Numerical Investigations on Superconducting Linear Acceleration System by Using Finite Element Method: Influence of Magnet Current on Pellet Velocity*)

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The performance of a superconducting linear accelerator (SLA) system for pellet injection in fuel nuclear fusion reactors was investigated numerically. To this end, a numerical code using the finite element method was developed to analyze the shielding current density and dynamic motion of the high-temperature superconducting thin film of the SLA system. The computational results showed that applying an exponential current to the electromagnet, significantly improved the acceleration performance. It was concluded that SLA systems of the order of several hundred meters, and with realistic acceleration distances using the proposed currents can be designed.

Keywords: electromagnet, finite element analysis, numerical simulation, superconducting linear accelerator, system improvement

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1. Introduction

Yanagi and Motojima (2017) proposed a superconducting linear acceleration (SLA) system to fuel magnetic confinement fusion reactors [1]. In this system, solid hydrogen pellets are placed in a container with a high-temperature superconductor (HTS) for acceleration and levitation. An acceleration magnet and electromagnetic rails are used to electromagnetically move the pellet container. It is estimated that an SLA system can achieve a maximum speed of 5 km/s. However, an SLA system as a pellet injection method for magnetic confinement fusion reactors is still at the prototype stage. The maximum pellet velocity has not yet been achieved experimentally. Therefore, numerical validation of the design of an SLA system is required.

Previous studies simulated an SLA system by solving the time evolution problem of the shielding current density in HTS thin film using an axisymmetric model [2–4]. For the estimation of the pellet velocity, the shielding current in the propulsion film attached to the pellet container and the dynamic motion of the film were analyzed. The results suggested that by aligning several electromagnets with each other, the target velocity of 5 km/s could be achieved in about 7 s. This required a 20 km long rail of electromagnets; therefore, it was concluded that the shape of the rail should be circular rather than straight.

In our previous study, we investigated increasing pellet velocity to minimize pellet acceleration time and distance [2]. Our suggestions included increasing the maximum magnetic current, placing external magnets, and optimizing the magnetic geometry. In order to increase the magnetic flux density, an additional electromagnet was placed outside of the conventional electromagnet, and the same current was applied to both. In our proposed model, the pellet speed took 2 s to reach 5 km/s, whereas in the conventional model it took 6 s.

In previous numerical studies, the distance of the electromagnet rail for the SLA system could not be reduced to 1 km or less by optimizing the shape of the electromagnets and adding external magnets. Therefore, an SLA system design with a straight electromagnet rail was considered infeasible.

The objective of this study was to improve the acceleration performance of an SLA system from a novel perspective to solve the above problem. We proposed to apply different currents to electromagnets and studied the influence of current parameters on the length of the electromagnetic rail required to achieve the target speed.

2. Simulation Model

Figure 1 shows a schematic of an SLA system simulated using an axisymmetric model in this study. A cylindrical coordinate system was adopted with the z-axis as the axis of symmetry and origin O as the centroid of the electromagnet. The electromagnet has an inner radius R_1, an outer radius R_2 and a length L. A disk-like HTS film with radius R and thickness b is also assumed.

In this study, we assumed that the electromagnets

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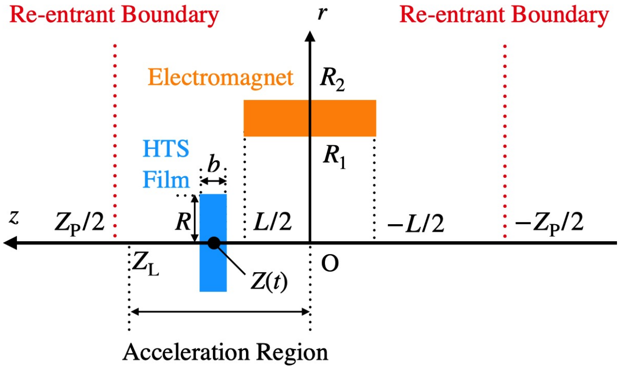

Fig. 1 Schematic of electromagnets for the SLA system.

are positioned with a constant separation Z_P along the z axis and that the distance between them is kept constant Z_P. Therefore, the re-entrant boundary condition shown in Fig. 1 was adopted. In this model, the pellets periodically pass through the section with $|Z| \leq Z_P/2$, which allows an unlimited number of accelerating magnets to be placed. Furthermore, the acceleration distance of a pellet in a section is given by $0 \leq Z \leq Z_L$, where Z_L is the left-end of the acceleration distance. The inequality $Z_P \geq 2Z_L$ must be satisfied to use this model. The advantage of this model is that it allows calculations with an infinite number of electromagnets. Simulations can be performed by specifying the number of electromagnets and the pellet velocity.

In the simulation of the SLA system, we solved the time evolution problem of the shielding current in the HTS and the dynamic motion of the HTS. The shielding current density equation was solved using the power law [5] and the thin-plate approximation [6], and the Newton's equation of motion was used to determine the dynamic motion. Details of the above equations can be found in Ref. [3]. The characteristic parameters of HTS are the critical current density (J_C), critical electric field (E_C), power N of the power law, and total mass (m) of HTS and pellet container.

The time evolution problem was reduced to solving a set of simultaneous ordinary differential equations by discretizing the initial boundary value problem with respect to space using finite element method (FEM) [2]. To speed up the analysis of the shield current density and avoid numerical instabilities, the 6-step 5th order Runge-Kutta method with adaptive step size control was applied to the ordinary differential equations. The radius R was equally divided into n finite elements.

We developed an FEM code to solve the initial boundary value problem for the governing equations and Newton's equations of motion. This code was used to investigate the acceleration performance of the SLA system. Since a single magnet could not achieve the target velocity required to enter the plasma core, multiple magnets were used to accelerate the pellets.

Here, we explain the case when a current is applied to an electromagnet. We define the following current expression:

$$I_E(t, Z) \equiv \begin{cases} I_0\{1 - \exp[-(t - t_{\min})/\tau]\} & (0 \leq Z \leq Z_L) \\ 0 & (\text{otherwise}) \end{cases} . \quad (1)$$

Thus, the electromagnet current exhibits a monotonic exponential increase with time before becoming constant. I_0 and $t_{\min}$ are the maximum value of the current and time at $Z = 0$ m, respectively, and τ is the time constant. Additionally, the HTS film is located at $Z = Z_0$ (> 0) at $t = 0$ as the initial condition (see Fig. 1).

The conventional current with the following expression was also used:

$$I_L(t, Z) \equiv \begin{cases} \alpha(t - t_{\min}) & (0 \leq Z \leq Z_L) \\ 0 & (\text{otherwise}) \end{cases} , \quad (2)$$

where α denotes the rate of increase in the current. Note that the maximum value is unknown for current I_L because the current increases infinitely with time.

In the next section, the use of two currents I_E and I_L to investigate the acceleration performance of the SLA system numerically is presented. The magnet currents, I_E and I_L, are called exponential and linear currents, respectively.

3. Improvement of Acceleration Distance

The performance of the SLA system was investigated using the FEM code. This section focuses on the applied current to improve the pellet velocity and the acceleration distance. In particular, the distance is an important factor in design because it directly affects the size of the SLA system. The value of the distance corresponds to the length of the electromagnet rail.

In this study, the values of geometric and physical parameters were fixed as follows: R = 4 cm, b = 1 mm, Z_0 = 1 mm, J_C = 1 MA/cm^2, E_C = 1 mV/m, N = 20, m = 10 g, R_1 = 5 cm, R_2 = 7 cm, L = 10 cm, α = 20 kA/ms, and n = 101, Furthermore, the interval, Z_P, was fixed as $Z_P = 2Z_L$, and the target pellet velocity was set as v = 5 km/s. The simulation of the SLA system was terminated when the target velocity was reached.

3.1 Effect of electromagnet current

First, we investigated the pellet velocity for the case where two currents I_E and I_L are applied to the electromagnets. Figure 2 shows the pellet velocity, v, as a function of time. It presents the pellet velocity, v, at exponential and linear currents, which were used in a previous study, when the pellet passes through five electromagnets. The figure clearly shows that when the pellet passes through the first magnet, the pellet velocity under the linear current is high. Consequently, this simulation yields that the final velocity is significantly improved by applying the proposed current to the electromagnets.

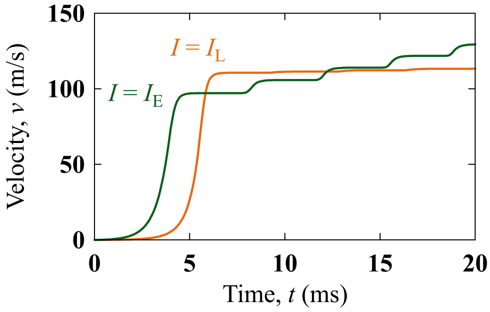

Fig. 2 Time dependence of pellet velocity v when pellet container passes through five magnets for $I_0 = 100$ kA, $\tau = 1$ ms, and $Z_P = 40$ cm.

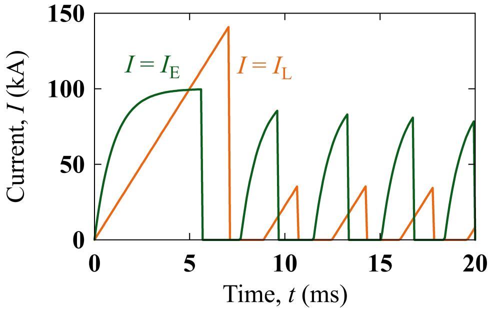

Fig. 3 Time dependence of magnet current when pellet container passes through five magnets for $I_0 = 100$ kA, $\tau = 1$ ms, and $Z_P = 40$ cm.

Figure 3 shows the time dependence of the magnet current, I. Noticeably, the exponential current, I_E, develops more rapidly than $I = I_L$. The maximum I_E current in the second and subsequent magnets is larger than the maximum linear current, I_L. Specifically, comparing the currents in the second magnet, the maximum I_E is 83 kA, whereas the maximum I_L is 35 kA, showing a large difference in the current values. After the third magnet, currents I_L and I_E show similar trends; specifically, the pellet velocity, v, increases because B_r also increases. Therefore, the proposed current is expected to improve the acceleration performance of the SLA system.

3.2 Reduction in acceleration distance for pellet injection

In this subsection, we consider the possibility of reducing the acceleration distance and present the numerically study on the parameters that reduce the acceleration distance to 1 km or shorter. In decreasing the acceleration distance, the present study focused on maximum current value I_0, time constant τ, and magnet interval Z_P.

First, we investigated the performance of the SLA system by changing the magnet interval Z_P. Figure 4 shows the time dependences of the pellet velocity, v. As shown in this figure, v reaches the target velocity of 5 km/s for all values of Z_P. In Fig. 5, we show the dependences of the pellet velocity, v, on the HTS position, Z.

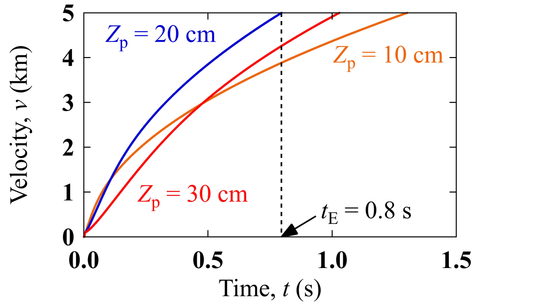

Fig. 4 Time dependence of pellet velocity v for $I_0 = 100$ kA and $\tau = 1$ ms.

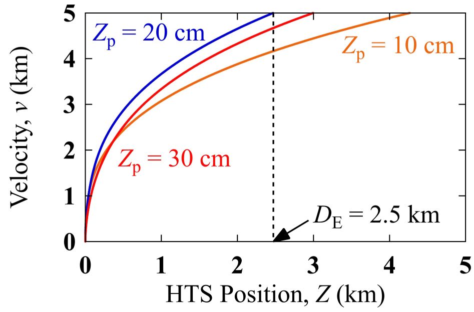

Fig. 5 Dependence of pellet velocity v on HTS position Z for $I_0 = 100$ kA and $\tau = 1$ ms.

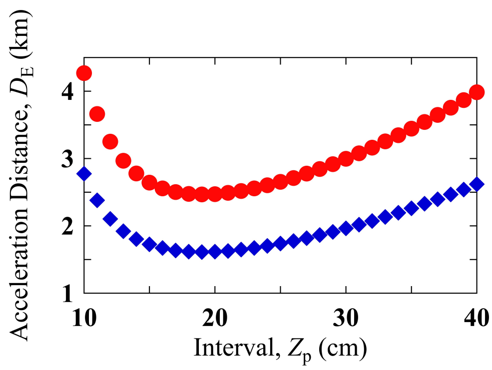

Fig. 6 Dependences of acceleration distance D_E on magnet interval Z_P for $\tau = 1$ ms. Here, •: $I_0 = 100$ kA and ♦: $I_0 = 150$ kA.

We calculated the corresponding times and distances required by the pellet to reach a velocity of 5 km/s to evaluate the performance of the SLA system. Specifically, the acceleration time for I_E was $t_E = 0.8$ s for $Z_P = 20$ cm (see Fig. 4), whereas it was $t_L = 4.16$ s for I_L. The acceleration distances for I_E were $D_E = 4.3$ km, 2.5 km, and 3.0 km for $Z_P = 10$ cm, 20 cm, and 30 cm, respectively. Therefore, the magnet interval Z_P depends on the acceleration performance of the SLA system and suggests that there is an optimal interval between the electromagnets.

Figure 6 shows the dependence of the acceleration distance, D_E, on the magnet interval, Z_P. Note that an acceleration distance, D_E, denotes the difference between the initial position Z_0 and HTS position Z at $v = 5$ km/s.

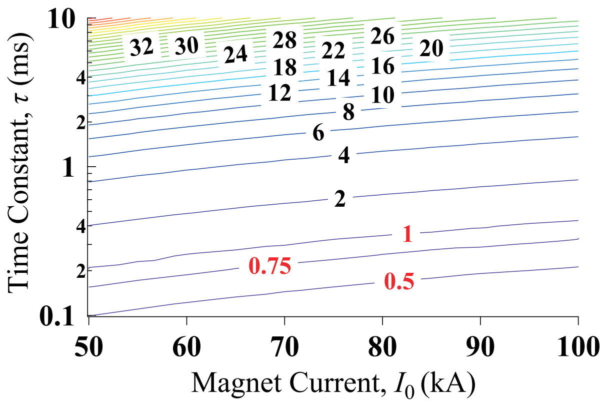

Fig. 7 Contour map of acceleration distance D_E to achieve pellet velocity v = 5 km/s.

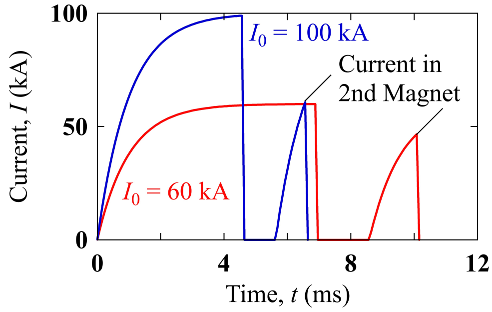

Fig. 8 Time dependence of the current I.

As shown in the figure, the acceleration distance, D_E, is a downwardly convex function for 10 cm $\leq Z_P \leq$ 40 cm. In addition, D_E becomes minimum at approximately Z_P = 20 cm. This trend does not change when the maximum current, I_0, is changed.

These results are attributed to two reasons: first, the longer the distance between the magnets, the longer the distance over which the pellet is accelerated, and therefore the longer the time it takes for the pellet to pass between the magnets. Second, in an electromagnet arrangement with, say, Z_P = 10 cm, the acceleration range is shorter than with Z_P = 20 cm, thereby reducing the amount of applied current. Therefore, the pellet velocity increases by a smaller amount, making the final distance longer. From this, there exists an optimum magnet spacing that maximizes pellet velocity.

Finally, we examined whether there exists a combination of the maximum current, I_0, and the time constant, τ, for which the acceleration distance of the pellets is shorter than 1 km. The magnet interval was fixed as Z_P = 20 cm. For this purpose, the ranges of I_0 and τ were set as 50 kA $\leq I_0 \leq$ 100 kA and 0.1 ms $\leq \tau \leq$ 10 ms, respectively. A contour map of the acceleration distance, D_E, is shown in Fig. 7. The computational results show that the acceleration distance range is 0.244 km $\leq D_E \leq$ 56.5 km. Moreover, the maximum current, I_0, has little effect on the decrease in the acceleration distance, whereas the time constant, τ, is an important parameter for it. This is because the maximum current applied to the second magnet is significantly reduced compared with that of the first magnet, and the magnitude of reduction is higher for larger values of I_0 (see Fig. 8). The current in the first magnet decreases from 100 kA to 60 kA (that is, a reduction of 40 kA), whereas it decreases from 60 kA to 47 kA (a reduction of 13 kA) for the second magnet. Likewise, the magnitude of reduction was found to get progressively smaller as the current passed through more magnets.

It is determined that SLA systems of the order of several hundred meters can be designed.

4. Conclusion

Based on previous numerical results, the acceleration distance required for the pellet velocity to reach the plasma core is limited to several tens of kilometers. Hence, designing an electromagnet rail as a straight line may be difficult. In this study, we simulated an SLA system for pellet injection using FEM. We investigate the influence of current on the length of the electromagnetic rail. To summarize:

1. By applying an exponential current to the electromagnets, we revealed the possibility of obtaining the target speed using a straight-line rail of several hundred meters.
2. The magnitude of the current applied to the electromagnets had negligible effect on the decrease in the acceleration distance, whereas the time constant was proposed as an important parameter for this purpose.

In conclusion, above numerical results showed that the proposed current is effective to improve the acceleration performance and allows designing SLA systems with realistic acceleration distances.

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[1] N. Yanagi and G. Motojima, private communication, National Institute for Fusion Science (2017).
[2] T. Takayama, T. Yamaguchi, A. Saitoh and A. Kamitani, IEEE Trans. Appl. Supercond. **30**, 4203505 (2020).
[3] T. Takayama, T. Yamaguchi, A. Saitoh and A. Kamitani, IEEE Trans. Appl. Supercond. **31**, 4100505 (2021).
[4] T. Takayama, T. Yamaguchi, A. Saitoh and A. Kamitani, IEEE Trans. Appl. Supercond. **32**, 4900805 (2022).
[5] E.H. Brandt, Phys. Rev. B **54**, 4246 (1996).
[6] A. Kamitani and S. Ohshima, IEICE Trans. Electron. **E82-C**, 766 (1999).