Electromagnetic Launch to Space

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ABSTRACT

A study was undertaken to determine if a ground-based electromagnetic (EM) acceleration system could provide a useful reduction in launch-to-orbit costs compared with current large chemical boosters, while increasing launch safety and reliability. The study evaluated the launch of a two-stage-to-low-Earth-orbit projectile, with the initial velocity being provided electromagnetically and the orbit insertion via a rocket motor. Several electromagnetic accelerator options are available but railguns were chosen for this study based on their demonstrated performance capabilities. The second stage of the system was assumed to be a chemical rocket that would carry a payload into low-Earth orbit.

Electromagnetic launch systems of this type will be governed by the same fundamental principles as tactical railguns with a major difference being that the EM accelerator track—which may be tens or hundreds of meters in length—cannot be powered only from the "breech" as in a tactical railgun, since electrical resistive losses will become unacceptably large. To overcome this, a distributed feed system will be required.

This study shows that the capital cost of the pulsed power system for the EM accelerator will dominate the system economics. With present pulsed power approaches, multiple launches will be required to offset the capital cost and provide low costs. The development of novel pulsed power concepts and/or low-cost manufacturing approaches will ensure that the EM system will be economically attractive and options for such approaches are discussed.

BACKGROUND

Figure 1 illustrates the basic concept of a railgun launcher in which a pulse of high current applied to the breech of the railgun causes an EM force to be generated that accelerates the launch package along the "barrel." For this simple configuration, high currents in the range of mega-amperes (MA) are required to launch masses of tens of kilograms. Unlike conventional powder propellant guns, the current pulse can be tailored to provide a relatively constant acceleration throughout the launch process. Taken with the absence of gas expansion limits, this allows hypervelocities (> 2000 m/s) to be achieved. For most tactical applications it is desirable to keep the barrel length to about ten meters or less, so that a hypervelocity launch necessarily requires the launch package to withstand very high accelerations. Typical parameters for a tactical railgun system are shown in Table 1.

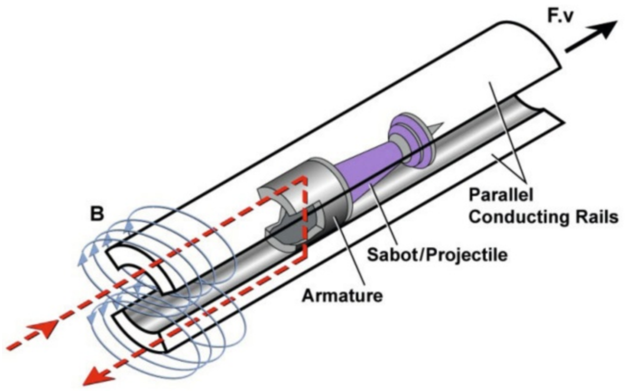

Figure 1. Basic railgun concept.

Table 1. Typical railgun parameters.

Parameter	Units	Value
Muzzle velocity	m/s	2000
Launch acceleration	kGees	30
Barrel length	m	12
Average current	MA	4.5
Launch mass	kg	16
Muzzle energy	MJ	32
Stored energy	MJ	105

Following earlier studies [1], the US Navy's Office of Naval Research (ONR) has publically stated that it is developing high energy tactical railguns for ship installation and deployment [2-6]. A large laboratory system is shown in Figure 2 and Figure 3 and an innovative naval prototype railgun undergoing testing is shown in Figure 4 and emplaced on a ship in Figure 5. The type of hypervelocity guided projectile planned for launch in this system would be similar to that shown in shown in Figure 6. This is essentially a small angle conical aerobody with fin stabilization.

Figure 2. Navy laboratory railgun [7].

Figure 3. Power feed to Navy laboratory railgun [7].

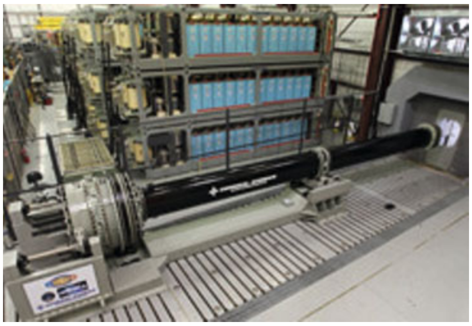

Figure 4. Laboratory tests of Navy railgun showing capacitor power supplies [6].

Figure 5. Railgun emplaced on ship deck [8].

Figure 6. Hypervelocity projectile [9].

Although this Navy system is still under development, much of the technology demonstrated in the laboratory could serve as the basis for the launch to space system described here.

As mentioned, unlike conventional powder propellant guns, railguns can achieve very high muzzle velocities using controlled pulses of electric current. Tactical guns that operate at sea level will be designed for velocities of 2 to 3 km/s but laboratory experiments have operated to over 5 km/s and small experiments to over 6 km/s. Figure 7 shows a 4.4 km/s non-aerodynamic 0.6 kg projectile shortly after launch from a railgun while the 20 m long distributed railgun barrel shown in Figure 8 achieved 5.5 km/s with a 0.1 kg projectile.

Figure 7. 4.4 km/s railgun experiment.

LAUNCH TO SPACE CONCEPT

Earlier EM launch to space studies have evaluated a range of different concepts, from 1000 kg flight bodies [10], airborne launch [11-20], to augmentation of large two-stage chemical boosters [21]. Studies have been done by several groups, including the German Aerospace Research Center, e.g. [22].

This preliminary study has built on these earlier studies and recent Navy developments to evaluate whether railguns could launch small payloads into low Earth orbit (LEO). The EM launcher required for this application will be similar to tactical railguns but the EM accelerator track may need to be tens to hundreds of meters long to reduce acceleration loads on the payload during launch. For this reason it cannot be powered from the breech as in a tactical railgun, since electrical resistive losses become unacceptably large. A distributed power fed system similar to – but longer than – that shown in Figure 8 will be required.

Figure 8. 20-meter long distributed railgun.

The launch package will consist of two parts – an aerobody similar to Figure 6 to withstand the aerothermal heating after launch and transit through the densest portion of the atmosphere and a lighter "second stage" containing the rocket motor and fuel required for orbit insertion and circularization, together with the payload. Depending on the launch velocity and angle, an apogee close to LEO can be achieved. At apogee, the aerobody will separate from the second stage containing the rocket motor, fuel and payload. This rocket-powered section is required to circularize the orbit from the horizontal component of the launch velocity. Some parameter examples are given in Table 2.

Table 2. Notional launch to space railgun parameters.

Parameter	Units	Value
Muzzle velocity	m/s	5500
Launch acceleration	kGees	10
Barrel length	m	154
Average current	MA	3.2
Launch mass	kg	25.4
Muzzle energy	MJ	384
Stored energy	MJ	512

Comparison with Table 1 shows similarities and differences. The launch to space system clearly requires a much higher muzzle velocity and, with an assumed lower payload acceleration limit, the "barrel" length is much longer. However, the average current is less than that considered for a tactical railgun and the launch mass is comparable (about 50% larger). The muzzle energy is ten times larger than the tactical railgun but the use of a more efficient distributed power feed system means that the required stored energy is only about five times larger.

Given the different mission requirements, a much lower firing rate has been assumed for the launch to space system than would be necessary for a tactical system. This impacts the rating of the power supply needed to recharge the energy storage system between launches. Assuming five launches per hour and that half of the time between launches is available for recharging the energy storage system (i.e., about 6 minutes), a diesel generator rated at about 1500 kWe could provide the required power.

To reduce aerothermal heating on the projectile nosetip, the launcher should be located at the highest altitude possible and near the Equator to benefit from the Earth's rotational contribution (Figure 9).

The notional design of the second stage was based on a launch angle of 40 degrees, yielding an apogee (without allowance for drag) of about 640 km and a horizontal velocity component of 4200 m/s. To achieve the total estimated delta-V of 9447 m/s (orbital velocity 7558 m/s plus an estimated aero and drag loss of 25%) a further $\Delta V = 4890$ m/s will be required. To achieve this a fuel $I_{sp} = 300$ sec was assumed, yielding a fuel mass of 14.9 kg which, with an aerobody mass of 7 kg, a second stage structure mass of 10% and a payload of 2 kg yielded a total launch mass of 25.4 kg.

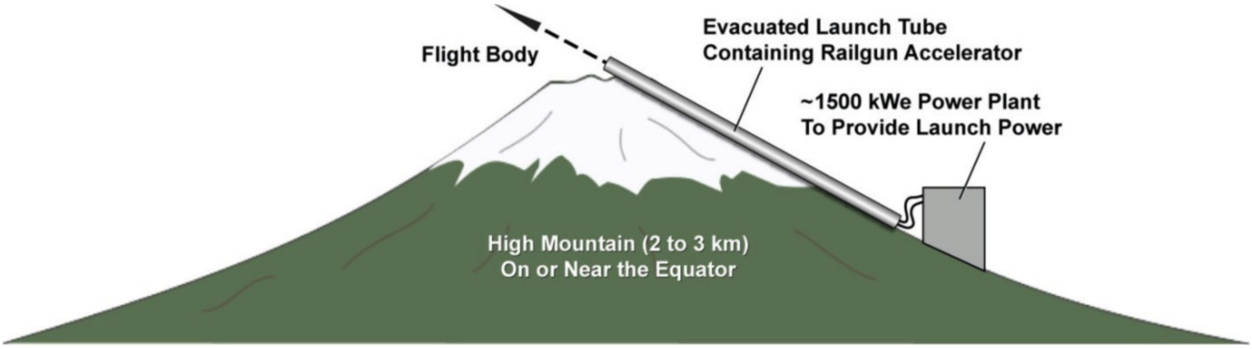

Figure 9. Schematic concept layout.

LAUNCH ECONOMICS

An initial estimate of the launch economics can be obtained by estimating the cost of the energy storage and launcher: range operating costs have not been estimated here but should be less than for chemical boosters given the likely improved reliability and safety.

The system investment cost will be dominated by the capital cost of the pulsed energy storage system. With larger-scale manufacturing and "lessons-learned" from the US Navy developments, it is conservatively estimated that the cost of the pulsed power can be reduced to \$0.25 per Joule. Together with an estimated launcher cost of \$100K/m, an approximate total EM system cost neglecting site preparation would be about \$144M.

The purpose of developing a system of this kind is to create a different paradigm for the launch of nanosatellites than exists at present with large chemical boosters. Thus, the facility would be expected to operate frequently and on a daily basis to place many nanosatellites into LEO. Over a five year period operating with 5 shots per hour for 8 hours per day and five days per week, about 50,000 launches could be achieved even including 10% down time for maintenance and repair. With a 2 kg payload per launch this would be 100 tonnes placed into LEO at an average cost of \$1440/kg. Future reductions in the cost of pulsed power can be expected to further reduce this cost.

CONCLUSIONS

This preliminary study shows that even with present pulsed power approaches, attractive low launch costs appear possible for an operating scenario based on the multiple launch capability for a system of this type. The capital cost of present-generation pulsed power technology dominates the capital cost but improved pulsed power concepts and/or low-cost manufacturing are expected to ensure that future EM systems are economically viable.

Many technical challenges remain to be overcome before a system of this type can be built with confidence. Nevertheless, this preliminary study indicates that further more detailed assessments should be worthwhile and could lead to a new, different and low cost launch system for the future.

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