A BEAM INTENSITY CONTROL METHOD FOR ION THERAPY

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Abstract

A beam-intensity control method has been developed at HIMAC in order to improve an irradiation accuracy and beam-utilisation efficiency for a multi-wobbling and a spot scanning method, and it is also required for a counter experiment such as a particle identify in a secondary-beam experiment. For the advanced irradiation methods, a beam intensity should be modulated around two-order during an extraction period, while the beam intensity should be decreased from 10^9 to the order of 10^5-10^3 ppp for the counter experiment. In order to cover such a wide range of the beam intensity, we have proposed the beam-intensity control method, which is based on changing a beam-pulse width and timing in an injection beam, and/or applying RF-KO in an injection period. The methods and experimental results are presented.

1 INTRODUCTION

At National Institute of Radiological Sciences (NIRS), the HIMAC accelerator complex has been operating since June 1994 to supply heavy-ion beams for cancer therapy and other experiments [1]. In order to improve irradiation accuracy and beam-utilisation efficiency for the cancer therapy, a multi-wobbling and a spot scanning method has been developed. In each method, a beam-intensity should be modulated around two-order during an extraction period in one operation cycle of the synchrotron, in order to obtain a uniform dose distribution in the lateral direction. For a secondary-beam experiment with ^{11}C or ^{10}C beam, the primary-beam intensity should be decreased by the order of 10^4 for the particle identification. In counter experiment, the beam-intensity should be decreased from 10^9 to the order of 10^3 ppp. Thus, a beam-intensity control method, which covers over the intensity range of 10^6, has been developed as an indispensable technique for our facility.

The HIMAC accelerator has two kinds of the "destructive" beam-intensity attenuation-devices, which are called "attenuators" and "scrapers", are very convenient tools to reduce a beam-intensity to the order of 1/10. Since they reduce the beam intensity by inserting them mechanically to the beam path, it is difficult to control the beam-intensity under a pulse-to-pulse operation. Therefore, we have proposed new beam-intensity control method (chopper method) by using a beam chopper that can control a time width of an injection beam [2]. The beam chopper, which is installed between the ion-sources and the RFQ linac, can adjust the beam-pulse width from 1 ms to 1 μs and can change injection timing. Consequently, the chopper method can control the beam-intensity in the ring by changing the multi-turn injection time. This method changes a size and a shape of the horizontal emittance, however, because an occupied area in the horizontal phase space is changed according to the beam-pulse width and the injection timing. As a result, a time structure of the extracted beam is also changed in using the RF-KO slow extraction method [3]. In case of a chopped beam, to obtain the similar spill structure as that in usual multi-turn injection, therefore, applying a transverse RF-field generated with a white noise to the beam just after the multi-turn injection is also planned. The reasons are as follows: (1) The RF-field can diffuse the particles in the phase space and broaden the particle distribution so as to occupy over the whole acceptance. Consequently, we will obtain the similar spill structure as that in usual multi-turn injection. (2) The RF-field can also adjust the beam intensity. We present experimental results.

2 EXPERIMENTS

One of our goals is to obtain a semi-empirical formula of an attenuation-ratio, which can be useful for a daily operation in the chopper method. Since the attenuation-ratio is obtained directly by measuring the relation between an extracted-beam intensity and a beam-pulse width. The intensity can be expressed principally through the product of a beam-injection intensity obtained from a multi-turn injection analysis, a beam-acceleration efficiency, and a beam-extraction efficiency. These data are obtained both experimentally and analytically, and make a comparison between them. The correlation between a start time of an extracted spill structure and a beam distribution in a phase space was also measured.

2.1 Experimental conditions

A fully stripped carbon beam was used in this experiment. The acceleration energy is 400 MeV/n. A typical pulse width of the injection beam is 350 μs, as same as the collapsed time of an injection bump orbit. Peak intensity of an injection beam is around 650 eμA, and their stability is ±3 % at 1σ with 10 times measurement. A revolution period of the injection beam is about 4 μs, so it takes 88 turns to complete a multi-turn injection. An operating period of the ring is 3.3 second and the accelerated beam can be extracted during 2 second. The RF-KO slow-extraction method has been used for a beam extraction. The circulating-beam intensity in the ring is measured with a DCCT, which can measure the intensity of more than 10^6 ppp. The extracted-beam spill structure (spill ripple) is measured by a ripple monitor comprised a plastic scintillation counter. The ionisation chamber is installed in the end of the extracted beam transport line. It can measure the intensity over 10^9-10^3 ppp with the accuracy of less than a few percent.

2.2 Beam injection property

A partial efficiency of the injection beam was measured by the similar manner in the ref. [4]. A "partial" beam is a beam whose emittance is occupied partly in a phase space diagram. In order to obtain the partial efficiency, a pulse width of the injection beam was set to be 20 μs by the beam chopper. It corresponds to a time of 5 turns in the ring. The efficiency was measured after the injection and in the flat top, as a function of the injection timing with the interval of 20 μs. The results are shown in Fig. 1. Particles in the pulse width of 320 μs can be survived around the ring after the multi-turn injection, although the pulse width of the injection beam is 350 μs. From among them, particles in the pulse width of 260 μs can be survived even after acceleration to a flat top. The survival intensity is obtained as a function of the injection pulse width, through integrating the beam-intensity injected into the partial acceptance. The result is shown in Fig.2. The partial efficiency is defined as the number of the survival particles normalised by a number of particles in single turn injection. The horizontal axis of abscissa shows the injection pulse width and the vertical axis of ordinate shows the partial efficiency. The solid line is obtained by fitting the normalised survival intensity based on a simple model through a multi-turn injection analysis [5]. The two data agree till the partial emittance was limited by the acceptance of the ring.

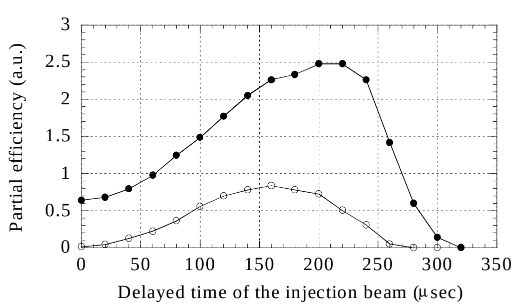

Figure 1: The partial efficiency measured by the chopped beam of 20 μs. the closed circles show the efficiency just after the injection and the open circles show the partial survival ratio on the flat top.

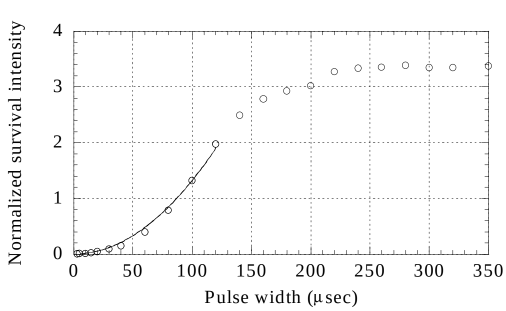

Figure 2: The normalised survival intensity as a function of the injection pulse width obtained through integrating the partial efficiency. The solid line is the fitting result obtained from the multi-turn injection analysis.

2.3 Extracted-beam intensity by the chopper method

Extraction efficiencies were measured under the various widths of the chopped beams. A timing of the injection beam is set on the top of the bump field. The RF-KO parameters for the beam extraction are fixed during the experiment. The result is shown in Fig. 3. Extraction efficiencies are almost constant in the pulse width of more than 20 μs. On the other hand, they are reduced in the pulse width of less than 20 μs. This is because a part of the circulating beam remains in the ring after the extraction process, although the efficiencies can be easily improved by adjusting the RF-KO parameters.

We measured the extracted intensity by the same way as the extraction-efficiency measurement. The obtained intensities under the various width of the injection beam pulse are normalised to a maximum one, as shown in Fig.4; we call the data attenuation-ratio. Two kinds of data, the open and the closed circles in the figure, were measured in the different machine-time to check the reproducibility of the system. The result multiplied the fitting function in the Fig.1 by the extraction efficiency is indicated by the solid line in the Fig.3. The expected function is in good agreement with the measurement data. Thus we can control the beam-intensity over the order of 10^4 only by adjusting the beam-pulse width. Considering the difference between the two kinds of the data, it seems that the reproducibility is enough high for the daily operation.

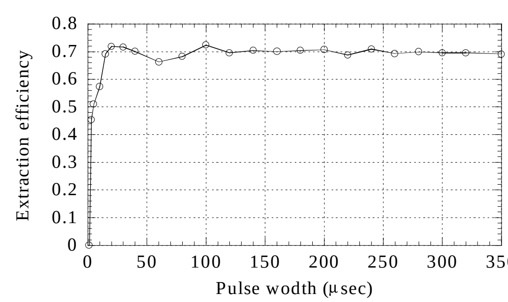

Figure 3: Extraction efficiency measured under the various widths of the chopped pulses. The efficiency at the shorter region changes by the RF-KO conditions.

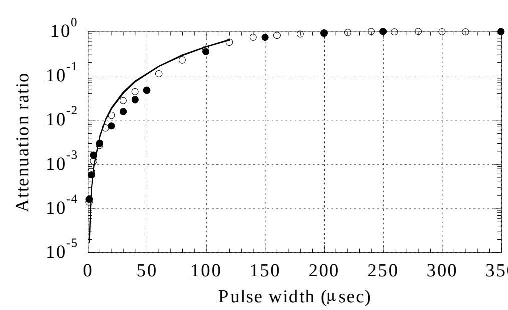

Figure 4: The extracted-beam intensity with a chopped beam, normalised by the maximum intensity. The open and the closed circles show the measured data obtained the different day. The solid line shows the expected one obtained from the multi-turn injection analysis and the extraction efficiency.

2.4 Extracted beam spill

We investigated the change of the spill structure under various injection timings. Figure 5 shows the head of the extracted beam under a pulse width of 10 μs. Figure 5(a) shows the beam spill, when the beam was injected on the top of the bump field. Figure 5(b) shows the beam spill, when the timing of the injection beam was delayed by 250 μs compared with the Fig. 5(a). The delayed time in the Fig. 5(a) and that in Fig. 5(b) are 40 ms and 8 ms, respectively. The difference of these delayed times is due to the change of beam distribution in the horizontal phase space. To minimise that delayed time of the partial beam, a hollow shape of the transverse emittance should be chosen rather than a centred one. Furthermore, a spill length of the partial beam with a hollow shape is the same as that of a beam with a full emittance.

(a) (b)

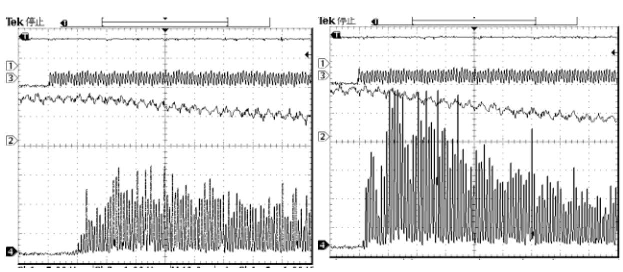

Figure 5: The spill structure of the extracted beam. The left figure, Fig. 5(a), shows the case of the beam injection on the top of the bump field. The right one, Fig. 5(b), shows the beam injected at the bottom of the bump field. In both cases, the pulse width of the chopped beam is 10 μs. A horizontal scale is 40 msec/div.

2.5 Applying RF-field after the multi-turn injection

Particle diffusion through the RF-KO is very convenient to make a uniform transverse phase-space distribution. Thus we applied the transverse RF-field generated with a white noise to the beam during 100 ms just after the multi-turn injection. This period includes a time from the beam injection to the acceleration beginning. Figure 6 shows the head of the extracted beam spill with and without RF-field after the multi-turn injection. Since the RF-field diffuse the particles in the phase space and broaden the emittance, we can obtain the similar spill structure the same as that with a hollow shape of the emittance. In compared with Fig. 5(b) and Fig. 6(b), the two figures have the same starting time of the spill.

3 SUMMARY

The extracted-beam intensity can be decreased by the order of 10^4 by a chopper method. It means that, the extracted beam intensity can be controlled from 10^9 to 10^5 pps. We find the attenuation-ratio can be estimated by using the simple multi-turn analysis. The starting time of the spill strongly depends on the beam distribution in the transverse phase space. In the partial beam injection, the hollow distribution in the phase space is more efficient than the central one to keep the start time as same as that

(a) (b)

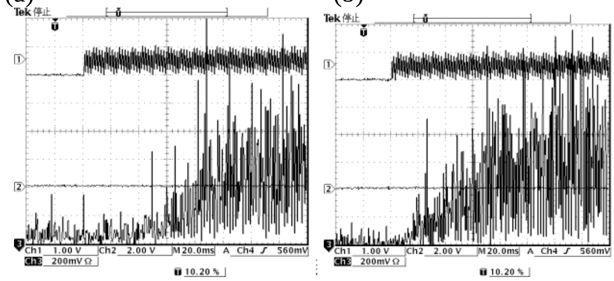

Figure 6: The spill structure of the extracted beam. The left figure, Fig. 6(a), shows the case without applying the RF-field. The right one, Fig. 6(b), shows the case with applying RF-field just after the injection. In both cases, the pulse width of the chopped injection beam is 30 μs. A horizontal scale is 20 msec/div.

of the injection beam with a full emittance. Applying the RF-field just after the multi-turn injection, we can obtain the similar effect as the chopper method. We will go on with study to find a correlation between the injection beam property and the extracted beam spill.

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