Developing a Launch Package for the PEGASUS Launcher

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***Abstract*—Rail guns are capable to far exceed the muzzle energies of current naval deck guns. Therefore, one of the most promising scenarios for the future application of rail guns in naval warfare is the long range artillery. Hypervelocity projectiles being propelled to velocities above 2 km/s reach targets at the distances of 200 km or more. At the French–German Research Institute, the PEGASUS launcher is used for investigations with respect to this scenario. The 6-m-long barrel has a square caliber of 40 mm. The power supply unit is able to deliver 10 MJ to the gun. Within this investigation, a complete launch package is being developed and experiments are performed that aim at showing that this package can be accelerated to velocities ranging from 2000 to 2500 m/s. A launch package consists out of an armature, a sabot, and the projectile. The armature ensures the electrical contact during launch and pushes the sabot with its payload through the barrel. The sabot guides and protects the payload during the acceleration. At the same time, the accelerating forces generated at the armature need to be transferred to the projectile. After the launch package has left the barrel, the sabot should open and release its payload, the projectile into free-flight. Here, the current status of the launch package development and results from Experiments with the PEGASUS rail gun is presented.**

***Index Terms*—Armature, payload acceleration, railgun.**

I. Introduction

THE PEGASUS railgun installation at the French-German Research Institute (ISL) is being used for experiments in support of research for a long range artillery scenario. In future and current modern naval ships, the electric power requirements for a large muzzle energy railgun can be met [1], [2]. Compared with the existing naval deck guns the large muzzle velocities of 2 to 3 km/s require the development of new guided hypervelocity projectiles. In response to this, activities for the design of such a projectile have started at ISL. The subcaliber projectile is embedded in a sabot when launched with a railgun. This sabot ensures the mechanical contact to the armature, guidance through the railgun barrel, and mechanical protection. Depending on the sensitivity of the on-board electronics of the projectile the sabot might also need to incorporate a shielding function against electromagnetic interference from the electromagnetic fields during railgun operation. The assembly of the armature, the sabot, and the projectile is termed launch package. After the launch package has left the barrel, the projectile has to separate from the armature and sabot to embark on its free flight trajectory. Work at other research laboratory concerning the development and testing of electromagnetic gun launch packages is described in the recent literature [3]–[6].The aim of the investigation described in this paper is to demonstrate that close to realistic projectiles can be successfully launched with the existing railgun technology. The experience gained with the experiments will allow to improve on the weak points of the preliminary design and to give the groups working on the hypervelocity projectile (payload, electronics, and the projectile itself) a framework in which testing in an actual railgun environment is possible.

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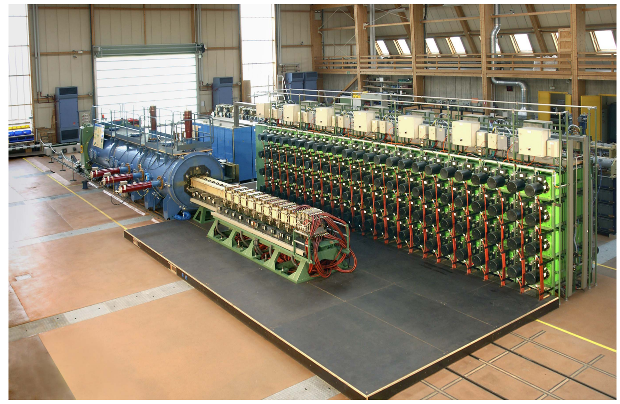

Fig. 1. PEGASUS railgun and its 10-MJ power supply.

II. PEGASUS Launcher Setup

The PEGASUS railgun used in these experiments is a 40-mm-square caliber and 6-m-long railgun. It is connected to a 10-MJ capacitor-based power supply. Each of the 200 capacitor modules can store up to 50 kJ. It is equipped with a thyristor, a crow-bar diode, a pulse forming coil, and a trigger circuit. Each module is connected by one coaxial cable to current injection points distributed along the first 3.75 m of acceleration length. This distributed energy supply (DES) scheme reduces the ohmic losses and minimizes the residual magnetic energy in the barrel. By correlating the release of parts of the stored energy with the progress of the armature through the barrel a relatively flat current pulse with a large DC contribution can be generated. The experimental setup is shown in Fig. 1. To the left in the figure, the 7-m-long catch tank is visible. To monitor the condition of the launch package or armature/projectile, a high-speed camera and several flash X-ray tubes can be mounted on the catch tank. Several

Fig. 2. Pushed c-shaped or hybrid armature.

B-dot sensors are placed along the barrel length. The signals from these sensors are used to calculate the armature velocity. Doppler radars inside the catch tank allow for an independent measurement of the end velocity. In recent experiments, using c-shaped aluminum armatures, velocities of more than 3 km/s were reached with an efficiency of approx. 40% including the power supply losses [7].

III. Hybrid Armature

A c-shaped aluminum armature establishes electrical contact to the rail surface via its two trailing arms. Once the current flow is established through the armature, the Lorentz force ensures that the arms are firmly pressed against the rail surface. During current ramp-up after triggering the launch, this contact force can be established by over-sizing the distance between the arm outer surfaces above the measured caliber. Unfortunately, it is not straight forward to calculate the amount of prestress and the arm distance being required to ensure a good electrical contact behavior during the start-up phase. In addition to this, the PEGASUS barrel shows caliber variations after usage. It is therefore not practical to correctly size the armature to the barrel condition. The hybrid armature as shown in Fig. 2 is the answer to this problem. A brush equipped glass–fiber reinforced plastic (GRP) armature (left side) is combined with a c-shaped aluminum armature (right side). The brush equipped armature is located at the rear of the combined armature and is equipped with a nose that fits into the spacing in between the c-shaped armature arms. There is a small space available in between the GRP nose tip and the c-shaped throat. The working principle of this hybrid technique is as follows: Initially, the brushes of the rear armature part carry (most of) the current and the so accelerated body pushes the projectile forward. The inertia of the aluminum part forces the nose into the available space and pushes the arms of the c-shaped armature apart and against the rails. At one point during acceleration, the brushes are eroded and the electric current is forced to use the short-circuit path through the arms of the aluminum armature. Due to the strong forces accelerating the projectile, the GRP armature forces the legs strongly against the rails. After the current has moved to the c-shaped armature, this part is further accelerated and the brush equipped part falls behind.

A. Hybrid Armature Experiment

Using 4.9 MJ of electrical energy a hybrid armature projectile with a total mass of 715 g was launched. The relevant launch parameters from this launch are shown in Fig.3. Within 0.2 ms, the current rises to 1.1 MA and then further increases to 1.5 MA during the launch. The velocity of the aluminum part including a payload cylinder with a combined mass of 450 g reaches a velocity of 2450 m/s. At about 4 ms and a velocity of 1450 m/s, the c-shaped armature separates from the GRP brush armature. A launch efficiency of 33% is calculated by dividing the kinetic energy by the initial energy stored in the power supply unit. This number includes the energy losses in the power supply unit and the cables to the launcher barrel. The muzzle voltage trace in Fig. 3 shows low values until shot-out at 5.8 ms. The electrical contact of the armature/rail interface was excellent during the full acceleration length. The contact losses amount to 110 kJ, corresponding to approximately 2% of the initial energy.

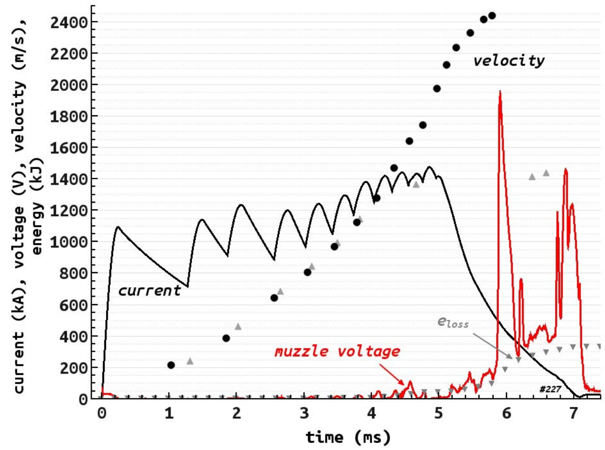

Fig. 3. Hybrid armature launch at 4.9 MJ. Shown are the current, the muzzle voltage, the velocity of the c-shaped armature (black dots), the velocity of the brush armature (upward, gray triangles) and the energy lost at the rail/armature interface (downward, gray triangles).

IV. Launch Package

In the long range artillery scenario, a large caliber railgun accelerates a hypervelocity projectile to a muzzle velocity above 2000 m/s. To minimize the effects of the lower, denser atmosphere on the projectile, the firing is under a steep angle. The projectile reaches its apogee at approx. 100 km height and descends on its ballistic trajectory until it enters again the denser part of the atmosphere. At a height of about 10 km, an active correction of the flight path using information from its internal guidance and navigation system allows to accurately hit a target at a distance of 100 km or more [1], [2]. As the flight time from firing the gun to hitting the target is several minutes, it is conceivable that the target data are being updated by using a radio link before the projectile reenters the atmosphere. The launch package developed for the 40-mm PEGASUS barrel is shown in Fig. 4. It consists out of the hybrid armature, a GRP sabot and the hypervelocity projectile model as payload. The projectile model is simplified in the sense, which it is made fully out of aluminum has no wings for guidance and contains no electronics and military payload. The c-shaped aluminum armature is equipped with a

Fig. 4. Launch package for the PEGASUS 40-mm barrel.

TABLE I
LENGTH AND MASS FOR THE INDIVIDUAL PARTS OF THE LAUNCH PACKAGE

Part	Length (mm)	Mass (g)
Brush armature	67	235
C-shaped armature	90	217
Damper	5	5
Sabot	260	590
Projectile	240	215
Total	370	1262

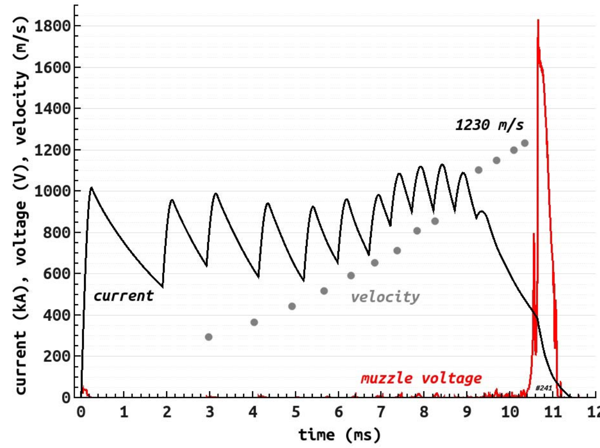

Fig. 5. Launch parameters for the first shot with the PEGASUS launch package.

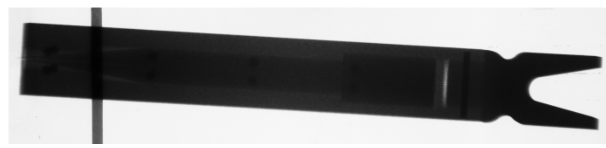

Fig. 6. PEGASUS launch package in free flight.

cylindrical nose that connects the armature mechanically with the sabot. In addition to this, a pin secures the connection between the aluminum armature and the GRP sabot. The GRP sabot is machined in a way that ensures a large area contact in between the embedded hypervelocity projectile and the sabot. In between the front of the cylindrical nose of the armature and the rear of the projectile a white plastic damper plate is supposed to dampen the mechanical shocks that come from the hard acceleration during current ramp-up and the not fully constant acceleration during launch. The sabot is fabricated out of two parts that are weakly connected by four small aluminum pieces on each side. The nose tip of the hypervelocity projectile protrudes out of the sabot and the central opening of the sabot front side is designed to allow for the opening of the sabot due to air pressure once the launch package has left the barrel. The total mass of the launch package is approximately 1.3 kg, with the individual masses itemized in Table I. Due to the large mass of the sabot, the payload-to-total-mass-ratio is rather small (17%).

V. EXPERIMENTAL RESULTS

A. First Launch

The developed launch package was used in a launch with the capacitors charged to a voltage corresponding to 4.2 MJ of electrical energy. Fig. 5 shows the measured data of this shot. At an average value of 805 kA until shot-out at 10.3 ms, the current reaches a peak value of 1.13 MA. Due to the DES setup of this PEGASUS barrel, with fixed distances in between the current injection points, shots with relatively low armature velocity generate the strong saw-tooth pattern of the current as seen in the Fig. 5. Only at velocities which correspond to the barrel design velocity of approx. 2500 m/s, the current trace becomes more DC like. During the full acceleration length, the muzzle voltage is at the lower values of the measurement range of the data-acquisition system and the energy lost at the rail/armature interface amounts to not more than a few kilojoules. The velocity at muzzle exit is 1230 m/s, with an overall efficiency of 22% for this shot. As the separation of the GRP-brush armature from the c-shaped armature only happens very late in the launch period (at about 8.6 ms), both parts leave the barrel with a very short distance in between each other. This is the cause of the double peak structure of the muzzle voltage trace just at 10.5 ms. In Fig. 6, a flash X-ray picture of the launch package just after it has left the barrel is shown. The aluminum c-shaped armature is seen in the right hand side of the figure. At the energy used in this shot, there are no visible signs of wear of the arms of the armature. At the time of the free flight phase when this X-ray picture was taken, the sabot is still closed. Visual pictures taken by a high-speed camera installed further down the catch tank show that the sabot opens later and frees the projectile.

B. Second Launch

With the aim to confirm the results of the first launch, a second experiment was set up. The second launch package was prepared and launched at the same energy. The result of this second launch is shown in Fig. 7. As expected, the time development of the current and muzzle voltage traces are similar, as is the muzzle velocity of 1225 m/s. The flash X-ray picture in Fig. 8 is taken just after both armatures have left the barrel. It shows the excellent condition of the c-shaped aluminum armature after the launch. The brushes of the brush

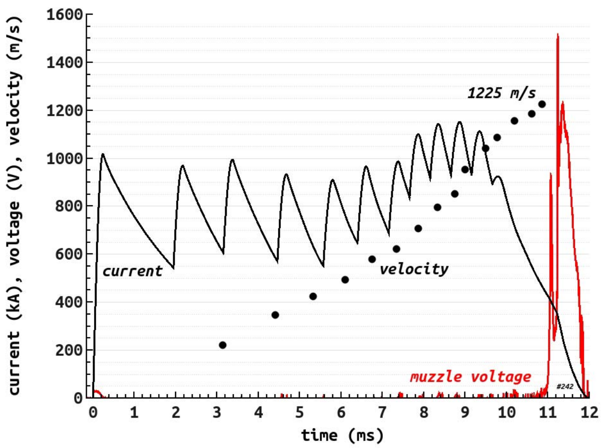

Fig. 7. Parameters of the second launch.

Fig. 8. X-ray picture of the armatures as they leave the barrel.

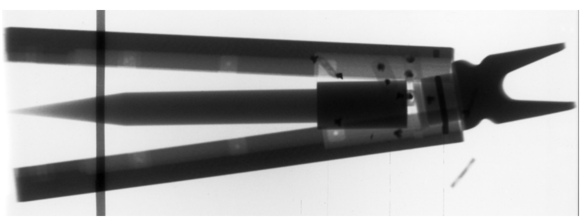

Fig. 9. Opening of the sabot during free flight.

equipped armature show clear signs of wear, more on the rear than on the front row. As in the first shot, the separation of the rear armature from the rest happened late in the acceleration, thus the velocity of the armatures is not very different. Clearly, the current load sharing in between the two armatures could be better balanced in future experiments, thus realizing an earlier separation. In Fig. 9 a second X-ray picture taken further down in the catch tank shows the launch package during its short free flight phase. The GRP sabot is just in the process to open and release the hypervelocity projectile, validating the design of the opening mechanism.

VI. Expected Performance

For the two experiments described, the initial energy being stored in the capacitors amounted to approximately half of the full complement. It is interesting to investigate what velocity could be possible if the full 10 MJ is being used. This was investigated by a SPICE simulation. Such a simulation can give answers to the electrical and dynamical behavior of the launcher and the projectile. Of course due to the many uncertainties in electromagnetic launch processes at higher energies, the simulation results are predictions that come with

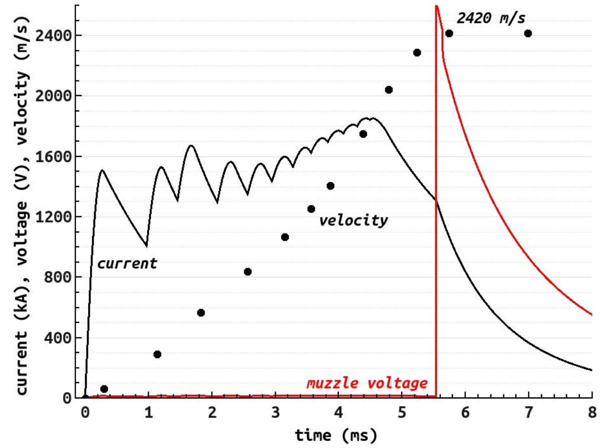

Fig. 10. Simulated launch behavior at 10 MJ.

a certain uncertainty. This uncertainty is hard to quantify, but from experience from comparing with already performed experiments one can estimate the uncertainty to be of the order of 10% to 20%. In Fig. 10, the current, muzzle voltage, and velocity trace are shown. At 10 MJ, the average current during the acceleration time amounts to 1.5 MA, and the peak value is 1.85 MA at 4.5 ms. Shot out is expected at 5.6 ms. The launch package is accelerated to a velocity of 2400 m/s. Comparing the current trace to the two experimental traces in Figs. 5 and 7 shows that the sawtooth pattern of the current is much less pronounced at this higher velocity. As a note of caution: it is not clear that this velocity can be reached with the developed launch package, as it assumes that the rail/armature contact does not fail during the launch process. Currently this can only be investigated experimentally.

VII. Summary

The usage of hybrid armatures, the combination of a brush equipped and a c-shaped aluminum armature allowed for a drastic reduction of losses at the rail/armature interface. Building on the encouraging results with this type of armature a launch package for the acceleration of hypervelocity projectiles was developed. The ability to accelerate launch packages is the prerequisite for the military application of a railgun in a long range artillery system. In experiments with the launch package developed at ISL using the PEGASUS 40-mm railgun barrel, it was shown that the payload could be guided through the railgun barrel and released after the package left the barrel. X-ray pictures showed the excellent condition of the c-shaped armature and the sabot after the launch to a velocity of 1230 m/s. Using a simulation, the expected velocity of the projectile, when launched with an energy of 10 MJ was evaluated to 2400 m/s. This validates that using the PEGASUS launcher it is possible to accelerate close to realistic models of hypervelocity projectiles to the military relevant velocity above 2000 m/s.

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Authors’ photographs and biographies not available at the time of publication.