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Railgun

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ABSTRACT

A railgun using electromagnetic propulsion was developed to launch hypervelocity projectiles. A 240 kJ, low inductance capacitor bank operating at 5 kV powered the railgun. Launchers and projectiles were designed and developed for this purpose. The currents producing the launch forces are of the order of hundreds of kA. Even very low impedances for the current through the railgun circuit are substantial sources of energy losses. A simulation code was developed to optimise the performance of the railgun. Control and instrumentation facilities were set up along with a computer-based data acquisition system for measurement and analysis. The capacity to launch projectiles of 3–3.5 g weight to a velocity of more than 2.00 km/s was demonstrated.

NOMENCLATURE

$A(t)$	projectile acceleration at time t
$E_{arc}(t)$	energy dissipated in plasma arc at time t
$E_l(t)$	energy of launcher at time t
$E_{proj}(t)$	kinetic energy of projectile at time t
E_{total}	total energy delivered by the power source
$F(t)$	force at time t
$I(t)$	current through the launcher at time t
L	inductance per unit length of the launcher
$L_{eff}(t)$	launcher efficiency at time t
m	mass of the projectile
$P(t)$	plasma pressure at time t
$PL_{eff}(t)$	power source to launcher efficiency at time t
$S(t)$	displacement of the projectile at time t
$S_{eff}(t)$	total railgun system efficiency at time t
$v(t)$	velocity of the projectile at time t
$V_{br}(t)$	voltage at the breech end of the railgun at time t
$v_{elmz}(t)$	velocity at the muzzle end of the railgun at time t
$V_{mvz}(t)$	voltage at the muzzle end of the railgun at time t

1. INTRODUCTION

A facility was developed to launch hypervelocity projectiles using electromagnetic energy. The projectiles were launched using a railgun. The railgun consists of two parallel rails and a conducting metallic foil placed behind the insulating projectile. When a high current flows through the rails, the foil explodes and forms a plasma armature. The force acting on the armature is given by

$$F(t) = 0.50 * L * I(t)^2$$

The railgun currents are in the region of hundreds of kA. This Lorentz force accelerates the projectile[1-3]. The railgun set-up is shown in Fig. 1.

2. POWER SUPPLY

An electromagnetic propulsion system requires a storage device with an energy density comparable to that of chemical explosives. The most expensive and technologically difficult part of the system is the high-energy electric source. The power sources considered for electromagnetic propulsion are well researched[4].

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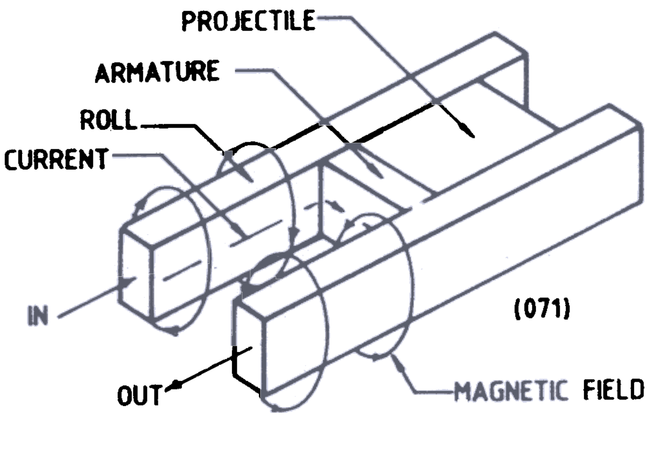

Figure 1. Basic configuration of the railgun.

2.1 Capacitor Bank and Charging Unit

The capacitor bank was used as a power source owing to its availability and lower cost despite its lower energy density[5]. A low-inductance, 240 kJ capacitor bank was set up to provide the basic power to the railgun. A high-voltage charging unit was used to charge the capacitor bank.

2.2 High Current Switches

The capacitor energy is switched into the railgun by high-power ignitrons. When the peak current is reached, additional high-power ignitrons are used to crowbar the capacitors out of the circuit to obtain a dc pulse. This minimises the stress on the capacitors, the launcher and the projectile. A schematic diagram of the railgun powered by the capacitor bank is shown in Fig. 2.

2.3 Transmission Lines

Low-inductance transmission lines were made using sandwiched conducting plates to maximize the energy transfer to the load. The transmission lines are subjected to repulsive forces owing to the passage of current through them. These forces were estimated to provide proper bolting and bracing to avoid deformation of the transmission lines.

3. LAUNCHER AND PROJECTILE

Launchers and projectiles are subjected to high plasma pressures, high magnetic fields and high temperatures. In the present railgun set-up, the plasma pressures generated varied between 100 and 150 MPa.

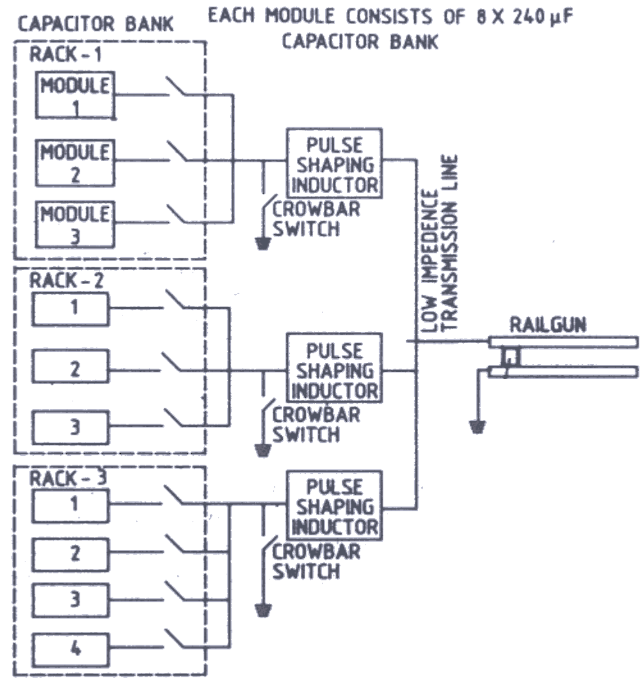

Figure 2. Schematic circuit diagram of the railgun powered by the capacitor bank.

Launcher: A simple, single pulse driven railgun launcher was developed with a minimum of metal components in proximity to the bore to maximize the inductance of the launcher and to improve the launch efficiency. The launcher has a 12 mm square bore cross-section. The launcher was fabricated with lengths ranging from 1 to 2 m. The following launcher designs were used for the firings:

(a) The copper rails and the insulator were rigidly contained within Perspex side plates and bolted. These launchers were found to be weak, getting damaged and cracking at higher plasma pressures.

(b) The copper rails and the insulator were rigidly contained using fibreglass side plates and potted in an epoxy resin. The assembly was housed in a cylindrical mild steel jacket.

(c) The copper rails and the insulator were rigidly contained using fibreglass side plates and wound with a fibreglass material. They were potted in an epoxy resin and the assembly was housed in a cylindrical nonmetallic jacket.

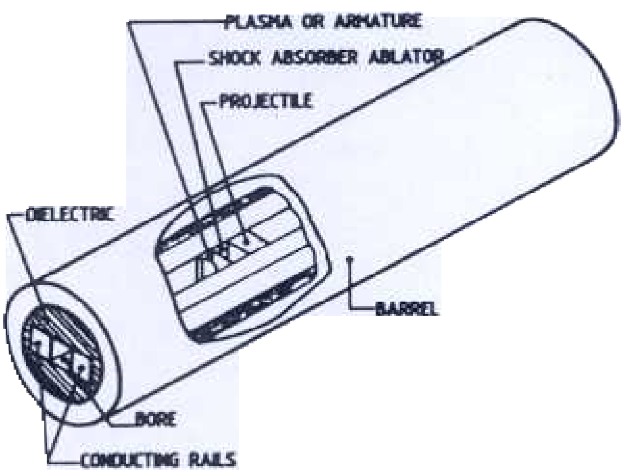

Figure 3. Construction details of the railgun.

The launchers with the last two design modifications proved more reliable and durable than the launchers based on the first design. The details of construction of the railgun are shown in Fig. 3.

Thermal energy transfer from the rails leads to ablation and the melting of the bore materials. Such ablation degrades the performance of the railgun by adding parasitic mass to the plasma. The bore materials should have a high melting point and superior erosion and ablation resistance. High rail conductivity necessitated the use of copper rails. Polycarbonate and fibreglass were most suitable as bore materials. Loose bore to projectile tolerances or variation in bore dimensions can result in plasma leakage. Most of the launchers showed marked deterioration after a few shots. The deterioration could be attributed to changes in the bore dimensions due to the rail insulator ablation. Substantial deposits of carbon were observed inside the bore of the gun and needed cleaning.

Projectile: The projectiles are made of Perspex or polycarbonate cubes of 12 mm length. Perspex projectiles tended to shatter. Polycarbonate projectiles survived the high plasma pressures. The plasma and the solid armature were both used for carrying the high currents. Most firings were carried out using plasma armature. A plasma armature is formed when *Al/Cu* foil melts/explodes on the passage of high currents. The foil vaporises by joule heating to produce a plasma to drive the armature. A neoprene obturator was placed at the rear of the projectile to seal the bore against plasma leakage around the projectile. As a deviation, a solid metallic projectile acting as an armature was also used to carry the current.

4. DATA ACQUISITION AND SIMULATION

4.1 Data Acquisition

A computer-based data acquisition system was set up to monitor important parameters that affect the performance of the railgun. Current transformers and Rogowski coils were used to measure the rail currents in the range[6] of 100 to 500 kA. Magnetic probes were used to get the position–time profile of the projectile inside the bore of the gun and railgun current distribution[7]. These probes help detect plasma leakage and formation of secondary arc. The velocity outside the bore of the gun was measured using shorting screens[8]. A high-speed camera was set up to measure the velocity of the projectile and establish the integrity of the projectile at the muzzle end. This is a non-contact method and is free from electromagnetic pickups.

4.2 Simulation

A simulation code was developed to predict the performance of the railgun. The performance of the model was evaluated by monitoring different parameters. Table 1 gives the equation used in the simulation and analysis. The current measured is used to derive other significant parameters like the displacement, velocity and acceleration of the projectile calculated from Eqns (1) – (3).

Table 1. Equations used for the analysis of the railgun system

$S(t)$	=	$[L'/(2*m)] * \int\int I(t)^2 * dt$	(1)
$V(t)$	=	$[L'/(2*m)] * \int I(t)^2 * dt$	(2)
$A(t)$	=	$[L'/(2*m)] * I(t)^2$	(3)
$P(t)$		$[L'/2] * I(t)^2/\text{area}$	(4)
$F(t)$	=	$[L'/2] * I(t)^2$	(5)
$E_1(t)$		$V_{br}(t * I(t) * dt$	(6)
$PL_{eff}(t)$	=	$E_l(t)/E_{total}$	(7)
$L_{eff}(t)$	=	$E_{proj}(t)/E_l(t)$	(8)
$E_{arc}(t)$		$V_{muz}(t) * I(t) * dt$	(9)
$E_{proj}(t)$	=	$(1/2) * m * V(t)^2$	(10)
$S_{eff}(t)$		$E_{proj}(t)/E_{total}$	(11)

5. ANALYSIS

All measurements were supported by appropriate software developed to analyse the entire performance

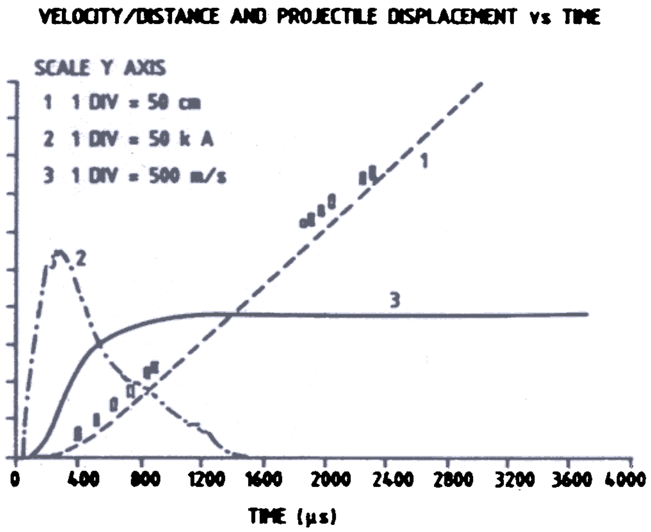

Figure 4. Projectile velocity and displacement computed from the current signal recorded on scopes. The inbore and shorting screen pulses with respect to time are also shown.

of the railgun. The current-time data are used to predict the displacement, velocity and acceleration of the projectile and the plasma pressure. Figure 4 shows the graphical display of the results derived from the measurements. Not only were the measured currents and the simulated currents compared, but also the results derived from these equations, to validate the computer model.

The breech and the muzzle voltages are monitored and along with the current signals are used to estimate the arc voltage and resistance. The energy of the launcher and the gun efficiency are also computed from Eqns (6) and (8). The projectile exit at the muzzle is also indicated on the muzzle voltage signal. The breech and the muzzle voltage signals along with the in-bore flux probes detected plasma leakages, attributed to low projectile velocities.

The magnetic flux probes were used to obtain the displacement of the plasma armature which leads to in-bore velocity and the acceleration of the projectile from Eqns (2) – (3). The plasma position-time history and the current signal help estimate the inductance per unit length of the railgun, a useful input to the simulation code (Eqn 1). The pulses from the shorting screens were used to monitor the velocity, acceleration and the kinetic energy of the projectile outside the bore of the railgun. There was a substantial agreement between the results predicted from the computer model and the actual measurements, thus validating the simulated model.

6. RESULTS

Some typical railgun trial results are given in Table 2. Projectile velocities greater than 2000 m/s were obtained for trial nos 1 to 3. The efficiency varied between 4 to 5 per cent with railgun current in excess of 260 kA.

Plasma leakage and formation of secondary arcs[8] were responsible for the lower projectile velocities than expected from the computer model for trial nos 5 to 7. Trial no. 7 was done using a solid conducting projectile made of aluminium. An armature was kept behind the projectile with no ablator. The armature vaporised and the plasma escaped ahead of the projectile. This led to a lower system efficiency and projectile velocity.

A solid projectile made of Perspex and armature made of several copper foils were used in trial no. 4. The mass of each foil was kept around 100 mg to avoid the melting of the armature owing to the high railgun current.

7. CONCLUSION

Our study has shown that projectiles attain hypervelocities by using a single small square bore railgun. In the existing railgun facility the efficiency varied between 4 to 5 per cent. Significant improvement in the efficiency of the railgun set-up is one of the key issues that will determine the use of railguns for various weapon applications. Hence we carried out detailed modelling and simulation of the entire railgun system. The results from the simulation were validated with the measurements. Measurements made at high common mode voltages of around 1000s of volts and high electromagnetic noise were exceptionally good, providing reliable and repeatable records. Intact projectile launch and 2-3 m of free flight projectile were studied using high-speed photography when punctures in the shorting screens were obsered. Using a high-speed camera the integrity of the projectile was established beyond doubt (Fig. 5). A 12 mm cubical polycarbonate projectile weighing about 3 g could defeat a 6 mm aluminium sheet at 2 m from the muzzle end of the gun (Fig. 6). The complete railgun system was also placed in a 5 m long vacuum chamber to study the railgun performance. Our studies are as yet inconclusive. Owing to the failure of some odd capacitors in the capacitor bank, repetitive trials could not be carried using the full energy of the bank. The energy extracted from the

Table 2. Some typical railgun results

Parameter	1	2	3	4	- 5	6	7
Mass of projectile, g	3.0	3.0	3.0	3.7	3.0	7.0	3.0
Type of armature	Plasma	Plasma	Plasma	Solid	Plasma	Solid	Plasma
Energy of bank, kJ	138.24	138.24	138.24	155.5	138.24	138.24	138.24
Peak, kA	298.0	296.0	290.0	267.0	271.0	287.0	234.0
Peak force on the projectile, kN	22	21	21	18	18	20	14
Peak acceleration on the projectile, k'g'	740	730	700	491	624	300	466
Peak pressure, MPa	154	152	146	123	128	143	95
Theoretical projectile velocity, m/s	2250	2250	2250	1730	2150	1250	2200
Measured projectile velocity, m/s	2080	2050	2000	1550	1700	588	1300
Kinetic energy of the projectile, kJ	6.49	6.30	6.00	4.44	4.35	1.20	2.56
System efficiency, %	4.69	4.56	4.34	2.58	3.13	0.87	.87

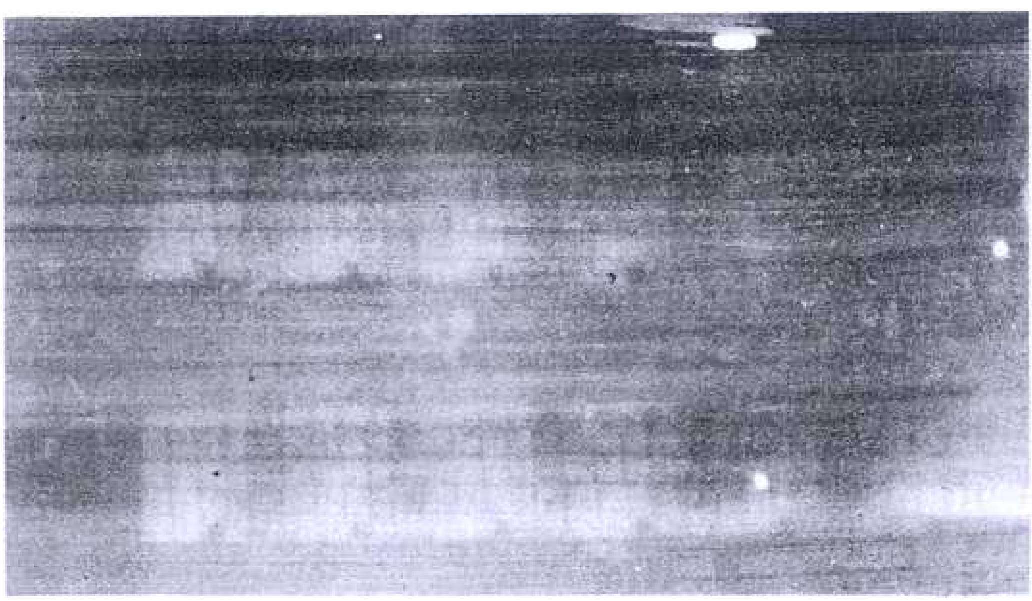

Figure 5. A polycarbonate projectile photographed through an Imacon high speed camera (framing speed : 500,000 frames/s; exposure time : 400 ns; flash duration : 500 μs; and aperture : 4).

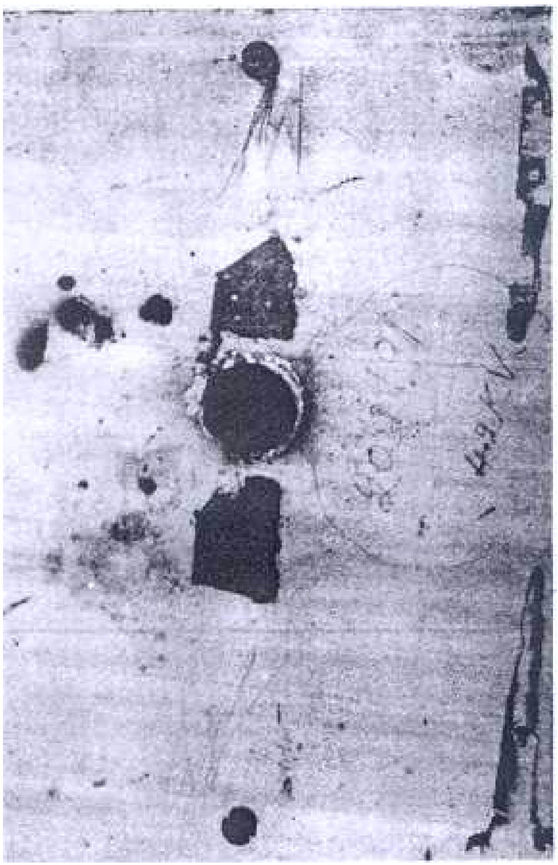

Figure 6. Penetration of the polycarbonate cube through a 6 mm aluminium sheet at 2 m from the muzzle of the railgun.

capacitor bank varied between 120 and 160 kJ. The kinetic energy of the projectiles can be increased substantially by using a higher-energy capacitor bank as a power source.

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