Double Magnetic Focusing Lens for a Pb-Coated Superconducting Inertial Fusion Energy Target

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The focusing performance of a double magnetic lens and the delay in the arrival time at the shot point are presented for a Pb-coated superconducting inertial fusion energy target injection system. Magnets placed symmetrically in the injection path adjust the target trajectory and focus it toward the designated point. When the target passes through the magnetic lens, it receives deceleration and acceleration forces, producing a delay in the arrival time.

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In a laser fusion reactor, the fuel target must be transported to the center of the reactor chamber to be shot by driver laser beams. A successful uniform implosion requires that the laser beams hit the fuel target from all sides with high accuracy. The traditional design concept is that the position and velocity of the fuel target in flight must be monitored, and calculation of the arrival time and arrival position at the reactor center must be performed in real time before the target reaches the reactor center. The mirrors must be steered to change the focal point according to the target trajectory calculation. The problem with a real-time steering mirror system is the challenge of simultaneously controlling a few hundred final mirrors of a large diameter (approximately 1 m) in a few milliseconds. However, greater target injection accuracy could reduce or even eliminate the need for laser beam steering.

To build an accurate target injection system, a target trajectory adjusting method using a magnetic lens for a Pb-coated superconducting inertial fusion energy (IFE) target was proposed [1, 2]. This system uses the repulsive force between a magnet and a Pb-coated, spherical, superconducting fuel target, which is cooled below 7.2 K before injection. A Pb layer thicker than 0.04 μm on a fuel target cooled below 7.2 K works as a superconductor. If the thickness is less than 0.16 μm, the target keeps a gain of over 100 [3]. The trajectory is adjusted by magnets placed symmetrically in the target injection path as shown in Fig. 1. The magnetic lens trajectory adjusting system can focus the target trajectory on a fixed focal point called the shot point.

In this paper, we extend the results of our previous study as well as indicate those of our present study, summarized as follows: (i) focusing performance of the target trajectory of a double magnetic lens system and (ii) delay in the arrival time of the target at the shot point.

A simple analytical model of a magnetic lens is composed of two equal magnetic point charge q_A $(= q)$ and q_B $(= q)$, placed at $A(0, -a)$ and $B(0, a)$ as shown in Fig. 2.

Consider the y component of the total force $F_{y(\text{total})}$ exerted on the spherical superconducting target in the effective interaction region $(-a/2 < x < a/2)$. The induced magnetic field occurs outside the target as if there were magnetic charges inside the target. These charges are composed of image point charges ($q_{A'}$ and $q_{B'}$) and image segment charges ($q_{A''}$ and $q_{B''}$) [4]. Calculating the force between the real magnetic charges and the image magnetic charges, we obtain the y component of the force $F_{y(\text{total})}$ as

$$\begin{aligned} F_{y(\text{total})} = & F_{y(AA')} + F_{y(AA'')} + F_{y(BB')} + F_{y(BB'')} \\ & + F_{y(BA')} + F_{y(BA'')} + F_{y(AB')} + F_{y(AB'')}, \end{aligned} \quad (1)$$

where the subscript in parenthesis denotes a pair of interacting charges. If we set the target center $O(x, y)$ on the y axis $(x = 0)$ and expand the force $F_{y(\text{total})}$ in the Taylor series around Y $(= y/a)$, the force is represented as the series of odd powers of Y

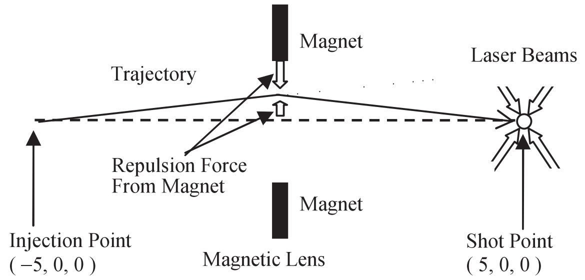

Fig. 1 Geometry of a magnetic lens system.

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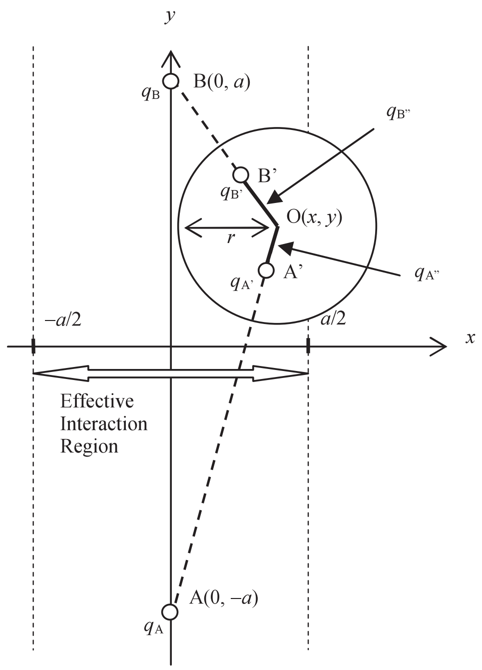

Fig. 2 Magnetic lens model.

$$F_{y(\text{total})}(Y) = \frac{q^2 ar}{4\pi\mu_0}[C_1 Y + C_3 Y^3 + O(Y^5) + \cdots], \quad (2)$$

$$C_1 = \frac{-8a^2r^2(a^2+3r^2)}{(a^2-r^2)^3(a^2+r^2)^2} < 0, \quad (3)$$

$$C_3 = \frac{-32a^4r^2(2a^6+7a^4r^2+4a^2r^4+3r^6)}{(a^2-r^2)^5(a^2+r^2)^3} < 0, \quad (4)$$

where r is the radius of the target [2]. If Y is small enough, the force $F_{y(\text{total})}$ is proportional to the target displacement at the magnetic lens, resulting in a lens action. The cubic term Y^3 causes a deviation Δy at the shot point. The force $F_{y(\text{total})}$ on the target in flight depends on x, i.e., t and is approximately a Gaussian function. A simple rectangular function model, with a peak $F_{y(\text{total})}(x = 0)$ and width a/V_x estimates the magnetic charge within a error of 2% [2].

Consider the deviation Δy for a target (5 mg mass and 2 mm radius) injected at $x = -5$ m with a speed of $V_x = 100$ m/s and $V_z = 0$ m/s, where the two equal magnetic charges are set symmetrically. Figure 3 shows the deviation at $x = 5$ m, the shot point, as a function of V_y. From the numerical trajectory simulation, the magnetic charges are set to eliminate the deviation Δy at $x = 5$ m for $V_y = 0.02$ m/s. If the trajectory of the target is unchanged, the velocity $V_y = 0.02$ m/s causes a deviation of 2000 µm at the shot point ($x = 5$ m). If the velocity V_y becomes larger than 0.02 m/s, over-feedback occurs because of the cubic term of the force Y^3, resulting in $\Delta y < 0$. The deviation for a double magnetic lens is $(2/3)^3$ times smaller than that for a single lens because its displacement at the magnetic lens is smaller than that of a single lens.

Figure 4 (a) shows the x component of the force $F_{x(\text{total})}$ for a single magnetic lens $q_{SG} = 1.19168 \times 10^{-4}$ Wb placed at (0, ±0.02, 0) m. The x component of the target velocity V_x varies as shown in Fig. 4 (b). There is a delay of the arrival of the target at the shot point. The delay of the arrival of the target Δt is 1.04×10^{-7} s for a double magnetic lens. This value is 1.51 ($= 2 \times (q_{DB}/q_{SG})^2$) times larger than that for a single lens. This delay induces the deviation $\Delta x = 10.4$ µm ($= \Delta t \times V_x$) for a double magnetic lens.

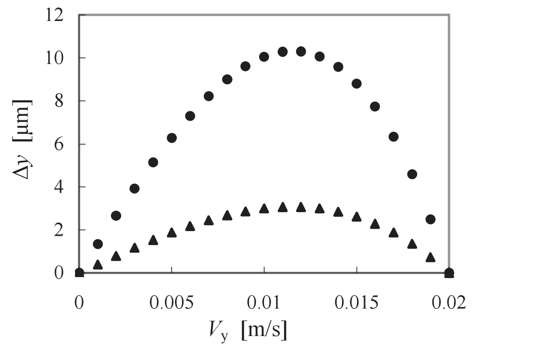

Fig. 3 Deviation of the target position Δy at $x = 5$ m. The circles represent a single magnetic lens $q_{SG} = 1.19168 \times 10^{-4}$ Wb placed at $(0, \pm 0.02, 0)$: triangles represents a double magnetic lens $q_{DB} = 1.03565 \times 10^{-4}$ Wb placed at $(-5/3, \pm 0.02, 0)$ and $(5/3, \pm 0.02, 0)$ m.

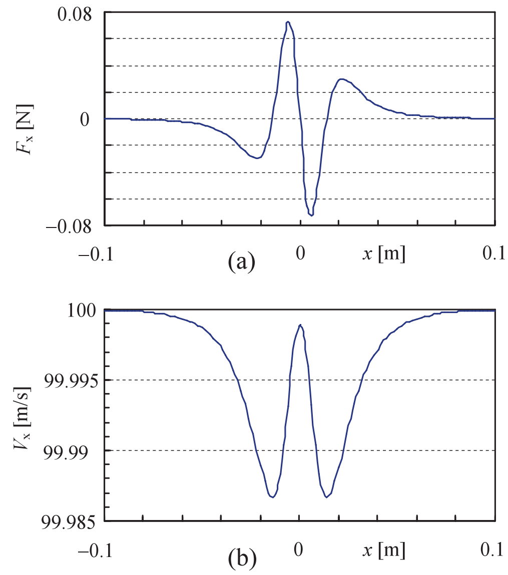

Fig. 4 (a) The x component of the force. (b) The x component of the target velocity.

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