Transactions of the Korean Nuclear Society Autumn Meeting
PyeongChang, Korea, October 30-31, 2008

Design of Focusing Quadrupole Lens for Low Energy Carbon Ions

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1. Introduction

Usually, a combination of two or three magnetic (or electric, sometimes combined) quadrupole lenses is used for focusing ions in accelerators [1]. The focusing quadrupole lens consists of an assembly of four magnets, where the magnets together produce a good approximation of quadrupole fields where ions are passing through (see Fig. 1). By varying its strength of the magnetic fields, the traveling charged heavy ions could be kept within the system, where the magnets are set in an iron cylinder with coils flowing currents [2]. The focusing system is combined of three quadrupoles, where the middle one is twice longer then others, rotating by 90 degrees around the central axis. Therefore, magnetic field produced by second quadrupole lens has the reverse polarity compared with other two magnets, applied reverse forces to traveling ions. The focusing effects due to the length of middle lens are the one of the interesting subjects regarding to transport ions effectively. In this study, the ray tracing simulation is carried by varying the width of middle lens from 1 to 3 times longer.

Recently, carbon ions are used as specie for cancer treatments at the clinical trials due to its high local ionization density. Irradiation with carbon ions is preferentially growing by showing the expected fast regression of tumors at low physical doses corresponding to a significantly elevated relative biological effectiveness. Some experiments such as study of biological response to micro-size ion beam, which will be irradiated into single cell, is required to use micro beam of ions. To reduce the beam diameter we usually use a collimator with a tiny hole, which is caused beam losses and unstable in beam current. In more effective and complicate method, a quadrupole lens is investigated theoretically to make micro ion beam without physical collimator. A system of magnetic quadrupole lenses is theoretically simulated to focus ions on to a target. A model of three consecutive quadrupole lenses, where carbon ions with the velocity of 0.01c ($c=3.8\times10^8$m/s) along the z-direction sent through a system of three consecutive quadrupole assemblies has been simulated and results of the model calculations are presented.

2. Simulation Methods

Magnetic lenses are very convenient for the focusing of ions, particularly where space is limited. Such lenses are simple to build and to control and require low operating voltages and have less spherical aberration than do axisymmeric electrostatic lenses. In this work, a magnetic quadrupole triplet lens having the 7 cm pole gap and 10 cm pole width is constructed in order to focus low energy carbon ions. The width of the second one is varying from 10 cm to 30 cm, one to three times longer than others.

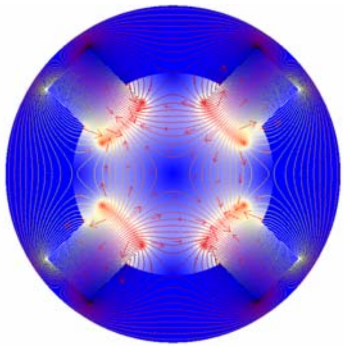

Fig. 1. The magnetic field density (M) inside of qudrupole lenses. The four magnets produce a good approximation of quadrupole fields along the central axis. The arrows indicate the direction of the field.

Each ion passing through the assembly (predefined magnetic fields) experiences Maxwell forces is equal to $F=qv \times B$, where v(m/s) is the velocity of the ion. To find the transverse position as a function of time, we are solving numerically Newton's second law for each ion, $qv \times B = ma$, where m is the ion mass(kg), and a its acceleration (m/s^2). The results of ray analysis of low energy carbon ions are presented in Fig. 2.

The focusing effect of the quadrupoles is demonstrated by tracking a number of ions starting evenly distributed along the circumstance of a circle with 3 cm diameter in the transverse plane, assumed to have a zero initial transverse velocity. Each quadrupole focuses the ions along one of the transverse axes and defocuses it along the other one. For instance, the ions are defocused along the y-direction while focused along the x-direction at the first quadrupole. Since the middle one is rotated by 90 degrees around the central axis so that the ions are forced into the central axis, focusing on x-direction along twice long distance. Finally the net effect after traveling through the three quadrupoles is focusing in all directions by showing ions contained within a 2 cm radius in the transverse plane (initially 3 cm radius). The final beam envelop could be adjusted more effectively in the case of three quadrupoles regulated separately.

3. Results and Discussion

From the Fig. 2, three quadrupoles are identical except the middle one is twice longer and rotated 90 degree along the central axis. The ray tracing are plotted as a function of the magnetization (MQ) applied on the magnets. Top row of the Fig. 2 is represented in x-z plane, middle row for y-z plane, and bottom indicated the x-y plane (along the ions' traveling direction). The arrows are indicated the direction of magnetization fields. The first and third ones are the same direction in magnetic field while the second one shows the reverse direction. As MQ increases, the ions are focused strongly in y-direction by the first and third quadrupoles, focal point is closer to the lenses. While the y-direction is strongly focused, x-direction of the ions are diverged, making the beam envelop larger. The ray tracing are represented as the strength of magnetization (MQ) increases, both x- and y-directions of ions are focused. Top row of the Fig. 2 is indicated clearly the focal point is moving toward the lenses as stronger magnetization applied in x-direction. Similarly, envelops of ions becomes narrower in y-direction as applied magnetic fields stronger. By adjusting the MQ, the shape of ions' envelop could be optimized to transport them effectively, even though it shows asymmetric distribution in x- and y-directions.

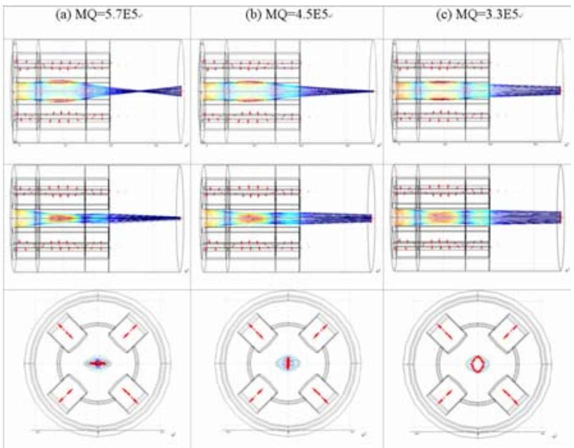

Fig. 2. Ions trajectories for twice longer at the middle one as a function of strength of magnetization (MQ). The second one is expanded twice longer then others, which will force the ions into the central axis. The ray tracing are represented as the strength of magnetization (MQ) increases, both x- and y-directions of ions are focused. By adjusting the MQ, the shape of ions' envelop could be optimized to transport them effectively.

Fig. 3 is summarized the above results, mentioning the diameters of ions in x- and y-directions with the strength of magnetization. The ratios width of three quadrupoles are simply represented by a:b:c, where a is represented the first quadrupole width, b is second, and c is for third one. A solid line is indicated as an initial ion distribution in this simulation. In the case of 1:2:1 (second lens is twice longer) configuration, the ion distribution size could be reduced in both directions, while the other configurations are very difficult to focus effectively. Even in 1:2:1 configuration, the focal points in x- and y-direction are not consistent with the magnetization, showing asymmetric distributions. Theoretically, there are still remained to investigate the rooms for the adjustment of focal power as changing its width of magnets in order to show a symmetric distribution.

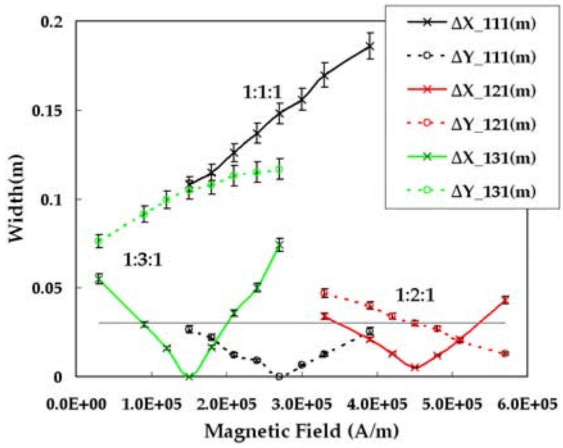

Fig. 3. The diameters of ions in x- and y-directions with the strength of magnetization. The ratios width of three quadrupoles are simply represented by a:b:c, where a is represented the first quadrupole width, b is second, and c is for third one. A solid line is indicated as an initial ion distribution in this simulation. In the case of 1:2:1 (second lens is twice longer) configuration, the ion distribution size could be reduced in both directions, while the other configurations are very difficult to focus effectively.

In conclusion, the configuration of the twice longer configuration at the middle one is the optimized design but there is still remained further investigation for the best focusing the ions on both directions. Also these configurations will be tested on the transporting for carbon ions with different charge states.

ACKNOWLEDGEMENTS

This work is supported by the promotion program of accelerator user supported by the Ministry of Science and Technology (MOST) of Korea.

REFERENCES

[1] L.R. Burns, J.D. Bouas, S. Matteson, D.L. Weathers, Evaluation of a novel design for an electrostatic quadrupole triplet ion beam lens, Nucl. Ins. Meth. in Phys. Res. B261, 75-78 (2007).
[2] Yong-Sub, Cho, Han-Sung Kim, and Hyeok-Jung Kwon, Compact magnetic quadrupole triplet for a low-energy high-current ion beam transport, Rev. of Scientific Inst. 79, 02B715 (2008)