Chapter 35

Electromagnetic Railgun Driven by Different Types of Energy Storage Capacitors

––Pankaj Deb

Electromagnetic (EM) Rail gun is a device, designed to have the capability of launching a mass with hypervelocity (in km/s) using an electromagnetic field. An EM Rail gun consists of two parallel conductor rails separated by a gap between them. The armature which is a conductive material is placed between the rails and the projectile is placed behind the armature. When a current is passed through rails and armature, it induces a magnetic field. The current through the armature and the induced magnetic field interaction produces an electromagnetic force J x B on the armature. Related to worldwide railgun status, BAE has developed railgun that can be mounted on ship. This railgun device can launch a projectile to MACH 7 velocity [1].

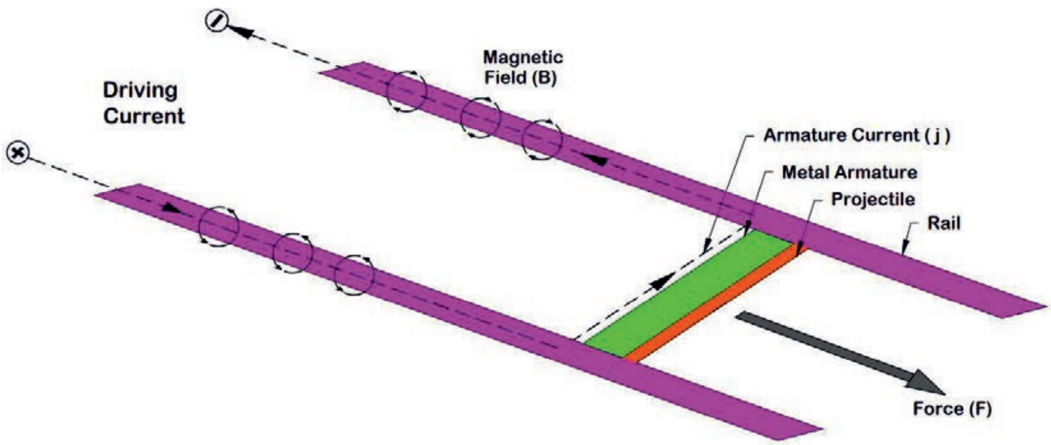


Figure 35.1. Electro-magnetic rail-gun.

Figure 35.1 represents the basic layout of railgun system. Electromagnetic Railgun typically requires a high magnitude current pulse with millisecond duration. Figure 35.2 represents the block diagram of capacitive powered rail-gun.

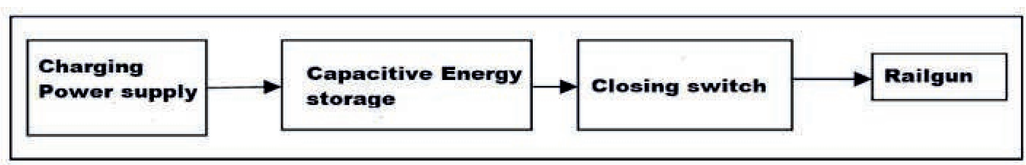


Figure 35.2. Block Diagram of Railgun system.

35.1. Capacitor and Switch Selection

High muzzle velocity (v) of armature in electromagnetic railgun system is proportional to action integral of rail current i.e. $\int i^2 dt$ [2]. Eq. (35.1) implies that to achieve high muzzle velocity, high energy density capacitors with high peak current is a suitable source in electromagnetic railgun system.

$$v=u+(L'/2m)\int i^2 dt \qquad (35.1)$$

where L^{l} = Inductance gradient of rail-gun; m = mass of armature; u = initial velocity of armature; i = current ; t = time. Accordingly, capacitors are selected for driving electromagnetic rail-gun. In rail-gun, high current of the order of 100 kA with a pulse duration typically1-4 millisecond is involved. Eq. (35.2) illustrates that charge transfer through closing switch in rail-gun system is high.

$$Q = \int idt \tag{35.2}$$

where Q = charge in coulombs; I = current; t = time. So Ignitron switch a reliable, capable of high charge transfer, is compatible for EM Railgun system.

Table 35.1 shows the detailed specification of medium voltage DC film capacitors and high voltage DC energy storage capacitors. Film capacitors have wide variety of application in power electronics and used as filtering capacitor, snubber circuits, commutation capacitor etc. [3]. Two capacitor banks 2 mF, 4.4 kV, 20 kJ with DC film capacitors and 1.78 mF, 15 kV, 200 kJ with high voltage DC energy storage capacitors has been commissioned for driving EM rail-gun respectively [3]. In DC film capacitor bank, twenty capacitors are connected in series and parallel configuration to increase the effective capacitance and voltage to 2 mF, 4.4 kV whereas in another bank ten capacitors are connected in parallel configuration to get effective capacitance and voltage 1.78 mF, 15 kV. Figure 35.3 & Figure 35.4 show the picture of commissioned capacitor banks.

Table 35.1. Specification of capacitors

Type	Medium voltage Film capacitors	High Voltage Energy Storage capacitors
Capacitance, Energy	1.67 mF, 1 kJ	0.178mF, 20 kJ
Charging Voltage	1.1 kV DC	15 kV DC
Dielectric	Polypropylene film	Paper / Castor oil
Self Inductance	70 nH	60 nH
Peak current	10 kA	150 kA
Weight, Energy Density, Energy/weight	3.5 kg, 0.27 J/cc, 0.28 kJ/kg	150 kg, 0.2 J/cc, 0.13 kJ/kg

35.2. Recoil in Railgun

Recoil in railgun happens when armature exits the muzzle end. The recoil forces are generated at the rail end and can be explained by momentum conservation. The recoil forces generated may damage the switches connected at the rail end which has been explained in reference [4]. Mounting of railgun should be rigid to avoid recoil on railgun.

Figure 35.3. Photograph of capacitor bank (a). 2 mF, 20 kJ and (b). 1.78 mF, 200 kJ.

35.3. Armature Contacts with Rail

There are three main types of armature utilized in rail-gun for accelerating a projectile. Plasma Armature, Metal Armature, Hybrid Armature (Figure 35.4(a), 35.4(b) and 35.4(c)) [5].

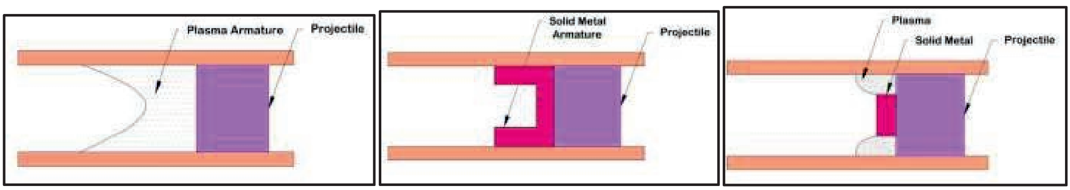


Figure 35.4(a). Plasma Armature, (b). Metal Armature and (c) Hybrid Armature.

Plasma Armature: When gas becomes ionised between the rails, it forms a plasma. This plasma is conductive and forms a closed circuit when current is discharged into rails. The projectile placed between rails moves forward due to this electromagnetic force exerted by this plasma on the projectile (Figure 35.4(a)) [5].

Metal Armature: The metal armature is placed between two rails. The closed current path is formed by rails and metal armature. The electromagnetic force J X B is exerted on the metal armature. The projectile placed ahead of metal armature move forward due to this electromagnetic force on armature (Figure 35.4(b)) [5].

Hybrid Armature: Hybrid armature occur when metal armature placed between the rails is not having full contact between the rails. In such phenomena contacts are established between rails and armature by arcing contacts or plasma contacts (Figure 35.4(c)) [5].

The efficiency of plasma armature increases relatively than metal armature after a certain velocity. The parameters which decides the efficiency scaling of different armatures has been explained with experimental investigations [5].

35.4. Basic Circuit, Inductance Gradient(L^I), Resistance Gradient(R^I)

The EM railgun circuit shown in Figure 35.5 consists of capacitor source of voltage **V**, charge transfer switch **S** and rail circuit $\mathbf{R_G}$. The source has a constant circuit inductance and circuit resistance $\mathbf{L_0}$ & $\mathbf{R_0}$ respectively. The rail circuit $\mathbf{R_G}$ has a time varying inductance $\mathbf{L_{RG}(t)}$ & time varying resistance $\mathbf{R_{RG}(t)}$. The equation of this circuit is a second order differential equation Eq. (35.3). Solution of this differential equation produces function of acceleration, velocity and location of armature inside rail barrel Eqs. (35.4), (35.5) and (35.6) [6]. Mass "m" is armature mass.

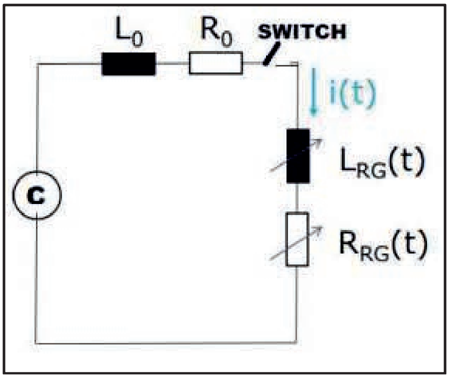


Figure 35.5. Capacitive driven Electromagnetic railgun circuit.

$$1/C \int i(t)dt - i(t)\big(R_0 + R_{RG}(t)\big) - (Lo + L_{RG}(t))di(t)/dt = 0 \quad (35.3)$$

$$acceleration\ (a) = L^I_{RG}\, i(t)^2/2\mathrm{m} \quad (35.4)$$

$$velocity\ (v) = \int adt \quad (35.5)$$

$$distance(x) = \int vdt \quad (35.6)$$

The ratio of difference in inductance with respect to armature displacement in rail is called Inductance Gradient (L^I) represented as dL/dx. Similarly, Resistance Gradient (R^I) is defined as dR/dx. The L^I of railgun is estimated by FEMM programme (Maxwell 2D) and different analytical formulas [7]. On the basis of inductance gradient (L^I), railguns can be compared. L^I of Augmented railgun is higher than conventional railgun.

35.5. Variation of L^I(Inductance Gradient), B (Magnetic Flux Density) and J (Current Density) with S/H Of EM Railgun

High frequency analysis of rails with different S/H ratio (S being spacing between rails and H being height of rail) is performed with Maxwell 2D software [8]. The B_{max} and J_{max} for 8 mm bore rail-gun for a peak current 225 kA found to be 6 T and 655 MA/m^2 respectively. The analysis is shown in Figure 35.6(a) and Figure 35.6(b). It is observed that with increase in value of S/H ratio (0.5 to 1.2), the inductance gradient (**L'**) of the rails increases which is already reported in Figure 35.7(a) [9]. Current density is higher (655 MA/m^2) nearer to the surface area of rail bore. An increase in S/H ratio (0.5 to 1.2) causes a decrease in current density distribution and magnetic flux density distribution over the rails as illustrated in Figure 35.7(b). Hence for optimum performance of railgun S/H ratio, armature weight values need to be suitably selected. Table 35.2 represents the detailed design parameter of electromagnetic railgun.

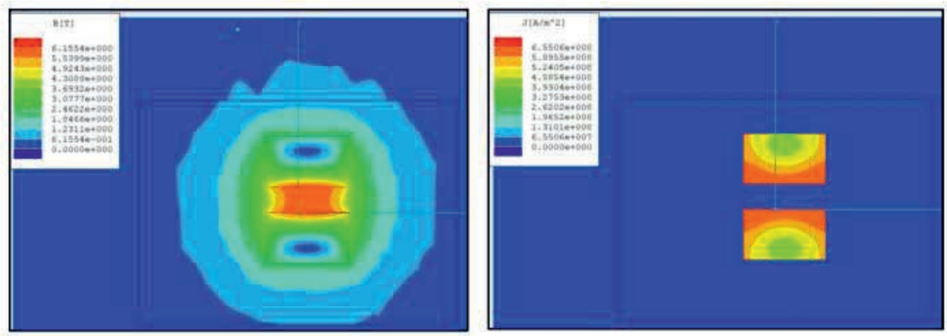


Figure 35.6(a) Magnetic flux density, (b) Current density.

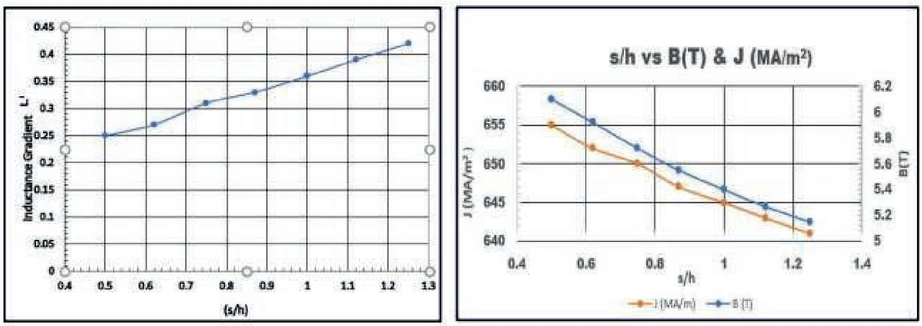


Figure 35.7(a). L'vs S/H ratio (b) B & J vs S/H ratio.

Table 35.2. Design Parameter of EM railgun

	Electromagnetic Rail-gun type	Conventional Rail-gun
1	Bore shape, Bore dimension	Square bore, 8 mm x 8 mm
2	Rail-gun length, L'	1 m, 0.26 μH/m
3	Rail thickness, Material	16 mm, ETP Copper
4	Rail cross sectional area, Insulator material	400 sq. mm, Garolite (G-10) FR-4
5	Armature(Shape, Material, Weight)	C -shape, Al 7075, 6.5g
6	Total weight of rail-gun	20 kg
7	Rail armature contact in rails	Metal armature contact

35.6. Features of EM Railgun

(i) Railgun type: Rail-gun can be designed in many different types Conventional Rail-gun system, Augmented Rail-gun System, Distributed Rail-gun system.

(ii) Bore shape: Rectangular bore, Square bore, Circular bore designs are used for EM Rail-gun. The gap area between two rails is defined as the bore size. An 8 mm square bore has gap between two rails and side-ways are 8 mm respectively.

(ii) Rail length: Rail length is decided by the distance travelled by the armature, so that armature covers the total rail barrel length.

(iv) Rail width: Rail width is selected on the bore dimension, effective stresses on rails and W/H ratio (W being width of rail and H being height of rail).

(v) Rail thickness: Rail thickness is decided by skin depth, current density and mechanical stability of rail.

(vi) Rail containment material: Fire retardant (FR4) glass reinforced resin insulator Garolite sheet (G-10) is most suited insulator material, used for rail containment.

(vii) Rail conductor: Material with high conductivity, resistance to corrosion, high melting point, high thermal conductivity should be chosen for rail conductor. Oxygen free copper (OHFC), Beryllium copper are typically used for rail conductors.

(viii) Rail Interconnection with capacitor bank: The energy storage capacitor bank is interconnected with rail-gun by parallel connection of URM 67 coaxial cables and copper bars.

(ix) Rail-gun coatings: After firing of rail-gun shot, resistive heating and arcing cause damage to armature-rail interface. The barrel wear and erosion can be improved by coatings on rails.

(x) Rail maintenance & weight: The rail structure is a bolted containment structure. After the rail-gunshots rail bars leads to get damage. The rail structure can be easily dismantled and again buffing of rails should be done for re-use of rail-bars in sequential shots.

35.7. EM Rail-Gun Assembly and Armature

The Railgun assembly as shown in Figure 35.8 consists of following part structures.

(i) Side support plate: The copper rails are supported by two support plates on right and left (Figure 35.8(b), Figure 35.8(c)).

(ii) Top and bottom support plate: Top and bottom support plate helps in pre-stressing the rails structure of railgun (Figure 35.8(d)).

(iii) Base Plate: The railgun is placed and fixed on a G-10 base plate (Figure 35.8(e)).

(iv) Nut-bolt arrangement: The side support plate and bottom support plate is compressed by nut-bolt arrangement to hold the rail-gun structure.

(v) Solid armature: 7075 Al is used as a rail armature. It is considered a good choice for rail-gun, due to its high strength/weight ratio, conductivity, low mass/volume ratio, poor weldability. Figure 35.9(a) is the constructed railgun structure. Pictures of aluminum armature used in rail-gun experiment is shown in Figure 35.9(b) and 35.9(c).

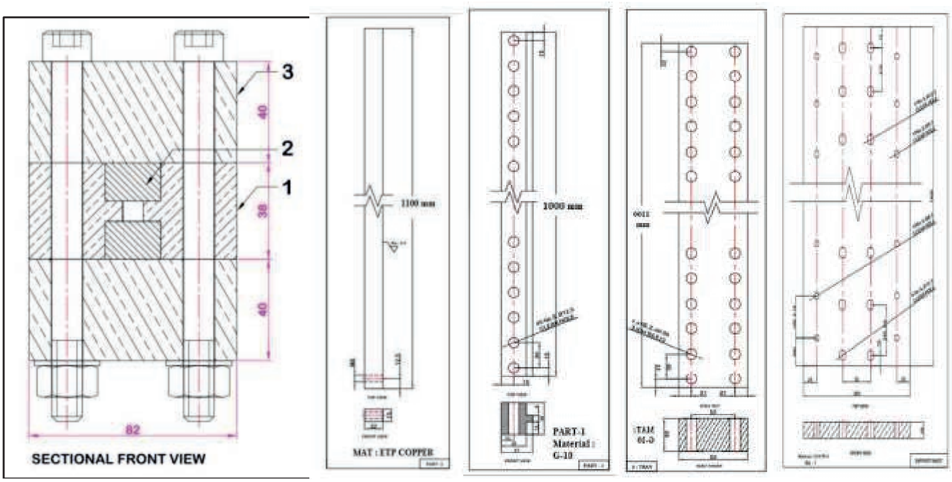


Figure 35.8(a) Rail-gun assembly, (b) Copper bars, (c) Side support, (d) Top and Bottom Support and (e) Base Plate.

Figure 35.9(a). EM Rail-gun structure, (b). 1 g armature and (c). 6.5 g armature.

35.8. Mechanical Stress on Rails Due to Force of Repulsion

Minimum no. of bolts required to withstand the exerted force on rails = Force/ tensile strength

Repulsive force for peak current 225 kA, 8mm bore rail-gun is 1265 kN/m,

Tensile strength of M-12 bolt = 70 kN. Considering a safety factor of 0.7, No. of bolt required: 1265/49 = 25 bolts. 64 nos. of M-12nut-bolt are mounted on rail-gun assembly to hold the rail-gun structure.

Compressive strength of garolite (G-10) sheet with safety factor 0.7 =290 MN/m^2.Total load on G-10 sheet= 290.08.1=23MN. Magnetic pressure generated on G-10 sheet of rail containment for I_{peak}=225kA = 1.1 MN. The magnetic pressure value generated on rail containment is less than total load onrailG-10 sheet. The design values shows, in safe margin for 8mm bore railgun.

35.9. Simulation

Figure 35.10 represents the circuit of railgun system. The R_0, L_0,$\mathbf{L^l}$, $R^l$are 5 mΩ, 3 μH, 0.26 μH/m, 0.6 mΩ/m of 8 mm bore, 1 m long rail-gun respectively. Armature weight is ~6.5 g. The simulation suggests that before rail-gun shot, the armature should be placed typically at 35 cm from the breach end of railgun to get maximum armature velocity of 350 m/s. Figure 35.11(a), Figure 35.11(b), Figure 35.12(a) and Figure 35.12(b) represent the simulation plots of railgun system.

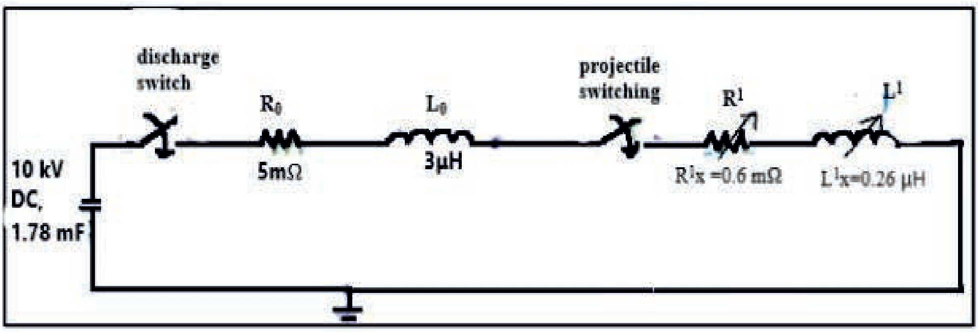
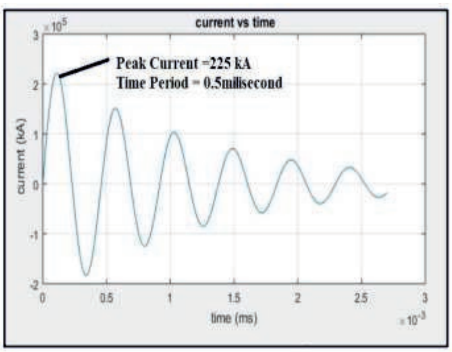


Figure 35.10. Simulation circuit of Electromagnetic railgun



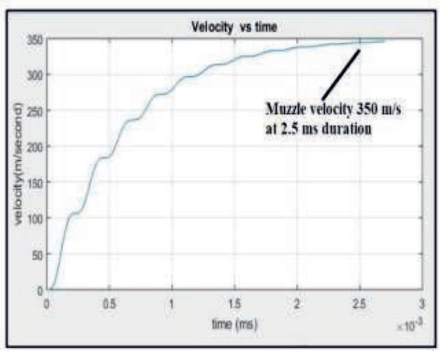


Figure 35.11(a). Capacitor discharge current with time (b). Armature velocity with time.

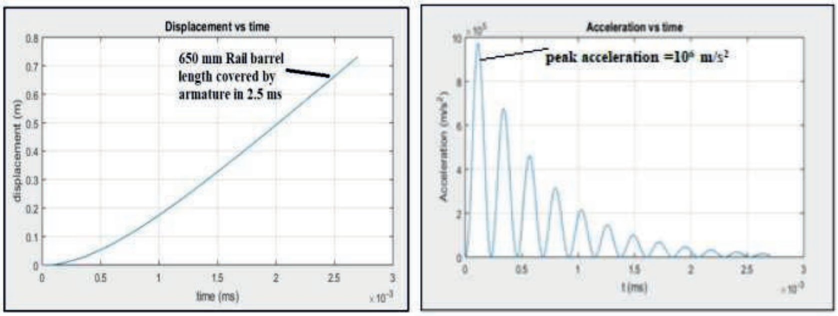


Figure 35.12(a) Armature location in barrel with time, (b). Armature acceleration with time.

35.10. Diagnostic and Measurement

(i) Current Measurement: Discharge current in rails is measured by current monitor.

(ii) Fiber cut: Optical fibers OF1 and OF2 are placed at 6mm apart at muzzle end. Laser light is transmitted through these fibers. Figure 35.13 is the velocity measurement setup. Interruption time in cutting of fibers measured 30 µs for 9mm armature length which provide the velocity information of armature at muzzle end Figure 35.14(a), Table 35.3 [10].

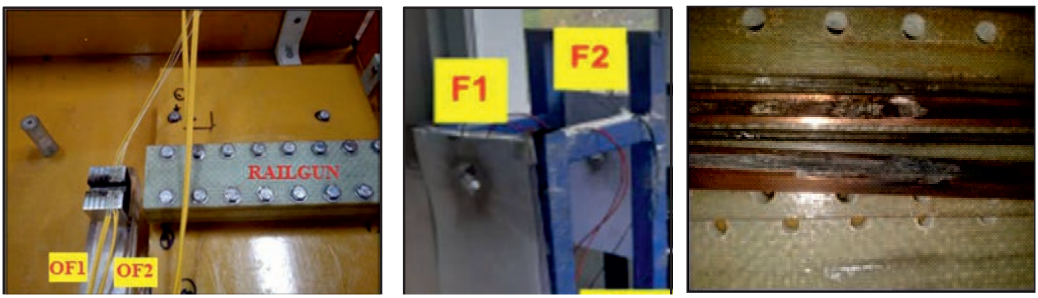


Figure 35.13(a). Optical fiber setup. (b). Shorting foil setup, (c). Copper rails after shot.

(iii) Aluminum shorting screen: The armature velocity is measured by the time interruption of shorting of aluminum foil. Figure 35.3(b) is the velocity measurement setup. The aluminum foils F1 and F2 is placed at 241 mm apart. The time interruption measured 689 µs for 45 mm armature length shown in Figure 35.14(b) and Table 35.3.

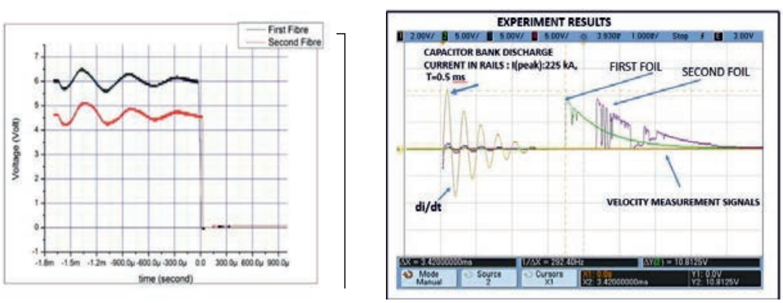


Figure 35.14(a). Velocity measurement by fiber cut,
(b). Velocity measurement by shorting screen.

35.11. Experimental Results

The experiment result is tabulated in Table 35.3.

Table 35.3. Experiments on 6 mm and 8 mm bore railgun.

Sr.	**Rail-gun detail**	**6 mm bore, 30 cm long**	**8 mm bore, 1 m long**
1	Capacitor bank type	Film capacitor	High voltage DC energy storage capacitor
2.	Peak Current, Energy, Time Period	75 kA, 12 kJ,0.5ms	225 kA, 89 kJ, 0.5 ms
3.	Armature weight, Muzzle Velocity	1 g, 200m/s	6.5 g, 350 m/s
4.	Diagnostic used for velocity measurement	Fiber-cut	Shorting-screen

35.12. Conclusion

Two square bore railgun were built and tested with 12 kJ and 89 kJ capacitor bank respectively. Experiments were performed with solid aluminum armatures. A mass of 6.5 g has been accelerated to a velocity of 350 m/s at 89 kJ. The energy conversion efficiency of the commissioned EM railgun system can be improved by augmentation of rails and minimizing the losses in rail barrels. On the other hand experiments performed with medium voltage film capacitor to drive railgun, indicates that film capacitor can be employed for compact source. Semiconductor switching devices could be utilized in such capacitors to drive EM railgun.

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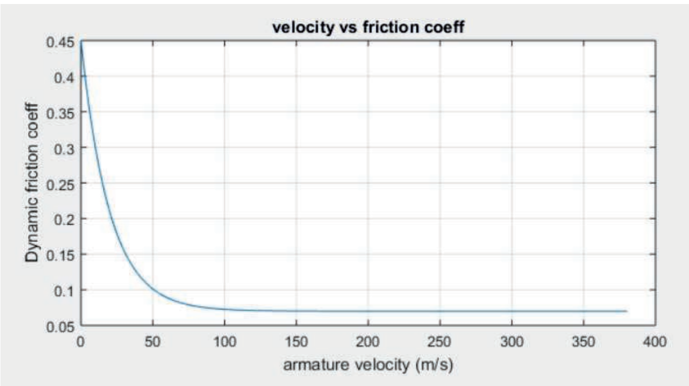
Questionnaire

1. Calculate the force on the armature in rail-gun for I = 100 kA, L^{l}(Inductance gradient) = 0.4 uH/m.

Hint : F= ½ $L^{l}.I^{2}$

Plot the variation ofdynamic friction w.r.t armature velocity when 6.5 g armature slides in rail-gun. Refer Current profile 35.11(a).

Hint :



2. Calculate the value of L^{l} for rail-gun parameter; rail height (h) =16mm, rail width (w)=25mm; space between rails = 8mm.

Hint : The inductance gradient can be calculated by formula below , Refer [8]

$$L^{I} = \frac{10^{-6}}{\frac{0.5986h}{s} + 0.9683\frac{h}{s+2w} + 4.3157\left(\frac{1}{\ln\left(\frac{4(s+w)}{w}\right)}\right. - 0.7831}$$

3. Explain the losses which limit armature velocity in rail-gun when it slides in rail barrel.

Hint : Frictional losses when armature slides in rails, resistive losses in rail barrels, energy dissipated in the armature, losses due to arcing, air drag.

Calculate the skin depth and temperature rise of rails in rail-gun system for a peak current 225kA, 2.5 millisecond duration pulse. Rail material =copper

Hint : skin depth $\partial = \sqrt{\pi\rho t/\mu_0}$where ρ = resistivity, μ_0 =permeability, t=pulse duration. Temperature rise in rails is calculated by $i^2rt = mc\Delta t$