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# Experiments with the Modular Augmented Staged Electromagnetic Launcher (MASEL) and Comparison to Simulations

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**ABSTRACT** – Augmented electromagnetic accelerators are advanced mass accelerators which are using an additional magnetic field to support the launching process. In conventional electromagnetic accelerators the electrical current through the rails and the armature has to be very large in order to achieve a sufficiently high electromagnetic force which accelerates the projectile. Due to magnetic flux diffusion effects, the electrical current is concentrated on the back of the armature, resulting in high current concentration and therefore heat generation. Together with the sliding contact between the armature and the rails, abrasive wear of the materials can occur and cause a transition from the solid contact to a plasma contact, which further increases the temperature and the wear of the rail/armature interface. To decrease the electrical current through the armature without decreasing the accelerating force on the projectile, an additional energy input mechanism has to be implemented, realized by an additional magnetic field, augmenting the magnetic field generated by the current through the main rails. This paper gives an insight to first achievements with the modular augmented staged electromagnetic launcher (MASEL), describes the experimental setup and compares the experimental results with simulations. Parts of this paper were already published in [1] and [2].

**INDEX TERMS** – Coils, electromagnetic launching, magnetic fields, railguns

## 1. Introduction

Electromagnetic launchers use electrical energy to accelerate masses and are capable of achieving velocities beyond 2 km/s [3]. An additional advantage of the electromagnetic accelerator is the ability to actively control the launching process by controlling the applied current pulse [4]. This allows exit velocity control for specific applications.

A basic electromagnetic launcher consists of two conducting rails and a sliding contact bridge. During the launching process, the sliding contact bridge enables a conducting connection between the rails. The amplitude of the electrical current in the rails and the sliding contact can reach values in the range of several kA (kiloamperes) to MA (megaamperes), depending on the size of the launcher [5],[6]. The magnetic field generated by the current through the rails and the interaction of the current through the armature with the magnetic field results in an electromagnetic force. This accelerates the armature.

A sliding contact presents challenges for the electromagnetic launcher design. Due to field diffusion effects, the electrical current is concentrated to certain areas of the armature-rail interface and causes local resistive heating [7]. Additionally, the friction of the sliding contact increases the temperature of the armature and causes abrasive wear at the rails and armature. These phenomena limit the current carrying capacity of the armature with a solid to solid contact. Beyond this limit, a small gap between the rails and the armature will occur and a plasma contact between the armature and the rail is established. The high temperature of the plasma accelerates the degradation of the rail-armature material and increases the gap. Due to the higher electrical resistance compared to the undamaged solid to solid contact, the plasma contact can be detected as an increase in the recorded muzzle voltage.

To minimize the damage on the rails and to operate the electromagnetic launcher in its most efficient way, a direct solid to solid contact must be maintained as long as possible during the launching process. One way to reduce the heat load on the contacts is to reduce the electrical current through the armature. This results in a smaller magnetic field and, therefore, a smaller acceleration of the armature. Using magnetic field augmentation, it is possible to compensate a reduced current through the armature by applying an external magnetic field which supports the magnetic field that is produced by the electrical current in the rails.

In this paper, we present a brief overview of some known magnetic field augmentation techniques and describe an advanced augmentation configuration which enables the augmentation with a rather strong magnetic field using external coils. Such a configuration was investigated experimentally and its resulting muzzle velocities are compared with values achieved by simulations.

## 2. Augmentation techniques

In the past, several augmentation techniques were suggested and several different experimental investigations have shown the great potential of magnetic field augmentation. In [8], permanent magnets are used to create an augmenting magnetic field. In [9] a muzzle shunt applied to the muzzle of the launcher resulted in an augmented magnetic field in the launcher. Another way of magnetic field augmentation is the multi turn electromagnetic accelerator in which there are multiple rails connected in series by the sliding contacts [10].

The most common ways to increase the magnetic field between the rails are the series augmented electromagnetic accelerator and the parallel augmented accelerators which are presented in the following.

### 2.1 Series augmented accelerators

In the series augmented configuration the augmenting rails are connected in series with the main rails as can be seen in Fig. 1. This is the most common augmentation technique and was applied in several experiments and its results were presented for example in [4], [11] and [12]. The augmentation can be done with one or more augmentation rail pairs. The main advantage of this configuration is that no additional power supply is necessary for the augmentation. According to [13] a 154 g heavy projectile had been accelerated to 1900 m/s using a series augmented electromagnetic accelerator.

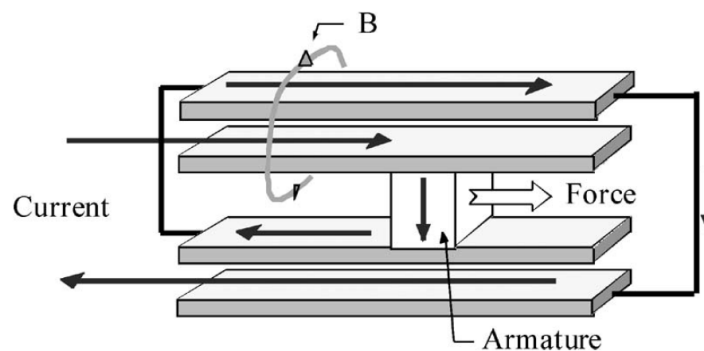


Figure 1 : Series augmented accelerator configuration (Source: [11])

### 2.2 Parallel augmented electromagnetic accelerator

The parallel augmented configuration can be realized similarly to the series augmentation setup with the difference that the augmented rails are connected in parallel to the main rails. This configuration can be seen in Fig. 2. This setup enables the control of the current in the augmentation rails and in the main rails separately, so that the electrical current in the augmentation rails can be higher than the electrical current in the main rails and the armature as it was done in [14].

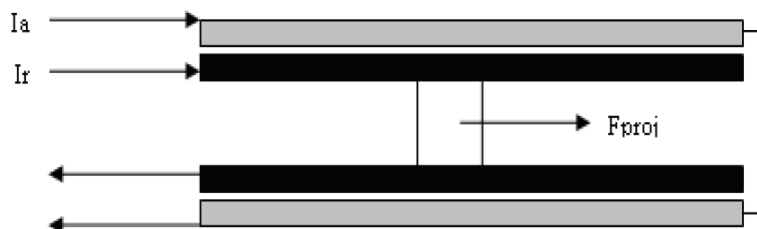


Figure 2 : Parallel augmented accelerator configuration (Source: [14])

### 2.3 Coil augmented electromagnetic accelerator

In the external coil augmentation an external coil is providing an additional external magnetic field for the acceleration process. This coil can either be supplied by a separated power supply or can be connected with the main rails. The advantage of an externally supplied electromagnetic coil is that a high electromagnetic field can be generated with it. This additional electromagnetic field can be produced by one or more external coils. In [15] an electromagnetic

accelerator with several augmenting coils is presented and can be seen in Fig. 3. This promising configuration has not yet been investigated experimentally.

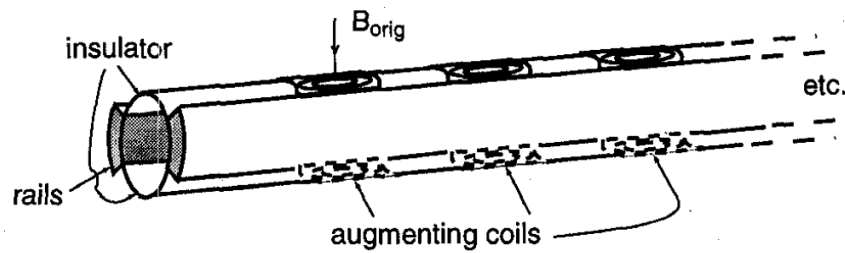


Figure 3 : Coil augmented electromagnetic accelerator concept (Source: [15])

### 3. Experimental setup

To study the magnetic field augmentation in a railgun using external coils, we design an experimental setup which enables the investigation of several coil configurations. The best way for a simple construction is a modular setup in which the augmenting coil modules could be replaced with low mechanical effort. For this reason we designed a launcher in which two glass fiber reinforced plastic (GRP) bodies are placed in the vicinity of the main rails. These GRP bodies will contain no coils if the railgun is operated in the conventional, non augmented configuration. For the augmented magnetic field configuration, the augmenting coils can be integrated into the GRP bodies and placed next to the main rails of the railgun. A CAD model of the modular coil augmented setup with augmenting coils with two windings can be seen in Fig. 4. In a staged setup, multiple coil modules can be placed behind each other to ensure a magnetic field augmentation along the rails when the projectile is passing. This configuration is called modular augmented staged electromagnetic launcher (MASEL) and is described in more detail in [1].

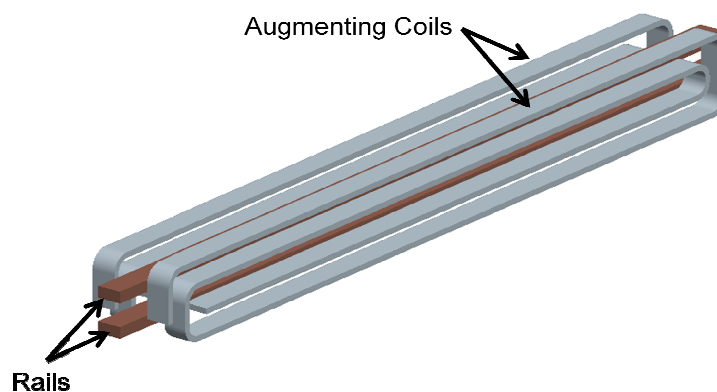
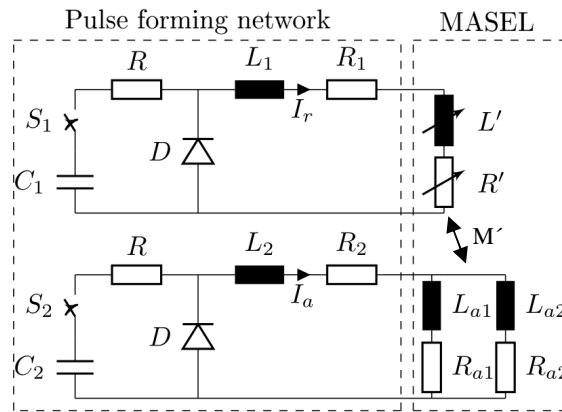


Figure 4 : Modular coil augmented setup (CAD model)

The caliber of the railgun was chosen to be 20 mm x 20 mm and the rails are rectangular copper rails with the dimensions of 10 mm x 20 mm. For a first proof of concept, one stage of the MASEL was built with a length of about 75 cm. Due to the large magnetic field produced by the augmenting coils and the railgun itself, the mechanical load on the housing of the components is extraordinary high. Using electrical and mechanical FEM simulations, the structure of the housing was optimized so that the displacement of the rails during the launching process is reduced to a minimum.

The projectiles used for the experiments were made of GRP as an insulation material. These so called sabots contained two copper brushes with a diameter of 6 mm. The copper brush projectiles were developed at the French-German Research Institute and proved its capabilities in various experiments [16].

The power supply unit consists of a capacitor bank, a switch and a pulse forming inductance. The electric diagram of the first stage of the MASEL in the parallel augmented configuration can be seen in Fig. 5.



**Figure 5 : Electrical diagram of the MASEL**

#### 4. Simulation of the performance of the coil augmented launcher

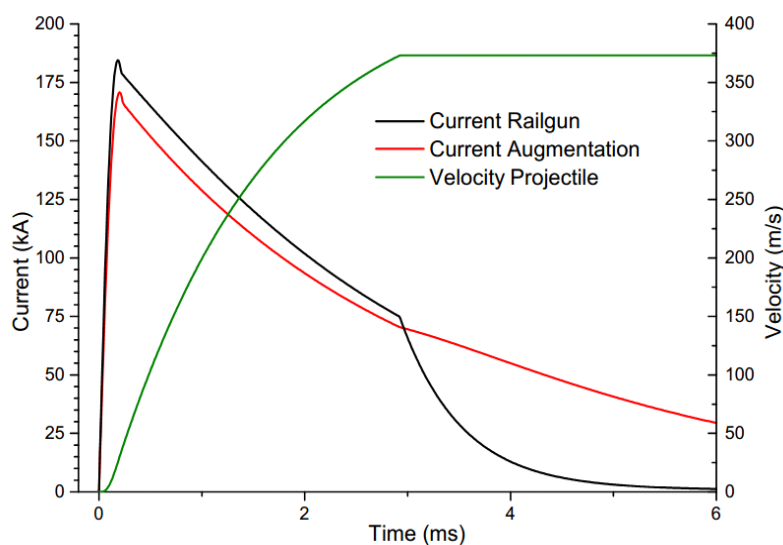
To enable an evaluation of the performance of the launcher before the experimental setup was build, we set up a simulation for the launching process of the projectile. In an augmented railgun, the force acting on the projectile can be calculated with the following equation from [17].

$$F = \frac{1}{2} L' I_r^2 + M' I_a I_r \quad (1),$$

where F is the accelerating force acting on the armature, L' is the inductance gradient of the railgun, I<sub>r</sub> is the electrical current in the railgun circuit, M' is the mutual inductance gradient between the augmenting coils and the railgun and I<sub>a</sub> is the electrical current in the augmentation circuit.

To calculate the acceleration force on the projectile the electrical current through the augmenting coils as well as the current through the rails and armature have to be known. The values for the electrical components of the pulsed power modules such as the capacity, the inductance of the pulse forming inductance and the resistance are well known. The railgun specific values like the inductance gradient and the mutual inductance gradient were approximated as concentrated wires [1]. Together with these values it is possible to calculate the electrical current in the rails and the armature as well as the current through the augmentation modules. Applying eq. (1) it is possible to calculate the accelerating force which is acting on the projectile. To take the friction into account, the accelerating force is reduced by a constant value.

The calculated electrical current in the rails and the armature and the electrical current through the augmenting modules can be seen in Fig. 6 together with the resulting velocity of a 71 g heavy projectile. The initial charging voltage of the capacitor banks for this calculation was 9 kV and the resulting velocity was 374 m/s.



**Figure 6 : Calculated electrical current profiles and the resulting velocity profile**

## 5. Experimental results

For the first experiments, the first stage was operated in the non augmented configuration. These reference experiments enable a later comparison with the experiments using the parallel augmented railgun setup.

### 5.1 First stage of MASEL operated in the non augmented configuration

In the experiments without magnetic field augmentation, one capacitor was used to power the railgun. The initial charging voltage of the capacitors was varied from 5.5 kV to 9 kV. During the experiments, the electrical current, the muzzle voltage and the breech voltage were recorded. The velocity of the projectile was measured by several light barriers. The measured electrical parameters for a shot with 9 kV initial capacitor charging voltage can be seen in Fig. 7.

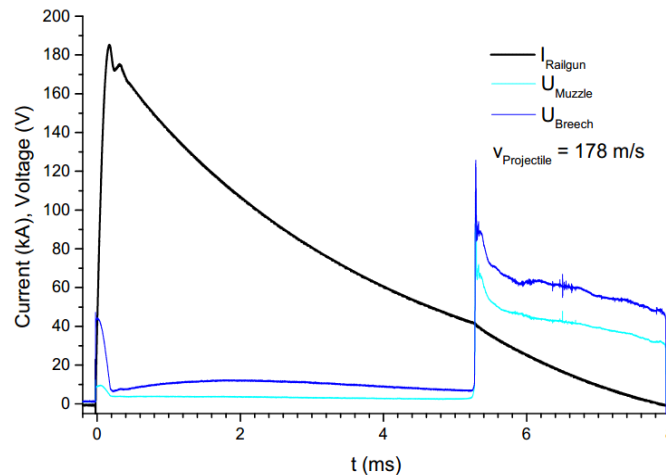


Figure 7 : Measured electrical current and voltage profiles of shot #31

### 5.2 First stage of MASEL operated in the parallel augmented configuration

For the experiments with the parallel augmented railgun configuration, two coils were installed as augmenting coils in the launcher. The coils consist of enameled copper wires with a rectangular cross section of 4 mm x 10 mm. Each coil had 2 windings and an inductance of about 2  $\mu\text{H}$ . The railgun was connected to one pulse forming network. A second capacitor bank was used to supply the augmenting coils which were connected in parallel to each other. The data acquisition of the previous experimental setup was extended by the electrical current in the augmenting coils. Both capacitor banks were charged to the same initial voltage in the range of 5.5 kV to 9 kV before the experiments. In Fig. 8, the electrical current in the rails and the augmenting coils is shown from an experiment with an initial charging voltage of 9 kV.

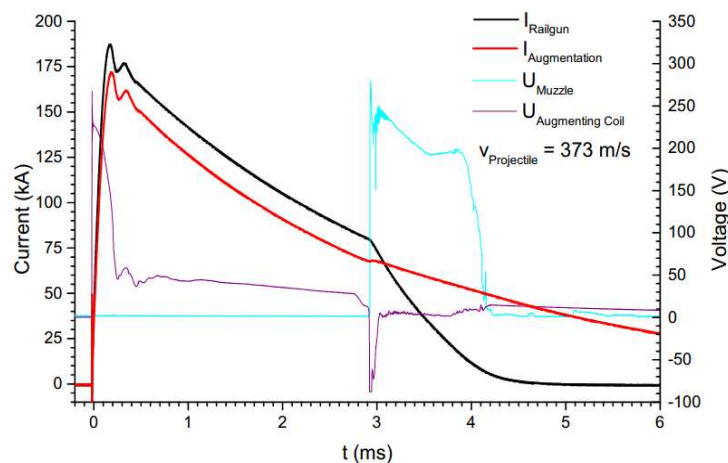


Figure 8 : Measured electrical current and voltage profiles of shot #52

### 5.3 Comparison of the achieved velocities

In the comparison of the experimental results in Fig. 9, it can be seen that the velocity with the non augmented configuration reaches a maximum value of about 180 m/s with a maximum peak current of 185 kA. Using the magnetic field augmentation the maximum velocity of the projectile reached values of about 380 m/s with a negligible higher electrical current of about 186 kA. This means that the velocity of the projectile is increased by more than a factor of two without an increased current in the armature of the projectile. Due to the dominant friction force at low energy experiments, the difference between the projectiles velocity of the augmented and non augmented configuration is higher at low initial charging voltages. At low velocities the projectile remains longer in the railgun than the duration of the electrical current pulse. After the electrical current reached a minimum value that is necessary to overcome the friction force, the projectile will be decelerated until it exits the railgun. In the experiments with 5.5 kV the ratio between velocities with the different configuration is about 4 and for 9 kV it is about 2.

Beside the velocity of the projectile, the efficiency of the launching process was increased as well. The efficiency is defined as the kinetic energy of the projectile divided by the initially stored energy in the power supply units. For the energy efficiency of the augmented railgun configuration the energy of both capacitor banks were taken into account. The highest energy efficiency is achieved with the high energy experiments using 9 kV initial charging voltage of the capacitors and reached a value of about 2 % in the magnetic field augmented experiments. In the non augmented configuration the efficiency reached about 0.9 % at 9 kV initial charging voltage.

The simulated velocities of the projectile show a good agreement with the experimentally achieved values.

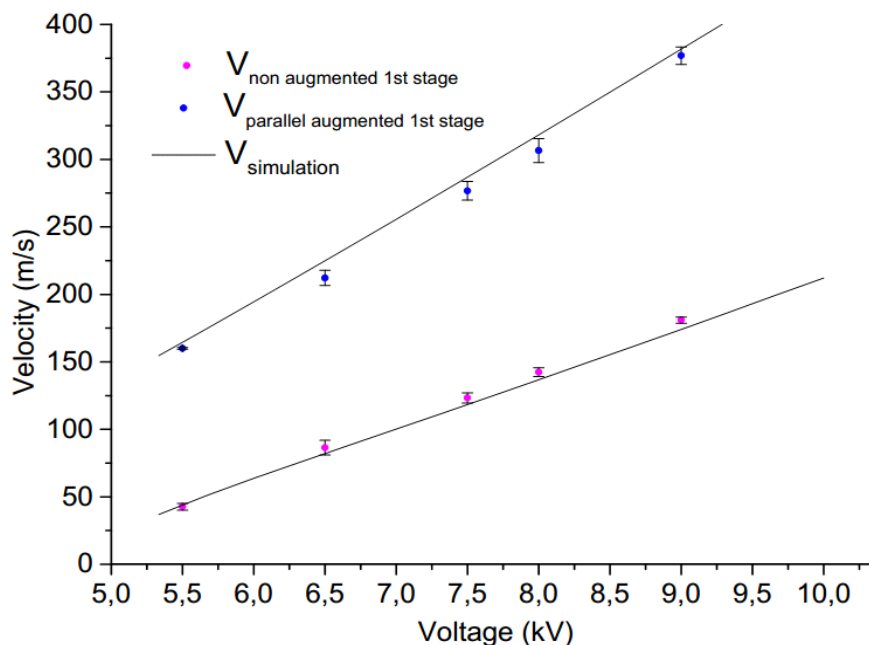


Figure 9 : Comparison of the achieved velocities

## 6. Conclusions

The experimental investigation with the first stage of the MASEL gives a good idea about the feasibility of the coil augmented configuration. The magnetic field augmentation enabled an acceleration of the projectile to a significantly higher velocity compared to the non augmented configuration. With the same electrical current through the armature, the projectile reached a velocity which was more than two times higher than the velocity of the projectile in the non augmented experiments. The challenging mechanical load that occurs during the launching process did not cause any damage of the construction of the MASEL. To increase the augmenting magnetic field in the railgun, the number of windings of the augmenting coils can be increased. This would lead to an increased inductance of the augmenting coils so that they might be suitable to replace the pulse shaping inductance in the power supply unit. To use the energy of the augmenting circuit, the electrical current could be used for the acceleration process of the projectile. For this the augmentation coils and the railgun are connected in series so that only one capacitor bank is required for an augmented launching process.

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