

# Magnetic Launches

## Barry Hansen

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Hands-On Ideas 10

May 22, 2013



**“He who controls magnetism, controls the universe”**

Diet Smith, as quoted in Dick Tracy comic strip, circa 1945

"Well, if you can't believe what you read in a comic book, what can you believe?!"  
*Bullwinkle J. Moose [Jay Ward]*



The Space Coupe is based on stories from the Dick Tracy newspaper comic strip. It was invented by Diet Smith, Tracy's friend, industrialist and brilliant inventor. The Coupe relied on the planetary magnetic field. His Magnetic Air Car was also a main feature of the series.



### **The Potential to Solve Real Problems**

“Magnetism is one of the six fundamental forces of the universe, with the other five being Gravity, Duct Tape, Whining, Remote Control, and The Force That Pulls Dogs Toward The Groins Of Strangers.” – Dave Barry

Modern electric motors are highly refined devices, capable of efficiency over 90%. But modern motors turn in circles. What if we could achieve the same degree of control and efficiency directly to motion along a line?

Many of the fanciful inventions from Dick Tracy are now commonplace. (Two-way wrist phone, anyone?)

Magnetically floating vehicles above a few inches is impossible, but what if more modest goals are achievable? Read on...

## About Barry

Seattle, Washington, USA

Married, 3 kids, software programmer



I live in the States in the Pacific Northwest corner of Washington state near Seattle. My three kids are in their 20s now, but my magnetic experiments started in their very early teens. My career is in software development and my degree is in electrical engineering. I've worked for HP, IBM and others, and am now an independent web developer.

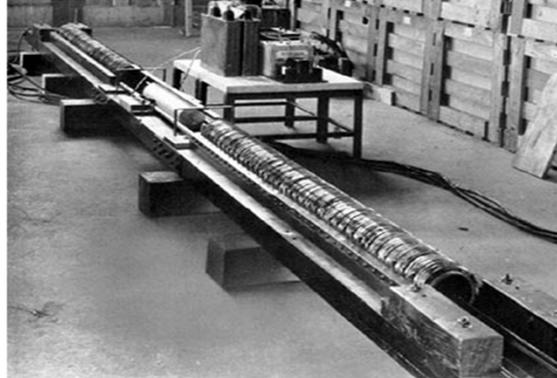
I will use the term "coilgun" and "magnetic launcher" interchangeably.

The "human kaleidoscope" picture was taken in a nature and wildlife center in Virginia.

<http://www.virginiaaquarium.com/>

## What inspired this work?

In 1937, Northrup published a feasibility study of a magnetic launch to moon, in his book “Zero to Eighty”



### **The Potential to Solve Real Problems**

In 1937, Edwin Finch Northrup wrote a book “Zero to Eighty”.

EF Northrup designed a linear induction motor for a moon launch. The hypothetical coilgun would be located in Mexico (Mt. Popocatepetl ) with a length greater than 100 kilometers and achieve 11.2 km/sec.

To support his story, Northrup presents a paper design for a prototype coilgun located in Salt Lake City, Utah of 1 kilometer length and 50G acceleration up to speeds of 1 kilometer/second. He built several small prototypes in the lab, with a 10-cm bore.

<http://www.electric-history.com/~zero/360-Northrup.htm>

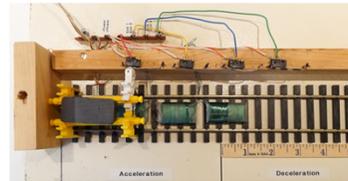
In this image from his lab, a three-phase induction motor accelerates an aluminum cylinder from one end, and decelerates it at the other end.

Henry M. Rowan built on Northrup’s study of induction motors to become the father of the modern induction heating furnace.

Recommended reading is “The Fire Within,” the story of big ambitions and Inductotherm Industries Inc, ©1995.

## Getting Started

- 1997 website “How to Colonize an Asteroid” with a 3-stage “Nail Shooter”
- Kids and science fairs
- Learning HTML
- Website generated lots of questions and ideas
- Simple magnetic rail car led to a launcher, then a better launcher, and more experiments



### Early Influences

As an early teenager, I found “The Boys Third Book of Radio and Electronics”. This reflected the time of hobbyists eager to share practical knowledge and construction techniques. This book, and others like it, were the “open source” movement in the 1960s.

<http://www.amazon.com/Boys-Third-Book-Radio-Electronics/dp/0684126982>

However, as a technology matures, any given subject gradually makes less impractical to home build useful things. Mass production and commercial refinement makes it less interesting to hobbyists. We want to build new things, and design stuff that has not been fully explored.

Worse yet for hobbyists, the highly trained commercial engineers tend to protect the most useful design principles as “trade secrets” which are not published. Hence, the wonderful books about practical electric motor designs were generally published from 1920 – 1950. Today, all you can find are books on electric motors that begin with calculus, rotating vectors and electromagnetic field theory. The hobbyist field is missing the intermediate knowledge level, that is, practical tips at a level between “start with calculus” and “start with a battery and a wire wrapped around a nail.” This is where today’s online collaboration fills a big need. This is the level at which my website is written.

Furthermore, today it’s easier than ever to share, produce and distribute a niche market item.

### The Kids

My kids needed a science project for elementary school. We built a simple “linear motor” on an HO-scale train track to propel a toy car carrying a permanent magnet. It had three stages, triggered by microswitches salvaged from computer mice. It was easy.

### The Project

In 1997, I read an interesting website about a three-stage coilgun that fired nails: “How to Colonize an Asteroid” by Robert Lyon Richards, with pages such as “Linear Induction Engines: The Nail Shooter”. [http://www.obtronics.net/htc/technogy/s\\_craft/nailsh.htm](http://www.obtronics.net/htc/technogy/s_craft/nailsh.htm)

This was in the day where searches were laborious and filled with irrelevant results. The first website went public only three years before, in April 30, 1993 by Tim Berners-Lee. The web was crude. The coilgun was crude. I thought: "I can do better than that." "All it needs is some good analysis and experiments."

### **The Workshop**

One reason this project attracted me is the mechanical portions are easy to build. My skills at mechanical assembly are terrible and I don't have much shop equipment. Virtually any iron of any shape can be launched. All it needs is a loose sliding fit in the barrel.

### **Learning HTML**

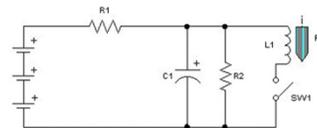
I was learning HTML in the 90s. I had too many bits of paper with notes. Half my mess was printed web pages. I needed an organizing system to keep track of things.

It *could* have gone into a Word document. But that was too inflexible. I believed that pages linked by hypertext was perfect. Since it was now already written in HTML, I published it online. It is written for people who want to spend time reading and experimenting, and learning with me. It is not a "how-to" cookbook. My website is my online engineering notebook.

<http://www.coilgun.info>

## Why Coilguns? All Electric

- Mechanical tolerance  
Loose fit, no wear
- Shape tolerance  
Launch any iron that fits in barrel
- Speed control  
Just twist a knob to choose speed
- Speed repeatability  
Add coil to fine-tune speed  
of an existing gun
- Simple  
Coil, capacitor, switch



### Advantages: All electric

#### Mechanical tolerance

Think: reliability

Conventional guns and rail guns require close-tolerance machining and cleaning.

#### Shape tolerance

Think: less wear and tear

Coilguns will accelerate almost any ferrous substance of any shape that fits into the barrel. From a cheap threaded screw to old pliers and wrenches, anything attracted to a magnet can be accelerated. If it fits, it ships.

#### Speed control

Think: twist a knob

Varying speed is easily accomplished through control of current and timing.

#### Speed fine-tuning

Think: retrofit

So, in theory, a coil could be fitted to the muzzle of a conventional gun to add/subtract velocity for minor and precise adjustment of exit velocity.

#### Repeatable speed

Think: each stage individually adjusts its energy based on entry velocity

#### Simple

Think: just dump energy into a coil

In this schematic resistor R1 controls time to charge, R2 is high resistance for very slow discharge for safety. Capacitor C1 stores electrical energy, inductor L1 is the coil.

## Why Coilguns? No explosion

- Hyper-velocity: Just keep adding coils
- Inert: No combustible gas expelled
- Quiet: No extra noise
- Storage safety: No combustible propellant



### **Advantages: No explosion**

Hyper velocity - conventional guns are limited to the "speed of sound" of the propellant gas. In theory, coilguns can continue adding stages indefinitely for ever-higher speed.

Exhaust gas composition – (think: hostile atmosphere)

Conventional guns discharge a cloud of flame and un-burnt propellant. Coilguns are inert and might be safer in combustible situation or environment.

Noise – (think: stealth)

Conventional guns include a loud explosion unless special measures are taken. Coilguns have no explosion. However, note that any projectile exceeding the speed of sound will make noise regardless of how it's accelerated.

Storage safety – (think: electric battleship)

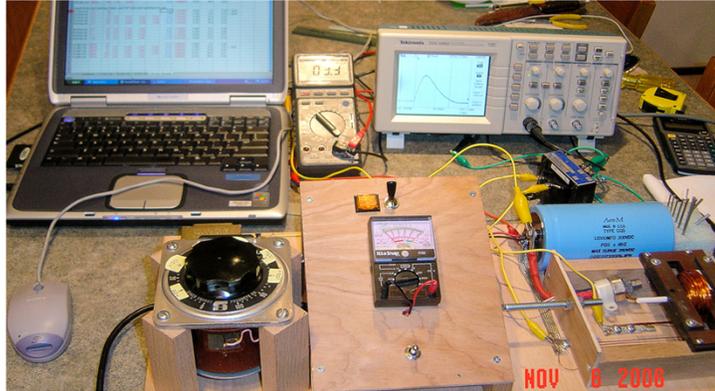
Conventional ammo contains explosives. Coilguns only require a power source. A fuel tank and generator is typically present in all vehicles.

The image shown illustrates the three key parts of a magnetic launcher:

1. Energy storage (blue capacitor)
2. Switch (red stud-type silicon controlled rectifier)
3. Coil (copper magnet wire bolted into iron leaves)

## What Barry Likes to Explore

- What is needed for a single stage to work well?
- Why are magnetic launchers so very *inefficient*?



Openly Disruptive

### Single Stage Launcher

A single stage launcher is a relatively simple problem, but it's still not simple.

The variables include voltage, capacitance, inductance, resistance, iron material properties, projectile length, starting position, coil geometry, wire size, switch characteristics, pulse waveform, external iron geometry, and more.

Most variables depend on others, e.g., changing the wire size will change the inductance and resistance and coil size.

### Efficiency

Conventional electric motors can achieve better than 90% energy conversion efficiency.

However, some of the better hobbyist magnetic launchers with a single stage, with a great deal of refinement and tuning, might be 1% - 5% efficient.

Note: For a fair comparison, a "single stage coilgun starting at rest" is most similar to an electric motor's initial startup.

# Magnetic Launchers

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Incremental Refinement



The next few slides show the progress from start to where I am today.

I'm a big supporter of the scientific method: isolate a concept and run experiments to learn how it works.

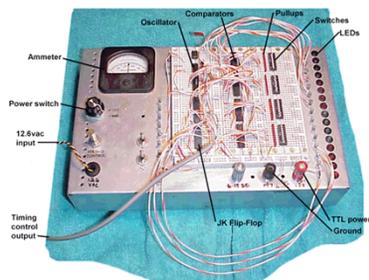
An experiment is trying something when you don't know the outcome.

A demonstration is trying something where you do know the expected result.

In theory, theory and practice are the same. In practice, they're not.

## Project: Mark 1

- A mashup of coils, timers, drill parts.
- Principle: Three coils, fired in overlapping sequence.
- Result: Poor. Fixed timing led to wildly variable results. Large inductance in coil slows down timing.



<http://www.coilgun.info/mark1/home.htm>

A mashup of coils, timer circuits and an electric drill; it is a Frankenstein of garage parts.

### Results and Lessons

It didn't work well. It wasn't consistent and sometimes fired backwards.

It is exquisitely sensitive to initial position with differences amplified by later stages.

Fixed timing, even if it's adjustable, simply won't work.

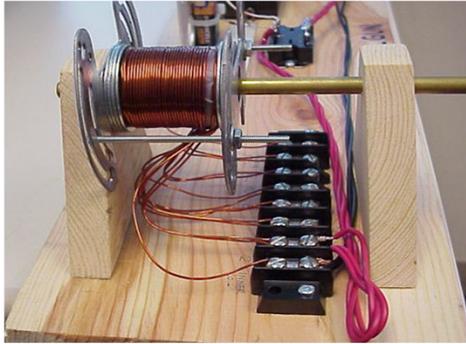
Inductance is important, and these coils have too much.

Inductance is the tendency to resist change in current and slows down the coil's response.

Next: what size coil works best?

## Project: Mark 2

- What size coil works best?
- Principle: One coil with taps between layers.
- Result: A small number of layers is best.



<http://www.coilgun.info/mark2/home.htm>

The fourteen-layer coil had a loop of magnet wire to a terminal strip, allowing a connection every other layer.

### Results

In theory, using fourteen layers would provide the most “turns per inch”.

In practice, the best performance happens with only two layers, the minimum available here.

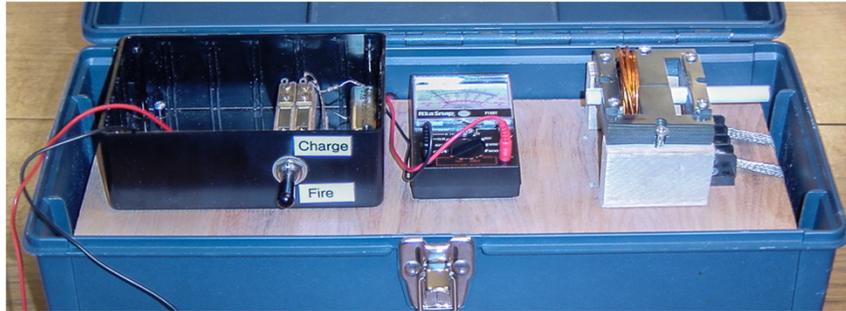
The extra outer layers add resistance and inductance. They are too far away from the projectile.

Notice the brass tube – this will later to be found a poor material because conductive tubes may have induced eddy currents.

Next: Will external iron improve the magnetic flux path?

## Project: Mark 3

- Portable low-power single-stage in a plastic toolbox
- Principle: One coil with iron to improve flux path
- Result: High efficiency (6%)



<http://www.coilgun.info/mark3/home.htm>

Now that I have some idea of the coil, what about guiding the magnetism with iron?

The Mark 3 is a low power launcher to study effects of external iron. And it turned out nicely portable.

I use this in demonstrations at local high school science classes.

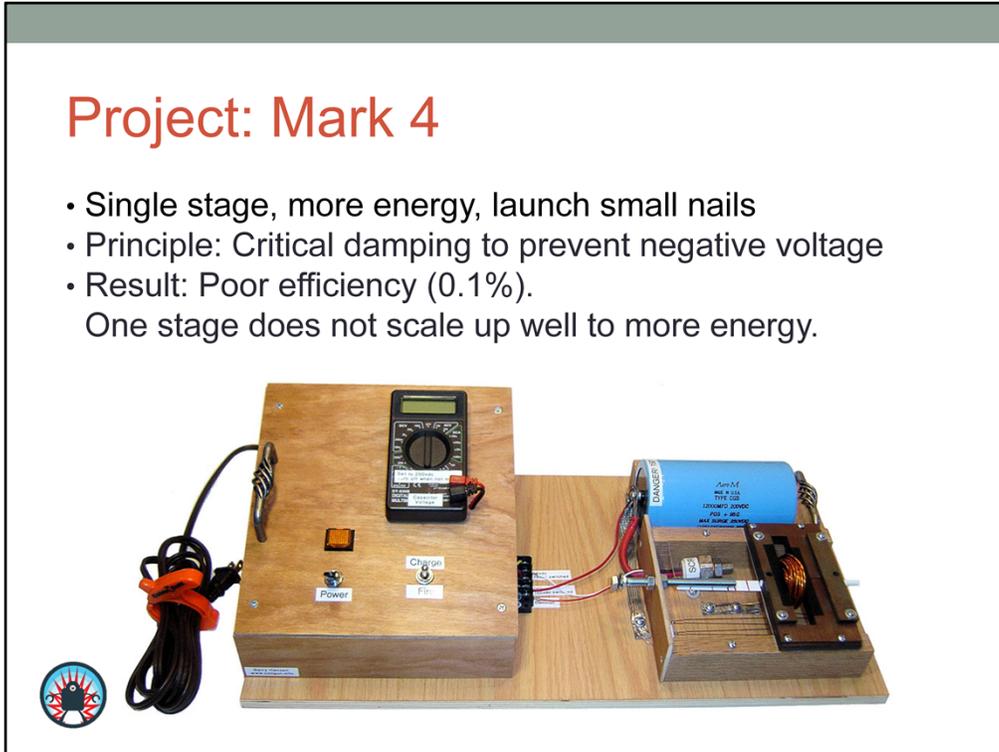
### Results

This turned out to be one of the highest-efficiency launchers in the world, with about 6% efficiency. It runs off a 12v lantern battery, capacitor and silicon controlled rectifier (SCR).

Next: What about ringing and damping oscillations? Am I damaging electrolytic capacitors with negative voltage?

## Project: Mark 4

- Single stage, more energy, launch small nails
- Principle: Critical damping to prevent negative voltage
- Result: Poor efficiency (0.1%).  
One stage does not scale up well to more energy.



<http://www.coilgun.info/mark4/home.htm>

The goal was to find out what happens when a small resistor is added to damp out oscillations.

### Results

The nails fly at 50 fps (15 m/s) but efficiency is very low, 0.25%.

The external iron again improved efficiency by 4x.

Magnetic retention bolt worked well: a light holding force and easy to adjust.

“Critically damped” design gave poor results.

Later, we developed the math to determine that a critically-damped circuit lowers peak current by 64%.

[http://www.coilgun.info/theoryinductors/critical\\_damping.htm](http://www.coilgun.info/theoryinductors/critical_damping.htm)

I will always use undamped designs (minimum possible resistance) from now on.

Does the voltage overshoot damage electrolytic capacitors?

In theory, yes. In practice, none have failed me yet.

Next: Will a good mechanical copper switch work better than an SCR (silicon controlled rectifier)?

## Project: Mark 5

- Single stage, copper switch, heavy projectile
- Principle:  
Copper wedge to close circuit
- Result: Work in progress



<http://www.coilgun.info/mark5/home.htm>

The goal is to find out what happens with a “new” wedge-shaped mechanical contactor switch. The switch design dates from power companies around 1960 and was successful in “Discovery Channel Launcher”.

A wedge with a critical angle will latch into a matching slot, without bouncing or falling out or becoming difficult to remove.

The critical angle depends on the material; for copper the angle is about 8 degrees.

The wedge provides large surface area for good conduction, without contact bounce or initial closure on small surface area that can cause pitting and arcing.

The goal is to improve conduction compared to SCRs, which have some resistance and a forward voltage drop.

The disadvantage is that a copper switch is not a diode; it will conduct for more than a half cycle. This circuit will ring until the current gradually ramps down to zero.

### Results

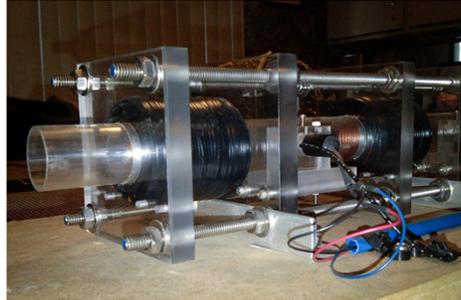
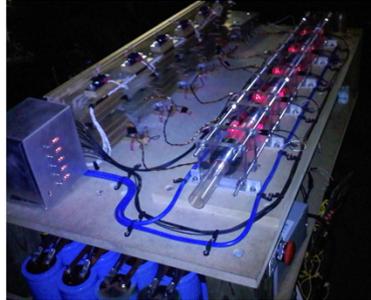
The switch, tested alone, is excellent switch. There was no contact bounce on the oscilloscope.

The Mark 5 needs considerable work to finish and test.

As of May 2013, the coil assembly has not been built.

## Project: Mark 6

- Five stage, optical sensors, puck SCR, heavy projectiles
- Principle: Efficiency via low energy stages, lots of stages
- Result: Future work



I bought some partial assemblies for a large-bore one-inch diameter (2.5 cm) from a retired coilgun.

This was originally built at the University of Toledo and decommissioned several years ago. The Mark 6 will be my future project after the Mark 5 and some other projects are completed.

It is currently a box of parts and will need significant engineering work to restore. As of May 2013, this project has not started.

## Discovery Channel Launcher



- Episode of “Engineering the Future” series
- Prof. Roger Angel at the Univ. of Arizona proposed trillions of lenses in space to reduce global warming
- Principle: Flat pancake coil repels aluminum plate



How do you launch a trillion lenses? With a giant coilgun, of course. I was hired as a coilgun consultant for the 7 kilojoule coilgun that was designed and built in England and filmed in Arizona for this Discovery Channel episode.

A talented group of FX engineers built the hardware.

This project’s goal was to achieve 1,000G of acceleration – successful!

<http://www.coilgun.info/discovery/photos.htm>

[http://www.coilgun.info/discovery/prof\\_angel\\_feasibility\\_study\\_pnas.pdf](http://www.coilgun.info/discovery/prof_angel_feasibility_study_pnas.pdf)

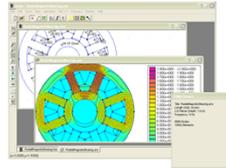
# Post-Project

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What's Next

## How you can build off this work: Experiments

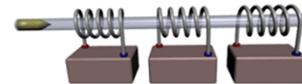
- Magnetic flux path



- Switching device:  
Contacts  
Mosfets  
IGBTs



- More stages



Build a simple coilgun. Almost anything will work, at least a little. Although it's difficult to make it work really well.

As long as magnetic launchers have such low efficiency as today, they will remain a toy. Experiments and new ideas will lead the way toward improving the technology.

Some interesting areas might include:

### **Magnetic flux path**

Launchers can be improved by finding better ways for the coil's magnetic field to couple with the projectile.

My tests found that iron surrounding the coil make a dramatic improvement by guiding the flux to where it does the most good.

How much, and what type or shape of iron works best?

Magnetic simulation software is useful, try FEMM (finite element method magnetics) by Dr. Meeker. <http://www.femm.info/>

### **Switching devices**

Coilguns are sensitive to small amounts of resistance in the high-current path.

It is important to use a switch with low losses.

- Copper contacts are very low resistance but, being mechanical, can only be used in the first stage.
- Mosfets have relatively low "on" resistance, but can we find an affordable mosfet with high current capability.
- SCRs (silicon controlled rectifiers) are more common, less expensive, very rugged, but may have higher losses than other devices.
- IGBTs (insulated gate bipolar transistors) such as used in golf carts are fairly common,

high power, low loss, but can be finicky to control properly to avoid damage.

- Other switches?

### **More stages**

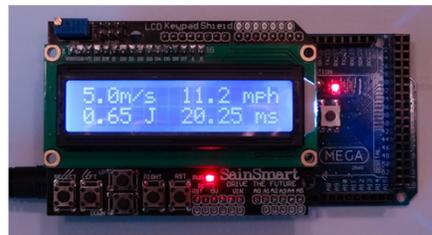
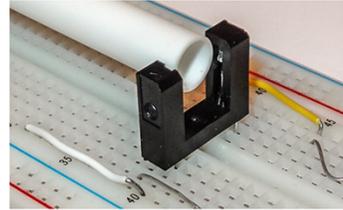
The first coil is the least efficient. And raising the power in a single stage will greatly lower the efficiency.

A higher entry speed into subsequent coils result in a shorter firing time, leading to higher efficiency.

Wouldn't it be interesting to find out what happens with a long launcher with lots of stages?

## How you can build off this work: Tools

- Optical detectors
- Arduino controllers
- Speed measurement



Makers would benefit from easy access to commonly used assemblies.

### **Optical detector**

For multiple stages, it is crucial to have an optical detector to trigger the next coil. Look for “opto interrupter” devices. They include an emitter and detector pair separated by a short gap.

Wouldn't it be nice to have recommendations and experience with parts to guide the next hobbyist?

### **Arduino**

Microcontrollers such as the Arduino are perfect for sensors, timing and controlling the coil. There are some motor control shields in the market but they don't support the large, short pulsed current needed.

Wouldn't it be nice to have published shields for single-shot coil control?

### **Speed measurement**

Typical results are loosely reported in casual terms, such as the amount of damage to cans or watermelons.

If an optical sensor and Arduino is already in use, it could also measure and report velocity. An early example is <http://www.megavolts.nl/index.php/en/projects/geweren/116-mv-speedometer>

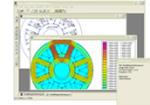
Although chronometers for paintball are commercially available, they could be an extra expense.

My image shown here is a mockup of one possible display.

Wouldn't it be nice to have more programming examples or a software library to work from?

## Further reading

- [www.coilgun.info](http://www.coilgun.info) – Barry Hansen
- [www.coilgun.com](http://www.coilgun.com) – James Paul
- <http://4hv.org> – High Voltage Forums
- [www.amazon.com/gp/product/0071755675](http://www.amazon.com/gp/product/0071755675)  
Ch.1 from “15 Dangerously Mad Projects for the Evil Genius” by Simon Monk
- [www.femm.info](http://www.femm.info) – Finite Element Method  
Magnetics, by Dr. David Meeker



Also see the “notes” section throughout this presentation for specific links to the projects mentioned.

There are many more excellent resources and forums across the web.

A search engine is your friend.

Download free instructions for building a portable coilgun, a sample chapter from “15 Dangerously Mad Projects”:

<http://mhprofessional.com/downloads/products/0071755675/675-monk-01.pdf>

# Question and Answers

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## Top Questions

- How fast a typical coilguns?
- Where can I find capacitors?
- Does high voltage work better than low voltage?
- What about launching a powerful magnet instead of iron?



### Typical Speeds

How fast are typical coilguns? See the “World’s Coilgun Arsenal” at <http://www.coilgun.ru>  
Most coilguns have speeds of 10-20 m/s (22-44 mph) (33-66 fps) and a few up to 40 m/s.  
Most coilguns have efficiency of 1-2% and very few above 5%.

### Capacitors

Look on eBay, Craigslist, Surplus Sales of Nebraska, other surplus electronics stores, etc.  
Usually, electrolytic capacitors are less expensive than other types.

Some say that camera shops may have disposable cameras with film removed.

Compare capacitors based on “potential energy”, which is a combination of voltage and capacitance:

$$PE = \frac{1}{2} C V^2$$

Where C = farads, V = volts, PE = joules

### Voltage

The strength of the magnetic field depends on current, not voltage.

Low voltage works fine and voltage less than 50 volts should be less dangerous.

The goal is “amp turns”, the simple product and current multiplied by the number of turns per inch.

### Magnets

Try it and see.

In theory, a strong magnet will interact with the applied magnetic field for a much faster launch.

In practice, hobbyists often find no difference in results and it can erase the magnet.