STUDY OF SCATTERER METHOD TO COMPENSATE ASYMMETRIC DISTRIBUTION OF SLOWLY EXTRACTED BEAM AT HIMAC SYNCHROTRON

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Abstract

In ion beam cancer therapy, it is generally essential for a scanning-irradiation method and a rotating gantry system to deliver a circular beam profile with a Gaussian distribution. A slow beam extraction method utilized in a synchrotron ring, however, can not deliver a beam with a Gaussian distribution in the horizontal phase space, because of its extraction mechanism. Thus, we have proposed a thin scatterer method in order to compensate for the phase-space distribution of a slowly extracted beam, although the emittance is slightly enlarged by scattering. As a result of particle tracking, we verified that the proposed method could change an asymmetric distribution to a Gaussian one in the horizontal phase space and realize a symmetric beam condition for the rotating gantry.

INTRODUCTION

Heavy ion beams have attracted growing interest for cancer treatment due to their high dose localization and high biological effect at the Bragg peak. In the scanning irradiation [1,2], it is essential to deliver a beam with a Gaussian distribution for a 3D conformal irradiation field, because a non-Gaussian beam profile causes a difference between the prescribed dose distribution and the measured one. In a rotating gantry system, furthermore, the horizontal and vertical profiles of the beam at the iso-center should have no correlation between the rotation angles [3]. Two methods were developed to satisfy these requirements. The first is the symmetric beam method which gives the same phase-space ellipse in the horizontal and vertical phase spaces at the entrance of the gantry. The second is the rotator method [3] which requires that a part of the transfer line just before the gantry rotates by half of the rotation angle of the gantry.

The slowly extracted beam from a synchrotron ring [4,5], however, which has been utilized for ion beam cancer therapy, has a non-Gaussian horizontal profile, owing to its extraction mechanism [6]. Further, its vertical emittance is normally different from the horizontal one. Such characteristics of a slowly extracted beam do not satisfy the above requirements. It should be noted that the rotator method cannot compensate for the asymmetric distribution of a slowly extracted beam.

In order to compensate for such an asymmetric distribution in the phase space and the difference between the horizontal emittance and the vertical one, we have proposed a technique employing a thin scatterer (thin scatterer method), although the emittance is slightly enlarged by multiple scattering. As a result of particle tracking, the following items were verified: 1) The asymmetric distribution was compensated by the thin scatterer set at the position with the optimum phase-advance from the entrance of the extraction channel. 2) The proposed method could realize the symmetric beam condition at the entrance of the gantry. 3) The horizontal and vertical profiles at the iso-center had no correlation between the rotation angles of the gantry while keeping their Gaussian profile. We have preliminary carried out the experiment in order to verify the proposed method. This paper describes the technique and simulation results.

SCATTERER METHOD

Method

The proposed method has as its basis that it is possible to obtain a Gaussian beam profile by optimizing the scatterer thickness and that it is possible to control the beam size by optimizing the focusing parameters based on twiss-scatterer formula for the thin scatterer [7]. Concerning the application for the rotating gantry, further, we can adjust the twiss parameters just after the scatterer so as to obtain the same emittance in each plane, as expressed schematically in Fig. 1. Further, we can change the non-Gaussian beam profile to the Gaussian one by choosing the phase advance to the scatterer from the initial position. This will be discussed later using the HIMAC (Heavy Ion Medical Accelerator in Chiba) [8] parameters.

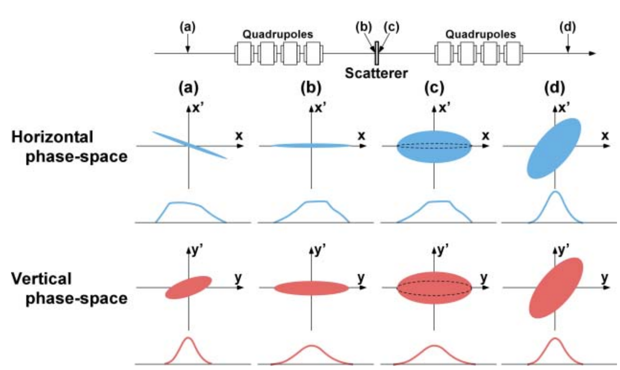

Fig. 1. Schematic of the method. Both the horizontal and vertical phase-space ellipses and profiles at (a) the extraction channel, (b) just before the scatterer, (c) just after the scatterer and (d) at the final beam position or the entrance of the rotation gantry.

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Simulation

A simulation was carried out in order to verify the feasibility of the proposed method. At first, particle tracking of the RF-knockout slow-extraction at the HIMAC was carried out in order to prepare the particle distribution at the entrance of the extraction channel as an initial condition of the transfer line. In this simulation, in order to obtain the phase-space distribution at an arbitrary position in the transfer line, each particle in the initial distribution was tracked by using the transfer matrices along the transfer line. The kick angle was calculated by using Molière's algebra under the assumption of the scattering angle with the Gaussian distribution, and a kick was added to each particle at the scatterer position. Figure 2 shows a typical calculated horizontal phase-space distribution of the particles just before and after scattering. As can be seen in Fig. 2, the asymmetric angle profile is changed to a Gaussian one by multiple scattering. After a horizontal phase-advance of $\pi/2+n\pi$ [rad] from the scatterer the Gaussian beam profile can be delivered.

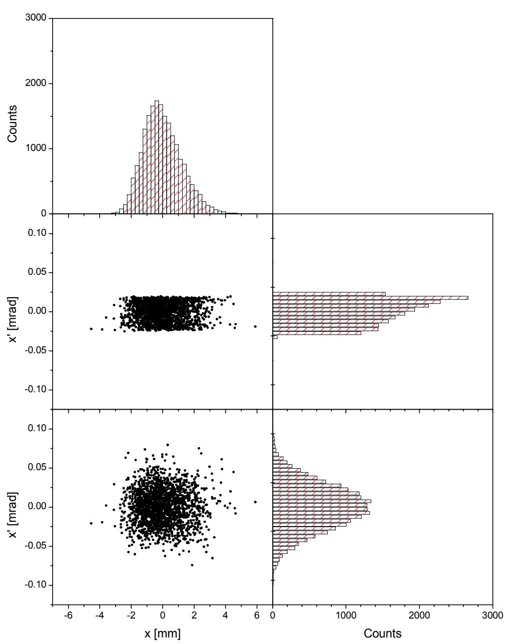

Fig. 2. Simulation result of the particle distribution in the phase space just before and after the scatterer with its position and angle projection.

In order to optimize the phase-advance from the extraction channel to the scatterer, a simulation was carried out for different phase-advances from the entrance of the extraction channel to the scatterer. Figure 3 shows the particle distribution in the normalized phase-space before and after passing through the scatterer with the worst and optimum phase advance. It seems from Fig. 3-(c) that the result has a symmetric 2-D Gaussian-like distribution after multiple scattering of 20 [μrad]. Further, the profile is a symmetric Gaussian-like distribution for each rotation angle. This suggests that it is possible to keep the Gaussian beam profile independently of the phase-advance from the scatterer to the final beam position.

(a)

(b)

(c)

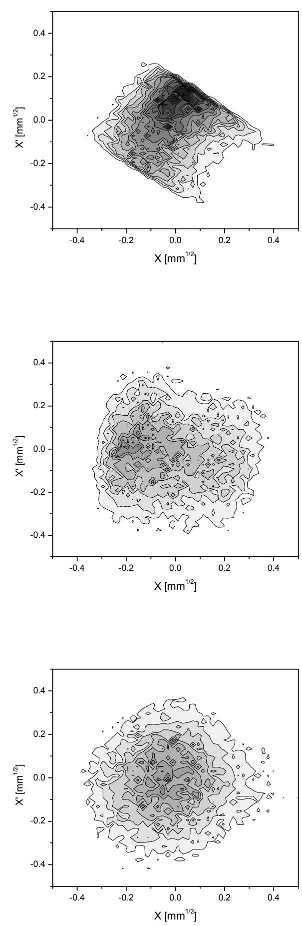

Fig. 3. Particle distribution in the normalized phase space: (a) before scattering, (b) after 20 [μrad] scattering with $\Delta\mu_x$=(n+0.05)·2π [rad], and (c) $\Delta\mu_x$=(n+0.35)·2π [rad].

Application to a rotating gantry

The rotating gantry system requires that the beam profiles at the iso-center have no correlation between the rotation angles. The symmetric beam method satisfies this requirement, under the condition that the beam has a Gaussian distribution in both the horizontal and vertical phase spaces. In order to realize the symmetric phase-space distribution at the entrance of the gantry, the simulation of the scatterer method was carried out. The beta functions at the scatterer and the scattering angle were optimized by considering the emittance growth and the energy loss by the scatterer. A scattering angle was set to be 0.4 [mrad] to obtain the same emittance in both plane from (ε_x, ε_y)=(0.015, 0.5) to (1.0, 1.0) [π mm mrad]. This scattering angle is typically given by aluminum foil of 200 [μm] thickness for a C^{6+} beam with an energy of 400 MeV/u. This scatterer also gives an energy-loss of $6\cdot10^{-4}$ in Δp/p. This value is not very large, but should be taken into account for the calculation. Since the symmetric beam condition was appropriately realized at the entrance of the rotating gantry, we achieve the beam profile at the iso-center that has no dependence on the rotating angle of the gantry while keeping its Gaussian profile. The calculated beam-size ratio at the iso-center for the different rotating angles is shown in Fig. 4. We clearly see that the beam sizes in both planes do not depend on the rotating angle of the gantry owing to the symmetric condition by applying the scattering technique.

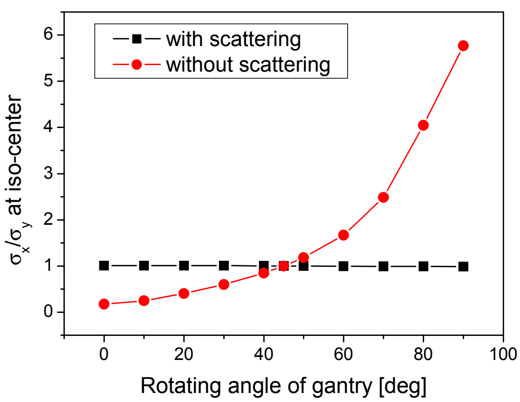

Fig. 4. Ratio of the calculated beam size at the iso-center for different rotating angles of the gantry.

EXPERIMENT

In order to verify this technique, the experiment was carried out at the HIMAC synchrotron and its transfer line. We employ the vacuum window (Al 0.7mm) of the beam profile monitor in the transfer line as a scatterer. It gives the 1σ scattering angle of 1.3 [mrad]. In this case, 1σ-emittance was increased from (ε_x, ε_y)=(0.015, 0.5) to (2.5, 2.5) [π mm mrad]. The parameters of focusing elements after the scatterer were set to match the twiss parameters after the scattering, which is calculated by using twiss-scatterer formula. The beam size at observation point was set to be σ_x=σ_y=4 [mm]. As shown in Fig. 5, it was verified that the simulated beam profile is in good agreement with the experimental one. This result support the simulation results described above.

SUMMARY

We proposed to employ a thin scatterer in the beam transfer line in order to compensate for the asymmetry of the phase-space distribution of a slowly extracted beam from a synchrotron ring. As a result of particle tracking, we verified that the asymmetric distribution was sufficiently compensated by a thin scatterer set at the position with the optimum phase-advance from the entrance of the extraction channel. In the case of HIMAC, a scattering angle of 20 [μrad] was sufficient to obtain a 2D Gaussian distribution in normalized phase-space. We also found from simulation that the proposed method could realize the symmetric beam condition for the rotating gantry. This technique allows us to deliver a beam with the predicted size and the Gaussian profile. Further, these results will contribute to the beam delivery system, such as for the rotating gantry system and the scanning irradiation system, with a slowly extracted beam.

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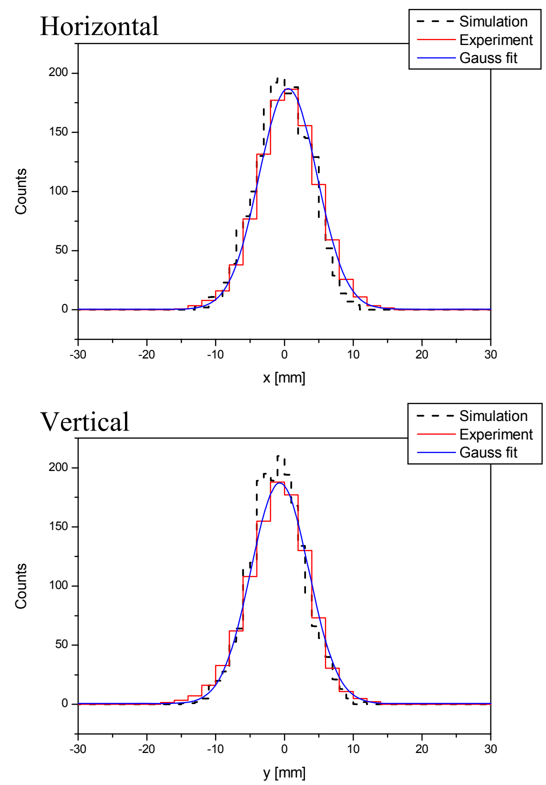

Fig.5. Comparison of the horizontal beam profile between the simulation and the experiment.

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