<u>Rail Guns</u>

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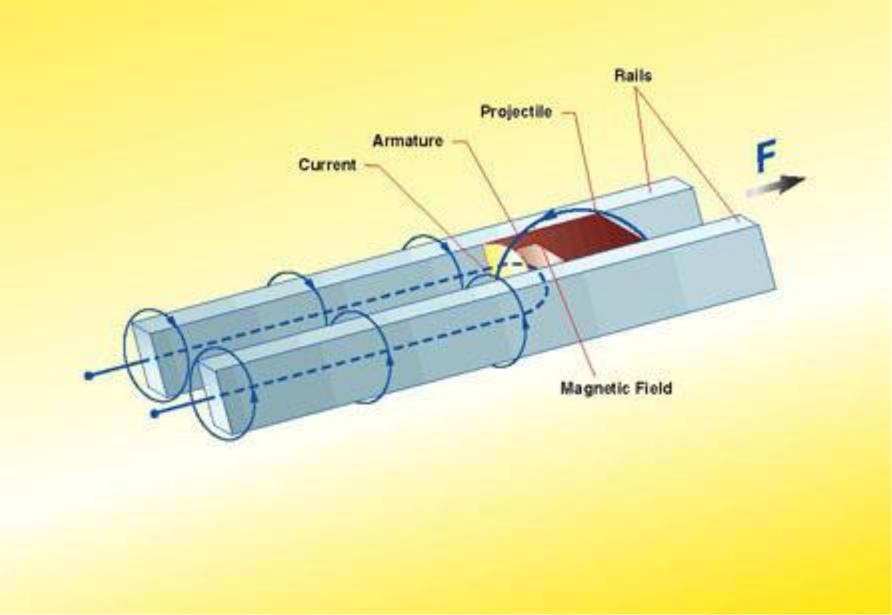
In recent years, research into rail gun technology has shown that the rail gun is a viable replacement for today's current ship-mounted artillery. The concept behind the rail gun is relatively simple, but the physics that drives it is much more complicated.

Rail Guns – Theory

Rail guns use a magnetic force known as the Lorentz force to accelerate projectiles to high velocities. The gun is set up with two conductive, parallel rails with a projectile in between them. The projectile is either enclosed in a conductive armature, loaded in front of a conductive armature, or is conductive and does not need an armature. A power supply is connected to provide the current which will create the magnetic field needed to accelerate the projectile (Harris).

The gun operates like an electrical circuit. Current flows from the power supply, down one of the rails, through the armature, and then out of the other rail. The resulting magnetic fields are shown in Figure 1. The result is a Lorentz force on the armature that accelerates the projectile to extremely high rates of speed (Barros).

Figure 1 – Rail Gun Model (Barros)



The Magnetic Field

In order to calculate the force that accelerates the projectile, the total magnetic field must be calculated first. To do this exactly, the field for infinitely small segments of wire (current elements) over the length of the rail will be summed. This will be done using an integral and the Biot-Savart Law. The Biot-Savart Law states that "the magnetic field $d\vec{B}$ produced by the current element $Id\vec{l}$ is:

$$d\vec{B} = \frac{\mu_0}{4\pi}\,\frac{I(d\vec{l}\,x\,\vec{r})}{r^3}$$

where $\vec{r}$ is the vector from the current element to the location where the field is computed." (Stewart, p.266) The variable *r* is the length of $\vec{r}$ and μ_0, the permeability of free space is the constant $4\pi \text{ x } 10^{-7}\ \frac{\text{Tm}}{\text{A}}$.

To begin the computation, the magnetic field from an arbitrary point *i* will be calculated at point P (representing the center of the armature). In order to do the integral, the equation must be written in terms of only constants (variables that don't change) and x variables. It is easiest to solve for the cross product $d\vec{l}\,x\,\vec{r}$ before solving for anything. In order to do that, consider the following picture looking down at one of the rails (point P is directly between the two rails):

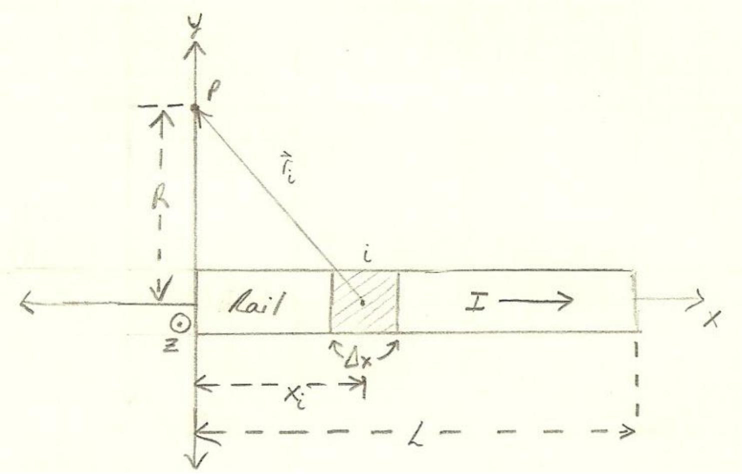


Figure 2 – Rail Diagram

Note that the z-axis goes out the page, towards the reader, perpendicular to the surface area of the page.

Since $d\vec{l}$ represents the length the current element, and the shaded region is the element producing the current for that given location, $d\vec{l}$ is just $\Delta x\hat{x}$. Written as a three dimensional vector, $(\hat{x}, \hat{y}, \hat{z})$, from the beginning of the segment to the end, it would be $(\Delta x, 0, 0)$, because there is no change in Y or Z components. The vector $\vec{r}$ is the vector from the current element, to the point being calculated. To get to point P from i, the line goes back x_i and up R. Therefore, $\vec{r} = (-x_i, R, 0)$.

Now that $d\vec{l}$ and $\vec{r}$ are known, the cross-product can be computed. By definition of cross-products in Cartesian Coordinates (standard x, y, z) (Stewart, p. 262):

$$\vec{C} = \vec{A} \text{ x } \vec{B} = (A_yB_z - A_zB_y)\hat{x} + (A_zB_x - A_xB_z)\hat{y} + (A_xB_y - A_yB_x)\hat{z}$$

Substituting in the values found above yields (note that all of the terms have at least one zero in them except for A_xB_y , so that term is the only one left):

$$d\vec{l} \text{ x } \vec{r} = (0)X + (0)Y + (\Delta xR)Z = (\Delta xR)Z = (0, 0, \Delta xR)$$

The original equation simplifies to:

$$d\vec{B} = \frac{\mu_0}{4\pi}\,\frac{I(d\vec{l}\,x\,\vec{r})}{r^3} = \frac{\mu_0}{4\pi}\,\frac{I(\Delta x R)\hat{z}}{r^3}$$

The next step is to solve for *r,* the distance of the vector $\vec{r}$. This can be solved by using the Pythagorean theorem (it works the same with three coordinates as it does with two):

$$r = \sqrt{\mathrm{X}^2 + \mathrm{Y}^2 + \mathrm{Z}^2} = \sqrt{x_\mathrm{i}^2 + \mathrm{R}^2}$$

Substitute in that value for *r*:

$$d\vec{B} = \frac{\mu_0}{4\pi}\,\frac{I(\Delta x R)\hat{z}}{\sqrt{x_\mathrm{i}^2 + \mathrm{R}^2}^{\,3}}$$

The equation above represents the magnetic field of an infinitely small portion of current centered at the point i. To find the total magnetic force at point P, the magnetic force of each infinitely small segment of current must be added together.

$$\vec{B} = \sum_i \mathrm{B_i}\,\hat{z} = \frac{\mu_0}{4\pi}\,\frac{I(\Delta x R)\hat{z}}{\sqrt{x_\mathrm{i}^2 + \mathrm{R}^2}^{\,3}}$$

Convert this to an integral that goes from 0 to L (L being the length of the rail):

$$\vec{B} = \int_0^L \frac{\mu_0}{4\pi}\,\frac{I(dxR)\hat{z}}{\sqrt{x^2 + \mathrm{R}^2}^{\,3}} = \frac{\mu_0 IR\hat{z}}{4\pi}\int_0^L \frac{dx}{\sqrt{x^2 + \mathrm{R}^2}^{\,3}}$$

The integral evaluates to (Massey[1]):

$$\vec{B} = \frac{\mu_0 IR\hat{z}}{4\pi}\,\frac{L}{\mathrm{R}^2\sqrt{L^2 + \mathrm{R}^2}} = \frac{\mu_0 IL\hat{z}}{4\pi\mathrm{R}\sqrt{L^2 + \mathrm{R}^2}}$$

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* Equation only verified with the source; all the work up to this point was done by the author

** Integral was not calculated by the author; it was computed using www.integrals.com where I is the current running through the rails, L is the length of the rails, and R is the distance from the center of the armature to the center of one of the rails.

The Lorentz Force

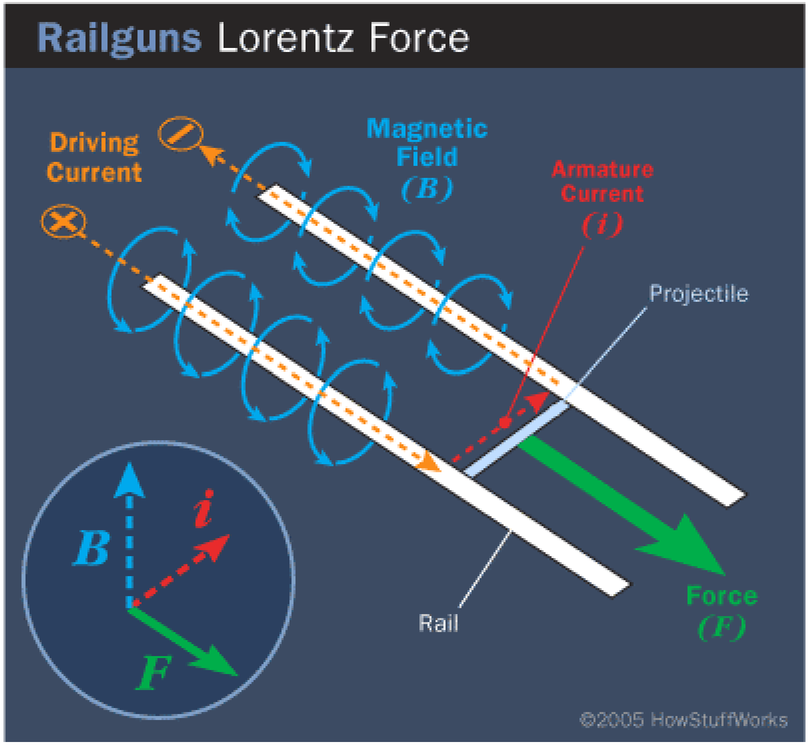

Figure 3 – Lorentz Force (Harris)

Magnet fields exert a force on any moving charge. They do not, however, exert a force on stationary charges. This does not mean that the armature has to be moving for the magnetic field to exert a field on it; current is the flow of charge. A magnetic field exerts force on any wire (or in this case, armature) carrying current (shown in Figure 3). The amount of force is given by the Lorentz Force (Stewart, p. 305):

$$d\vec{F} = Id\vec{l}\ x\ \vec{B}$$

Since the spacing between the rails, and thus the length of the armature, is relatively small, the magnetic field across the length of the wire can be considered constant for simplicity.

Therefore, the following equation can be used:

$$\overrightarrow{F} = I\vec{l}\, x\, \vec{B}$$

Note that $\vec{l}$ is the length of the armature and in the direction of current flow, not that of the rail. The current is the same as that which goes through both rails. It also must be noted that the magnetic field calculated previously was for one rail. The net field on the armature is double that. The length of the armature is 2R, considering that it is defined as the distance from the center of the armature to one of the rails. Since the current flows down in relation to Figure 2, the direction of the vector is negative. Therefore, the Lorentz Force is:

$$\overrightarrow{F} = I\left(-2R\hat{y} \text{ x } \frac{\mu_0 IL\hat{z}}{4\pi \mathrm{R}\sqrt{L^2 + \mathrm{R}^2}}\right) = \frac{-\mu_0 I^2 L\hat{\mathrm{x}}}{2\pi\sqrt{L^2 + \mathrm{R}^2}}$$

As the equation shows, the most influential part of obtaining a large force on a projectile is the current running through the rails.

Rail Guns – How They Work

Putting this theory into practice is relatively simple. The most basic rail gun needs two things: a way to keep the bullet moving straight through the rails and a means of running current through the gun. A barrel is used to keep the bullet moving straight, with the rails acting as the sides of the barrel so that the armature comes in direct contact with the rails. For small amounts of current, any power supply will supply enough current to launch a projectile. However, once the amounts of current get high enough to make the weapon lethal, it becomes a lot more complicated (Massey).

When large currents are utilized, capacitors become a necessity. Because the current only needs to run through the gun while the projectile is moving through the barrel, capacitors are effective. They can store large amounts of electric energy and discharge high currents in a short amount of time. Devices called compulsators (short for compensated pulsed alternator) are also used. Instead of using electric fields to store energy like capacitors, they use mechanical flywheels. In general, compulsators can store much larger amounts of electric energy for their size than capacitors, so they are used for larger guns. Neither capacitors nor compulsators produce electrical energy, they only store it and discharge it. When these are added, so must an energy source of some form (Massey).

As the currents grow larger and larger, problems begin occurring with the simple rail gun design. When the gun is fired and current begins flowing through the rails and armature, extremely intense heat is produced. This heat can cause the armature to actually weld itself to the rails. In order to prevent this, something called an injector is added to larger rail guns. The injector pre-accelerates the armature so that when it reaches the rails and current starts flowing through it, it is moving fast enough that spot welding does not occur. Injectors also serve as a way to make the most of the superior acceleration the rail gun provides. Armatures are accelerated to the limits of traditional guns before they reach the rails, allowing the armature to make the most of the acceleration provided by the rails (Barros).

Armatures

There are two types of armatures that are used in rail guns: solid and plasma. Solid armatures are much simpler than plasma. A solid armature can literally be a piece of conducting metal that fits between the rails such that it touches both rails. Ideally, the armature maintains perfect electrical contact with the rails at all points. If this were possible, there would be negligible voltage drop across the armature, little or no arcing, and thus minimal erosion on the rails. However, maintaining perfect contact is almost impossible with two metallic surfaces.

Some are designed V or U-shaped that bow outwards, pressing against the rails, and ensure good electrical contact. Another attempt at perfect contact is using metal brushes to run along the sides of the rails, but this method causes irregularities in the current running through the armature. On top of all the problems with solid armatures, as the projectiles approach extremely high speeds, arcing occurs and causes metallic breakdown on the armature, which produces a plasma coating around the armature (Barros).

Plasma armatures are used in arc-driven rail guns. In arc-driven rail guns, plasma is placed behind a non-conductive projectile. When the gun is fired, controlled arcing in the plasma provides the force that pushes the projectile forward. The arcing of the plasma causes significant damage and erosion to the rails of the gun. Although they cause this damage, plasma armatures have been thought to be the only way to fire projectiles at speeds of over 5km/s, but new research is being done on materials to allow solid armatures to move faster (Barros).

In 2006, Power Labs tested its rail gun for an episode of a television show aired on the Discovery Channel. The builder of the gun, Sam Barros, used a solid armature made from a new material that was supposed to allow solid armatures to reach much higher speeds. According to Barros**,** "through advances in materials science a special copper / carbon composite has been made which will retain its dimensional stability due to the extreme heat resistance of carbon, while at the same time not causing excessive resistive losses thanks to a high degree of copper imbedded in it. Other advantages of this material include low residue, the inherent lubricating properties of carbon, ease of machining (can be machined with HSS tools), and the fact that it can never weld itself to the rails."(Barros) A second aluminum armature was developed in case the never-before tested copper / carbon armature failed. When the gun was fired, the new armature actually exploded in the gun, and sent fragments flying out of the muzzle.

Military Rail Gun

The primary application for work with rail guns is military. The Office of Naval Research has been researching rail guns, and as of January 2008, fired the most powerful rail gun in the world. The weapon fired a projectile at 2,520 m/s, produced a muzzle energy of 10.64 mj (Babb).

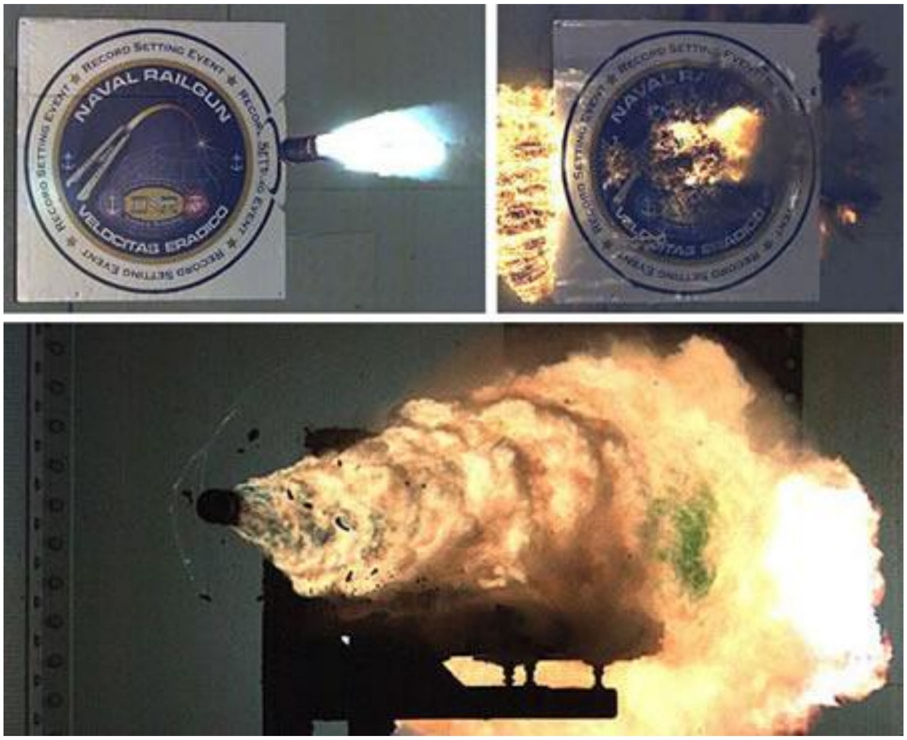

Figure 4 – Military Rail Gun (Newlaunches)

Rail guns hold many advantages over classic armaments that utilize chemical reactions to propel the projectile. One of the most notable advantages is a drastic increase in firing range. The Mk 45 5-inch/45 naval gunfire system, the gun that the rail gun will replace, has a range of a little over 13 nautical miles; the rail gun is predicted to vastly outmatch this with a range of well over 200 nautical miles. Projectiles will reach hypersonic speeds of Mach 7, equivalent to 5,550 miles per hour. In addition, the weapon will be able to fire into the stratosphere (versus the relatively flat trajectories of current guns), and actually have the ability to hit enemies on the other side of mountains by using extremely high-angle trajectories (Babb).

Ammunition for rail guns is completely non-explosive, thus making it much safer to handle. The damage will be done strictly through the use of kinetic energy. When the projectile hits its target at Mach 7, shrapnel from whatever it hit will all be moving at lethal velocities. Col. Steven Bullmore, of the Army Capability Integration Center says that “It allows me to get energetics, powder and explosives off of combat systems, I still have the ability to kill things, but I no longer have things on a combat vehicle with soldiers that explode, things that could hurt the soldier other then the enemy.” (Babb) Three types of ammunition are currently being developed for the gun: solid rounds for “hard” targets such as bunkers, or any other form of prepared defense, a rod-dispensing round for vehicle targets, and a pellet-dispensing round for ground targets. In addition, the ammunition will be equipped with some form of guidance system (Babb).

The rail gun is still undergoing research and development by the military. Even though there is still work to be done, the rail gun shows much promise in becoming the next generation of advanced military weapons.

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