Nuclear Instruments and Methods in Physics Research B xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Emittance matching of a slow extracted beam for a rotating gantry

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ARTICLE INFO

Article history:
Received 4 August 2016
Received in revised form 18 January 2017
Accepted 7 March 2017
Available online xxxx

Keywords:
Emittance matching
Slow extracted beam
Rotating gantry

ABSTRACT

The introduction of a heavy-ion rotating gantry is in progress at the Heavy Ion Medical Accelerator in Chiba (HIMAC) for realizing high-precision cancer therapy using heavy ions. A scanning irradiation method will be applied to this gantry course with 48–430 MeV/u beam energy. In the rotating gantry, the horizontal and vertical beam parameters are coupled by its rotation. To maintain a circular spot shape at the isocenter irrespective of the gantry angle, achieving symmetric phase space distribution of the horizontal and vertical beam at the entrance of the rotating gantry is necessary. Therefore, compensating the horizontal and vertical emittance is necessary. We consider using a thin scatterer method to compensate the emittance. After considering the optical design for emittance matching, the scatterer device is located in the high-energy beam transport line. In the beam commissioning, we confirm that the symmetrical spot shape is obtained at the isocenter without depending on the gantry angle.

1. Introduction

Particle therapy with carbon ion was first conducted in 1994 at the Heavy-ion Medical Accelerator in Chiba (HIMAC) via the broad-beam irradiation method; more than 10,000 patients have been treated since then [1]. Afterward, the 3D scanning irradiation system, which achieves more accurate irradiation, was applied to tumors having more complicated shapes, also allowing for a reduction of the extra dose to the normal tissue. Treatment with this system started in 2011 [2]. Recently, the rotating gantry was introduced, which enables irradiation from various directions to a patient [3]. The rotating gantry comprises ten superconducting dipole magnets, eight of which are combined with a quadrupole coil [4]. A scanning irradiation method will be applied to this gantry course with beam energy from 48 MeV/u to 430 MeV/u.

In the rotating gantry, a quadrupole magnet behaves as a skew quadrupole magnet by its rotation. Therefore, beam parameters, such as emittance and Twiss parameters, are horizontally and vertically coupled and the beam spots at the isocenter have a tilt. To obtain a circular and symmetrical spot shape at the isocenter for any gantry angles, matching the horizontal beam parameters with the vertical ones at the entrance of the rotating gantry is necessary. However, in general, the horizontal and vertical slow extracted beams from the synchrotron show different emittances. The emittance at HIMAC is $\varepsilon_x < \varepsilon_y$. Moreover, the horizontal beam profile of the slow extracted beam does not show a Gaussian distribution because the slow extracted beam is shaved off by the electric septum electrode (ESD). To realize a symmetrical spot shape at the isocenter, improving this unsymmetrical distribution is also essential. To improve these matters, we adopt the scatterer method [5]. There are other methods to obtain a symmetrical beam spot without depending on the gantry angles [6,7], which is necessary to change an optical design for each gantry angles. On the other hand, the scatterer method can use the same optical design for every gantry angles, although one of the matching points is added at the scatterer position. By using the scatterer method, a spot adjustment at isocenter is needed only for a few gantry angles and it is expected to reduce the commissioning time. In this paper, we describe the optical design that allows emittance matching, verify the emittance matching by calculating the particle tracking, and present the result of the beam commissioning using the rotating gantry.

2. Principles

2.1. Emittance matching

The proposed emittance matching method utilizes the multiple scattering, which occurs at the high-energy ions passage through the scatterer. Assuming that the scatterer is very thin, the beam size immediately in front of and behind the scatterer does not vary;

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http://dx.doi.org/10.1016/j.nimb.2017.03.038
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Please cite this article in press as: T. Fujimoto et al., Emittance matching of a slow extracted beam for a rotating gantry, Nucl. Instr. Meth. B (2017), http://dx.doi.org/10.1016/j.nimb.2017.03.038

only scattering angle is added [8]. In this case, the relations between the Twiss parameters are expressed as that in Eq. (1).

$$\begin{aligned} \varepsilon_2\gamma_2 &= \varepsilon_1\gamma_1 + \theta_0^2 \\ \varepsilon_2\beta_2 &= \varepsilon_1\beta_1 \\ \varepsilon_2\alpha_2 &= \varepsilon_1\alpha_1 \end{aligned} \tag{1}$$

where the indices 1 and 2 show the location of the high-energy ions just in front of and behind the scatterer, respectively. θ_0 is the scattering angle added by the scatterer. Eq. (1) can be revised to Eq. (2) using the relation among the Twiss parameters as follows:

$$\varepsilon_{2x} = \varepsilon_{1x}\sqrt{1 + \frac{\beta_{1x}\theta_0^2}{\varepsilon_{1x}}}, \quad \varepsilon_{2y} = \varepsilon_{1y}\sqrt{1 + \frac{\beta_{1y}\theta_0^2}{\varepsilon_{1y}}} \tag{2}$$

Emittance matching is achieved when $\varepsilon_{2x} = \varepsilon_{2y}$. In the emittance-matching condition, by the scatterer method, emittance growth occurs due to the multiple scattering. To obtain a small spot size at the isocenter for scanning irradiation, suppressing the emittance growth as much as possible is important. Fig. 1 shows the beam emittance of the slow extracted beam at HIMAC. The relation between the horizontal and vertical emittances is $\varepsilon_x < \varepsilon_y$ for all extracted beam energies. Therefore, to suppress the emittance growth after passage through the scatterer, the following conditions have to be met in the optical design: (1) the vertical beta-function at the scatterer must be as small as possible and (2) the horizontal beta-function must be as large as possible to reduce the scattering angle.

2.2. Phase advance

The horizontal beam profile of the slow extracted beam from the synchrotron does not show a Gaussian distribution because the beam is extracted while being shaved off by the ESD. Therefore, an asymmetric distribution will appear when the phase advance from the ESD becomes $\mu_x = n \times \pi$, where n is an integer. On the contrary, the slow extracted beam fluctuates with a 50-Hz frequency, which is caused by the dipole magnet of the HIMAC synchrotron. To hide this influence at the isocenter, adjusting the phase advance from the ESD to isocenter with $\mu_x = n \times \pi$ is necessary. Therefore, improving the asymmetric distribution to realize a symmetric distribution at the isocenter is essential.

Fig. 2 shows the horizontal beam profiles with the phase advance of $\mu_x = n \times \pi$ from the ESD. The profiles show that beams pass through the scatter with a phase advance of $\mu_x = (n + 0.5) \times \pi$ and $\mu_x = n \times \pi$, respectively. In case of the $\mu_x = (n + 0.5) \times \pi$ beam, it is confirmed that the beam profile has a symmetric distribution. Therefore, we attempt to obtain not only $\varepsilon_{1x} = \varepsilon_{1y}$ but also the symmetric horizontal distribution using the scatterer method.

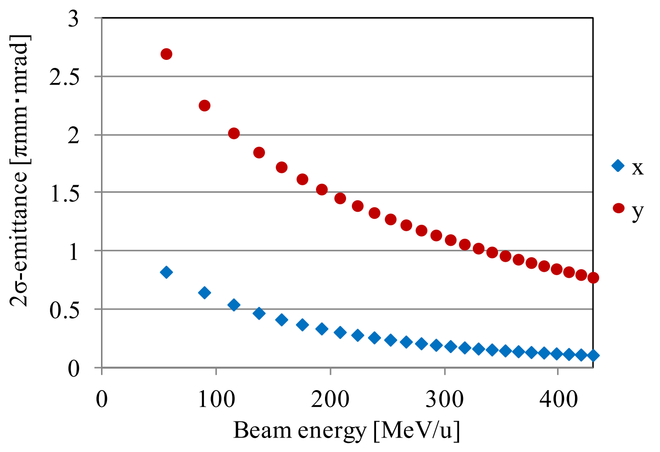

Fig. 1. Beam emittance of the slow extracted beam from the HIMAC synchrotron.

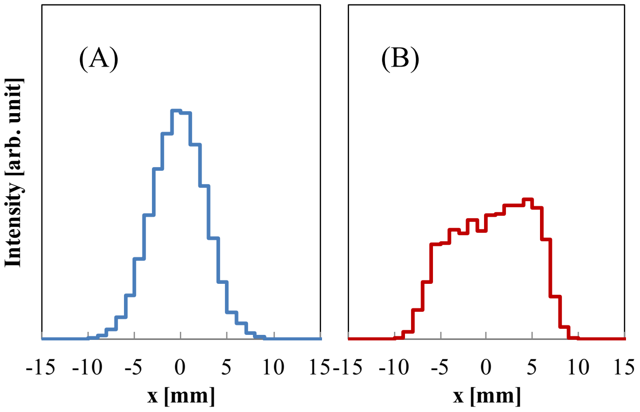

Fig. 2. Horizontal beam profile at the phase advance of n × π from ESD. (A) and (B) show the profiles after passage through the scatterer with $\mu_x = (n + 0.5) \times \pi$ and $\mu_x = n \times \pi$, respectively.

2.3. Emittance compensator

After considering the optimized optical design, which can realize emittance matching with the optimized phase advance, we designed and produced an emittance compensator and installed it in the high-energy beam transport line. The scatterer was as thin as possible to suppress the emittance growth, as lower beam energy produced a larger emittance growth. However, when the thickness of the scatterer was suitable for the lower beam energy, it became difficult to achieve emittance matching for a higher energy beam because a larger beta function at the scatterer was required for emittance matching. Accordingly, we adopted a tilting structure for the scatterer device to achieve matching reasonably well for the wide energy range of 48–430 MeV/u. Effective thickness of the scatterer (t) for the beam direction is written as $t = t_0/\cos\theta$, where t_0 is the scatterer thickness and θ is the tilt angle of the scatterer. To calculate the scattering, we selected Polyimide film (Kapton) with a 15-µm thickness as the scatterer material. The specifications of the matching device are shown in Table 1.

2.4. Tracking calculation

We calculate particle tracking to verify the emittance matching using the optimized beamline optics and scattering angle. Table 2 shows the conditions for the tracking calculation for 430 MeV/u.

Fig. 3 shows the phase space distribution just in front of and just behind the scatterer based on the calculated particle tracking. It was possible to confirm that the horizontal emittance accorded with the vertical one. The horizontal beam size became large when the emittance matched; however, it was acceptable enough for the aperture of the beam transport line.

Table 3 shows the beam parameters just in front of (a) and just behind (b) the scatterer for beam energies of 56 MeV/u and 430 MeV/u, based on the present calculation. The rotation angle

Table 1
Specifications of the matching device.

Beam energy	48–430 MeV/u
Scatterer material	Polyimide film (Kapton)
Scatterer thickness	15 µm
Tilt angle	0°–60°
Tilting speed	100 ms/energy step

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