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

Vilius Vertelis[1,2], Saulius Balevičius[2], Markus Schneider[1]

[1] French-German Research Institute of Saint-Louis, Saint Louis, Franc
[2] Center for Physical Sciences and Technology, Vilnius, Lithuania

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Introduction

Electromagnetic (EM) launch is a technology which produced a significant science-to-technology breakthrough in the field of solid body acceleration up to space velocities. The list of its possible applications includes space launch [1], transportation [2], material research [3-4] and even defense technologies [5]. A coil accelerator or coilgun, also known as a Gauss gun, is a type of EM launcher that accelerates ferromagnetic (reluctance coilgun) or conductive (induction coilgun) armatures to high velocities by employing magnetic fields.

At present, only a relatively small number of investigations of the EM launch of type II superconducting armatures have been performed compared to those which investigated the launch of armatures made from normal metals. Calculations performed in [6] demonstrated that a pre-magnetized superconducting armature (using FC) can be accelerated more effectively by a pulsed magnetic field than an armature made from conventional metals. However, this method of acceleration is more complicated as it adds a preparation stage that requires energy. Unfortunately, up to now, incisive investigations of the electromagnetic launch of non-magnetized superconducting armatures have not been conducted.

In this contribution, we are presenting the results of both experimental and theoretical investigations of the electromagnetic acceleration of an ZFC armature made from a type II superconductor. For these studies, we used a disk-shaped superconducting armature made from bulk YBCO, which was launched vertically by a magnetic field generated by a pancake coil. The investigation of the magnetic field dynamics was carried out by FEM in combination with the experimental measurements obtained using a unique CMR-B-scalar sensor that was specifically adapted to the experimental conditions.

Model

The eddy current problem was defined in H formulation.

$$\nabla \times \mathbf{E} + \mu \frac{\partial \mathbf{H}(t)}{\partial t} = 0 \qquad (1)$$
$$\nabla \times \boldsymbol{H} = \boldsymbol{j}.$$

Power law E-J relationship was assumed for the superconducting domain:

$$\mathbf{E} = E_C \left(\frac{|\mathbf{j}|}{j_C}\right)^n \frac{\mathbf{j}}{|\mathbf{j}|} \qquad (2)$$

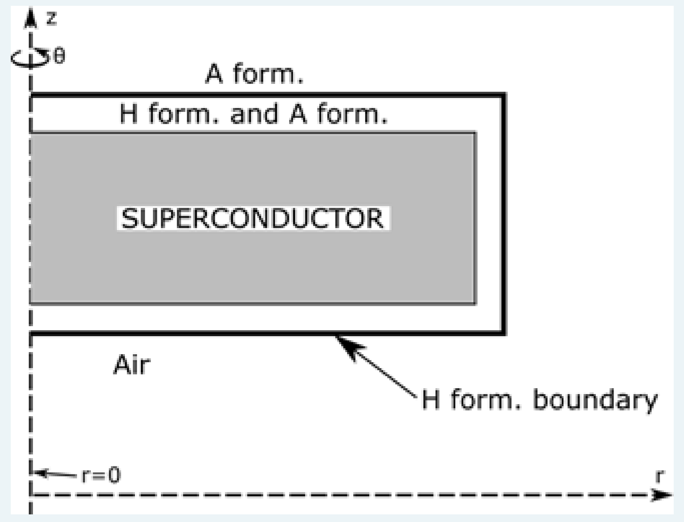

Figure 1. Model geometry.

The magnetic field at the solution boundary was defined as the superposition of the pancake coil field $\mathbf{H}_{PC}$ and the field induced by the superconductor $\mathbf{H}_{SC}$.

$$\mathbf{H}(r,z,t) = \mathbf{H}_{SC} + \mathbf{H}_{PC}. \qquad (3)$$

$\mathbf{H}_{SC}$ was calculated from $\mathbf{j}$ and $\mathbf{H}_{PC}$ was calculated by using a magnetic field map $\mathbf{F}(r,z)$ of the pancake coil and multiplying it by a current pulse $G(d \cdot t)$ with an amplitude of I_{amp}.

$$\mathbf{H}_{PC} = \mathbf{F}\big(r, z + l_{cd} + D(t)\big) \cdot I_{amp} G(d \cdot t) \qquad (4)$$

The dynamics of the superconducting armature were calculated using the Lorentz force taking gravity into account.

$$m\frac{d^2 D(t)}{dt^2} = \int (j_\theta \cdot \mu H_r) dV \; - mg \qquad (5)$$

Experimental validation

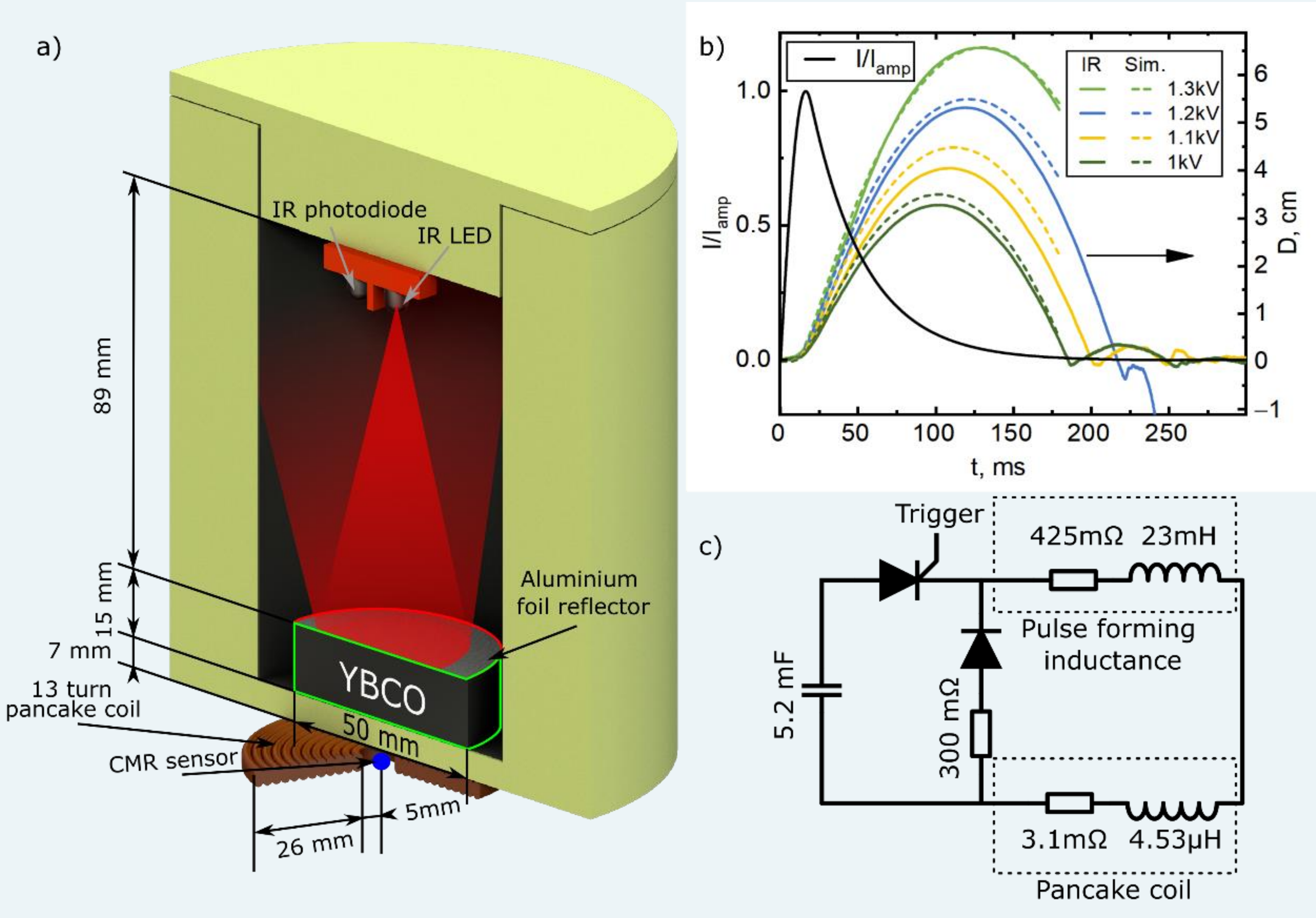

*Figure 2. Experimental setup: schematic diagram and geometry of the coilgun (**a**), normalized current pulse produced by the pulse forming unit (black curve) and typical displacement measurements (**b**). An electrical diagram of the pulse forming unit is presented in (**c**).*

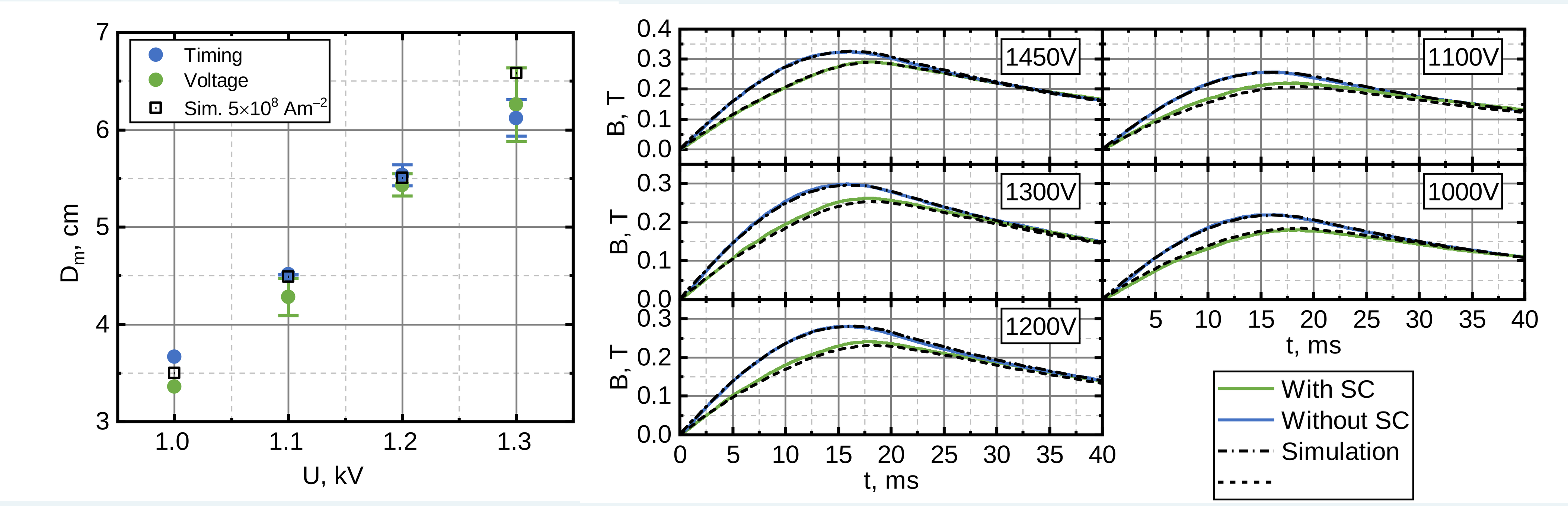

Figure 3. Maximal displacement reached by the disk vs. the capacitor voltage and magnetic field dynamics. Experiments and simulations.

Results

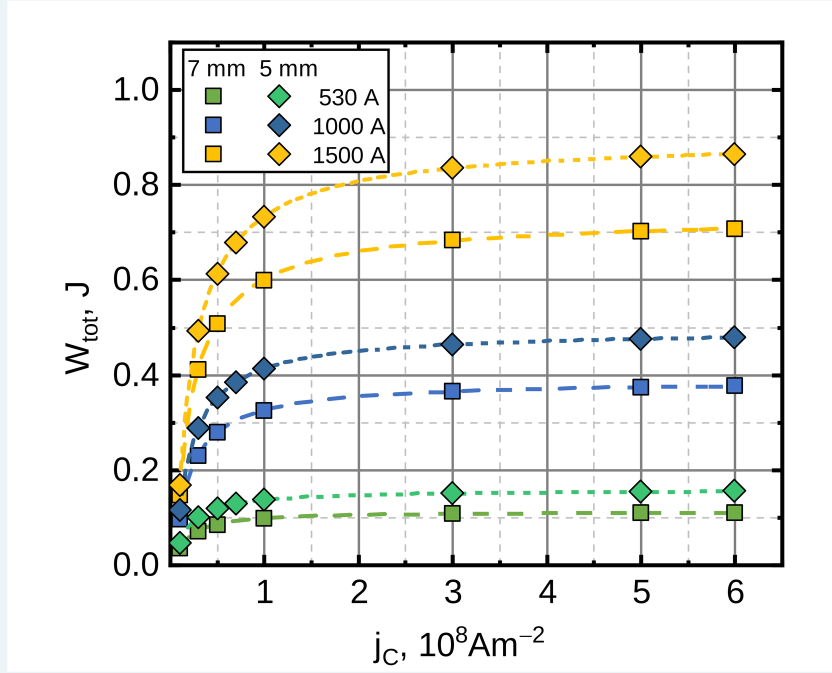

Figure 4. The influence of the critical current density on the total mechanical energy transferred to the superconductor for different current pulse amplitudes and starting heights. The symbols represent the simulation data.

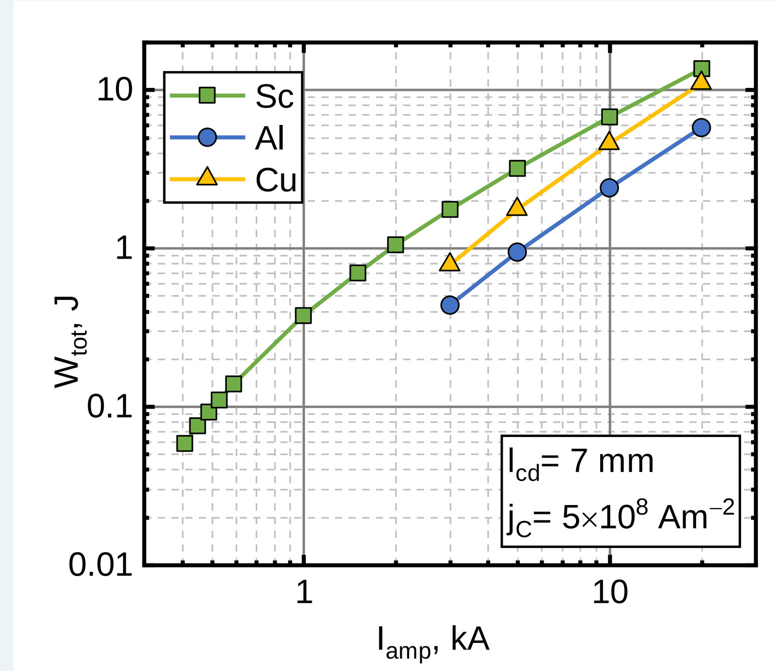

Figure 5. The influence of the current pulse amplitude on the total mechanical energy transferred to an armature made from a type II superconductor, copper or aluminum using the experimental pulse shape and duration.

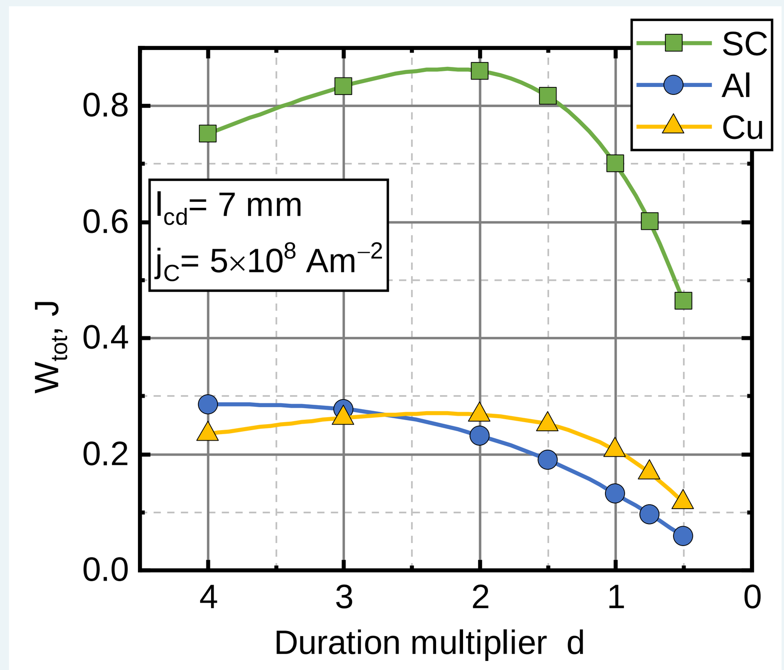

Figure 6. The influence of pulse duration on the total mechanical energy transferred to armatures made from type II superconductor, copper or aluminum. The pulse amplitude was 1.5 kA.

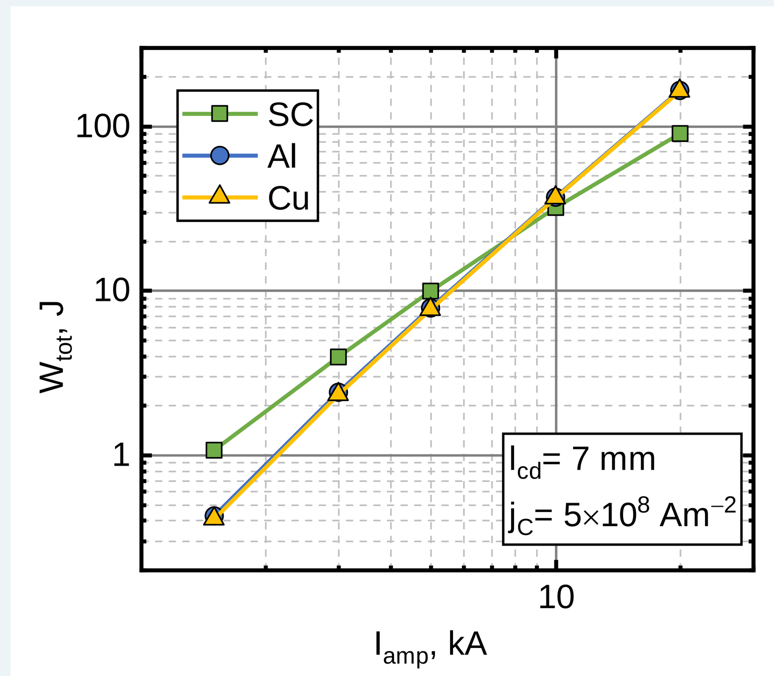

Figure 7. The influence of step-like current pulse amplitude on the total mechanical energy transferred to an armature made from type II superconductor, copper or aluminum.

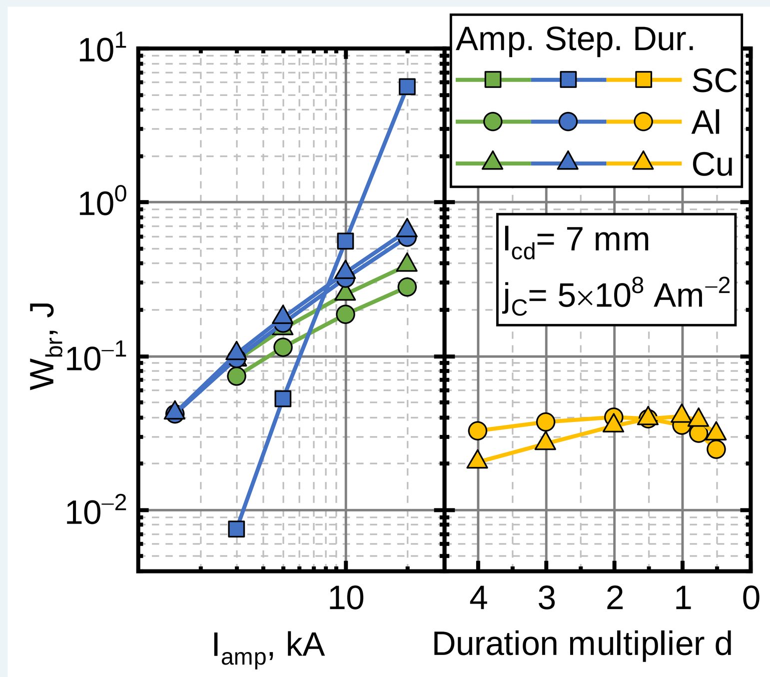

Figure 8. Total mechanical energy lost to magnetic braking. The green line (left) illustrates the effect of the experimental pulse shape amplitude, the blue line, the step-like current pulse amplitude. The yellow line(right) depicts the effects of the pulse duration.

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