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Shielding Current Analysis in High-Temperature Superconducting Film and Its Application

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I. Introduction

Background

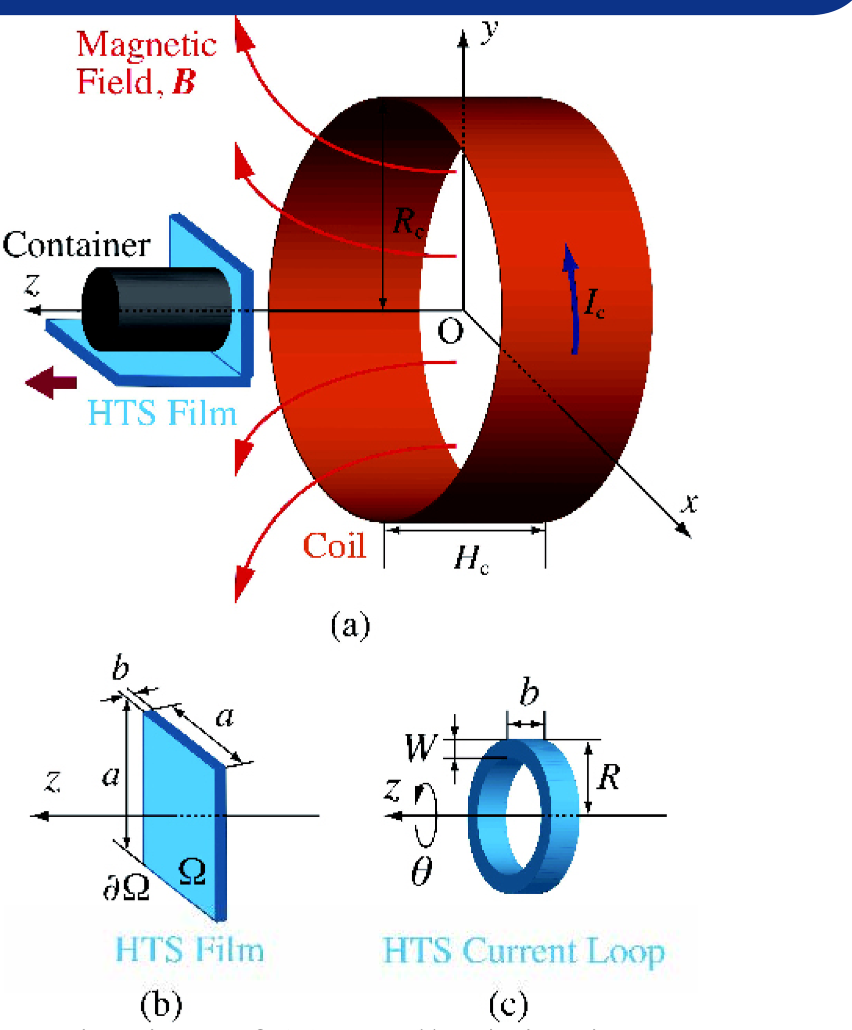
Pellet Injection System

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 Electromagnetic Launch System (SELS)

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 propulsion and levitation.

➡ **They calculate the maximum 10 km/s as the velocity of the pellet injection.**



A schematic view of (a) a pellet injection system used in the SELS, (b) an HTS film for the propulsion and (c) an HTS current loop.

Purpose

(1) *To develop the numerical codes for analyzing the time evolution of the shielding current density by means of the FEM model and the equivalent circuit model for the SELS.*

(2) *To investigate the acceleration performance of the pellet injection system by using the SELS by using two codes*

II. Governing Equation and Motion Equation

A. FEM Model

Shielding Current Density in HTS Sample

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

Here, $S(\boldsymbol{x}, t)$: scalar function, b : thickness.

Integro-Differential Equations

$$\mu_0 \frac{\partial}{\partial t}\left[\iint_\Omega d^2\boldsymbol{x}' Q(|\boldsymbol{x}-\boldsymbol{x}'|)S(\boldsymbol{x}', t) + \frac{2}{b}S\right] + \frac{\partial}{\partial t}\langle \boldsymbol{B}\cdot\boldsymbol{e}_z\rangle + (\nabla\times\boldsymbol{E})\cdot\boldsymbol{e}_z = 0 \quad (2)$$

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

$$m\frac{dv}{dt}z = 2\iint_\Omega \nabla S\cdot\langle \boldsymbol{B}\rangle d^2\boldsymbol{x}. \quad (4)$$

Here, m : mass of container.

Initial and Boundary Conditions

$$S = 0 \ \text{at}\ t = 0, \quad (5a) \qquad v = v_0 \ \text{at}\ t = 0, \quad (5b)$$
$$z = z_0 \ \text{at}\ t = 0, \quad (5c) \qquad S = 0 \ \text{on}\ \partial\Omega. \quad (5d)$$

Ordinary Differential Equations (ODEs)

$$\frac{d}{dt}\begin{bmatrix} \boldsymbol{S} \\ v \\ z \end{bmatrix} = \begin{bmatrix} -W^{-1}U[\boldsymbol{e}(\boldsymbol{S}) + v\boldsymbol{c}(z) + \boldsymbol{h}(z)] \\ \frac{2}{m}\boldsymbol{a}^T(z)\boldsymbol{S} \\ v \end{bmatrix} \quad (6)$$

B. Equivalent Circuit Model

Faraday's law

$$\frac{dI}{dt} = -\frac{1}{L}\left[M(z)\frac{dI_c}{dt} + \frac{dM}{dz}vI_c + e\right]. \quad (7)$$

Here, L : self-inductance of HTS current loop; M : mutual inductance between the coil current I_c and a shielding current I; e : induced electromotive force of the HTS current loop, $e = e_C(|I|/I_C)^N\mathrm{sgn}(I)$, where I_C: critical current and e_C : critical voltage.

Newton's law of motion

$$m\frac{dv}{dt} = -2\pi RB_r(R, z)I. \quad (8)$$

Here, $B_r(r, z)$: r-component of an applied magnetic field $\boldsymbol{B}$.

ODEs

$$\frac{d}{dt}\begin{bmatrix} I \\ v \\ z \end{bmatrix} = \begin{bmatrix} -\frac{1}{L}\left[M(z)\frac{dI_c}{dt} + \frac{dM}{dz}vI_c + e\right] \\ -\frac{2\pi RB_r(R, z)I}{m} \\ v \end{bmatrix}. \quad (9)$$

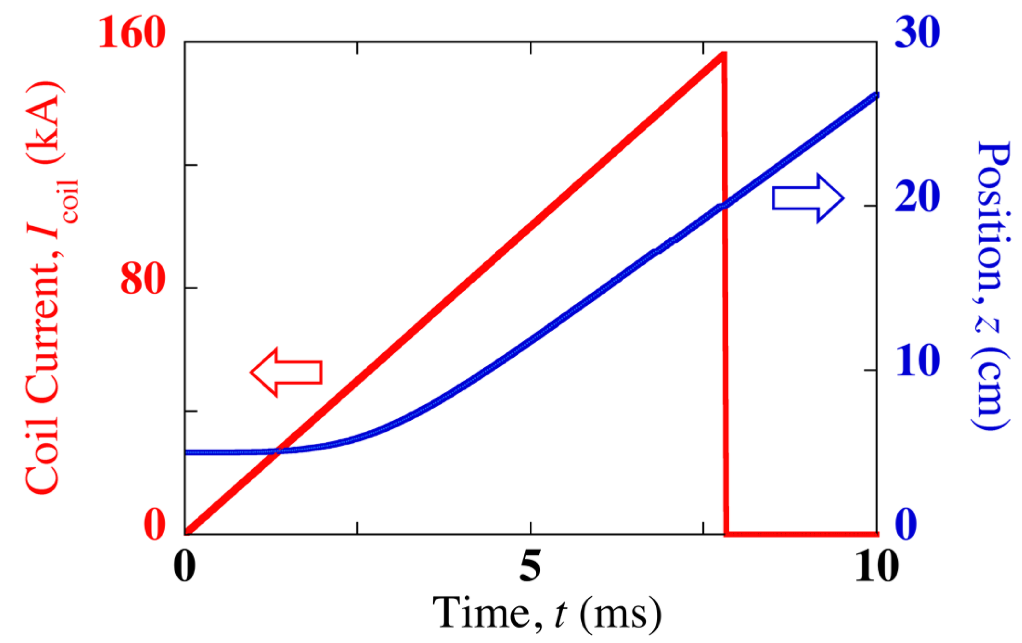
Parameters

R_c = 5 cm, H_c = 10 cm, m = 10 g, v_0 = 0 m/s, N = 20, E_C = 1 mV/m, j_C = 1 MA/cm^2, a = 7 cm, b = 1 mm, R = 3.5 cm, W = 5 mm.

III. Simulation of Pellett Injection System

A. Single Coil for FEM and Equivalent Circuit Models

Coil Current and HTS Position

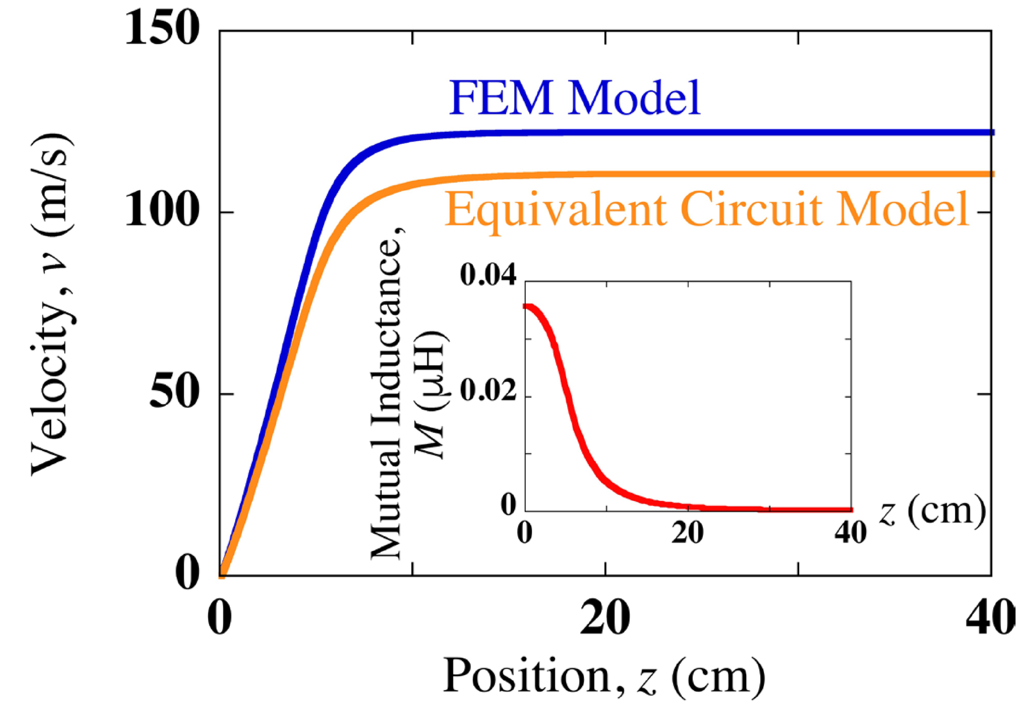


Dependence of the coil current I_c and position z on the time t for the case with α = 20 kA/ms and z_0 = 1 mm. The coil current:

$$I_c(t, z) = \begin{cases} \alpha t & (0 \le z \le z_{\mathrm{limit}}) \\ 0 & (\text{otherwise}) \end{cases}$$

, where z_{limit} is limit of acceleration region, and its value is fixed as z_{limit} = 20 cm.

Velocity and Mutual Inductance

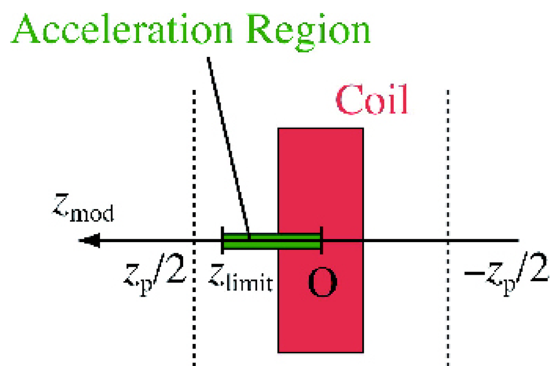


Dependence of the velocity v on the position z for the case with α = 20 kA/ms and z_0 = 1 mm in the FEM model and the equivalent circuit model. The inset indicates the mutual inductance M on the position z for the case with α = 20 kA/ms and z_0 = 1 mm.

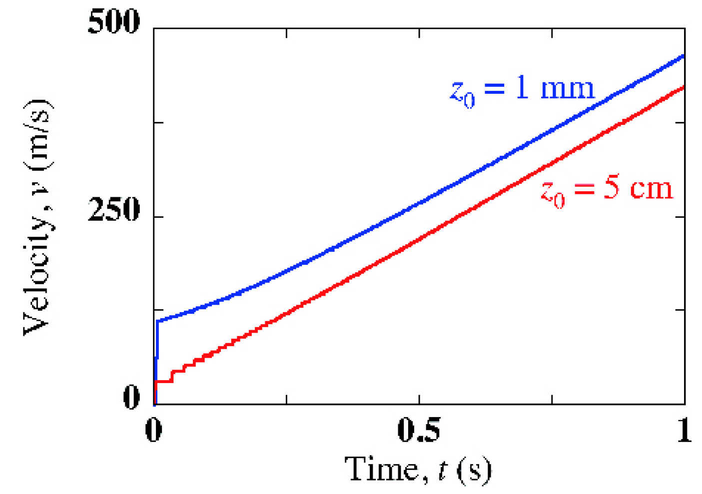
B. Multiple Coils for Equivalent Circuit Model

$$I_c(t, z_{\mathrm{mod}}) = \begin{cases} \alpha(t - t_{\mathrm{min}}) & (0 \le z_{\mathrm{mod}} \le z_{\mathrm{limit}}) \\ 0 & (\text{otherwise}) \end{cases}$$

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

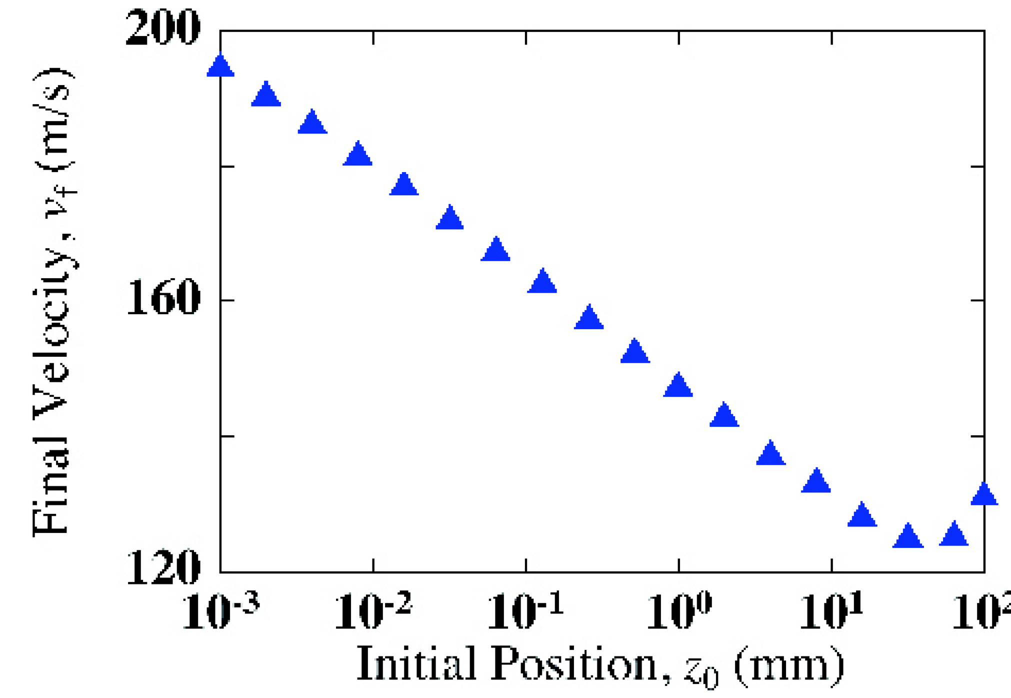


A schematic view of the modeled multiple coils.



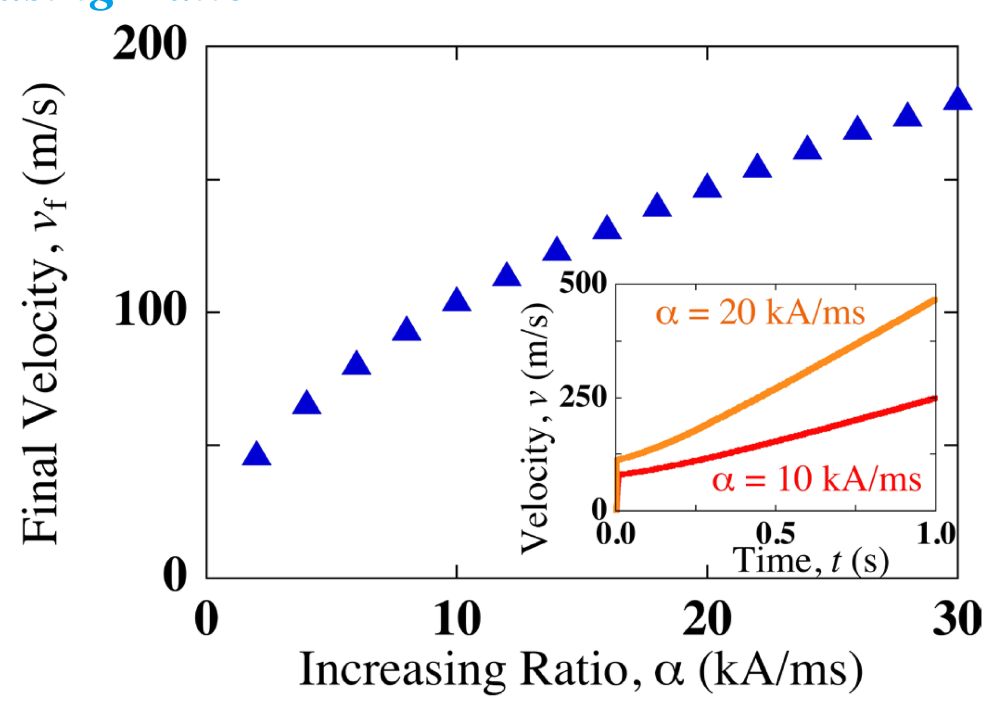
Dependence of the velocity v on the time t for α = 20 kA/ms and z_p/z_{limit} = 5.

Initial Position



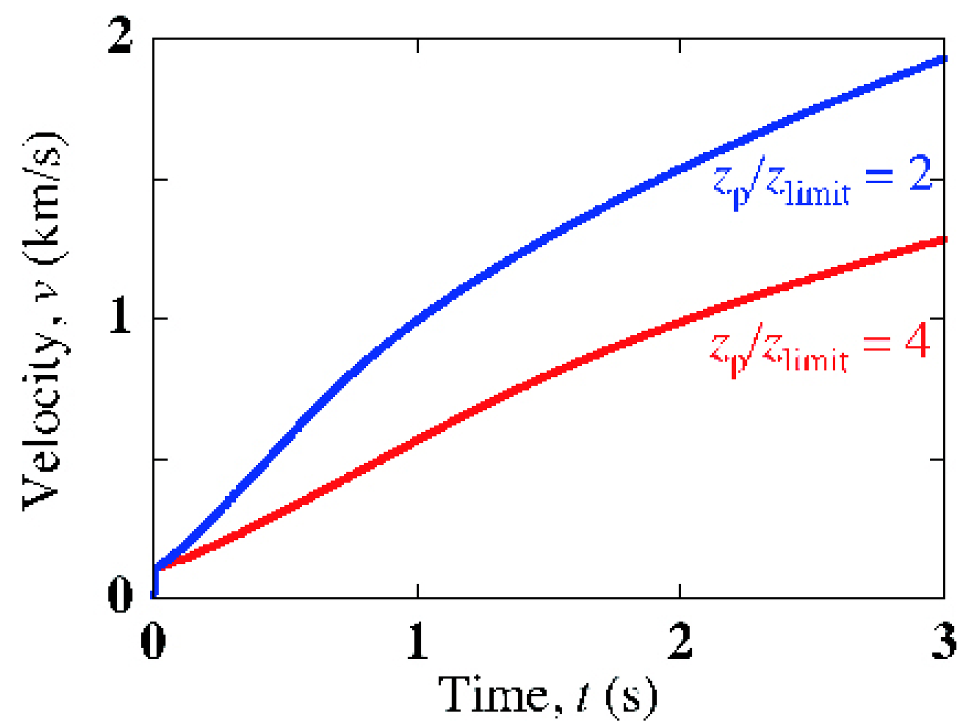
Dependence of the final velocity v_f on the initial position z_0 for the case with α = 20 kA/ms and z_p/z_{limit} = 5.

Increasing Ratio



Dependence of the final velocity v_f = 1 mm and z_p/z_{limit} = 5 on the increasing ratio α for z_0 = 1 mm and z_p/z_{limit} = 5. The inset indicates the velocity v on the time t for z_0 =1 mm and z_p/z_{limit} = 5.

Coil Interval



Dependence of the velocity v on the time t for the case with α = 20 kA/ms and z_0 = 1 mm.

IV. Conclusion

(1) *Although the velocity for the FEM model is larger than that for the circuit model, the behavior of the velocity hardly change qualitatively. However, the FEM model is quite time-consuming because requires a large number of FEM nodes.*

(2) *As the initial position approaches the origin, the acceleration performance improves.*

(3) *The results of the computations show that the velocity increases with the increasing ratio. As a result, the increasing radio of the coil is preferably as large as possible.*

(4) *The pellet injection system using the SELS has the acceleration performance similar to the centrifugal acceleration method.*