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Simulation Study of a Focusing Quadrupole System for Low Energy Protons

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1. Introduction

As a part of the MC50 cyclotron [1] application supporting program, we at Korea Institute of RAdiological and Medical Sciences (KIRAMS) are developing beam transport systems, which will improve beam quality in order to satisfy user's requirements for the purpose of micro-scale experiments. Some experiments such as study of biological response to micro-size proton beam, which will be irradiated into single cell, is required to use micro beam of protons. 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 this study, a quadrupole lense is investigated theoretically to make micro proton beam without physical collimator. A system of magnetic quadrupole lenses is theoretically simulated to focus protons in a beam line to a target. A model of three consecutive quadrupole lenses, where protons are going through has been simulated and results of the model calculations are presented.

2. Methods and Results

In this section model definition and configuration of the focusing system used in this study are described. A brief mathematical description is also included.

2.1 Model Definition

Just like light (a kind of electromagnetic wave) focused by using optical lenses, beam of charged particles can be also focused by electric and magnetic lenses. Usually, a combination of two or three magnetic quadrupole lenses is used for focusing ions in accelerators [2]. The quadrupole consists of an assembly of four permanent magnets as shown in Fig. 1, where the magnets together produce a good approximation of quadrupole fields where ions are passing through. By varying its strength of the magnetic fields, the traveling charged particles could be kept within the system, where the magnets are set in an iron cylinder with coils flowing currents. The direction of currents is determined that of magnetic fields.

The focusing system employed in this study is combined of three quadrupoles, where the middle one is twice longer (2 m), rotating by 90 degrees around the central axis. The magnetic field produced by second quadrupole has the reverse polarity (reverse direction as indicated in Fig. 1) compared with other two magnets.

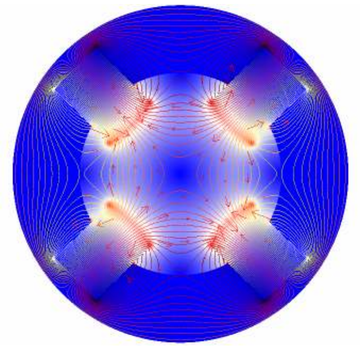


Fig. 1. The magnetic field density (M) inside of qudrupole lenses. The four magnets produce a good approximation of quadrupole fields along the central axis. The arrows indicate the direction of the field.

Protons with the velocity of 0.01c ($c=3.8\text{x}10^8$m/s) along the z-direction are sent through a system of three consecutive quadrupole assemblies. The focusing effect of the quadrupoles is demonstrated by tracking a number of protons 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 protons are defocused along the x-direction while focused along the y-direction at the first quadrupole. Since the middle one is is rotated by 90 degrees around the central axis so that the protons are forced into the central axis (focusing effect) along twice long distance. Finally the net effect after traveling through the system of the three quadrupoles is focusing in all directions as shown in Fig. 2, showing protons contained within a 1 cm radius in the transverse plane (initially 3 cm radius).

2.2 Mathematical Description

The magnetic field is described using the magnetosatics equation, solving for the z-component of the magnetic potential A(Wb/m) giving in eq.(1):

$$\nabla \times (\mu_o^{-1} \nabla \times A_z - M) - \sigma \vec{v} \times (\nabla \times A_z) = \sigma \nabla V / L \quad (1)$$

where $\mu_o = 4\pi \times 10^{-7} H/m$ denotes the permeability of vacuum, **M** is the magnetization (A/m), σ the conductivity (S/m), and **v** the velocity of the medium(m/s). The magnetic potential is everywhere defined from the equation $B = \nabla \times A$. For the boundary condition, the magnetic field is approximately parallel to the exterior boundary of the iron cylinder. To enforce this, use the magnetic insulation boundary condition, stating that Az=0. Each ion passing through the assembly experiences Maxwell forces 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).

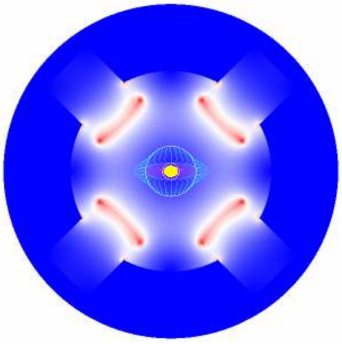


Fig. 2. Particle tracing trajectories of the focusing lenses. Two identical quadrupoles Q1 and Q3 have the same magnitude of field but point in the opposite direction as the corresponding in Q2. The fringe field is neglecting in this simulation.

2.3 Simulation Analysis

Fig. 3 shows the proton trajectories as they are passing through the focusing system. The position of protons at the end of the first quadrupole (a), at the end of second one (b), and after pass through the system(c), are indicated, respectively.

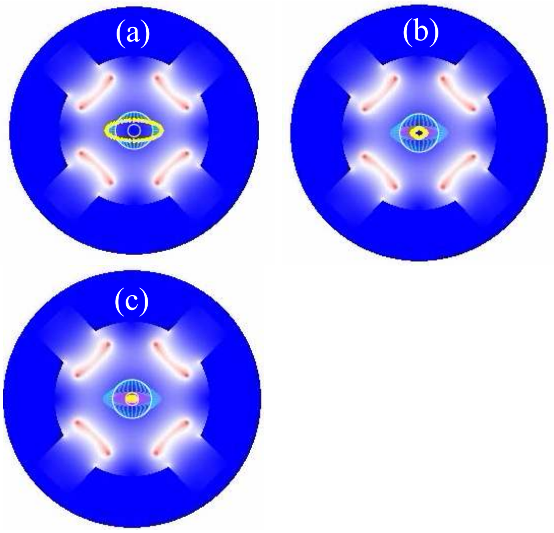
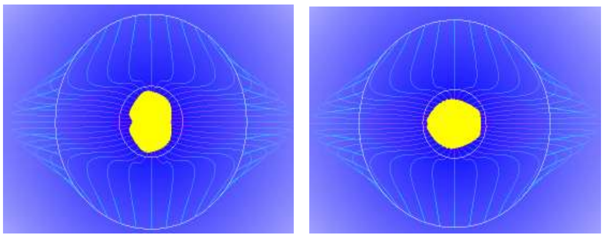
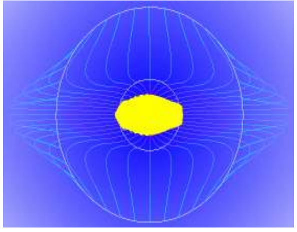


Fig. 3. Protons trajectory at the end of Q1(a), Q2(b), and after Q3(c). Yellow color indicates the position of protons.

The Fig. 3(a) indicated the protons focused at y-direction while defocused at x-direction until they meet Q2. The twice longer Q2 focuses proton at x-directions so that the beam diameter becomes smaller. The third one keeps the protons within 1 cm diameter. The net reducing ratio of the initial and final beam diameter is larger than 3. We try to make even strong reducing power by changing quadrupole magnetization, which is indicted in Fig. 4. The yellow area in Fig. 4 represents the diameter of final beam and the optimized condition is corresponding to (b). Therefore, it is concluded that with this configuration the beam diameter can be reduced by the factor of three. To make an effective micro-proton beam an initial beam diameter is enough small to make micro-beam or a second focusing device is adopted in series combination with one another.



(a) M=2,900 A/m (b) M=3,000 A/m



(c) M=3,100 A/m

Fig. 4. Beam profiling as a function of quadrupole magnetization. Yellow represented the contained area where protons are kept.

3. Conclusions

Simulation techniques using numerical analysis with COMSOL Multiphysics program can be useful tools for designing beam transport systems as well as focusing devices. The model we simulated is useful for focusing protons and applying to make micro-proton beam with an appropriate configuration.

REFERENCES

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