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# ANALYSIS OF THE ADVANTAGES OF APPLYING HTC SUPERCONDUCTORS IN ELECTROMAGNETIC DRIVES

**ABSTRACT** *The paper discusses the possibilities and advantages of using HTc superconductors in electromagnetic launchers. It addresses launchers of objects like rail guns as well as ones using pulsed magnetic field. The advantages of using superconducting materials in these launchers are discussed, and the possibility of constructing a new type of electromagnetic launcher based on the ideal diamagnetism of superconductors. These devices are* compared and found superior to powder launchers.

**Keywords**: *electromagnetic launcher, HTc superconductivity, ideal diamagnetism*

## 1. INTRODUCTION

The issue of movement has always been a major aspect of human activity. It concerns, on the one hand, the travel of people between various cities and countries, and on the other, the motion of objects thrown during hunting, such as arrows from bows or the famous boomerangs, which ensured humanity its survival. Currently there are basically four types of drive technique in common use: mechanical drive applied e.g. in windmill devices in renewable energy systems, thermodynamic drive that combines combustion and steam systems, chemical propulsion used in missiles, and electric drive, based on electromechanical effects. This latter type includes electromagnetic drive, which is the subject of this study. Electromagnetic drives are used in various constructions aimed at mechanical launching of objects, starting with small telecommunication satellites and ending with long range missiles. The present paper discusses the advantages of using HTc superconductors in these electromagnetic drive machines.

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Superconducting materials can be used in electromagnetic launchers in the windings of electromagnets, the source of the strong magnetic field, as well as current buses in the railway type of launcher. The main advantage here is the lack of resistivity of superconductors, although this statement concerns stationary cases only. In electromagnetic launchers a dynamic situation occurs leading to electromagnetic losses. The losses generated during the current pulse through the superconductors are a superposition of the resistance, ohmic type of losses described by the Joule formula, as well as electromagnetic losses connected with the time variation in the wire of the magnetic induction generated during the current pulse.

This effect is described by the relation: $L_e = \vec{j} \cdot \vec{E}$ in which $L_e$ is the density of generated electromagnetic losses on the unit volume of the superconducting material, $\vec{j}$ current density, while $\vec{E}$ – the electric field generated by variation of magnetic induction. For determination of the Joule type losses in superconductors $L_J$, we can use a power-like expression with power coefficient $n$ for the generated electric field and then obtain the result: $L_J = \kappa j\,(j/j_c)^n$, where κ is the material coefficient of the proportionality.

Electromagnetic gun drives are constructed in the most developed countries, both from the economic and military-technological point of view. They are especially widely developed in the United States and China in military applications, for instance in the US Navy destroyer of the DDG 1000 type. These electromagnetic guns are expected to shoot 10 kg bullets with the velocity of 7 Machs. The price of one such shot is US$25.000, in comparison to US$500.000, the price of a modern racket. Electromagnetic guns can be used for defence purposes in the navy, to combat missiles, and in space exploration [1-2]. The high power and range of the gun allows to send small satellites with measuring instruments and supplies to space stations. An important advantage is the low launching cost compared to conventional methods providing the same parameters as well as the high ejection speed, and therefore a large range compared to methods used in the usual powder guns.

## 2. ANALYSIS OF AN ACTION AND ADVANTAGES OF USING HTC SUPERCONDUCTORS IN ELECTROMAGNETIC LAUNCHING DRIVES OF THE RAILWAY AND COIL TYPES

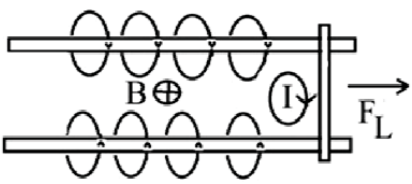


**Fig. 1. Scheme of the railway type electromagnetic drive**

Currently there are usually two kinds of electromagnetic launchers in use. One is based on the system of two buses onto which a conducting current rod is put, moving according to the Lorentz force generated during the current pulse. In this kind of device, shown in Figure 1, the railway type electromagnetic drive is used, while the advantages of using HTc superconducting buses in this construction are connected especially with the smaller losses generated in the process, a subject which will be discussed here.

In the other solution an electromagnetic launcher is constructed by generating a strong magnetic induction in the coil, which then attracts a magnetic steel bullet, as is shown in Figure 2. In this solution, instead of the Lorentz force, a magnetic force arises between a magnetised steel bullet and the coil, generating a high magnetic field. This force, in approximation of two interacting magnets, is described by the following relation:

$$\vec{F}_m = \mu \cdot \mu_0 \frac{m_1 \cdot m_2}{4\pi d^2} \tag{1}$$

where $m_1$ and $m_2$ are according to magnetic Coulomb law magnetic poles of the interacting objects, $\mu$ – relative magnetic permeability, $\mu_0 = 4\pi\ 10^{-7}$[V s/(A m)] – the magnetic permeability of vacuum, and $d$ – the distance between the interacting objects. In this case a pulsed, appropriately profiled high-current wave-form should also be applied just as in the first case, leading to a continuous acceleration of the bullet.

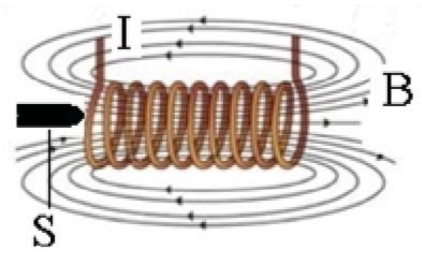


**Fig. 2. Scheme of the electromagnetic launcher based on the attraction between the steel bullet (S) and superconducting coil through which flows current (I) generating strong magnetic induction (B)**

In both of the above-presented solutions there are advantages of using superconducting wires instead of the conventional ones. It concerns the almost resistivityless transport current flow through the superconductors, which effect allows to construct buses for large current pulses and high magnetic fields. A disadvantage is the cost of materials and cooling, which, however, for HTc superconductors requires only liquid nitrogen. The large current flow generates electromagnetic losses according to the formula $L = \int \vec{j} \cdot \vec{E}\, dV$ . In the case of the copper wire of the length of 1 m and cross-section of 1 cm$^2$ for the 10 kA current and copper resistivity of $\rho = 1{,}7\ 10^{-8}\ \Omega$ m [3], losses per unit volume bring the value of 1,7 $10^4$ W. The electric field in the 1 m long wire then reaches the value of 1,7 V. For a superconducting material, however, the generated electric field in the resistive state is described by the power-like law: $\vec{E} = \beta \left( \vec{j} / \vec{j}_c \right)^n$, where $n$ is a power exponent, while $\beta$ a material parameter. It is equal in the superconducting wires in resistive state to about 100 μV/m. For the same current of the range of 10 kA, losses in the superconducting wires are then equal to 1 W, which result indicates the advantage of using superconductors in high power machines, especially with high critical temperature. We remember that actually highest critical temperature of superconducting material reaches value of 203 K in an $H_3S$ compound [3] or even 250 K in $LaH_{10}$ [4] compound under giant pressure. However, besides these Joule-type losses there are also electromagnetic losses connected with the dynamic effect of the penetration of magnetic induction into superconductors in the form of vortices, which lead to the generation of the electric field according to Maxwell's law $\vec{E} \sim -\frac{\partial \phi}{\partial t}$, where $\Phi = \vec{B}\vec{S}$ is magnetic flux penetrating the closed surface S. Analysis of these losses will be performed now. For linear pulsing in time the electric current derivative $d\vec{B}/dt$ is constant, while these losses will also increase with time and the total losses will be the superposition of both these complementary mechanisms. Figure 3 shows the profiles of the magnetic induction during the transport current ramp. It is a schematic picture of the penetration of magnetic induction during the increase with time of the current up to the maximal value $I_m$, followed by the decrease of the current to null. Direction of the current change and the profile of the magnetic induction following it is denoted by arrows in this figure. After decrease of the current to zero, the remanent magnetic induction is retained in the bulk of the superconductor, while its profile is described schematically by the shape of the triangle shown at the bottom of Figure 3. Following its increase in the current during the subsequent and following cycles of the applied pulsed current lead to the magnetic induction profiles denoted by arrow ↑ in Figure 3. For calculations of the profiles of the magnetic induction distribution shown in Figure 3, Maxwell's equation has been used, which for that case brings the form:

$$\mu_0 \vec{j} = rot\ \vec{B} \tag{2}$$

Applying then Stokes' theorem and integrating Eq. 2 at the edge *l* of the surface *S*:

$$I = \int \mu_0 \vec{j} d\vec{S} = \int rot\ \vec{B}\ d\vec{S} = \oint \vec{B}\ d\vec{l} = 2\pi r B \tag{3}$$

we obtain an expression for the magnetic induction distribution in the considered here case of the electric transport current flowing through the superconducting material:

$$B = I/2\pi r \tag{4}$$

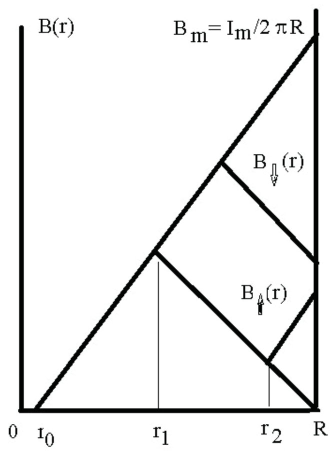


**Fig. 3. Schematic view of the magnetic induction distribution B(r) in linear approximation in the superconductor for the first and following ramps of the transport electric current of the amplitude $I_m$ flowing through the superconductor of the thickness 2R.** Arrows ↑ and ↓ indicate, respectively, the current increase and decrease.

# 3. ELECTROMAGNETIC LOSSES GENERATION DURING LINEAR CURRENT INCREASE

For describing the current distribution in superconducting wire, which effect plays a crucial function in the determination of electromagnetic losses, we apply the critical state approximation. According to it, for the case of the first increasing linear rise of the transport electric current $I = \propto \cdot t$, it penetrates the sample up to the depth $r_0$, determined by the expression:

$$r_0 = R \cdot \sqrt{1 - I/I_c} \tag{5}$$

Here $I_c$ is the critical current of the superconducting wire determined by the condition $I_c = \pi R^2 j_c$, α – the coefficient of proportionality, $t$ – time, while the amplitude of flowing transport current is connected with the radius $r_0$ by the relation:

$$I = \pi j_c (R^2 - r_0^2) = I_c - \pi j_c r_0^2 \tag{6}$$

From the above relations the magnetic induction profiles have been calculated firstly for initial rise of the current

$$B_{\uparrow 1}(r) = \frac{\mu_0 I_c}{2\pi r} \cdot (\frac{r^2}{R^2} - 1 + \frac{I}{I_c}) \tag{7}$$

and then connected with this induction magnetic flux generated in the region ($r_0$ – $R$) of the unit length of the superconductor, according to the notation of Figure 3.

$$\emptyset_{1\uparrow}(r_0, R) = \frac{\mu_0 I_c}{4\pi} \left[\left(1 - \frac{I}{I_c}\right) \cdot \ln\left(1 - \frac{I}{I_c}\right) + \frac{I}{I_c}\right] \tag{8}$$

Variation of this magnetic flux with time, which determines the generated electric field in a unit length of wire, is as follows:

$$\frac{\partial \emptyset_{1\uparrow}}{\partial t} = -\frac{\mu_0 \alpha}{4\pi} \ln (1 - \frac{I}{I_c}) \tag{9}$$

Based on these equations, the losses generated during the first, initial increase of electric current have been determined:

$$L_{1\uparrow} = -\frac{\mu_0 \alpha}{4\pi} \mathrm{I} \cdot \ln (1 - \frac{I}{I_c}) \tag{10}$$

For decreasing current the magnetic induction profiles then generated are marked in Figure 3 by arrow ↓. Length $r_1$ denoted in Figure 3 is given by:

$$r_1 = R\sqrt{1 - \frac{\alpha(t-t_n)}{2I_c}} \tag{11}$$

$(t - t_n)$ is the time running from the start of the decrease of the current from maximal intensity in the *n*-th cycle, $t_n$ is the time of the start of the n-th current cycle.

Following this decrease of the current, in the subsequent *n*-th cycle current increases and then the magnetic induction at the depth inside the sample of the range $r_2 < r =< R$, shown in Figure 3, is mathematically given by:

$$B_{2\ldots n,\uparrow}(r) = \frac{\mu_0 I_c}{2\pi r}\left[\frac{r^2}{R^2} - 1 + \frac{I}{I_c}\right] \tag{12}$$

where

$$r_2 = R\sqrt{1 - \frac{\alpha(t-t_n)}{2I_c}} \tag{13}$$

The current then flowing in this outer part of the wire is given by:

$$I(r) = I_c\left(\frac{r^2}{R^2} - 1 + \frac{I}{I_c}\right) \quad \text{for } r_2 < r =< R \tag{14}$$

The magnetic flux for the unit length of superconductor penetrating onto the depth $r_2$, caused by the increasing current flow in the second and following increasing cycles of the current pulses is given by the relation:

$$\emptyset_{2\ldots n,\uparrow}(r_2, R) = \frac{\mu_0 I_c}{4\pi}\left[\left(1 - \frac{I}{I_c}\right)\ln\left(1 - \frac{I}{2I_c}\right) + \frac{I}{2I_c}\right] \tag{15}$$

The time derivative of this flux is:

$$\frac{\partial\emptyset_{2\ldots n,\uparrow}(r_2,R)}{\partial t} = -\frac{\mu_0 \propto}{4\pi}\left[\ln\left(1 - \frac{I}{2I_c}\right) + \frac{I}{2(I-2I_c)}\right] \tag{16}$$

The electromagnetic losses generated in unit length of the superconductor and connected with the magnetic induction varying inside the sample on the depth $r_2 - R$, in the second and further ramping increase of current are therefore equal:

$$L_{2\ldots n,\uparrow}(r_2, R) = -\frac{\mu_0 \alpha I}{8\pi}\left[\ln\left(1 - \frac{I}{2I_c}\right) + \frac{I}{2\cdot(I-2I_c)}\right] \tag{17}$$

In analogous way we calculate losses generated in the region ($r_1$, $r_2$) and obtain final losses in increasing second increase of the current:

$$L_{2\ldots n,\uparrow}(r_0, R) = \frac{\mu_0 \alpha I}{8\pi}\left[\frac{I_m}{2\cdot(2I_c - I)} - \ln\left(1 - \frac{I}{2I_c}\right)\right] \tag{18}$$

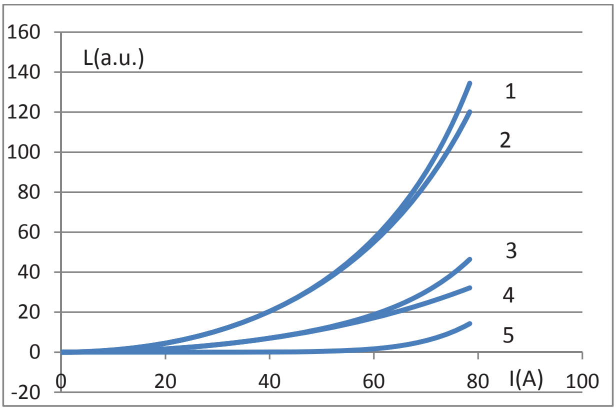


**Fig. 4. Dependence of the losses generated in HTc superconductor on the linearly varying current**
(1) Losses generated in the first rise of the linearly varying current and ohmic losses, (2) Losses generated in the first growth of the linearly varying current (3) Losses generated in subsequent increases of the linearly varying current and ohmic losses (4) Losses generated in subsequent increases of the linearly varying current and (5) pure ohmic Joule losses.

The results of the calculations of the electromagnetic losses arising during linearly sweeping current, which generates appropriate profiles of the magnetic induction inside the wire discussed above, are shown in Figure 4. As it follows from this Figure generated losses decrease in subsequent current cycles in comparison to the first one. It has meaning from the point of view of exploitation of these devices and indicates on the importance of the hysteresis effects and their influence on the electromagnetic phenomena as losses in superconductors.

## 4. ANALYSIS OF NEW ELECTROMAGNETIC LAUNCHER BASED ON THE IDEAL DIAMAGNETISM OF SUPERCONDUCTORS

Above presented theoretical analysis concerning the generated losses indicates on the advantages of using HTc superconductors in electromagnetic launching devices and presents their unique properties. In the present point it will be given the analysis of work still one new type of the superconducting launcher based on applying in its construction the second essential property of superconductors, beside null resistivity, which is an ideal diamagnetism of these materials [5]. In this solution the repulsion between the ferromagnet, in present case shown in Figure 5 of the geometrical shape of the horseshoe and a diamagnetic superconducting element is obtained due to distortion of the magnetic field force lines as is here shown.

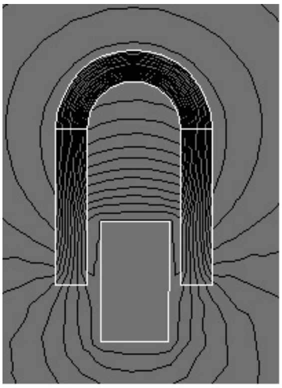

**Fig. 5. Modelling view of the electromagnetic launcher based on the Meissner effect, using diamagnetic HTc superconducting bullet**

In the equilibrium position the magnetic field force lines tend to bring the linear shape as is shown in the upper part of Figure 5, which means equal magnetic field value. The curvature of these lines connected with the existence of the superconducting, diamagnetic element leads to the increase of magnetic induction on the upper edge of the bullet and decrease of induction at the bottom edge. This means that the Lorentz force $F_L$ acting on the surface element of the bullet will be different for these two planes: $\vec{F}_L = \vec{j}_c x \vec{B}_p$ . $j_c$ is the critical current density screening the magnetic induction in superconducting element, while $B_p$ – magnetic induction parallel to the surface. The difference between these forces acting on the upper and bottom surface of superconductor will give the total force $F$ accelerating the bullet. In this solution the superconducting bulk element will be the active one from the magnetic point of view, onto which is put track or bullet moving and accelerated in this process. Figure 6 shows the dependence of the force of acceleration $F$ calculated according to above analysis and acting on such a kind of object in the function of the position of the upper surface of the

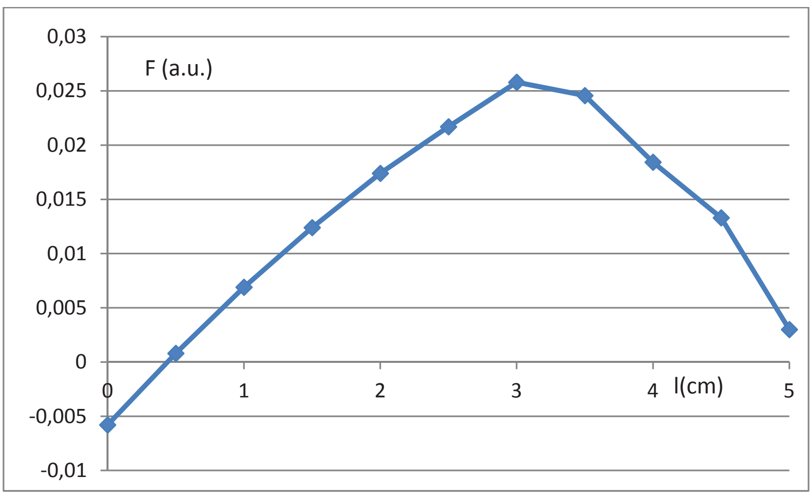


**Fig. 6. Dependence of the force of acceleration F (in arbitrary units), acting on the moving object containing a bulk HTc superconducting element**

superconductor versus the horseshoe magnet shown in Figure 5. The integral from this force versus the movement gives the value of the kinetic energy and then velocity of the movement of the accelerated object, according to:

$$v = \sqrt{\frac{2\int F dx}{m}} \tag{19}$$

where $m$ is the mass of the total moving object. For the bullet of the mass $m = 0{,}1$ kg and the electromagnetic force $F = 10$ N of accelerating object on the distance of 1 m, we obtain the velocity of movement $v = 50{,}91$ km/h. This result again indicates that for obtaining a large velocity of movement it is necessary to apply a high magnetic field achievable just by the superconducting electromagnets.

## 5. CONCLUSIONS

The paper has discussed the advantages of using HTc superconductors in electromagnetic type drives. Three kinds of drives in which application of HTc superconductors should be useful have been considered. In the railway type and pulsed magnetic field guns the advantages following from the almost null resistivity effects have been regarded. In the third solution the ideal diamagnetism of HTc superconductors has been utilised for modelling of the new type of launcher.

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ANALIZA ZALET ZASTOSOWANIA NADPRZEWODNIKÓW WYSOKOTEMPERATUROWYCH W NAPĘDACH ELEKTROMAGNETYCZNYCH

Jacek SOSNOWSKI

**STRESZCZENIE** *W pracy przedyskutowano alternatywny rodzaj napędów jakimi są napędy elektromagnetyczne i możliwości wykorzystania w nich elementów nadprzewodnikowych. Rozpatrzono wyrzutnie obiektów typu działa szynowego, jak też z użyciem uzwojeń wytwarzających silne, impulsowe pole magnetyczne. Omówiono ich zastosowania. Przedstawiono generowane w elementach nadprzewodnikowych straty mocy i porównano ze stratami w rozwiązaniach konwencjonalnych. Omówiono nowy rodzaj wyrzutni oparty na idealnym diamagnetyzmie nadprzewodników i przedstawiono wymagane parametry materiałowe.*

**Słowa kluczowe**: *napędy elektromagnetyczne, nadprzewodnictwo wysokotemperaturowe, idealny diamagnetyzm*

**Professor Jacek SOSNOWSKI** has graduated from the Physics Faculty of the University of Warsaw. Since 1980 he has been employed in the Electrotechnical Institute in Warsaw. He has specialised in investigations of superconducting materials, recently especially in their electromagnetic properties connected with the critical currents phenomena and applications of the high-temperature superconductors in electric devices, such as cables. He has supervised PhD and DSc theses in the area of superconductivity and has received the full professor title. He is the author of about 300 papers published in Polish and international journals. He was awarded the prize of the International Electrotechnical Commission (IEC). He has taught superconductivity at the Warsaw University of Technology and at the Extramural PhD Course in the Electrotechnical Institute. He has made study visits to Russia, Germany, France and Japan.