# Inductive sensor of projectile for multistage reluctance accelerator

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## Abstract

The idea to control position of projectile inside a coilgun's barrel is not new. I have constructed special stand to investigate influence of accelerated projectile on the current form in coil, and possibility of utilization this influence to synchronize switching of the coils. Since this phenomenon is determined by inductive EMF in coil caused by moving projectile, the according detector is hereinafter called inductive sensor (IS). This article presents the results of my experiments conducted on the abovementioned stand during 2008-2009 years.

## Introduction

Before detailed description of the IS' operation principles and experimental results let's in brief remember why this question is important. It is known that some devices (detectors) are needed to switch accelerating coils in sync with projectile movement. By this moment only 3 types of detectors are well investigated and applied in coilguns:

1) Photodetectors (most popular).
2) Inductive detectors (less widespread but also used in many constructions for instance in James Paul's coilgun). In this scheme controlling signal appears in a small additional winding situated near to accelerating coil when projectile is passing through.

3) Contact detectors (switching is made by mechanical contact with projectile).

Neglecting all advantages and disadvantages of those detectors, one should remark their common feature – the control signal is determined by geometrical coordinate of projectile. I.e. the coil is switched when projectile is passing the sensor.

There is difficulty for such sensor in multistage system caused by variation of optimal switching coordinate (it is usually moving away from according coil, i.e. activation must be ahead to projectile entering the coil). As a result, there can be situation when the sensor which activates (*N+1*)th coil must be placed in a middle of *N*th stage (see fig. 1).

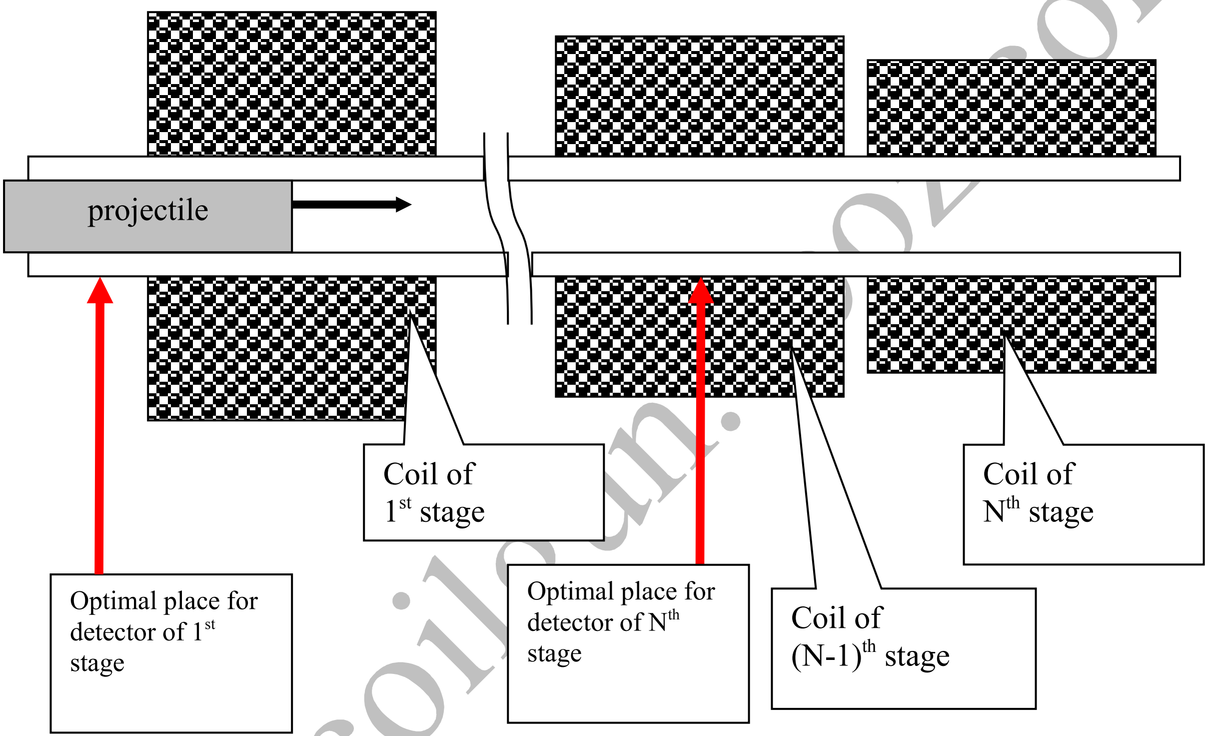


**Fig. 1. Problems attributed to sensor position in a multistage coilgun.**

To avoid this problem some delay (positive and negative) is organized between the moment when projectile is passing the sensor and switching on (or off) the current. In this case the constructor is more free in situating the sensor[1], but schematics becomes more complicated and adjustment of coilgun becomes tricky. In any case, one should use some aprioristic information about position of projectile while it is passing a coil usually with the help of modeling in programs like FEMM. However, very few works exists dedicated to comparison of calculations and experiments investigating electromagnetic reluctance acceleration in multistage systems, all in narrow energy and speed bands. Thus, even completely calculated system must be tuned experimentally before practical shooting.

[1] It is obvious that situating the sensors closely to the coils is optimal because maximum number of coils must be housed in a fixed length (like shown in fig. 1).

It seems very attractive idea to control the projectile position by the form of current. As shown below, the projectile passing the center of the coil must generate "*inductive current spike*". Registrated and somehow used for current switching, this spike would allow us to build IS with two serious advantages. First, the construction of multistage coilgun can be made easier because one doesn't have to put the sensors between the coils, to drill the barrel etc. Secondly, as the surge appears just when the projectile is in the center of coil, the *self-synchronization* takes place, i.e. the constructor doesn't need to do anything to switch the coil in desired moment. So, no more testing shots for tuning.

In fact, there is another one feature (not so obvious) which will be told about later.

To finish this section I must say that inductive EMF sensing has been widely used in brushless DC motor control and is attributed to so called "sensorless" control methods. The theory of this method can be found here or here. Some ICs are manufactured with the special algorithms incorporated (for example, this one). But, as far as I know, no attempts were made to apply such method in amateur coilguns. Moreover, there is a steady opinion that it is impossible because of negligible variation of current caused by the projectile movement.

These doubts will be refuted, and really working scheme of IS will be demonstrated in the next chapters.



## Mathematics

In this section some simple math will be done to prove the theoretical possibility of IS.

At first, let's consider a typical coilgun which in fact is nothing else but serial *RLC*-circuit well known from theory (see fig. 2). Doing this we will suggest that inductance *L* varies in time, in contradiction to classical case.

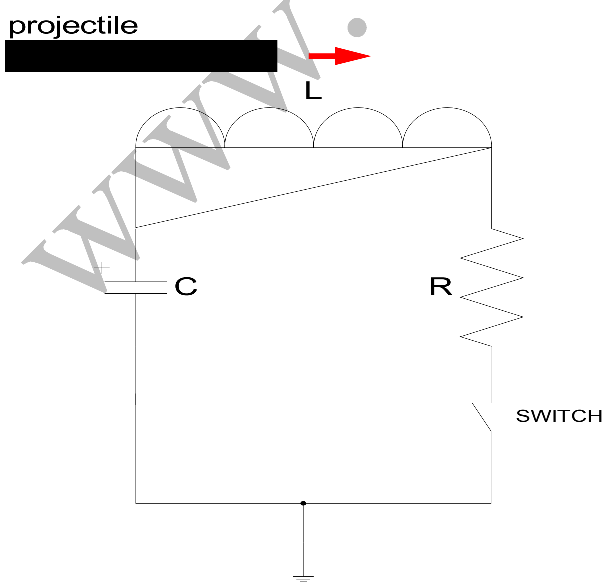


**Fig. 2. Picture of simple one-stage coilgun circuit. Direction of projectile acceleration is shown by arrow. Resistance *R* is considered to be constant and includes capacitor's ESR, coil winding resistance, interconnections etc (i.e. total active resistance of the chain).**

The second Kirchhoff's law must be written:

$$U_C = U_R+U_L \tag{1}$$

where $U_C$ is capacitor voltage,
$U_R$ is ohmic voltage drop across the active resistance,
$U_L$ is inductive EMF.

Writing the latter two voltages, we have:

$$U_C = i\cdot R + d(L\cdot i)/dt \tag{2}$$

where $i$ is circuit current,
$L$ is instaneous inductance ($L(t)$ would be more precisely).

Differentiating (2) on time and rewriting $dU_C/dt = -i/C$ (capacitance considered constant) we finally get for current: $i = -(di/dt)\cdot RC - C\,d^2(L\cdot i)/dt^2$, or unfolding the first and second derivatives :

$$(d^2i/dt^2)L+(di/dt)\cdot(R+2dL/dt)+i\cdot(1/C+d^2L/dt^2)=0 \tag{3}$$

This is well known equation for *RLC*-circuit with $L$ varying with time. Let's simplify it by assessing the parameters for real coilguns. $L$ has an order of hundreds….thousands microHn, and variation of $L$ during a shot (about $10^{-4}\ldots10^{-3}$ seconds) makes no more than some percents (i.e. $dL\sim10^{-6}\ldots10^{-5}$ Hn). Thus, $dL/dt$ has an order of $10^{-2}\ldots10^{-1}$ Hn/sec. It's obvious that in the third summand $1/C\sim10^3\ldots10^4$ mkF$^{-1}$ is much more than $d^2L/dt^2$, so the latter may be ignored.

The value $dL/dt$ in the second summand has physical meaning of active resistance (its dimension of Hn/sec is easily transformed to Ohms). Substituting $dL/dt = (dL/dx)\cdot(dx/dt)$ to (3), we finally have:

$$(d^2i/dt^2)L +(di/dt)\cdot(R+2v\{dL/dx\})+i/C\approx0 \tag{4}$$

where $v = dx/dt$ – velocity of projectile.

Thus, projectile's movement through a coil is equivalent to some additional *resistance* in a circuit, which changes its sign when the projectile is passing geometrical center of coil (this point will hereinafter be called "zero point", or ZP). This change is easily explained: prior to ZP inductance is increasing ($dL/dx > 0$), in ZP $dL/dx = 0$, after ZP inductance is decaying ($dL/dx < 0$) while the projectile is flying out. This behavior is illustrated in fig. 3.

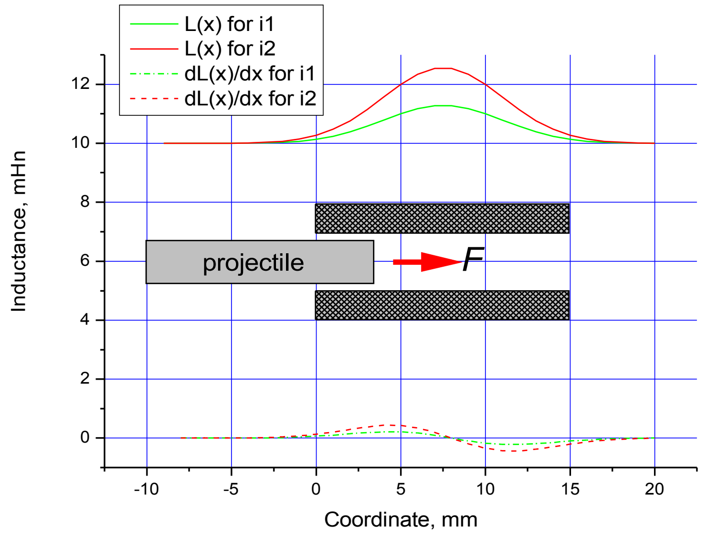


**Fig. 3. Inductance and its gradient change during projectile moving through conventional coil with proper inductivity 10 mHn. Two cases are shown: large current (*i1*) and small current (*i2*). For the latter case inductance changes less because the projectile is further from saturation.**

The force on projectile *F* is also changing its sign in ZP.

How all those processes influence on current? Eq. (4) shows that when dL/dx is crossing zero, effective resistance $R+2\cdot v\{dL/dx\}$ of a circuit decreases, and faster for higher speeds of projectile in ZP. So one can expect for current spike on an oscillogram rising above a background of the "main" pulse.

How pronounced this spike can be, or it will be masked by other factors (such as front of the "main" pulse or its decay)? Generally, what are the best conditions to watch this effect? Why most of the investigators don't observe it? To answer, one should examine behavior of current in *RLC*-circuit in a range of parameters. Such analysis has been made in nearly all books on circuit theory and in many amateur sites (for example, here). We will not focus on the details here, just examine qualitatively two critical cases – "thick" and "thin" coils.

Let us suggest a capacitance *C* charged initial voltage $U_0$ and a coil with inside diameter $D_{min}$ and resistance *R* (serial resistance of cap is neglected). Fig. 4 shows current curves for two such coils with different outside diameter $D_{max}$ and inductance *L*. These graphs can easily be got from any simulator or with the help of the before mentioned FEMM. I used a simple MathCad script.

In other words, we take the same caliber barrel and wind two coils of the same length, but different diameter in such way, that their resistances are equal. The inductance of the larger ("thicker") coil will appear to be more than one of the smaller ("thinner") coil[2] (I'll not prove this statement here - it is enough to make a simple calculation according to known formulae).

Considering a projectile is passing ZP on 1 ms (see fig. 4, distinguished by dotted line), one can ask what coil is more suitable to watch the inductive current spike. The answer is quite obvious: the "thinner" one, because the spike would be watched on a background of gentle slope of the "main" pulse, and must manifest as a short transition across zero of *di/dt* derivative.

[2] The wire diameter for these cases will be also different.

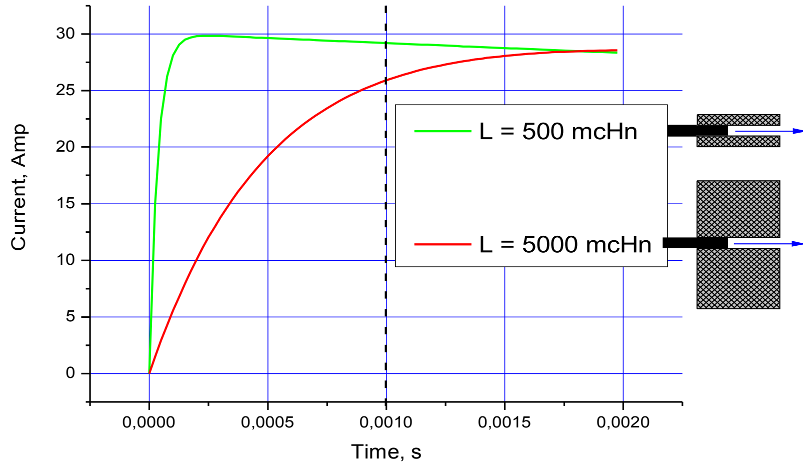


**Fig. 4. Currents for "thin" (500 mcHn) and "thick" (5 mHn) coils. For certainty the following parameters are chosen: capacitance 3300 mcF, initial voltage 300 V, resistance 10 Ohm.**

Another condition to watch the spike is *weak field strength* (*low current*). It is clear from the fact that the weaker the field is, the further is material of projectile from saturation, and the higher is variation of inductance during the projectile's flight (see also fig. 3 and eq. 4). Note that this condition also increases the overall acceleration efficiency. In other words, the more efficient coilgun we are building (i.e. with longer barrel and smaller energy supplied to each stage), the higher is probability to see the spike.

At last, eq. 4 says that the spike would be more visible when projectile is moving faster.

## • FEMM modeling

After determination of the optimal conditions for investigation of the inductive spike, I decided to execute FEMM modeling to check my conclusions. The feature of this modeling was that *I didn't try to find parameters providing maximum velocity of projectile* (as FEMM is often used for). To my surprise, the very first run gave a positive result:

Simulation begins 05/01/07 20:35:44
Capacitance, mcF = 450
Initial voltage, V = 500
Total resistance, Ohm = 6.207563977972148
Parasitic resistance, Ohm = 0.3611111111111111
Coil resistance, Ohm = 5.846452866861037
Number of turns = 639.4557823129259
Wire diameter, mm = 0.35
Wire length, m = 32.14255340723813
Coil length, mm = 30
Outside coil diameter, mm = 20
Outside magnetic core, mm = 0
Material of magnetic core, mm = № 0 Air
Barrel outside diameter, mm = 12
Projectile mass, g = 18.3783170235003
Projectile length, mm = 30
Projectile diameter, mm = 10
Initial position inside the coil, mm = 0

Projectile material = № 154 Iron
Total process duration, mcs = 4899.999999999998
Time step,  mcs =50
Projectile energy gain, J =1.522818731445051
Projectile energy, J = 1.522910623030169
Cap energy, J = 39.44509994871898
Acceleration efficiency (%)= 3.860603049364326
Initial velocity, m/s = 0.1
Final velocity, m/s = 12.87358000912023
Maximum velocity, m/s = 16.60209148334091
End of simulation 05/01/07 20:42:36

-------------------------------Intermediate data--------------------------------

| Current (A) | Force (H) | Velocity (m/s) | Coordinate x(mm) | Time(mcs) |
|---|---|---|---|---|
| 10.23548735606626 | 2.565108367573465e-018 | 0.1 | 0.005 | 50 |
| 19.14548063024375 | 2.721377062978326 | 0.107403771138289 | 0.01018509427845723 | 100 |
| 26.87733111691114 | 9.565229901516709 | 0.133426909952593 | 0.01620586130572927 | 150 |
| 33.56196261477217 | 18.75888713542633 | 0.1844622879783377 | 0.02415309125400254 | 200 |
| 39.32026349601599 | 29.53245379913843 | 0.2648082025726266 | 0.03538485351777665 | 250 |
| 44.25739460916278 | 40.67803523165766 | 0.3754767561176623 | 0.05139197748503387 | 300 |
| 48.48543631062712 | 51.13098558258506 | 0.514583578350634 | 0.07364348584674128 | 350.0000000000001 |
| 52.09449857687953 | 60.97815653299533 | 0.6804805874593101 | 0.1035200899919899 | 400.0000000000001 |
| 55.14343216880555 | 69.00169600384946 | 0.868206416531736 | 0.1422372650917661 | 450.0000000000001 |
| 57.68203070900949 | 75.74699176065523 | 1.074283479147964 | 0.1907995124837586 | 500.0000000000001 |
| 59.75482682853419 | 81.7408832018732 | 1.296667506742415 | 0.250073287131018 | 550.0000000000001 |
| 61.40627805393752 | 86.98096030863772 | 1.533307674058648 | 0.3208226666510446 | 600.0000000000001 |
| 62.68694822265884 | 91.23431373040695 | 1.781519503285846 | 0.4036933460846569 | 650.0000000000002 |
| 63.63876777290385 | 95.03025453512738 | 2.040058558884931 | 0.4992327976389263 | 700.0000000000002 |
| 64.30294206430015 | 98.52380775849132 | 2.308102166013129 | 0.6079368157613778 | 750.0000000000002 |
| 64.71285823500706 | 103.4999549042508 | 2.589683865719108 | 0.7303814665546837 | 800.0000000000002 |
| 64.90245164391072 | 105.3271319221754 | 2.876236578319217 | 0.8670294776556419 | 850.0000000000002 |
| 64.89876184936522 | 107.7486532930497 | 3.169377275465946 | 1.018169824000271 | 900.0000000000003 |
| 64.72566228111856 | 110.6812688861972 | 3.470496438729561 | 1.184166666855159 | 950.0000000000003 |
| 64.40505134057257 | 113.1857209146592 | 3.778429207464394 | 1.365389808010008 | 1000 |
| 63.95710283132876 | 115.0987935531803 | 4.091566676488363 | 1.562139705108827 | 1050 |
| 63.39749248272886 | 117.6517716829494 | 4.411649770964611 | 1.774720116295151 | 1100 |
| 62.74328348978159 | 119.0559157774761 | 4.735552976098247 | 2.003400184971723 | 1150 |
| 62.00621919677807 | 121.1499737300227 | 5.06515326968092 | 2.248417841116202 | 1200 |
| 61.20036984048961 | 121.9555671711385 | 5.396945258618738 | 2.509970304323693 | 1250 |
| 60.33347763931692 | 123.3929964213284 | 5.732647913719164 | 2.788210133632141 | 1300 |
| 59.41537893731805 | 124.4793763215414 | 6.071306171062234 | 3.083308985751676 | 1350 |
| 58.45467558505538 | 125.4287173776703 | 6.412547203136294 | 3.395405320106639 | 1400 |
| 57.46116063516053 | 125.611095001258 | 6.754284411283916 | 3.724576110467144 | 1450 |
| 56.43821949062878 | 126.3084728752657 | 7.097918903805063 | 4.070881193344368 | 1499.999999999999 |
| 55.39440017143931 | 125.7606324761429 | 7.440062943205769 | 4.434330739519639 | 1549.999999999999 |
| 54.33117389212611 | 126.1396495333185 | 7.783238135395631 | 4.814913266484674 | 1599.999999999999 |
| 53.25549682273667 | 125.6883924903963 | 8.125185638884876 | 5.212623860841687 | 1649.999999999999 |
| 52.16993721539056 | 125.5072870049452 | 8.466640427276161 | 5.627419512495712 | 1699.999999999999 |
| 51.07942045792041 | 124.66270567233 5 | 8.805797449959275 | 6.059230459426598 | 1749.999999999999 |
| 49.98930190518849 | 123.3543077512797 | 9.141394848767737 | 6.507910266894773 | 1799.999999999999 |
| 48.89929428037666 | 122.1869517902191 | 9.473816342079608 | 6.973290546665957 | 1849.999999999999 |
| 47.81419007460216 | 120.7889116591735 | 9.802434331160766 | 7.455196813496966 | 1899.999999999999 |
| 46.73626169961751 | 119.3088176859511 | 10.12702558054827 | 7.953433311289691 | 1949.999999999999 |
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| 39.53029938122744 | 105.1723994760976 | 12.25332377140845 | 11.87795445115256 | 2300 |
| 38.56570742179237 | 102.8490967601755 | 12.53313474819338 | 12.49761591414261 | 2350 |
| 37.62462505601386 | 100.0492432327279 | 12.80532845098128 | 13.13107749412197 | 2400 |
| 36.70435075104711 | 97.49425578438155 | 13.07057106177017 | 13.77797498194076 | 2450 |
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| 34.93007170694178 | 92.03403387701502 | 13.57969906005158 | 15.11069731070323 | 2550 |
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| 32.44620110659084 | 83.94192471118595 | 14.28836564761087 | 17.20156508386214 | 2700.000000000001 |
| 31.66829262555677 | 81.25252259572524 | 14.50942104265011 | 17.92150975111866 | 2750.000000000001 |
| 30.92181817331051 | 77.94464656579649 | 14.72147703903468 | 18.65228220316078 | 2800.000000000001 |
| 30.19914768244708 | 75.32785516763308 | 14.92641379976013 | 19.39347947413065 | 2850.000000000001 |
| 29.5050766597787 | 72.30522548959564 | 15.12312720229079 | 20.14471799918193 | 2900.000000000001 |
| 28.84414472035149 | 68.92373718745603 | 15.31064093681643 | 20.90556220265961 | 2950.000000000001 |
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| 26.55847707006926 | 54.35303904244294 | 15.96327092825031 | 24.0354836051206 | 3150.000000000002 |

| | | | | |
|---|---|---|---|---|
| 26.08653566136258 | 50.21104004203995 | 16.09987494911315 | 24.83706225205469 | 3200.000000000002 |
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| 24.74425081120666 | 28.2896079060264 | 16.50607394698729 | 28.10162035116073 | 3400.000000000002 |
| 24.58864144176561 | 20.51194456228085 | 16.5618786883465 | 28.92831916704408 | 3450.000000000003 |
| 24.52399003896722 | 11.76322188204155 | 16.59388167824758 | 29.75721317620893 | 3500.000000000003 |
| 24.53998244867751 | 3.017648014125108 | 16.60209148334091 | 30.58711250524864 | 3550.000000000003 |
| 24.64857662083749 | -7.233321645556653 | 16.58241252787315 | 31.41672510552899 | 3600.000000000003 |
| 24.80733025770762 | -15.67866263345547 | 16.53975720036572 | 32.24477934873497 | 3650.000000000003 |
| 25.00644227038301 | -24.15974447341048 | 16.47402826435238 | 33.07012398535292 | 3700.000000000003 |
| 25.2088080035332 | -30.80511228394661 | 16.39021995849783 | 33.89173019092417 | 3750.000000000003 |
| 25.40139404631069 | -36.86097250951395 | 16.28993609555657 | 34.70873409227554 | 3800.000000000004 |
| 25.56667452701231 | -41.81987922653175 | 16.17616104430173 | 35.52038652077199 | 3850.000000000004 |
| 25.692090435064 | -45.78095422758842 | 16.05160950302336 | 36.32608078445512 | 3900.000000000004 |
| 25.77922887074423 | -49.52693204981664 | 15.91686666452926 | 37.12529268864393 | 3950.000000000004 |
| 25.83046307391189 | -53.1224114194307 | 15.77234197450595 | 37.91752290461981 | 4000.000000000004 |
| 25.8286649377111 | -55.11147970088106 | 15.62240583065118 | 38.70239159974874 | 4050.000000000003 |
| 25.78869264386199 | -57.58780109905384 | 15.46573261344251 | 39.47959506085108 | 4100.000000000003 |
| 25.70025017756275 | -58.83579686018996 | 15.30566410231345 | 40.24887997874498 | 4150.000000000003 |
| 25.58624852858605 | -61.20935129765395 | 15.13913810534815 | 41.01000003393653 | 4200.000000000003 |
| 25.42123840229644 | -61.27584169395825 | 14.97243121478901 | 41.76278926693995 | 4250.000000000002 |
| 25.21843798917552 | -61.64282360081147 | 14.8047259142384 | 42.50721819516564 | 4300.000000000002 |
| 24.9826146908811 | -61.83256048158767 | 14.63650441603885 | 43.24324895342256 | 4350.000000000002 |
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| 23.45555415319878 | -60.52169230200509 | 13.79890517189198 | 46.79707048937106 | 4600 |
| 23.09288300857545 | -59.53815571580476 | 13.63692582514419 | 47.48296626429697 | 4650 |
| 22.72256553416731 | -58.94803145543771 | 13.47655196887634 | 48.16080320914748 | 4699.999999999999 |
| 22.33678934871153 | -57.50476247688431 | 13.32010466632042 | 48.8307196250274 | 4749.999999999999 |
| 21.94194717711258 | -56.23106641471894 | 13.16712257785493 | 49.49290030613179 | 4799.999999999999 |
| 21.54206742067074 | -55.00871384979941 | 13.01746601849898 | 50.14751502104063 | 4849.999999999998 |

As we see, on background of the gentle slope of the "main" pulse after 3,5 ms current is *increasing* during about 500 mcs. Another example with close parameters:

Simulation begins 05/01/07 20:07:33
Capacitance, mcF = 450
Initial voltage, V = 400
Total resistance, Ohm = 6.207563977972148
Parasitic resistance, Ohm = 0.3611111111111111
Coil resistance, Ohm = 5.846452866861037
Number of turns = 639.4557823129259
Wire diameter, mm = 0.35
Wire length, m = 32.14255340723813
Coil length, mm = 30
Outside coil diameter, mm = 20
Outside magnetic core, mm = 0
Material of magnetic core, mm = № 0 Air
Barrel outside diameter, mm = 12
Projectile mass, g = 18.3783170235003
Projectile length, mm = 30
Projectile diameter, mm = 10
Initial position inside the coil, mm = 0
Projectile material = № 154 Iron
Total process duration, mcs = 5749.999999999993
Time step,  mcs =50
Projectile energy gain, J =1.111232421592612
Projectile energy, J = 1.111324313177729
Cap energy, J = 28.55081011960125
Acceleration efficiency (%) = 3.89212220927387
Initial velocity, m/s = 0.1
Final velocity, m/s = 10.99721045656318
Maximum velocity, m/s = 13.73855277510354
End  of simulation 5/01/07 20:15:10
------------------------------Intermediate data--------------------------------

| Current (A) | Force (H) | Velocity (m/s) | Coordinate x(mm) | Time (mcs) |
|---|---|---|---|---|
| 8.188389886598753 | 2.565108367573465e-018 | 0.1 | 0.005 | 50 |
| 15.31705961858333 | 1.740230591172162 | 0.1047344666787142 | 0.01011836166696786 | 100 |
| 21.50263022567036 | 6.117184162184194 | 0.1213768615029034 | 0.0157711448715083 | 150 |
| 26.85218036571602 | 12.07091653442787 | 0.1542169646499784 | 0.02266099052533034 | 200 |
| 31.45923169457169 | 18.85519808193721 | 0.2055143659784763 | 0.03165427379104171 | 250 |
| 35.4076679905281 | 26.00548712954191 | 0.2762648245114551 | 0.04369875355329 | 300 |
| 38.77281211077622 | 32.81020227459533 | 0.3655281728165284 | 0.05974357848648959 | 350.0000000000001 |
| 41.6196364620326 | 39.77488260592696 | 0.473739611750428 | 0.08072527310066351 | 400.0000000000001 |
| 44.00934112466419 | 46.02521305525595 | 0.5989556829401992 | 0.1075426554679292 | 450.0000000000001 |
| 46.00050962182087 | 51.48150264495047 | 0.7390161209528889 | 0.1409919505652564 | 500.0000000000001 |
| 47.63504340615985 | 56.47364777233657 | 0.8926581756092644 | 0.1817838079793102 | 550.0000000000001 |
| 48.9513396110228 | 60.80231169091082 | 1.058076781712215 | 0.2305521819123472 | 600.0000000000001 |
| 49.98165099464723 | 64.66873249046373 | 1.234014361871954 | 0.2878544605019515 | 650.0000000000002 |
| 50.76069497760039 | 67.54774632038512 | 1.417784579335316 | 0.3541494340321332 | 700.0000000000002 |
| 51.31528285437476 | 70.63006370253967 | 1.609940541201207 | 0.4298425620455463 | 750.0000000000002 |
| 51.67165767472586 | 72.96926882028242 | 1.808460538236237 | 0.5153025890314825 | 800.0000000000002 |
| 51.85326489860276 | 75.23095035894275 | 2.013133659999087 | 0.6108424439873657 | 850.0000000000002 |
| 51.8799104168309 | 78.70809219129616 | 2.227266684504684 | 0.7168524525999599 | 900.0000000000003 |
| 51.77365658979554 | 79.12516156842153 | 2.442534386839028 | 0.8335974793835528 | 950.0000000000003 |
| 51.55014429887547 | 80.84237840068371 | 2.662473944681324 | 0.9612226876715616 | 1000 |
| 51.22420137828438 | 82.79693751322593 | 2.887731070802703 | 1.099977813058662 | 1050 |
| 50.81048202953278 | 83.90961049073192 | 3.116015332042285 | 1.250071473129787 | 1100 |
| 50.31986228413724 | 85.4603043775646 | 3.348518406911128 | 1.411684816603622 | 1150 |
| 49.76394963632736 | 86.44552914824577 | 3.583701881648527 | 1.584990323817614 | 1200 |
| 49.15159185386493 | 87.88273676207821 | 3.822795419565255 | 1.770152756347958 | 1250 |
| 48.49113446568105 | 88.89023017477965 | 4.064629941358289 | 1.967338390371047 | 1300 |
| 47.79006841342552 | 89.64417030235322 | 4.30851563064019 | 2.176667029671009 | 1350 |
| 47.05299670115853 | 90.94579357623789 | 4.55594251270982 | 2.398278483254759 | 1400 |
| 46.28718628395424 | 91.48120981632043 | 4.804826046766132 | 2.632297697241658 | 1450 |
| 45.49649395339753 | 92.36770717011507 | 5.056121383145422 | 2.878821382989447 | 1499.999999999999 |
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| 43.86000384999174 | 92.80439350337854 | 5.56256494513906 | 3.409792619251197 | 1599.999999999999 |
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| 36.22414516200168 | 88.8728726180838 | 7.813401518773391 | 6.422878740007037 | 2049.999999999999 |
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| 33.76150523747005 | 85.28531949358238 | 8.523151545943081 | 7.648469101599341 | 2199.999999999999 |
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| 32.17492628248854 | 82.93260435283239 | 8.978130166226869 | 8.523626341666866 | 2300 |
| 31.39948769137282 | 81.66839385759243 | 9.200316979505701 | 8.978087520310179 | 2350 |
| 30.64022872290607 | 79.76240432471674 | 9.417318362773615 | 9.443528403867163 | 2400 |
| 29.89157465870407 | 78.71819669511817 | 9.631478877565208 | 9.919748334875633 | 2450 |
| 29.16217829520939 | 76.5136505633602 | 9.83964171006375 | 10.40652634956636 | 2500 |
| 28.45508183620397 | 73.89815418527603 | 10.04068883013134 | 10.90353461307124 | 2550 |
| 27.7545658403706 | 73.34240100926866 | 10.24022396959891 | 11.41055743306449 | 2600.000000000001 |
| 27.07615852284483 | 70.87406329021225 | 10.43304375608857 | 11.92738912620668 | 2650.000000000001 |
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| 23.32826451822082 | 60.75196221963203 | 11.49840515568045 | 15.22127442977629 | 2950.000000000001 |
| 22.76746924603106 | 58.75010289842503 | 11.65824052804698 | 15.80019057186948 | 3000.000000000001 |
| 22.22228065166614 | 57.15112612999068 | 11.81372572850606 | 16.3869897282833 | 3050.000000000001 |
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| 18.5650579231531 | 41.70593742863379 | 12.87006790309284 | 21.33531765028232 | 3450.000000000003 |
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| 16.69563156756379 | 28.80811130194468 | 13.43248615978367 | 25.28604784471858 | 3750.000000000003 |
| 16.48088296932041 | 25.63393897225899 | 13.50222578539651 | 25.95941564334809 | 3800.000000000004 |
| 16.28662837944806 | 23.36868710461204 | 13.56580257285406 | 26.63611635230435 | 3850.000000000004 |
| 16.13423304527537 | 19.76639009267673 | 13.61957896072299 | 27.31575089064378 | 3900.000000000004 |

| | | | | |
|---|---|---|---|---|
| 16.01027433419818 | 16.807687001001 | 13.66530590889651 | 27.99787301238427 | 3950.000000000004 |
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| 15.86896462057499 | 9.9045173330612 | 13.72760193440005 | 29.36772849502215 | 4050.000000000003 |
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| 16.01372537608719 | -5.098678474339552 | 13.72370461515839 | 31.42781760082329 | 4200.000000000003 |
| 16.12602223140969 | -9.443363833850876 | 13.69801302484091 | 32.11336054182328 | 4250.000000000002 |
| 16.27086142145281 | -14.45182654882472 | 13.65869542429472 | 32.79727825305167 | 4300.000000000002 |
| 16.40704632715876 | -17.28796943754229 | 13.61166182101256 | 33.47903718418434 | 4350.000000000002 |
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| 16.78681724927673 | -26.11030620526816 | 13.41879234692064 | 35.50704916068651 | 4500.000000000001 |
| 16.88386930766002 | -28.82739675572491 | 13.34036460862757 | 36.17602808457521 | 4550 |
| 16.9581193247122 | -30.82509101168022 | 13.25650194869993 | 36.84094974850839 | 4600 |
| 17.00843106709706 | -32.61308940312284 | 13.16777486514429 | 37.5015566688545 | 4650 |
| 17.02910657366938 | -33.83255612802147 | 13.07573010368774 | 38.1576442930753 | 4699.999999999999 |
| 17.03771869625587 | -35.97059945251347 | 12.9778685872972 | 38.80898426034992 | 4749.999999999999 |
| 17.00867362368433 | -36.2873723801788 | 12.87914525932931 | 39.45540960651559 | 4799.999999999999 |
| 16.95554949667561 | -37.13820592156849 | 12.77810715591081 | 40.09684091689659 | 4849.999999999998 |
| 16.88370390360971 | -38.10035480253286 | 12.67445143282742 | 40.73315488161504 | 4899.999999999998 |
| 16.78848290375959 | -38.52348497540187 | 12.56964454293064 | 41.364257281009 | 4949.999999999998 |
| 16.67035741509392 | -38.70383308531282 | 12.46434699844977 | 41.99010706954351 | 4999.999999999997 |
| 16.53616193956672 | -39.07813521399167 | 12.35803112860156 | 42.61066652271979 | 5049.999999999997 |
| 16.37722525878013 | -38.60683446679087 | 12.25299747830207 | 43.22594223789238 | 5099.999999999997 |
| 16.2119083868835 | -39.13923496286688 | 12.14651538064095 | 43.83593005936596 | 5149.999999999996 |
| 16.03490193173742 | -39.15981114175017 | 12.03997730348275 | 44.44059237646905 | 5199.999999999996 |
| 15.83767331736161 | -38.35622063331756 | 11.93562547250641 | 45.03998244586878 | 5249.999999999996 |
| 15.63203217159592 | -38.13922402846995 | 11.83186400191119 | 45.63416968272922 | 5299.999999999996 |
| 15.4145731794093 | -37.46578283861319 | 11.7299346936108 | 46.22321465011726 | 5349.999999999996 |
| 15.18945432318368 | -36.92549968901366 | 11.62947527819807 | 46.80719989941248 | 5399.999999999996 |
| 14.95333099103683 | -36.031863157491 | 11.5314470879361 | 47.38622295856584 | 5449.999999999995 |
| 14.71235004831464 | -35.40202731024429 | 11.43513242739081 | 47.96038744644901 | 5499.999999999995 |
| 14.47784132274257 | -35.5162564857727 | 11.33850699525696 | 48.5297284320152 | 5549.999999999995 |
| 14.22023230103767 | -33.28228788607732 | 11.24795929210351 | 49.09439008919921 | 5599.999999999994 |
| 13.96123065249374 | -32.17243033244584 | 11.16043106443362 | 49.65459984811265 | 5649.999999999994 |
| 13.70274603282094 | -30.79979046240318 | 11.07663723711249 | 50.21052655565129 | 5699.999999999994 |

Amplitude of the spike is 2-3% of the maximum value of current in both cases, so it must be visible on oscillogram.

## Stand making and experimental results

Thus, modeling proves a hypothesis about inductive current surge in a coilgun. On this stage it was time to check the theory by experiment. To do this I constructed a little accumulator-powered stand (see fig. 5).

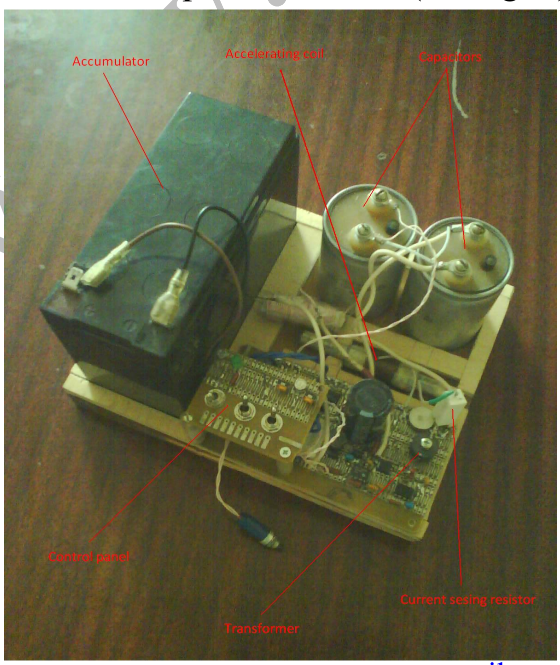



**Fig. 5. Experimental stand.** **7,2 A·h lead-acid accumulator from UPS is used.**

Off-the-shelf components used were:

1) Two electrolytic capacitors 63V, 15 000 mcF each.
2) PWM-controller IC UCC1801 to charge the caps (best recommendations from me).
3) Power switch IRF540.
4) Logics CD4049A (power switch driver) and CD4093 (controlling block).
5) Comparator LM293 (current sense signal processing).

A little transformer (see photo) had been used as current sense (CS), but I rejected that idea and inserted simple 0.1 Ohm resistor (exactly, 104 mOhms). Principal scheme of the logic part of the stand is shown on fig. 6).

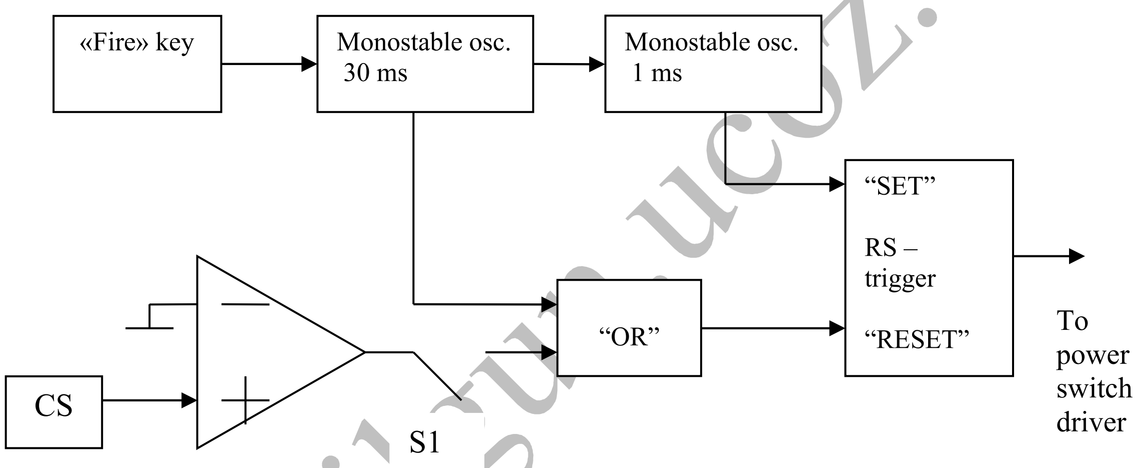



**Fig. 6. Logic scheme.**

A simple RS-trigger on CD4093 was utilized as a core. It is launched by a chain of monostable oscillators controlled by "fire" button. The first one generates 30 ms pulse which back end resets the trigger, and the second prevents reset from the "main" current pulse. The trigger can be also reset by comparator which processes CS signal. To analyze the effect of that signal it is possible to make shots without the reset by means of disconnection of the comparator output and RESET input with S1 switch. When this is done, the power switch is left open until capacitors are completely discharged (more correctly, during the cycle of the first oscillator, i.e. for about 30 ms).

Accelerating coil is wound around paper-and-epoxy barrel and has 140 mcHn inductance and 880 mOhm resistance (which gives exactly 1 Ohm together with interconnections, capacitor ESR and CS resistor). Caliber of the projectile is 6 mm.

All signals were measured with simple PC-connected oscilloscope.

The first oscillogram shows the signal from CS resistor when there is no projectile (fig. 7).

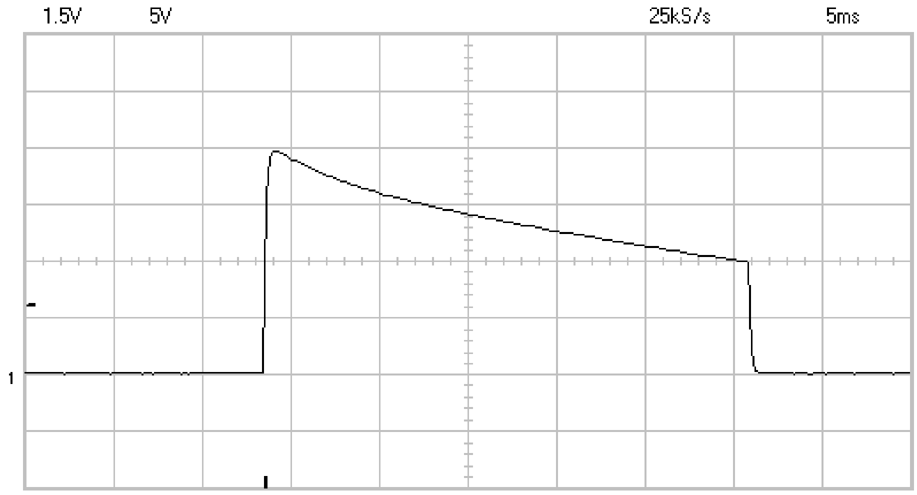



**Fig. 7. Voltage on CS resistor (no projectile). Scale on vertical axis – 1.5 V/div (thus, maximum current is about 60 A).**

Here we see an ordinary current form for an overdamped circuit, with gentle slope driven by *RC*-constant which is relatively large for chosen parameters. I.e. the condition concerning a form of pulse, favorable to watch the inductive surge, seems to be executed. The field strength is also small (less than in common coilguns), because the residual voltage on capacitor is about 30 V, which gives the total energy loss approx. 46 J and shot power 46 J/30 ms ≈ 1.53 kW – this is an order of magnitude less than the power of weakest coilguns. Such assessment is of course rough (because, for instance, instant power is higher in the beginning of the pulse), but suitable for our estimation.

As for velocity, I didn't do anything to increase it. It would possibly be better to accelerate the projectile preliminarily with a help of an additional starting coil, but it was too tricky for such simple experiment.

So, all preparations have been executed, and I made a shot with projectile inside. That's what I saw after that shot (see fig. 8).

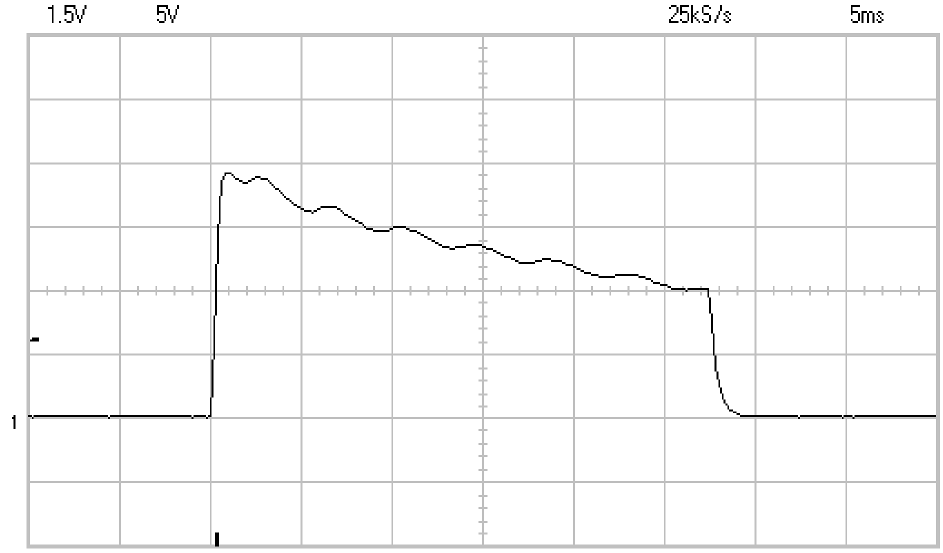


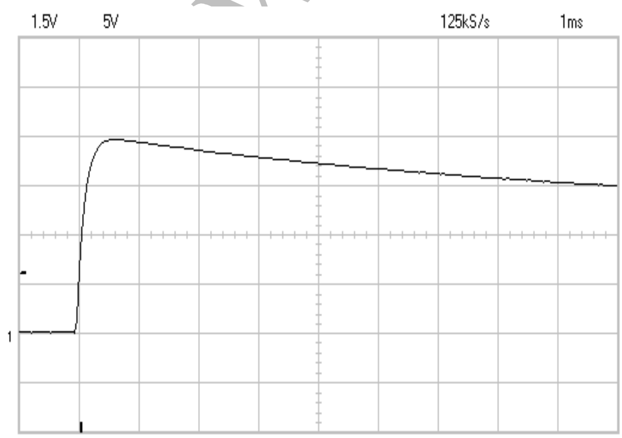

**Fig. 8. Coil current with projectile inside. Inductive spikes are clearly seen.**

Not one, but *six* local maximums are seen on the graph! It is not hard to explain this picture: the projectile is *repeatedly* passing through ZP. I.e. the projectile oscillates inside the coil until, at last, the current is switched off during one of the cycles, and the projectile continues moving by inertia. The direction of movement changes between the neighboring maximums. As the projectile after shot flew in a proper direction (forward), it is clear, that the projectile after changing direction, was moving forward but didn't reach ZP before the current was switched off.

The speed was not measured during the experiment, but seemed to be about 10 m/s.

By some modification of an initial position, I got the projectile after shot moving in an opposite direction. The number of maximums became odd. I could probably have had the same effect by changing the pulse duration, but there were no such adjustments in my device.

Fig. 9 shows the magnified initial piece of the graph without (left) and with (right) the projectile inside.



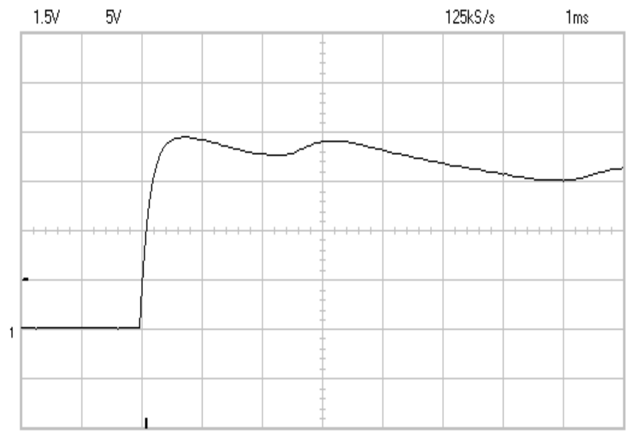




**Fig. 9. The initial piece of current pulse without (left) and with (right) the projectile inside.**

## Development of the inductive sensor

Thus, the effect of current surge was successfully registered, and I could start development of electric scheme intended for capture the spike and switch-off the current. I provided a little current transformer wound on 14-mm cup core (see fig. 2). Its primary winding consisted of one turn connected in series with the accelerating coil and power switch. The secondary winding was 100 turns of thin wire connected through low-pass *RC*-filter to comparator which controlled RS-trigger (see fig. 10).

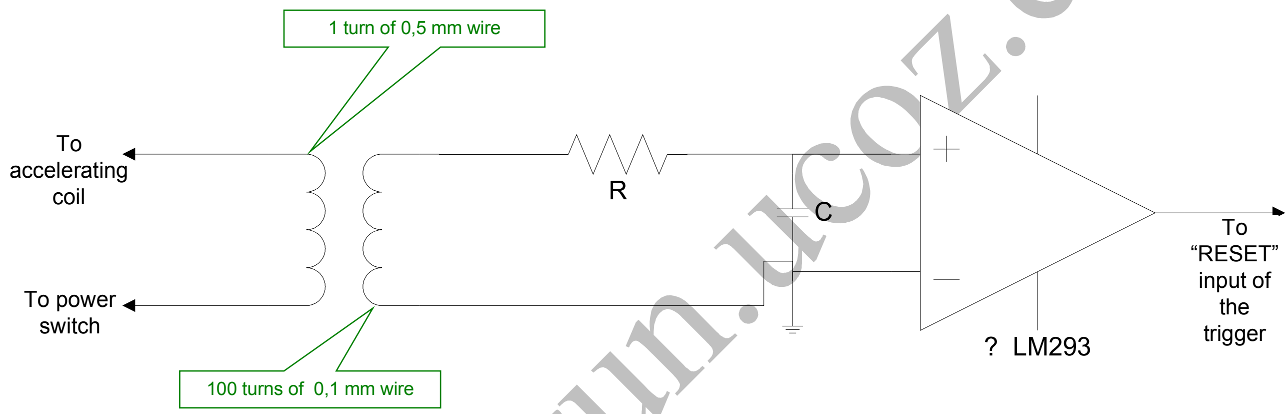



**Fig. 10. Primary scheme of the inductive sensor.**

The nominal values of components were chosen to suppress all possible noises ($RC \approx 10$ mcs), *R* was 1 kOhm. Thus, the secondary was in idle mode, and its voltage amplitude was proportional to current derivative in primary, so I expected the comparator to switch form one state to another when the derivative was crossing zero.

Unfortunately, the circuit hasn't worked as it had to. I didn't find out why it happened. Probably, the assembly was not quality enough, and a noise penetrated to the sensor scheme (from PWM controller UCC1801, for example). Fig. 11 shows the signals from the gate of the power switch (up) and from the transformer output (down). One can see the oscillogram to be definitely "littered" with a periodic signal, which I suppose to origin from UCC1801.


**Fig. 11. The signals from the power switch's gate (upper) and comparator input (lower). The comparator output and "Reset" input of RS-trigger are disconnected (i.e. the circuit generates 30 ms pulse). The reaction to front and back of this pulse, and the noise signal are clearly visible.**

I didn't want to analyze that fail further, and decided to reconstruct my circuit in a following way (see fig. 12):

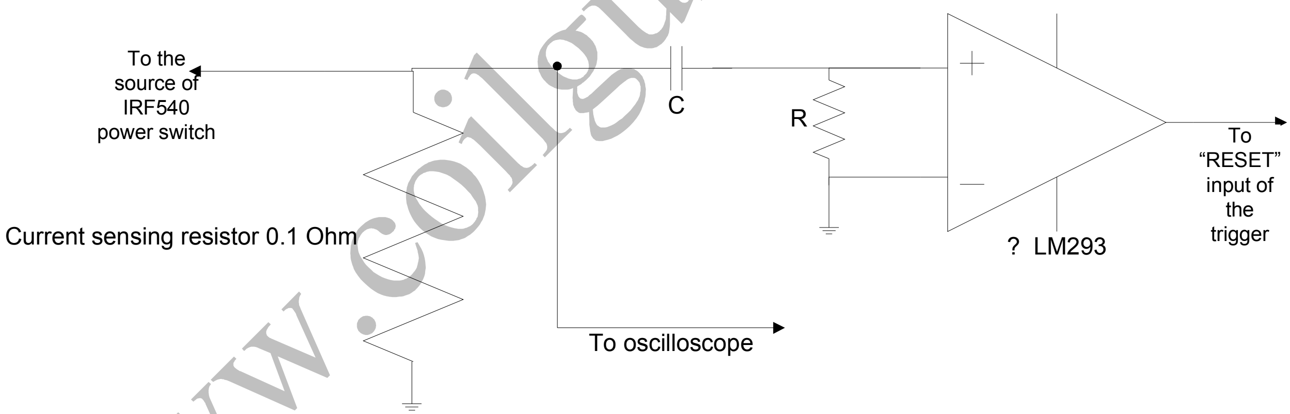



**Fig. 12. Final (workable) scheme of the inductive sensor.**

Now the signal is caught just on the sensing resistor, and through differentiating RC-chain fed to the comparator. Following picture shows the voltage on the comparator input.

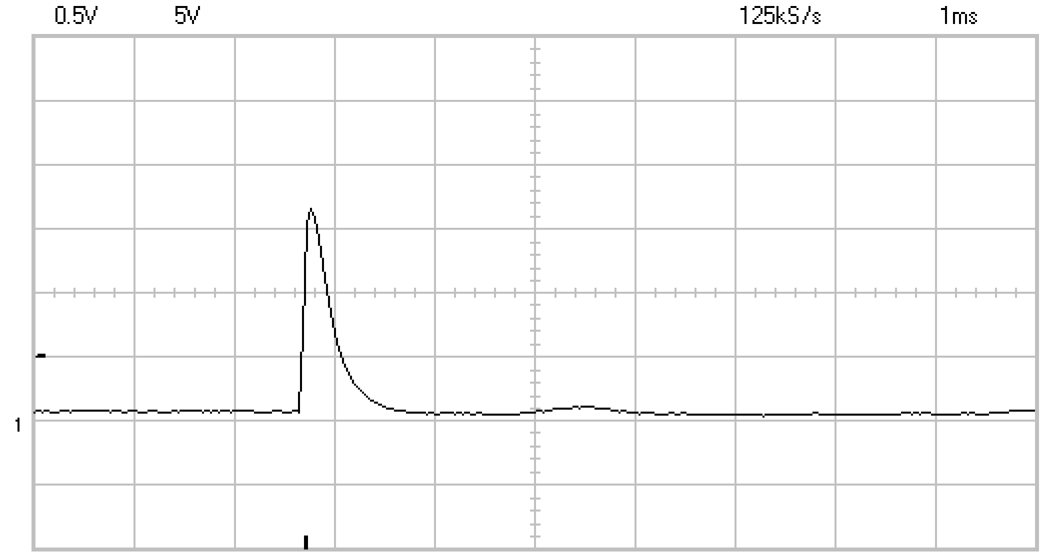



**Fig. 13. Signal after RC-chain (input of the controlling comparator).**

As result, the scheme is switched in a desired moment.
Thus, the work on experimental circuit of ID has been finished.

## Conclusions and reflections

As results of my work, the following conclusions may be made:

1) The inductive spike, caused by a projectile passing center of a coil, exists on current curve. Under certain conditions it may be experimentally observed.
2) The favorable conditions for the observation are:
   - high initial velocity of projectile;
   - low current (field strength) in a coil;
   - small outside diameter of a coil.

The first two requirements increase the amplitude of the spike, and the latter one shortens the front end of the "main" current pulse which can mask the spike.

3) It is possible to build the inductive sensor (IS) to switch off the current in appropriate moment. One of the feasible constructions is demonstrated.

Now it's time to say about another "hidden" advantage of IS which was hinted on above. Imagine that we spent a lot of time and money and built a multistage coilgun (for example optically triggered). Then we conducted prolonged adjustment shooting to determine necessary delays for all detectors (between the moments of projectile passing by and switching off the current). It seems to be all right, but there is one unpleasant feature: now we have the coilgun *tuned for specific set of parameters* (length and mass of the projectile, capacitance and initial voltage). In case of one of these parameters change we must redo all our adjustments. Meanwhile, although the projectile's characteristics may be somehow fixed, the capacitance drift during operation can make ±50%. The temperature also has its influence.

From this point of view, IS is very attractive because it generates the signal just on the necessary moment *independently* of the shape and mass of projectile and other conditions. It means that IS-equipped coilgun is able to shoot various projectiles from different capacitors charged to a range of voltages – the unique property!

IS has some disadvantages, too:

1) It can be used to switch *off* the current only.
2) The switch off takes place in ZP - not very good because strong suck back begins immediately after ZP. It means that high voltage switches must be used (to provide the fastest decay of current).
3) The accelerating coil, optimized to catch the inductive spike, may be not optimal concerning accelerating efficiency. I.e. the gain of IS usage may be less than total efficiency decrease.

The latter point must be not so important in multistage system, because they have as a rule thin coils and high speeds, which is itself optimal combination for IS.

Sincerely yours, *Eugen*.