Numerical Investigations on Enhanced-Performance
Superconducting Linear Acceleration System for Pellet Injection

T. Takayama1), T. Yamaguchi2), A. Saitoh2), A. Kamitani1)
1) Yamagata University, Japan; 2) SOKENDAI, Japan

I. INTRODUCTION

Background
Superconducting Acceleration System for Pellet Injection
Conventional systems, a pneumatic pellet and a centrifuge pellet injections, inject ice pellets of frozen hydrogen gas into the fusion reactor at the velocity of 1-3 km/s.

Superconducting Linear Acceleration (SLA)
In order to inject the ice pellets into the plasma core, Yanagi et al. recently propose a novel pellet injection system. This system electromagnetically accelerates the ice pellets on the magnetic levitation train. They adopt two types of high-temperature superconducting (HTS) film for acceleration and levitation.

They estimate 5-10 km/s as the velocity of the pellet injection.

Purpose
(1) To develop the numerical code for analyzing the time evolution of the shielding current density by means of the finite element method (FEM).
(2) To decrease an acceleration time during which a pellet speed reaches 5 km/s. To this end, outer coil is placed outside of the conventional one.

II. GOVERNING EQUATION AND EQUATION OF MOTION

Shielding Current Density in HTS Sample
\[ j = \frac{\partial S}{\partial t} + \mathbf{E} \times \mathbf{B} \] (1)
Here, \( S(r, t) \) : scalar function, \( b \) : thickness.

Integro-Differential Equations
\[ \mu_0 \frac{\partial}{\partial t} \left( Q(r, r') S(r', t) r' dt' \right) + \frac{2}{b} \frac{\partial}{\partial r} \left[ (B \cdot e_z) \frac{\partial}{\partial r} (E \cdot e_b) \right] = 0. \] (2)
Here, \( B \) : applied magnetic field by permanent magnet, \( E \) : average operator over the thickness of the HTS, \( E \) : electric field.

J-E Constitutive Equation (Power Law)
\[ E = \frac{1}{\gamma} \left( B \right) \] (3a)
\[ E = E_0 \left( \frac{\gamma}{\gamma_0} \right)^N \] (3b)
Here, \( \gamma \) : critical current density, \( E_0 \) : critical electric field, \( N \) : index.

Newton’s law of motion
\[ \frac{d^2 z}{dt^2} = \frac{4\pi}{m} \int \frac{dS}{dr} \left\{ B(r, z) \right\} dt \] (4)
Here, \( B(r, z) \) : r-component of an applied magnetic flux density \( B \), \( m \) : total mass of the pellet container.

III. SIMULATION OF SLA SYSTEM FOR PELLET INJECTION

A. Single Acceleration Coil

The current of the inner coil: \( I_{in}(t, z) = \begin{cases} 0 \quad (0 < z < z_{min}) \Rightarrow \text{the acceleration region} \\ \alpha (t - t_{min}) \quad (z_{min} \leq z \leq z_{ext}) \Rightarrow \text{outside of the acceleration region} \end{cases} \)

where \( z_{min} \) and \( z_{ext} \) are the limit of the acceleration region and the increasing rate of the inner coil current. These values are fixed as \( z_{min} = 20 \) cm and \( \alpha = 20 \) kA/ms. On the other hand, the current of the outer coil: \( I_{out}(t, z) = \beta I_{in}(t, z) \), where \( \beta \) is a constant (0 \leq \beta \leq 1).

Pellet Speed

\[ v(t, z) = \frac{d}{dt} \left( v_f (z) + \frac{r_c}{r_i} \right) \] (5a)
\[ z_f (t, z) = \frac{z}{\beta} \] (5b)

Dependence of the final velocity \( v_f \) on the increasing rate \( \beta \) of the outer coil current for \( L_{in} = L_{in}/2 \). Here, \( v_f \) : the velocity at which the film passes through the 1st acceleration region.

Influence of Length of Outer Coil on Pellet Velocity

Dependence of the acceleration time ratio \( \tau(\beta)/\tau(0) \) on the increasing rate \( \beta \) of the outer coil current. Here, \( \tau(\beta) \) : the time during which the pellet velocity reaches 5 km/s, and \( \tau(0) \) : the acceleration time for the case without the outer coil.

Acceleration time and the distance of the electromagnetic rails when the pellet velocity reaches 5 km/s.

IV. CONCLUSION

(1) We attempt to decrease an acceleration time by locating another coil on the outside of the conventional coil.
(2) It is found that when the pellet velocity reaches 5 km/s, the acceleration time is 2.1 s by using both the inner and outer coils. In particular, we found that the acceleration becomes shorter by approximately 13%.
(3) The distance of electromagnetic rails is reduced to 13% or less. However, the distance even 6.5 km is too long for the SLA system. Therefore, it is necessary to make the shape of the rail not straight but circular. In the future, our study also needs to be discussed in the circular shape.