Numerical modelling of a type II superconducting disk electromagnetic launching using a pancake coil

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***Abstract*— In this work, we present a numerical simulation of the magnetic field and electrical current distribution inside a single domain YBCO disc exposed to "tooth" shaped magnetic field pulses generated by a pancake coil. The investigation of the magnetic forces acting on a zero field cooled (ZFC) disc at 77K was carried out in both static and dynamic (vertical acceleration) regimes, assuming that the superconductor is a nonlinear conductor with a "power-law" relationship between the electric field and the current. It was demonstrated that a 170 g mass disk can reach accelerations up to 2.5 km/s^2 using magnetic field pulses with amplitudes of several T and rise times of tens of milliseconds.**

Keywords—Coilgun, High temperature superconductivity, Electromagnetic acceleration

I. Introduction

Electromagnetic (EM) launchers are devices that accelerate objects using electrical power. Three types of materials can be launched in this way: metals, permanent magnets and superconductors. In all these cases, it is necessary that the accelerated object be placed in a pulsed, nonhomogeneous magnetic field. During the several past decades, intensive experimental and theoretical investigations have been conducted on conductor acceleration by the pulsed magnetic fields induced by eddy currents. The interest to this type of acceleration was due to its possible applications in the construction of electromagnetic railguns and coilguns (see review [1]). Wide studies of permanent magnet acceleration have also been focused on the development of linear motors [2]. However, relatively little attention has been paid to the electromagnetic launching of superconductors [3,4] or incorporating them in launchers [5]. The high values of the upper critical magnetic fields and critical currents of high temperature superconductors (HTS) [6] raise the possibility of generating large accelerating forces while using pulses with lower magnetic field derivatives, than those needed for the normal acceleration of metals. In this work, we present a numerical investigation of the electromagnetic acceleration of a disk made from a type II superconductor, using a pancake coilgun.

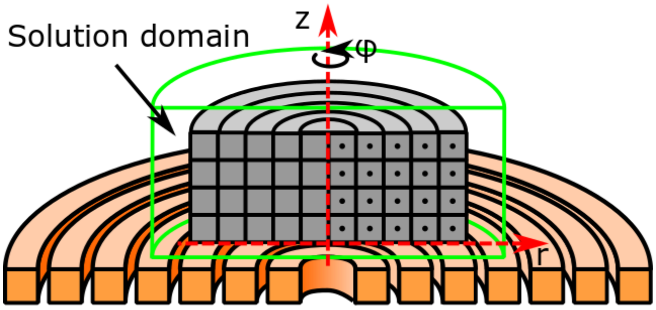

Fig. 1 Model geometry. The superconductor is represented in gray and the pancake coil in orange.

II. Modelling

The modeling geometry used can be seen in fig 1. In order to obtain the 2D axis-symmetric eddy current distribution within the solution domain, we used Maxwell's equations in the H-formulation, which were solved by using Comsol multiphysics commercial software, while taking into account this boundary condition [7]:

$$\vec{H}_{\mathrm{bc}} = \vec{H}_{\mathrm{SC}} + \vec{H}_{\mathrm{ext}}. \quad (1)$$

Here the external magnetic field ($\vec{H}_{\mathrm{ext}}$) generated by the pancake coil is the product of a current pulse $I(t)$ and a spatial map $F(r, z(t))$ which was numerically calculated separately.

$$\vec{H}_{\mathrm{ext}} = \vec{F}(r, z + z_d(t)) \cdot I(t). \quad (2)$$

$\vec{H}_{\mathrm{SC}}$ in (1) is calculated by subdividing the superconducting domain into rectangular sections which correspond to rings in 3D. H_{SC} is the sum of the magnetic fields generated by each ring.

$$\vec{H}_{sc} = \sum_i (\vec{H}_{ri} + \vec{H}_{zi}) \quad (3)$$

The magnetic field (far enough from the section) due to the current flowing in one ring can be calculated by

$$H_{ri}(r,z) = \frac{C\_iz}{2\alpha_i^2 \beta_i r}\Big((a_i^2 + r^2 + (z - z_{0i})^2)E(k_i^2) - \alpha_i^2 K(k_i^2)\Big) \quad (4)$$

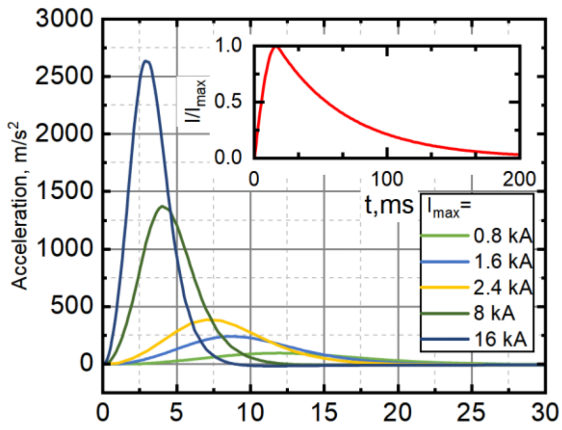

Fig. 2 Acceleration profiles for different pancake current amplitudes. Inset shows the normalized current pulse.

$$H_{zi}(r,z) = \frac{C_i}{2\alpha_i^2\beta_i}\Big((a_i^2 - r^2 - (z - z_{0i})^2)E(k_i^2) + \alpha_i^2 K(k_i^2)\Big) \quad (5)$$

, where

$$\alpha_i^2 = a_i^2 + r^2 + (z - z_{0i})^2 - 2a_i r,$$
$$\beta_i^2 = a_i^2 + r^2 + (z - z_{0i})^2 + 2a_i r,$$
$$k_i^2 = 1 - \frac{\alpha_i^2}{\beta_i^2}, \quad (6)$$
$$C_i = \frac{1}{\pi}\int J\, dA_i$$

a_i – is the radial distance from the central axis and the center of a section (radius of the ring), r and z are the usual cylindrical coordinates, z_{0i} is the ring's distance from the z axis, K and E are the complete elliptic integrals of the first and second kind and J is the current density [8].

When modelling the superconductor, we neglected the Meissner state and regarded it as a nonlinear conductor with a power-law *E-J* relationship, assuming that j_c is constant.

$$E = E_c\left(\frac{J}{J_c}\right)^n. \quad (7)$$

The displacement, velocity and acceleration were calculated from the Lorentz force, taking gravity into account. The problem was then solved by making the superconductor the frame of reference. The distance between the superconductor and the pancake coil was simulated by offsetting the spatial magnetic field map of the coil. The dynamic equation for the vertical displacement (z_d) was:

$$m\frac{d^2 z_d(t)}{dt^2} = \int (J \times \mu H_r)dV - mg \quad (8)$$

here m (in our calculations 170 g), V, g and μ are the disk mass, volume, standard gravity (9.8 m/s^2) and the magnetic permeability, respectively.

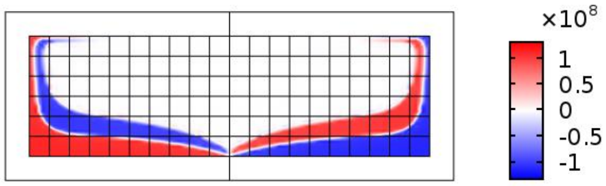

Fig. 3 Current density distribution through the cross-section of the superconducting armature for the 16kA pulse at 44 ms.

III. Results

We modelled the static (projectile fixed) and dynamic (projectile free to move) EM launch scenarios using several current pulse amplitudes, ranging from 0.8kA to 16 kA and passing through a 7 turn pancake coil. The current pulse waveform used for the modeling (see inset in fig.2) was similar to that, which we could produce experimentally in our facility. It was obtained that at the same time instant, the magnetic field penetrates deeper inside the superconducting disk in the case of the static regime, than in the dynamic one. However, the current and magnetic field distribution profiles are similar (see Fig. 3).

The investigation of the disk acceleration dynamics demonstrated that the value of the maximal disk acceleration increased (see fig.3) linearly with the increasing current amplitude ($I_{\max}$). Meanwhile, the acceleration duration (τ_a) decreased as $(I_{\max})^{-1/2}$. It was observed that the acceleration peak occurs before the current pulse reaches $I_{\max}$ (see fig.3 and insert), implying that the current pulse could be shortened for better efficiency. It also needs to be noted that in the case of the high amplitude current pulses (8 kA and 16 kA), after the rapid acceleration, a slight magnetic breaking (acceleration < -g) was observed.

Finally, we concluded that a projectile made from ZFC HTS can be effectively accelerated by magnetic field pulses generated using conventional millisecond electrical pulse techniques.

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