Chapter 6

POWER SOURCES AND DIAGNOSTIC SYSTEM FOR RAILGUN

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Summary. Power sources and a diagnostic system have been developed for railguns with medium size projectile having the order of ten grams. The power source composed of a capacitor bank and a pulse transformer has been constructed and examined using 30 mm square bore railgun. Experimental results demonstrated that the use of the pulse transformer improved its efficiency by approximately five times for 30 grams projectile. The behavior of projectile in 14 mm round bore was examined in details. Flat-type explosive magnetic flux compression generators were developed for the power source of railgun and tests with 300–400 kA initial currents were demonstrated.

1. Introduction

A number of experimental and theoretical studies have been made on various kinds of electromagnetic acceleration of macroparticles (projectiles) as methods to exceed the limiting velocities attained by the conventional techniques using light-gas guns or explosives. A railgun, which has been demonstrated experimentally first by Rashleigh and Marshall (1978) to have the capability to accelerate a 3 gram projectile up to a velocity of 5.9 km/s, is based on a simple principle. An armature which may be solid metal or plasma is placed between two parallel conducting rails. The Lorentz force resulting from the interaction of the current flowing in the armature and the magnetic fields generated by rail current pushes the armature together with a projectile to the
muzzle of the railgun. Velocities up to 10 km/s for 3 gram projectiles have been obtained by Hawke et al., (1982) with the railguns powered by explosive generators, and are some of the highest values achieved with current technology. Projectiles with hypervelocities are suggested to be useful to various fields: generation of dynamic high pressures, simulation of impact of meteoroids, direct launching of payloads to earth orbit, space propulsion and so on.

In this article we report studies on the railgun system (Usuba et al., 1986) developed in National Chemical Laboratory for Industry (NCLI) for the purpose of generating high pressure and applying it to solid state physics, material syntheses and treatments, and chemical reactions. For these applications, projectiles with relatively wide crosssection area, and thus relatively large mass, of the order of 10 grams, are needed to ensure precise measurements of shock parameters. We have constructed a power source composed of a capacitor bank combined with a pulse transformer, which is suitable to the large mass accelerations, and examined its performance for the projectile with mass of 15–30 grams. A projectile detector using a continuous X-ray beam was developed to confirm the position of moving projectiles independently from the armature current movements. It was tested for the relatively light projectile (2–4 g) and was useful for reliable triggering of other diagnostic instruments. This technique should be quite helpful for successful operations of multi-stage railguns. Furthermore we have examined another power source system. This is an explosive magnetic flux compression generator, which can serve both as a power source and an accelerator, and will make it possible to accelerate the projectiles to higher velocities, although it is destructive.

2. Power Source Using Pulse Transformer

In usual non-destructive operation, pulsed currents of the order of one million amperes with duration of a few milliseconds are needed to accelerate projectiles of a few tens of grams. Capacitor banks are frequently used as the conventional power source to generate pulsed currents. In case of them being applied to railguns which have very small inductance, typically, 1 µH or so, it is difficult to construct the banks with large enough capacity to make the current last for the long period. In some cases a storage inductor is employed to make the current pulse durations longer. Resistive losses, however, in the inductor as well as in the switching circuit and transmission line cannot be ignored for large current. Especially for large mass projectiles the losses become larger because of the lower speed of the projectiles.

To avoid these difficulties we employed a pulse transformer with \( n:1 \) turn ratio in the power source system shown in Fig. 1. In a simplified equivalent circuit, circuit constants of primary side of the transformer are transformed as \( R \rightarrow R/n^2, C \rightarrow n^2C, L \rightarrow L/n^2 \) and \( V \rightarrow V/n \), where \( R, C, L \) and \( V \) are resistance, capacitance, inductance and voltage, respectively. Thus, it becomes
possible to elongate the pulse current period and to reduce Ohmic losses remarkably.

![Diagram of circuit of power source using pulse transformer]

Fig. 1. Circuit of power source using pulse transformer.

The transformer winding was composed of 12 winding stacks, each comprising a primary copper coil of 32 turns and a secondary thick single-turn coil made of aluminum. The turn ratio can be altered to $n = 16$ or 8 by changing connections among the secondary coils. Into these stacks a core made by piling up silicon steel plates was inserted. Preceding a capacitor discharge the core is inversely magnetized by bias current flowing into a third coil to avoid its saturation. Estimated voltage-times-time constant and leakage inductance were 0.4 Vs and 0.2 μH, respectively.

The capacitor bank with 10 kV in maximum chargeup voltage and 200 kJ in maximum storage energy was connected with rails through the pulse transformer. Secondary peak current of 750 kA was obtained when the output of the transformer was shorted.

The employment of the pulse transformer is of advantage to a discharge switch. Because the switch is required to turn on the primary current of only a several tens of kiloamperes, i.e. secondary current divided by turn ratio, it becomes possible to make the switch simply using an ignitron.

3. Diagnostic System

A full diagnostic system is shown schematically in Fig. 2. Motion of plasma armature in the railgun bore was detected by two methods—with pickup coils and with optical probes. Because the pickup coil is mounted in the polycarbonate spacer with its plane perpendicular to the bore axis, it produces an emf proportional to the time derivative of the magnetic fields caused by armature
Fig. 2. Schematics of whole diagnostic system.
currents. In the opposite side of the bore an end of a long optical fiber is placed to form the optical probe with a PIN photodiode. The light emitted from plasma arc enters the optical fiber through 5mm thick polycarbonate wall and is transmitted to the diode without electromagnetic interferences.

It is very difficult to detect the passage of the projectile itself in the bore, because there exist electromagnetic interferences due to discharge of large current and intense light emissions of plasma. We made a projectile-detecting system using a continuous X-ray beam (XPD), as shown in Fig. 3. Photons are generated by a d.c. operated X-ray tube with a tungsten target ordinary used in diffraction measurements, pass across the railgun bore through a slit and the polycarbonate spacers, and are detected by a plastic scintillator with a photomultiplier tube. A comparator continues to count photons every preset time interval (1 to 5 μs), and generates a pulse as result of decrease of photons below a preset value if the projectile intercepts the beam. The output pulse of the comparator is used to trigger flash X-ray tubes described below and other electronic instruments. Several tens of photons were counted every microsecond in this optical system. Since this number is not large enough for high reliability of XPD system, a gate circuit inhibits unexpected outputs of pulses caused by statistical fluctuation of photon number as well as by electromagnetic disturbances. X-ray beam intensity is also monitored by means of integrating the photomultiplier tube output voltage by an RC integrator with a time constant of 1 μs.

Positions and attitudes of the projectile after being ejected from the muzzle are recorded on films with the flash X-ray shadowgraph technique. It is also possible to measure the velocity of the projectile using two X-ray tubes which are aligned along the line of the flight and flash at times different each other.

In some cases we used a foil switch or a piezoelectric pin detecting the collision of the projectile with it, pickup coils detecting the passage of the projectile in which permanent magnets are buried, or a fine copper wire cut by the projectile.

4. Barrel and Projectile Assembly

Figure 4 shows the crosssectional view of a barrel and a projectile assembly of a large mass railgun which has a 30 mm square bore and is 3.0 m in length. Square rails and insulators are rigidly contained by steel plates to form a barrel. Copper rails were selected because of its high conductivity. Insulators forming the inner surface of bore are Mycalex plates 5 mm in thickness, and those supporting the rails against electromagnetic force and plasma pressure are fiberglass-reinforced epoxy resin plates 30 mm in thickness, which also reduce the eddy current losses in outer steel plates. The projectile is made of polycarbonate or Nylon. An armature consists of a copper plate 1 mm in thickness and phosphor bronze fins which ensure good electrical contact with the
rails. Total mass of the projectile was 15–30 grams. This railgun was used examining the performance of the power source.

![Cross-sectional view of square-bore railgun (upper) and projectile assembly (lower).](image)

To test the diagnostic system we constructed another railgun with smaller bore. Since projectiles are lighter than those described above, they make it possible for us to obtain higher velocities with the same power source. As shown in Fig. 5, its bore has a round crosssection 14 mm in diameter and is 2.4 m in length. Copper rails and insulating spacers, all of which are shaped into square rods with one concave corner with 7 mm radius, are combined and clamped by steel supports forming the roughly round bore. The spacers are made of polycarbonate, since the inner surface of the bore has to be smoothly finished by reaming (Usuba, Kondo, Sawaoka, 1986; Usuba, Kakudate, et al., 1986). Damage to the bore caused by plasma arc may be easily removed also by reaming without replacement of the barrel components. A projectile assembly is also shown in Fig. 5. The projectile is composed of a phosphor bronze fuse and a polycarbonate body in which lead foil or powder is buried with epoxy resin, to
absorb X-rays used in projectile detection system. In some experiments small ferrite magnets were buried in the projectile for the detection of its passage by pickup coils, while they served as X-ray absorbers. The mass of the projectile is in the range about 2–4 grams.

![Diagram](image)

**Fig. 5.** Crosssectional view of round-bore railgun (upper) and projectile assembly (lower).

All experiments for both railguns were made without evacuation of the bore.

5. Experimental Results for Large Mass Accelerations

Ten shots were done with the large mass railgun in the mass range from 15 to 30 grams. The components forming the bore were used without replacement through all shots. Since the rail surfaces suffered severe melting or vaporization at an initial position of the armature due to almost static arc, the initial position had to be moved towards the muzzle end by a few centimeter after every shot.
Fig. 6. Peak rail current as a function of chargeup voltage of capacitor. Open circles are measured current and are numbered in order of shots. Mass of Projectile; 3rd shot: 15 g, 4, 8, 9, and 10th shots: 20 g, 6th shot: 25 g, 5th shot: 30 g. A full line and a dashed line indicated calculated peak current in case of 30 and 20 gram projectile, respectively.

In Fig. 6 peak currents are plotted as a function of chargeup voltages of capacitor. Numbers in the figure are order of shots. The peak current seems to become zero at 2.5 kV chargeup voltage, corresponding in the secondary circuit of the transformer to about 160 V, which should show arc voltage drop between rails. The peak currents which were calculated considering skin effect, on the assumption of constant arc voltage drop, are also shown in Fig. 6. A full and a dashed line correspond to the case for 30 and 20 grams projectile mass, respectively. The peak currents have a tendency to decrease with increasing shot number although the projectile mass are not the same. This shows that there is a large effect of the rail surface damage on the effective resistance of rails, because the skin depth is of the order of 0.1 mm.

Projectile trajectory was measured by wire cutting and piezoelectric pin method because the XPD system had not yet been constructed. Projectile positions were calculated by integrating a simple equation of motion including only an electromagnetic force, \( F = (1/2) L' \dot{I} \), where \( I \) is measured rail current and \( L' \) is inductance gradient of rail which was taken as 0.28 \( \mu \)H/m to fit the calculated positions to observed ones (Fig. 7). The value of \( L' \) is a little smaller than theoretical one, which may be due to an effect of ablation of bore wall discussed below. Using \( L' \) as well as other circuit parameters, efficiencies defined as ratios of kinetic energy of projectile to electric energy stored in capacitor are calculated for circuits with and without the pulse transformer in the case of 30
gram projectile mass (Fig. 8). Calculated results showed that there exists optimum turn ratio, and insertion of the pulse transformer with 16:1 turn ratio improves the efficiency by about five times at 10 kV chargeup voltage.

Fig. 7. Projectile position as a function of time for square bore railgun with capacitor charged to a voltage $V_c$. Full lines were calculated by means of measured current profiles.

Fig. 8. Calculated dependence of efficiency on turn ratio of the pulse transformer in case of 30 gram projectile and rail length of $L$. An arrow indicates calculated one without the transformer.
6. Experimental Results for Small Mass Accelerations

The results of several shots for small mass accelerations are summarized in Table 1. After each shot we observed the inner surface of the bore with a bore scope, or by disassembling the barrel. The rail surfaces exhibited melting and vaporization near the breech and some arc tracks in the central region of the rails. Since these were able to be refined by enlarging the bore by about 0.1 mm in radius except for the deeply eroded damage just at the position the fuse contacted, several shots were done without replacement of the barrel components.

An example of the X-ray shadowgraphs of the projectiles in free flight is shown in Fig. 9. No deformation of the projectile was observed, although it showed slight lateral tilting, which ensures no fragmentation of the projectile in the bore.

![Fig. 9. Flash X-ray shadowgraph of projectile in free flight.](image)

To examine the behavior of the plasma acting as an armature, we measured its relative position with the projectile and its spatial distribution using the XPD system, a pickup coil and an optical probe placed about 1.8 m from the breech. An X-ray beam is separate from the other two probes by 4 mm along the bore axis. Taking the velocity of the projectile, 2.0 km/s, into consideration, a time axis for X-ray intensity was already shifted by 2.0 μs in results shown in Fig. 10. Intensity of the light began to increase just after the passage of the back surface of the projectile, then the output voltage of the pickup coil crossed zero 40 μs later, at which time the mean position of the distributed plasma current should pass through the probe position. The distance between the back face of the projectile and the mean point of plasma current
Table 1. Summary of experimental results for small round bore railgun.

<table>
<thead>
<tr>
<th>Shot number</th>
<th>Chargeup energy (kJ)</th>
<th>Mass of polycarbonate (g)</th>
<th>Mass of fuse or armature (g)</th>
<th>Projectile velocity (km/s)</th>
<th>Kinetic energy (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>86-1</td>
<td>128</td>
<td>4.09</td>
<td>0.24</td>
<td>1.95</td>
<td>7.78</td>
</tr>
<tr>
<td>86-2</td>
<td>128</td>
<td>4.20</td>
<td>0.24</td>
<td>2.01</td>
<td>8.48</td>
</tr>
<tr>
<td>86-8</td>
<td>128</td>
<td>2.16</td>
<td>2.17(copper)</td>
<td>2.2</td>
<td>5.2</td>
</tr>
<tr>
<td>87-2</td>
<td>200</td>
<td>4.20</td>
<td>0.20</td>
<td>2.44</td>
<td>12.50</td>
</tr>
<tr>
<td>87-3</td>
<td>200</td>
<td>2.10</td>
<td>0.18</td>
<td>2.57</td>
<td>6.94</td>
</tr>
<tr>
<td>87-4</td>
<td>200</td>
<td>1.98</td>
<td>0.18</td>
<td>2.49</td>
<td>6.14</td>
</tr>
<tr>
<td>87-5</td>
<td>200</td>
<td>2.26</td>
<td>2.15(copper)</td>
<td>2.59</td>
<td>7.58</td>
</tr>
<tr>
<td>87-6</td>
<td>200</td>
<td>1.80</td>
<td>2.89(aluminum)</td>
<td>2.34</td>
<td>4.93</td>
</tr>
</tbody>
</table>
may be estimated to be about 10 cm which is the same order obtained by a theoretical consideration (Ray, 1986). There was a depression or fluctuation in the time profile of the light intensity. Such a structure was often observed in other shots (see also Fig. 11), and reported by other researchers (Jamison et al., 1984). These results suggest complicated spatial distributions of plasma density, temperature and so on.

![Diagram](image)

Fig. 10. Time dependence of intensity of continuous X-ray beam, pickup coil emf and light intensity emitted from plasma when the projectile passed about 1.8 m from breech of the round bore railgun. Slight difference among positions of probes was corrected taking the velocity of the projectile into consideration.

Figure 11 is an example of all probe signals recorded in one shot. In Fig. 11 (a) projectile positions as a function of time detected by foil switch, X-ray shadowgraphs and the XPD system are plotted. Signals of the pickup coils and the optical probes are also shown in such a way that the origins coincide with positions of probes in the left vertical scale. Hollow circles in Fig. 11 (b) are mean velocities obtained from measured time when the projectile passed and when optical probe signals arose rapidly. Full lines in Fig. 11 (a) and (b) are calculated projectile positions and velocities as a function of time using observed current profile shown in Fig 11 (c), where energy dissipation caused by generation of shock waves in air were taken into account in the cases of both
Fig. 11. Probe signals for shot no. 87-4; (a) projectile position as a function of time detected by a foil switch, X-ray shadow graphs and the XPD system, and time profile of optical probe and pickup coil signals whose origins coincide with their positions on the left vertical scale, (b) mean velocities obtained from measured time when projectile passed and when optical probe signals arose rapidly, and (c) rail current profile. Full lines in (a) and (c) were calculated taking into account the energy dissipation caused by generation of shock waves in air and assuming increment of accelerated mass upto $m^*$. 
within bore and open air. Calculated velocity is rather higher than observed. It is
pointed out in some reports (Hawke, 1986; Ray, 1986; Schnurr et al., 1986)
that effective mass of projectile (m*) should increase due to ablated wall
materials, so we took m* = 3.75 g instead of real projectile mass (2.16 g)
assuming that the effective mass is time independent. But no reasonable results
were obtainable for positions and velocities of the projectile. In particular,
although it is expected that the ablation is the most severe when the projectile
velocity is low and the current takes its peak value because of large electron and
ion bombarding per unit time and unit area, calculated results without increasing
of mass show good agreement with the observed ones up to the time that current
reaches its peak. On the other hand, if atmospheric density was varied as a
parameter, calculated results, both the positions and the velocities, were able to
coincide with the experimental ones. This suggests the large effect of viscous
drag of the plasma armature because both air and plasma cause the drag force
proportional to the square of the velocity. More detailed studies on the plasma
armature are needed experimentally as well as theoretically to get further
acceleration of a projectile.

7. Assembly of Explosive Generator

Since explosive magnetic flux compression generator is very useful when
operated at high current levels, some research groups have used it to accelerate a
projectile electromagnetically (Anisimov, 1986; Fowler et al., 1982; Hawke et
al., 1982;, Sakharov, 1966). The explosive generator we made is similar to the
strip generator that Fowler et al. (1872) have developed, but we plan to operate
it in such a way that the volume for flux compression serves for railgun bore. A
liner which is driven down by the explosive into contact with a stator and
continually pushes the trapped magnetic flux ahead of it acts as rails together
with the stator. The projectile placed between the liner and the stator is
accelerated by pressure of magnetic field which increases with decreasing distance
between explosive-driven part of the liner and an armature behind the projectile.
The initial position of the projectile should be determined so as to minimize
useless magnetic energy in dead space behind the projectile, taking account of
the damage of the rails due to magnetic force and ablation by large current.

Figure 12 is the side and the crosssectional views of the explosive
generator tested in present work. U-shaped aluminum channels 30 mm in width
were employed to hold the volume for flux compression due to its structure
hardly deformed. Because the density of aluminum is low, a bottom plane of the
upper channel was used as the liner which is driven by explosive (plastic bonded
PETN) placed inside the channel. A copper plate was put on the top of the lower
channel as the stator because of its high electrical conductivity, and was soldered
at an end with a brass block which was shaped to form a single turn coil to
measure currents. This block will be removed when the acceleration experiments
Fig. 12. Cross-sectional (upper) and side view (lower) of flat-type explosive magnetic flux compression generator.
will be done. The effective compression length was one meter. Several clamps were used to reduce the deformation of the generator components from the magnetic pressure. Initial flux was supplied by a capacitor bank with 300 kJ of maximum storage energy (1.5 mF, 20 kV).

8. Experimental Results on Explosive Generators

Amplified current profile is shown in Fig. 12 where a result for a simpler generator with the lower aluminum channel serving for the stator instead of the copper plate is also indicated. The capacitor bank was operated at 16 kV chargeup voltage, and initial currents were 340 and 410 kA for generators with the aluminum and with copper stators, respectively.

Numerical calculations, results of which are also shown in Fig. 13, were done considering flux diffusion into conductors and increase of the resistance of liner materials by its deformation in the process of acceleration by explosions. The calculated current agreed with observed for the generator with the copper stator except for the final stage of the compression, while it poorly agreed for the one with the aluminum stator.

![Graph](image)

Fig. 13. Measured and calculated time profiles of amplified currents \( I \) in logarithmic scale for explosive generators with copper stator and with aluminum stator. Currents were normalized with currents \( I_0 \) at 0 \( \mu \)s when the flux compressions just began.

To estimate the performance of the projectile acceleration, tentative numerical simulations were made by combining this calculation method with that for railgun. For 2 meter long generators with the copper stator and 20 gram
projectile, it shows unfeasible result that peak current becomes 8 MA when the moving liner is close to the projectile by several centimeters, because the initial current is not large enough to generate high magnetic pressure. Taking account of the overestimate of the amplified current, it is necessary to provide 1 MA initial current which should reduce the peak current to about 3 MA and increase the distance between moving liner and projectile to about 20 cm. To increase the initial current, combination of coaxial generators (Sakharov, 1966) which have been developed in our laboratory will bring a solution.

9. Conclusions

We constructed a railgun energy source composed of 200 kJ capacitor bank and a pulse transformer. Its performance was examined using 30 mm square bore railgun. Experimental and calculated results showed that the insertion of the pulse transformer improved efficiency by approximately five times when a projectile mass is 30 grams. The pulse transformer has a considerable advantage in case of the large mass projectile.

A projectile detector using a continuous X-ray beam was developed and enabled us to examine behavior of the projectile and a plasma armature independently from each other.

Using 14 mm round bore railgun, which is reusable by removing the damaged inner surface of rails by reaming technique, behavior of an accelerated projectile was examined in detail. Lowering of efficiencies is presumed to result from rail melting and/or viscous drag of the plasma armature.

Flat-type explosive magnetic flux compression generators were tested with 300–400 kA initial currents. Numerical calculation showed that it is necessary to provide higher initial current level when the generator serves both as power source and accelerator.

REFERENCES


