Executive Summary

Electromagnetic Railgun Technology Assessment Study - Bridging Phase -

Ref.: CCN No. 02 & 03 to ESA Contract No. 13420
1 Introduction

This particular study, named "Railgun - Bridging Phase", is the direct continuation of two former studies under ESA contract 13420/99/NL/MV, which were concentrating on possible railgun space applications and related market aspects. This present study aims at further detailing the concept of the selected suborbital reference mission in theory and demonstrating the performance of an electromagnetic railgun by first experiments.

As the railgun technology is a rather new and unconventional propulsion technique for space applications, two basic questions have been identified in the previous GSP study to be of special interest, which should be answered in a subsequent study to enhance the confidence in this technology and to minimize future development risks:

1. Can the electromagnetic railgun accelerate a higher mass (4 kg rocket)?

Railguns have been reported to accelerate typically low masses of just a few hundreds grams in the frame of military research programs. However, for space applications higher launch masses are required even to transport small scientific experiments. For the first identified space application (launch of suborbital meteorological payloads, the so-called reference mission) the entire launch package to be accelerated has been estimated to be ~4kg. Therefore the approach proposed for this study was to test fire repeatedly by means of the ISL Pegasus-Railgun dummy masses with the aim

- to demonstrate the capability of the electromagnetic railgun to launch higher masses,
- to demonstrate its performance,
- to demonstrate the reproducibility of the test results by
- covering the entire application range from 1 kg to 4 kg.

New projectiles have been designed by ISL, which consisted of a sabot, made of Glass fiber Reinforced Plastic (GRP), an armature with different numbers of metallic fiber-brushes (depending on the entire mass) and a payload made of tungsten (different masses according to the envisaged launch mass). During the tests several parameters have been measured to verify the railgun performance and flash radiographs have been taken to verify the integrity of the projectiles.

2. Are non-exotic materials able to protect the payload in flight?

The clarification of this question is important due to the fact that the first railgun application will penetrate a so-called low-cost market segment. To compete economically with existing conventional rocket systems, it is mandatory, that the materials applied and the manufacturing process of the projectiles is inexpensive. This can be achieved only, if "normal", "non-exotic" and inexpensive materials are used.

To define selection criteria for these materials, it is of primary importance to determine the mechanical and thermal loads, acting on the projectile.

In the previous study the aero(thermo)dynamic characteristics of the hypersonic projectile for the suborbital flight (115 km altitude) could be determined for a few points at steady flow conditions along the flight trajectory only. These results gave a first hint that the expected loads can be sustained by standard materials.
However, to detail this open issue, a prediction of the pressure and thermal loads, in particular in unsteady flow conditions, for the first seconds of free-flight have been put in the focus of this study.

Similar to the previous study the study management has been done by EADS SPACE Transportation-, Bremen, in joint cooperation with the French-German Research Institute of Saint-Louis (electromagnetic railgun aspects) and DLR -Institute for Aerodynamics and Flow Technology- (hypersonic projectile aero(thermo)dynamics issues). The performed work includes two parts, namely the

- baseline proposal covering basic investigations on the railgun system incl. test shots with 1kg and 2kg projectiles and the aero(thermo)dynamics of the hypersonic projectile as well as
- option#2 comprising two additional experimental test firings with 3kg and 4kg dummy masses.

Option#1, covering payload aspects has not been selected by ESA.

From the programmatic point of view different major milestones have been achieved during the course of this GSP study:

- Start (CCN No. 02): September 7\textsuperscript{th}, 2004
- Start (CCN No. 03): December 15\textsuperscript{th}, 2004
- Progress-Meeting: December 01\textsuperscript{st}, 2004 at ISL, Saint Louis
- Final Presentation: September 14\textsuperscript{th}, 2005 at ESTEC, Noordwijk
2 Electromagnetic Railgun

Starting from the characteristics of the railgun able to launch a meteorological probe established in the previous work, the characteristics of the energy supply meeting the requirements have been determined. The study will give the description of the 22-m-launcher facility (volume and mass of the electric storage system) and a first layout of the implementation of the different current injections along the tube. A complete description of the energy system will be outlined.

The second part of this report presents test shots with dummy masses of 1, 2, 3 and 4 kg, fired with the PEGASUS facility. The lighter projectiles are fired twice to repeat and confirm the acceleration versus time profiles. The test results are compared to theoretical derived values to verify the performance of the railgun.

2.1 Energy supply of the railgun for a suborbital launch

ISL has chosen to use a capacitor bank to feed the railgun. This technology is well-known and reliable. The capacitor bank is composed of 50 kJ modules connected to a semiconductor switching unit, a pulse forming inductance and a coaxial cable. Each module has a charging voltage of about 10 kV and can deliver a peak current of about 50 kA.

The railguns used at ISL are usually fed using the Distributed Energy Storage (DES) principle (where the energy is distributed along the rails) in order to enhance the efficiency of the railgun system and to allow a smooth variation of the mean acceleration. A first layout of the 22-m-railgun is given in the sketch shown in Figure 1. The railgun is equipped with 20 injection points to which the 80 energy stages (4 stages per injection point) are connected.

![Figure 1](image_url)  
First sketch of the 22-m-railgun equipped with 20 injection points for 80 time-triggered energy-stages

Taking into account the out-to-out dimension of a power supply unit (50 kJ), it can be compared to a parallelepiped with a volume of 0.168 m³ and a mass of about 175 kg. We need 640 modules, which means a volume of 107.5 m³ and a mass of about 112 t.
2.2 Test firings

2.2.1 Description of the railgun facility PEGASUS

The PEGASUS (Program of an Electric Gun Arrangement to Study the Utilization in Systems) railgun facility was built in 1998 at ISL. It is a distributed energy storage (DES) railgun fed by a 10-MJ capacitor bank made of 200 modules of 50 kJ each (Figure 2).

This facility was built to accelerate projectiles with a mass of 1 kg up to velocities greater than 2000 m/s with an acceleration in the order of 70000 g's in the medium-caliber range (30, 40 and 50 mm).

The tests presented in this report were carried out with the 6-m-long and 40-mm-square-bore launcher tube currently connected to the PEGASUS facility.

2.2.2 Projectiles with a mass of 1kg (Baseline Proposal)

The projectile consists of a sabot made of Glass fibre Reinforced Plastic (GRP), armatures made of 8 metallic fibre-brushes and a payload made of tungsten to reach the mass of 1 kg (Figure 3). Two test shots were fired with a stored electrical energy of about 2.6 MJ in order to achieve accelerations smaller than 13000 g's. The measured accelerations were respectively 12700 and 12000 g's for the first and the second shot. The variation as a function of time of the projectile position, the current and the muzzle voltage measured during the two test shots are shown Figure 4. The muzzle velocity is measured with an accuracy of about 10 %. In the case of the two test shots, the measured muzzle velocities were about 933 m/s and 962 m/s. The shots are perfectly reproducible within the measurement error.

The flash radiograph of the 1-kg-projectile in flight at 2.74 m from the muzzle is shown in Figure 5.
**Figure 3**  Photographs of the 1-kg-projectile

**Figure 4**  Position, muzzle voltage and current as a function of time for two shots made with the 1 kg projectile (maximum acceleration = 11200 g's and 12000 g's respectively)

**Figure 5**  Flash radiograph of the 1-kg-projectile at the muzzle (shot 90)
2.2.3 Projectiles with a mass of 2 kg (Baseline Proposal)

Also in this case the projectile consists of a sabot made of GRP, armatures made of 15 metallic fiber-brushes and a load made of tungsten to reach the mass of 2 kg (Figure 6).

As the reproducibility was demonstrated for the test with the 1-kg-projectile, we have fired the two 2-kg-projectiles with two different electric energies in order to verify the behavior of the projectile prototypes for two different situations.

The first shot was fired with a charging voltage of $U_0 = 7$ kV. The muzzle velocity is about 873 m/s for a maximum acceleration of 11300 g's. A second shot was fired with a charging voltage of $U_0 = 8$ kV, which means with 30% more electric energy. The muzzle velocity is about 1000 m/s for a maximum acceleration of 15700 g's.

![Figure 6](image)

Photograph of the 2-kg-projectile

2.2.4 Projectile with a mass of 3 kg (Option #2)

The projectile consists of a sabot made of GRP, provided with 21 metallic fiber-brushes, and a payload made of tungsten to reach the mass of 3 kg (Figure 7). To reduce the friction between rails and armature, the length of metallic fiber brushes was reduced to 45.4 mm for the 5 rear rows of fiber brushes and to 42 mm for the 2 front rows (instead of 45.5 mm for all the rows used for the 1-kg and 2-kg projectiles). One test shot was fired with a stored electrical energy of about 4.2 MJ (charging voltage of 7 kV) in order to achieve accelerations smaller than 10000 g's. The measured acceleration was 7800 g's. The measured muzzle velocity was about 670 m/s ±10 %.

![Figure 7](image)

Photograph of the 3-kg-projectile showing the brush armatures, the GRP sabot and the W-rod
2.2.5 Projectile with a mass of 4 kg (Option #2)

The projectile consists of a sabot, provided with metallic fiber-brushes (24 fiber-brushes in this case to conduct the current during a longer time interval), and a payload made of tungsten heavy alloy to reach the mass of 4 kg (Figure 8). In this case the length of the metallic fiber brushes was chosen in order to avoid the ignition of a plasma arc before shot-out. The 7 rear rows of brushes had a length of 45.5 mm and one row toward the front of the projectile had a length of only 42 mm to reduce the friction during the introduction of the projectile in the railgun tube. The shot was made with a charging voltage of $U_0 = 7$ kV ($E \approx 4.2$ MJ). The muzzle velocity is about 495 m/s for a maximum acceleration of 4800 g's. No plasma was generated during this shot. The muzzle voltage shows no increase before shot-out and the projectile left the railgun intact.

![Figure 8](image-url)  Photograph of the 4-kg-projectile showing the brush armatures, the GRP sabot and the W-rod
2.3 Comparison between experimental and theoretical simulation results

The shots were simulated with the lumped parameter code ISLAM, developed at ISL to calculate and design new railguns before construction. The accuracy of the results is within ±10% for the muzzle velocity.

The results of the numerical simulation were compared to the measured values (Table 1). The values of the muzzle velocity and of the maximal current are within 10% and thus within the measurement errors. The calculated acceleration values are always higher than the experimental ones. The maximum difference between the calculated and measured acceleration is in the order of 30% in the case of the 1 kg projectile and in the order of 20% for the 2 kg projectile. A more accurate code, taking into account the mass loss of the armature, will be written using the software Mathematica. This new simulation will be available in the future allowing a better fit of the experimental data.

<table>
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<td>932</td>
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<td>( \gamma_{\max} ) ( [10^5 \text{m/s}^2] )</td>
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Table 1: Comparison between experimental and theoretical values
3 Projectile Real-time Unsteady-loads Computation

As stated in the previous study the mission requirement for the proposed railgun-suborbital projectile requests to deliver a small payload of about 400 g to an altitude of 115 km. Since the projectile is exposed to a large air drag force, in particular due to wave and base drag, during its flight in the dense atmosphere, a low drag shape selection is very important.

Since the projectile moves out the atmosphere in a very short time, it is important to quantify the impact that such decelerated motion may have on the projectile loads, in particular the thermal ones. While the previous study reported first estimations of such loads based on semi-empirical assumptions, in the following CFD solutions representing real time trajectory points are employed to assess the projectile loads.

3.1 Numerical Tools

The numerical solutions are obtained by coupling the DLR Navier-Stokes TAU code with the 3DOF trajectory program. The format and volume of data to be transfer can be changed upon the requirements but the minimum data set shall include global time for every trajectory point, physical time-step between two trajectory points, Mach number, atmospheric pressure or temperature for each trajectory point and Reynolds number for each trajectory point.

The 3DOF program is based on a 3 degree of freedom mass pointed method where all the forces like inertia, gravitation, drag and thrust are applied to a moving point in the space. The numerical integration is done by means of a Runge-Kutta technique. The method takes into account the effects of centrifugal and coriolis forces as well as wind profile. It considers also the changes of the gravitational constant with altitude, the effect of the Earth rotation, the projectile initial velocity and its aerodynamic performance, in terms of lift and drag, the distribution of thrust over time, etc. Also, different atmospheric models can be selected by input.

The TAU code is a finite-volume Euler/Navier-Stokes solver working with hybrid, unstructured or structured grids. The code is composed of three independent modules: a pre-processing module, a solver and a grid adaptation module. In TAU, there are several turbulence models available, ranging from 0 to 2 equations models and also Reynolds stress and Detached Eddy.

For the present study the one-equation transport model according to Spalart and Allmaras is selected. The model uses only local quantities for calculating turbulent transport which makes it suitable for unstructured methods. For time-accurate solutions a global as well as a dual time-stepping scheme is implemented. The dual time stepping scheme follows the approach of Jameson, where the Runge-Kutta scheme is slightly changed in order to avoid instabilities while dealing with small physical time-steps. The time discretization can be chosen to be first, second or third order (where a higher order implies increased overhead).

The numerical discretization of the geometrical shape is done by means of the Centaur™ hybrid grid generator. The prismatic and tetrahedral grids are combined into one hybrid grid which is than used for simulations.

3.2 Study Constrains

It is assumed, that the projectile is absolutely stable and that the flight path is tangential to the trajectory. Flow separations are neglected with exception of the after body, which however is considered non-critical. In addition, transonic unsteady effects are excluded from the analysis, because the projectile flies hypersonic. Also aerelastic effects are neglected since the projectile's body is considered rigid. It turns out that as potential source of flow unsteadiness shock-wave boundary-
layer interactions phenomena and unsteady shock motion due to projectile deceleration have to be considered only. Furthermore, since such phenomena are of short duration they are referred as transient or pseudo-unsteady for the present study. For the calculation of heat flux and surface temperature distribution in the heat balance equation convective and radiation heat fluxes are taken into account.

Absence of ablation and gas radiation is assumed, so the correlated fluxes are zero. Also the interaction effects between the flow and the structure are not considered and therefore the related heat fluxes stored by the structure and the conductive heat flux, orthogonal to the surface, are not taken in account.

Within the first 20 msec the acceleration of the projectile in the railgun tube will reach high values. Once the projectile moves out of the railgun, air drag and gravitation will suddenly decelerate it. While the influence of the Earth gravitation is approximately constant and equal to 1g, the deceleration due to air drag has a maximum already at the railgun exit. Indeed, after 6 seconds of free flight, the projectile acceleration reduces to 5g and after 20 sec close to 1g, while the projectile is already at 30km altitude. It turns out that with the exception of the first few seconds outside the gun, the projectile deceleration due to air drag is moderate and after 20 sec of flight negligible.

In hypersonic regime there are only few methods, all of them semi-empirical, for predicting turbulent/laminar flow transition. One of the most commonly used is that from Bowcutt and Anderson. Based on this criteria it is found that the transition Reynolds number is in the vicinity of $R_e=2.9$ million, a Reynolds number value which is firstly reached at an altitude of 27 km. At this altitude the heat loads and surface temperature of the projectile are no more critical.

### 3.3 Results and Discussion

#### 3.3.1 Numerical Discretization

For the CFD solutions a hybrid 3-D grid is created with the grid generator Centaur. The flow field comprises a blunted semi cone of 2.4 m length (Figure 9). This enables to capture the bow shock wave and also the flow properties directly behind the projectile boat-tail, like expansion fan, recirculation and recompression regions.

To compute the boundary-layer flow, 22 prismatic layers are generated close to the projectile's surface, resulting in a final grid (used for both, steady and unsteady solutions), which contains 8.6 millions elements, 52 % of them in the prism layer.

![Figure 9](image)
3.3.2 Initial Conditions
As a first approximation it is assumed that the surface temperature of the projectile when it leaves the railgun muzzle is 298 K (cold wall). The launch velocity is \( v_o = 2122 \text{ m/sec} \) and the corresponding mach number \( M_a = 6.226 \). The total pressure is \( p_k = 50.7 \text{ bar} \) and the atmospheric conditions are given for an altitude of 1 m above sea level. A surface emission coefficient of \( \varepsilon = 0.85 \) is assumed.

3.3.3 Computational Strategy
In order to draw an upper boundary of the expected thermal loads, five steady state solutions for selected trajectory points are firstly obtained for zero angle of attack and neglected spinning, i.e. roll angle equals zero (Figure 10-Figure 14). They are:

1. Launch point, \( M_a = 6.22 \), radiation-adiabatic wall, full catalytic surface, turbulent flow
2. Launch point, \( M_a = 6.22 \), constant wall temperature, turbulent flow
3. Trajectory point \( M_a = 5.5 \), i.e. 3.1 sec of flight, altitude \( H = 5724 \text{ m} \), radiation-adiabatic wall, full catalytic surface, turbulent flow.
4. Trajectory point \( M_a = 4.4 \), onset of turbulent laminar transition
5. Trajectory point \( M_a = 4.276 \) (20 sec flight, altitude \( H = 30078 \text{ m} \)), radiation-adiabatic wall, full catalytic surface, laminar flow.

Also, to assess the numerical error, two different grids are used for the \( M_a = 4.4 \) case: 7.5 and a 8.6 million elements. Furthermore, the comparison of the CFD values for temperatures with those obtained by means of the Fay – Riddell formulation shows an agreement within 5 % or less.

Since real-time unsteady computations are highly demanding on computational resources and computing time, only the first three seconds of flight are here considered (Figure 15 - Figure 24). Concerning the thermal loads, this time interval is the most critical one since both, the projectile velocity and the air density exhibit the largest values. In order to achieve a high degree of accuracy while keeping computational efficiency, the computational time step shall increase as the time flight increases. This strategy is implemented here subdividing the time domain in three segments:

1. From gun exit to 0.0258 sec flight time, Mach range \( 6.22 < M_a < 6.217 \)
2. From gun exit to 0.97 sec flight time, Mach range \( 6.22 < M_a < 5.918 \)
3. From gun exit to 3.1 sec flight time, Mach range \( 6.22 < M_a < 5.5 \)

In general a good agreement between the solutions obtained with different time steps for the same physical time can be shown. Also, the figures show that the pressure distribution achieves the steady state condition already in a few milliseconds, whereas the area of the fins require a longer time (22 msec). The CFD simulations also show that within the first 20 msec the surface temperature achieves its maximum values. Highest heat loads and temperatures occur, as expected, on the nosecap, leading edges of fins and body-fin junctions. As the projectile continues its flight, the surface temperature reduces to levels close to steady state. In the course of time the heat fluxes and surface temperatures, after they have reached their maximum in the first milliseconds of flight, decreases within the first 3 seconds to levels acceptable for a number of standard aerospace materials.

The comparison between the pseudo-unsteady solutions with the steady one (Figure 23 - Figure 24) indicates a lower heating on the projectile front part during the transient motion but a moderate larger heating on fins and aft part, with temperature variations in the order of 50 to 100 K. Only at the stagnation region the differences are larger, exhibiting the transient solution almost 180 K less than the steady state case. Beside the potential impact of the numerical error that usually exhibits each solution at the stagnation point, there is a physical explanation for the observed difference: In the first few seconds of flight the projectile experiences a large deceleration and hence the bow shock moves continuously upstream direction, i.e. away from the nosecap, having no steady condition. After 3.1 sec of flight time (\( M_a = 5.5 \)) the, only minor differences are observed. Finally, Table 2 displays the computational strategy and the required effort to obtain the present solutions.
Table 2: Time dependencies for carried coupled simulations on 64 bit workstation Siemens – Fujitsu with dual – processors AMD OPTERON (8 GB RAM)

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Mach number $M_a$ range</th>
<th>Calculated number of trajectory points</th>
<th>Time steps $\Delta t_R = \Delta t_{Ph}$ [sec]</th>
<th>Number of relaxation time steps</th>
<th>Number of relaxation iterations</th>
<th>Calcul. Flight time [sec]</th>
<th>Calcul. comp. Time [days]</th>
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<tr>
<td>1</td>
<td>6.226– 6.217</td>
<td>2</td>
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<tr>
<td>2</td>
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<td>48</td>
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<td>35</td>
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<tr>
<td>3</td>
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<td>136</td>
<td>0.0155 to 0.0264</td>
<td>1</td>
<td>500</td>
<td>3</td>
<td>77</td>
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Figure 12  Temperature distribution, steady case, $M_a=6.226$, turbulent flow, radiation adiabatic conditions

Figure 13  Temperature distribution, steady case, $M_a=4.276$, laminar flow, radiation adiabatic conditions

Figure 14  Heat flux distribution for two different boundary conditions, steady case, $M_a=6.226$, turbulent flow
Figure 15  Transient $C_p$ distribution along the longitudinal x-axis of the projectile (time interval 0 to 22 msec)

Figure 16  Transient temperature distribution along the longitudinal x-axis of the projectile (time interval 0 to 22 msec)
Figure 17  Transient temperature distribution at the stagnation point (SP)
A: time interval 0 to 27 msec, B: time interval 0 to 3.1 sec

Figure 18  Cp distribution along the longitudinal x-axis for different time steps
Figure 19  Heat flux distribution along the longitudinal x-axis for different time steps  
(time interval 0.0246 msec – 2.88 sec)

Figure 20  Temperature distribution along the x-axis for different time steps  
(time interval 0.0246 msec – 2.88 sec)
Figure 21  Transient temperature distribution, $M_a=6.226$, turbulent flow, radiation adiabatic conditions, physical time step $\tau = 0.0197$ sec (this time point display the maximum $T_W$)

Figure 22  Transient temperature distribution, $M_a=5.5$, turbulent flow, radiation adiabatic conditions, physical time step $\tau = 3.1$ sec
Figure 23  Temperature distribution along the longitudinal x-axis for steady and transient conditions

Figure 24  Heat flux distribution along the longitudinal x-axis for steady and transient conditions
4 Conclusion

This study, the successor of the ESA funded "Railgun Feasibility Study", was split into a theoretical and an experimental part, covering those issues, which have been identified to be of basic interest for a possible suborbital application: the aero(thermo)dynamic characteristics of the hypersonic projectile and the verification of the general capability of an electromagnetic railgun to accelerate the envisaged masses.

Both issues have been completed with just positive and very satisfactory results.

The test shots have been performed by means of the ISL Pegasus Railgun. They comprised 1-kg- and 2-kg-projectiles (accelerations smaller than or close to 15000 g's) as well as 3-kg- and 4-kg-projectiles (at accelerations smaller than or close to 8000 g's) and have worked perfectly and proved the reliability of the railgun eventually. Within the measurement accuracy all experimentally derived results could be verified by theory.

The sabot (GRP body) of one 3-kg-projectile was broken by the plasma generation. But the payload (W-rod) flew intact out of the railgun. After making the fiber brush armature longer, this problem was completely avoided for the 4-kg-projectile which was accelerated intact (sabot and payload) up to about 500 m/s with currents in the same order of magnitude (1 MA).

In the case of the suborbital application the railgun energy supply system seems feasible based upon today's knowledge and the use of already existing technology. No major issues have been identified which could not be implemented.

Furthermore, a detailed assessment of the railgun-suborbital projectile has been conducted. While in the previous study thermal and pressure loads have been estimated by means of semi-empirical assumptions, now CFD solutions representing real time trajectory points have been employed. Real-time unsteady solutions have been obtained by coupling the DLR Navier-Stokes solver with the 3DOF trajectory program. To keep the computational effort within an acceptable level, only the first 3 seconds of flight, which are the most critical one, have been considered.

After 3 seconds flight the time dependent solutions agree everywhere rather good with those obtained for steady state except at the stagnation point, where the time dependent solutions exhibit a lower heating. The CFD results show that the projectile achieves almost after the first 25 milliseconds a steady state, being the level exhibit for the heat fluxes and surface temperature similar to those predicted in previous study by means of semi-empirical methods. It turns out the thermal environment of the railgun-suborbital projectile is well within the boundary of today classical aerospace materials.