SIMULATION AND EXPERIMENTS WITH RAILGUN FOR HIGH SPEED PELLET INJECTIONS

Major Project Report

Submitted in Partial Fulfillment of the Requirements for the degree of

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IN

ELECTRICAL ENGINEERING

(Power Apparatus & Systems)

By

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CERTIFICATE

This is to certify that the Major Project Report entitled "**SIMULATION AND EXPERIMETNS WITH RAILGUN FOR HIGH SPEED PELLET INJECTIONS**" submitted by Mr. **VIJAYAKUMAR BANDARU** (05MEE020) towards the partial fulfillment of the requirements for the award of degree in Master of Technology (Electrical Engineering) in the field of Power Apparatus & Systems of Nirma University of Science and Technology is the record of work carried out by him under our supervision and guidance. The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

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Abstract

A **tokamak** is a machine producing a toroidal (doughnut-shaped) magnetic field for confining a plasma. Fusion power reactors based on tokomak concept use isotopes of hydrogen like deuterium, tritium as fuel, there are several ways to replenish the spent fuel. Successful fuelling in tokomaks requires that the time needed for the fuel to penetrate injected material is disassembled, ionized and captured by the local magnetic field. Fueling of plasma device can be done by gas injection or pellet injection methods.

High-speed hydrogen ice injection (pellet injection) is the dominant refueling method. The method of injection fuel (hydrogen pellets) consists of condensing the H_2 isotopes to form solids (pellets), accelerating it to high speeds, transporting the pellet deep into plasma core. The experimental devices like centrifuge or pneumatic devices meeting the fueling requirement with difficult due to large size and high electron densities & temperature of the plasma. Hypervelocity pellets of a substantial size need to be injected into the plasma continuously at high repetition rates.

Advanced technologies, such as rail gun pellet injector are being developed to meet such demands. This designing of rail gun is based upon the required velocity and armature & rail sizes. The proper design of rail gun requires a special consideration of the interaction between the proper design of power supply on one hand and exact mechanical design of rails, barrel and armature on other hand. The dissertation work involves designing and developing a rail gun by taking the effect of rail & armature geometry, current distribution into the rails and inductance gradient on acceleration of armature into consideration.

Railgun is designed by taking the velocity requirement into consideration. According the design, the railgun is developed and tested for various velocities. The analysis of various parameters like rails, coating of lubricant on rails, and different power supplies was carried out to test the railgun performance.

Acknowledgement

I take the opportunity to express a very sincere thanks to **Mr. N. Ravi Prakash** (Engineer SD) for providing me an opportunity to work on such an interesting project, without whose help I could not have done it satisfactorily. His valuable guidance has proved to be a key to my success in overcoming challenges I faced during the course of project work.

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Vijayakumar Bandaru

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Chapter 1

Introduction

1.1.Introduction:

The purpose of this project is to support the full-scale development of an Electro Magnetic Launch (EML) gun, commonly known as railgun. The type of gun would be capable of taking full advantage of producing very high velocities. Interest in launching mm-size projectiles to higher velocities is generated by many potential applications. Among them are fuel pellet injection into fusion machines, pellet probing of the hot thermonuclear plasma, and debris of anthropogenic origin, development of techniques of eliminating this debris, etc. The main purpose of this project is to develop an optimized power supply and a proper mechanical design for a railgun for a pellet injection system of a fusion device.

1.2. What is Pellet Injection System?

Magnetically confined plasmas used in fusion research are refueled primarily by injecting high-speed pellets composed of frozen hydrogen isotopes. Injection of hydrogen pellets is viable method of fuelling the plasma devices. The method of injection fuel (hydrogen pellets) consists of the following things ---

- Condensing the H_2 isotopes to form solids (pellets)
- Accelerating it to high speeds
- Transporting the pellet deep into plasma core.

Rather than using gas directly as fuel, it is very advantageous to convert it into solid particles and those solid particles are known as pellets. We can achieve better speed with pellets when compared with the normal gas injection. It is required that, these hydrogen pellets should be accelerated with a very high speeds, other wise due to its less yield strength they may get vaporize before reaching the target i.e., nothing but center of the plasma core. And at the next these pellets should be transferred deep into the plasma core to achieve proper burning of fuel.

Pellet refueling becomes more challenging as experimental fusion reactors approach the scale of operational power plants. Hypervelocity pellets of substantial size must be injected into the plasma continuously and at high repetition rates due to the large size and the high electron densities and temperatures of the plasma.

1.3. Why RAILGUN?

To meet the demand of hyper velocities as mentioned above, advanced technologies, such as the railgun pellet injector, are being developed. Electromagnetic railguns accelerate pellets by applying Lorentz force to a conducting armature behind the pellet. Ideally, the acceleration is proportional to the current squared. Therefore, by shaping the current pulse the acceleration profile can be controlled. This feature gives railguns a distinct advantage over gas gun, centrifugal and electro-thermal injectors. Railgun pellet velocities are not limited by the sound-speed constraints of gas guns. In addition, the pellet yield strength is enhanced by the support of the railgun barrel, unlike centrifugal accelerators.

1.4. Some Applications of Railgun

- There is interest in using railguns as mass drivers for space exploration and mining.
- Rail guns have been proposed for use in delivering projectiles to space, especially from bodies without atmospheres (such as the Moon).
- Also, railguns may be used to initiate fusion reactions, by firing pellets of fusible material at each other.
- Railguns can simulate the high velocity of a low mass projectile such as a lost nut or bolt in a zero gravity environment.
- Railguns are being pursued as weapons with projectiles that do not contain explosives, but are given extremely high velocities: 3500 m/s or more.

- Due to the very high muzzle velocity that can be attained with railguns, there is interest in using them to shoot down high-speed missiles.
- Naval forces are also interested in railgun research. Current ship guns store their explosive shells in a large magazine underneath the gun.
- Research into tank-portable railguns is in very early stages.

1.5. Literature Survey

This project work mainly focused on the design of “Railgun” and to do experiments on the railgun to achieve hyper velocities. To understand the basics of the railgun there are various IEEE papers, which are listed in the bibliography. Brief description about the railgun that discussed in various surveys is given below:

1.5.1. D.J.Wehlren and J.H.Gully, “***Small Caliber Mobile EML***”, IEEE Transaction on Magnetics, Vol.MAG-22, No.6, November 1986[1].

In this paper the authors have discussed about the various power supplies used for the electromagnetic launchers, and their consecutive advantages and disadvantages. Particularly this paper concentrated on the details of the power supply feasibility study, including evaluations of batteries, capacitors, homopolar generators, and compensated pulsed alternators are discussed. And also discussed about the power supply design for a particular velocity and rail dimensions. The current calculations, force calculations and deciding the power supply range according to the velocity requirement is shown with the help of all formulae and with a given example also. Authors have concluded the things as follows:

(i) If low rate-of-fire, single shot operations is desired, then the electrolytic capacitor system has the lowest possible power supply mass.

(ii) CPAs are the only candidate systems, which can deliver multi-shot or burst mode operation without the use of the mechanical operating switch.

(iii) The energy densities of both compulsator systems are much greater than that of any other system considered.

1.5.2. ***“PowerLabs Railgun 2.0 Research”***[2]

In this paper, the authors have successfully designed and constructed an electromagnetic accelerator, which is capable of accelerating a lightweight payload to velocities greater than 1000m/s. And in this paper, authors explained their complete details of experiments, power supply, mechanical design of the railgun, about the injector. If full power was to be applied to a static armature the rails and whatever was between them would instantaneously melt under the intense localized heat produced by ohmic heating as 100thousand amperes tried to make it through the contact resistance. In order to prevent the Rail Gun from becoming a spot welder it is necessary that the armature be moving with some initial speed prior to electromagnetic acceleration. Furthermore, there is no point in wasting valuable electrical energy stored in expensive capacitor banks to accelerate the projectile during the first couple hundred meters per second. In this paper authors also shown the various types of armatures they have built and explained about them.

1.5.3. Richard A. Marshall, “***Railgunnery: Where Have We Been? Where Are We Going?***” IEEE Transactions on Magnetics, Vol. 37,No.1, January 2001.[3]

The author discussed about the complete basic requirements of the rails and the problems of the railgun. This paper particularly specifies about the two main armature-rail problems, gouging and transition. Initially in this literature, author discussed about the main interest areas of railgun and the pulsed power supplies for railguns. In the sub chapter pulsed power supplies for the railgun author discussed about various types of supplies like batteries, kinetic storage devices like flywheel, high tensile steel ring, carbon fiber ring, capacitors, rifle cartridge etc., on the basis of the energy per unit weight. In the preceding chapters he has also discussed the armature problems like melting, gouging etc. To avoid this type of problems author suggested pseudo-liquid armatures and laminated rails.

1.5.4. E. Spahn, G. Buderer, "***A flexible pulse power supply for EM-and ETC launchers***", French-German Research Institute of Saint-Louis **(ISL), 5,** rue du GCntral Cassagnou, F-68301 SAINTLOUIS-CEDEX, France.[4]

Authors have presented a modular pulsed power supply for operation voltages up to 10 KV for railgun and ETC-applications. After the introduction they have explained the electric equivalent circuit for the complete railgun setup. They have given the detailed explanation about the each and every part of the railgun. In this paper it is discussed about the semiconductor devices, which can be used, for the switching the railgun and also given a brief discussion about the crowbar diode. The setup of the railgun in the experiment done by these authors consists of pulse forming units with an energy of 50 watts. Each unit is composed of a capacitor (C=865 pf), semi-conducting switches (thyristors, crowbar diode) a pulse shaping inductor (L=30 pH) and a coaxial cable, which is used for connecting the units to the load. Due to the use of semiconducting switches the pulse forming units have a high reliability and flexibility concerning operation voltage.

1.5.5. Ales A ielinski and K.A.Jamison, "***A Solid State Switched Power Supply for Simultaneous Capacitor Recharge and Railgun Operation***" U.S. Army, Ballistic Research Laboratory, LABCOM Aberdeen Proving Ground, Maryland.[5]

This paper discusses about a new circuit for the continuous charging and discharging of the capacitor bank after each and every shot. The circuit is constructed such that half the bank capacitance is initially charged while the other half is uncharged. Both halves are connected in series with the load and diodes across each prevent voltage reversal. When the discharge is initiated, the current passing though a railgun simultaneously charges the uncharged section of the capacitor bank. In this thesis one more useful graph shown is the energy budget for the power supply for driving a railgun, which explains about the various losses in the railgun system. Finally authors concluded that the concept of simultaneously recharging a capacitor bank during the firing of a railgun offers several attractive features. It recovers the magnetic field energy from the railgun bore. This benefits efficiency, and provides a current zero at the end of the acceleration time. The current zero is well suited to SCR switches, which commutate open at the end of the discharge cycle.

1.5.6. Brain Kuhn, Scott Sudhoff, "***Pulsed Power System with Railgun Model***", A deliverable for ONR contract N00014-02-0623 "National Naval Responsibility for Naval Engineer: Educational and Research for the Electric Naval Engineer".[6]

In this paper, the authors discussed about a railgun which they have developed and also discussed how to illustrate a discharged event on an energy storage capacitor. The force calculations also described in brief and explained shown the simulated railgun model. In order to compute the force that is generated to accelerate the armature, it is necessary to derive an expression for the inductance of the loop in the railgun. For simulated model, they have split the inductance into two components as the inductance of source and its connections and the inductance of the loop around the bars and armature. The simulation results are also shown and the changes in various parameters while firing of the railgun are explained with the help of figures. They have utilized two various types of charging circuits using uncontrolled and controlled rectifier with buck converter. Authors have concluded that the railgun model can be utilized with both charging circuit implementations the controlled rectifier and uncontrolled rectifier with a buck converter.

Chapter 2

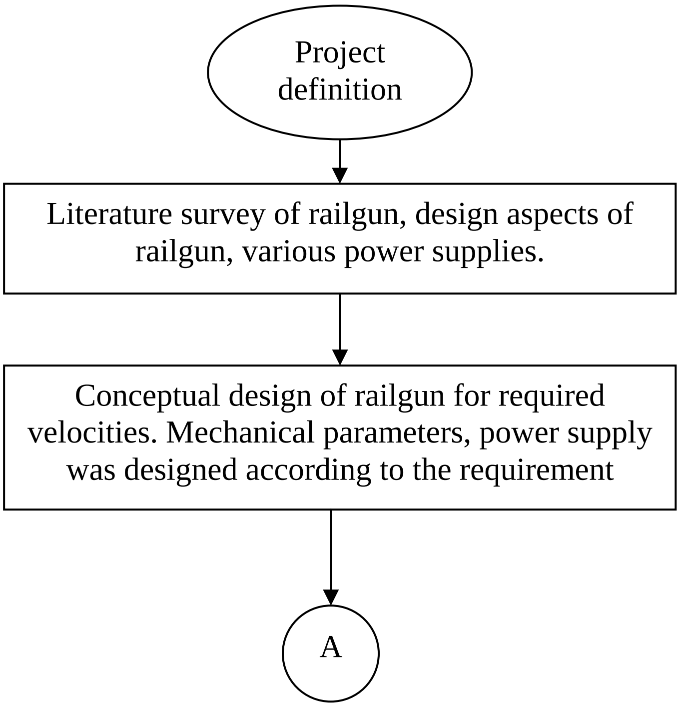
Thesis Definition

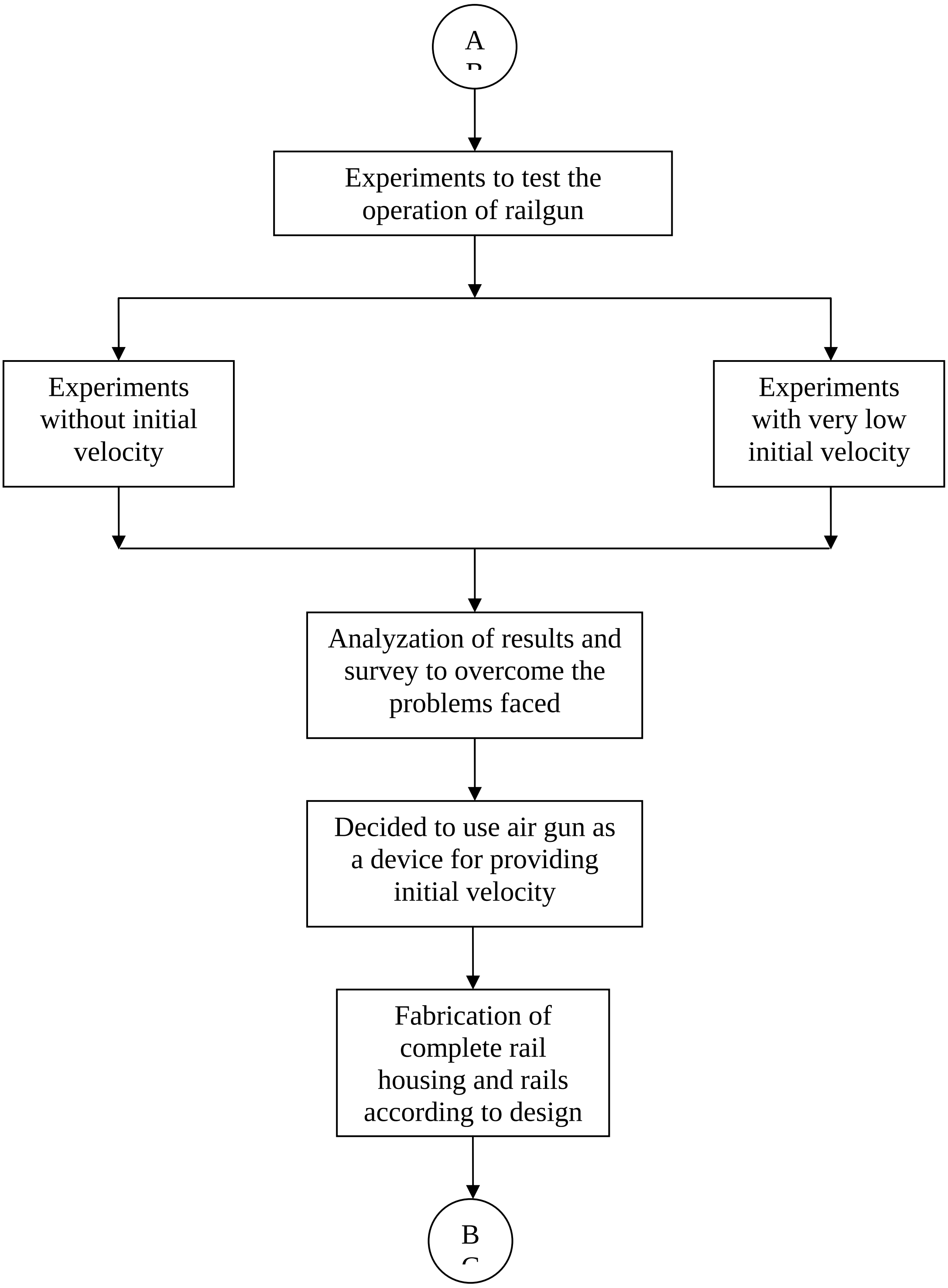
2.1. Thesis Definition:

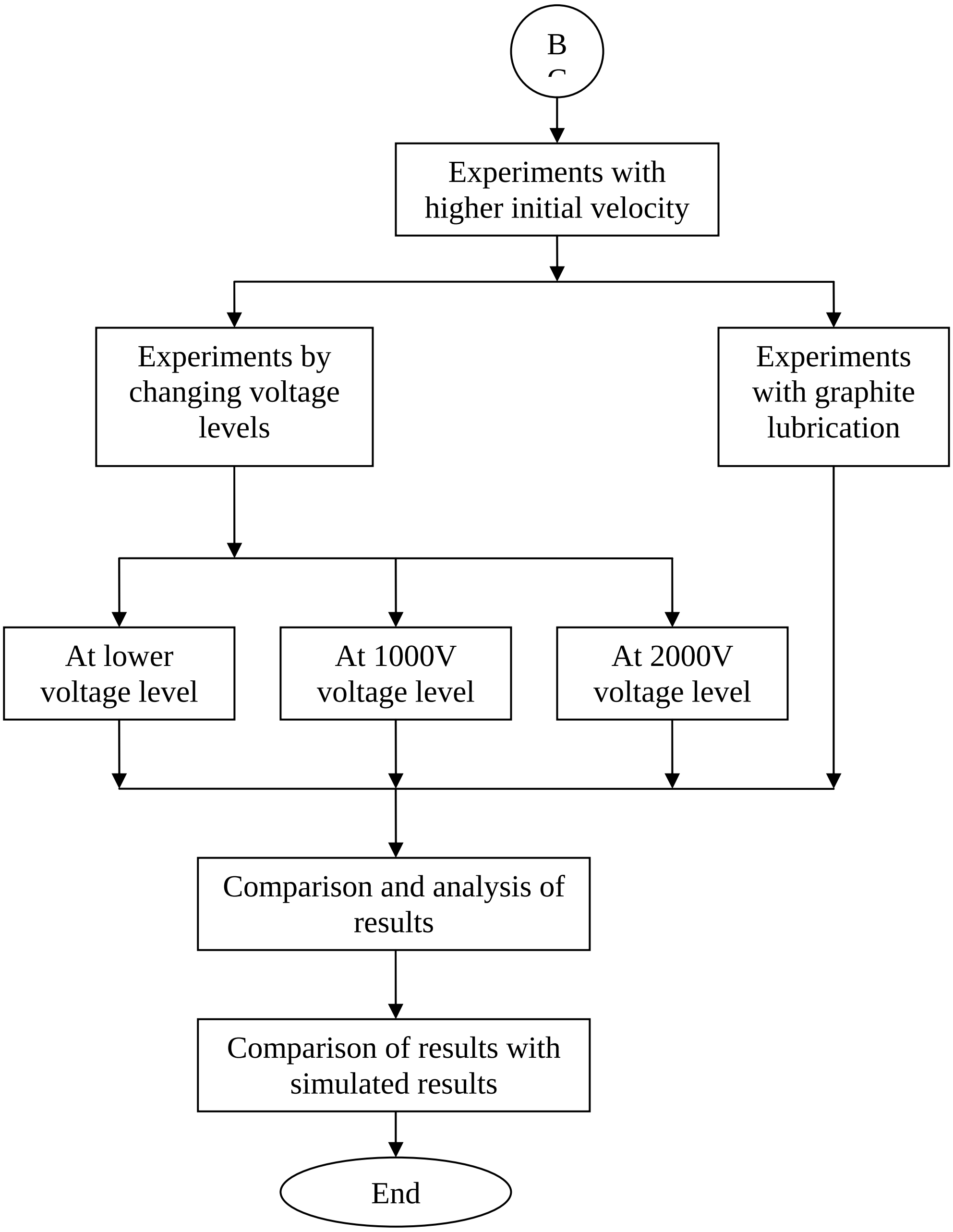
The aim of this project is develop a full scale model of railgun for pellet injection system. According to the required velocities the mechanical model of railgun should be design and fabricated. At the same time the power supply is to be designed to achieve the required velocities. The proper power supply should be decided according to their advantages and suitability for the railgun operation. And the fabrication of power supply should be carried out according to the requirement. Analysis should be carried out for various levels of power supplies.

2.2. Thesis flow:

The following flow chart can explain the flow of the thesis work carried out.




A
Experiments to test the operation of railgun
Experiments without initial velocity
Experiments with very low initial velocity
Analyzation of results and survey to overcome the problems faced
Decided to use air gun as a device for providing initial velocity
Fabrication of complete rail housing and rails according to design
B


B
C
Experiments with higher initial velocity
Experiments by changing voltage levels
Experiments with graphite lubrication
At lower voltage level
At 1000V voltage level
At 2000V voltage level
Comparison and analysis of results
Comparison of results with simulated results
End

Chapter 3

Railgun Application for Pellet Injection System

3.1 Introduction:

A **tokamak** is a machine producing a toroidal (doughnut-shaped) magnetic field for confining a plasma. Fusion power reactors based on tokamak concept use isotopes of hydrogen like deuterium, tritium as fuel there are several ways to replenish the spent fuel. Successful fuelling in tokamaks requires that the time needed for the fuel to penetrate injected material is disassembled, ionized and captured by the local magnetic field. For example, for a single atom the injection energy must be in excess of 100Kev to produce penetration greater than a few cm. This may require prohibitively large amount of power.

The three important processing going on in the tokamak device are

1. Fuelling
2. Burning of the fuel
3. Confining

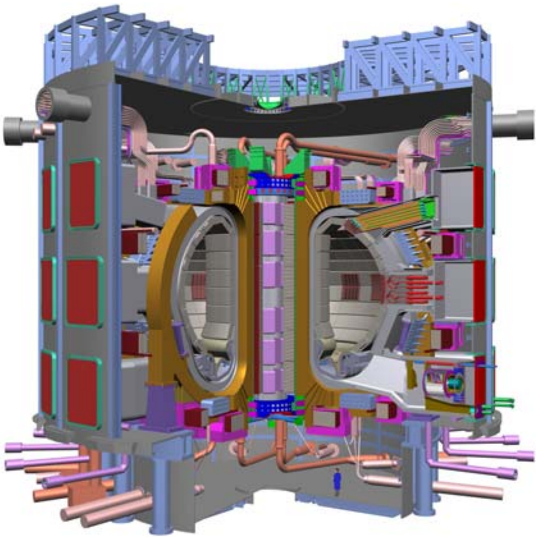


Figure 3.1: Tokomak "fusion device"

The fueling system maintains the balance between the plasma inventory and the burn-up and the convective losses. For steady state operation, the fueling has to be accomplished in a gradual and continuous fashion so that there will not be an unacceptable fluctuation in the fusion power due to density or temperature perturbations. In addition to global particle balance in tokamak, the fueling has to sustain a steady state profile through some desirable deposition profiles and particle diffusion process.

There are various methods for refueling the tokamak device. And some of those are

1. Gas puffing
2. Pellet injection.

3.1.1 Gas puffing:

By releasing puffs of fuel or impurity gas from valves into the plasma chamber it is possible to fuel the outer regions of the plasma. Fuel pellets are used to fuel deeper into the plasma. The fuel gas (Hydrogen, Deuterium and Helium) is injected in the Torus by means of four distributed piezoelectric valves which are driven by a programmed voltage waveform**.** But the main problem with this gas puffing method of fuelling is that, it can not fuel the gas into the center of the plasma core, it can puff up to the surface of the plasma device. Due to this cause the burning process will not complete satisfactorily.

3.1.2. Pellet Injection System:

High-speed injection of frozen macroscopic mm-size pellets of the isotopes of hydrogen has become the leading technology for fueling magnetically confined plasmas. This approach to plasma fueling has been demonstrated conclusively on a number of toroidal magnetic confinement configurations including (tokamaks, stellarators and reversed-field pinches) other related effects such as beneficial improvements in energy confinement. Properties, which have also been observed experimentally on several confinement devices, are generally associated with modifications in the plasma density and/or temperature profiles as a result of the fueling or particle deposition profiles.

3.2. Various methods for Pellet Injection System.

Injection of hydrogen pellets is viable method of fuelling the tokamaks. The method of injection fuel (hydrogen pellets) consists of the following things ---

- Condensing the H_2 isotopes to form solids (pellets)
- Accelerating it to high speeds
- Transporting the pellet deep into plasma core.

Rather than using gas directly as fuel, it is very advantageous to convert it into solid particles and those solid particles are known as pellets. We can achieve better speed with pellets when compared with the normal gas injection. It is required that, these hydrogen pellets should be accelerated with a very high speeds, other wise due to its less yield strength they may get vaporize before reaching the target i.e., nothing but center of the plasma core. And at the next these pellets should be transferred deep into the plasma core to achieve proper burning of fuel.

There are different methods in process for this pellet injection and each method its advantages and disadvantages.

- Centrifuge (mechanical device)
- Gas gun (pneumatic injection device)
- Rail gun technique.

3.2.1. Centrifuge (mechanical device):

A centrifuge is a piece of equipment that puts a substance in rotation around a fixed axis in order for the centrifugal force to separate lighter and heavier substances. Isotope separation is the process of concentrating specific isotopes of a chemical element by removing other isotopes. This centrifuge here used for the same process of isotope separation. As it is a mechanical device it has some disadvantages like less speed and it can not create that much force which is required to fuel the gas into the center of the plasma device core. So, due this also the burning of fuel will not be completely.

3.2.2. Gas gun (pneumatic injection device)

The principle in pneumatic pellet injector is internal energy of a compressed gas is converted in the expansion process to kinetic energy of projectile. The gas gun permits us to fire hypervelocity projectiles into highly instrumented targets shocking matter to extreme conditions for a millionth of a second or less.

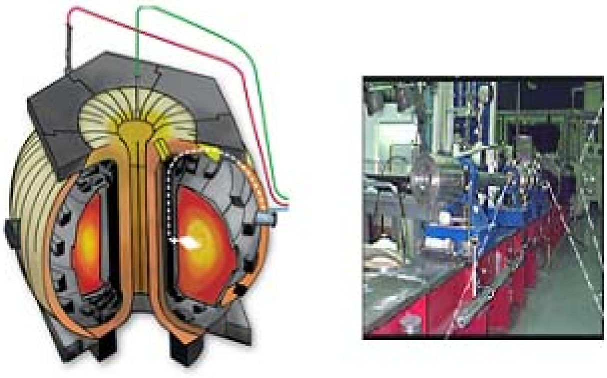


Figure 3.2: Pellet injection system.

Railgun Pellet Injector

To achieve sufficient pellet penetration into plasma core the pellet should be accelerated with hyper velocities. Most successful contemporary pellet injectors, which are based on centrifugal or pneumatic acceleration are however only capable of achieving speeds ≤ 1 km/s. It consists of a pellet generator/gas gun assembly for freezing hydrogen pellets and injecting them into the railgun at velocities as high as 1.5 km/s. A plasma armature is formed by ionizing the low-Z propellant gas behind the pellet and firing the railgun. The railgun system has several features that distinguish it from its predecessors, including: (1) a more compact, versatile pellet generator, (2) a new gas gun configuration that produces significantly higher pellet speeds, (3) a perforated coupling piece between the gas gun and railgun to prevent spurious arcing, and (4) ablation-resistant sidewalls, perforated sidewalls and transaugmentation to reduce inertial and viscous drag, the primary obstacles to achieving hypervelocity. The block diagram for railgun pellet injection system can be shown as below:

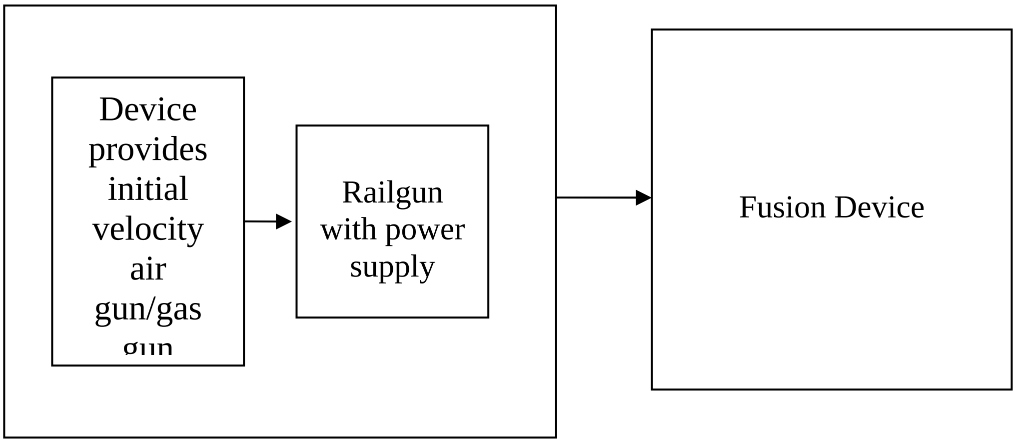


Figure 3.3: Block diagram for railgun pellet injector

3.4. Advantages of Railgun Pellet Injector

(1) Pellets can be dielectric,

(2) Pellets can be fed into the open breech as rapidly as they are launched,

(3) Current can be controlled to ensure isentropic acceleration,

(4) The mass of the propulsive arc is less than the pellet mass,

(5) Cryogenic and vacuum operation is possible, and

(6) The pellet is provided lateral support permitting acceleration stresses in excess of its tensile strength, which results in shorter injectors, acceleration times, and higher repetition rates.

Chapter 4

Theoretical background of RAILGUN

4.1. Theory of rail gun:

A railgun is a form of gun that converts electrical energy – rather than the more conventional chemical energy from an explosive propellant – into projectile kinetic energy. The term railgun is also used for conventional firearms used in the unlimited class of bench rest shooting.

Railguns utilize an electromagnetic force called the Lorentz force to propel an electrically conductive projectile that is initially part of the current path. Sometimes they also use a movable armature connecting the rails. The current flowing through the rails sets up a magnetic field between them and through the projectile perpendicularly to the current in it. This results in a mutual repulsion of the rails and the acceleration of the projectile along them.

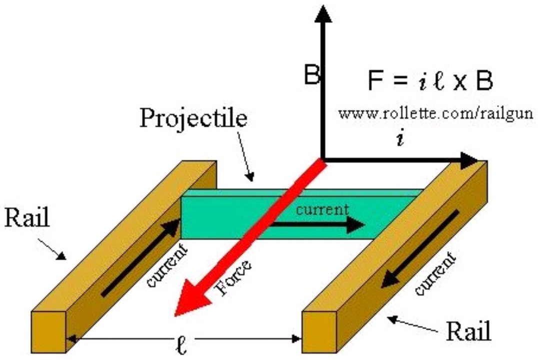


Figure 4.1: Figure showing the principle of railgun.

A wire carrying an electric current when in a magnetic field, experiences a force perpendicular to the direction of the current and the direction of the magnetic field. This is the principle behind the operation of an electric motor, where fixed magnets create a magnetic field, and a coil of wire is carried upon a shaft that is free to rotate. When electricity is applied to the coil of wire, a current flows causing it to experience a force due to the magnetic field. The wires of the coil are arranged such that all the forces on the wires act to make the shaft rotate, and so the motor runs.

A railgun is even simpler than a motor. It consists of two parallel metal rails (hence the name) connected to an electrical power supply. When a conductive projectile is inserted between the rails (from the end connected to the power supply), it completes the circuit. Electrical current runs from the positive terminal of the power supply up the positive rail, across the projectile, and down the negative rail back to the power supply again.

This flow of current makes the railgun act like an electromagnet, creating a powerful magnetic field in the region of the rails up to the position of the projectile. In accordance with the right-hand rule, the created magnetic field circulates around each conductor. Since the current flows in opposite direction along each rail, the net magnetic field between the rails (**B**) is directed vertically. In combination with the current (**I**) flowing across the projectile, this produces a Lorentz force which accelerates the projectile along the rails. There are also forces acting on the rails attempting to push them apart, but since the rails are firmly mounted they cannot move. The projectile is able to slide up the rails away from the end with the power supply.

If a very large power supply providing a million amperes or so of current is used, then the force on the projectile will be tremendous, and by the time it leaves the ends of the rails it can be traveling at many kilometers per second. Twenty kilometers per second has been achieved with small projectiles explosively injected into the railgun.

4.2. Railgun Background [7]

The way a railgun works is based on the following principle. The current density in the rails flows through the armature creating a magnetic field. The armature is the conductive element that pushes on the projectile if it is present. The current density and magnetic field together cause a force on the armature and rails. The direction of the force can be seen by the right hand rule. The armature begins to move once the force has become greater than the static frictional force on the rails, if the armature is at rest initially; otherwise the armature just picks up speed. The rails try to move apart themselves, but are confined to the casing of the railgun.

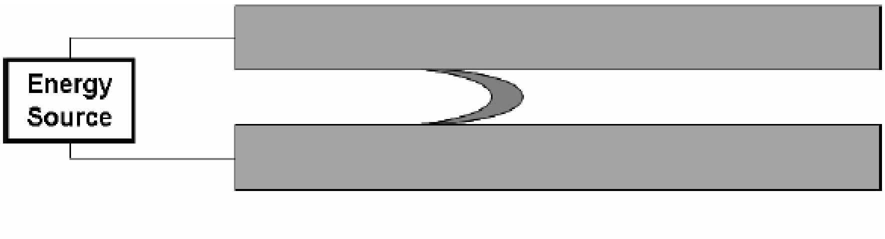


Figure 4.2: Operation of Railgun

The equation can be simplified to equation given in 4.2. The L’ is the inductance gradient of the rails and F_D is the frictional drag on the armature. The inductance gradient is a function of the rail width, thickness, and distance between the rails.

$$F = J \times B \qquad \text{……….. (4.1)}$$

$$F = 1/2\, L' I^2 \qquad \text{……….. (4.2)}$$

` As the armature advances down the rails, the resistance and inductance increases like two parallel transmission lines. The current begins to decrease because inductive energy is getting stored in the rails and lost due to rail resistance, where rail resistance is a function of the current penetration into the rail. The acceleration of the armature can be determined by dividing equation 4.2 by the mass of the armature. This shows that the acceleration is proportional to the current squared which means that given a constant current, the acceleration should be constant and the velocity should be linearly increasing. However, this applies to higher velocity armatures where frictional drag is negligible or much smaller than the current squared.

$$a = (L' I^2)/2m \qquad \text{……… (4.3)}$$

Re-striking inside the railgun is caused by a breakdown in the electric field across the rails. This event only occurs in plasma armature railguns usually at the breech end; however, the event can be seen at any location behind the armature.

The energy source for the railgun is an important factor because it determines how constant current is delivered to the rails. The majority of the railgun applications use capacitor banks. Another form of energy source that can be used is a flywheel to store energy from a generator.

Another factor to consider in railguns is the electrical efficiency. The electrical efficiency is defined as the ratio of the kinetic energy to the total stored electrical energy. The electrical energy transferred to kinetic energy should not exceed 50 % due to the inductive storage being equivalent to the kinetic energy.

4.3. Basic Design of the RAILGUN:

The fundamental railgun design derives from the concept of a linear electromagnetic motor. A conducting bar (the armature) slides along two parallel conducting rails placed in a strong magnetic field. The accelerating force on the armature is produced by current flow through the rails and the armature. The figure shows the conceptual design of railgun.

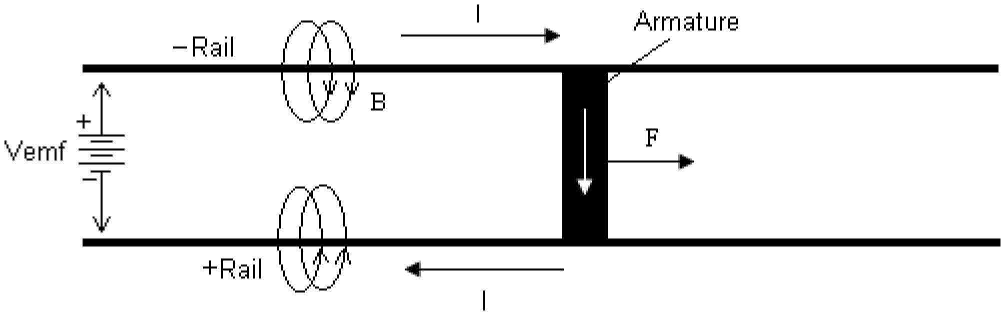


Figure 4.3: Figure Explaining Rail gun Theory of Operation

A sliding armature provides a closed electrical path between the rails. When current is applied to the rails, a Lorentz force is *created* by the interaction of the armature current with the magnetic field of the rail current. This force accelerates the armature from the railgun breech toward the muzzle. For a straight conductor of length L with current, I, perpendicular to a magnetic field, B, the Lorentz force F, is given by

$$F = BIL \text{ Newtons} \qquad \text{………………………..(4.4)}$$

For a pair of circular rails with center-to-center separation **S,** the magnetic field induced by the rail current at the armature midpoint is

$$B = \frac{\mu I}{\pi S} \qquad \text{………………………(4.5)}$$

So, the Lorentz force governs the force generated in the armature and the formula for the Lorentz force can be given as follows:

$$F = \frac{\mu_0 2I^2}{4\pi}\left(\frac{l}{d}\right) \qquad \text{………………….. (4.6)}$$

For calculation of minimum pulse width, peak current flowing into the circuit and the mechanical force produced in the armature the governing equations are given as follows:

The force acting on the projectile $$F = \frac{L' I^2}{2} \qquad \text{…………… (4.7)}$$

Projectile acceleration $$a = \frac{L' I^2}{2m} \qquad \text{…………… (4.8)}$$

Projectile final velocity $$v = \frac{L' I^2 T}{4m} \qquad \text{……………. (4.9)}$$

Effective gun length $$l = \frac{vt}{2} \qquad \text{…………. (4.10)}$$

Inductance Gradient $$L_{wire-pair} \approx \frac{\mu_0 \mu_r}{\pi} \cosh^{-1} \frac{d}{2a} \qquad \text{…………….. (4.11)}$$

$$d >> a$$

Where V$_{emf}$ = applied electric potential difference between the rails (volts)

l = length of the armature bar (meters)

m = mass of the armature (kilograms)

B= magnetic flux density (Tesla)

v = velocity of the armature (m/s.)

I = current flowing into the armature (amperes)

L'= the inductance gradient of the railgun

d = distance between centers of the rails

a = half of the width of the rails

$\mu_0 = 4\pi \times 10^{-7}$ H/m

μ_r = Relative permeability of the material between the rails.

4.4. The Primary Power source and charging power supply[8]:

The prime power output must be processed to provide suitable charging profile to maximize charging efficiency and minimize charging time. This can be done with a simple DC/DC converter with appropriate controls. At the few kilojoules per second charging rate envisioned here such a charger can process about 2 W/g, independent of the voltage level of the prime power source.

4.4.1. Batteries: Rechargeable batteries are now widely used in portable hand tools and can easily deliver several hundred watts at voltages up to about 24 VDC. Both NiMH (nickel metal hydride) and Li (lithium) batteries can provide up to about 40 J/g.

4.4.2. Motor Generator: There are no commercially available motor generator sets that have been miniaturized for this type of application. The model industry does build both internal combustion (IC) engines and brushless DC motors at the kW power level which give us a good baseline on the power densities that can be achieved. Miniature IC engines can deliver between 1.5 and 3 W/g. Brushless DC motors can be operated as generators and miniature motors are readily available which can deliver 3 to 5 W/g. Thus a complete MG set could conceivably be built which would have a power density of 1-2 W/g, about the same as batteries. Fuel would be negligible mass for most missions.

4.4.3. Human Powered: An interesting option provided by this system is that the capacitors could be charged manually using a small hand cranked, or foot pedaled, generator, thus making a very high performance version of the familiar hand pumped air rifle. Such a generator might be constructed using the same generator technology as described above for the motor generator option but driving it with a gearbox and crank system. This generator system might be capable of 1 W/g. A physically fit person can develop around 500 W for a reasonable period of time, so an appropriate generator might weigh 500 g.

4.4.4. Pulse power supply: Capacitors can also be used as the power source. By charging the capacitor with high DC voltages and this stored energy can be used to produce required current pulse in small time duration. Discharging the charged capacitors within very short period through the rails can do this, so that the current pulse with very high di/dt can be produced. In our experiments, this capacitor based power source is used as supply for this high di/dt. The basic pulsed power supply circuit can be explained from the following circuit diagram. The capacitive energy will be switched into the rail load with the help of the switch (SCR shown in the figure). Semiconducting devices are used, because of their high reliability and flexibility in respect to different operating voltages. The cabling between the supply and load will be act as an inductance and it will work as pulse shaping inductance, which is shown as separate inductance in the figure.

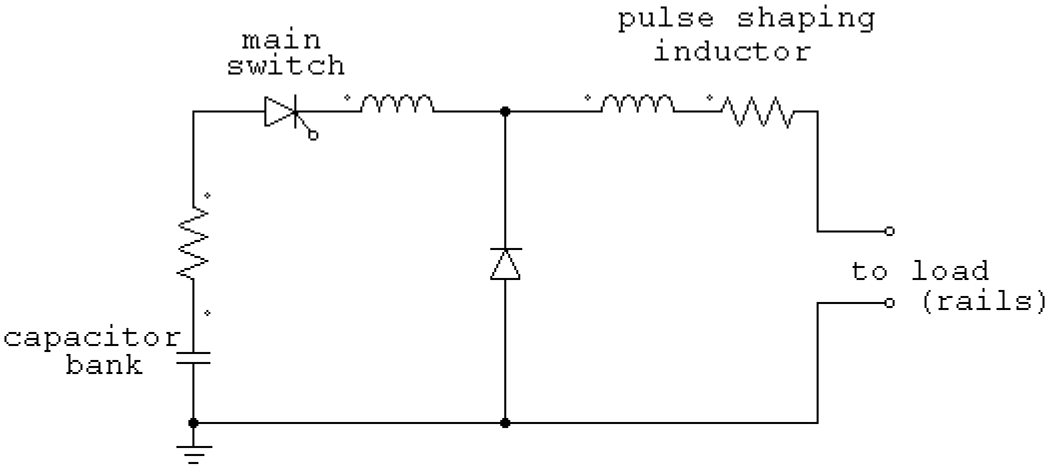


Figure 4.4: Electrical Circuit of Pulse Power Supply for Railgun

4.5. Change in Various Parameters of RAILGUN During Firing [9]:

The changes in the various parameters of the railgun like capacitive energy, voltage applied, current in the system etc. can be explained as follows. When the system is given to fire the railgun, the full capacitor voltage is applied across the railgun. At the same time, the position of the projectile is started at $x = 0$ and the velocity is set to some initial value. When the projectile has reached the end of the railgun, it will be assumed that the energy left stored in the magnetic field will be lost. It will be useful to watch the energy in the railgun components during a firing event. The energy stored in the capacitor

$$E_{cap}=1/2\ CV_{cap}^2 \qquad \text{………..……(4.12)}$$

V_{cap} is the capacitor voltage. By the time of firing completion the complete energy from capacitor will discharged into produce the motion in the projectile. This can be seen in the figure. (4.5)

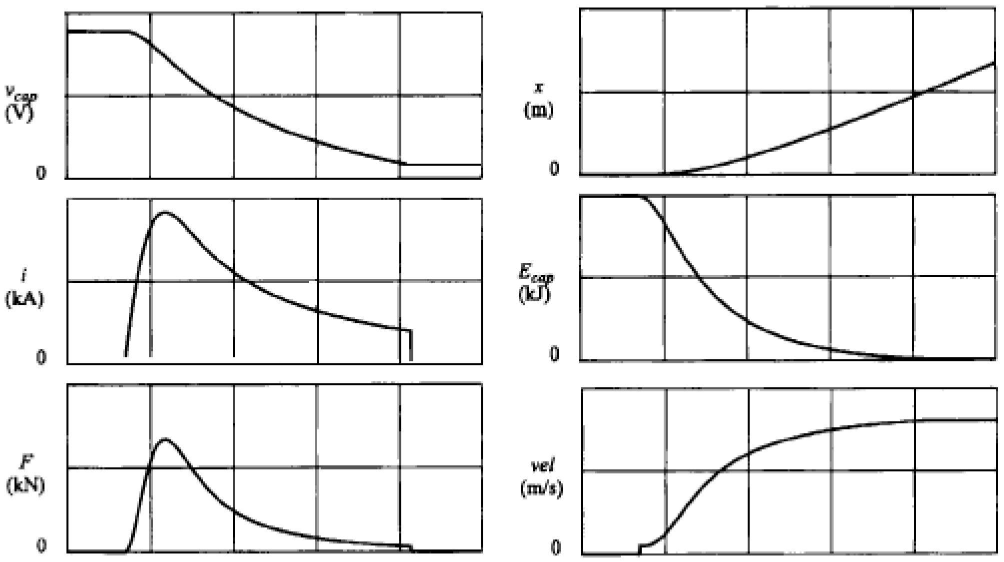


Figure 4.5: Railgun variables during firing

The capacitor voltage, V_{cap} is initially at maximum voltage level and after the event of firing it has dropped up to few tens of volts. The current out of the capacitor and in the rails peaks early in the event will go up to some few Kilo amperes. As the force is directly proportional to the square of the current, it touches its peak value whenever the current reaches its peak value. The projectile reaches to a maximum velocity and is ejected from the barrel when its position reaches at final point of the barrel, continuing afterwards along its trajectory but not being accelerated. The energy initially stored in the capacitor is $1/2\ CV_{cap}^2$. After the event, the energy is almost completely gone, with very few joules left in the capacitor.

4.6. Major Components in the RAILGUN circuit:

The major components in the railgun circuit can be listed as follows:

1. Power supply
    a. Cockroft-walton voltage multiplier
    b. Thyristor based series switch
    c. Triggering circuit for SCR series switch
    d. Crowbar diode
2. Mechanical setup
    a. Injector
    b. Rails and barrel
    c. Armature

4.6.1. Power Supply

4.6.1.1. Cockroft – Walton Voltage Multiplier:

Voltage multiplier is an electrical circuit that converts AC electrical power from a lower voltage to a higher DC voltage by means of capacitors and diodes combined into a network.

Voltage multipliers can be used to generate bias voltages of a few volts or tens of volts or millions of volts for purposes such as high-energy physics experiments and lightning safety testing.

The CW is basically a voltage multiplier that converts AC or pulsing DC electrical power from a low voltage level to a higher DC voltage level. It is made up of a voltage multiplier ladder network of capacitors and diodes to generate high voltages. Unlike transformers, this method eliminates the requirement for the heavy core and the bulk of insulation/potting required. Using only capacitors and diodes, these voltage multipliers can step up relatively low voltages to extremely high values, while at the same time being far lighter and cheaper than transformers. The biggest advantage of such circuits is that the voltage across each stage of the cascade is equal to only twice the peak input voltage, so it has the advantage of requiring relatively low cost components and being easily to insulate. One can also tap the output from any stage, like a multi-tapped transformer.

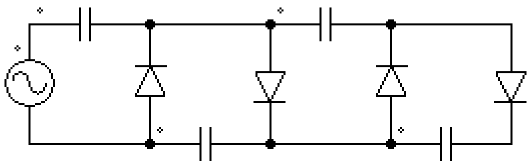


Figure 4.6: Voltage Multiplier Circuit

The output of the voltage multiplier depends upon the number of stages in the circuit and the rms value of input voltage. The output voltage can be given from the following formula:

$$E_{out} = 2 * n * 1.414 * E_{rms}$$

The voltage drop under load can be calculated as

$$E_{drop} = \frac{I_l}{(f * c)\left(\frac{2}{3}n^3 + \frac{n^2}{2} - \frac{n}{6}\right)}$$

Where I_l = load current

C = stage capacitance

f = AC frequency

n = number of stages

The ripple voltage can be calculated from

$$E_{ripple} = \frac{I_{load}}{(f * c) * n * \frac{n+1}{2}}$$

Increasing the frequency can dramatically reduce the ripple, and he voltage drop under load, which account for the popularity driving a multiplier stack with a switching power supply.

4.6.1.2 Thyristor based switch:

As the circuit is operating at very high voltages and a high di/dt rating so a SCR series circuit will be provided to divert the large amount of stored energy in the capacitor bank. This SCR series switch can be designed by using spark gaps, gas discharge tubes and semiconductor devices like thyratrons, thyristors etc.,

The thyristor circuit consists of a number of thyristors connected in series. They require very precise firing pulses as even slight differences in the operation times can lead to large voltage transients. The voltage across the device is minimal, leading to very little energy loss with in the actual SCR series.

Some special requirements for SCR series switches used in this circuit are:

a. Continuous high voltage dc operation without self-breakdown.
b. High-pulsed currents and high di/dt during the starting phase of the capacitor discharge.
c. High charge transfer capability due to large smoothing capacitors and the follow through current of the power supply.
d. Low trigger delay.

While connecting the SCRs in series, it should be kept in mind that the voltage distribution across each thyristor should be same. This can be achieved by connecting dynamic equalizing circuit across each thyristor.

4.6.1.3. Triggering circuit of SCR switch:

This triggering of the thyristors is one big task, as it required that all the thyristors should receive the gate pulse simultaneously at a time. It can be achieved in different manners – two of those are

1. Simultaneous triggering by using pulse transformer with multiple secondary windings
2. By using the opto-coupler circuit.

By using the pulse transformer with multiple secondary windings: The circuit for triggering pulse using pulse transformer with multiple secondary winding is shown as follows (refer figure 4.7.):

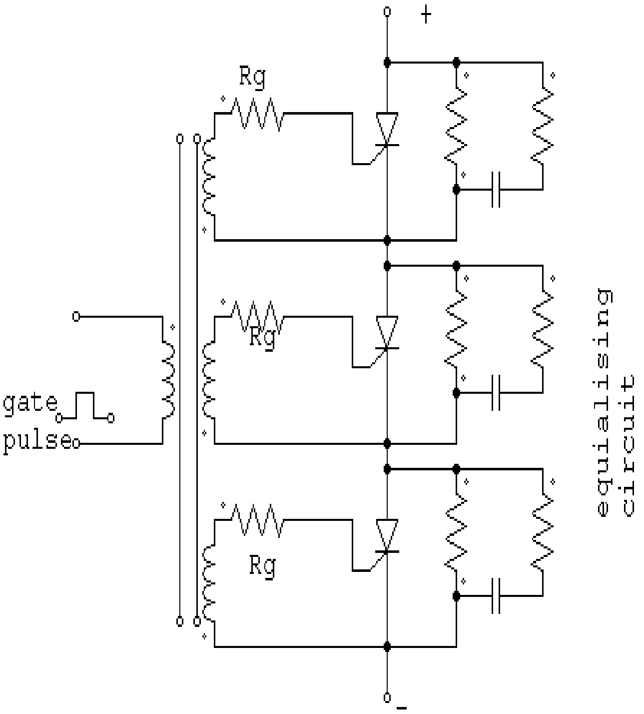


Figure 4.7: Triggering circuit using pulse transformer

Normally most available are of pulse transformers with two secondaries. For more than two SCRs special triggering transformer has got to be made. Also, when using pulse transformer particular attention should be given to the insulation between windings, this insulation must be able to support at least peak of supply voltage.

By using opto-coupler circuit: By using opto coupler as shown in this manner below, we can trigger the series connection of SCRs simultaneously. (Refer figure 4.8.)

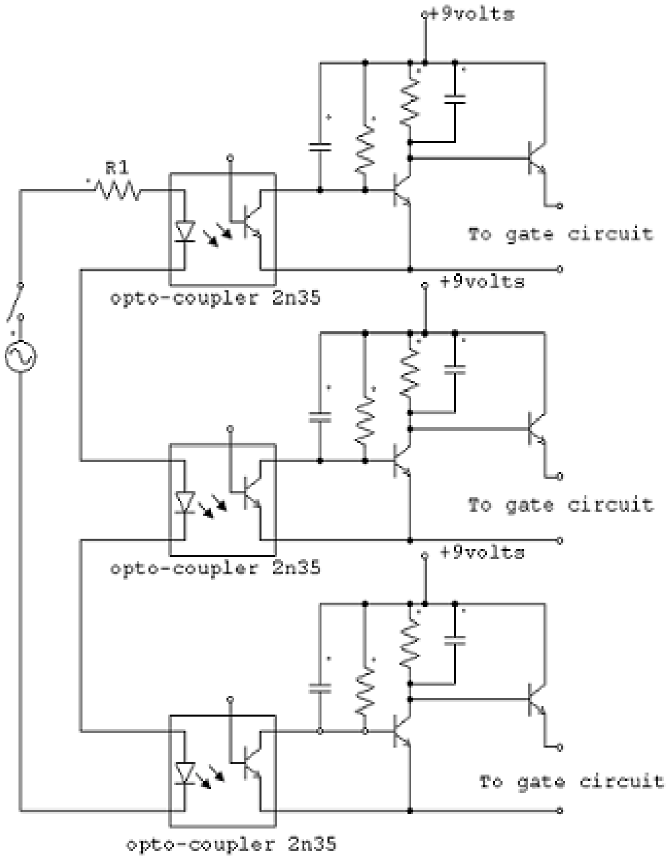


Figure 4.8: Triggering Circuit for Thyristors Using Opto-Couplers

4.6.1.4. Crowbar diode:

Crowbar switches cause a short circuit when they close. They are frequently employed in pulsed-power circuits in which a capacitor is discharged into an inductive load, either to prevent an excessive reversal of voltage on the capacitor or to provide a free-wheel path for the inductive load current. Nevertheless, these high-current single shot crowbar switches are often preferred to diode stacks for repetitive operation, because of size, lower impedance and reduced cost.

4.6.2 Mechanical setup

4.6.2.1 Injector

The armature should be forced into the rails with some initial velocity otherwise the following problems can occur:

1. If full power to be applied to a static armature, the rails and whatever between them would instantaneously melt under intense localized heat produced by ohmic heating.
2. High-speed delivery is required to overcome premature breakdown.
3. The valuable electrical energy stored in capacitor banks is wasted to accelerate the projectile during the initial position.

To overcome this problem, the armature should be forced into rails with some initial velocity, which should be less than that of original required armature velocity. Using following different ways can provide this.

1. Spring loaded injection system
2. Centrifugal force
3. Compressed air injection system.

Compressed gas is far more efficient and economical way of pre-accelerating the projectile until it starts moving at speeds where electrical accelerations makes more sense.

Spring loaded launcher consisting if a bolt connected to fixed part with a spring on the bolt and a bloc on the end of spring to press against. This is the way is suggested by the guide for our experiments. The visual image made by using spring-loaded launcher is shown below:

4.6.2.2. Rails and Barrel:

Important characters of good rail material are high conductivity, high strength, high machinability, resistance to corrosion, high melting point, availability, compatibility with slug material, and finally price. Coming to shape point of view, the primary purpose of the rails in a railgun is to conduct electricity to the projectile, build a magnetic field, and a guide the projectile out of the device. The actual shape of the rail is important in two instances. 1) The contact path between rail and projectile. 2) The structural rigidity of the rail in the horizontal plane (in plane with but perpendicular to projectile motion). The best shape for this interface is flat. This shape of the rail not in contact with the projectile must be designed for the utmost in structural rigidity. An ideal rail support (structural backing for contact/conducting surface) would resemble a beam or truss designed for maximum resistance to bending.

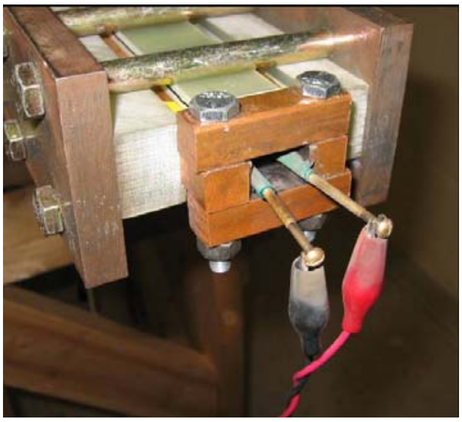


Figure 4.9: Figure explaining the shape of barrel [10]

4.6.2.3. Armature:

A railgun can fire a solid conducting armatures, and plasma copper armatures. A railgun can fire virtually any type of projectile, provided that a least some portion of it conducts electricity and makes contact with rails. Welding is the most common problem in home railgun design, and is difficult to overcome using traditional methods. Welding is strictly a problem of current density and heat. Current density refers to the amount of current flowing through a particular portion of the circuit, and generally reaches its highest levels at the interface between the slug and the rails.

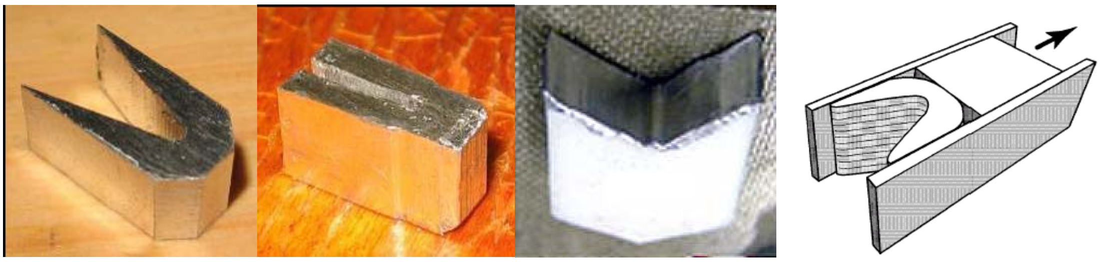


Figure 4.10: Figure showing various types of armatures

The contact area between the armature and rails must be as large as possible to keep the current density from welding the two together before the projectile can begin moving. In an advanced high power design, the projectile will ionize due to the heat generated by the extremely high currents involved. The major difficulty in getting optimum rail to armature contact is the balancing act of projectile to rail surface are contact, aerodynamic stability of projectile, heat dissipation, and friction with rails.

4.7. Factors Effecting the Railgun Performance:

The various factors, which affect the performance of the railgun, can be explained as follows:

4.7.1. Inductance Gradient (L'):

Inductance Gradient means inductance per unit length of the material. It is one of the principal parameters to predict the acceleration performance of the complete railgun system. The driving force acting on the projectile F is given by

$$F = \frac{1}{2} L' I^2$$

Where force as well as acceleration is depends on the inductance gradient. The inductance gradient is depends upon the distance between the rails and width of the rails using in the railgun and it can be predicted by the following formula:

$$L_{wire-pair} \approx \frac{\mu_0 \mu_r}{\pi} \cosh^{-1} \frac{d}{2a} \qquad d >> a$$

Where d = distance between centers of the rails

a = half of the width of the rails

$\mu_0 = 4\pi \times 10^{-7}$ H/m

μ_r = Relative permeability of the material between the rails.

So, it can be concluded that with the rail dimensions the inductance gradient will affect, due to this the force as well as the acceleration of the projectile also effects.

4.7.2 Current pulse:

The force acting on the projectile also depends upon the square of the current applying into it. Very high and shortly pulsed current should be required for the railgun for proper velocity of the armature. And this current should be equally distributed in the projectile.

4.7.3. Contact area:

The area of contact between armature and rails can also show the effect on the velocity of armature. Even then a good metallic contact between armature and rails can be established higher velocities. Why because, if the contact area increases, the resistance acting in the load circuit will be decreases. So that for particular source, the current value can be increases and so force.

4.7.4. Rail & Armature Geometry:

The distribution of current in the conductors which is the affected by the geometry of the armature is plays an important role in the performance of the electromagnetic launcher. In general, current density distribution over the armature is affected by a number of parameters such as the velocity of the moving armature, the armature geometry, etc. In addition, L' also affects due to the rail and armature geometry which further causes an effect in the railgun performance. So, it can conclude about this affect of rail geometry that the relative position between the contact leading edge and the root trailing edge, and similarly the geometry of rail/armature is the most important geometrical parameter since it determines the lowest inductance path.

4.7.5. Rail support:

The rail supporting structure is also one major requirement and if it is not suitable, the performance of rail will affect. Mainly the rail supporting structure serves for a triple purpose: to withstand the repulsive rail forces, those occurring between rails and current input connections and to transmit the recoil to the recoil system.

Chapter 5

Conceptual design of railgun

5.1. Design calculations railgun model:

The specifications for the railgun were assumed as:

- Final velocity is 300 m/sec.
- Length of the rail is 30 cm.
- Armature length is 6 mm.
- Mass of armature is 1 gram.
- Initial velocity is 25 m/s

Here the velocity is given by an **air pistol**, which can provide velocity of 50m/s^2. The typical velocities of air pistols, which are available in market, are nearly equal to 25 m/sec to 50 m/sec.

- The current pulse should be designed such that the armature should leave the barrel exactly or just before the current pulse going to zero…

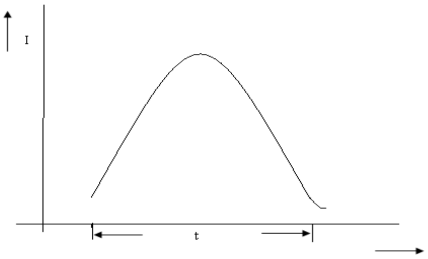


Figure 5.1: figure showing the current pulse

So,

The final velocity $v = u + at$ ……………. (5.1)

$$300 = 25+at$$

The length of barrel $S = ut + \frac{1}{2}at^2$ ……………… (5.2)

$$30e-2 = 25*t + 0.5*a*t^{2.}$$

t = 1.8 m.sec

- From this the time period of the current pulse can be calculated, and the pulse width getting is **t = 1.8 m.sec**
- And the acceleration is given from the equation (5.2), and the value of the acceleration is 148.9km/sec.

So, the force is given by *F = ma*

$$F = 1 \times 10^{-3} * 147000$$
$$= 148.9 \text{ Newton}$$

By using this force value the current magnitude can be decided as follows:

$$F = \frac{1}{2} L' I^2 \qquad \text{……………… (5.3)}$$

$$148.9 = ½ * 0.25 \times 10^{-6} * I^2$$
$$I = 35.91 \text{ kA}$$

Where L’ = inductance gradient of rails

(Note: normally for square cross sectional rails this inductance gradient value will be near to 0.5 μH/m^2) (Refer appendix-C)

From these calculations the current value getting is 35.91 kA

I = 35.91 kA

5.1.1. Design of mechanical parameters:

For deciding the complete dimensions this force should be made equal to the Lorentz force formula, which can be given as follows:

$$F = \frac{\mu_0 2 I^2}{4\pi}\left(\frac{l}{d}\right) \qquad \text{………………… (5.4)}$$

So, the *l/d* ratio from the above formula getting is 1.25

Here, *l* is the length of the armature

d is the width of the rail

- So, for 6 mm length of armature the width of the rails can be selected as **4.8 mm**.

(According to availability the width is selected is **4.5mm**)

- And the height to width ratio for the rails should be greater than 2,

  So, the rail height is taken as **10mm.**
- The mechanical output energy is given by

$$E = ½ mv^2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots (5.5)$$

$$=31.25 \text{ J}$$

5.1.2. Design of the power supply:

To decide the required power supply ratings, it should be required to calculate the energy loss due to the rail resistance…

The efficiency should be achieved is taken as 10%,

The energy consumed in the resistive part of rails can be 281.25 J.

According to these numerical, the total energy supplied should be enough sufficient to able to supply this load also,

So, the energy required for this rail gun operation is 312.5 J

For this energy, the voltage and capacitor combination can be given by:

$$312.5 = ½ CV^2$$

$$= ½ * C * (1300^2)$$

So, C =369 μf

1300V, 369μf.

If voltage is selected as 2500 volts,

$$312.5 = ½ CV^2$$

$$= ½ * C * (2500^2)$$

So, C =100 μf

2500V, 100μf.

So, complete specifications can be given by

Table 5.1: specifications of railgun

Specification	Value
Required final velocity	300 m/s
Initial velocity	25 m/s
Length of rail	30 cm
Width of rail	4.5 mm
Height of rail	10 mm
Armature dimensions	6 mm
Mass of armature	1 g
Power source ratings	1300 V, 369 μf
--do--	2500 V, 100 μf

Various types of power supplies for the railgun are discussed in chapter 3 (refer article 4.3). According to the availability and advantages, the power supply selected is pulsed power supply in which capacitors were used as power source. These capacitors were charged up to the required level voltage from a DC supply. This DC supply can be a rectifier, battery or a voltage multiplier. But as the required voltage level is very high, so it has been decided to use the voltage multiplier for the purpose of charging the capacitor bank.

5.2. Design of Voltage Multiplier

Voltage multiplier is an electrical circuit that converts AC electrical power from a lower voltage to a higher DC voltage by means of capacitors and diodes combined into a network.

The circuit diagram for the voltage multiplier is shown below.

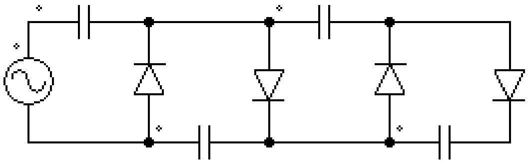


Figure 5.2: voltage multiplier

The output of the voltage multiplier depends upon the number of stages in the circuit and the rms value of input voltage. The output voltage can be given from the following formula

$E_{out} = 2*n*1.414 * E_{rms,}$ ……………(5.6)

Required $E_{out} = 1300$ V

$E_{rms} = 230$ V (the normal supply AC voltage)

So, the number of stages **n = 2**

Similarly, for 2500 V level, the number of stages will be

From equation (5.6), n = 3.8

$\mathbf{n \approx 4}$

The simulation results for the above combination can be shown as below: (as per limitation only 2-stage voltage multiplier is shown).

5.2.1. Simulation of voltage multiplier:

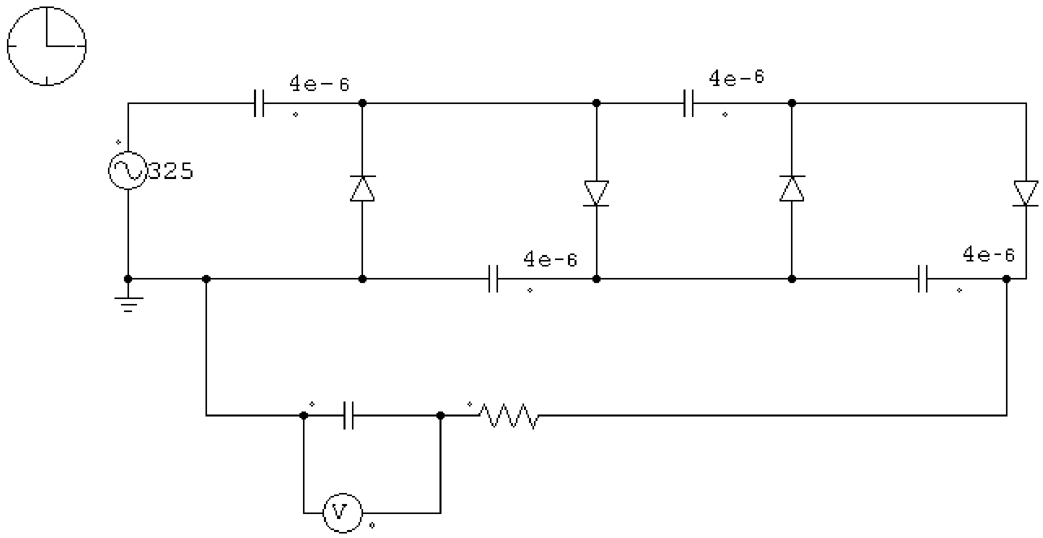
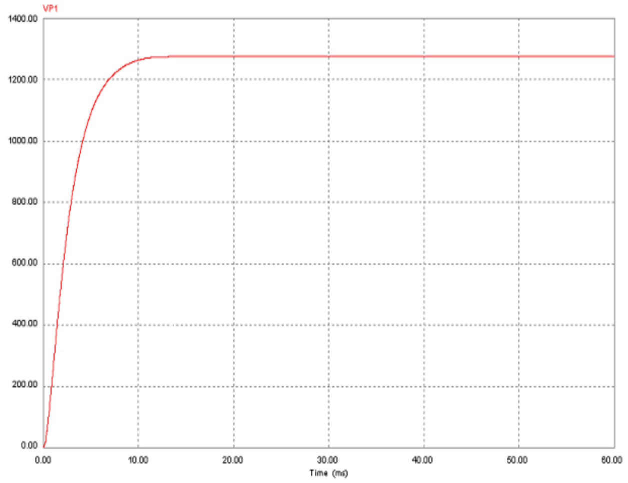


Figure 5.3: simulation circuit for 2-stage voltage multiplier



scale: y-axis: 1 div = 500 volts
x-axis: 1div = 5 m.sec.

Figure 5.4: simulation output for 2-stage voltage multiplier

Figure 5.4: simulated output of 2-stage voltage multiplier

To discharge this charged voltage of rails into the rails at instant a series switch is required. Due to the higher voltage levels, and heavy currents drawn into the circuit, normal mechanical switch will not work up to the level. Switch by using semi-conductor devices like SCRs, diodes can meet the required level. Series connection of the SCRs was used as a switch for this purpose. Here the SCR used is

25RIA60 (refer appendix B), which has maximum repetitive peak off voltage, and peak reverse voltage of 600V.

For the gate triggering circuit, already two types of discussed in chapter 3 (refer 4.6.3). According to the advantages of the triggering circuit using the opto-couplers, it was used in this circuit. And the opto-coupler used in the circuit is 4N25 (refer appendix A). And the circuit simulation of this triggering circuit is shown in the following.

5.3**. Design of Series switch with SCRs and its triggering circuit:**

The circuit is operating at very high voltages and a high di/dt rating; it is required to provide a series switching circuit to divert the large amount of stored energy in the capacitor bank.

The thyristor circuit consists of a number of 3 thyristors connected in series. They require very precise firing pulses as even slight differences in the operation times can lead to large voltage transients. The voltage across the device is minimal, leading to very little energy loss with in the actual SCR series. So, in this triggering circuit opto couplers 2N35 were used. (Refer appendix – A & B for datasheets)

The simulation circuit and results for triggering circuit was shown below:

5.3.1. Simulation of the triggering circuit for SCRs

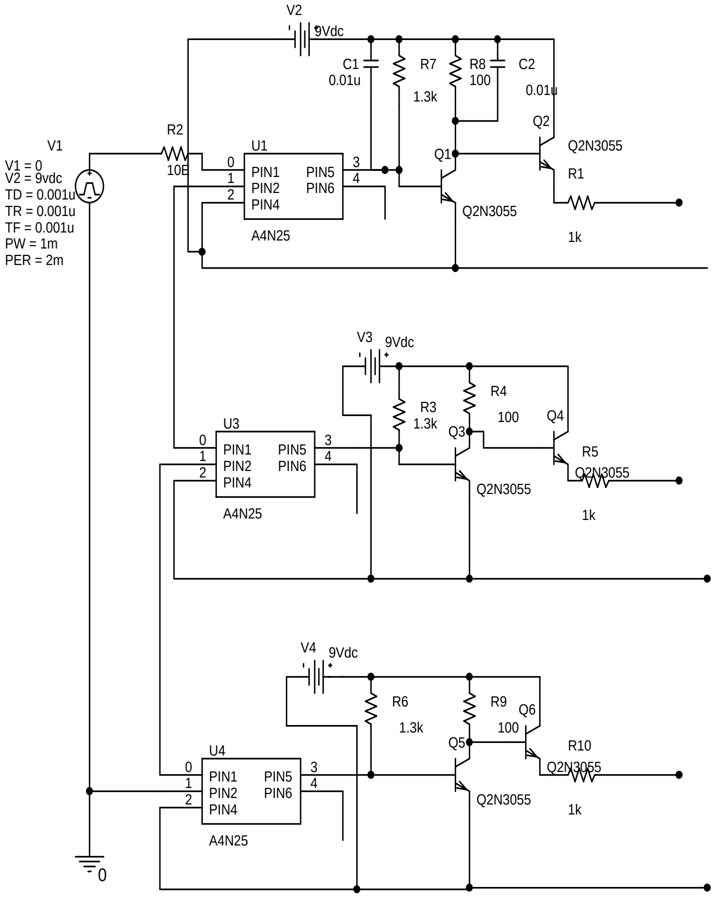
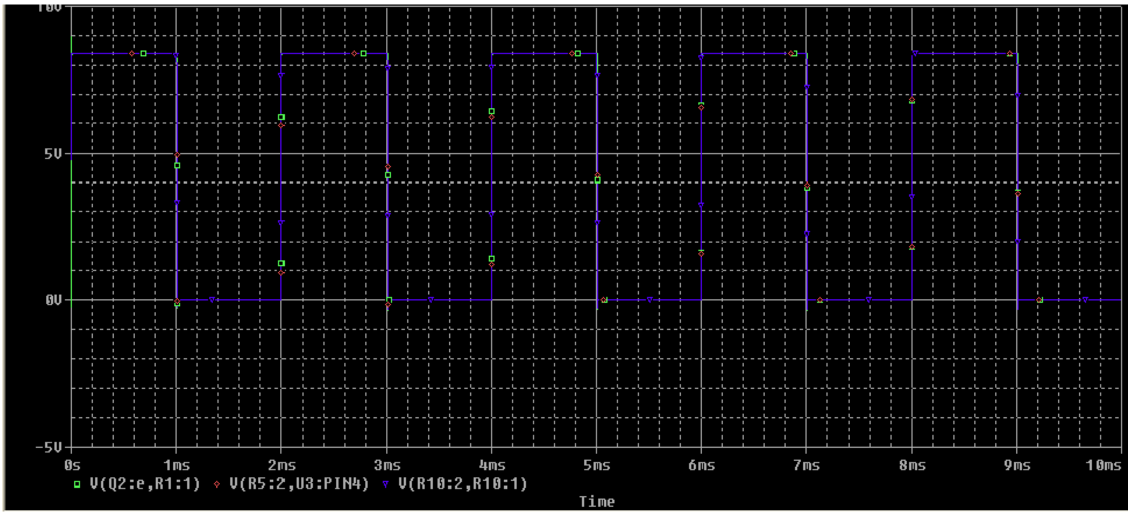


Figure 5.5: simulation circuit for triggering circuit



Scale: x-axis: 1div = 5 m.sec
y-axis: 1 div = 5 volts

Figure 5.6: Simulated output for triggering circuit

5.4. Complete railgun equivalent model simulation:

By using the above-calculated values, the complete railgun electrical model is simulated in PSIM, and the results were compared with real time output. In this railgun model a single SCR is used as switch. The complete cabling system is represented as an inductance with a value of 0.1 n Henry. The resistance of the complete system is taken as 0.089 ohms. And the capacitor bank value is of 105 μf that is taken as fully charged initially to a voltage level of 2500 volts. The current and the time period can be calculated as follows:

It represents a pulsed power system. The current relation is given by

$$I_{peak} = (0.763*V)/R_{load} \qquad \ldots\ldots\ldots\ldots\ldots (5.7)$$

The time period depends upon the values of inductance and capacitance. And the equation for current is given by

$$t = 2*\pi*\sqrt{LC} \qquad \ldots\ldots\ldots\ldots\ldots (5.8)$$

So, for present system these values are given by 23.843 kA, 0.643 μsec. The simulated circuit and the results are shown:

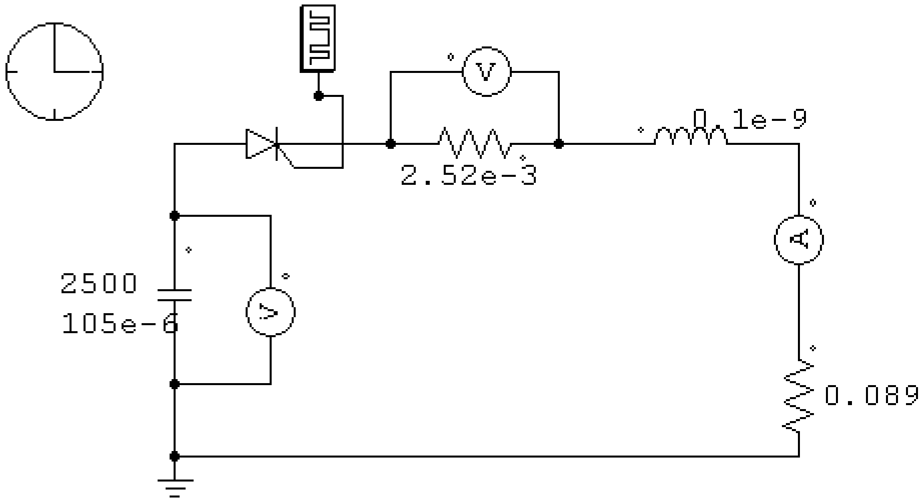
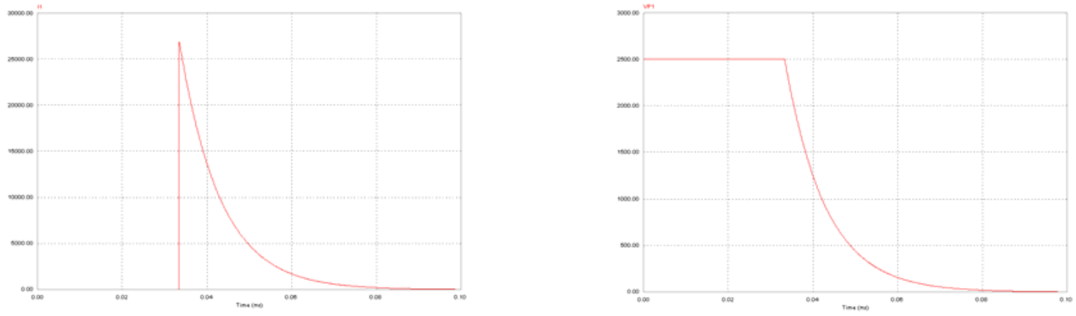


Figure 5.7: complete railgun model



(a)Current waveform in the circuit

scale: X-axis: 1 div = 0.02 m.sec
Y-axis: 1 div = 5 kA

(b)Voltage waveform in the circuit

scale: X-axis: 1 div = 0.02 m.sec
Y-axis: 1 div = 500 volts

Figure 5.8: simulated outputs for the railgun model

5.5. Velocity measurement circuit:

For measuring these hyper velocities producing from the railgun there is no availability of meters in normal. So electronic circuits are necessary to measure the velocities. The following one, which is designed with the help of photo detectors, serves the purpose of measurement of high velocity.

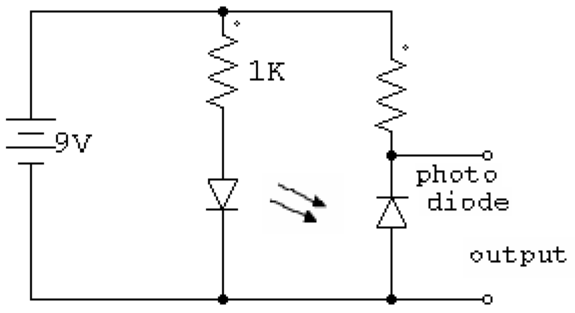


Figure 5.9: circuit for velocity measurement

5.5.1. Descriptions of the circuit:

- Supply voltage should be as constant as possible. Because of with small ripple disturbance in the supply also giving pulse in the output terminal.
- Whenever light falls on the photo diode the complete voltage will appear across the resistor only. If any obstruction occurs in between the light source and the photo diode, it will start diode action and become open circuit. So the voltage across the resistor will be come zero. Whenever

the light source is on, the voltage across is 6 volts, and if any obstruction occurs the voltage across the photo diode will go to the maximum level of supply voltage.

- Battery operated torch was giving good and proper results in form of pulses according to requirement. The infrared LED can be act as a source as light source, but the photo diode will be not able to sense the light source.

5.5.2. Measurement of velocity:

- The velocity can be measured by using the similar two circuits and by maintaining a considerable length between the sources-detector pair. The distance divided by the time difference between the two pulses will give the velocity of the pellet.
- It is possible to measure the velocity by using only single source and detector--- whenever the obstruction came in the way of light source to the detector the pulse starts rising/falling and it reaches its peak value when the source is completely obstructed by the pellet and whenever the obstruction crosses the source of light the pulse will reaches its original value. So, if the velocity of the obstruction is high the pulse will be sharper and from the detector width and time period the velocity can be measured. And the velocity is given by the width of photo detector divided by the pulse width of the time period.

For calibration purpose, an experiment has been conducted by measuring the acceleration due to gravity. For this purpose a small set of pipe with flanges connected on both sides of the pipes is used. And such types of two circuits are used in the both flanges and torches as light sources.

And the length between the both points is of 53.2 cm.
The supply voltage applied first is of 9 volts.

- Theoretically, as we know the acceleration due to gravity is 9.81

- The experiment is conducted by keeping the setup vertically and dropping a ball into the pipe, so this ball will act as a obstruction between the light source and the photo diode and it will give two pulses.

As we know, $S = ut + \frac{1}{2}at^2$

So, the time period can be 319 m.sec

- Practically two different pulses occurred and the time period between those two pulses is of 320 m.sec So, this setup can be successfully used for the testing of railgun velocity measurement experiments.

Chapter 6

Experiments with railgun

6.1. Complete set up of the railgun:

The complete block diagram for the railgun setup is as shown

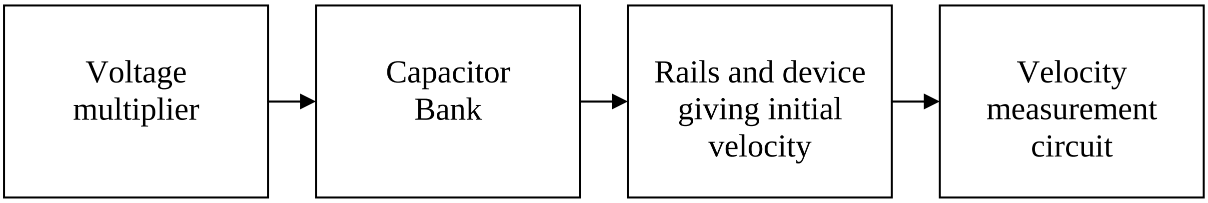


Figure 6.1: Basic block diagram for railgun set-up

Voltage multiplier feeds the capacitor bank at the required voltage level, and the output of the capacitor bank is connected to the rails through a series shunt, which is meant for current measurement. And finally the velocity measurement circuit is connected at the end barrel from where the armature ejects from the rails. The device used for giving the initial velocity is an *air-pistol.* The brief discussion about air gun is given below.

6.1.1. Air-Gun

An air gun is a pneumatic gun which fires projectiles using compressed air or other high pressure gas as a propellant. There are three different methods of powering the air-gun. These methods can be broadly divided into 3-groups – spring-piston, gas ram and pneumatic. Spring-piston guns operate by means of a coiled steel spring-loaded piston contained within a compression chamber, and separate from the barrel. Pressurized air or nitrogen is held in a special chamber built into the piston, and this air is further pressurized when the gun is cocked. It is, in effect, a gas spring more commonly referred to as a "gas-ram" or "gas strut". Pneumatic-type airguns require the pre-compression of air in a chamber prior to the gun being used. Single-stroke and multi-stroke guns utilize an on board pump, while PCP guns use either a high-pressure hand pump or air compressor to pressurize the air.

The air gun used in these experiments is of spring-loaded (He-Man toy air-pistol). The specified velocity for this air gun of 25-40 m/s. It is tested and confirmed that the velocity of the air-pistol is 25 m/s. The visual image of the air gun used is shown below:

Figure 6.2: Visual image of air-gun

6.2. Experiments to test the operation of the railgun:

Two different experiments were conducted to test the railgun operation. These two sets of experiments were conducted one without giving any initial velocity, and the second one is with very less initial velocity.

6.2.1. Experiments without giving the initial velocity:

According to the block diagram shown in the figure (), the set up was established and the first experiments were performed to test the operation of railgun without giving the initial velocity. Here for this experiment rails with different dimensions, which are not related to design were used according to availability. And here a stainless steel ball is used as armature. The complete specifications of these experiments were given below:

The first experiments were conducted by using the following parameters.

Voltage applied to in the circuit	= 1350 volts,
Capacitor bank used of value	= 120 μf,
Armature used in the exp.	= stainless steel ball of 6 mm dia.
Mass of armature	= 0.9046 grams
Rails used are made of	= copper
Rail dimensions	= 4mm x 3mm x 130mm

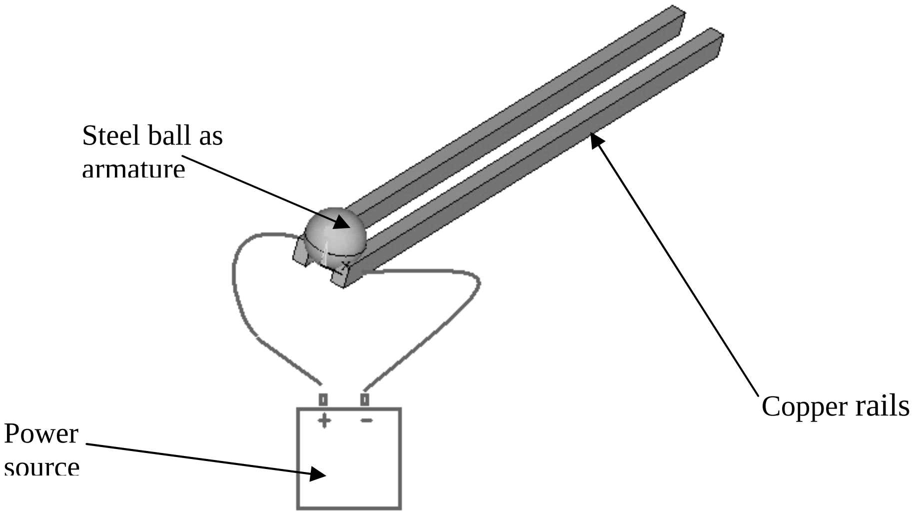


Figure 6.3: Figure showing the setup for the exp. Without initial velocity

Observations from this experiment:

The first set of experiment was conducted by using the parameters above specified. Here initially the armature (ball bearing) was kept in steady position and the energy is switched into the rails by using the SCR series switch. The complete energy is wasted to overcome the static friction of the armature and there is only a small considerable jump (movement) in the armature in upward direction. The practical outputs of voltage multipler for 1300V and output of triggering circuit of SCRs are shown below:

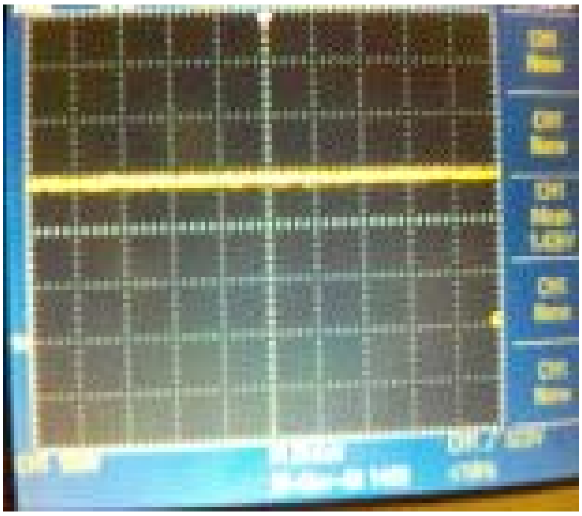


Figure 6.4: Output of the 2-stage voltage multiplier
Scale: on x-axis 1 div = 1 ms,
On y-axis 1 div = 500V

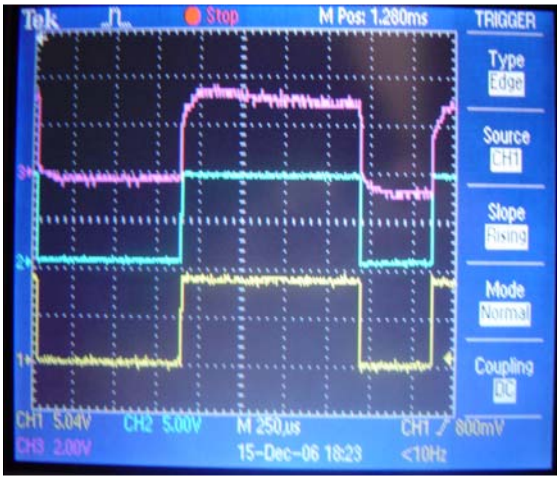


Figure 6.5: Practical output of the triggering circuit of SCRs
Scale: on x –axis: 1 div = 250 µs
on y- axis 1 div = 5V

From the results, the calculations were made as follows:

- E_o = n * the peak amplitude of the input voltage *2
  =2 * (325) *2
  = 1300 V
- So, the electrical energy inducing in the circuit is
  $E_i = ½ CV^2$
  = ½ 120e-6 * 1300 *1300
  = 101.4 J

From the results, current calculated is 3 K Amp. This current is measured by measuring the voltage across a shunt, which is connected in series with the rail. The voltage waveform is given below. And the shunt parameters are 150 mV, 2 amps.

The railgun dimensions are:

Length = 13 cm,
Width of rails = **0.3cm**;

- The Lorentz force induced can be calculated as follows:

$$F = \frac{\mu_0 2 I^2 L}{4\pi d};$$

Here L = length of the rails;
d = width of the rails.

$$F = \frac{(4\pi * 10e-7) * 2 * 3000^2 * 0.6e-2}{4 * \pi * 0.3e-2}$$

= **3.6 Newtons**

Initial velocity u = 0;

It jumps in upward direction at a height of **2 to 3mm.**

h = 2.5mm

Gravitational constant g = 9 .81m/sq.sec

Velocity $v = \sqrt{2gh}$

$= \sqrt{2*9.81*2.5e-3}$

=0.2214 m/s

And $v = u + at$

So the acceleration, a= 3690 m/s^2

- The time period is calculated as follows:

The resistance of the complete system is measured through the graph as follows:

Voltage applied V = 1350 volts

Current attained I = 3 kA

So, resistance R = 1350/3000

= 0.45 Ω

The complete resistance is taken as 0.45Ω, and the time period is 0.06m.s.

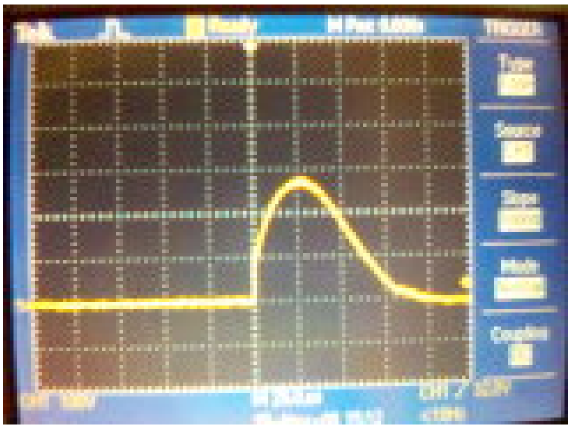


Figure 6.6: the current pulse with shot-1
Scale: on x-axis:1 div = 20 µs
on y-axis: 1 div = 100volts

Then force $F = ma$

= 0.9047e-3 * 3690

= 3.33 Newton

Both forces are nearly matching.

Here, the energy efficiency can be calculated as follows:

Input energy $E_i = 101.4$ J

Output energy $E_o = ½ mv^2$

$= ½ * 0.9046 \times 10^{-3} * 0.2214$

$= 0.1$ mJ

Efficiency $= E_i / E_o$

$\cong$ 0%

Due to the high energy loss in the resistive part, there is a lot of production of heat which to melt the copper part and cause for the welding of armature to the rails. It can be proved from the following calculations:

The energy in the resistive part $E_R = I^2Rt$

$= (3000)^2 * 0.45 * 0.02$m.sec.

$= 81$ J

The temperature produced can be calculated by equating this energy to the following equation

Energy $Q = mC\delta t$

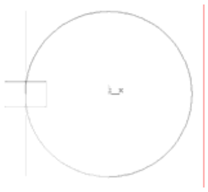
Here m = mass of the contact at which the heat energy produced

C = specific heat of copper (0.385 J/kg.°c)

δt = change in temperature

Mass of the contact can be calculated as follows:

To calculate the mass of the contact, cylindrical analogy was assumed. Means, the contact area is of 1mm, and depth also assumed as 1mm. So, the complete volume is given by



Volume $= (\pi*(1\text{mm})^2)*1\text{mm}$

$= 3.142\ \text{mm}^3$

*Mass = volume * density*

$= 3.142 \times 10^{-3} * 8.96$ (density of copper is 8.96 gm/cm^3)

$= 0.0281486$ gm.

(0.0281486/0.9046 = 0.03, 3% of total mass is coming under the localized heat)

The mass will act both sides of the armature which was in contact with rails. So, the complete mass is takes as 0.0281486

So, the temperature value will be

$$Q = mC\delta t$$

$$40.5 = 0.0281486 * 0.385 * \delta t$$

(Since, temperature is calculated by taking energy loss only one side of the contact.)

$$\delta t = 3737\ °c$$

And, room temperature is 36 °c, so the final temperature induced in the system is 3701°c, which is very high than the copper melting point (1084°c)

The visual images of voltage multiplier, capacitor bank and SCR series switch is used in this experiment are shown below:

Figure. 6.7: visual image of voltage multiplier

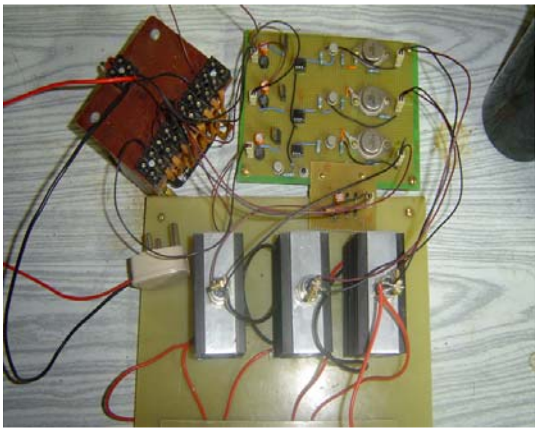


Figure. 6.8: visual image of SCR series switch

Figure (6.9): visual image of the capacitor bank used in the circuit

Conclusions:

- The complete energy is wasted in overcoming the static friction only.
- High temperature were produced which was caused to weld the armature to rails

6.2.2. Problems faced and Ways to overcome these problems:

- The armature used for this experiment is welded up to the rails.
- The armature is giving an upward movement from the rails.

- Welding of armature to rails: Welding is strictly a problem of current density and heat. The contact area between the armature and the rails must be as large as possible to keep the current density from welding the two together before the projectile can begin moving. The major difficulty in getting optimum rail to armature contact is the balancing act of projectile to rail surface is contact, aerodynamic stability of projectile, hear dissipation, and friction with rails.

Solution to these issues, which results in exceptional projectile performance are

- Using of the rectangular block shaped armature.
- To avoid the track welding, lubricate the track with graphite and having high fast pre-injection.
- Providing the initial velocity by means of external devices like compressed air/gas, mechanical injections system etc.

In the first set of experiments ball bearing have been used as armature, and it is making only point contact with the rails. Now the armature shape changed into rectangular block with required dimensions.

- Upward movement of the armature: The initial thrust will be always in upward direction only. And once the armature given as upward movement, it will loose contact with rails, which will not take further control, so there will no chance to produce any further acceleration. The rails design should be such that it should resist the initial upward movement of the armature. To obstruct the upward movement the rails should be enclosed and should be made as channel type design in which armature goes in forward freely.

- Requires the initial velocity: The armature should be forced into the rails with some initial velocity otherwise the following problems can occur:
    - If full power to be applied to a static armature, the rails and whatever between them would instantaneously melt under intense localized heat produced by ohmic heating.
    - High-speed delivery is required to overcome premature breakdown and welding problem also.
    - The electrical energy stored in capacitor banks is wasted to accelerate the projectile during the initial position.

To overcome this problem, many designs call for a mechanical injection system to give the projectile forward motion before it comes in contact with the rails and currents. If an injection system is desired, there are a number of ways to “squirt” the projectile into the rails. For this purpose spring-loaded, centrifugal, compressed air methods can be used.

- Compressed gas is far more efficient and economical way of pre-accelerating the projectile until it starts moving at speeds where electrical accelerations makes more sense.

- Spring loaded launcher consisting if a bolt connected to fixed part with a spring on the bolt and a bloc on the end of spring to press against.

6.2.3. Experiments with less initial velocity:

Specifications for this experiment:

Voltage applied to in the circuit = 600 volts,

Capacitor bank used of value = 2.62 m. farads,

Armature used in the exp. = Aluminum block of 5.7mm x 5mm x 5mm dimensions

Rails used are made of = aluminum

Rail dimensions = 64mm x 6mm x 140mm

In second set of experiments, the energy is increased by increasing the capacitor value. Even though the voltage is reduced, due to the increment in the capacitor value the energy will be improved.

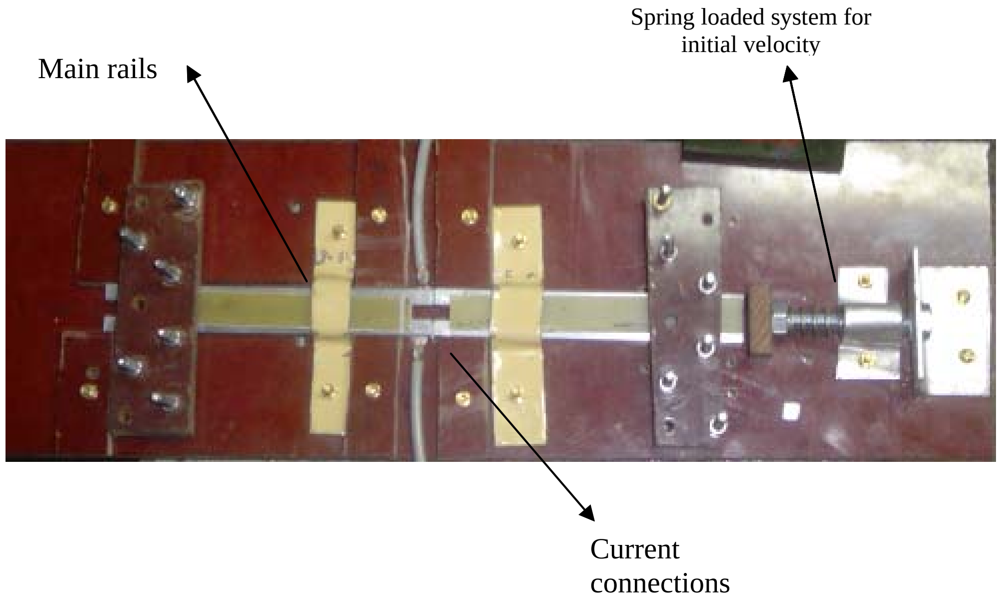


Figure 6.10: experimental set-up with low initial velocity

Observations:

- Due to the increment in energy there is a considerable change in the spark produced between the rails and armature.
- Heavy currents damaged the rails severely.
- The armature again get struck to the rails and welded in between the rails.

Conclusions:

- The spring-loaded system is failed to produce the required initial velocity to the armature. So, from these first two experiments it was concluded that the initial velocity is the major constraint, which decides the velocity produced in the armature and it should be enough sufficient to overcome the frictional force, which lies between the rails and armature.
- Compressed air or gas can be produced the required initial velocity to push the armature with more force than spring load into the rails and can be causes it to be further movement.

- The mechanical design will also play an important role in the performance of the railgun. The rail support should be such that the rails should not move due to the heavy force generating.

6.3. Experiments with higher initial velocity:

The complete designed parameters are shown in the chapter no.4 (refer 4.1). According to the dimensions designed, the rails were fabricated with copper. The complete housing for the copper rails was fabricated with Perspex. The cross section view and the complete set up diagram are shown below:

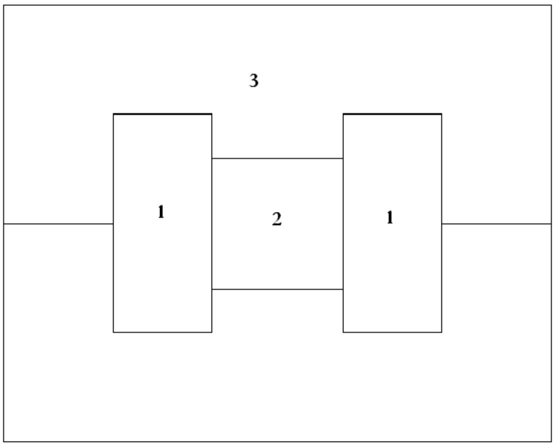


Figure 6.11: cross section of rail barrel

1. Copper rails, 2. Slot for armature, 3. Perspex rail housing

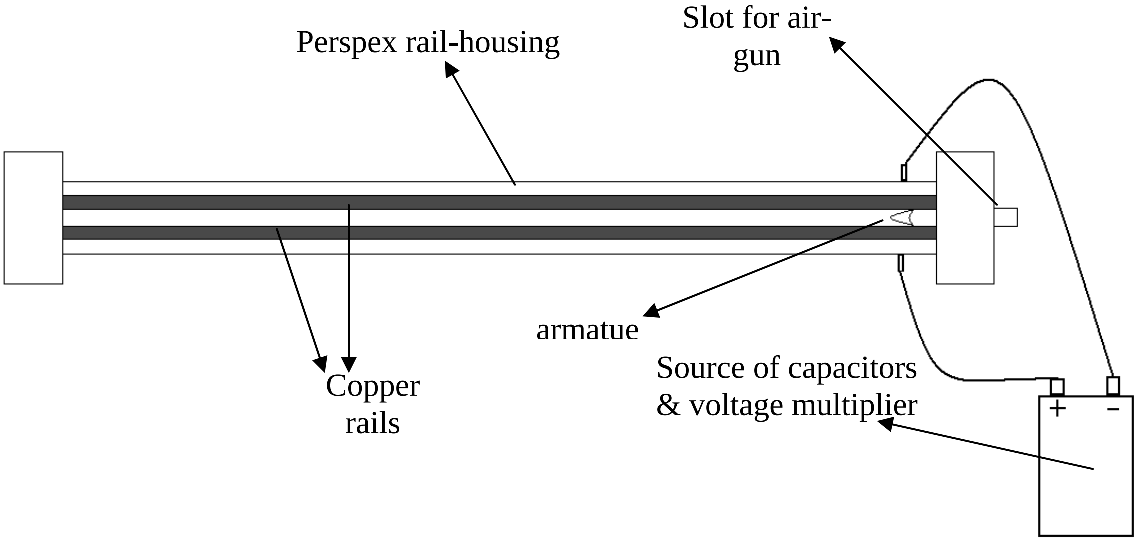


Figure 6.12: Figure showing the complete set-up of railgun with initial velocity

The visual images for the above cross-section and the velocity measurement set up are shown below:

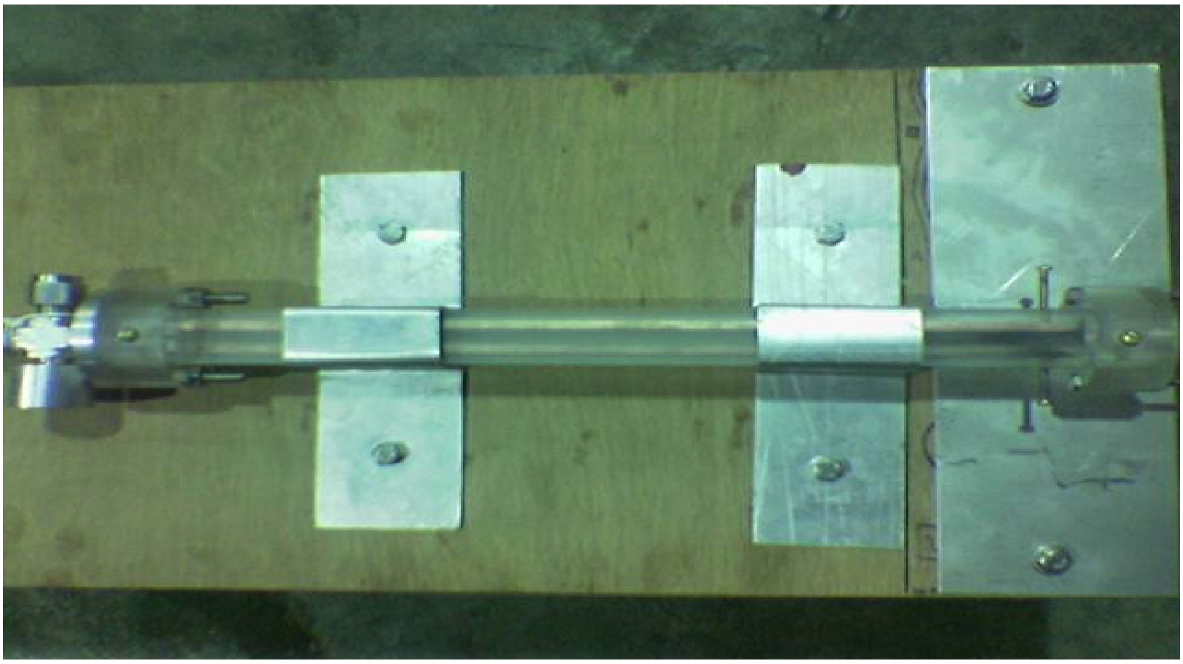


Figure 6.13: Rail support and complete railgun structure

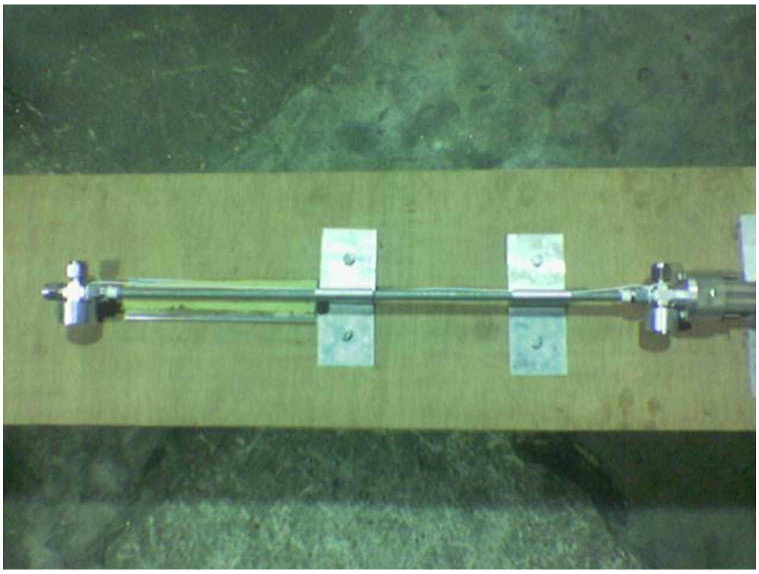


Figure 6.14: set up for velocity measurement

In these experiments the initial velocity is provided by an air-pistol. This air-pistol can provide velocities up to a level of 25 m/s. The initial velocity has been tested by using the velocity measurement circuit. The plot for the initial velocity and the calculation is shown below:

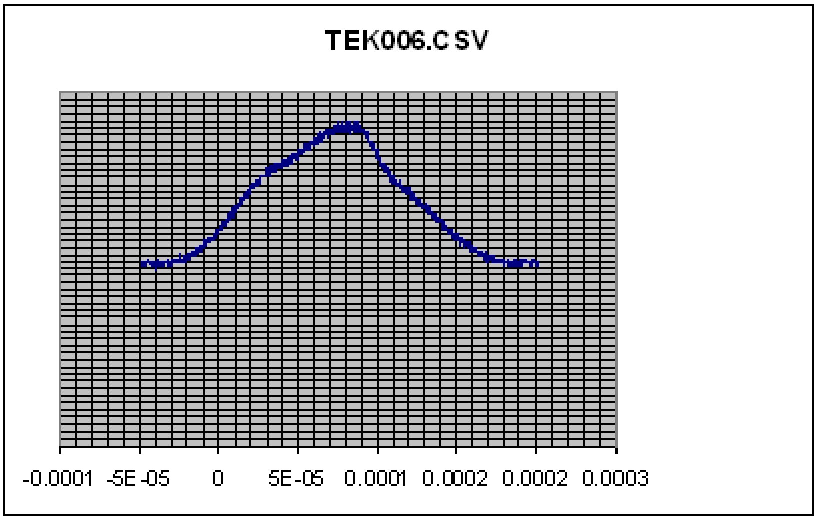


Figure 6.15: waveform showing the initial velocity.

The response time of the pulse is varying between 225 μ.sec. to 300 μs. The width of the photo detector is 5 mm. So, it has been determined that the initial (air pistol) velocity is as 16.66 m/s to 22.22 m/s.

The figures of armature and the device, which is used for giving of initial velocity, are also shown below:

Figure 6.16: Armature used in the experiments

6.3.1. Experiments with railgun at lower level of voltage:

Specifications for this experiment:

Rail dimensions = 4.5 X 10 X 300 mm^3

Armature dimensions = 6 mm dia at bottom and bullet shaped.

Voltage rating = 650 volts

Capacitors = 2.62 mf.

The energy of the complete system (from equation ½ CV^2) is increased to 450 joules. Initially, a voltage level of 600 volts only applied gradually to the system.

Observations:

The capacitors were not discharged properly and there is no improvement in the velocity of the pellet. With the same system it has tried several times, but there is no acceleration in the pellet. By increasing the voltage level from 600 volts to 650 volts, there was acceleration but not up to the expecting level. The cause for this failure of acceleration is that the voltage level of the 600 volts is not sufficient to break the micron level gap between the armature and the rails.

Conclusions:

- From this experiment it has been concluded that the voltage level should be such that it should break down the air gap between the armature and rails.
- Because current pulse is completely depending on the voltage level, and at lesser level the current level also less so, the problem of breakdown occurred.

6.3.2. Experiments by varying the voltage level

The velocity is depends upon the energy level applying in the rails. And this energy level is directly proportional to capacitor value and square of the voltage. The energy can be varied either by varying the voltage level or capacitor value. Here the results of experiments by varying the voltage level are given.

6.3.2.1. With voltage level of 1000 V:

Specifications for this experiment:

Rail dimensions = 4.5 X 10 X 300 mm^3
Armature dimensions = 6 mm dia at bottom and bullet shaped.
Voltage rating = 1300 volts
Capacitors = 120 μf.

Now, the capacitors were charged up to the voltage level of 1000 volts. After ejecting of the pellet from the barrel, the remaining voltage level in the system is 42 volts. The utilized voltage level 958 volts and hence the he energy supplied will be 110 joules.

Observations:

The response of the pulse is 200 µs. The velocity obtained is 25 m/s. The pulse period is shown in the following figure.

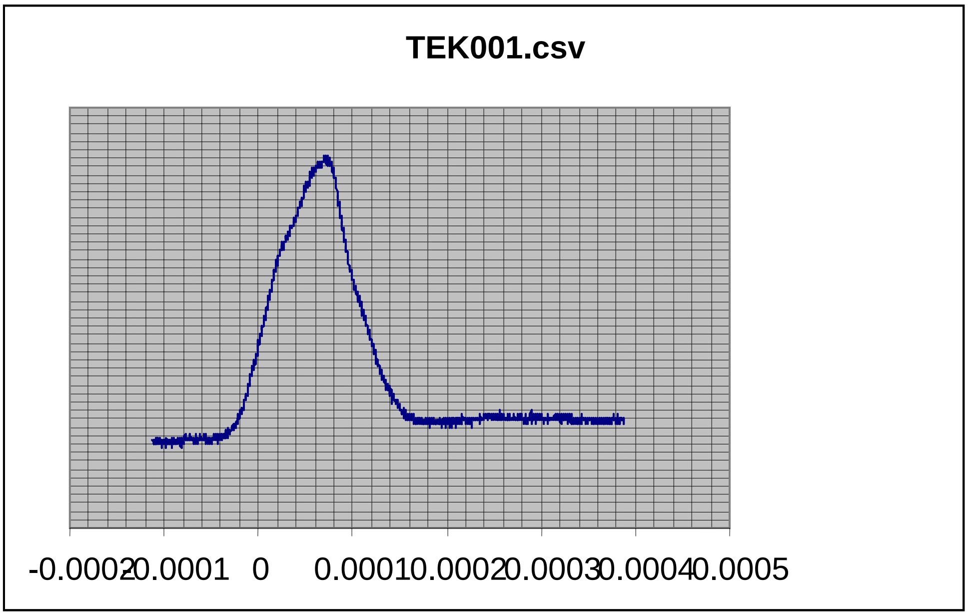


Figure 6.17: waveform explaining the velocity with primary source.

The firing of the pellet is continuing with the same level of voltage and same arrangement of capacitors. And the velocity is getting consistently. All the readings can be tabulated as follows:

Table 6.1: Results from exp at 1000 V level

Shot no.	Charged voltage (volts)	Remained voltage (volts)	Input energy (joules)	Response time of the pulse. (µs.)	Velocity (m/s)	Out put energy* (joules)	Efficiency (%)
1	1000	42	55.06	180	27.78	0.38	0.69
2	1150	48	72.8	180	27.78	0.38	0.52
3	1050	44	60.71	180	27.78	0.38	0.63
4	1000	40	55.29	180	27.78	0.38	0.70

The basic calculations for one shot are shown below:

Total applied voltage = 1000 V

Remained voltage = 42 V

Capacitor value = 120 µf

The input energy E_i = ½ CV^2

= ½ * 120 x 10^{-6} * $(1000\text{-}42)^2$

= 55.06 J

The pulse width of voltage pulse across the photo diode = 180 µs.

So, the velocity achieved = $5x10^{-3} \big/ 180^{-6}$

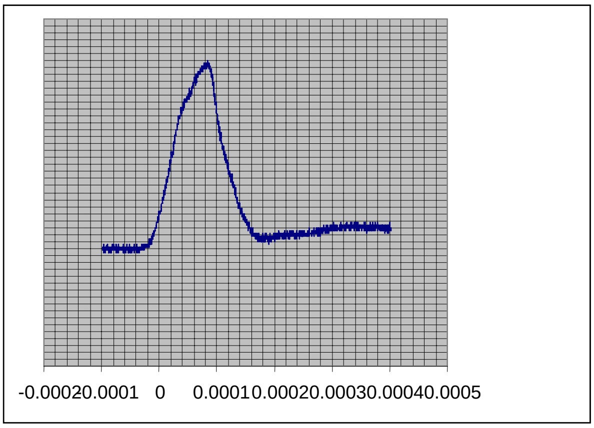
= 27.78 m/s

Output energy E_o= ½ m v^2

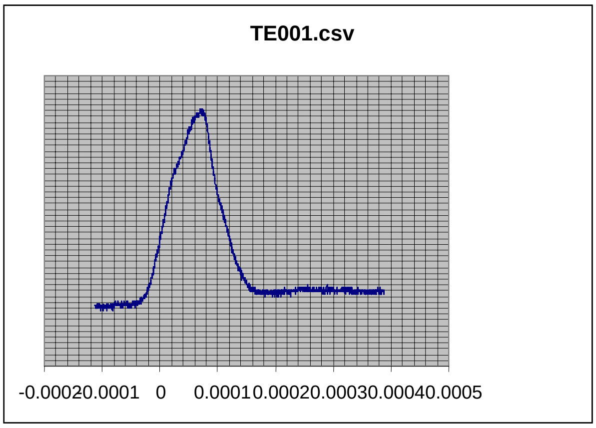
= ½ * 1 x 10^{-3} * 27.78^2

= 0.38 J

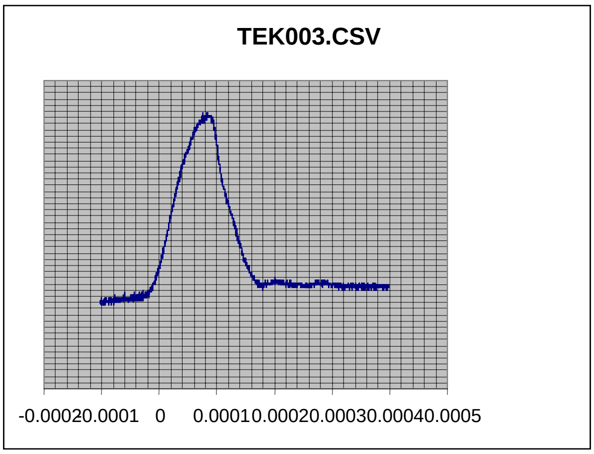
The efficiency = E_o / E_i = 0.69 %



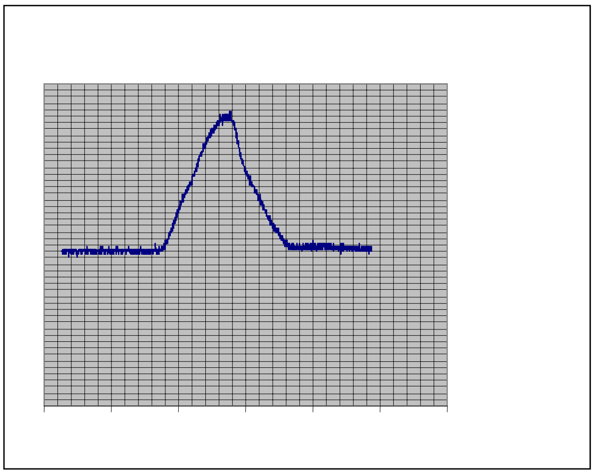
(a)


TE001.csv

(b)


TEK003.CSV

(c)



(d)

Figure 6.18: waveforms showing the velocity with 1300, 120 μ farad supply.

Conclusions:

- All the problems faced in the previous experiments like the welding and pitting of armature to the rails, upward motion of the armature were solved with this current set up of the railgun which is supported by the Perspex rail housing and the usage of air pistol for initial velocity.

- To obtain more velocity it is required to increase the energy level. It is possible either by increasing either voltage level or capacitor bank values.

6.3.2.2. At voltage level of 2000 V:

Specifications for this experiment:

Rail dimensions = 4.5 X 10 X 300 mm^3
Armature dimensions = 6 mm dia at bottom and bullet shaped.
Voltage rating = up to 2000 volts
Capacitors = 85 μf.

The existing voltage multiplier is of 2-stages only and it can give only 1300 volts level. To get more voltage level it is required to add two stages. Two more stages were added to obtain a voltage level of 2800 volts.

Observations:

Table 6.2: Results from exp at a voltage level of 2000 V

Shot no.	Charged voltage (volts)	Remained voltage (volts)	Input energy (joules)	Response time (μ.s.)	Expected velocity* (m/s)	Velocity (m/s)	Output energy (joules)	Efficiency (%)	Fig. no.
1	2000	42	162.9	50	127.63	100	5	3.086	TEK0054
2	2000	51	161.44	50	127.05	100	5	3.07	TEK0055
3	1500	42	90.35	80	95.05	62.5	2	2.21	TEK0056

* To calculate the expected velocity, the efficiency is assumed as 5%. Efficiency is energy efficiency, i.e. output energy/input energy

The calculations for one set of reading as shown below:

Shot no. 1: $C = 85\ \mu f$,

$V = 1958$ volts

Energy $= \frac{1}{2} CV^2$

$= \frac{1}{2}\ 85 * 10^{-6} * 1958^2$

$= 162.9$ J

By assuming 5% efficiency,

The output energy $=162.9 * 0.005$

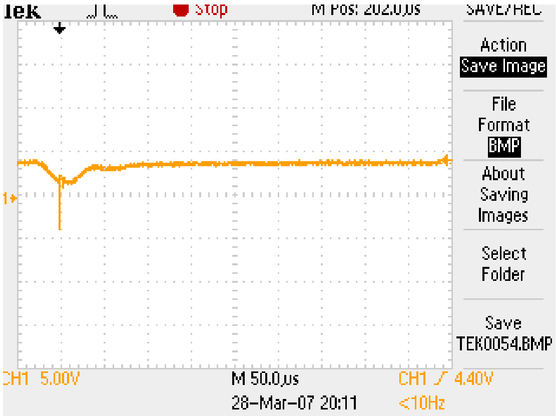
$= 8.145$ J.

Output energy, $= \frac{1}{2} mv^2$

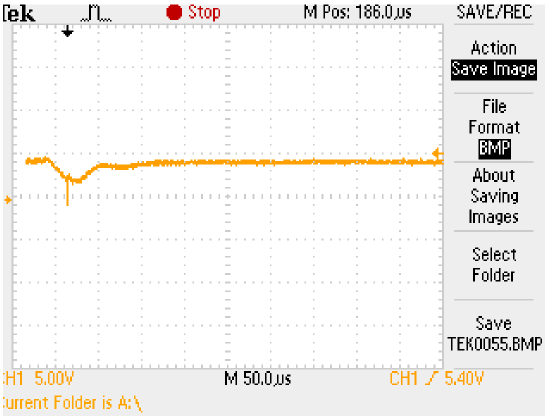
$8.145 = \frac{1}{2} * 1e\text{-}3 * v^2$ (mass of the bullet is 1 gram)

$v = 127.63$ m/s

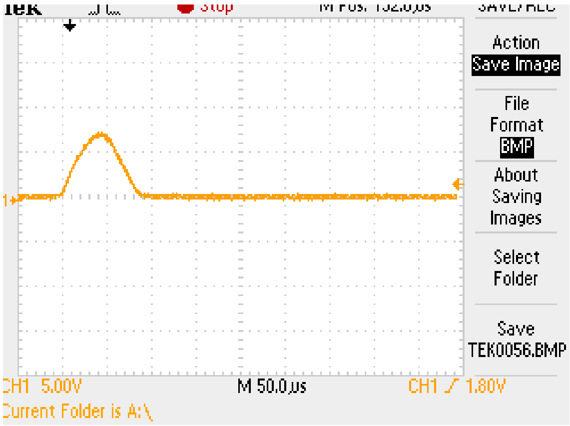
The various waveforms justifying the above table are shown in the following figure.



(a) TEK0054



(b) TEK0055



(c) TEK0056

Figure 6.19: Waveforms explaining the velocity in the experiment with higher voltage level.

- The armature was pierced into the one wall of a cardboard box with wall thickness of 3mm, which was kept at a distance of 6.5 m.
- A good spark was observed while firing the armature in the rails.

Conclusions:

- By improving the voltage level, there was a considerable change in velocity.
- Efficiency of 3% was achieved.

6.3.2.3. Comparison of results for these different voltage levels:

Table 6.3. Comparison of results at various voltage levels

	at 1000 V	*at 1500 V*	*At 2000V*
Charged voltage level	1000V	1500V	2000V
Remained voltage level	42V	42V	42V
Input energy	52.29 J	90.35 J	162.9 J
Velocity achieved	27.78 m/s	62.5 m/s	100 m/s
Output energy	0.38 J	2 J	5 J
Efficiency	0.7 %	2.21 %	3.086 %

Conclusions:

- As the voltage increases, the velocity achieved is increased to expected level.
- Due to change in the velocity level, there is a considerable change in efficiency also.

6.4. Methods to improve the efficiency of the railgun system.

- Lot of energy is wasting in the resistive part of the system. The resistive loss is given by I^2Rt. As the applying current is in tens of kilo amperes, the energy loss in the resistance is more. To improve the efficiency the resistance should be decreased. But, as the mechanical system and capacitor bank is fixed according to the dimensions and calculations, it is not possible to reduce the resistance as required.
- Similarly, the loss in the inductive part also very high. ($1/2\ LI^2$), here the cable connected from the power source to rails forms the

inductance and it is not possible to further reduce the length of the cable as it is already in selected suitably.

- By applying the lubricant on the rails, which should be a good conductor, good acceleration can be achieved because this lubricant will act as a slide for the armature. So, the efficiency can be increased.

Graphite is selected as a lubricant material, and applied on the rail part.

6.5. Experiment by applying the graphite coating:

Specifications for this experiment:

Rail dimensions = 4.5 X 10 X 300 mm^3
Armature dimensions = 6 mm dia at bottom and bullet shaped.
Voltage rating = up to 2000 volts
Capacitors = 85 μf.
Lubricant applied on the rails is **Graphite.**

By applying the graphite coating and improving the voltage level to a small extent, efficiency may improve to some level. And now for these calculations, the improvement in efficiency is assumed as 20%. So, the theoretical calculations and the results obtained are matching near.

Observations:

Table 6.4. Results from exp by graphite lubrication

Sr. no.	*Charged voltage (volts)*	*Remained voltage (volts)*	*Response time (μs.)*	*Velocity (m\s)*	*Input energy (joules)*	*Output energy (joules)*	*Efficiency (%)*	*Theoretical velocity* (m/s)*
1	2120	42	25	200	184	20	10.86	271.29
2	2240	44	25	200	204	20	9.86	285.66
3	2080	44	25	200	176	20	11.36	265.33
4	2340	36	25	200	224.2	20	8.92	299.47
5	2400	42	15	333.33	236	55.5	23.5	307.24

Here the electrical efficiency is calculated as follows:

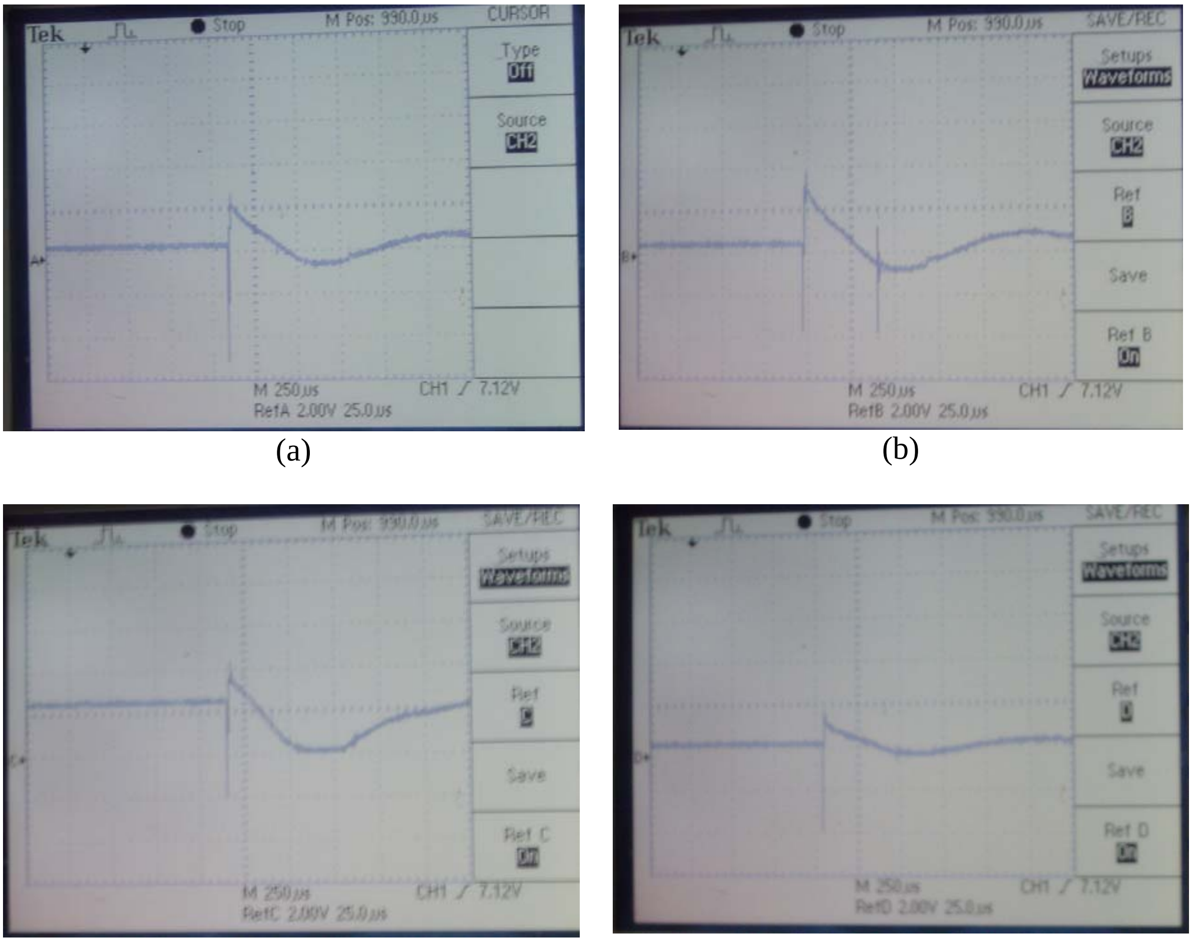
$$\eta = E_o/E_i$$

$= 55.55/236$ (reading no.5)

$= 23.5\%$

* To calculate the theoretical velocity the efficiency is assumed as 20%

The plots to justify the above results are shown below:



(a) (b)

(c) (d)

Figure 6.20: waveforms justifying the velocity

- The armature was pierced into the both walls of a card-board box with wall thickness of 3mm which is kept at a distance of 6.5 m.
- A bright spark was observed while firing the armature in the rails.
- Due to the high currents the contact of current connections were damaged.

figure 6.21: figure showing the damaged armature after acceleration

Figure 6.22: figure showing the damaged rails after acceleration of pellet

Conclusions:

- Due to the graphite coating and small improvement in voltage level, the efficiency was improved from a range of 3% to 23.5%.

6.5.1. Comparison of results with and without applying the lubrication

Table 6.5. Comparison of results with and with out lubrications

	Without lubrication	With lubrication
Charged voltage level	2000 V	2120 V
Remained voltage level	42 V	42 V
Input energy	162.9 J	184 J
Velocity achieve61d	100 m/s	200 m/s
Output energy	5 J	20 J
Efficiency	3.086 %	10.86 %

Conclusions:

- By applying a lubrication coating on the rails, there was considerable change in velocity from 100 m/s to 200 m/s at the same voltage level.
- And efficiency also increased to 3.086 % to 10.086% at same voltage level

6.6. Current Calculations in the railgun:

In our experiments pulsed power supply is selected as power source for railgun. And the current and time period calculations for the pulsed power supply are given below:

The current relation is given by

$$I_{peak} = (0.763*V)/R_{load} \qquad \text{…………… (6.1)}$$

The time period depends upon the values of inductance and capacitance. And the equation for current is given by

$$t = 2*\pi*\sqrt{LC} \qquad \text{…………… (6.2)}$$

As the current is in kilo amperes, it is not easy to measure with the help of normal current meters. So, a shunt has been designed such that it will show the 2000 ampere level as a voltage of 5 volts. So, for this purpose the shunt has been prepared with the following specifications:

Shunt material is copper conductor (of round cross section)

Diameter of the copper wire (d) = 1.2m.m.

Length of the copper wire (l) = 17 cm.

Resistivity of the copper (ρ) = 16.78 nΩ-m

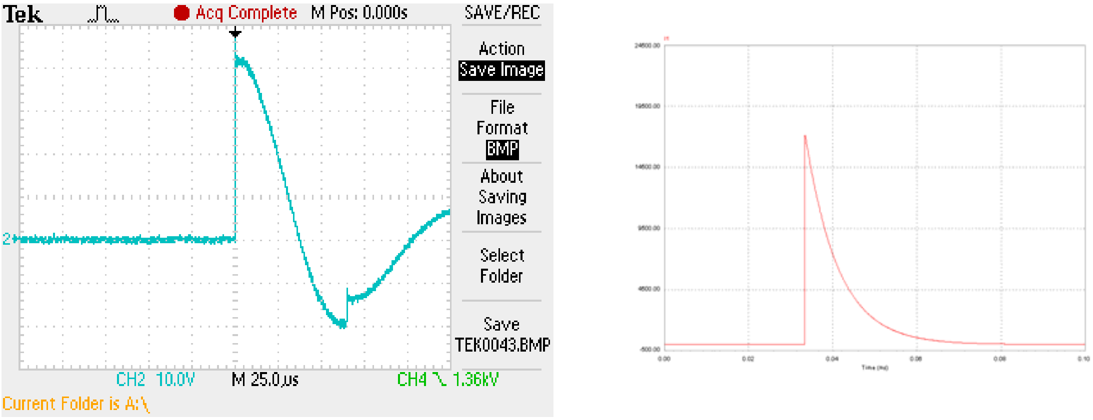
Area of cross-sections (a) = 1.13 mm^2

Resistance of the shunt (R) = $\rho\, l/a$ = 2.52 mΩ

And this shunt is connected in series with supply and load. By measuring the voltage drop across the shunt, the current value can be calculated as follows:

6.6.1. Current measurements at 1600 V level

With 1600 volts, capacitor bank of 85 μf, and a cabling inductance of 0.1 n. Henry, the practical current pulse got as shown below. According to eq. (5.1 & 6.2), the current pulse for 1600 volts will be has a peak value of 15.26 kA.



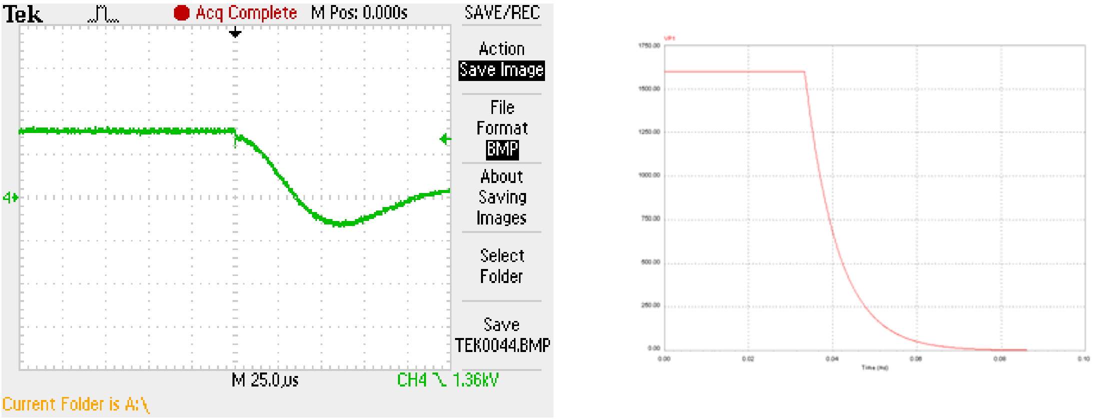
(a) practical waveform of current pulse
Scale: on x-axis 1 div = 25 µ.sec
on y-axis 1 div = 10 volts

(b) simulated output for current pulse
Scale: X-axis: 1 div = 0.02 m.sec
Y-axis: 1 div = 5 kA

Figure 6.23: comparison of simulated and practical current pulse for 1600V

So, the voltage peak across the shunt is 40volts, and the shunt value is 2.52mΩ, so, the current value is 15.87K.amps.

The voltage drop will also follow the current pulse, and the waveform is also shown.



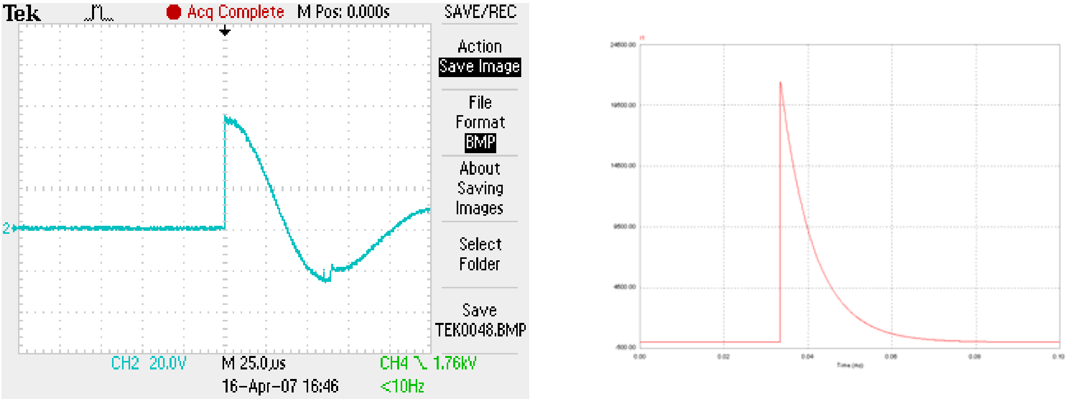
(a) practical output for voltage drop while injection of pellet
Scale: on x-axis 1 div = 25 µs
on y-axis 1 div = 1 kV

(b) simulated output for voltage drop while injection of pellet
Scale: on X-axis: 1 div = 0.02 m.sec
on Y-axis: 1 div = 250 volts

Figure 6.24: comparison of simulated and practical voltage waveforms at 1600V

6.6.2. Current measurements at 2000 V level

With 2000 volts, capacitor bank of 85 µf, and a cabling inductance of 0.1nH, the practical current pulse got as shown below. According to eq. (6.1 & 6.2), the current pulse for 2000 volts will be have a peak value of 25.00 kA.

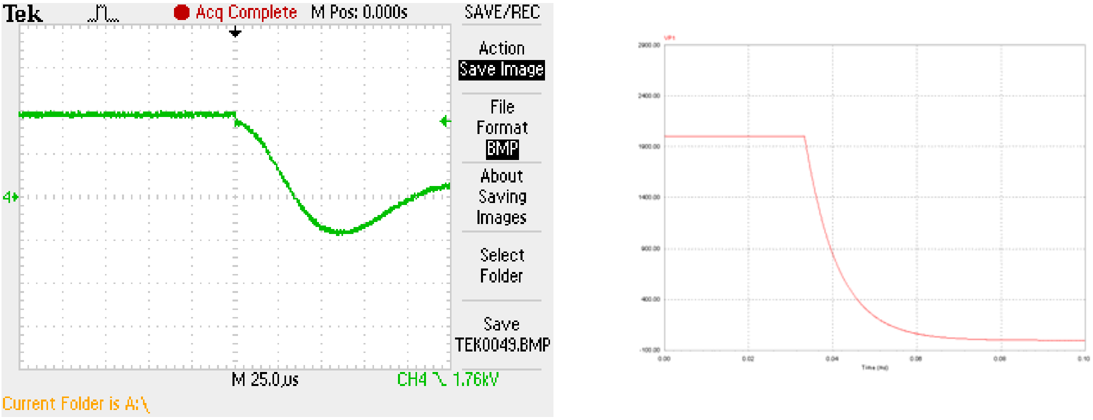


(a) practical waveform of current pulse
Scale: on x-axis 1 div = 25 µs
on y-axis 1 div = 20 volts

(b) simulated output for current pulse
Scale: on X-axis: 1 div = 0.02 m.sec
on Y-axis: 1 div = 5 kA

Figure 6.25: comparison of simulated and practical current pulse for 2500V

And, the voltage peak across the shunt is 55 volts, and the shunt value is 2.52mΩ, so, the current value is 22.22kA



(a) practical output for voltage drop while injection of pellet
Scale: on x-axis: 1 div = 25 μs
on y-axis: 1 div = 1 kV

(b) simulated output for voltage drop while injection of pellet
Scale: on X-axis: 1 div = 0.02 m.sec.
on Y-axis: 1 div = 500 volts

Figure 6.26: comparison of simulated and practical voltage waveforms at 2500V

Conclusions:

- Due to the reverse charging of the capacitors the current pulse and the voltage curve are going into negative direction.
- Simulated and practical results are matching properly.

Chapter 7

Conclusions & Future Scope

A complete railgun model was designed and fabricated according to the design. And various experiments with different power supply ranges and using separate methods were performed. Both power supply and the mechanical design plays important roles in the performance of the railgun. For the experiments an air-gun which can provide 25m/s velocity is used to provide initial velocity. In various experiments the velocities up to the level of 330 m/s was achieved. To avoid the problems like welding and pitting of armature to the rails, sufficient initial velocity is very important. As mentioned earlier, he initial velocity is provided by using an air-gun. To improve the efficiency, various methods like reducing the system resistance, inductance and applying the lubrications to the rails are in usage. In these experiments, the graphite lubrication method is used for efficiency improvement and got success to get highest efficiency of 23.85%. Along with energy, the level of voltage is also an important factor to breakdown the micron level gap between the rails and armature. At lesser level it is not possible to achieve the above thing. The current calculations, simulation results are exactly matching with the practical results.

Future Scope:

Future scope of this project is, by using this railgun set up the pellet injection should be tested. For pellet injection system, velocities up to a level of 1500m/s are required. For this purpose the power supply design should be changed to achieve the velocity of near to the level accordingly. In pellet injection system with railgun, the armature will contain hydrogen pellets, and this armature guides the hydrogen pellets into the fusion device. For this purpose the railgun set up should be made more compact according to the fusion device.

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APPENDIX-A

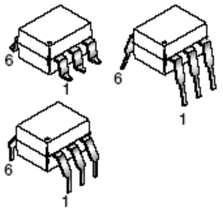
Data sheets used in the circuits: Data Sheet Of Phototransistor Opto-coupler:

FAIRCHILD
SEMICONDUCTOR®

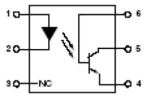
GENERAL PURPOSE 6-PIN PHOTOTRANSISTOR OPTOCOUPLERS

4N25	**4N26**	**4N27**	**4N28**	**4N35**	**4N36**
4N37	**H11A1**	**H11A2**	**H11A3**	**H11A4**	**H11A5**

WHITE PACKAGE (-M SUFFIX)

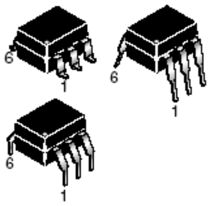


SCHEMATIC



PIN 1. ANODE
2. CATHODE
3. NO CONNECTION
4. EMITTER
5. COLLECTOR
6. BASE

BLACK PACKAGE (NO -M SUFFIX)



DESCRIPTION

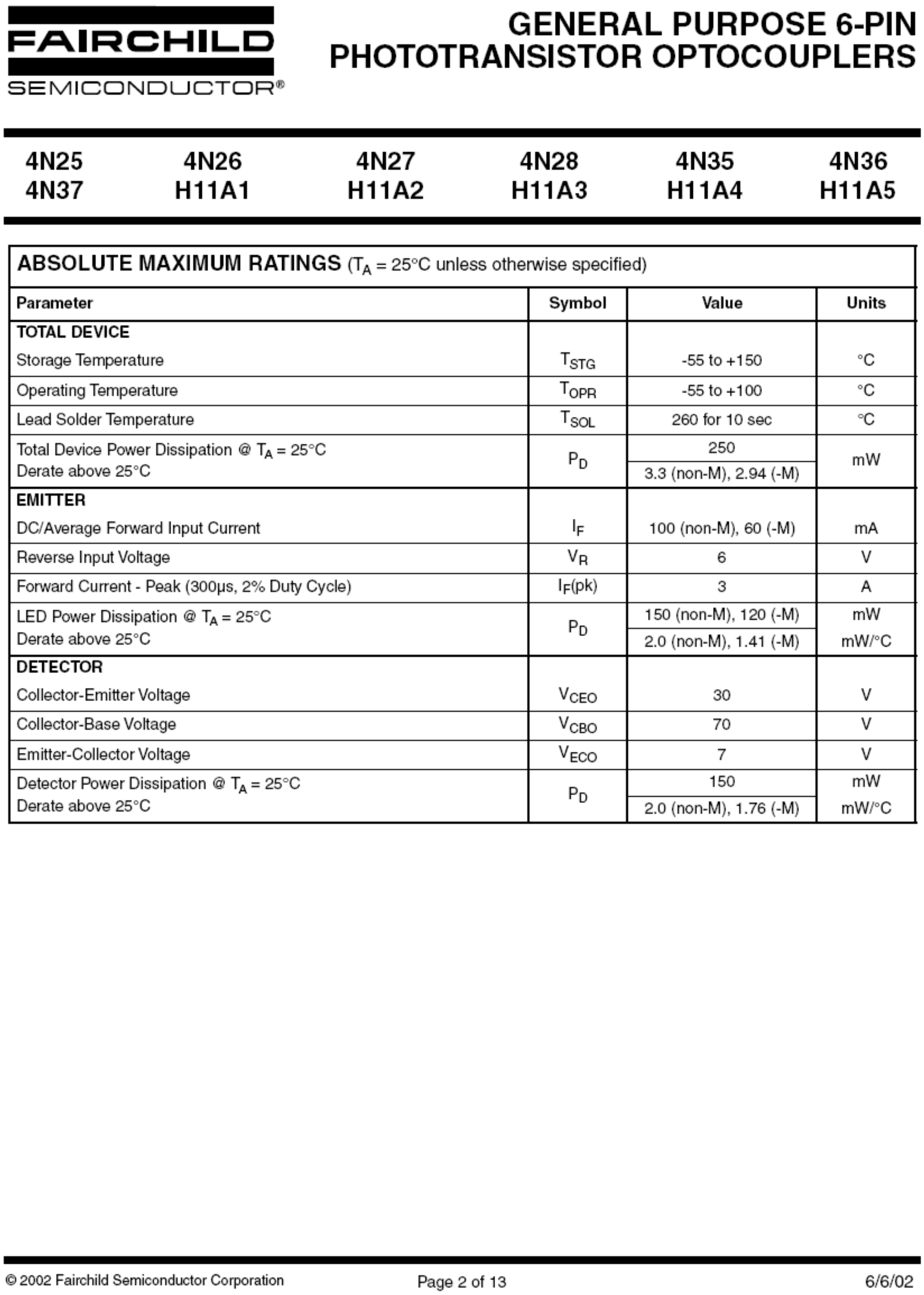
The general purpose optocouplers consist of a gallium arsenide infrared emitting diode driving a silicon phototransistor in a 6-pin dual in-line package.

FEATURES

- Also available in white package by specifying -M suffix, eg. 4N25-M
- UL recognized (File # E90700)
- VDE recognized (File # 94766)
  - Add option V for white package (e.g., 4N25V-M)
  - Add option 300 for black package (e.g., 4N25.300)

APPLICATIONS

- Power supply regulators
- Digital logic inputs
- Microprocessor inputs



FAIRCHILD SEMICONDUCTOR®

GENERAL PURPOSE 6-PIN PHOTOTRANSISTOR OPTOCOUPLERS

4N25	**4N26**	**4N27**	**4N28**	**4N35**	**4N36**
4N37	**H11A1**	**H11A2**	**H11A3**	**H11A4**	**H11A5**

ABSOLUTE MAXIMUM RATINGS (T_A = 25°C unless otherwise specified)

Parameter	Symbol	Value	Units
TOTAL DEVICE			
Storage Temperature	T_{STG}	-55 to +150	°C
Operating Temperature	T_{OPR}	-55 to +100	°C
Lead Solder Temperature	T_{SOL}	260 for 10 sec	°C
Total Device Power Dissipation @ T_A = 25°C Derate above 25°C	P_D	250 3.3 (non-M), 2.94 (-M)	mW
EMITTER			
DC/Average Forward Input Current	I_F	100 (non-M), 60 (-M)	mA
Reverse Input Voltage	V_R	6	V
Forward Current - Peak (300µs, 2% Duty Cycle)	I_F(pk)	3	A
LED Power Dissipation @ T_A = 25°C Derate above 25°C	P_D	150 (non-M), 120 (-M) 2.0 (non-M), 1.41 (-M)	mW mW/°C
DETECTOR			
Collector-Emitter Voltage	V_{CEO}	30	V
Collector-Base Voltage	V_{CBO}	70	V
Emitter-Collector Voltage	V_{ECO}	7	V
Detector Power Dissipation @ T_A = 25°C Derate above 25°C	P_D	150 2.0 (non-M), 1.76 (-M)	mW mW/°C

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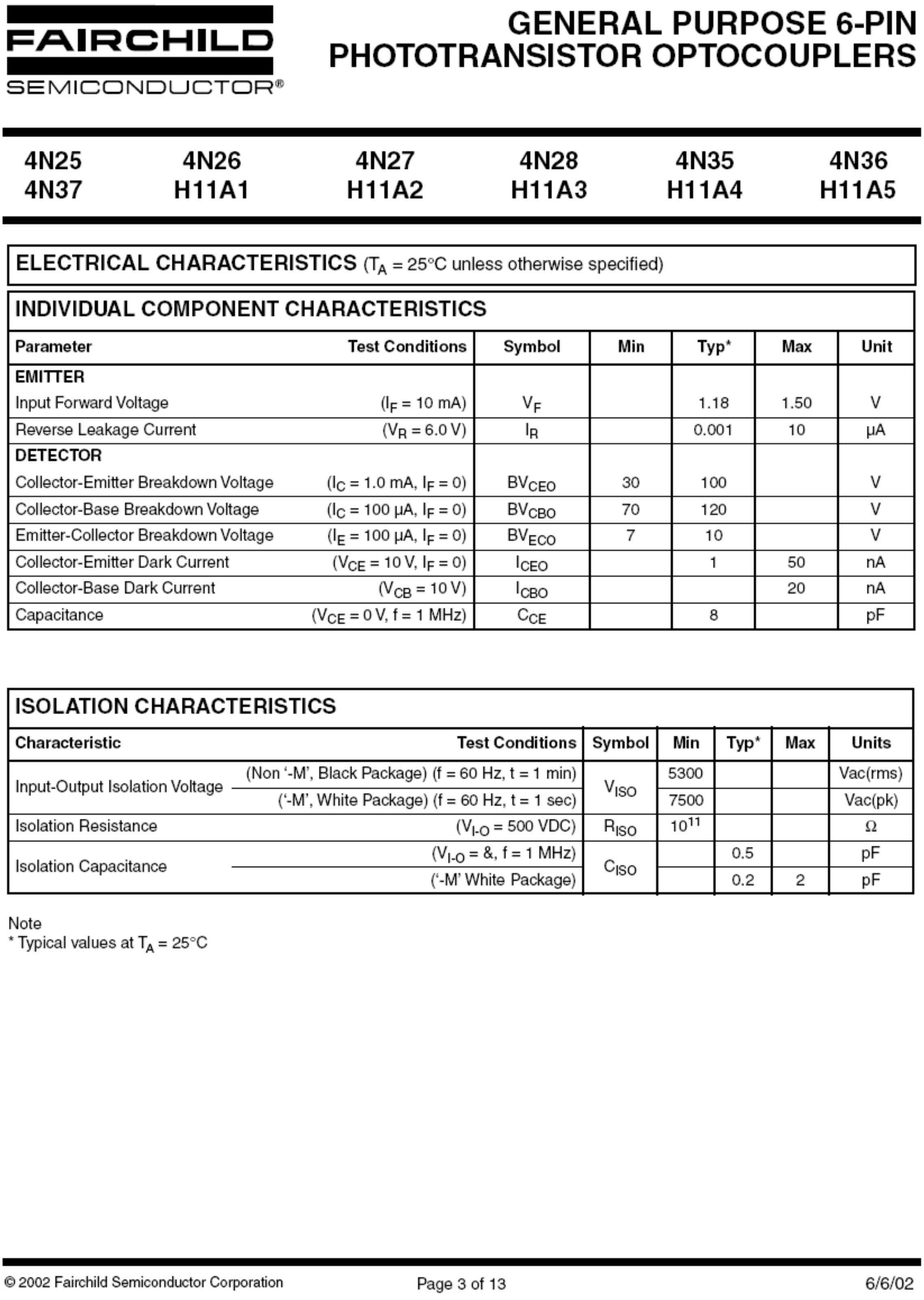

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GENERAL PURPOSE 6-PIN PHOTOTRANSISTOR OPTOCOUPLERS

4N25	**4N26**	**4N27**	**4N28**	**4N35**	**4N36**
4N37	**H11A1**	**H11A2**	**H11A3**	**H11A4**	**H11A5**

ELECTRICAL CHARACTERISTICS (T_A = 25°C unless otherwise specified)

INDIVIDUAL COMPONENT CHARACTERISTICS

Parameter	Test Conditions	Symbol	Min	Typ*	Max	Unit
EMITTER						
Input Forward Voltage	(I_F = 10 mA)	V_F		1.18	1.50	V
Reverse Leakage Current	(V_R = 6.0 V)	I_R		0.001	10	µA
DETECTOR						
Collector-Emitter Breakdown Voltage	(I_C = 1.0 mA, I_F = 0)	BV_{CEO}	30	100		V
Collector-Base Breakdown Voltage	(I_C = 100 µA, I_F = 0)	BV_{CBO}	70	120		V
Emitter-Collector Breakdown Voltage	(I_E = 100 µA, I_F = 0)	BV_{ECO}	7	10		V
Collector-Emitter Dark Current	(V_{CE} = 10 V, I_F = 0)	I_{CEO}		1	50	nA
Collector-Base Dark Current	(V_{CB} = 10 V)	I_{CBO}			20	nA
Capacitance	(V_{CE} = 0 V, f = 1 MHz)	C_{CE}		8		pF

ISOLATION CHARACTERISTICS

Characteristic	Test Conditions	Symbol	Min	Typ*	Max	Units
Input-Output Isolation Voltage	(Non '-M', Black Package) (f = 60 Hz, t = 1 min)	V_{ISO}	5300			Vac(rms)
	('-M', White Package) (f = 60 Hz, t = 1 sec)		7500			Vac(pk)
Isolation Resistance	(V_{I-O} = 500 VDC)	R_{ISO}	10^{11}			Ω
Isolation Capacitance	(V_{I-O} = &, f = 1 MHz)	C_{ISO}		0.5		pF
	('-M' White Package)			0.2	2	pF

Note
* Typical values at T_A = 25°C

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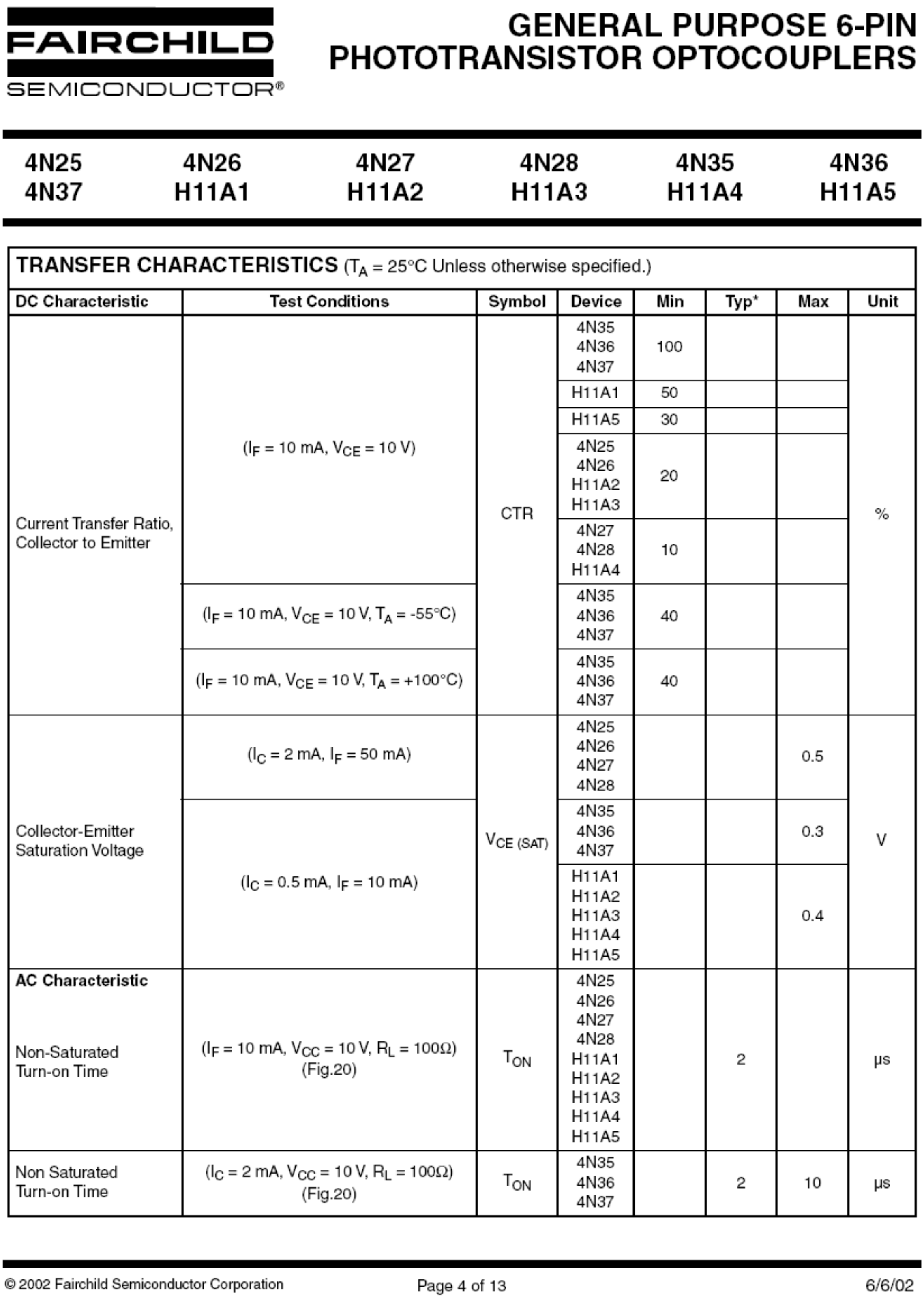

FAIRCHILD
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GENERAL PURPOSE 6-PIN PHOTOTRANSISTOR OPTOCOUPLERS

4N25 4N26 4N27 4N28 4N35 4N36
4N37 H11A1 H11A2 H11A3 H11A4 H11A5

TRANSFER CHARACTERISTICS (T_A = 25°C Unless otherwise specified.)

DC Characteristic	Test Conditions	Symbol	Device	Min	Typ*	Max	Unit
Current Transfer Ratio, Collector to Emitter	(I_F = 10 mA, V_{CE} = 10 V)	CTR	4N35 4N36 4N37	100			%
			H11A1	50			
			H11A5	30			
			4N25 4N26 H11A2 H11A3	20			
			4N27 4N28 H11A4	10			
	(I_F = 10 mA, V_{CE} = 10 V, T_A = -55°C)		4N35 4N36 4N37	40			
	(I_F = 10 mA, V_{CE} = 10 V, T_A = +100°C)		4N35 4N36 4N37	40			
Collector-Emitter Saturation Voltage	(I_C = 2 mA, I_F = 50 mA)	$V_{CE\ (SAT)}$	4N25 4N26 4N27 4N28			0.5	V
	(I_C = 0.5 mA, I_F = 10 mA)		4N35 4N36 4N37			0.3	
			H11A1 H11A2 H11A3 H11A4 H11A5			0.4	
AC Characteristic Non-Saturated Turn-on Time	(I_F = 10 mA, V_{CC} = 10 V, R_L = 100Ω) (Fig.20)	T_{ON}	4N25 4N26 4N27 4N28 H11A1 H11A2 H11A3 H11A4 H11A5		2		μs
Non Saturated Turn-on Time	(I_C = 2 mA, V_{CC} = 10 V, R_L = 100Ω) (Fig.20)	T_{ON}	4N35 4N36 4N37		2	10	μs

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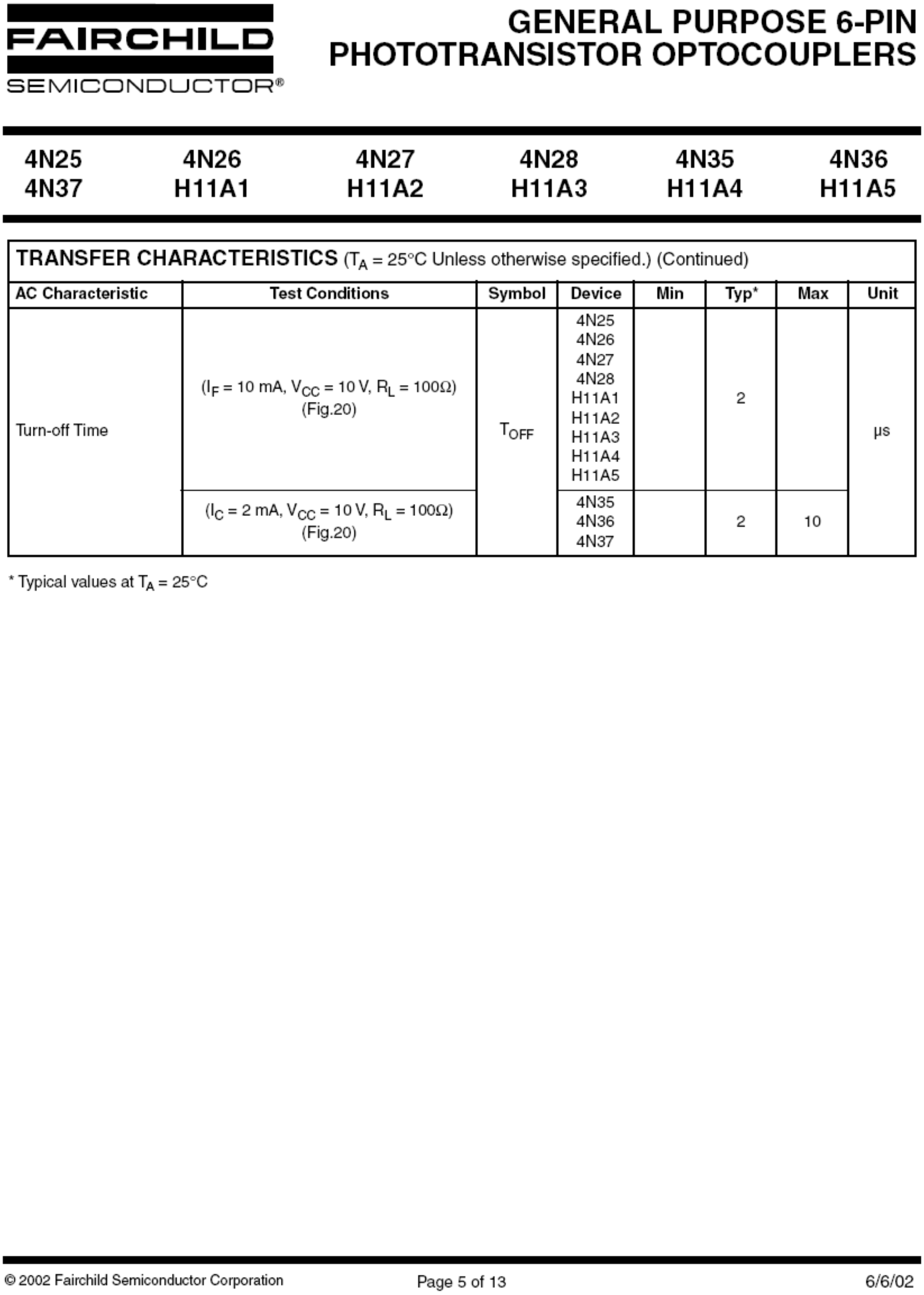

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GENERAL PURPOSE 6-PIN PHOTOTRANSISTOR OPTOCOUPLERS

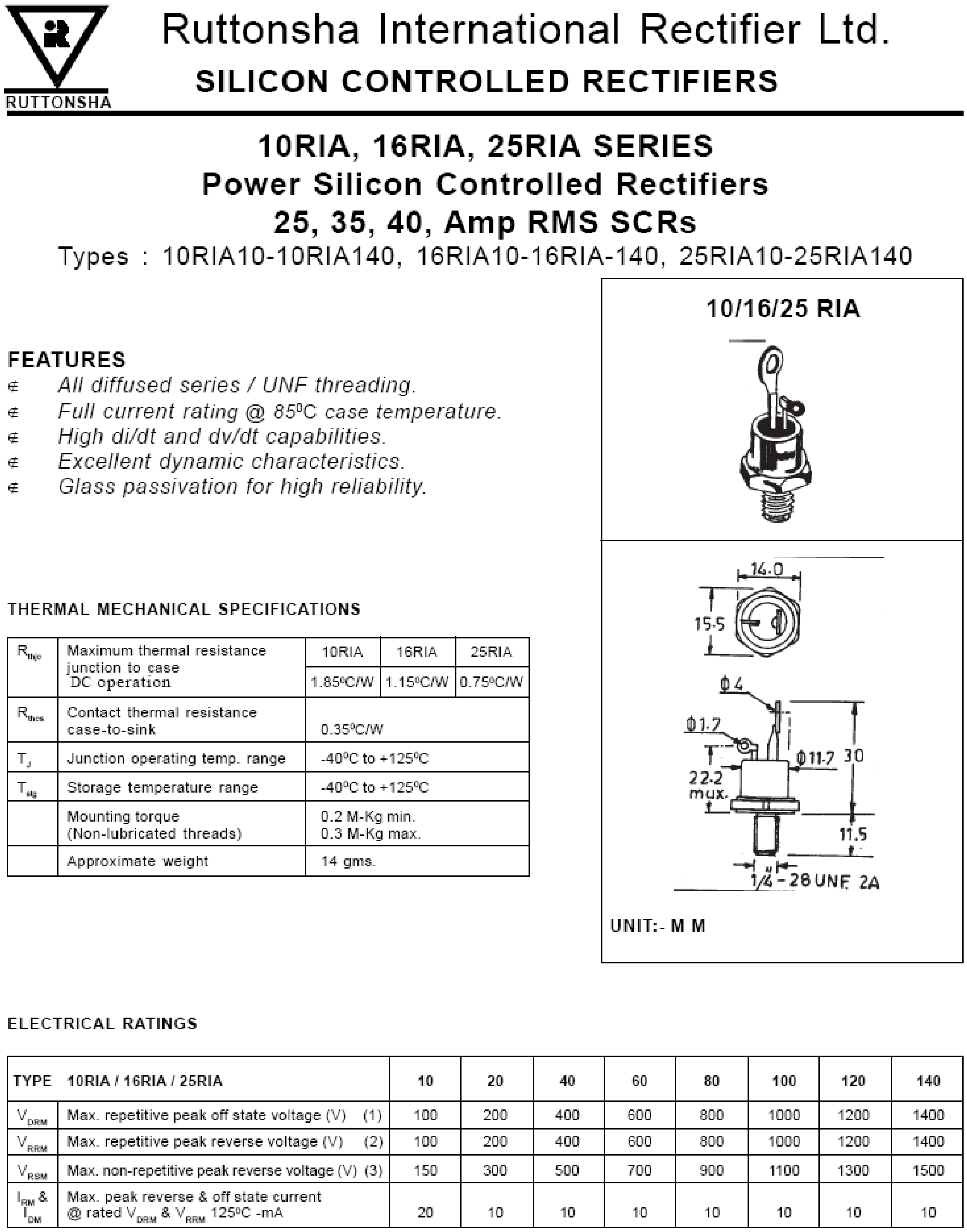
4N25 4N26 4N27 4N28 4N35 4N36
4N37 H11A1 H11A2 H11A3 H11A4 H11A5

TRANSFER CHARACTERISTICS (T_A = 25°C Unless otherwise specified.) (Continued)

AC Characteristic	Test Conditions	Symbol	Device	Min	Typ*	Max	Unit
Turn-off Time	(I_F = 10 mA, V_{CC} = 10 V, R_L = 100Ω) (Fig.20)	T_{OFF}	4N25 4N26 4N27 4N28 H11A1 H11A2 H11A3 H11A4 H11A5		2		μs
	(I_C = 2 mA, V_{CC} = 10 V, R_L = 100Ω) (Fig.20)		4N35 4N36 4N37		2	10	

* Typical values at T_A = 25°C

Appendix - B



Ruttonsha International Rectifier Ltd.

SILICON CONTROLLED RECTIFIERS

10RIA, 16RIA, 25RIA SERIES

Power Silicon Controlled Rectifiers

25, 35, 40, Amp RMS SCRs

Types : 10RIA10-10RIA140, 16RIA10-16RIA-140, 25RIA10-25RIA140

10/16/25 RIA

FEATURES

- *All diffused series / UNF threading.*
- *Full current rating @ 85⁰C case temperature.*
- *High di/dt and dv/dt capabilities.*
- *Excellent dynamic characteristics.*
- *Glass passivation for high reliability.*

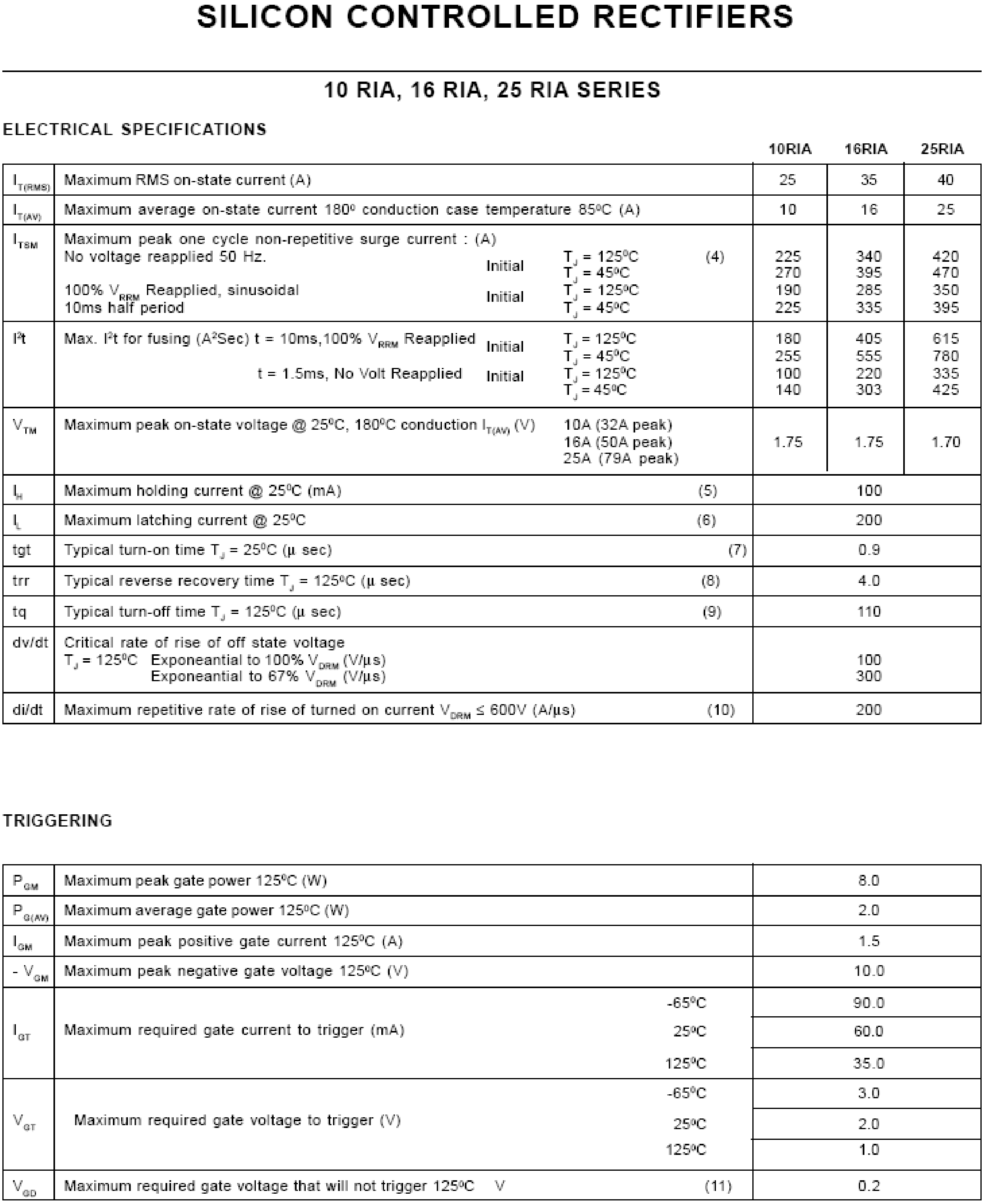
THERMAL MECHANICAL SPECIFICATIONS

R_{thjc}	Maximum thermal resistance junction to case DC operation	10RIA	16RIA	25RIA
		1.85⁰C/W	1.15⁰C/W	0.75⁰C/W
R_{thcs}	Contact thermal resistance case-to-sink	0.35⁰C/W		
T_J	Junction operating temp. range	-40⁰C to +125⁰C		
T_{stg}	Storage temperature range	-40⁰C to +125⁰C		
	Mounting torque (Non-lubricated threads)	0.2 M-Kg min. 0.3 M-Kg max.		
	Approximate weight	14 gms.		

UNIT:- M M

ELECTRICAL RATINGS

TYPE	10RIA / 16RIA / 25RIA	10	20	40	60	80	100	120	140
V_{DRM}	Max. repetitive peak off state voltage (V) (1)	100	200	400	600	800	1000	1200	1400
V_{RRM}	Max. repetitive peak reverse voltage (V) (2)	100	200	400	600	800	1000	1200	1400
V_{RSM}	Max. non-repetitive peak reverse voltage (V) (3)	150	300	500	700	900	1100	1300	1500
I_{RM} & I_{DM}	Max. peak reverse & off state current @ rated V_{DRM} & V_{RRM} 125⁰C -mA	20	10	10	10	10	10	10	10



SILICON CONTROLLED RECTIFIERS

10 RIA, 16 RIA, 25 RIA SERIES

ELECTRICAL SPECIFICATIONS

			10RIA	16RIA	25RIA
$I_{T(RMS)}$	Maximum RMS on-state current (A)		25	35	40
$I_{T(AV)}$	Maximum average on-state current 180° conduction case temperature 85°C (A)		10	16	25
I_{TSM}	Maximum peak one cycle non-repetitive surge current : (A) No voltage reapplied 50 Hz.	Initial T_J = 125°C (4)	225	340	420
		T_J = 45°C	270	395	470
	100% V_{RRM} Reapplied, sinusoidal 10ms half period	Initial T_J = 125°C	190	285	350
		T_J = 45°C	225	335	395
I^2t	Max. I^2t for fusing (A^2Sec) t = 10ms,100% V_{RRM} Reapplied	Initial T_J = 125°C	180	405	615
		T_J = 45°C	255	555	780
	t = 1.5ms, No Volt Reapplied	Initial T_J = 125°C	100	220	335
		T_J = 45°C	140	303	425
V_{TM}	Maximum peak on-state voltage @ 25°C, 180°C conduction $I_{T(AV)}$ (V)	10A (32A peak) 16A (50A peak) 25A (79A peak)	1.75	1.75	1.70
I_H	Maximum holding current @ 25°C (mA)	(5)	100		
I_L	Maximum latching current @ 25°C	(6)	200		
tgt	Typical turn-on time T_J = 25°C (µ sec)	(7)	0.9		
trr	Typical reverse recovery time T_J = 125°C (µ sec)	(8)	4.0		
tq	Typical turn-off time T_J = 125°C (µ sec)	(9)	110		
dv/dt	Critical rate of rise of off state voltage T_J = 125°C Exponeantial to 100% V_{DRM} (V/µs)		100		
	Exponeantial to 67% V_{DRM} (V/µs)		300		
di/dt	Maximum repetitive rate of rise of turned on current $V_{DRM} \leq 600V$ (A/µs)	(10)	200		

TRIGGERING

P_{GM}	Maximum peak gate power 125°C (W)		8.0
$P_{G(AV)}$	Maximum average gate power 125°C (W)		2.0
I_{GM}	Maximum peak positive gate current 125°C (A)		1.5
$-V_{GM}$	Maximum peak negative gate voltage 125°C (V)		10.0
I_{GT}	Maximum required gate current to trigger (mA)	-65°C	90.0
		25°C	60.0
		125°C	35.0
V_{GT}	Maximum required gate voltage to trigger (V)	-65°C	3.0
		25°C	2.0
		125°C	1.0
V_{GD}	Maximum required gate voltage that will not trigger 125°C V	(11)	0.2

Inductance Gradient Calculations:

The dimensions of rail: height = 10 mm

Width = 4.5 mm

Length = 300 mm

The dimensions of armature = 6 mm dia.

The equation to calculate the inductance gradient (*L'*) is

$$L_{wire-pair} \approx \frac{\mu_0 \mu_r}{\pi} \cosh^{-1} \frac{d}{2a}$$

Where d = distance between the rails

a = half of the width of the rails

Distance between the rails'*d*' is taken as 6 mm, which is the dia of the armature using in the experiment. And '*a*' is 2.25 mm.

L' = 0.228 µH/m (as per the equation given above)