# ESSENTIAL LAUNCHING CHARACTERISTICS OF FOUR TYPICAL ELECTROMAGNETIC RAILGUNS LAUNCHERS MODELS

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## *Abstract*

The essential launching characteristics of four typical electromagnetic railguns models were comparatively reviewed referring to the current distribution in conductors. Such four models were as a small conductive simple railgun, the large resistive simple one, the large conductive simple one, and the large conductive complex one. First, according to strict physical theories, a small conductive copper-and-aluminum simple railgun and the proportionally-enlarged large simple railgun with deliberately-designed resistive materials could satisfy the same equations, the similar forms of current distributions, the same temperatures distributions at the corresponding positions, and the same launch velocity, etc. The small model can absolutely express the large one and vice versa. Second, the large resistive simple railgun and a conductive copper-and-aluminum simple railgun with the same structures could launch approximate projectiles to the same velocity, with the same temperature distribution on the surfaces at the corresponding positions. On the one hand, the large conductive approximate railgun is a little excellent than the large resistive one because of the less Ohmic loss; on the other hand, the resistive one has merely a little higher induction gradient than the conductive one. Third, the large conductive simple railgun carried a mal-distributed current and had a limited launching ability, while, the large conductive complex railgun carried a much evenly-distributed current and had a more powerful launching ability. The conclusions reached were: according to the large resistive simple model as a key reference lever, the small conductive simple railgun was an economic experimental facility to research the launching characteristics of both small and large conductive railguns; the large conductive complex model was a practical railgun model deserving investments for research.

## I. INTRODUCTION

As a kind of new concept weapons using electromagnetic force, railgun can effectively accelerate macro objects to hypervelocity for military applications. The typical simple railgun has a U-shaped armature, two parallel insulated rails and other supporting structures. As shown in Fig. 1, when a pulsed power supply energizes the circuit, the current and magnetic field can make action to accelerate the projectile to hypervelocity [1-2].

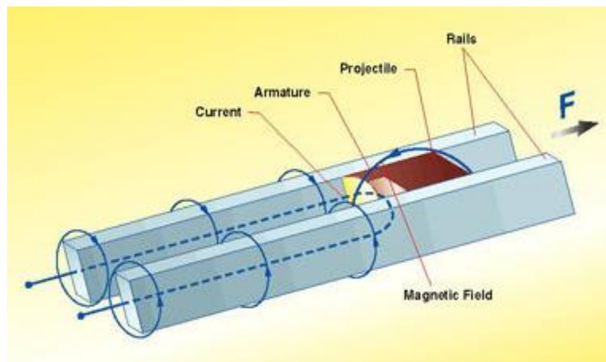


**Figure 1.** A simple electromagnetic railgun consists of an armature, two insulated parallel rails, a projectile, and the un-shown Pulsed Power Supply (PPS)..

Nowadays, many institutes researching the railguns adopt their respective structures, materials, parameters concerning railgun, and how to evaluate their characteristics remains a task. In this paper, four typical railgun models were analyzed, and their essential launching characteristics were comparatively reviewed. The four typical models were a small conductive simple railgun, the deliberately-designed large resistive simple railgun, the large conductive simple railgun, and the large complex railgun.

## II. THEORY OF RAILGUN LAUNCHER MODEL

A small simple railgun model is widely accepted by most theoretical and experimental researchers for convenience. The conductive materials are adopted to decrease Ohmic heating, a U-shaped aluminum monolithic armature and two copper alloy rails forming a basic railgun. The theory of railgun is the followings.

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### A. Dynamic and Kinetic Equations

The electromagnetic driving force of a railgun is

$$F = \frac{1}{2} L' I^2, \tag{1}$$

where $L'$ is the inductance per unit length of rails or inductance gradient and $I$ is the circuit current. The sliding friction between armature and rails is proportional to the normal contact stress, and the contact force of the legs of the U-shaped armature on rails is mainly the electromagnetic force during launching [4]. And the electromagnetic normal stress is proportional to the longitudinal electromagnetic force $F$. So the resultant force on the armature and projectile for acceleration can be expressed as $F\cdot(1\text{-}\gamma)$, where $\gamma$ is a drag coefficient. The kinematics equations of the armature and projectile can be listed

$$a = \frac{F \times (1-\gamma)}{m}, \tag{2}$$

$$v = v_0 + \int a \mathrm{d}t, \tag{3}$$

$$s = s_0 + \int v \mathrm{d}t. \tag{4}$$

Where $a$ is the acceleration, $m$ is the mass of the armature and projectile, $v$ is the velocity, $v_0 = 0$ is the initial velocity, $s$ is the displacement of the armature and projectile along the rails, $s_0 = 0$ is the initial displacement, and $t$ is the time.

### B. Inductance per Unit Length of Rails

The inductance per unit length of rails $L'$ in (1) strongly depends on the magnetic field distribution in and around the railgun. The Maxwell's equations in and around conductors for the pulse current with ms order of magnitude have the forms of

$$\begin{aligned} \nabla \times \boldsymbol{E} &= -\frac{\partial \boldsymbol{B}}{\partial t}, \\ \nabla \times \boldsymbol{H} &= \frac{\partial \boldsymbol{D}}{\partial t} + \boldsymbol{J}, \\ \nabla \cdot \boldsymbol{D} &= 0, \\ \nabla \cdot \boldsymbol{B} &= 0. \end{aligned} \tag{5}$$

The Ohm's law has the form of

$$\rho \boldsymbol{J} = \boldsymbol{E}. \tag{6}$$

And the velocity skin depth of the current distribution in the high-speed sliding interface for railguns can be [3],

$$\delta_v = k_e \sqrt{4\rho l / (\pi \cdot \mu \cdot v)}. \tag{7}$$

Where $k_e$ is an approximation index, $\rho$ is the resistivity of rail, $l$ is the length of sliding contact interface between armature and rail, $v$ is the armature's instantaneous velocity.

According to (5-7), if two railguns have the same ratios of the magnetic energy per unit length of rail to the square of the circuit current have the same values $\int B^2 \mathrm{d}w\mathrm{d}h / (\mu_0 I^2)$, the inductances per unit length $L'$ of two railguns are equal. Where $w$ is width and $h$ is the height. The inductance per unit length of rails $L'$ for a square bore of a typical simple railgun is approximately 0.4 μH/m [1].

### C. Ohmic Heating

The pulsed electromagnetic energy can be used to launch projectile, however it also has unexpected side-effect, for example, ohmic heating. The local ohmic heating of conductors has the form of

$$Q = \int J^2 \rho \mathrm{d}t. \tag{8}$$

Where $Q$ is the local Ohmic heat, $J$ is the local current density, $\rho$ is the instantaneous resistivity of conductor. Copper and aluminum are common conductors to lessen Ohmic heat. The serious Ohmic heat may lead the conductor to a so high temperature as to melting. A layer of slightly melting of armature in the sliding interface can produce wet friction, which is good for sliding contact of a launcher to increase the system efficiency. But excessively melting may lead to an instable movement of the armature and projectile.

## III. SMALL COPPER/ALUMINUM SIMPLE RAILGUN AND LARGE RESISTIVE SIMPLE RAILGUN

With economic convenience, small copper-aluminum railgun can successfully accelerate a small projectile to more than 2.5 km/s without transition or gouging. Most research institutions adopt the small copper-aluminum railgun to perform research work. However, the heavy projectiles with hypervelocity have obviously many military purposes [5], so the large railgun takes strategists and scientists' attention. How to judge the launching characteristics of a large railgun remains a task, referring to the launching characteristics of a small railgun.

### A. Parameters Prescript of Two Models

We consider a small conductive simple railgun and a special large resistive simple railgun whose parameters are proportional to each other: if the small model has the structure parameters as $l_i$, $w_i$, $h_i$, the similar large model has the structure parameters as $kl_i$, $kw_i$, $kh_i$, where subscript $i$ =1, 2, 3… and $k$ is a coefficient to describe the similarity structures. The materials' densities of the two models are the same. So the length ratios are all 1:$k$, and the masses ratios of every parts are all 1:$k^3$.

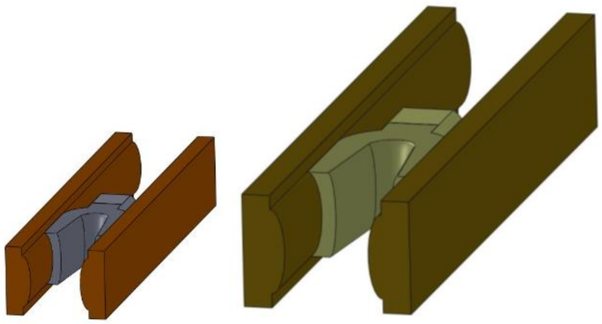

**Figure 2.** A small conductive simple railgun (left) and the deliberately-designed large resistive simple railgun (right).

**Table 1.** Typical parameters of the small conductive simple railgun and the large resistive simple railgun.

| **typical parameters or functors** | **small conductive simple railgun** | **large resistive simple railgun** |
|---|---|---|
| space coordinates | $x,y,z$ | $kx,ky,kz$ |
| time coordinate | $t$ | $kt$ |
| differential operator | $\nabla$ | $\nabla/k$ |
| derivative operator | $\frac{\partial}{\partial t}$ | $\frac{1}{k}\frac{\partial}{\partial t}$ |
| structure (length, width, height) | $l_i$, $w_i$, $h_i$ | $kl_i$, $kw_i$, $kh_i$ |
| volume | $V_i$ | $k^3V_i$ |
| density | $\rho_i$ | $\rho_i$ |
| mass | $m_i$ | $k^3m_i$ |
| resistivity | $\rho_j(T)$ | $k\rho_j(T)$ |
| circuit current | $I(t)$ | $kI(kt)$ |
| typical skin depth | $\delta(x,y,z,t)$ | $k\delta(kx,ky,kz,kt)$ |
| current density | $J(x,y,z,t)$ | $J(kx,ky,kz,kt)/k$ |
| magnetic field | $B(x,y,z,t)$ | $B(kx,ky,kz,kt)$ |
| railgun inductance | $L(t)$ | $kL(kt)$ |
| inductance per unit length of rails | $L'(x,t)$ | $L'(kx,kt)$ |
| accelerating force | $F\cdot(1-\gamma)$ | $k^2F\cdot(1-\gamma)$ |
| acceleration | $a(t)$ | $a(kt)/k$ |
| muzzle velocity | $v(t)$ | $v(kt)$ |
| displacement | $s(t)$ | $ks(kt)$ |
| kinetic energy | $K(t)$ | $k^3K(kt)$ |
| local Ohmic power density | $q(x,y,z,\mathrm{d}t)$ | $q[kx,ky,kz,\mathrm{d}(kt)]/k$ |
| local Ohmic heat accumulated | $Q(x,y,z)$ | $Q(kx,ky,kz)$ |
| temperature | $T(x,y,z,t)$ | $T(kx,ky,kz,kt)$ |

If the materials' resistivities of the small conductive railgun are $\rho_i$, the large resistive railgun materials' resistivities are $k\rho_i$; if the current in the small model has a waveform of $I(t)$ and the current in the large model is $kI(kt)$. The structures of the two railgun models can be seen in Fig. 2. The parameters prescript of the two launcher models is listed in Table 1.

### *B. Launching Characteristics Analysis*

We discuss comparatively the launching characteristics of the small conductive simple railgun and the deliberately-designed large resistive simple railgun.

The space coordinates of $x,y,z$ to $kx,ky,kz$, the time coordinates of $t$ to $kt$ , the differential operators of $\nabla$ to $\nabla/k$ and $\partial/\partial t$ to $\partial/k\partial t$ are all taken into count. According to the structure of $l_i,w_i,h_i$ to $kl_i,kw_i,kh_i$, the said current density of $I(t)$ to $kI(kt)$, the resistivity of $\rho_j(T)$ to $k\rho_j(T)$, equations (5-7) have strictly the similar boundary conditions, the similar initial conditions, and the similar distributions of magnetic fields. So the current density of the two models are $J(x,y,z,t)$ and $J(kx,ky,kz,kt)/k$, the electromagnetic field parameter is $B(x,y,z,t)$ to $B(kx,ky,kz,kt)$. And the launcher inductance is $L(t)$ to $kL(kt)$, the inductance per unit length is $L'(l,t)$ to $L'(kl,kt)$.

The circuit current is $I(t)$ to $kI(kt)$, and $L'(l,t) = L'(kl,kt)$, equation (1) is considered, so the accelerating force is $F\cdot(1-\gamma)$ to $k^2F\cdot(1-\gamma)$. When the masses ratio is 1:$k^3$, the accelerations ratio is $k$:1 according to (2). As both the time and the length ratios are 1:$k$, The muzzle speeds of the two models are the same according to (3), the muzzle kinetic energies of the two models are of 1:$k^3$. Equation (4) is satisfied, and the length prescript of $l_i$, to $kl_i$ is justified.

By the way, the skin depth is $\delta(x,y,z,t)$ to $k\delta(kx,ky,kz,kt)$, the velocity skin depth ratio is 1:$k$, the structure ratios of two models are all 1:$k$, so the current density ratio of $J(x,y,z,t)$:$J(kx,ky,kz,kt)/k$ is justified. The local Ohmic heating density is $q(x,y,z,\mathrm{d}t)$ to $q[kx,ky,kz,\mathrm{d}(kt)]/k$, the local resistivity is $\rho_j(T)$ to $k\rho_j(T)$, the temperature distributions are similar as $T(x,y,z,t)$ to $T(kx,ky,kz,kt)$ [6,7] without regard to the heat conductance. The highest temperature in the interfaces between armature and rails because of ohmic heating of the two models can get the same values, the launching conditions in the interfaces of the two models are similar.

Taking all parameters into consideration, we can see that a small copper-aluminum simple railgun can absolutely express the deliberately-designed large resistive simple railgun and vice versa.

## IV. LARGE RESISTIVE SIMPLE RAILGUN AND LARGE CONDUCTIVE SIMPLE RAILGUN

Because resistive materials produce more ohmic heats than conductive materials, the familiar large railgun are of aluminum and copper. In 2012, U. S. navy conducted a full-powered railgun launching experiment [8]. The experimental rails are made of copper alloy, and the 10-kg monolithic armature is made of aluminum.

How to review a large resistive simple railgun and large conductive simple railgun remains a task.

## *A. Parameters Prescript of Two Models*

We consider two large simple railguns models. Their shapes and structures are the same except for the projectile's length. Their densities are the same, respectively. The projectile's length, volume and mass are justly adjusted to suit the change of the inductance gradient. The conductive one adopts aluminum as armature and copper alloy as rails with resistivity of $\rho_i$, where $i$ = 1, 2, 3, respectively, while the resistive one adopts materials with resistivity of $k\rho_i$, respectively. The $\rho_i$ and $k$ are the same as that in Table 1, respectively. Two launchers models can be seen in Figure 3. The parameters of two launchers models are listed in Table 2. It is worth to note that parameters of large resistive simple railgun in Table 2 are the same as that in Table 1.

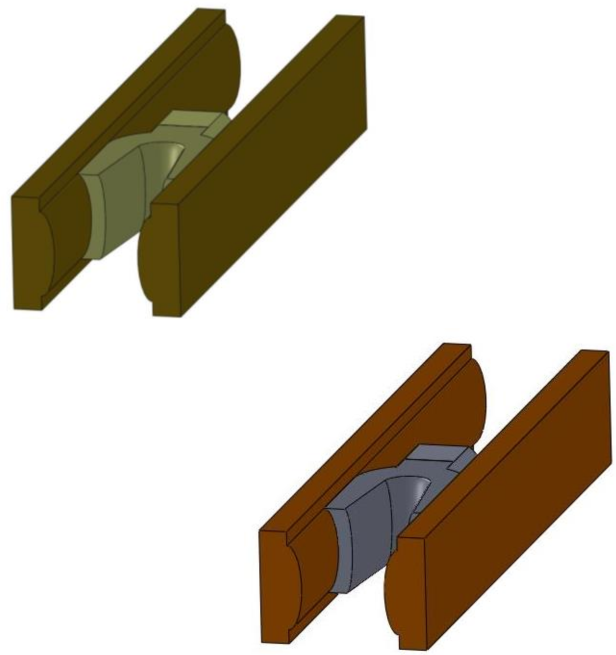

**Figure 3.** The large resistive simple railgun (up) and the large conductive simple railgun (down) are with the same structures except for the length of projectiles.

**Table 2.** Typical parameters of the large conductive simple railgun and the large resistive simple railgun

| **typical parameters** | **large resistive simple railgun** | **large conductive simple railgun** |
|---|---|---|
| space coordinates | $kx,ky,kz$ | $kx,ky,kz$ |
| time | $kt$ | $kt$ |
| coordinate (length, width, height) | $kl_i$, $kw_i$, $kh_i$ | $kl_{i\text{-}1}$, $kl_p(1\text{-}\Delta L'/L')$, $kw_i$, $kh_i$ |
| volume | $k^3V_i$ | $k^3V_{i\text{-}1}$, $k^3V_p(1\text{-}\Delta L'/L')$ |
| density | $\rho_i$ | $\rho_i$ |
| mass | $k^3m_i$ | $k^3m_{i\text{-}1}$, $k^3m_p(1\text{-}\Delta L'/L')$ |
| resistivity | $k\ \rho_i(T)$ | $\rho_i(T)$ |
| circuit current | $kI(kt)$ | $kI(kt)$ |
| typical skin depth | $k\delta(kx, ky, kz, kt)$ | $k^{0.5}\delta(kx, ky, kz, kt)$ |
| surface current density | $J(kx, ky, kz, kt)/k$ | $J(kx, ky, kz, kt)/k^{0.5}$ |
| inductance per unit length | $L'(kl,kt)$ | $L'(kl,kt)\text{-}\ \Delta L'$ |
| accelerating force | $k^2F(1\text{-}\gamma)$ | $k^2F(1\text{-}\gamma)(1\text{-}\Delta L'/L')$ |
| acceleration | $a(kt)/k$ | $a(kt)/k$ |
| velocity | $v(kt)$ | $v(kt)$ |
| displacement | $ks(kt)$ | $ks(kt)$ |
| muzzle kinetic energy | $k^3K(kt)$ | $k^3K(kt)\ (1\text{-}\Delta L'/L')$ |
| surface ohmic power density | $q[kx, ky, kz, d(kt)]/k$ | $q[kx, ky, kz, d(kt)]/k$ |
| surface heat accumulated | $Q(kx,ky,kz)$ | $Q(kx,ky,kz)$ |
| surface temperature | $T(kx,ky,kz,kt)$ | $T(kx,ky,kz,kt)$ |

## *B. Launching Characteristics Analysis*

According to reference [1], $L'$ mainly depends on the railgun structure and the magnetic diffusion extent. As we know [9], the diffusion into conductive materials takes more time, leading a less magnetic energy and a less $L'$ than that into a resistive one. Two kind diffusions into the different materials with the same shapes can have the same distribution of magnetic energy when one kind of diffusion is into conductive materials for a longer time and the other diffusion is into resistive material for a shorter time. As to the two large railguns models, the resistive one has a little bit of higher value of inductance gradient $L'$ than $L'(l,t)$ - $\Delta L'$ of the conductive one at the same time, and the difference of $\Delta L'$ can be calculated correctly. The magnetic distribution of the resistive model can be regarded as a kind of subsequent diffusion state for a long time of the conductive model.

The circuit currents of the two models are the same, the inductances have a little bit deference, According to (1), the electromagnetic force of the conductive railgun model decreases a little bit, too. That is $k^2F(1\text{-}\gamma)$ to $k^2F(1\text{-}\gamma)(1\text{-}\Delta L'/L')$.

If we deliberately change the projectile's length $kl_p$ and mass $k^3m_p$ to a little bit as $kl_p(1\text{-}\Delta L'/L')$ and $k^3m_p(1\text{-}\Delta L'/L')$ for the conductive railgun model, the acceleration can be just as much as that of the resistive model. And the speeds, the displacements are all the same, respectively. The relevant parameters of the two large simple railgun models are listed in Table 2.

As shown in Table 2, the two models have the approximate inductance per unit length of rails, the approximate masses of projectiles, and the approximate muzzle kinetic energy.

By the way, the two models have the same distribution of temperature on the conductors' surfaces. Because of the higher skin depth, the resistive model produces more ohmic heat than the conductive one. The large conductive simple railgun seems to have advantage as low ohmic heat.

Nowadays, the large conductive simple railgun is the main objective for military use. In Nov. 2016, U. S. navy performed a large conductive electromagnetic railgun prototype launching experiment. The experiment system can be seen in Fig. 4.

**Figure 4.** U.S. navy electromagnetic railgun prototype experimented in NSWC Dahlgren in Nov. 2016. The large railgun may adopt copper alloy as rails and aluminum as armature.

However, the conductors of the conductive railgun in Table II are hollow carrying current. For example, the skin depth of copper at room temperature for 50-Hz-current is about 9 mm, and the rail thickness of the large railgun is more than 40 mm.

## V. LARGE CONDUCTIVE COMPLEX RAILGUN

Restricted by the skin depth, the large conductive simple railgun in Table 2 is with low efficiency. So we proposed a complex launcher model in 2012 [10]. As seen in Fig. 5, the practical launcher model has an armature and four group rails, each group has $n = 3$ units. The armature has two groups, each group has $n$ units. Each metal unit of armature or rails has a strip form. The metal strips has a thickness of about 10 mm, the gaps between every two adjacent strips is about 5 mm to avoid discharge. The complex railgun works like two enlarging coil with $n$ turns.

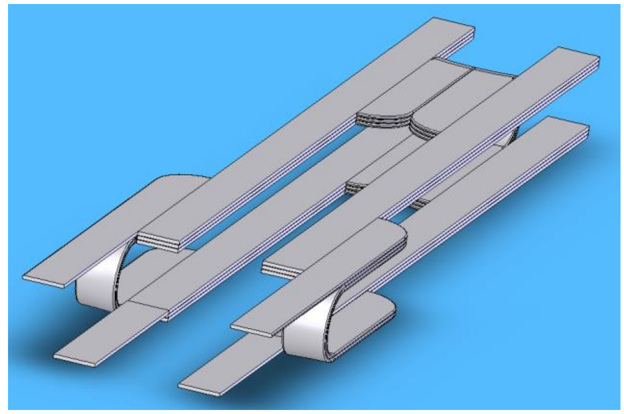

**Figure 5.** A kind of practical launcher model. The complex railgun has four groups of parallel rails. Each group has $n$ strip-like rail units. The complex U-shaped armature is set between the 4 groups of rails. And the connectors are set at the outside of the rails' rear end [10].

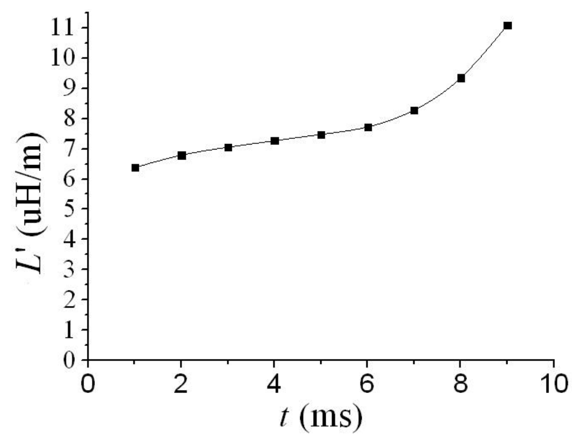


**Figure 6.** The inductance coefficient per unit length $L'$ of the prototyped launcher changed with time $t$ when a pulse current flowed through the rails of the launcher [9]. The current had a half-period sine form with a frequency of 50 Hz.

The complex railgun has advantages as the followings. First, referring to the skin effect, the current in each conductor strips is much evenly distributed than that in bulky metals for the large conductive simple railgun model with the same caliber. Second, the inductance per unit length rail $L'$ is much larger than that of a simple railgun [9]. According to the electromagnetic force expression $F = 0.5\ L'I^2$, the higher $L'$ is an effective method to increase the force. Third, the complex railgun has the characteristics of high voltage and low current, which is effective to decrease the energy loss in the circuit. Fourth, a kind of flexible sliding contact between armature and rails can resolve to a large extent such problems as slowly loading, excessive abrasion, transition to arc contact, gouging, and grooving [4].

According to the launcher model in Figure 5, we have designed a practical complex railgun prototype, which has 3 × 4 = 12 rails, forming a 100 mm × 100 mm caliber. Each rail has a 10mm × 50 mm cross section. The typical inductance per unit length has been calculated as about 7 - 10 μH/m when the current is with a half-period sine form of 50 Hz, as shown in Figure 6.

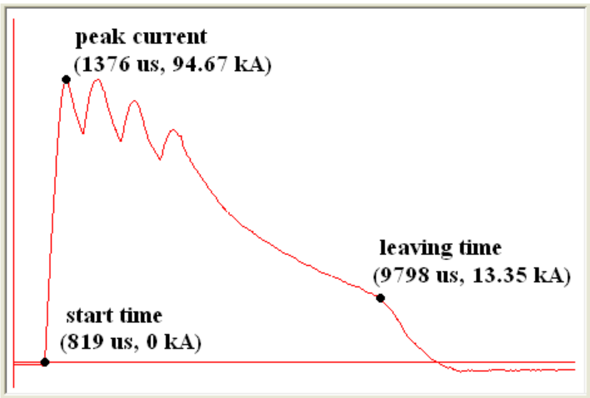


**Figure 7.** The current waveform was collected by the measure and control system. The six pulse power modules was trigged according to the sequential four steps. The first trigger worked at 819 μs. The peak current was 94.67kA at 1376 μs. And the armature rushed out of the railgun bore at 9798 μs.

After the railgun prototype is fabricated, we have performed tentarive launching experiments with low energy. A typical discharge waveform of current can be seen in Figure 7. In Figure 7, the six pulse power modules are trigged according to the sequential four steps. The first trigger works at 819 μs. The peak current is 94.67kA at 1376 μs. And the armature rushes out of the railgun bore at 9798 μs when the current amplitude is still 13.35 kA. According to (1), the peak value of electromagnetic force pushing the armature is about 32kN.

In a word, the practical launcher model has advantages over the large conductive simple railgun model in smoothly-distributed current, high value of $L'$, high launching efficiency, high loading speed, high reliability etc.

## VI. CONCLUSION

A small experimental facility can be made with easy, thus the relevant small conductive simple railgun model is suitable to perform the theoretical and the experimental research. The large resistive simple railgun model is a key reference lever, making strict relationship between the small conductive simple railgun model and the large conductive simple railgun model.

The conductive railgun has priority to the resistive one with the same shapes and structures on account of the approximate launching ability and the lower ohmic heat loss.

With many advantages over the large conductive railgun model, the practical electromagnetic launcher with multi-turn coils and the flexible sliding electrical contact has significance, deserving investments of research.

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