



## Rail Launchers to reach Hypervelocity

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**Summary**—In this paper we present a theoretical study of a 80 mm round bore railgun which allows us, by a current distribution along the projectile, to accelerate a long rod penetrator with a fineness ratio of 30 up to a muzzle velocity of 2500 m/s with an overall efficiency greater than 30 %.

This study was started because an optimal impact velocity which allows a given depth of penetration to be reached with a minimum kinetic energy exists for all the targets (homogeneous, composite, structured or reactive). Two years ago we showed that this impact velocity is always greater than 2300 m/s for a heavy alloy penetrator with  $L/D = 30$ . For these velocities the electromagnetic rail launchers may have efficiencies over 35 % when classical powder guns have efficiencies about 20 %.

### INTRODUCTION

The experimental and theoretical studies of the terminal efficiency of long rod projectiles [1-5] as a function of their mass and velocity have allowed to determine the penetration depth and have shown the existence of an optimal velocity for which the penetration  $P$  in a given target is maximum. These studies were made essentially for homogeneous targets [1-4] and sometimes for so called "modern" targets [5].

The classical powder guns can only accelerate projectiles up to velocities of about 1650 m/s with interesting efficiency of about 25 % [6]. One has to double the powder mass to increase this velocity by 20 % and reach 2000 m/s. The use of electric launchers in the anti-armor mission allows to reach velocities higher than 2000 m/s [4, 7, 8], but the energy storage systems are still very large and it is useful to think about their optimization. To reduce the volume of these energy sources it is first important to find the minimal energy necessary to achieve a given performance. For the anti-armor application, we have shown for the first time the existence of a penetrator minimal kinetic energy at high velocities for a given penetration [9]. We have also shown that the optimal impact velocity which allows to reach this given depth of penetration is always greater than 2300 m/s for a heavy alloy penetrator with  $L/D = 30$ . Also in the anti-aircraft mission, the hit probability of non guided projectiles increases with the velocity. Values of about 3000 m/s or more are very interesting for the air defense applications [10]. All the military applications have shown the interest of velocities between 2000 m/s and 4000 m/s. The rail launchers are able to reach these high velocities with an overall efficiency (kinetic energy of the projectile/stored electrical energy) which can be greater than 30 %.

In this paper we start from the terminal ballistic results [9] for a long rod penetrator with a fineness ratio of 30 and show with a numerical simulation that a 80 mm round bore railgun allows us to accelerate this penetrator up to a muzzle velocity of about 2500 m/s.

## PENETRATOR CHARACTERISTICS

We have shown [9] that there is a minimum energy which allows us to achieve a given penetration in a homogeneous target. Knowing this minimal impact energy  $E_i$  and the associated velocity  $v_i$  one can calculate the mass of the penetrator.

In this paper we consider a penetrator made of heavy metal with a fineness ratio of 30. The penetrator characteristics are then  $E_i \approx 8$  MJ,  $v_i \approx 2300$  m/s,  $m \approx 3$  kg. If we assume a velocity loss in the air of 60 m/s per kilometer and a range of 3000 m, the muzzle velocity must be about 2500 m/s to achieve the required performance.

## SABOT CHARACTERISTICS

## 1 Stress distribution along the projectile

To know the muzzle energy, one has to estimate the sabot mass i.e. the sabot design. For classical powder guns the accelerating forces generated by the gas pressure act essentially on the rear side of the sabot and cannot be distributed along the penetrator. In this case tensile stresses appear at the back of the projectile and compressive stresses at the front side (Fig. 1a). It means that it is difficult to accelerate a long rod projectile because of buckling appearing with a bad strength distribution over the length of the projectile. In the railgun on the other hand one may distribute the current and so the stresses along the sabot (Fig. 1b,c) [11]. This leads us to a new sabot design with several injection points. In a first time, we chose to inject the propulsive forces at two different injection points (Fig. 1b).

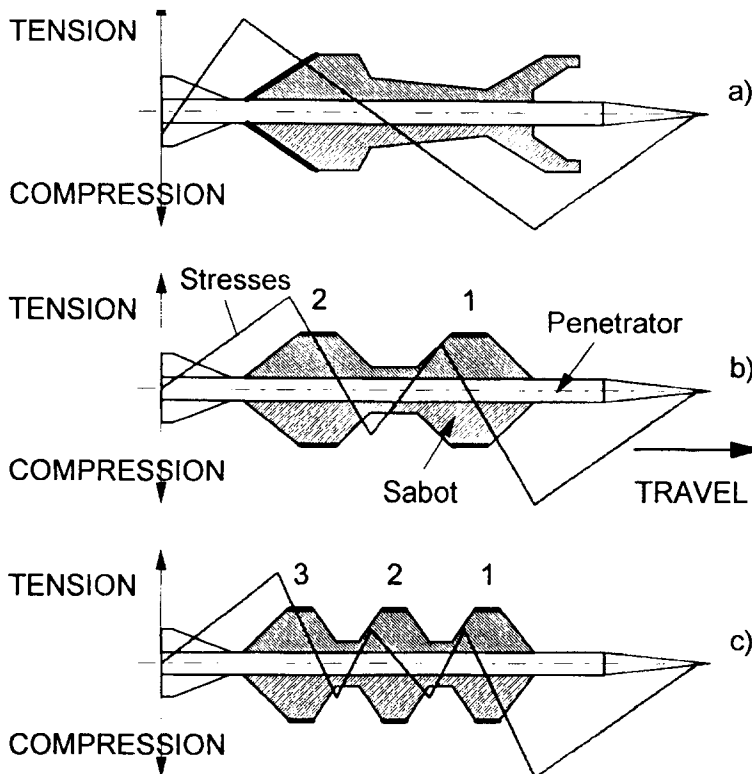


Fig. 1. Axial stresses in the penetrator: a) powder gun, b) and c) railgun with distribution of the current in 2 (b) or 3 (c) injection points

The accelerating force in a railgun results from the interaction between the current and the magnetic induction. The forces  $F_1$  and  $F_2$  acting respectively on the first and second armature are (Fig. 1b):

$$F_1 = I_1 l \times B_1 \quad (1)$$

$$F_2 = I_2 l \times (B_2 + B_{1,2}) \quad (2)$$

where  $I_i$  ( $i = 1$  or  $2$ ) is the current in the first or second armature

$B_i$  ( $i = 1$  or  $2$ ) is the magnetic induction at the first or second armature

$B_{1,2}$  is the magnetic induction at the second armature due to the current  $I_1$

$l$  is the width of the armature.

From these two expressions one can see that the forces acting on the armatures cannot be equal when the currents are equal. Assuming that the rails of the launcher are two infinite long threads and without taking into account skin and proximity effects one can obtain equal forces on the leading and trailing armatures when  $I_1 = 0.62 I$  and  $I_2 = 0.38 I$ , where  $I$  is the total current. This current distribution can be obtained using different rail pairs [11]. This solution allows the use of hybrid armatures but needs two different energy storage systems. Another way to distribute the current is to modulate the armature impedance. This solution needs only one energy storage system but requires solid armatures made of adequate materials with adequate design. In a first time we neglect the skin, proximity and thermal effects and assume one can distribute the current in the right way.

## 2 Requirements for sabot design

To design a sabot for a long rod penetrator which can be launched with a railgun we assume:

- the accelerating forces can be distributed along the projectile,
- to inject the current at two different positions and to avoid the thermal erosion of the penetrator due to the current flow, one has to insulate the sabot from the penetrator,
- the chosen materials must withstand the stresses at their interface (shearing stresses),
- the sabot material must have good electrical properties: relatively high resistivity to have a large skin depth,
- the sabot materials must be light to reduce the total mass of the projectile and to minimize the stored electrical energy.

## 3 Sabot design

### 1 Electrical point of view

The sabot part in contact with the rails must lead high currents. We have shown [12] that an armature, for example a ring, made of titanium is appropriate to the rail launcher. This allows i) to limit the sabot mass, titanium being a relatively heavy material ( $\rho = 4540 \text{ kg/m}^3$ ) and ii) to have no currents in the penetrator. The length of the ring is given by the penetration of the current lines, its thickness by thermal and mechanical considerations. One has to consider the velocity skin effect. For a given velocity the length  $\delta_s$  over which the current penetrates in the armature is approximately given by:

$$\delta_s \approx 2\delta_r \frac{\sigma_r}{\sigma_s} \quad (3)$$

where  $\delta_r$  : skin depth in the rails at the velocity  $v$

$\sigma_r, \sigma_s$  : electrical conductivity of the rail and sabot material respectively.

The skin depth in the rails at the velocity  $v$  is given by:

$$\delta_r = \sqrt{\frac{\pi}{R}} \delta_{r0} \quad (4)$$

where  $\delta_{r0}$  : skin depth in the rails at the velocity  $v = 0$   
 $R$  : Reynolds number

$$R = \mu v \sigma_r \delta_{r0} \quad (5)$$

where  $\mu$  : magnetic permeability of rail material  
 $v$  : projectile velocity.

For a frequency of 200 Hz the skin depth  $\delta_s$  in titanium is of the order of 40 mm for a velocity of  $v = 1000$  m/s. We assume two rings of 45 mm in length (Fig. 2). If each ring has to conduct a current of 2 MA during 5 ms and if we assume that the contact between rails and sabot is metallic with an electrical resistance of about  $30 \mu\Omega$  the ohmic energy loss  $E_J$  will be about 600 kJ. The mass of the Ti was chosen so that the temperature reached by each ring after adiabatic heating remains lower than the liquefaction temperature of Ti ( $T_f = 1670^\circ\text{C}$ ). For a ring mass  $m = 850$  g, the heating will be:

$$\Delta T = \frac{E_J}{m C_v} = 1340\text{K} \quad (6)$$

where  $C_v$  : specific heat of Ti.

To avoid current flow in the penetrator we insulate the rings from the inner part of the sabot. From the electrical point of view this inner part could be made of insulator material but the yield stresses appearing in the sabot are too large for the known insulator materials. So we chose to use reinforced Al (Fig. 2) [13].

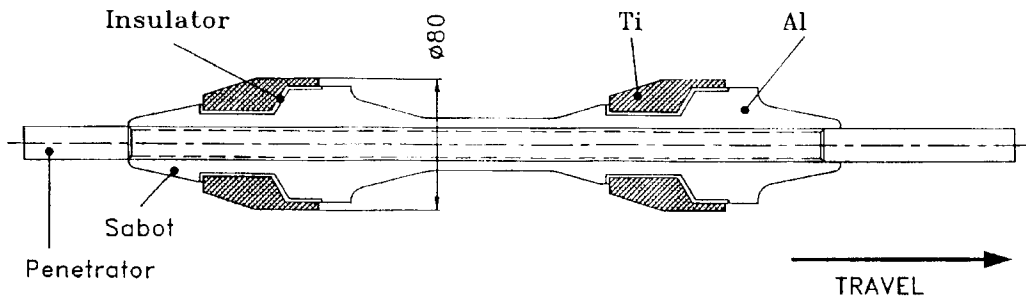


Fig. 2. Sabot design for an 80 mm railgun [13]

## 2 Mechanical point of view

We assume a maximal acceleration of  $10^6 \text{m/s}^2$  and that the forces are uniformly distributed on the two rings. The compression between a ring and the body of the sabot is about 960 MPa for a 80 mm caliber on the circular ring surface. If we want to reduce the caliber to 60 mm (to reduce the total mass of the projectile) then the compression will be about 2800 MPa.

The yield strength of the chosen materials imposes a minimal caliber of 80 mm for an acceleration of about  $10^6 \text{ m/s}^2$ .

The other important component of stress in the sabot is the shear stress which requires a sufficient length of Al material in front of the pushing titanium rings. To know the total length of the sabot one has to consider the tension and compression forces on the penetrator. For the chosen quality of tungsten sinter-alloy the permitted length behind the sabot is 63 mm (tension) and the length in front of the sabot is 115 mm (compression). If we also consider buckling this length can only be 104 mm. All these considerations lead to a sabot mass of 3 kg (50 % of the total mass). The sabot design and the materials used are given in Fig. 2. This version of sabot has a cylindrical part between the two Ti ramps because it is not easy to distribute symmetrically the accelerating forces. In the future a better understanding of the stresses and their distribution would allow to withdraw this central part and to lighten the sabot of about 20 %. The required muzzle energy for the 3 kg sabot is then 18.8 MJ.

### RAILGUN DESIGN FOR ANTI-ARMOR APPLICATION

The caliber is given by the mechanical resistance of the sabot material (see above): 80 mm. To limit the acceleration to values under  $10^6 \text{ m/s}^2$  we chose a 6 m long tube and we distribute the energy along it (DES: Distributed Energy Storage). The railgun is supposed to be fed by 6 stages. For the numerical simulation using the ISLAM code [14] we assume the rail design shown in Fig. 3 ( $e = 10 \text{ mm}$ ,  $\theta = 45^\circ$ ,  $L' = 0.48 \text{ } \mu\text{H/m}$ ). The simulation results give an overall efficiency of about 33 % and the stored energy has to be about 60 MJ (Fig. 5).

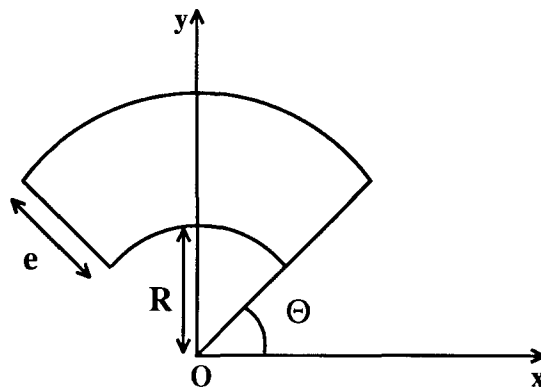


Fig. 3 . Copper rail design used for the numerical simulation

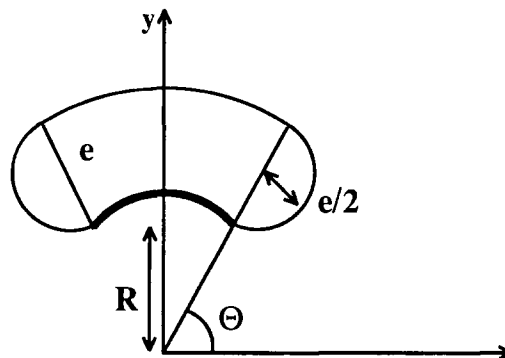


Fig. 4 . "Banana" rail design (the thick line presents the contact surface with the projectile)

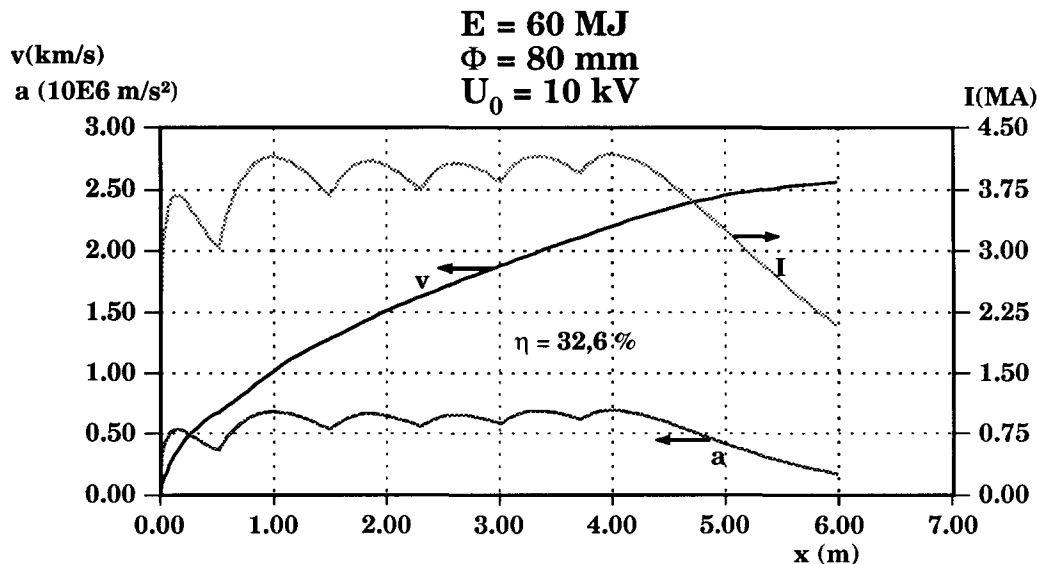


Fig. 5 . Current, velocity and acceleration as function of the projectile position for an 80 mm railgun

We have shown that the current distribution is more homogeneous with "banana" shaped rails ( $e = 10$  mm,  $\theta = 60^\circ$ ,  $L' = 0,63$   $\mu\text{H/m}$ ) (Fig. 4) [15]. We also made the numerical simulation with this sort of rails the railgun being always fed by 6 stages. Now the calculated overall efficiency is about 38 % (Fig. 6) and the stored energy has to be about 50 MJ. The use of the "banana" geometry would allow to reduce the energy source of about 17 % and to achieve the same terminal ballistic results than with the rail design shown Fig. 3. This shows that it is very important to choose the right parameters for the railgun. The first experimental studies have shown that the electrical efficiency (kinetic energy of the projectile/energy injected in the tube) of the railgun may be about 45 % [16]. At the present time the essential part of the energy losses comes from the PFN (Pulse Forming Network) one needs to feed the gun.

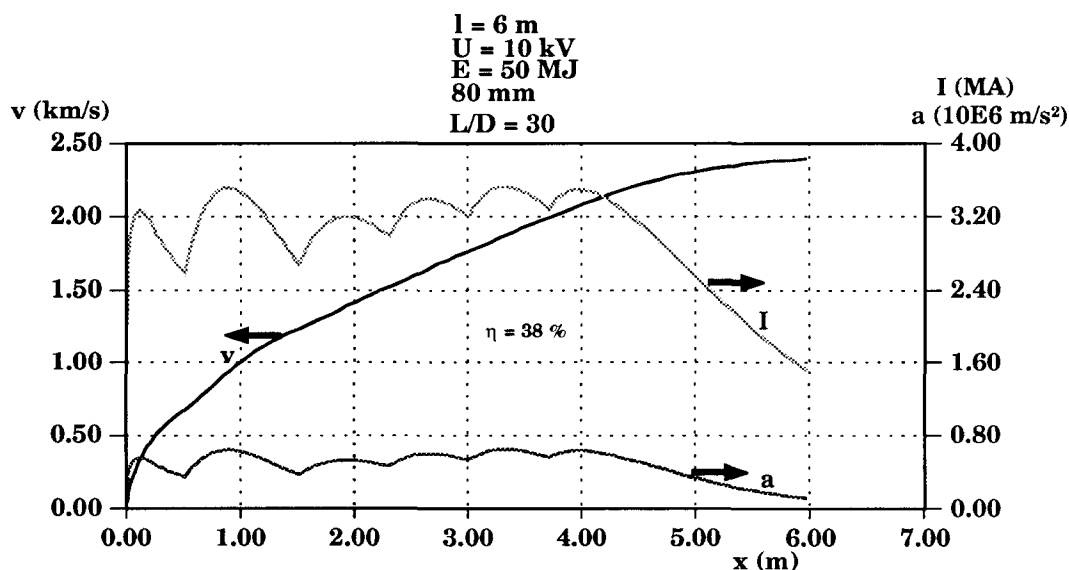


Fig. 6 . Current, velocity and acceleration as function of the projectile position for a railgun with "banana" shaped rails

## CONCLUSIONS

In this paper using a lumped parameter simulation code we have demonstrated the possibility to achieve velocities over 2300m/s with a railgun with overall efficiencies greater than 30 %.

With railguns much greater performances than with classical powder guns can be obtained. Nevertheless a great effort must be done to reduce the energy storage system volume and to reduce the electrical resistance of the PFN. The gun tube alone already today has efficiencies lying about 45 %.

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