VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ
BRNO UNIVERSITY OF TECHNOLOGY

FAKULTA ELEKTROTECHNIKY A KOMUNIKAČNÍCH TECHNOLOGIÍ
ÚSTAV ELEKTROTECHNOLOGIE

FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION
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ELECTROMAGNETIC PULSE ACCELERATOR OF PROJECTILES

BAKALÁŘSKÁ PRÁCE
BACHELOR'S THESIS

AUTOR PRÁCE JAN ŽAMBERSKÝ
AUTHOR

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VYSOKÉ UČENÍ
TECHNICKÉ V BRNĚ

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a komunikačních technologií

Ústav elektrotechnologie

Bakalářská práce

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NÁZEV TÉMATU:

Elektromagnetický pulzní urychlovač projektilů

POKYNY PRO VYPRACOVÁNÍ:

Pojednejte o strukturách a vlastnostech magnetických materiálů, přičemž se detailně zaměřte na skupinu feromagnetik. Prostudujte jejich chování v magnetickém poli a sumarizujte technologie využívající účinky magnetického pole v technické praxi.
Vyberte vhodné řešení, navrhněte a sestrojte mikrokontrolérem řízený coilgun, tj. zařízení schopné střílet feromagnetické projektily, urychlené silným magnetickým polem. Při návrhu a realizaci hardwarového zapojení jednotlivých částí zařízení respektujte následující požadavky
- vyšší počet urychlovacích cívek a jejich postupné spínání, umožňující dosažení maximální účinnosti,
- volba vhodného materiálu projektilu s ohledem na minimalizaci ztrát magnetického obvodu,
- měření úsťové rychlosti vystřeleného projektilu,
- měření a zobrazení velikosti napětí na kondenzátorech a jejich automatické nabíjení,
- možnost napájení zařízení z baterie.

Praktickou funkčnost sestaveného zařízení ověřte v laboratorních podmínkách, změřte jeho základní charakteristiky a vyhodnoťte jeho vlastnosti.

DOPORUČENÁ LITERATURA:

Podle pokynů vedoucího bakalářské práce.

Termín zadání: 10.2.2014 ***Termín odevzdání:*** 5.6.2014

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doc. Ing. Jiří Háze, Ph.D.
Předseda oborové rady

Abstract

This work focuses on using magnetic field to accelerate projectile in a device called coilgun.

It consists of two parts, first is theoretical discussing magnetism and its use, the other part is about coilgun itself, its benefits and drawbacks. Followed by series of measurements on two experimentally built coilguns and trying optimize it to achieve best results.

First part discusses multiple topics. In the beginning, there is a small section defining magnetic field and other constants and phenomenons connected with it.

Next two chapters are focused on different types of material, mainly ferromagnetics, how they react to magnetic field and what parameters we can follow, followed by a list of several applications of magnetic field in different areas of human society.

The second part describes main principle of coilgun and how the prototypes were made.

Measurements on a first prototype consist of trying different materials for projectile, various dimensions of it and benefits of using external shell for accelerating coil. There is also a chapter discussing velocity measurement of a projectile. Second prototype is trying to avoid all the flaws, which were found on the first prototype and find a benefits of using multiple acceleration stages.

Keywords

Coilgun, Gauss rifle, Linear motor, Magnetism, Magnetic materials

Prohlášení autora o původnosti díla:

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1 INTRODUCTION

Magnetism has wide usage in almost every field of human development. One of not so fortunate quality of human character is however that almost every invention is tried being turned into a weapon of some kind. Most conventional firearms are using gas expanding from burning the gunpowder to accelerate a projectile in a barrel. This concept was invented in China in 12th century and haven't changed much since. Even though a 1260 hand cannon wouldn't stand a chance against modern firearms, both are using same principle to accelerate the projectile, with all the pros and cons it has.

Modern developments in electricity are opening a gate to another ways to give a kinetic energy to a projectile. Since current generates a magnetic field, it can be used to set a projectile in motion. There are two main concepts, railgun and coilgun. Railgun, as the name suggests, consists of two rails which are conductively connected with a projectile. With passing current, the projectile is pushed due to a generated magnetic field on the rails. With high enough current and long enough rails, hypersonic speeds can be achieved.

The second type, the coilgun, is using coils as electromagnets to accelerate the projectile by sucking it into their core and then letting it continue by its inertia. Using multiple coils, also called multiple stages, can as well lead to achieving basically unlimited speed.

Both of them has many advantages over conventional weapons, most notably the higher velocities, but many problems are connected with it as well and are still a field, which is being explored.

2 MAGNETISM

Magnetism is a physical phenomenon, which is caused by motion of an electric charge. This motion can be either electrical current as a movement of charged particles from one place to another, or movement of electrons ”spinning” in atomic orbitals and their spin.

This movement generates magnetic field, which has force effect on another magnetic particles. Among with gravitation and strong and weak interaction, electromagnetism is one of the fundamental interactions.

2.1 Magnetic field

Change of an electric field, caused by moving electrical charge, generates a magnetic field. It can be described by magnetic induction **B**, or intensity of magnetic field **H**. Both of them are vector fields.

Unit of magnetic induction is Tesla and can be defined by Laplace law 2.1, where d**F** is a force subjected to a d**l** element of a conductor carrying a current i

$$d\mathbf{F} = i \cdot d\mathbf{l} \times \mathbf{B} \tag{2.1}$$

To define magnetic field, with a unit of ampere per meter, we can use magnetic permeability μ. Magnetic permeability is a constant of proportionality between magnetic induction and magnetic field, as shown in following equation:

$$\mathbf{B} = \mu \mathbf{H} \tag{2.2}$$

Permeability of vacuum μ_0 is $4\pi \cdot 10^{-7}$, unit of permeability is henry per meter. Then we can also define magnetic flux Φ of field **B** going through surface **S** as follows [15]:

$$\Phi_B = \iint_s \mathbf{B} \cdot d\mathbf{S} \tag{2.3}$$

If we measure magnetic flux over a closed surface (such as a spherical surface), total magnetic flux equals zero, meaning magnetic fields has no sources or sinks. Written in differential form, divergence of magnetic field equals zero:

$$\nabla \mathbf{B} = 0 \tag{2.4}$$

That basically means, contrary to electric field, that there are only magnetic dipoles, that magnetic monopole doesn’t exist [7].

2.2 Relative permeability, magnetization, susceptibility

As seen in eq. 2.2, permeability determines how strong magnetic induction is for certain strength of magnetic field.

When we put some material into magnetic field, it modifies magnetic induction in a certain way. Since constant of proportionality is permeability, it must be specific for every material. We define relative permeability as a constant, how much stronger or weaker the magnetic induction is compared to one in vacuum:

$$\mu_r = \mu/\mu_0 \tag{2.5}$$

Reasons for this are permanent or induced magnetic dipoles in atoms. Without external field, they are mostly oriented randomly, but when subjected to magnetic field, dipoles orient themselves accordingly, which results in magnetic field generated also by the material. This is called magnetization **M** and has the same unit as magnetic field strength.

Magnetisation then represents increase of an inductance and eqn. 2.2 can be modified to following:

$$\mathbf{B} = \mu\mathbf{H} + \mu\mathbf{M} \tag{2.6}$$

Magnetic susceptibility χ is the ratio between magnetization and applied field and gives the amplification of magnetic field produced by the material.

$$\chi = \frac{\mathbf{M}}{\mathbf{H}} \tag{2.7}$$

Both μ_r and χ refer to a degree to which the material enhances the magnetic field and are therefore related by:

$$\mu_r = 1 + \chi \tag{2.8}$$

Mostly materials with high susceptibility are important for electrotechnical use [5].

3 MATERIAL CLASSIFICATION

As mentioned in the beginning, magnetic field can be generated by spinning electrons and their spin, so every electron in a material is a magnetic dipole. Magnetic field of orbital spinning is negligible compared to one generated by electron spin. However every energy level in atom can contain two electrons with opposite spin, so when both electrons are present in an energy level, net magnetic moment of these two electrons is zero. The easiest example are noble gasses with all orbitals full. All moments are compensated, thus don't have permanent magnetic moment.

Odd number of electrons means there is energy level with an unpaired electron. This is mostly in the valence layer, but because valence electrons from each atom interact with others, magnetic moments cancel each other.

There are elements like transition metals, where energy level of valence orbital 4s is lower than energy of orbital 3d. These electrons don't interact with other electrons and generate permanent magnetic moment [15].

When we apply magnetic field to a material, each atom reacts to it and based on its structure and bond with other atoms, we can observe different behaviours.

3.1 Diamagnetism

Based on Lenz's law, when we change magnetic field, it induces a current. On atomic level, it means orbiting of electrons which goes against the change of magnetic flux. That results in negative susceptibility, hence reducing the magnetic field. Diamagnetism occurs in every material, but since induction change is small (susceptibilities in order of 10^{-5} to 10^{-6}), when any other behaviour is present, it's suppressed by larger effect of a different phenomenon.

Noble gases, metalloids, metals such as Cu, Zn and some others, and many organic compounds are diamagnetic. Also all superconductors must be diamagnetic. Except for superconductors, diamagnetic materials are of low interest of engineers [15].

3.2 Paramagnetism

Atoms in paramagnetic materials have unpaired electrons, so their spins are not compensated by paired electrons on the same quantum level. This uncompensated spin results in permanent magnetic moment, however not coupled with other atoms. Under the action of magnetic field, these moments tend to align themselves with it. Since they are not coupled together, thermal motion, which randomizes the orientation of atoms, causes magnetization to remain low with susceptibility between 10^{-6} to 10^{-3} with positive sign. Furthermore, magnetization disappears as soon as the magnetic field is removed.

Paramagnetism is found in materials such as aluminium, titanium and copper alloys.

Most of paramagnetic materials obey Curie's law, which means susceptibility varies inversely with absolute temperature [15].

3.3 With coupled magnetic moments

Materials with highest values of susceptibility and due to this also most important from engineers' point of view have permanent magnetic moments, which are coupled, meaning they are spontaneously heading same (or opposite, depending on type of coupling) direction. It could lead to an idea of permanent magnetic moments of a material sample, but because of domain structure, macroscopic samples mostly exhibits no magnetic moment. More about this will be mentioned in the next chapter.

Reason for this coupling can be found in an exchange force, or sometimes called exchange interraction. Origin of this force can be found in quantum physics, but for this work is sufficient to mention, that this force depends on the distance of neighboring atoms and the diameter of the not completely filled orbital. More precisely, their ratio. For ratio value above 3, coupling can be found, while for smaller ratios, materials are mostly paramagnetic [10].

Based on the way moments are coupled, material can be then sorted into one of three following groups.

3.3.1 Ferromagnetism

Ferromagnetism results from aligning magnetic moments parallel to each other by interaction called ferromagnetic coupling (fig. 3.1). As a result, there is also a spontaneous polarization, which is the strongest of all mentioned in this section.

Ferromagnetic materials also have Curie temperature, above which they become paramagnetic with susceptibility obeying Curie-Weiss law.

Ferromagnetic materials are iron, cobalt and nickel. Due to its susceptibility up to 10^6, they are widely used in engineering [5].

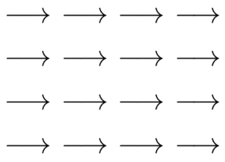

Fig. 3.1: Magnetic dipoles arrangement in ferromagnetics

3.3.2 Antiferromagnetism

Atoms in antiferromagnetic materials have permanent magnetic moments coupled in an antiparallel arrangement as shown on fig. 3.2 .

$$\begin{array}{cccc}
\longrightarrow & \longleftarrow & \longrightarrow & \longleftarrow \\
\longleftarrow & \longrightarrow & \longleftarrow & \longrightarrow \\
\longrightarrow & \longleftarrow & \longrightarrow & \longleftarrow \\
\longleftarrow & \longrightarrow & \longleftarrow & \longrightarrow
\end{array}$$

Fig. 3.2: Magnetic dipoles arrangement in antifferomagnetics

When increasing temperature, at some point, the arrangement breaks and antiferromagnetic material becomes paramagnetic. This point is called Neel temperature. However, before antiferromagnetic alignment disappears, increasing temperature causes decrease of forces holding alignment, which results in bigger polarization (increase of susceptibility) [15].

3.3.3 Ferrimagnetism

Ferrimagnetic materials are ceramic materials, in which there are different ions with permanent magnetic moments. These ions have similar alignment to antiferromagnetic materials, but magnetic moments in one direction are different from magnetic moments in opposite direction (fig. 3.3). This results in permanent magnetization, even without application of external magnetic field.

Temperature increase tends to direct ions in random direction, resulting in susceptibility decrease. When certain point is reached, for ferrimagnetics called Curie temperature, susceptibility progressively returns to paramagnetic behaviour [15].

Ferrimagnetism is a magnetism appearing in a class of metal oxides called ferrites [5].

$$\begin{array}{cccc}
\leftarrow & \longrightarrow & \leftarrow & \longrightarrow \\
\longrightarrow & \leftarrow & \longrightarrow & \leftarrow \\
\leftarrow & \longrightarrow & \leftarrow & \longrightarrow \\
\longrightarrow & \leftarrow & \longrightarrow & \leftarrow
\end{array}$$

Fig. 3.3: Magnetic dipoles arrangement in ferrimagnetics

4 MATERIAL BEHAVIOUR

Materials with spontaneous polarization are connected some phenomenons, which some of them are wanted and useful, some are not. But first let's explain, as promised in previous chapter, why macroscopic samples mostly exhibits no permanent magnetic moment.

4.1 Magnetic domains

Ferromagnetic and ferrimagnetic materials have spontaneous magnetization. The question is, why macroscopic sample of i.e. iron is mostly not magnetic. Answer to this can be found in magnetic domains. Equally polarized atoms are only in small sections of material and the whole sample is divided into a large number of these regions, called magnetic domains or Weiss domains. Weiss domains are diagrammatically shown on figure 4.1.

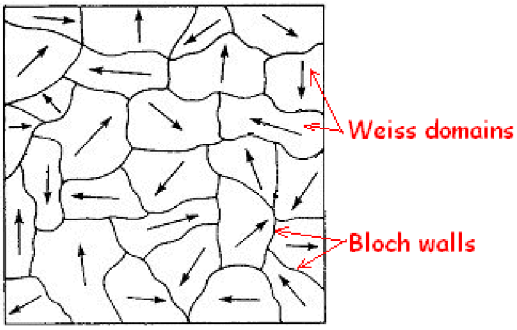

Fig. 4.1: Weiss domains

In each Weiss domain, polarization is independent to polarization of other domains and since distribution of magnetic moments is random and there is a large number of domains, macroscopic piece of sample shows no net magnetization.

Size of a domain is typically around 50 µm or less, but can extend under influence of external magnetic field, which will be mentioned later [15].

Boundaries between two neighbouring magnetic domains are made of Bloch walls. Bloch walls are about 100 nm thick transition areas between two differently polarized domains, where polarization continuously changes from that of one domain to that of the next, as seen on figure 4.2 [5].

4.2 Polarization of domain-structured materials

Polarization of paramagnetic materials happens as a "battle" between aligning dipoles on the same direction and thermal motion turning them into random orientation, whereas polarization in ferri and ferromagnetics happens by more different mechanisms and as a

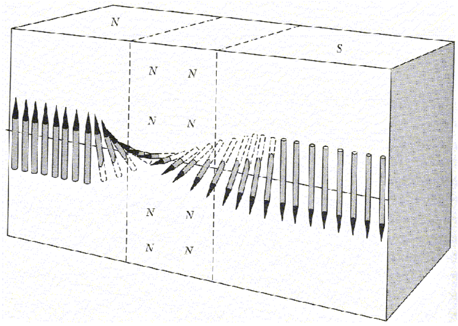

Fig. 4.2: Bloch wall [9]

side effect is non-linear.

Weiss domains are defined by imperfections in materials and between these imperfections, Bloch walls are linear. When low-strength external field is applied, Bloch walls deform in favour of enlarging domains with similar magnetic orientation as external field. This change is reversible (fig 4.3b).

When we apply stronger field, pinning points jump to another deformation, further enlarging accordingly aligned domains. This change is irreversible (fig 4.3c and d).

For further enforcing field strength, whole sample turns into single domain, which is oriented parallel to the nearest easy magnetization direction (fig 4.3e).

When we increase field even more, polarization deviates from easy polarization direction and aligns itself with external field. At this point, there is no way material can be polarized even more. We reach a maximum value, which called saturation (fig 4.3f) [15].

$B = f(H)$ function of non-magnetized material is called initial magnetization curve [5].

4.3 Hysteresis

Because of the irreversible nature of polarization, in decreasing field, magnetization doesn't follow initial magnetization curve. Material previously subjected to magnetic field shows magnetization even when external field is no more applied. Its called remament induction B_r.

To turn domains into random orientation, so that the sample doesn't show external magnetization, we need to put it into a field of opposite direction. Strength of this field is, as well as remanent induction, material parameter and is called coercive field H_c.

In alternating magnetic field, induction versus field strength traces out a hysteresis loop. Shape of the loop depends on amplitude of this field. Typical shape of hysteresis loop for different amplitudes is shown on figure 4.4. On hysteresis loop can be found remanent induction, where curve intersects y-axis (marked as b and e) and coercive field when crossing x-axis (c and f). Points a and d represent material saturation [15].

Hysteresis loop varies from one material to another.

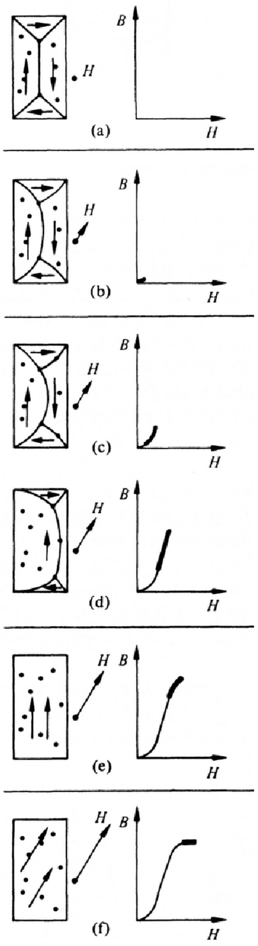

Fig. 4.3: Magnetization of ferromagnetic material [15]

4.4 Hard and soft magnetic materials

Soft magnetic materials are those with small coercive field and a small area of hysteresis loop. Permalloy and isoperm are examples of such materials. Hysteresis loops of those are on the left side and the middle of figure 4.5.

On the contrary, hard magnetic materials have a higher value of coercive field and large area of hysteresis loop. Bloch walls are strongly pinned. Alnico, with hysteresis loop on the right of fig. 4.5 is magnetically hard material. The hardest known material is neodymium, iron and boron alloy, used for neodymium magnets [5].

4.5 Magnetic losses

In changing magnetic field, magnetization doesn't occur without any loss of energy. This energy causes material to heat up. Losses cause time shift between magnetic field strength and induction. Three principles are distinguished:

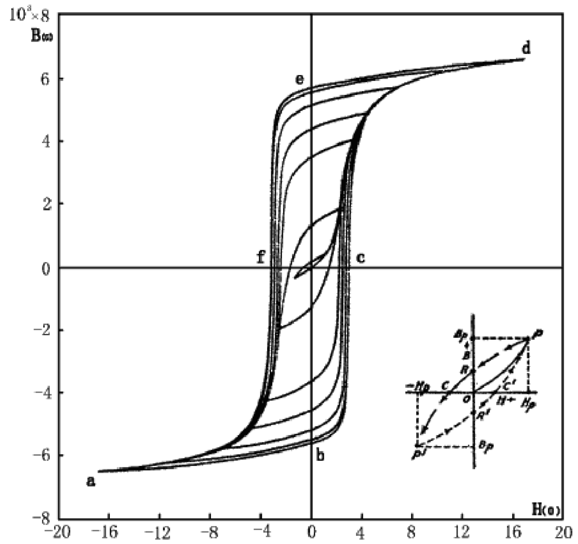

Fig. 4.4: Hysteresis loop for different magnetizations [18]

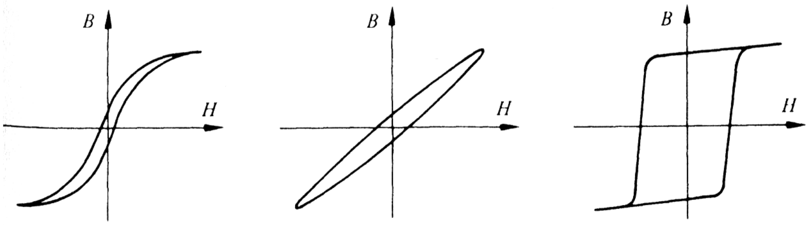

Fig. 4.5: Hysteresis loops of different materials [15]

- Hysteresis loss
- Eddy currents
- After-effect loss

Hysteresis loss is due to the work needed to move Bloch walls. Therefore, the more work needed (magnetically harder material), the bigger hysteresis losses are. Hysteresis losses are related to the area of hysteresis loop [5].

Eddy currents are generated by change of magnetic field according to Lenz's law. Current closes itself in a magnetic material and produces Joules heating. Furthermore, flowing current produces an opposite magnetic field, pushing magnetic field out of the material. Eddy currents are more severe when operating at higher frequencies. They can be reduced by increasing resistivity of material or making inductance loop smaller by e.g. stacking multiple sheets into a sandwich/pressing small grains of material together.

After-effect losses are due to the delay in the change of the induction with respect to the change of the field. Reason for them are electrons trying to change their motion as reaction to changing the magnetic field. Are particularly severe in ferrimagnetics [15].

5 USE OF MAGNETISM

Due to its inevitable connection with electric field, it is hard to set some boundary, whether to consider devices such as cell phones as using magnetism. This chapter will focus on devices using more or less static fields, meaning not using electromagnetic waves. These devices are mostly based on simple attraction/repulsion, or using Lorentz force.

Lorentz force (5.1) applies to electric charge q moving in magnetic field $\mathbf{B}$. With absence of external electric field $\mathbf{E}$, this force is perpendicular to the magnetic field and direction of movement $\mathbf{v}$ [6].

$$\mathbf{F} = q \cdot (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \tag{5.1}$$

Magnetism is widely used in almost every corner of industrial society, so it makes it basically impossible to name all the devices and technologies.

5.1 Magnetism in everyday life

Apart from obvious things, like keeping refrigerator doors closed and keeping shopping lists on them, there are plenty other applications.

Probably the first use of magnetism was in navigation, when it was discovered that magnetic needle keeps heading toward north. Principle of compasses hasn't changed much since. Every airliner or boat is still equipped with them, even though in GPS navigation era, it has more of a backup role.

It is commonly known, that without magnetism, there would be no electromechanical conversion. Both electric motors and alternators use rotating magnetic field. In case of a motor, field is induced by electrical current and then has rotatory effect on a magnet or electromagnet (depends on the exact construction). Alternators work the opposite way. Mechanical force rotates magnet, which generates electricity in nearby coils. Hence every power plant (except for solar), car alternator, trolleybus, kitchen blender and many others work only thanks to a magnetic field. To change voltage of an alternating current, there are transformers, two coils on one magnetic core. One coil generates magnetic field in the core, this magnetic field induces voltage in the other one.

Electroacoustics also mostly rely on magnetism, since the most fundamental part of a loudspeaker is a coil in a permanent magnet. Only a few years ago, the most common way of audio and video storage was on magnetic tapes. Plastic stripe was covered with thin film of magnetizable coating. Its magnetization was analogical to the level of signal which was stored there. In times of digital computers, data storage on hard drives works on the same principle except that it's not on a plastic stripe, but on an aluminium or glass disc [5].

Doorbells and relays are electromagnets, which attract a metal piece. Debit cards have a magnetic stripe, which similarly to hard drives stores information about that card. Mostly in banking environment, magnetic ink is printed on cheques, so it can be read automatically. Cyclocomputers use magnetic contacts, which connect in proximity of magnet pinned to the wheel. Electric guitar has coil with permanent magnets as a core. Vibrating string changes magnetic field, thus generates electricity in a coil. Moving lenses to focus camera can be done using electromagnet.

Magnetostriction (change of geometrical dimensions under magnetic field) complicates life of shoplifters thanks to electronic article surveillance. If a shoplifter still manages to escape, magna brush may be then used to get his fingerprints.

Sorting the waste, for example cans, is also done by magnets. Iron cans by simple magnetic attraction, aluminium cans using eddy currents.

Maglev trains might be the technique of future transportation, since they are reducing friction, are much more silent and speed limitation, especially in vacuum tubes, is much higher than for wheeled trains.

5.2 Magnetism in medicine

Nuclear magnetic resonance imaging (NMRI) is a non-invasive imaging method using a strong magnetic field to obtain images of body tissues. Big advantage is there are no known health risks, contrary to i.e. computed tomography (CT) using x-rays.

In strong homogeneous magnetic fields, atoms with permanent magnetic moment align themselves parallel or antiparallel with this field. When subjected to a perpendicular alternating magnetic field with the frequency of the resonance frequency of an atom (in medicine, hydrogen is used), precession movement is induced. Alternating field is then turned off and while atoms align themselves back with homogeneous field, they emit energy, which is detected and used to reconstruct image of a tissue.

Image 5.2 shows coming back to alignment with homogeneous magnetic (z-axis) field while emitting energy. Alternating field was in x and y axis [16].

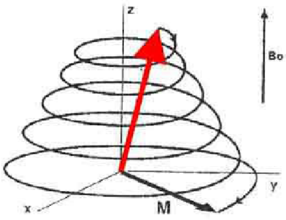

Fig. 5.2: Precession of atom [16]

Controversial use of magnetism in medicine is magnet therapy, where are no known scientific benefits, but some people find it helpful.

5.3 Magnetism in measurement

Before digital multimeters, electrical measurements were done by magnetoelectric, electrodynamic (5.3) of ferromagnetic measuring devices. All of these devices work in such a way, that measured current goes through a coil, which is either attracted to a permanent magnet, another electromagnet or sucks ferromagnetic core into itself. This movement is then connected to a pointer which shows result on a scale.

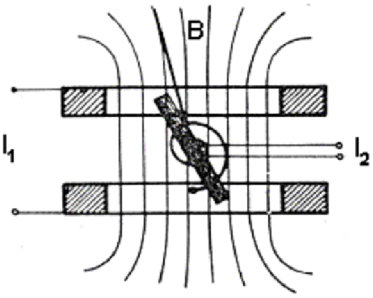

Fig. 5.3: Electrodynamic measuring device

In electromechanical induction watt-hour meters, there are coils generating eddy currents in non-magnetic, but conducting disc, which are then attracted by a permanent magnet, resulting in disc rotation, related to power consumption [3].

When conductor is placed in perpendicular magnetic field, every moving charged particle is under effect of Lorentz force (5.1), which pushes it to one side of a conductor when positively charged and to the other one, when negatively, resulting in voltage between two sides of the conductor, which is proportional to field strength. It's called Hall effect and is used on DC brushless motors, in teslameters or DC clamp meters.

5.4 Magnetism in vacuum techniques

Some vacuum components are using magnetic field to alter the trajectory of moving charged particles. One of the to-be-extinct devices is CRT screen. Cathode is emitting electrons, which are then focused and deflected using electromagnets to reach desired position on the screen.

Very similar to this are electron microscopes, where electron beam is also focused with focusing coils and in REM microscopes also deflected to raster over the sample.

Magnetron is a vacuum tube, where emitted electrons due to Lorentz force in strong magnetic field turn their trajectory to a circular, generating high frequency electromagnetic waves. Magnetrons can be found in for example microwave ovens.

Colliders use magnetic field to accelerate particles into relativistic speeds, in ring accelerators to keep their trajectory circular, again using Lorentz force.

In the need to separate charged particles with different mass or speed, they can be pushed to fly through magnetic field, which, with accordance to Lorentz force, alter they path. When we select only particles heading right direction after passing through, we have ones with desired energy/mass. These devices are called magnetic separators (5.4 [8].

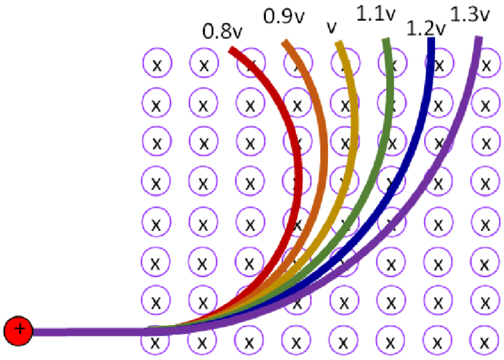

Fig. 5.4: Magnetic separator [8]

5.5 Magnetism in power generation

Magnetohydrodynamic (MHD) generator is not very well known power generator, which transforms thermal and kinetic energy into electricity. At high temperatures, atoms break into ions. When they pass through a magnetic field, Hall effect separates positive and negative charges and induces voltage [2].

Thermal fusion in tokamaks may be solution of increasing electricity demand. Extra high temperature plasma in them is held in ring away from the walls by magnetic field, preventing it from damaging tokamak shielding.

5.6 Magnetism in space programmes

Some satellites use electromagnets to rotate themselves into desired orientation using Earth's magnetic field to interact with. There is no need to burn any fuel [4].

Plasma thruster is a type of rocket engine, where electric and/or magnetic fields are used to push on the electrically charged ions and electrons to provide thrust. Compared to conventional rocket engines, plasma thrusters use much higher particle velocities, so for the same thrust, they consume much less fuel [14].

5.7 Magnetism in semiconductor production

While testing chips on wafer, when malfunction is found, chip is marked with magnetic colour. After dicing, they can be easily separated from others using just a magnet.

6 COILGUN

The above list of devices using magnetism is of course not complete. One, which was not mentioned is coilgun and rest of this work is going to focus on it. Coilgun is mostly connected with weaponry, in science fiction is often called Gauss rifle and is basically a linear motor.

6.1 Basic principle

Coilgun uses force of sucking core with positive susceptibility into solenoid to accelerate projectile (eqn. 6.1). When strong current pulse is applied to coil, the core, which is not placed in the middle of the coil, is set in motion and by its inertia continues even when current pulse is over. Figure 6.2 shows axial cut of a coilgun.

$$F = \frac{1}{2} I^2 \frac{dL}{dz} \tag{6.1}$$

where I is net current in all turns of coil, L inductance and z axis of projectile movement [13]

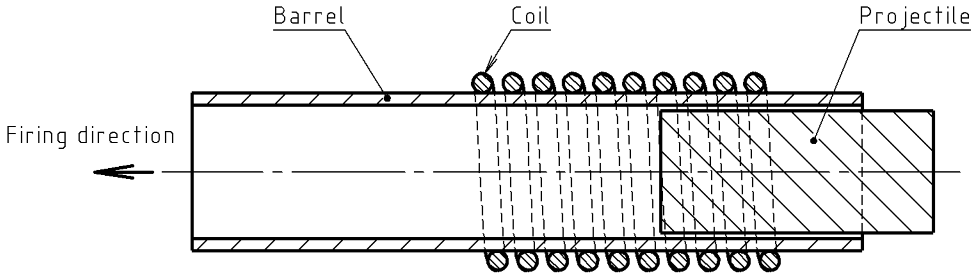

Fig. 6.2: Axial cut of a coilgun

To achieve as high speed as possible, it is essential to time the current pulse precisely. In case of projectile passing the centre of solenoid with current still on, force turns the opposite direction, breaking the projectile. This is called suck-back effect.

Another way of increasing speed, and where lies the biggest potential of coilguns is using multiple coils to accelerate projectile. When it passes through the first coil, it gets into proximity of second coil, which is then turned on, accelerating projectile even more and so on. Theoretically, there is no limitation of number of accelerating stages, thus reaching very high velocities. Apart from weapon industry, this leads to ideas such as launching projectiles onto orbit, using huge coilgun-principle accelerator.

Advantages of coilgun making it interesting for weapons are:

- No moving parts apart from projectile
- Much more silent except for potential sonic boom
- No smoke or flash from gunpowder explosion

There are however problems, including need for electricity, small efficiency and need for long barrels for reaching higher muzzle velocities. It makes them more suitable for vehicles than rather than firearm.

6.2 Energy storage

Simple version of coilgun can be build using capacitors as energy storage. Energy stored in a capacitor is a function of voltage and capacitance, defined by equation 6.3. It's obviously much more effective to increase voltage, since energy increases with a square of it, however capacitance is only on power of one. To reach desired energy storage, it might be necessary to connect capacitors in series or parallel. While connecting in parallel, capacitance is simply a sum of all connected capacitors (analogical to resistors in series). In series connection, final capacitance is counted over sums of inverted capacitances (6.4), analogical to resistors in parallel.

$$E = \frac{1}{2}CU^2 \tag{6.3}$$

$$\frac{1}{C} = \sum_{i=1}^{n} \frac{1}{C_i} \tag{6.4}$$

Advantage of capacitors is their capability of releasing all of their charge over a short period of time and stop by themselves when no residual charge is present. Disadvantage is the need to protect against opposite voltage, which may be induced in the main accelerating coil. Another disadvantage is, when connecting in series, the need to watch charging of each individual block to same value. Disbalance would also result in reverse polarization of less charged capacitors while discharging.

6.3 Triggering

High demands are placed on a switching device. Pulse currents are hundreds or even thousands of amperes while hundreds of volts (in ”hobby” devices). There are several ways to trigger the circuit.

The first, most simple way is using a thyristor. Thyristors are devices, which can sustain high current pulses, which makes them suitable for this application. Disadvantage is however obvious. Once you switch the thyristor on, there is no way to switch it back off when desired. It stays open until there is some current flowing through the coil, which might be even after projectile has passed through center of a coil and result in suck-back effect.

More complex ways are using a semiconductor device capable of being switched off. For these voltage and current demands, mostly IGBT transistors and FET transistors. Compared to thyristors, we can control how long current pulse is going to be and turn it off after passing through centre point of accelerating coil. This way, we save some of the energy in capacitors, which increases efficiency and furthermore doesn't brake the projectile hence increasing efficiency even more.

6.4 Coil

Coil is inductance load, so turning it on and off is not as simple, as it may have sounded in the previous chapter. Compared to resistive load, where change in voltage means immediate response of current, Coil connected to capacitors forms RLC circuit with it's transient response depending on a damping factor, defined by equation 6.5.

$$\zeta = \frac{R}{2L} \tag{6.5}$$

Depending on damping factor ζ, circuit can by overdamped for $\zeta > 1$, critically damped for $\zeta = 1$ or underdamped, when $\zeta < 1$. Corresponding responses are shown on fig 6.6.

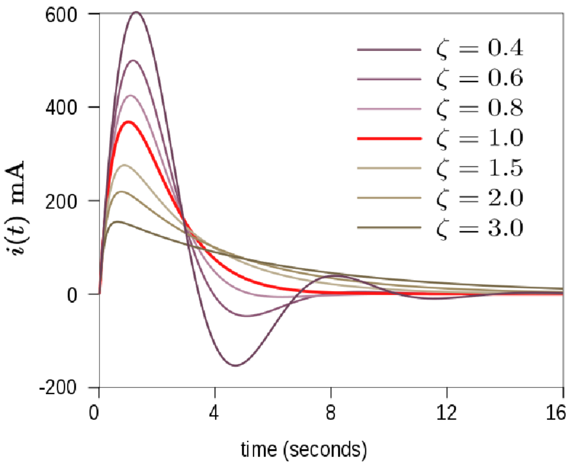

Fig. 6.6: RLC circuit response [17]

Based on the equation 6.7 describing magnetic inductance in solenoid, it is obvious that higher current means higher inductance. Thus overdamped circuit is not desired. The highest current peak is in an underdamped circuit, but resonance generates waves of opposite polarity. These waves could damage both triggering semiconductor and capacitors. Peaks of opposite voltage can be eliminated using anitiparallel diode connected to a coil, as shown on figure 6.8.

$$B = \mu \frac{NI}{l} \tag{6.7}$$

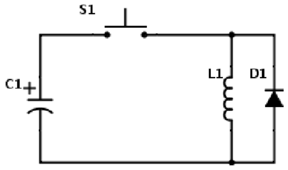

Fig. 6.8: Connecting protective diode

6.5 Speed measurement

In order to calculate coilgun's efficiency, we need to know the kinetic energy of a projectile. A mass is defined by its shape and the material it's made of. Speed measurement can be done in multiple ways. There are many mechanisms using "external" device, such as ballistic pendulum, measuring time difference between shooting and projectile hitting obstacle in known distance or just shooting horizontally and calculating ballistic trajectory, if we measure how far from a gun did the projectile fall on the floor.

To make a measuring device part of the gun, the most straightforward way is an optical gate. For projectile of known length, it's possible to have one gate and to measure the time between projectile blocking the beam and again exiting from it. For unknown length, there must be two of them in known distance.

Another possibility is to use detecting coils. This method uses principle of inducting voltage in a coil, when projectile enters as it's core. Ideally, projectile has no magnetic moment, so steady current must flow through a coil to build magnetic field around it. Having two of these coils in the path of projectile and measuring time between two induced voltage peaks is enough to measure speed.

6.6 No capacitor design

Different approach, however requiring triggering device, which can be turned off, is to use batteries instead of capacitors. Modern Li-poly batteries mainly designed for RC models and similar applications can handle more than a 100C burst current. With the battery pack of let's say 4 Ah, battery pack can handle short burst 400 A current. Battery based design can benefit from no need of charging, thus much faster rate of fire. On the other hand, one cell has nominal voltage of 3,7 V, so there has to be more cells in series, than in case of using capacitors

7 SINGLE-STAGE PROTOTYPE

7.1 Energy storage

The design which was designed for measurements was using capacitors, since there was no suitable battery pack available and triggering device capable of off switching.

Capacitors were from computer power supply units, which are designed for over 200 V. They are not optimal, compared to low ESR capacitors have higher equivalent series resistance, which limits maximal current, hence elongate pulse. After connecting them, they formed a capacitor battery of two 14 mF, 200 V blocks in series, so 7 mF, 400 V in total. Application of eqn. 6.3 gives stored energy of up to 1,12 kJ.

Charging them is done by alternating current via two diodes, where one half-period charges first block, the other one second block. This should ensure approximately the same charge in both blocks, but still to prevent reverse-polarizing of capacitors, there are two antiparallel KY717 (140 A peak [1]) diodes, one on each block.

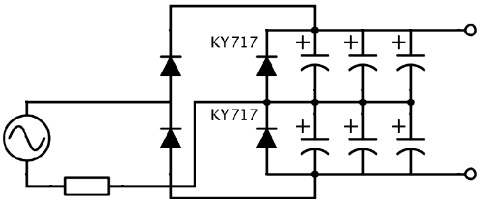

Fig. 7.1: Capacitor storage schematics

Charging them shows voltage difference of maximum around 2 %, which diodes should handle without any risk.

7.2 Triggering

As a switching device, thyristor T 955-63-12 was used. With maximum voltage 1 200 V and 10 ms pulse current of 2 100 A should be more than sufficient. Gate current to switch thyristor on is 300 mA.

7.3 Coil

The coil was winded with 0,8 mm coated wire and designed to launch projectiles of maximal diameter of 5 mm. Coil had 175 turns and dimensions are shown on figure 7.2. Tube needed in center of the coil had to be thin, strong and not interacting with magnetic field. It was made of a paper saturated with waterglass, solution of sodium silicate and water, winded on a rod of the desired diameter. When it became dry, it was removed from the rod and it made a tube hard enough for this use.

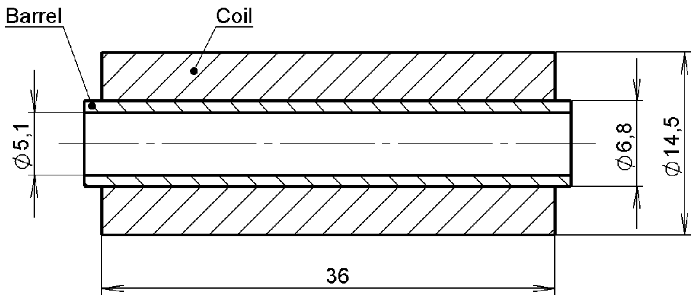

Fig. 7.2: Coil dimensions

For experiments with shell as external magnetic circuit, a stripe of 3 % Si transformer metal sheet 0,25 x 40 mm was used, rolled in 20 layers to form a shape shown on fig. 7.3, which allowed the coil to be put inside. In the middle of both shorter sides, Hole for the projectile to pass were drilled. Cross section of 5 mm round projectile is around 20 mm^2, whereas cross section of external shell is 10 mm^2 for each stripe, making it 400 mm^2 in total for both sides, twenty times more than the projectile. This way, there is no risk of saturating the external shell.

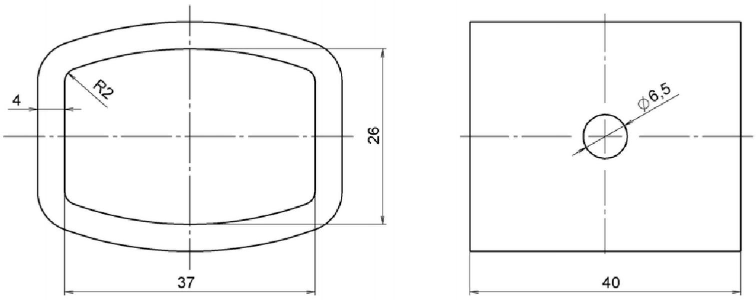

Fig. 7.3: Coil shell

When the projectile is inside the coil, magnetic circuit closes through the projectile, small air gaps and cage around the coil, maximizing induction inside the coil.

7.4 Projectiles

Most of the projectiles for testing had dimensions of a cylinder 4,5 x 48 mm. Different materials were used to compare them and find the most suitable one.

As a representative of most basic iron served a 5 mm nail, which was trimmed to the desired dimensions. To compare magnetic losses, there was one made one of powder somaloy, which is alloy for high frequency applications [11], thus with low hysteresis losses. It was formed of powder glued together with epoxy. One more projectile was also made of powder the same way as one made of somaloy, but the material was Fe_3O_4, ferrimagnetic material. Last one was prepared of transformer metal sheets stacked on top of each other, until it reached desired thickness, welded together and then grinded into shape. Projectiles used for testing are shown on picture 7.4.

Fig. 7.4: Projectiles, from left to right: Fe_3O_4, somaloy, transformer sheets, nail

Weight of projectiles is shown in tab. 7.5

Tab. 7.5: Projectiles mass

Material	Mass (g)
Nail	4,70
Somaloy	3,00
Fe_3O_4	2,60
Transformer plates	4,36

7.5 Speed measurement

Both pair of detecting coils and optical gate were constructed to try them both and compare, which design is better.

7.5.1 Detecting coils

Two coils were winded, both made of 0,2 mm coated wire, both winded on core with inner diameter of 9 mm, length also 9 mm, one of them having around 650 turns, the other one around 350. These coils were put in series with resistors and then connected to a power source, as seen on fig. 7.6. The distance between coils for measurement was 60 mm.

7.5.2 Optical gate

To construct the optical gate, LITEON LTH301-07 optical gate was taken, but had to slightly modified. The gap between two sides of the original gate was 5 mm, which

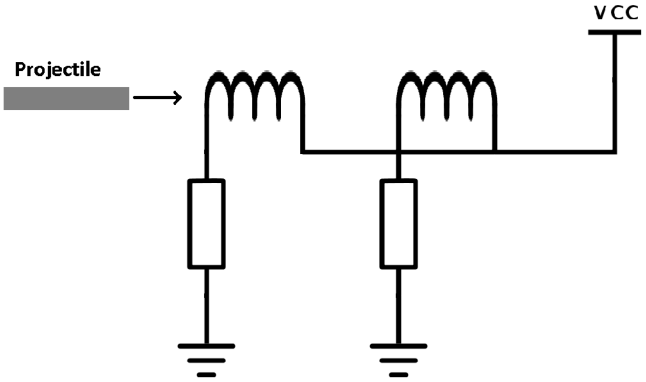

Fig. 7.6: Schematics of coil detector

was increased to 7 mm by cutting it into half and then gluing it together in the needed distance. It was necessary to put resistors on both the transistor and the diode to work on +5 V from USB as supply voltage. As an input device served an Arduino Nano board with an ATmega 328 microcontroller, where interrupts were used to detect rising and falling edge of signal from optical gate.

8 TESTING

8.1 Speed measurement

Measuring speed of projectile was a key feature needed to work to evaluate different projectiles and cage around coil, so making it work was the first priority.

8.1.1 Detecting coils

First of the two methods which was tested were coils. Oscilloscope was connected to the coils themselves to see the shape of a signal coming out of them. Supply voltage was altered, until around 80 mA was going through both coils. When the nail projectile was launched, oscilloscope showed the signal displayed on figure 8.1.

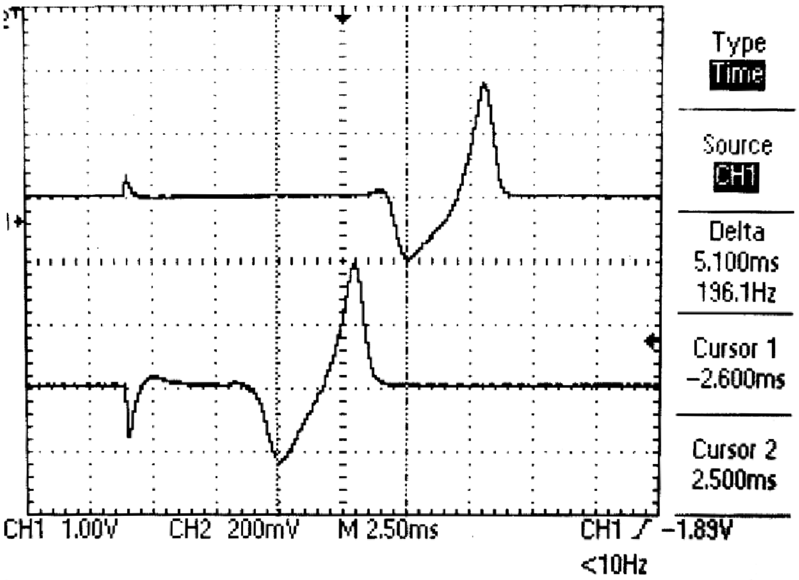

Fig. 8.1: Voltage on detecting coils - nail projectile

On both channels, there are two obvious peaks, one in the beginning, which is in the same time on both coils. It is most probably induced from main accelerating coil. Then there is this "Z" shape, induced by passing projectile. It's easy to measure time shift between these two peaks and calculate projectile speed. In case shown on picture, 11,7 m/s. Amplitude of induced voltage is somewhere around 2 V for one coil, 400 mV for the other one. This should be easy enough to convert into digital signal and using some timer get time difference. Things however got messier using other projectiles.

On picture 8.2 is shown outcome of detecting the somaloy projectile, from only one coil. Its obvious, that voltage peak is much smaller, only around 40 mV, which compared to peak from accelerating coil is smaller. This would be bigger problem to detect using some other device than human reading from oscilloscope.

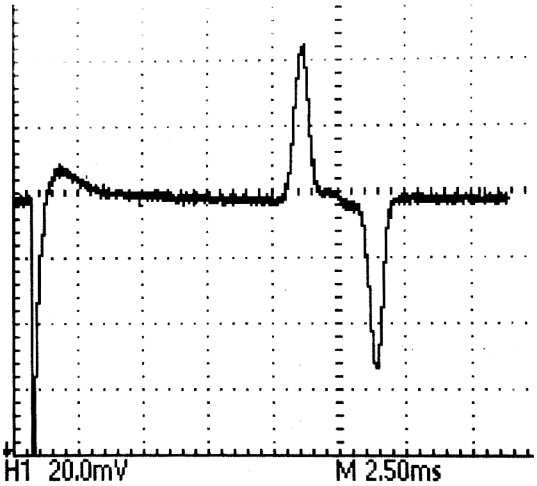

Fig. 8.2: Voltage on detecting coil - somaloy projectile

By the way, there is obvious difference in the shape of induced voltage. Signal from nail is made of one peak in the beginning and opposite one in the end with almost linear ramp between them, whereas the somaloy one is made only from two peaks and between them the signal is returning to zero. Most probable explanation of this phenomenon is remanent magnetization, which in case of nail was much bigger, so while passing through coil, there was constantly induced voltage, whereas in case of somaloy, which is much softer material, there were only peaks caused by change of coil inductance while ”inserting” core.

Detecting the Fe_3O_4 projectile was even harder, than one made of somaloy. Lower voltage than in case of somaloy and the shape was much more complicated.

Another problem with this method was with small speeds of projectile. While launching at lower voltage, the speed of projectile was getting lower, hence induced voltage was getting lower and it was causing problem even for a triggering circuit of oscilloscope.

8.1.2 Optical gate

Measuring with optical gate was way easier. Only resistor in series with phototransistor had to be selected so it gave voltage above and below the threshold of log.1 for microcontroller, which was 2k2, microcontroller had to be programmed and for certain length of projectile, microcontroller was returning speed. No oscilloscope was needed. However, measuring was done to see if it works correctly. Outcome is on fig. 8.3.

This signal is obviously much easier to detect than the one from detecting coils. It has sharp rising and falling edge and has only two values. The value microcontroller was returning was found to be correct.

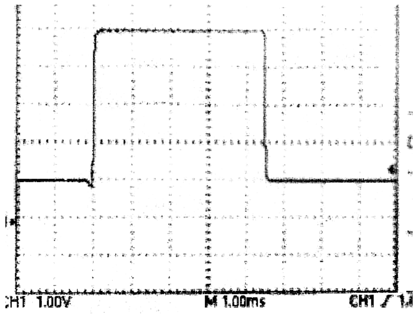

Fig. 8.3: Signal from optical gate

8.1.3 Conclusion

Comparing these methods, optical detection is obviously much more practical and easier to assembly. There could be a situation, where its impossible to use it, for example measuring speed of a projectile of conventional firearms, where it is impossible to penetrate the barrel to insert optical gate. In cases like this, there could be coil detection useful, however for coilgun use, optical gate is definitely a better way.

8.2 Discharge

Using voltage divider and oscilloscope again, capacitors discharging was measured. Measuring voltage on coil, done for 200 V charge, gave the result shown on figure 8.4. Voltage is approaching discharged level and doesn't cross it into reverse polarity, which indicates critically damped or overdamped circuit. Picture can be used to approximately calculate current and from known parameters of coil, magnetic induction inside a coil can be approximately calculated. Using 6.7, induction in solenoid for free space is between 5 and 6 Tesla. In other words, far beyond saturation of any normal material [5].

Approximation of function using intersections of a plot with grid on oscilloscope gave a cubic function, which derivated in the point of maximal current, 0,3 ms from launch, multiplied with known capacitance returned maximum current 900 A. That means resistance of circuit around 0,2 Ω.

8.3 Firing different materials

8.3.1 Starting position

Designed coilgun was using thyristor, so it was impossible to turn it off the moment projectile passes midpoint. To minimize the suck-back effect, but to use as much energy as possible to transfer into projectile, optimal starting position for projectile had to be found.

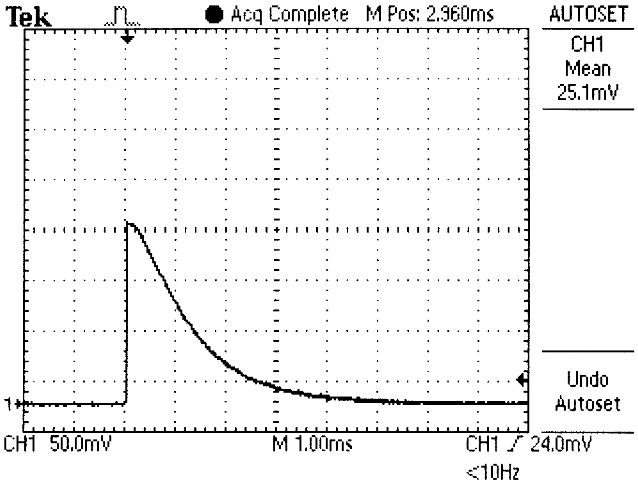

Fig. 8.4: Capacitors discharge for 200 V

Minimizing suck-back basically means pushing the projectile further from the coil, so it takes longer for it to travel that way and meanwhile the capacitors can discharge. However if projectile is pushed too far, gradient of induction gets too small to suck the projectile in, so both processes are going against each other and there must be one optimal position, where projectile is launched with biggest kinetic energy.

To find this spot, a ”zero mark” on a board was marked around 5 cm from coil’s midpoint. All distances are measured relatively to this point. Multiple launches from different distances and for different voltages were made. Figure 8.5 shows result.

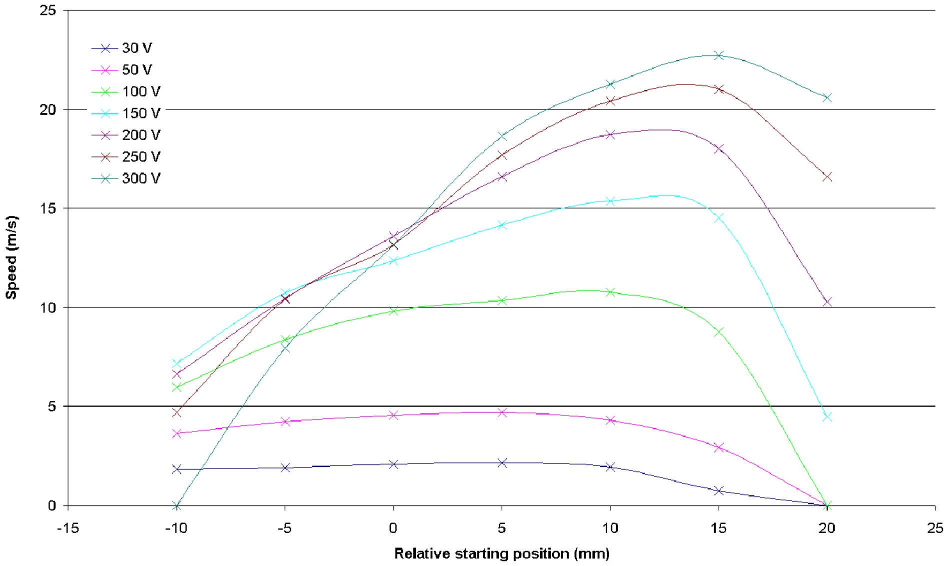

Fig. 8.5: Relation between speed and starting position for different voltage. Plot is for somaloy with caged coil.

Reading from the graph shows, that for lower voltage it's much less important to properly place the projectile, but the higher the voltage, the more precise placing is required. It's also interesting, that there is some point, from which it's better to use lower voltage.

Most possible explanation is that when charging to a higher voltage, projectile starts to move faster and reaches midpoint sooner, when there is still some charge in capacitors. When it reaches the midpoint too soon, it can even stop, like in case of the 300 V and -10 mm position. In this case, projectile must have reached the midpoint when over 50 % of energy was still in capacitors. Whereas when charged to a lower voltage, projectile didn't move that fast and capacitors were completely, or almost completely empty, when reaching midpoint.

Conclusion

For testing every material, there was series of measurement to be done to determine, where the most effective starting position is. There is much bigger field to be examined, if one had a device capable of turning to off-state before current goes through zero, such as FET of IGBT transistors. It is possible that speed would go even higher, if coil was turned off when projectile in midpoint. Or maybe not faster, but there would still be some energy left in capacitors, hence efficiency of the whole device would be better.

Graphs shown later on in this text are made using only the "top speed" which is obtained by a series of multiple measurements, as shown above on figure 8.5.

Note: All measurements are done only to max. 300 V, even though it's possible to charge up to 400 V. This is mostly as a security precaution, operating with 400 V capacitors with 1 kJ stored energy was something which was considered too much of a risk compared to the value it could have.

8.3.2 Without external cage

Fig. 8.6 shows the speeds reached using different projectiles.

There is a disappointment with somaloy performance, which is supposed to be a material that could be suitable for this application. Projectile made of iron oxide was by far the worst, which is not very surprising, since it's ferrimagnetic, which gives it smaller susceptibility and is sooner saturated. It could however serve for following comparison. Powder-made projectiles have to carry certain mass of magnetically inactive compound (epoxy), which increases mass, but doesn't increase the accelerating force. As an effect, it decreases speed.

One more projectile was made, also of ferrite, but now it was ferrite antenna, made "professionally", so there should be much higher density of material, without any unnecessary glue. When shaped to the same dimension as powder-made one, it was measured. Figure 8.7 shows result.

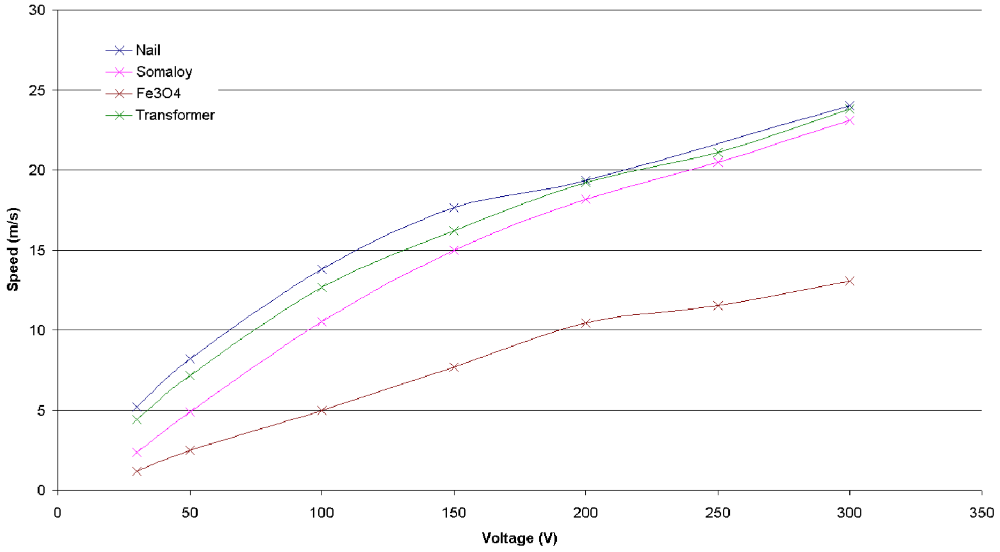

Fig. 8.6: Speed of different projectiles for different materials, without external cage

Apart from a small difference on 200 V, the two lines are almost identical, which leads to a conclusion, that since imperfect fabrication in case of iron oxide doesn't make that much of a difference, it is probably the same with somaloy. Even if it was fabricated using advanced metallurgy, the difference would most probably not be as significant.

8.3.3 With external cage

Then the coil was inserted into cage made of transformer plates (fig. 7.3) and measurements repeated, this time only for ferromagnetic materials. Fig. 8.8 shows the results. Corresponding colours are the same materials, light is without and dark is with the cage.

Results shows mostly an insignificant difference. In case of somaloy and transformer projectile, the difference is negligible, using nail-made projectile gives a slight difference in medium voltages.

Possible explanation is that, on low voltages, capacitors discharge while there is still big air gap in the middle of the coil. Air gap is then a dominant magnetic resistance, so the external shielding, which by its own has a much smaller effect than core inside a coil, doesn't play a big role. Getting the same results on high voltage may be caused by a saturation of the projectile, which is then limiting factor. Only in medium voltage, where air gap is getting small enough to lose its dominance and projectile is not yet saturated, the external cage has its effect.

8.4 Effect of different size of a projectile

This chapter will focus on determining the optimal projectile dimension.

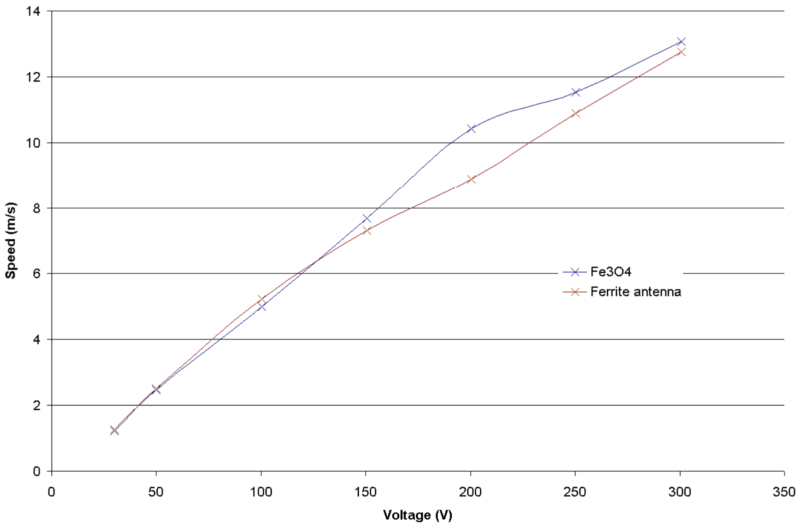

Fig. 8.7: comparison of two different ferrites

8.4.1 Different length

First experiment in this field was trying different lengths of the projectile. New 5 mm nail was cut into 100 mm long cylinder. Then while removing small parts of it, speed was measured for multiple lengths. Fig. 8.9 shows, what was measured.

All projectiles had the same shape and material, so there was no problem with counting the kinetic energy, which is also printed in the graph. Mass was counted only analytically, from known shape and approximate density of iron 7,8 g/cm^3.

On the graph, there is an obvious peak for length around 3,5 to 4 cm. This length is also the length of a coil or the coil with a little piece of external cage. For projectiles longer than this, kinetic energy decreases slowly, contrary to the shorter projectiles, where decrease is more rapid. Explanation can be found in the fact that longer projectiles are able to close magnetic circuit with minimal amount of air gaps, whereas shorter projectiles can't do that, so magnetic induction doesn't reach that high.

8.4.2 Different cross section

If we took a smaller diameter of projectile, then the measurement would be affected by a change of an air gap between the projectile and the external cage. In order to eliminate that, projectiles with inside of them removed were fabricated, leaving a tube shaped projectile. Three projectiles were made, with 2,5, 3 and 3,5 mm inside diameter.

But still, two more standard nails, one with diameter 2,8 mm, the other one 3,6 mm were measured. Table 8.10 shows results.

Inner diameter of the coil was reduced, because it was designed to launch larger projectiles and smaller ones were not passing through the optical gate. As a side effect of inserting a spacer, it had much less friction, which can explain the higher speeds than

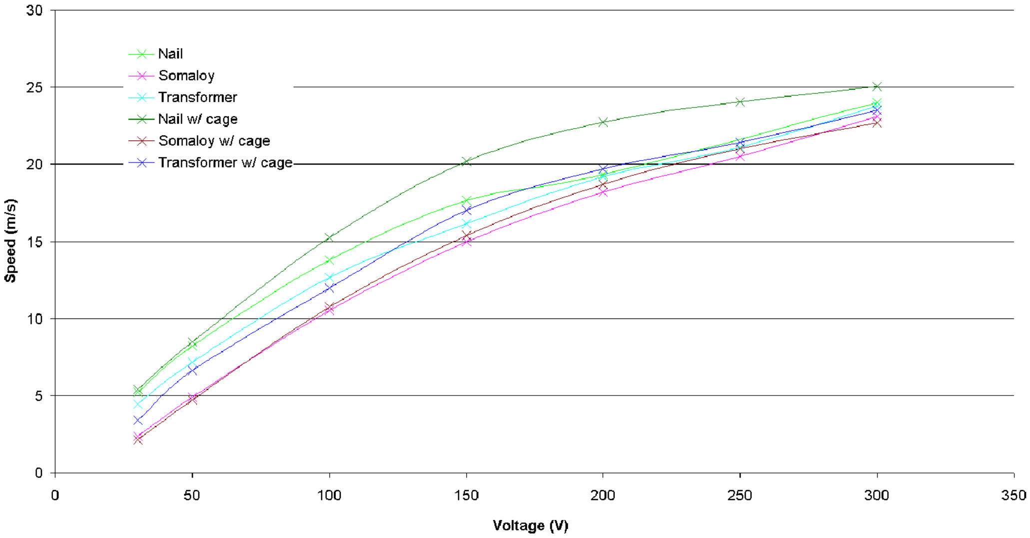

Fig. 8.8: Speed of projectiles using external cage

Tab. 8.10: speed and energy of different projectile diameters

Diameter (mm)	Cross section (mm^2)	Speed (m/s)	E_k (J)
2,8	6,1	15,0	0,22
3,6	10,2	14,8	0,35
5	19,6	12,8	0,50
5, inner hole 2,5	14,7	13,6	0,42
5, inner hole 3	12,6	14,2	0,39
5, inner hole 3,5	10	14,1	0,31

5 mm projectiles, however there is no difference between the two smaller diameters. Considering kinetic energy, bigger diameter means much bigger kinetic energy. There is a small decrease in speed for the heaviest projectiles, but kinetic energy is still increasing. The friction issue however complicates comparing 5 mm projectiles with smaller ones.

Nevertheless, same speed for smaller projectiles leads to an idea, that when fabricating a projectile with smaller cross section, they can be compared using only speed. This obtained knowledge led to a production of one last projectile, made of a transformer metal sheet.

When producing the first one, some extra glue was added and during welding, which melts the iron, it could have lost its magnetic capabilities. Now, just a 40 x 40 mm piece was taken, which gives a cross section of 10 mm^2 and was bended over and over, until it fit inside. This way, it was possible to launch it while being sure that there is no extra ”non-magnetic” mass and the material still has its qualities. However, testing in the same conditions as tests shown on table 8.10 gave speed of only around 13 m/s, so it’s still not better than basic nail iron.

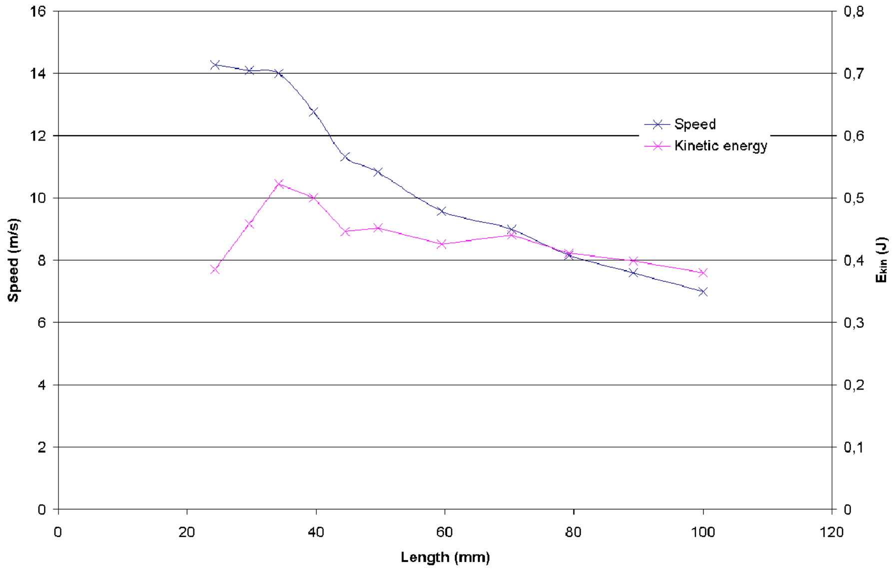

Fig. 8.9: Speed of projectiles using external cage for different lengths, measured with 100 V charge

9 CONCLUSION OF FIRST PROTOTYPE PERFORMANCE

There is still much to be explored, like where is the limit for increasing diameter of projectile. Equation 6.7 doesn't contain diameter, so increasing it shouldn't effect field much, while increasing kinetic energy of a projectile.

From these researches, there are however some interesting outcomes. Printing energy and efficiency graphs were avoided so far, mostly because what was mentioned in the chapter "Effect of different size of a projectile". Figures 9.1 and 9.2 show, how much energy does the projectile gain and how much it is compared to energy stored in capacitors.

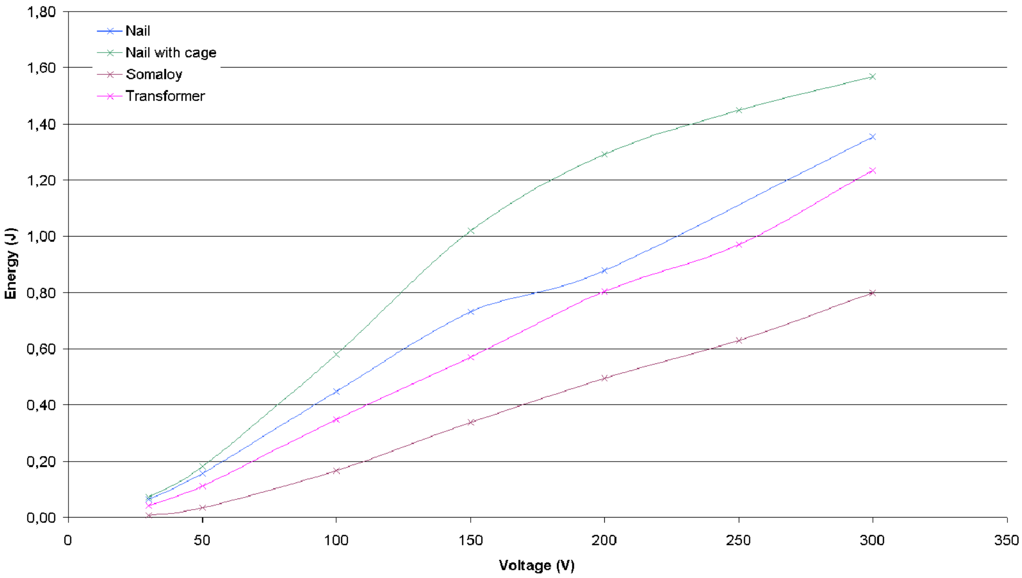

Fig. 9.1: Energy of projectiles for different voltages

Efficiency decreases with capacitor voltage, with top value at around 2 %. From these graphs, using of external cage seems much more beneficial, than it seemed from the plot showing speed. Peak increase of kinetic energy with cage was more than 50 % for the nail-made projectile.

Curve showing projectile energy of nail with cage (without cage also, if we consider value for 200 V an error and place it a bit higher) resembles the initial magnetization curve, which for higher voltages is reaching to saturation. This would also explain projectile launched without cage catching up with one with cage. Projectile started to be bottleneck for magnetic flux, hence external cage didn't bring much benefit.

Magnetic losses in a projectile are most probably not very dominant. Using low-loss materials didn't show any better performance, than iron nail, which is optimal environment for eddy currents and hysteresis loop is probably also pretty big. This guess is based on presence of big remanent magnetization, when after launching, projectile stayed magnetized enough to be sticking to screwdriver and other iron materials.

Design of coilgun with better efficiency would lead to the multi-stage design, where area

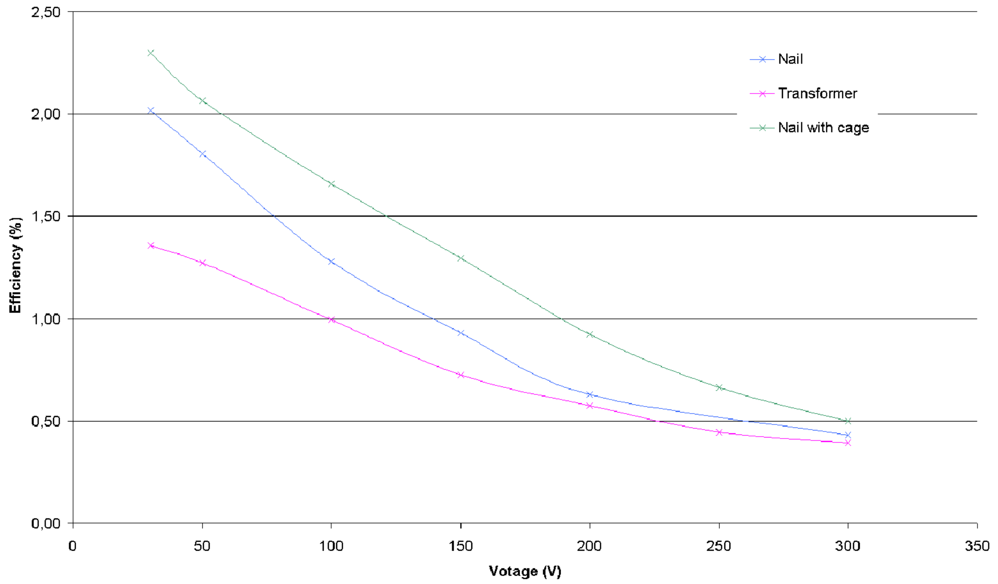

Fig. 9.2: Efficiency of energy conversion

of low voltage and better efficiency can be used and high velocity reached via multiple accelerations. Best performance was reached with a projectile with a length of a coil and using external cage. Diameter of the projectile should be as big as possible to put in a coil while trying to make wall between coil and projectile as thin as possible. Optimizing current pulse time with better triggering device could lead to better results as well.

10 MULTISTAGE DESIGN

Based on knowledge gained with a previous prototype, on multistage design, some changes were made. As was measured, increasing diameter should increase efficiency, at least to some point. Instead of using 4,5 mm diameter, new barrel and coils were made for using 6 mm diameter projectiles. Another modification was using wire with slightly bigger cross section for acceleration coils. Instead of 0.8 mm diameter, 0,95 mm diameter was used. Most important modification was however using multiple accelerating stages with power MOSFET transistor switching, giving an option not only to turn the coil on, but also to turn it back off before reaching 0 V in the capacitor bank.

Capacitors available gave the best option to split them into four 7 mF / 200 V banks, hence pointed the direction into doing four-stage design.

Designing multistage design carries out much bigger controlling demands, which following chapters discuss

10.1 Monitoring position

In order to achieve maximal efficiency, precise position of the projectile in the barrel must be known. Instead of simple one optical gate on the exit of the coil for speed measurement as in thyristor single-stage design constructed in previous chapters, there are few more gates required.

For minimizing the ”suck-back” effect, the moment when projectile starts to exit the coil, in other words ferromagnetic core starts to disappear from it hence making coil inductance smaller, based on the equation 6.1, that is the moment when acceleration turns the opposite direction and is the moment the coil should be disabled. Based on the same equation, there is no point in turning the coil on before the projectile starts to enter into the core of a coil. Inductance change would be small in that case and most of the energy would get lost as a Joule heating in the circuit.

Based on the experiments with different lengths of a projectile, the best performance was achieved with projectile around the same length as the coil. This simplifies the situation in a way that there is no need for separate optical gate for detecting entering the core and passing midpoint in the coil. When projectile starts to exit out of the coil on one the other side, it is also the moment the last tip of it disappears in it on the back side. Which means only one optical gate can be placed on the entrance of the coil and turns the coil on the moment it gets blocked by the passing projectile (meaning it starts to enter the coil) and turn it off the moment it gets unblocked again (meaning projectile is starting to exit on the other side). For determining an efficiency of every specific stage, Δv of every stage must be know, meaning additional gate for speed measurement, which can be placed anywhere between exit from one stage and entrance into the other, but due to the friction losses, position as close to exit as possible is preferred. Another way would be to measure time duration between exiting one optical gate and blocking the next one, which is moment the projectile is not accelerating and speed can be calculated. If using microcontroller unit (further referred to as MCU) to trigger the stages, this way it would place higher demands on speed it can process the code, because not only it had to trigger the stage, but also record the time of passing the gate.

Another reason for placing additional gate for speed measurement is that there are physical limitation of placing the gate directly at the entrance and some gap will always be present. With this gap, let's say 5 mm, the coil would be turned on with projectile still 5 mm away from the coil, probably reducing efficiency. This could be compensated from known distance of the gate from the coil and known speed by calculating time delay to turn the coil on. With optical gate used only for speed measurement, the speed can be know before the projectile reaches the gate at the entrance of next stage and doesn't have to be calculated before making the adjustment for delayed turning on, further reducing demands on MCU.

This led to the need of eight optical gates for 4-stage design, always one on the entrance and one on the exit of every stage.

10.2 Electrical circuit design

10.2.1 Power source, +5 V source

As a main power source, there is a 3s Li-po battery pack, voltage ranging from 12,6 to 9 V. To get stabilized 5 V, simple linear 7805 stabilizer is used. Figure 10.1 shows schematic.

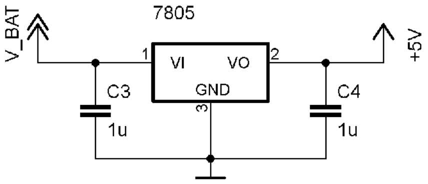

Fig. 10.1: +5 V voltage source

10.2.2 Optical gate diodes source

Optical gates are modified TCST1103 to have a wider gap around 8 mm. Emitting diodes are connected in series by four to reduce the current drain from a battery. The current is biased to around 50 mA using 1:2 current mirror with NX7002 N-channel MOSFETs. Schematic diagram shown on figure 10.2.

10.2.3 Optical detectors logic

This amount of optical gates would place high demands on MCU in a different way. Eight gates would mean eight I/O pins used only for optical gates, so putting it through

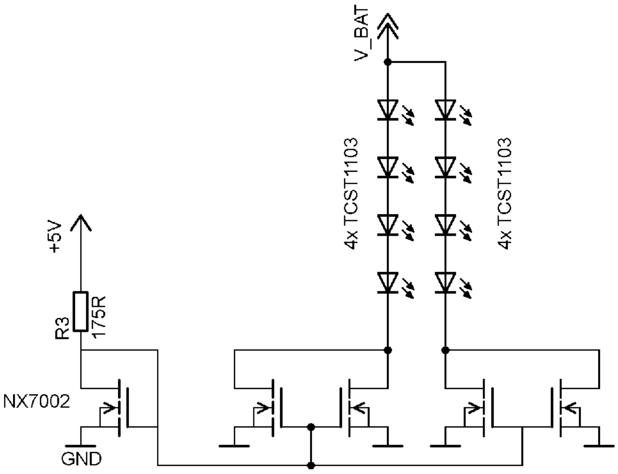

Fig. 10.2: Optical gate diodes source

some logic to convert it into binary code comes handy.

Into this logic between optical gates and MCU, another element was integrated. To understand this element, short introduction into transistor characteristics should be done. While a transistor is turned fully on, it has only tiny resistance, generating only small thermal energy. But the transition state between being in off-state and on-state is the moment when the series resistance of a transistor is big and passing current, which is in this application prety big, can harm it. In order to prevent it from happening, two rules should be obeyed. First: Turn the transistor on/off as fast as possible. Second: Minimize the amount of turning it on/off.

Transition time cant be solved in this part of a circuit, but adding hysteresis circuit between optical gate and a MCU should prevent it from switching between log.0 and log.1 states few times due to some imperfections in signal from optical gate, caused either by its proximity to the coil, which is a big source of EMI (Electromagnetic Interference), or by some imperfections in a projectile shape.

Turning the coil on/off is the highest priority task the MCU should do, so interrupt is used to perform this task. One pin of it used as an interrupt signal, so all the gate signals are apart from 8-to-3 decoder led to 8-input NOR gate to get a change in its value every time any gate goes blocked or unblocked. Meaning however, that gates must be further from each other than one length of a projectile.

Zener diodes for 5.1 V were used to protect the logic elements from possible induced spikes.

Simplified schematic with only one detector input shown is shown of figure 10.3.

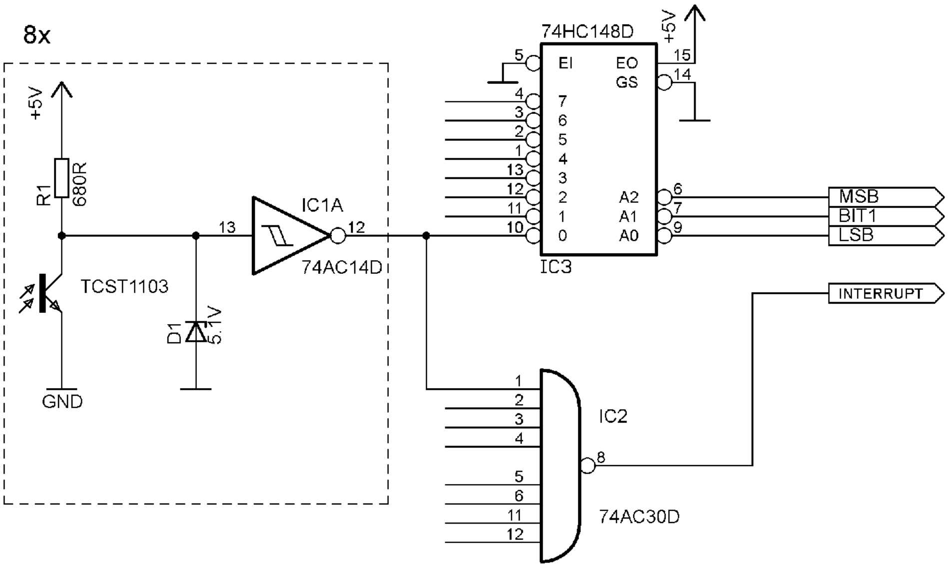

Fig. 10.3: Optical gate detector logic

10.2.4 MOSFET drivers

Although MOSFET transistors are voltage controlled, logical outputs of a MCU are not suitable for driving them directly. One reason is that operating voltage of MCU's is not high enough to fully open transistor, which would result in higher thermal losses in it, possibly damaging it or at leas reducing efficiency of a device. Another is gate capacity of a power transistor, where short current burst is needed to achieve desired U_{GS} voltage in as short time as possible. Gate drivers are components designed specifically to solve these two problems. Maxim Integrated 4420CSA+ gate driver was suiting this application. Schematic of one of the MOSFET drivers is shown on figure 10.4, but four of them are present, one connected to individual MCU pin and to one accelerating stage.

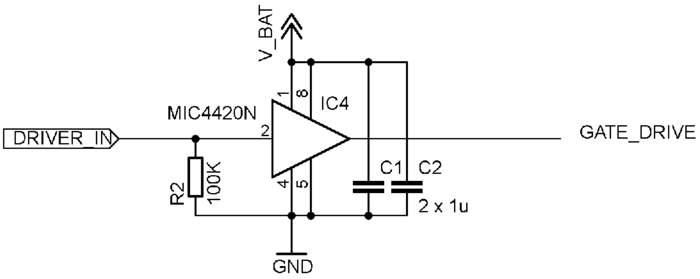

Fig. 10.4: Main MOSFET drivers

10.2.5 Capacitor charging circuit

To charge the capacitor bank from a battery is task analogical to charging flashlight capacitors in cameras. Specialized circuits are being made to perform this. Principle of their work is PWM switching current into primary winding of the transformer, inducing higher voltage in a second one. Detailed description can be found in a datasheet of LT3750, which is also the one which was used in this design [12].

One of the feature is sensing the capacitor voltage without any feedback from them and turning the charging cycle off when desired voltage is reached. To get the capacitor voltage is important for MCU to count the efficiency, so there is still a voltage divider and output goes to ADC in the MCU, which then can turn the charging on/off when desired using the CHARGE pin of the LT3750, but this integrated functionality can be set as an safety feature to turn off the charging in case MCU stops working for some reason. Charge signal from MCU doesn't go to a charging circuit directly, but into NOR gate together with signal from a switch, using which the charging cycle can by also controlled. Capacitor charging circuit is displayed on figure 10.5.

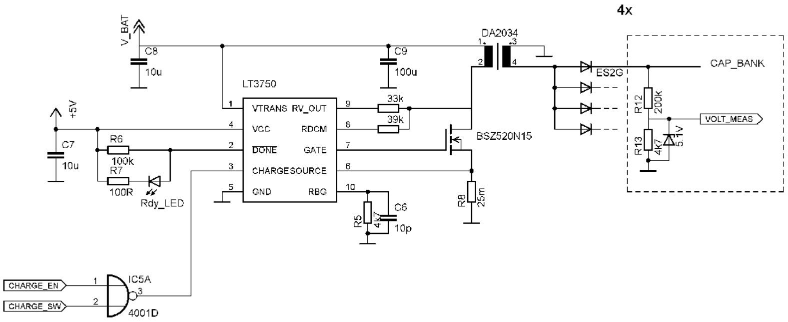

Fig. 10.5: Capacitors charger circuit

10.2.6 Power MOSFETs

Based on previous prototype, power MOSFETs should be designed to currents around 1 kA. Connecting two IRFP4668 in parallel should handle pulsed current of just about that value with maximal U_{DS} of 200 V, which also suits the capacitor bank. Due to the supply shortage, only two stages use these transistors and 2 remaining stages are switched with different transistors capable of only 100 V, so all the measurements will be limited by this value. Connection of power MOSFETs is on figure 10.6. Four of these circuits are present, one four each individual stage.

10.2.7 Discharge circuit

Feature also added since the first prototype is a circuit which can be used to safely discharge the capacitors without launching a projectile. This is simply by discharging the

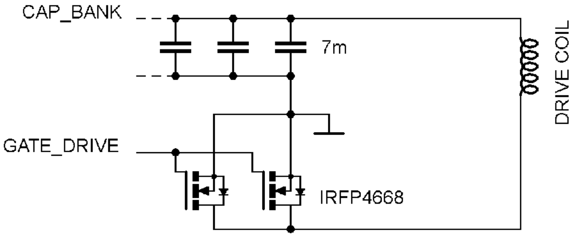

Fig. 10.6: Accelerating stage power circuit

charge into 220R 20W resistors via BT169 thyristor. Capacitor discharge circuit diagram is displayed on figure 10.7. Four of these circuits are present, one four each capacitor bank.

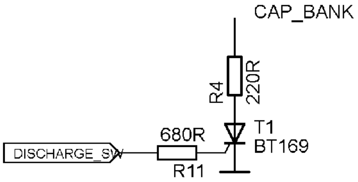

Fig. 10.7: Discharge circuit

10.2.8 Microcontroller unit

All together, there are 4 signals with capacitor voltage, 3 bits of blocked optical gate + 1 interrupt, 4 gate drivers, 6 pins are used to communicate with 20*4 character HD44780 lcd display, one pin for controlling the capacitor charge and one for trigger. That together makes 20 I/O pins required, four of them capable of A/D conversion. For this prototype, also Arduino Nano module was used, mostly for more simple programming. With ATmega328p, it has just exactly amount of pins needed for this application. Exact connection of signals to the board is following:

Display: (rs, enable, d4, d5, d6, d7) D7,8,9,10,11,12
Interrupt: D3 (on schematic displayed as signal INTERRUPT)
Opt. gate: D4,5,6 (signals MSB, BIT1 and LSB)
trigger: D13
Charge enable: A0 (signal CHARGE_EN)
Gate triggers: D2, A3, A4, A5 (signal DRIVER_IN)
Capacitors: A1, A2, A6, A7 (displayed as signal VOLT_MEAS)

10.2.9 Switches

There are four switches connected as follows:

Without arretation:
Trigger: with pull-up resistor, connecting to the ground
Safe discharge: Connects to +5 V (signal DISCHARGE_SW)

With arretation:
Capacitor charge: with pull-up resistor, connecting to the ground (signal CHARGE_SW)
Backlight: Connects cathode of a backlight to the ground

Connection of pull-up switch is shown on figure 10.8

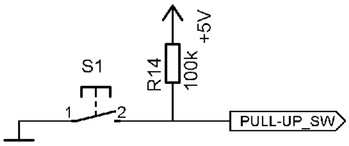

Fig. 10.8: Pull-up switch connection

10.2.10 Board layout

Circuits were done on multiple boards, one for logical circuits, another for capacitor charging circuit, current source and voltage dividers. Possibility of EMI of capacitor charging circuit was the main step for putting it on a separate board. Both of these boards are double-sided with one side as a ground. Power MOSFETs are also separated, because of EMI as well.

Board layouts and component placement can be found in attached documents. Attachment A and B are for the board with logic circuits and gate drivers, attachments C and D are for board witch charging circuit, current sources and voltage dividers. Note, that the component names doesn't correspond to names on simplified schematics above. For full schematics with corresponding names, refer to attached CD.

10.3 Accelerating coils, projectile

As was mentioned, the coils are winded with 0,95 mm wire to into to same cage as previous prototype (fig. 7.3), but hole drilled to 7 mm diameter to fit the bigger projectile. Dimensions are shown on figure 10.9. Every coil has 35 turns in one layer, 6 layers, making it in total 210 turns.

As a testing projectile, cylinder of 6 mm diameter and 42,5 mm long made out of rod made of 1.4301+2H steel.

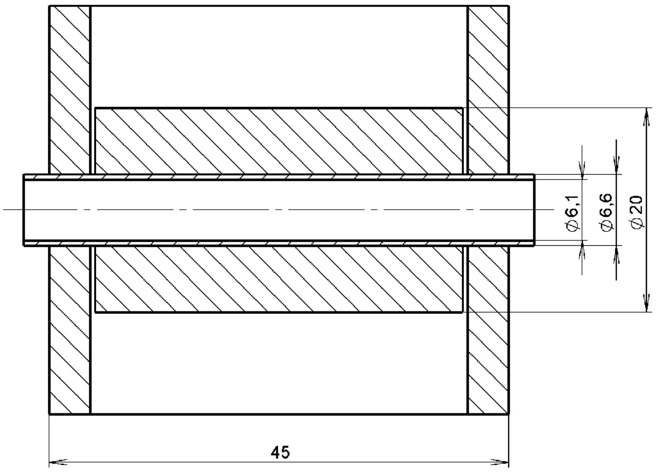

Fig. 10.9: Dimensions of accelerating coil

10.4 Controlling program

Following flowchart displays, how the MCU is programmed. The top chart is the repeating loop, the bottom chart is interrupt service routine. The time delays in switching are results of extensive test, which will be discussed later. Source codes can be found on attached CD.

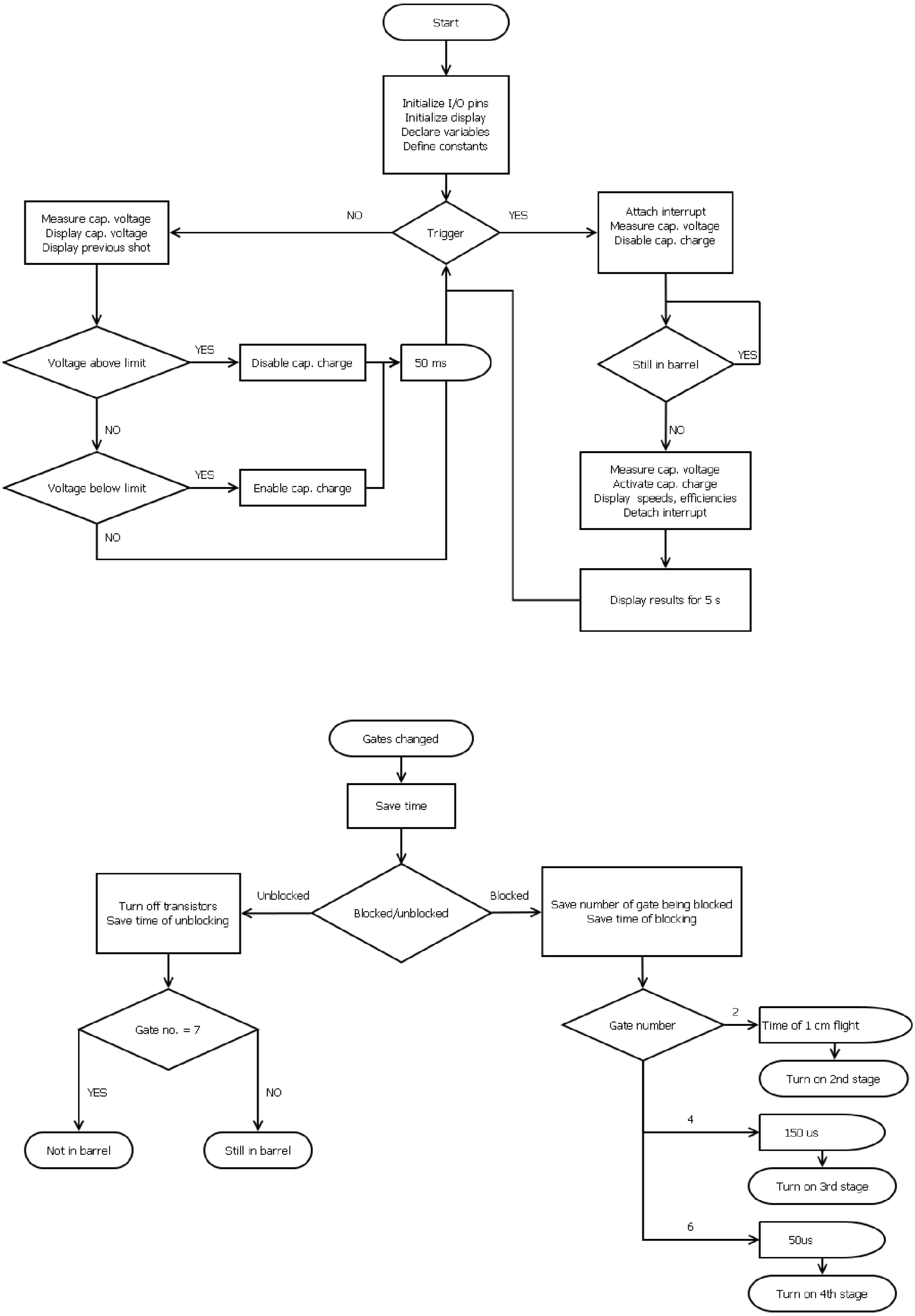

Fig. 10.10: Controlling program flowchart. Top is program cycle, bottom is interrupt handler

11 TESTING OF MULTISTAGE DESIGN

11.1 Advantage of turning the coil off

First step was to compare advantages of being able to turn the coil off to eliminate suck-back effect. In order to achieve this, multiple measurements were done with modified program, where switching the coils off was disabled and with only one accelerating coil active.

Figure 11.1 shows two dependencies of efficiency on starting position for both modes tested. Note that the efficiency is not calculated accurately, constants for mass and capacity were omitted, so it serves only as comparison between these two modes. The 0 mm mark is 40 mm from coil midpoint and back of the projectile was aligned with it.

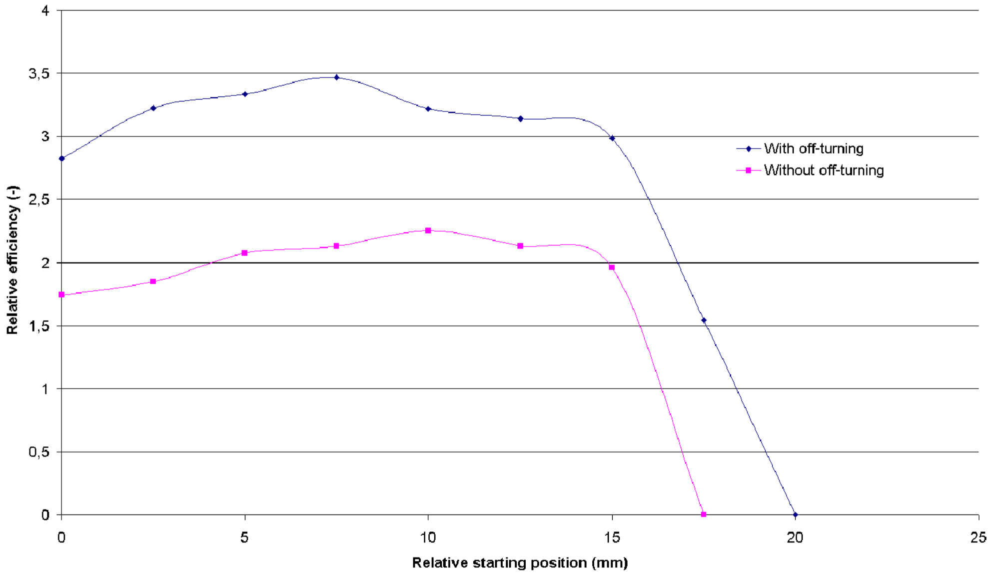

Fig. 11.1: Dependencies of relative efficiency on starting position

The efficiency is almost two times better thanks to this capability. Not only eliminating suck-back effect which increases speed, but also some of the charge is left in the capacitors, which also has positive effect on efficiency. Small bonus is slightly smaller dependency on precise starting position.

Testing this on the first stage was however not so effective since almost all charge was used even when turning off. So the same measurements were done for next stages. Again keep in mind, that efficiency is only relative. Figure 11.2 shows the results.

With increasing speed of a projectile, time with the projectile in an ideal position for being accelerated is getting shorter and the efficiency with off-turning is increasing. On the fourth stage, the efficiency with turning off is around five time better.

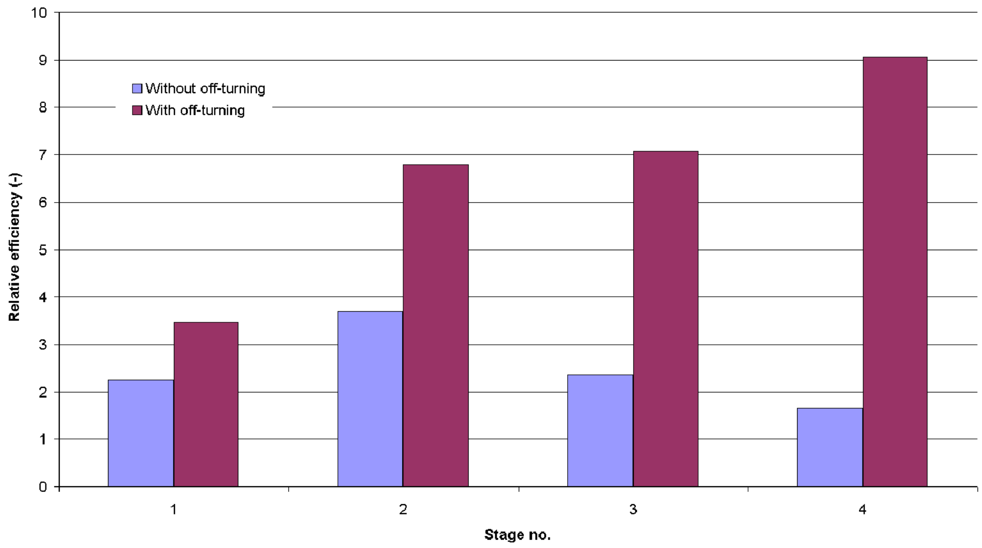

Fig. 11.2: Efficiencies of different stages

11.2 Advantage of delayed stage launching

As was mentioned in earlier chapter, there is a physical limitation of placing the optical gate. With prototype made, distance between light beam and beginning of the coil (meaning front end of the magnetic circuit around the coil) was around 5 mm. While charging to 50 V, exiting speed from the first stage was around 10 m/s, so the coil would be launched 500 µs too early. Delayed launch was then tested for various delays for all the stages and the dependency is printed on figure 11.3. There are only 4 values printed for each stage, but every one of them is an average of 5 measurements, so there should not be any mistake caused by one wrong launch.

For every stage, there is a peak on a value which corresponds with around 10 mm travel, so the best efficiency was achieved with launching the coils with projectile 5 mm already inside of them. For the second stage, the efficiency is changing by a large margin, because the projectile is travelling there slower compared to later stages, meaning more energy is wasted before it reaches the area where it gets affected by the magnetic field and starts to accelerate.

From figure 10.10 is obvious, that tested prototype can be programmed to any desired charge voltage, unless it reaches the limit the capacitor charger is designed to. Then there is however problem, that charging to different voltage changes speed of a projectile throughout the stages and the time delay won't fit the desired 10 mm travel.

This problem can be solved by variably counted delays using known time of projectile travelling its own distance. Simply delaying the launch by one fourth of a time previous optical gate was blocked should give an optimal launch delay.

Laboratory experiment proved this right for the second stage, where experiments with

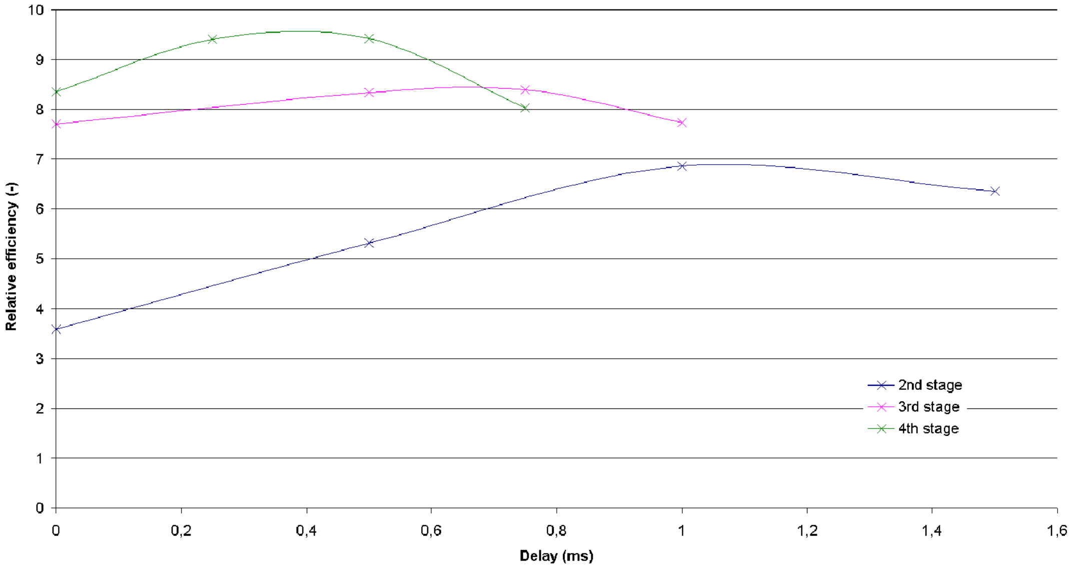

Fig. 11.3: Efficiencies of stages vs. launch delay

dynamically counted delay compared to fixed one obtained from figure 11.3 showed better results. Figure 11.4 shows comparison between using fixed 1 ms delay and dynamically counted delay giving the projectile 10 mm of travel before launching the stage. Most obvious advantage is while using lower voltages, where lower projectile speed causes discharging most of the energy before the projectile can be effectively accelerated. For higher voltages, the difference in efficiency is not that significant because both coils were launched when projectile was already in ”effective acceleration zone”. Higher speeds were however achieved with variable delay, because the launch was sooner and distance over which the projectile was accelerating was longer.

With later stages however, the situation gets more complex. Figure 11.3 shows, that there is not so significant difference in efficiencies for delayed launch, but some improvement still can be achieved.

Counting the delay dynamically proved to be most efficient for low voltages and low speeds when there was enough time for MCU to perform the task. However with projectile travelling in higher speeds, putting static delay proved to be more of an advantage, because no task had to be performed. Figure 11.5 shows efficiencies comparison for different delaying methods. For higher voltages it might appear it doesn’t matter, but taking higher energy gain into account (only fourth stage showed for clarity), overall performance for higher voltages is better for static delay.

As an optimal way might appear to set different delays for different voltages, but time MCU needs to process the more complex function is also causing a trouble with precise switching.

The best compromise over all voltages was found dynamic delay for the second stage and fixed delay on later ones.

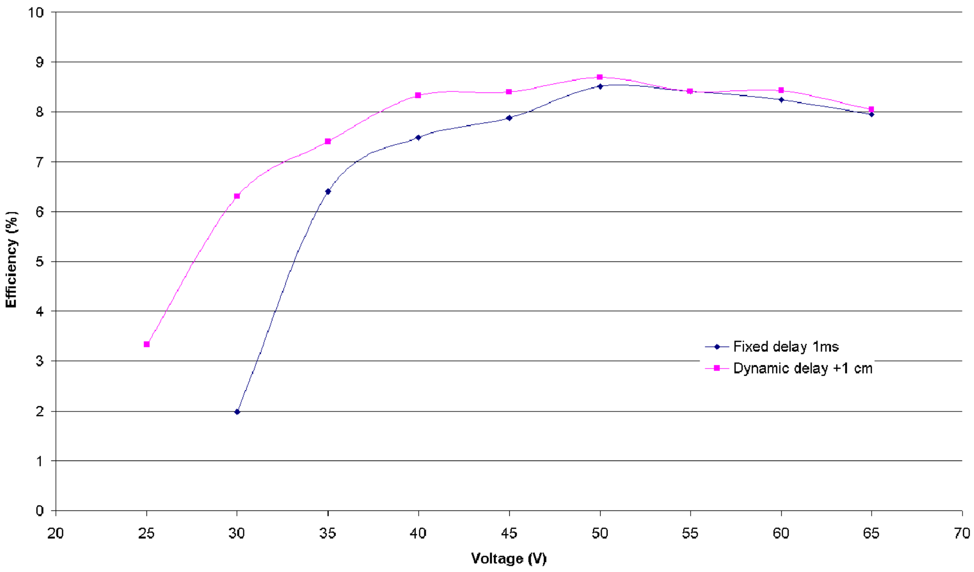

Fig. 11.4: Comparison between different delaying methods for 2nd stage

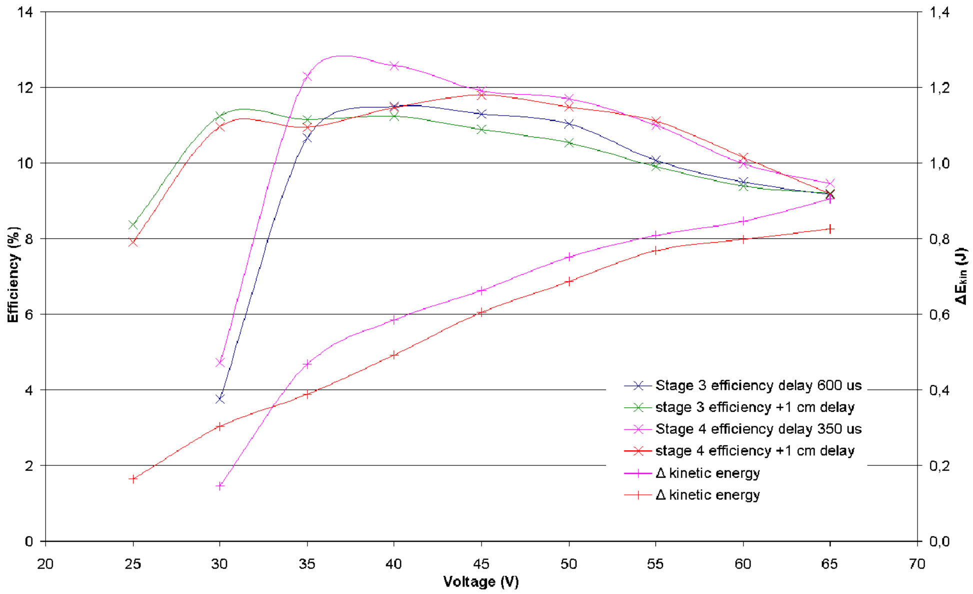

Fig. 11.5: Comparison between different delaying methods for later stages

From the point of view that maximizing efficiency is a way of reaching maximal muzzle velocity, optimal static delay had to be found for close to maximal voltage.

Figure 11.6 shows efficiency and kinetic energy change dependencies for last two stages while charging to 80 V. Effect on the efficiency of the 3rd stage is minimal. Fourth stage is more sensitive to the precise timing. As some optimal value and compromise between energy gain and efficiency could be considered 300 µs for 3rd stage and 100 µs for 4th stage.

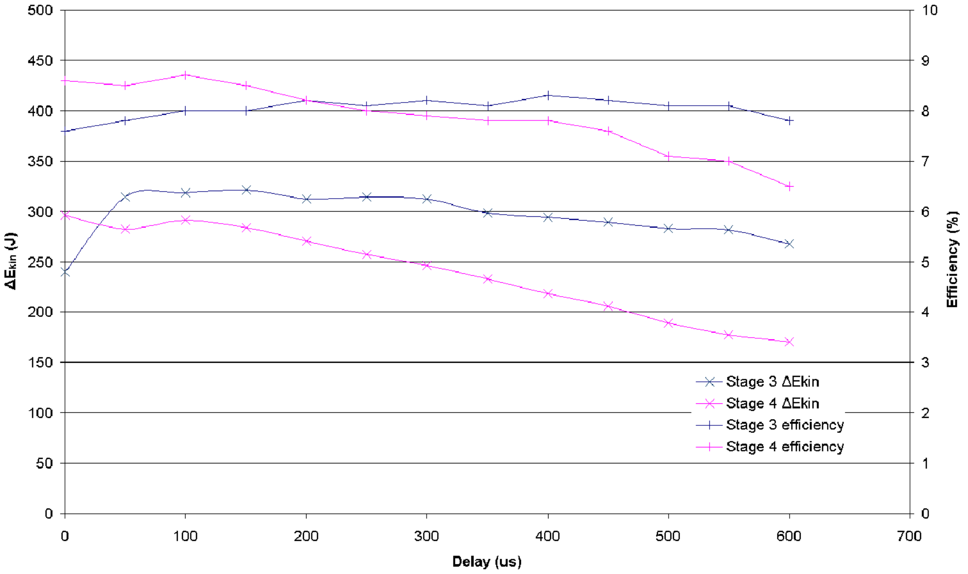

Fig. 11.6: Effect of different delays on efficiency and kinetic energy. 80 V charge

Some tested modes are printed in figure 11.7. Blue one is the final setting of a coilgun delays. Even though its not as efficient for low voltages, speed advantage in higher voltages is large and also efficiency is best out of all tested. The one with switching modes was programmed to use the same delays for above 50 V, 1000, 600, 350 delays between 35 and 50 V and dynamic delays below, but due to the MCU latencies, it was performing much worse.

11.3 Effect of different pulse duration

Precise timing to turn the coil on is one thing, but another one is whether the coil is turned off at the right moment. Measuring this was done on the last coil, where the projectile goes fastest, so the transition between on-state and off-state of the stage might take long enough to affect the projectile after passing the midpoint of the coil. To measure this, MCU program was modified not to turn the coil off by signal from the optical gate, but after different pulse durations. Fig. 11.8 shows effect of different pulse duration.

Peak for both efficiency and delta v is at value 1550 µs. Measurements with unmodified program showed, that the pulse duration with using the optical gate to switch the stage off is between 1650 and 1700 µs.

There is a small advantage with precise pulse measurement, but using it would mean creating a function for different voltages as in case of turning the stage on. Difference would however be, that turning off requires much more precise timing as the function of speed and energy is a little steeper and wrong turning on by 200 µs means around half a percent difference in efficiency for turning on, however in case of turning off it could be around twice that much.

11.4 Impact of wrong coil orientation

During the acceleration, the projectile is being magnetized by the coils. If all the coils are turned the same direction, magnetization direction is the same. If the coils are not arranged in the same direction and projectile has some remanent magnetization, it has to be demagnetized first and then magnetized in the opposite direction. To measure the impact of wrong coil polarity arrangement, series of measurements was done with all the coils in the same direction but also with coils arranged in a way, that every next one is in the opposite direction than the previous one, so the projectile had to be remagnetized on every stage. Figure 11.9 show advantage of having the coils in a right arrangement.

Worst case scenario results in around 10 % worst performance in efficiency and 8 % in projectile energy.

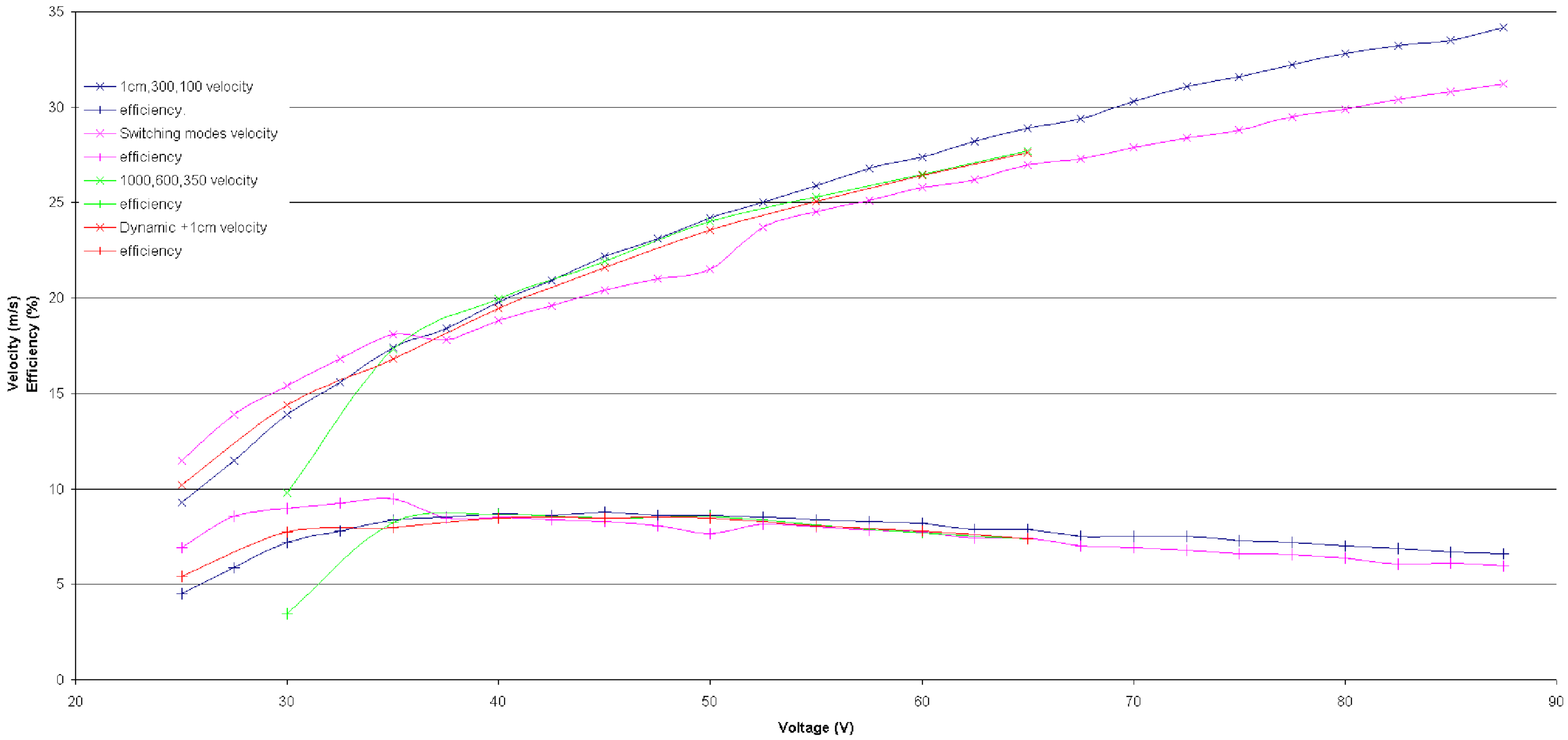

Fig. 11.7: Efficiency and muzzle velocity dependencies for different switching modes and different charge voltage

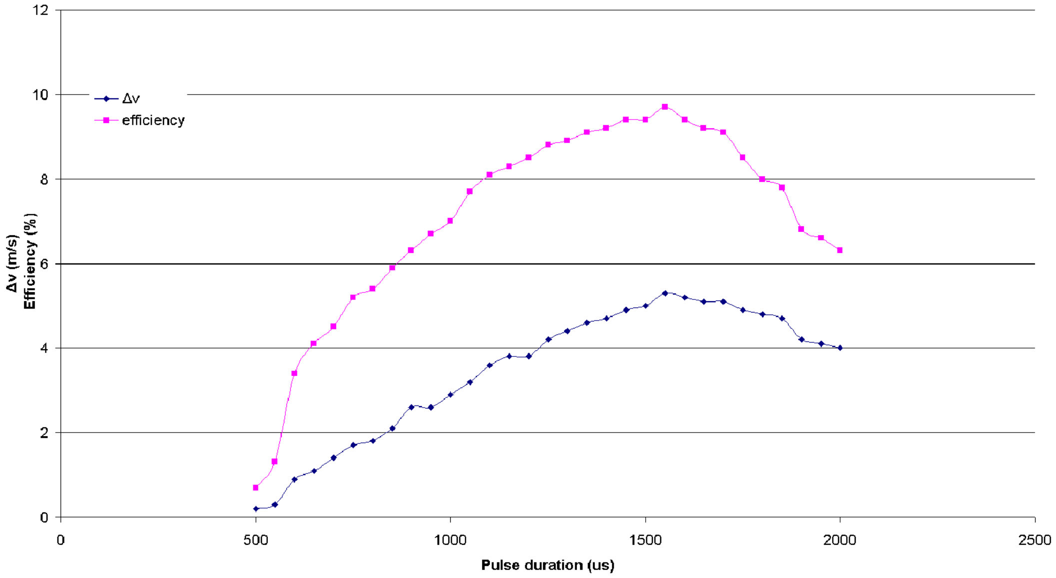

Fig. 11.8: Efficiency and Δv dependency on pulse duration. Stage 4, 70 V charge.

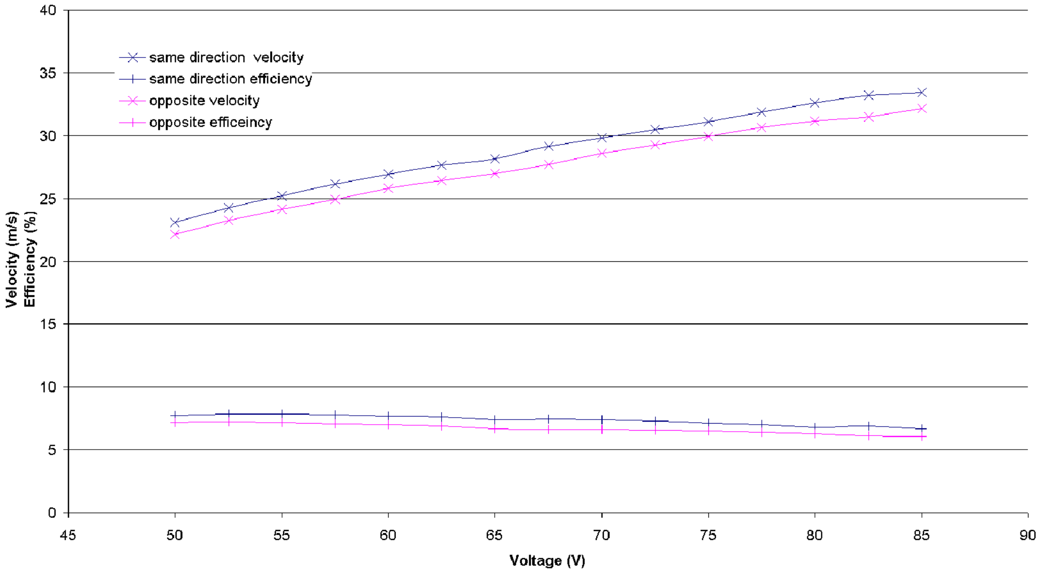

Fig. 11.9: Impact of wrong coil orientation

12 CONCLUSION

Advancing to multi-stage design brought much better performance than with the first prototype. Peak efficiency, which was possible to reach with a single-stage coilgun was around 2 %, whereas with multi-stage design, values around 8 % were possible to reach overall. Increase of the projectile diameter from 4,5 mm to 6 mm gave around twice the projectile mass for the same length and together with the increased efficiency, projectile energies around 6 J were reached. Compared to 1,6 J maximum reached with first prototype and considering the fact that in order to reach 1,6 J with the first prototype, capacitor charge of 315 J was required, whereas for the 6 J launch with multi-stage design, only 85 J of charge was needed, improvements with the second prototype can be considered as a huge step forward.

As was proven, turning the stages off increases efficiency mainly for higher stages up to five times. Precise timing of turning the stages on and off was not so easy-to-solve problem, as was expected. Requirement for different delays for different speeds together with limitation of MCU processing speed made it impossible to reach optimal delays for every charge voltage. Compromise always had to be selected for the charge which is preferred, but other charge values were then affected by suboptimal timing.

Placing the optical gate directly into the coil would solve this problem, because no delay would have to be counted and the coil would be turned on with the projectile in the optimal position. Probably optic fibres would be required then to lead the signal into the desired destination because of the lack of space for emitter and detector. This concept was however impossible to test for obvious reasons.

Using the MCU with higher working frequencies would also solve this problem until certain velocities were reached.

If bigger projectiles energies are desired, maximal voltage launch left approximately 35 J still in capacitors, which could be used in additional stages. Another possible way of maximizing the energy is reducing the coil inductance by reducing the coil turns and increasing wire diameter in later stages, so the current rises more rapidly and reaches higher values, so more charge is consumed in the given time interval. Time demands on winding the coil and changing it in the device prevented from testing different coil, so the second possibility is only a presumption based on theoretical guess.

Wrong coil orientation together with using material with remanent magnetization led to about 10 % worse performance, but this value is strongly dependant on a projectile material, however since basic iron proved to be close to optimal option, proper orientation should be inspected while constructing a multi-stage coilgun.

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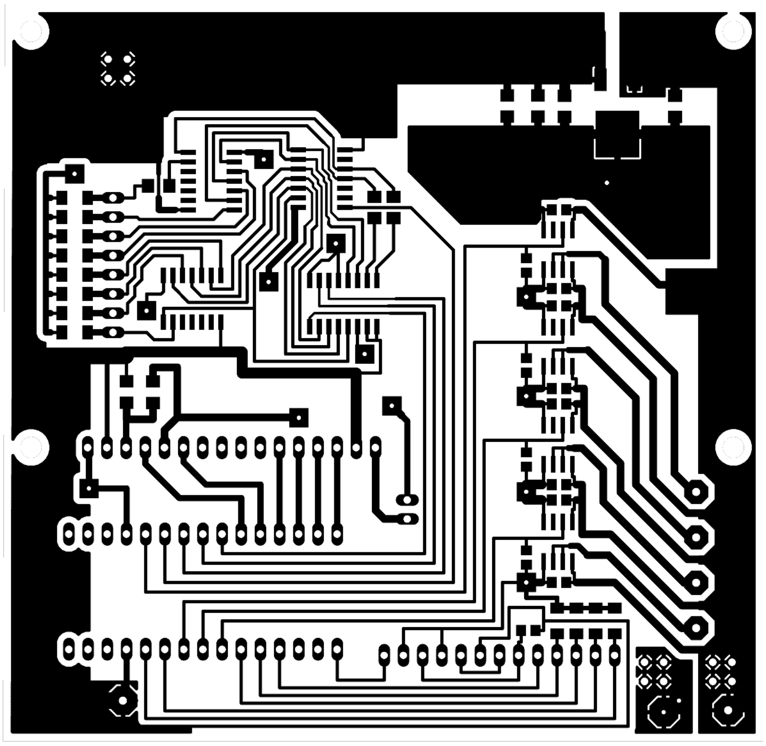
LIST OF SYMBOLS

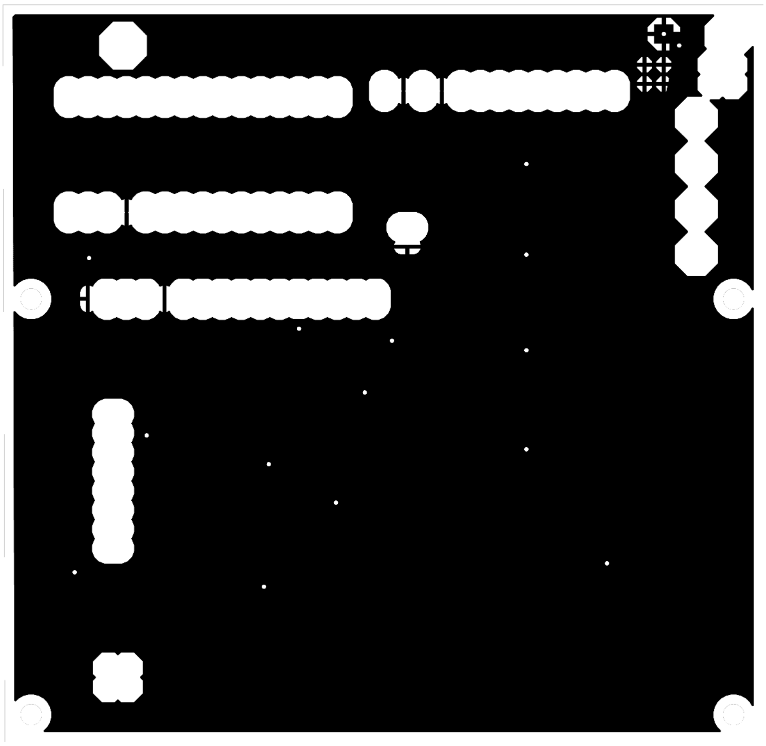
$\mathbf{B}$ (T)	Magnetic induction
$\mathbf{F}$ (N)	Force
$\mathbf{H}$ (A/m)	Magnetic field strength
i (A)	Electric current
$\mathbf{l}$ (m)	Length
$\mathbf{M}$ (A/m)	Magnetization
$\mathbf{S}$ (m^2)	Surface
μ (H/m)	Permeability
μ_0 (H/m)	Permeability of free space
μ_r (-)	Relative permeability
Φ (Wb)	Magnetic flux
χ (-)	Magnetic susceptibility

APPENDIX

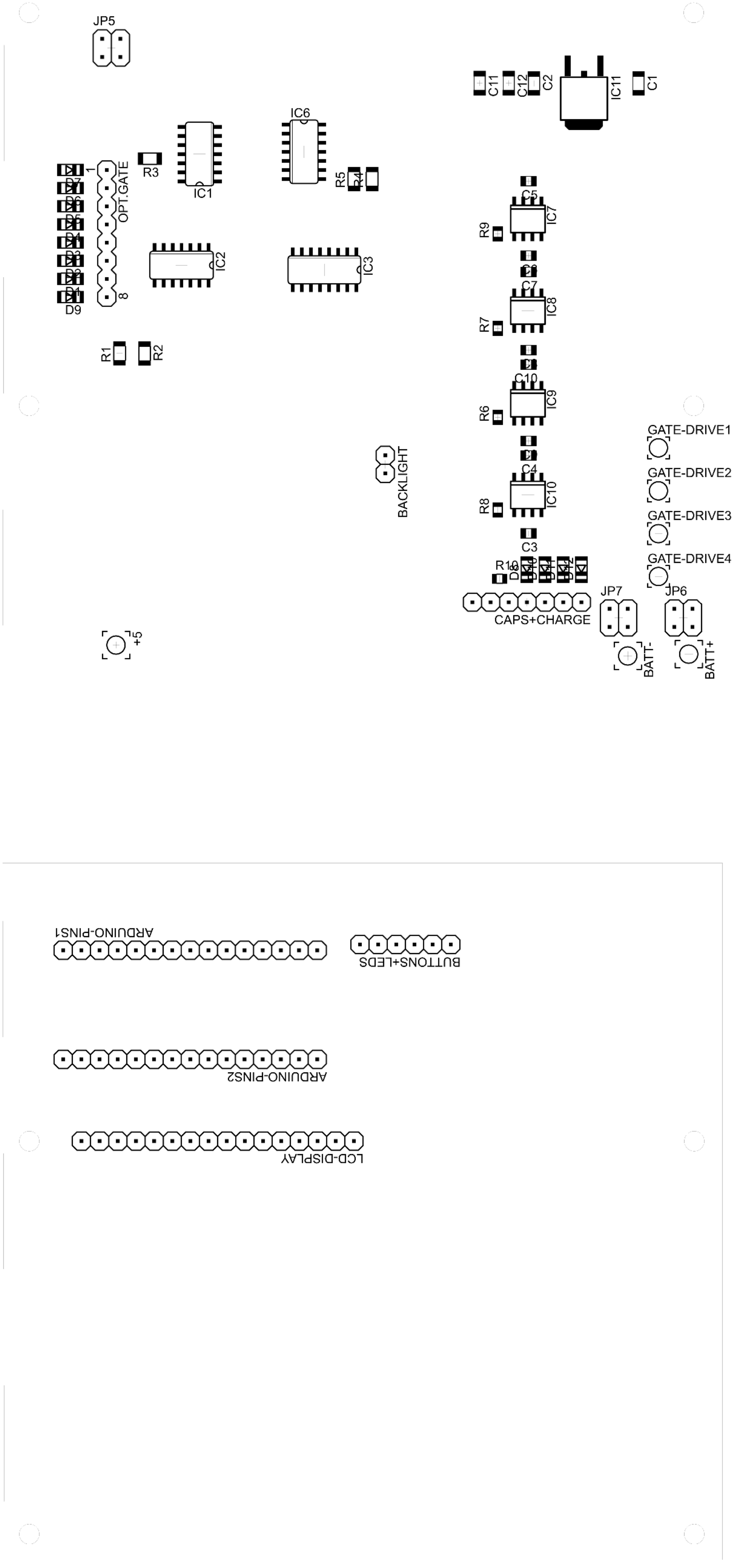
A First board layout
C First board component placement
D Second board layout
E Second board component placement

A FIRST BOARD LAYOUT

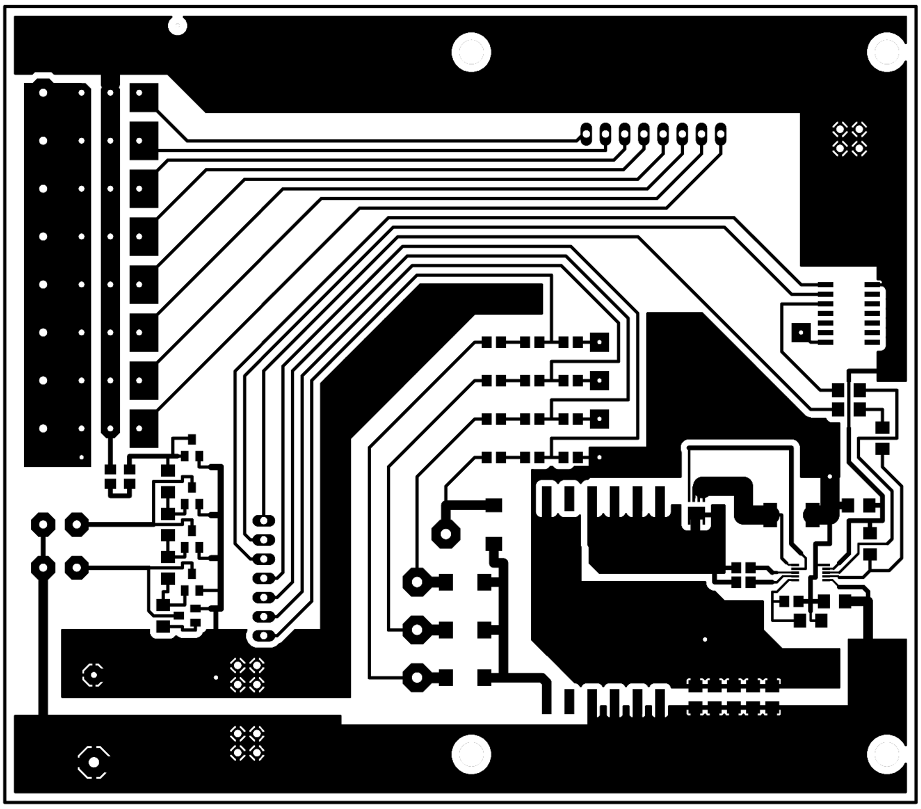


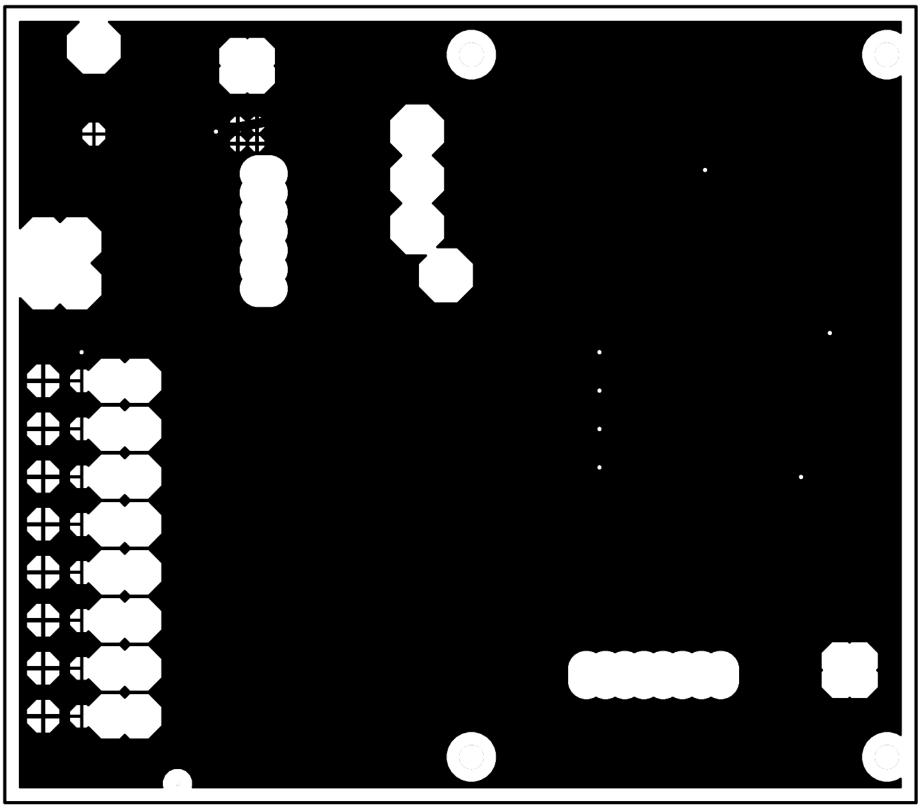


B FIRST BOARD COMPONENT PLACEMENT



C SECOND BOARD LAYOUT





D SECOND BOARD COMPONENT PLACEMENT