 2: A current pattern for the main-bending magnets in the ring as a function of time. The currents of the 11 flattops correspond to the beam energies of 430, 400, 380, 350, 320, 290, 260, 230, 200, 170, and 140 MeV/u.

Once the required dose is given to the corresponding depth of the target, the beam is then turned off, using the RF-KO extraction method[4], and decelerated to the next requested energy. By using the multiple-energy operation with quasi-DC extension of flattops, the beam energy can be continuously varied directly by the accelerators, and hence no energy degrader is required.

Since the synchrotron ring of the HIMAC can accelerate a few $\times 10^{10}$ of carbon ions within one synchrotron cycle, and numbers of carbon ions as required to treat a typical size of tumours are an order of 10^9 particles, most of the treatments can be completed within a single synchrotron cycle, provided that most of the accelerated particles are actually utilized in treatment dose. Consequently, having applied the multiple-energy operation to the fast raster-scanning irradiation, the total irradiation time is considerably decreased down to a few seconds.

BEAM ACCELERATION TESTS

To prove a principle of the multiple-energy operation, we have performed beam acceleration and extraction tests using stepwise operation patterns. A current pattern for the main-bending magnets in the ring, as used in the tests, is shown in Figure 2. This pattern has 11 short flattops, corresponding to the beam energies of 430, 400, 380, 350, 320, 290, 260, 230, 200, 170 and 140 MeV/u. The similar patterns were prepared for the other devices, such as the main quadrupole and sextupole magnets as well as the acceleration RF cavity and the extraction channel. By using these operation patterns, the beam will be first accelerated to 430 MeV/u, and then decelerated successively down to 140 MeV/u by an energy step of 20 MeV/u or 30 MeV/u. Having extended the flattops and extracted the beams, as requested by the irradiation control-system, heavy ion beams having the 11 energies can be provided to the treatment rooms within the single synchrotron cycle.

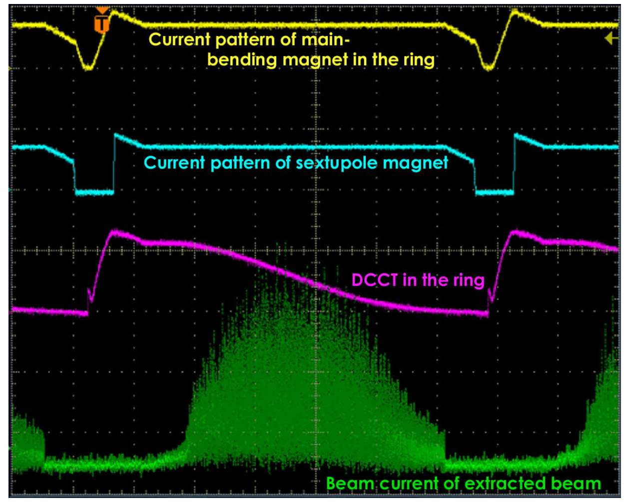

Figure 3: Current patterns for the main-bending magnets (yellow), the sextupole magnets(blue), DCCT in the ring (pink), and the measured beam current of the extracted beam (green). The 6th flattop, corresponding to the beam energy of 290 MeV/u, was extended, and the beam was extracted during that flattop.

A result of the beam acceleration and extraction tests is shown in Figure 3. The yellow and blue lines in the figure show current patterns of the main bending and sextupole magnets in the synchrotron ring, respectively. The pink line is the current of the circulating beam in the synchrotron ring, as measured with the DCCT. The green line shows the measured current of the extracted beam with the monitor, located at the extraction channel. In this test, the 6th flattop, corresponding to the beam energy of 290 MeV/u, was extended, and the beam was extracted during that extended flattop using the RF-KO extraction method. No appreciable beam loss during the acceleration to the first flattop and further deceleration between the short flattops was seen in the test. The beam extraction efficiency, as determined by a ratio of the measured beam currents of the circulating beam in the ring and the extracted beam, was measured to be as high as more than 90%. The similar beam-extraction tests for the other flattops were made, and also provided the good extraction efficiencies of more than 90%.

FUTURE PLAN

The final goal of this project is to control the depth dose-distribution by varying the beam energy from the accelerators. To accomplish this, it is required to change the beam energy successively by an energy step corresponding to the water range of 2 mm. Since the maximum and minimum energies, as used in the raster-scanning irradiation, are 430 and 80 MeV/u, respectively, and the corresponding water ranges for these energies are 309 and 17.1 mm, the synchrotron patterns having the 146 flattops will be needed to cover the entire energy range. Figure 4 shows an example of the 146 flattop pattern.

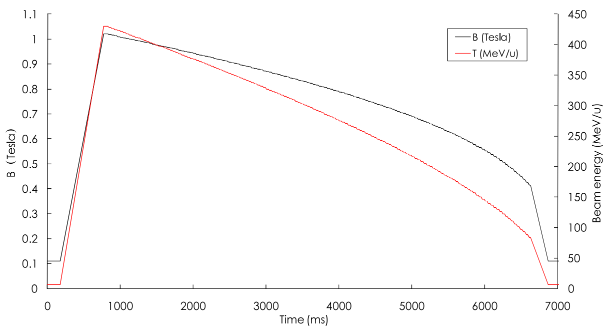

Figure 4: A magnetic-field pattern of the main-bending magnets for the ring and corresponding beam energy as functions of time for the 146 flattop pattern.

The black and red lines in the figure show the magnetic-field pattern of the main-bending magnets and the corresponding beam energies as functions of time, respectively. The beam energies at the first and last flattops are 430 and 80 MeV/u, respectively, and the difference in the beam energies between the neighbouring short flattops corresponds to the water range of 2 mm. The time lengths of the each decelerating and flattop sections are both 20 ms. Any of the 146 flattops can be extended, and the beam can be extracted during the extended flattop. Hence, with this operation pattern having the 146 flattops - *the universal pattern*, the depth dose-distribution could be controlled without using any energy degrader.

Since the present control-system of the accelerators may not be able to handle the operation patterns having a pattern length of more than 3.3 seconds, the universal pattern could not be yet tested. However, to confirm the feasibility of the multiple-energy operation with the universal pattern, we prepared operation patterns having the first 46 flattops out of 146, as presented in Figure 5, and performed beam acceleration and extraction tests with the patterns. Results are shown in Figure 6. In the test, the 29th flattop was extended, and the beam having the energy of 379.5 MeV/u was extracted.

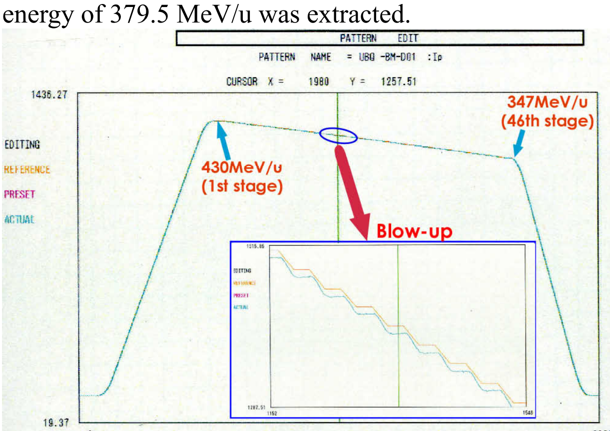

Figure 5: A current pattern of the main-bending magnets in the ring. The currents of the flattops for the 46 stages correspond to the energies between 430 and 347 MeV/u.

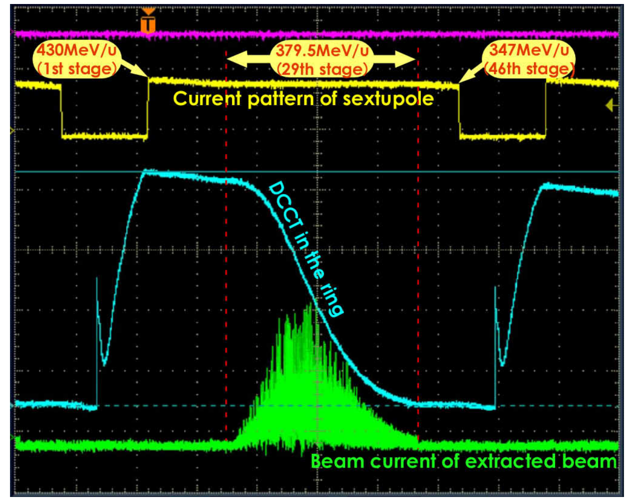

Figure 6: A current pattern for the sextupole magnets (yellow), the DCCT in the ring (blue), and the measured beam current of the extracted beam (green). The beam energy of the extracted beam is 379.5 MeV/u.

As was found in the tests for the 11 flattop pattern, no beam loss during the acceleration and deceleration as well as the good extraction efficiency was found in the tests with the 46 flattop pattern. This result indicates the feasibility of the multiple-energy operation with the universal pattern.

SUMMARY

We have developed the multiple-energy operation with quasi-DC extension of flattops. With this operation, the beam energy can be successively varied within a single synchrotron-cycle, and therefore no energy degrader is required. Having applied this operation to our fast raster-scanning irradiation, we can considerably reduce the total irradiation time and obtain an excellent depth dose-distribution. The successful results of the beam acceleration and extraction tests proved the effectiveness of this accelerator operation.

ACKNOWLEDGEMENTS

We thank members of the Accelerator Engineering Corporation (AEC) for technical assistance, and members of Hitachi Zosen Corporation and Future Development Corporation for their helps in developing of the accelerator control system.

REFERENCES

* Corresponding author. E-mail: y_iwata@nirs.go.jp

[1] Y. Hirao *et al.*, Ann. Rep. HIMAC, NIRS-M-89/HIMAC-001 (1992).
[2] K. Noda *et al.*, TUOCRA01 in these proceedings.
[3] T. Furukawa *et al.*, Med. Phys. 34 (3) (2007) 1085; T. Furukawa *et al.*, MOPEA007 in these proceedings.
[4] K. Noda *et al.*, Nucl. Instrum. and Meth. in Phys. Res. B **374**, 269 (1996).