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

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I. INTRODUCTION

Background

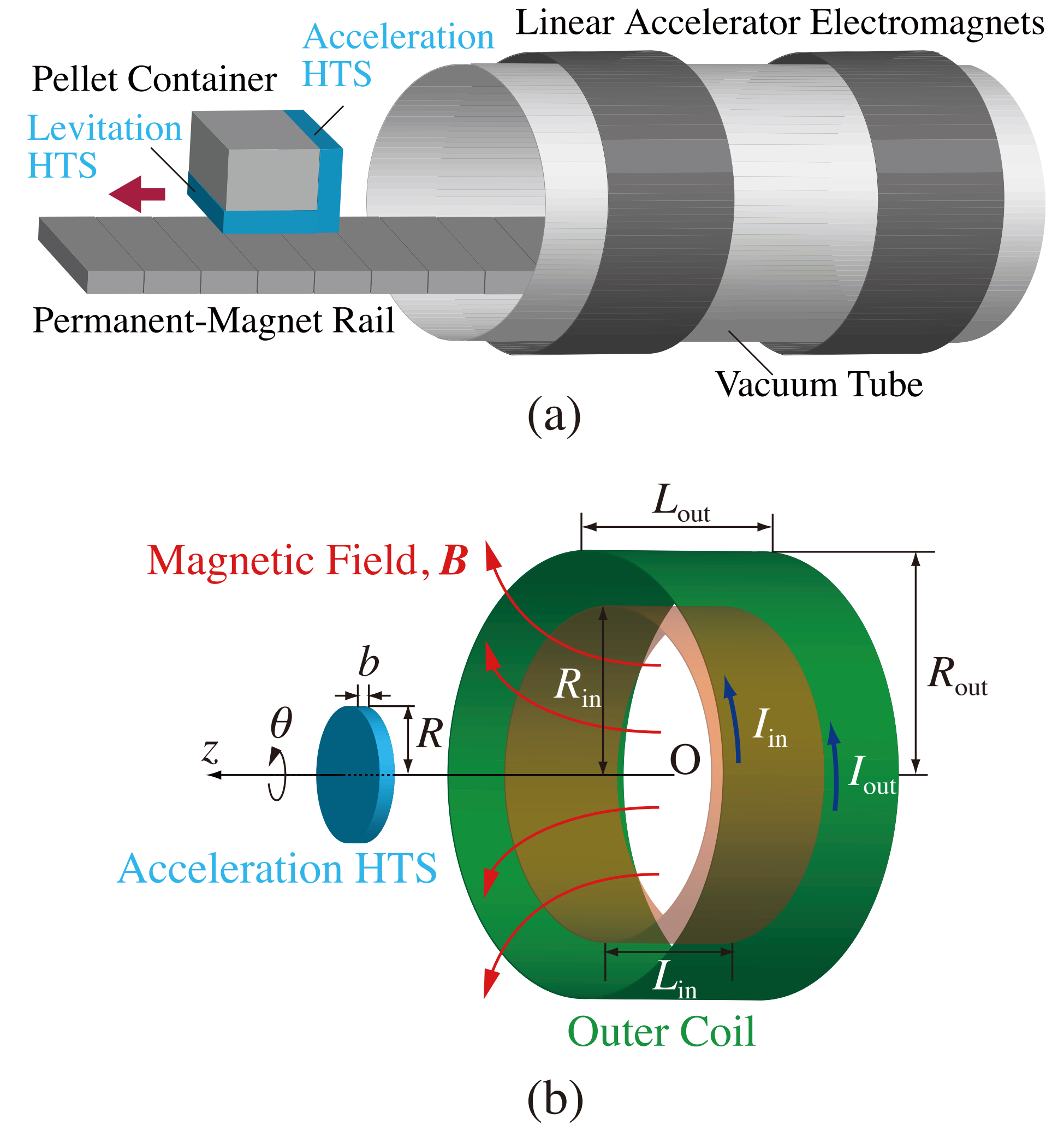
Superconducting Acceleration System for Pellet Injection

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 1-1.5 km/s.

Superconducting Linear Acceleration (SLA)

In order to inject the ice pellets into the plasma core, Yanagi *et al*. recently propose an 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.



(a)

(b)

A schematic views of (a) the superconducting linear acceleration system, (b) SLA system using an inner and outer coils for the axisymmetric model.

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

$$\boldsymbol{j} = \frac{2}{b}\nabla S \times \boldsymbol{e}_z, \quad (1)$$

Here, $S(r, t)$: scalar function, b : thickness.

Integro-Differential Equations

$$\mu_0 \frac{\partial}{\partial t}\int_0^R Q(r,r')S(r',t)r'dr' + \frac{2}{b}S + \frac{\partial}{\partial t}\langle \boldsymbol{B}\cdot\boldsymbol{e}_z\rangle + \frac{1}{r}\frac{\partial}{\partial r}r(\boldsymbol{E}\cdot\boldsymbol{e}_\theta) = 0, \quad (2)$$

Here, $\boldsymbol{B}$: applied magnetic field by permanent magnet, $\langle\ \rangle$: average operator over the thickness of the HTS, $\boldsymbol{E}$: electric field.

J-E Constitutive Equation (Power Law)

$$\boldsymbol{E} = E(|\boldsymbol{j}|)\frac{\boldsymbol{j}}{|\boldsymbol{j}|}, \quad (3a) \qquad E(j) = E_C\left(\frac{j}{j_C}\right)^N, \quad (3b)$$

Here, j_C : critical current density, E_C : critical electric field, N : index.

Newton's law of motion

$$\frac{d^2 z}{dt^2} = \frac{4\pi}{m}\int_0^R \frac{\partial S}{\partial r}\langle B_r\rangle r dr \quad (4)$$

Here, $B_r(r, z)$: r-component of an applied magnetic flux density $\boldsymbol{B}$, m : total mass of the pellet container.

Initial and Boundary Conditions

$$S(r,0) = v = 0 \quad \text{at} \quad t = 0 \quad (5a)$$
$$z = z_0 \quad \text{at} \quad t = 0 \quad (5b)$$
$$S(R,t) = 0 \quad (6)$$

Here, z_0 : initial position of the acceleration HTS film.

Ordinary Differential Equations (ODEs)

$$\frac{d}{dt}\begin{bmatrix}\boldsymbol{S}\\ v\\ z\end{bmatrix} = \begin{bmatrix}-W^{-1}U[\boldsymbol{e}(\boldsymbol{S}) + v\boldsymbol{c}(z) + \boldsymbol{h}(z)]\\ \frac{4\pi}{m}\boldsymbol{a}^T(z)\boldsymbol{S}\\ v\end{bmatrix} \quad (7)$$

Here, $W \equiv UW^*U + F$ (8)

Also, W^* : symmetric matrix by $Q(r, r')$ and FEM's shape functions,
U, F : matrix determined from the boundary condition,
$\boldsymbol{S}$: nodal vector corresponding to the scalar function $S(r, t)$,
$\boldsymbol{e}(\boldsymbol{S})$: nodal vector corresponding the electric field $\boldsymbol{E}$,
$\boldsymbol{a}(z)$, $\boldsymbol{c}(z)$, $\boldsymbol{h}(z)$: nodal vector corresponding to the applied magnetic flux density $\boldsymbol{B}$.

➡ ODEs (7) are solved by the Runge-Kutta method with the adaptive stepsize control.

Parameters

R = 5 cm, b = 1 mm, m = 10 g, z_0 = 1 mm, N = 20, E_C = 1 mV/m, j_C = 1 MA/cm^2, R_{in} = 4 cm, L_{in} = 10 cm, R_{out} = 10 cm, n = 101.

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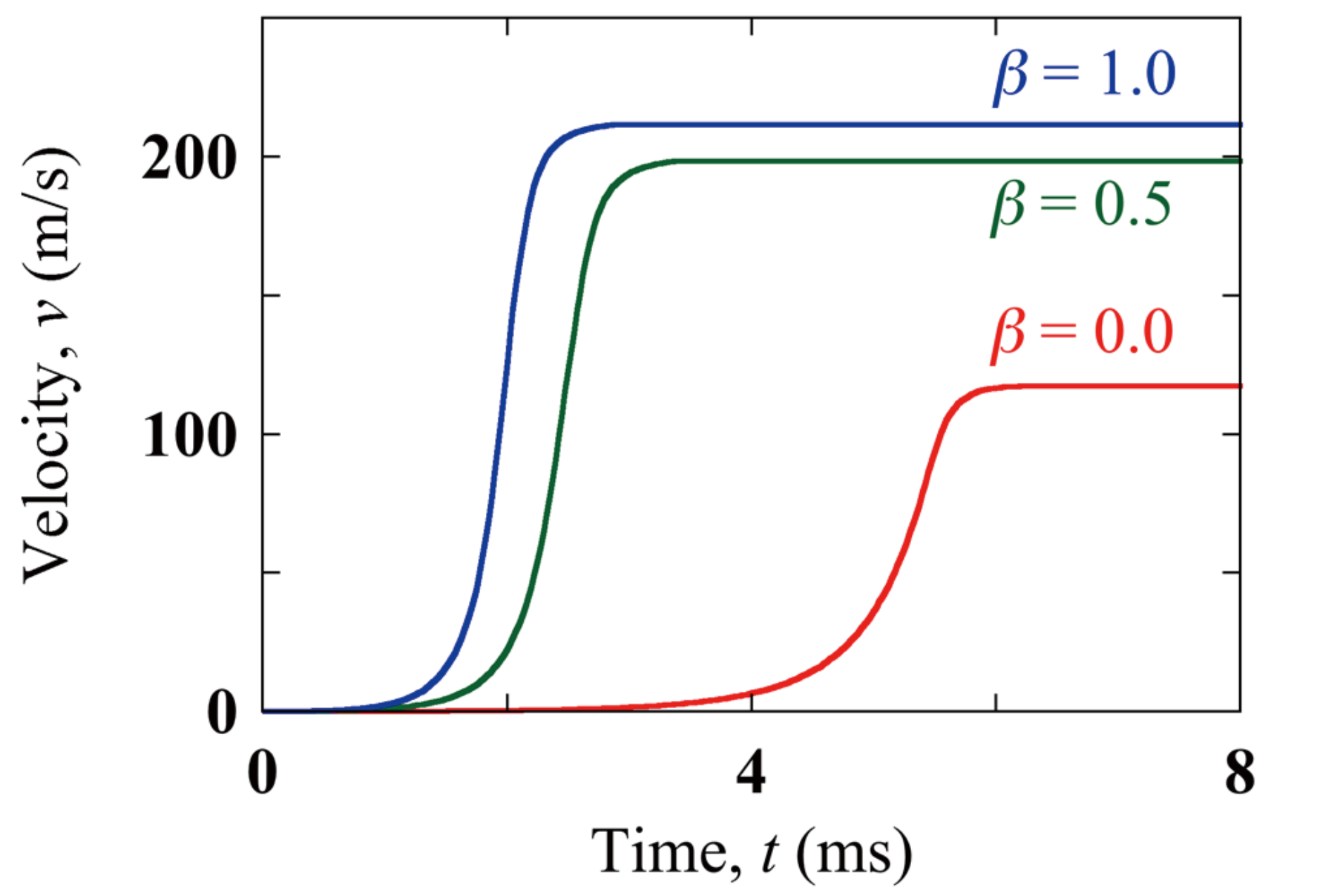
III. SIMULATION OF SLA SYSTEM FOR PELLET INJECTION

A. Single Acceleration Coil

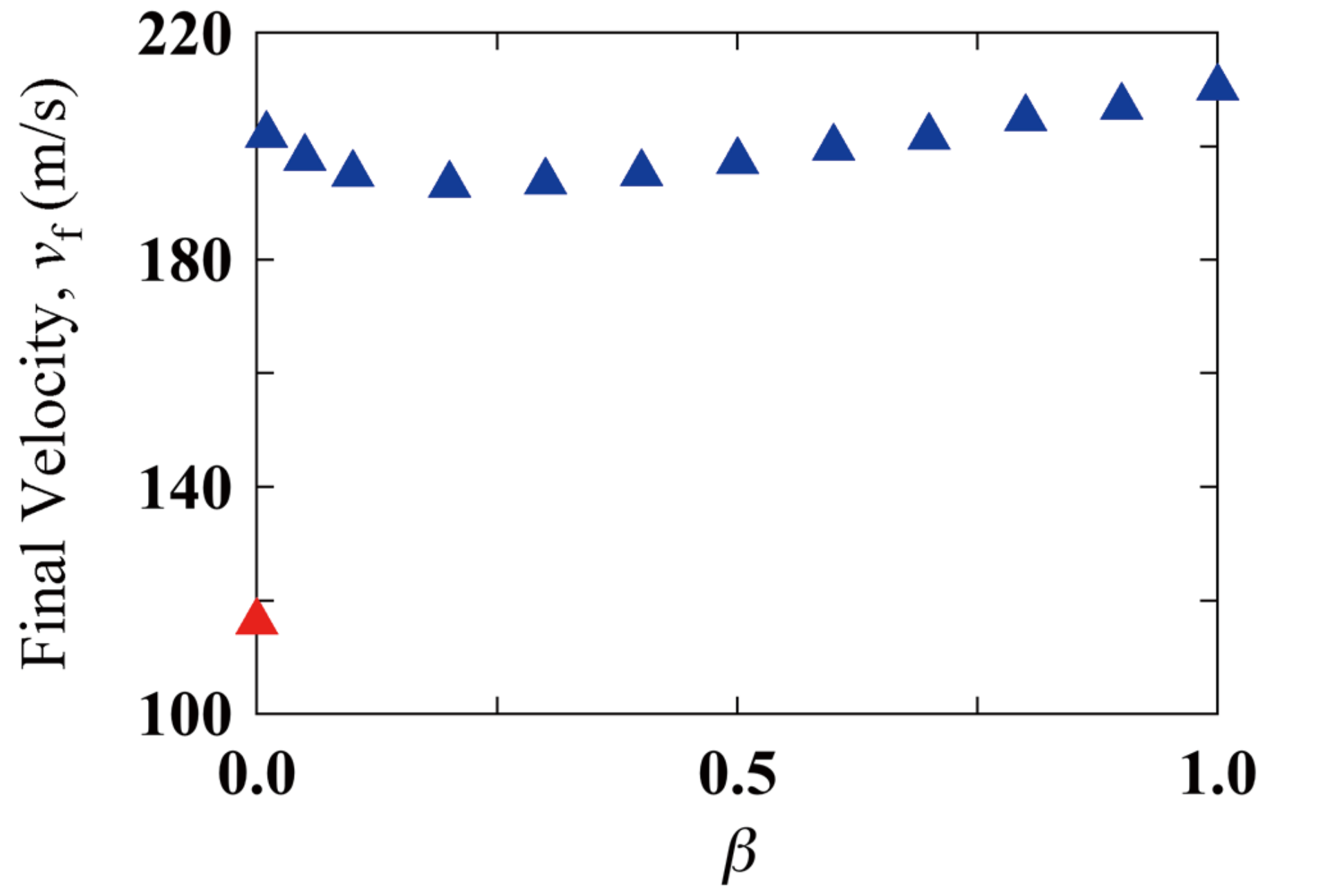
The current of the inner coil: $I_{in}(t,z) \equiv \begin{cases}\alpha t & (0 < z < z_{limit})\\ 0 & (\text{otherwise})\end{cases}$,

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

Pellet Speed

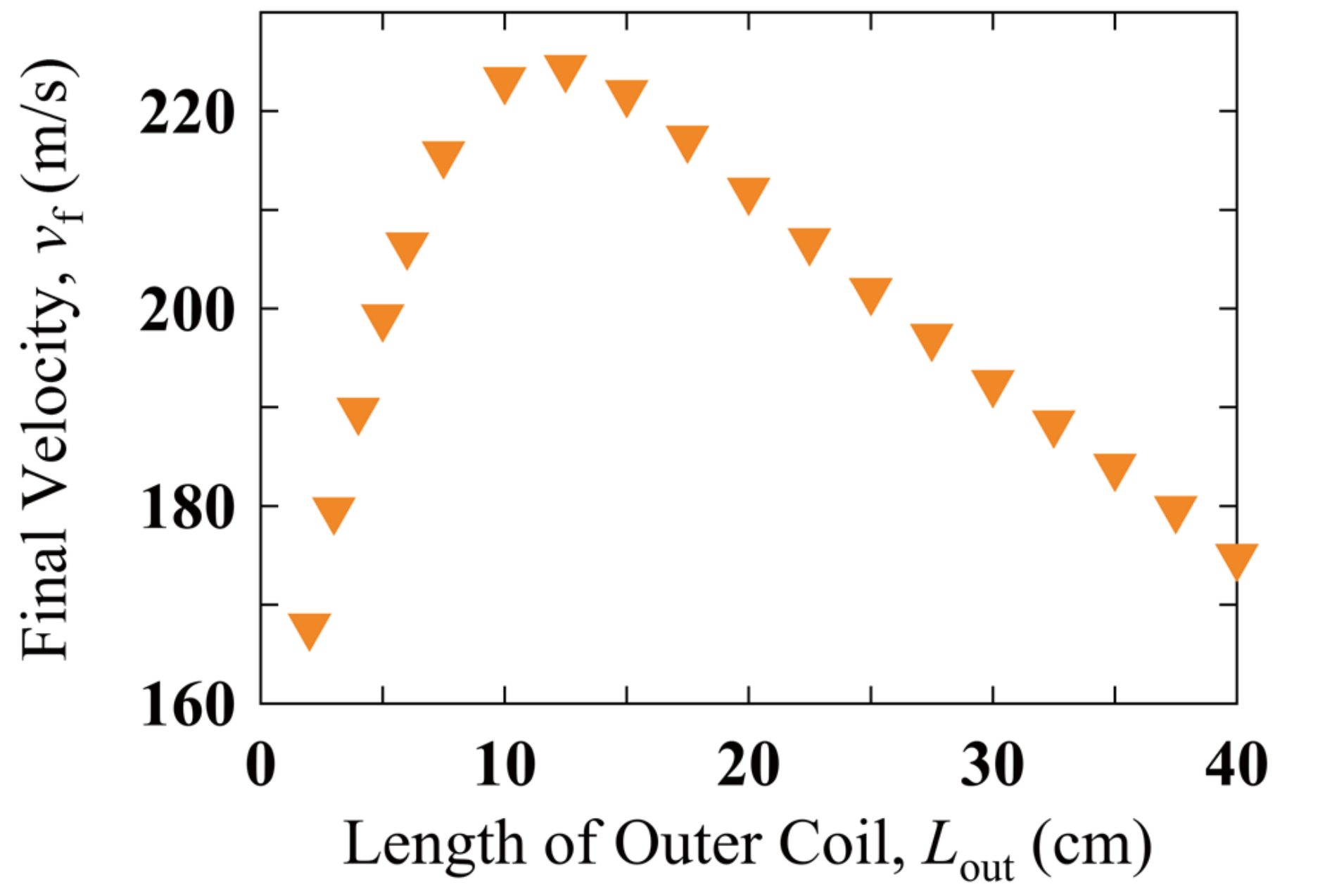


Time dependence of the pellet velocity for the case with $L_{out} = L_{in}/2$.



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

Influence of Length of Outer Coil on Pellet Velocity

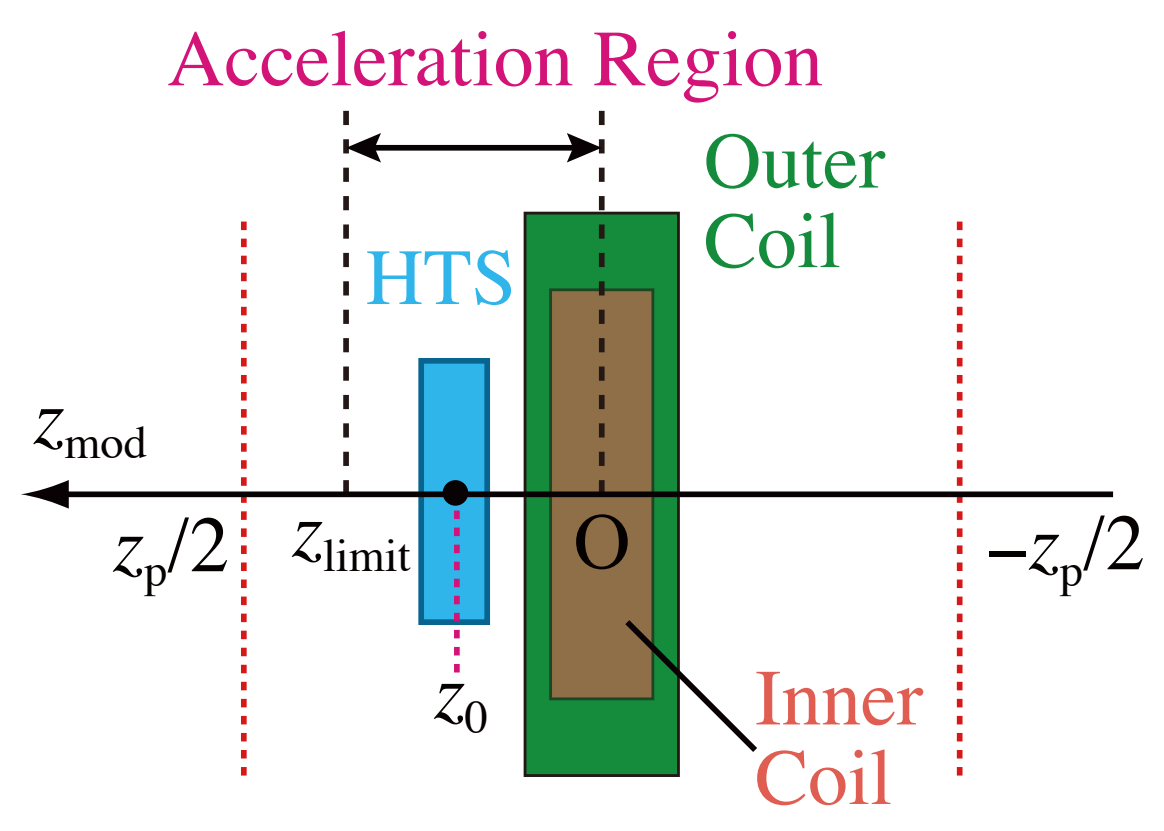


Dependence of the final velocity v_f on the length of outer coil for β = 0.5. In the following, we use L_{out} = 12.5 cm.

B. Multiple Coils

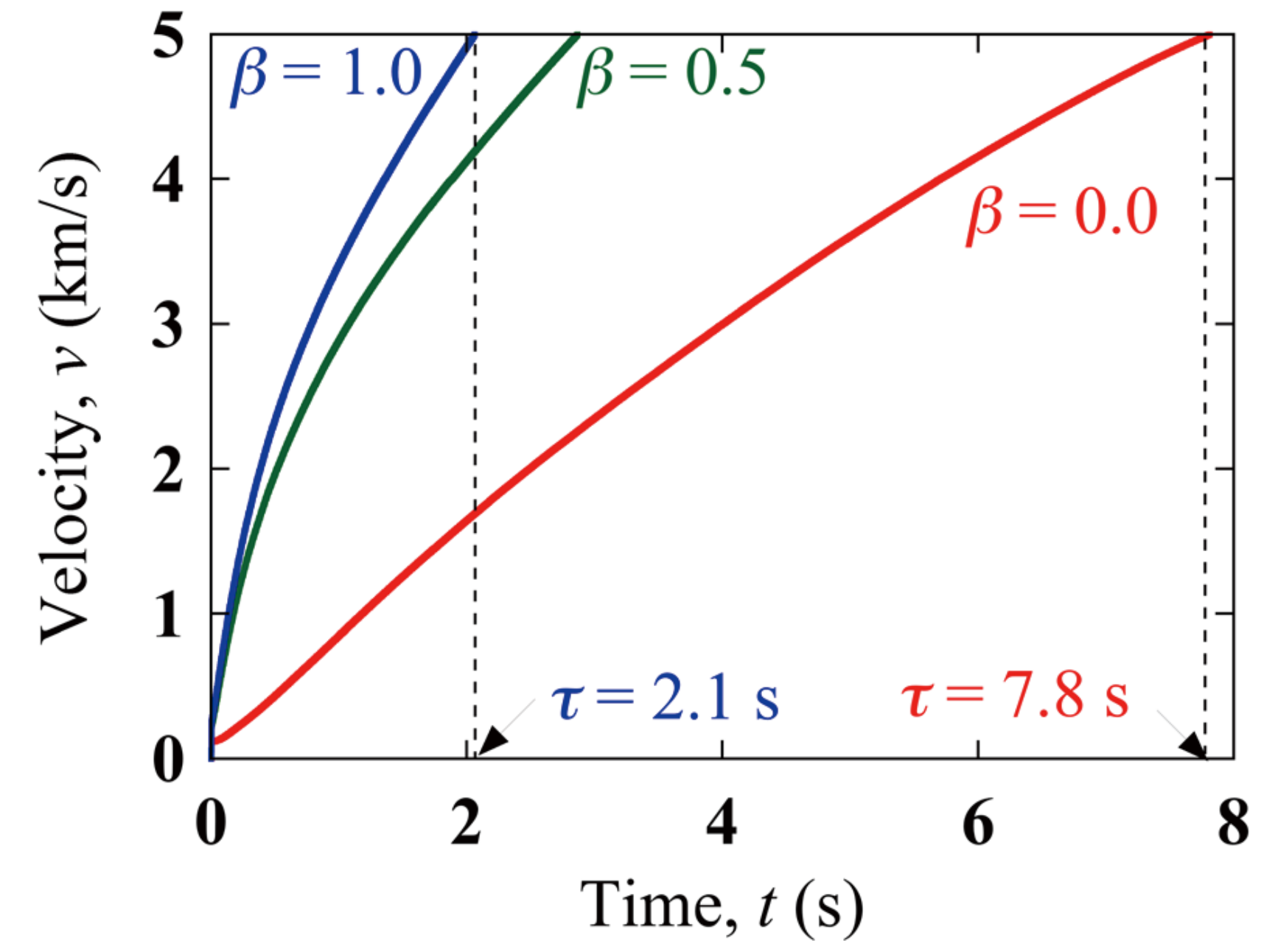
$$I_{in}(t, z_{mod}) = \begin{cases}\alpha(t - t_{min}) & (0 \leq z_{mod} \leq z_{limit})\\ 0 & (\text{otherwise})\end{cases}$$

Here, $z_{mod} = \text{mod}(z + z_p/2, z_p) - z_p/2$, where z_p is a coil interval and t_{min} is the time at z_{mod} = 0 m.



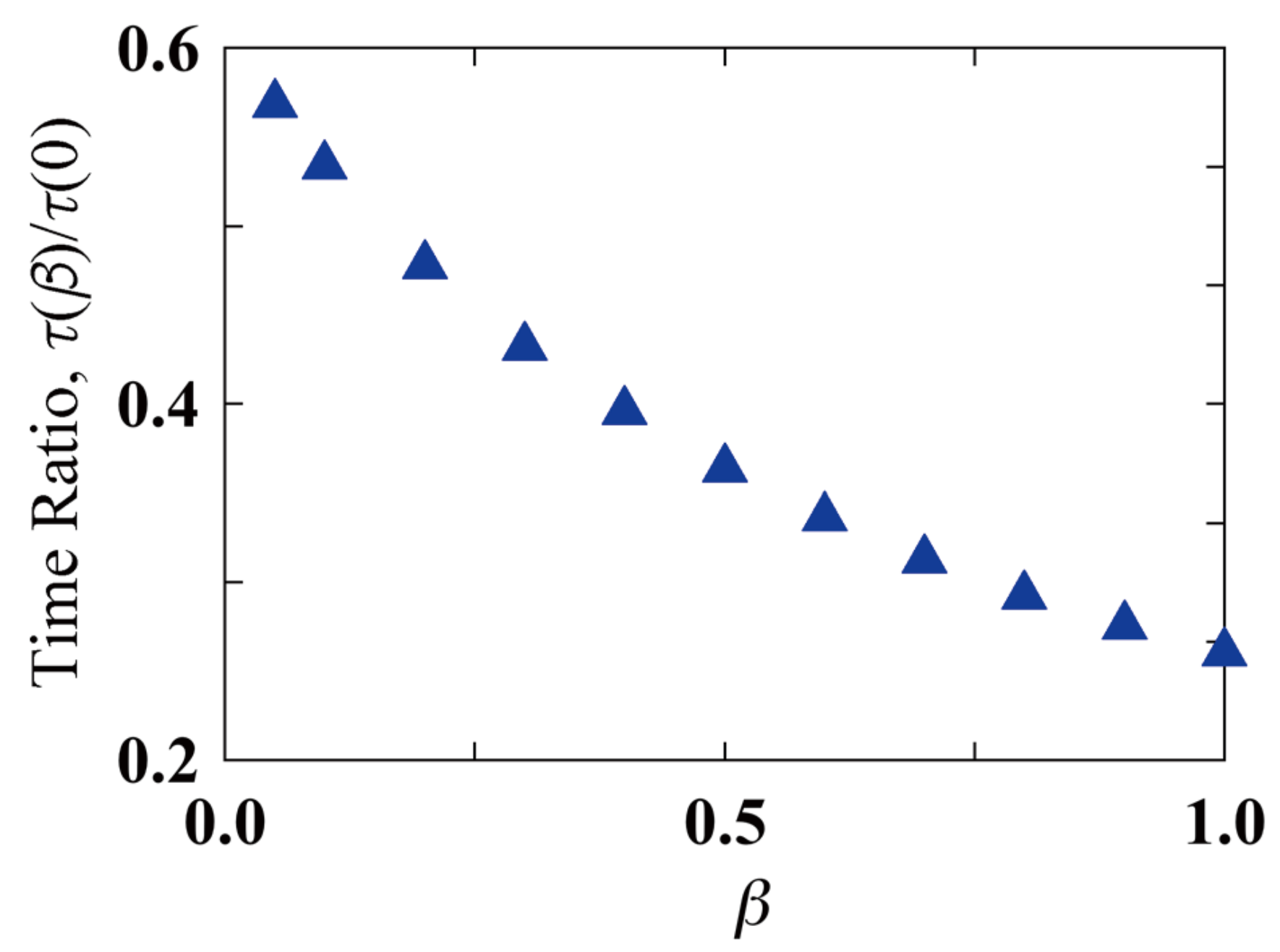
A schematic view of the multiple coils.

Pellet Speed



Time dependence of the pellet velocity.

Comparison of Acceleration Time



Dependence of the acceleration time ratio τ(β)/τ(0) on the increasing rate β of the outer coil current. Here, τ(β) : the time during which the pellet velocity reaches 5 km/s, and τ(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.

	Acceleration time (s)	Distance of electromagnetic rails (km)
Only inner coil	7.8	21.8
Both inner and outer coils	2.1	6.8

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 time becomes shorter 5.7 s.

(3) The distance of electromagnetic rails is reduced to 1/3 or less. However, the distance even 6.8 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.