Physics of an axial coil gun

Part V – The effect of a bigger slug and an initial speed

The effect of a bigger slug

In previous parts of this paper, the slug we considered was modeled on Luger's Parabellum cartridge. In particular, the slug had a diameter of 9 mm, a length of 20 mm and a mass of 9.9879 grams. The thinnest coil we considered – the 96-turn model – has a core diameter of 2 cm, so all four coils which we considered before can handle a bigger slug.

So, let us consider using a bigger slug. "Bigger" can mean in length or in diameter, or both. To separate out the effects, we will consider three variations of the base case. It the first two cases, which I have called "Disk A" and "Disk B", the slug is given a bigger diameter, but its length is shortened by just the amount needed to keep the mass of the slug the same as in the base case. In the third variation, which I have called "Heavy slug", the slug is longer and has a bigger diameter than the base case case. The details dimensions of the four different slugs are as follows:

Slug name →	**Base case**	**Disk A**	**Disk B**	**Heavy slug**
Diameter	9 mm	13.5 mm	15 mm	15 mm
Length	20 mm	8.889 mm	7.2 mm	30 mm
Mass	9.9879 g	9.9879 g	9.9879 g	41.6163 g

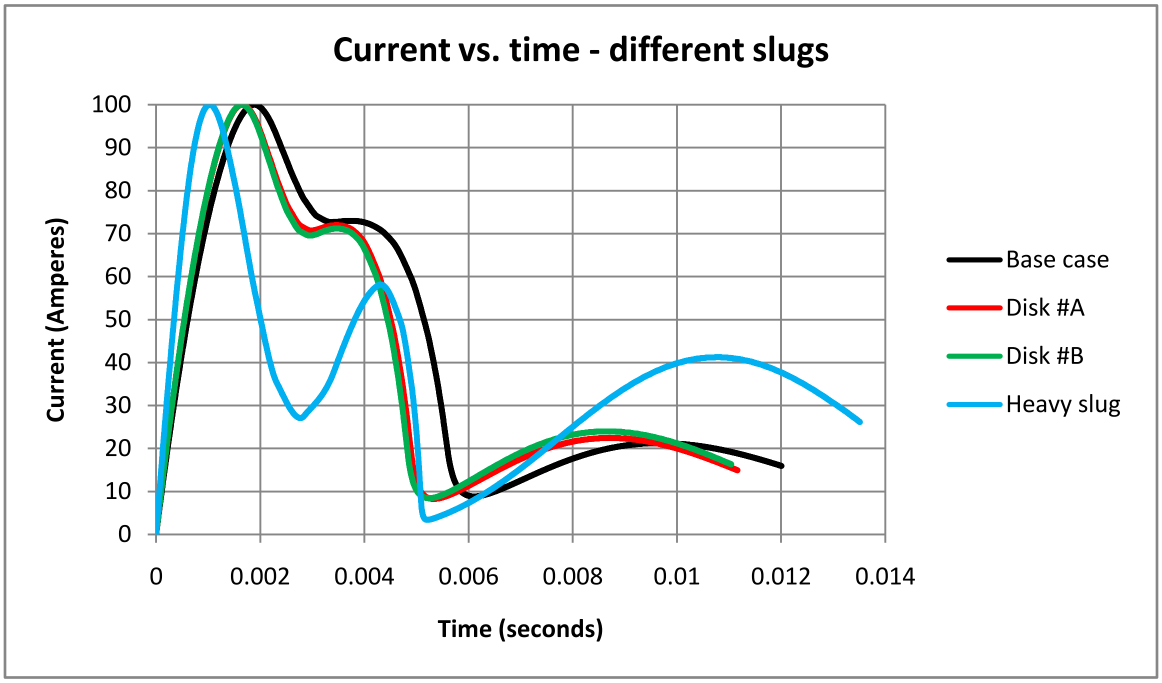
The following table sets out the highest speeds obtained from the 96-turn four-layer coil. In each of these runs, the current was limited to a maximum of 100 Amperes and the recoverable energy when the slug reached the center of the coil was limited to one percent of the initial energy stored in the capacitor. These requirements on the current mean that the optimal capacitor, starting voltage and starting position for the slug vary from case to case.

Slug name →	**Base case**	**Disk A**	**Disk B**	**Heavy slug**
Capacitor	11.0 mF	8.8 mF	8.8 mF	6.6 mF
Initial voltage	46.500 V	51.310 V	51.462 V	77.614 V
Initial energy	11.892 J	11.584 J	11.653 J	19.879 J
Starting position	0.28950 m	0.28600 m	0.28575 m	0.28725 m
Ending speed	31.189 m/s	32.613 m/s	33.005 m/s	25.818 m/s
Slug's ending energy	4.858 J	5.314 J	5.440 J	13.870 J
Efficiency	40.85%	45.85%	46.68%	69.78%

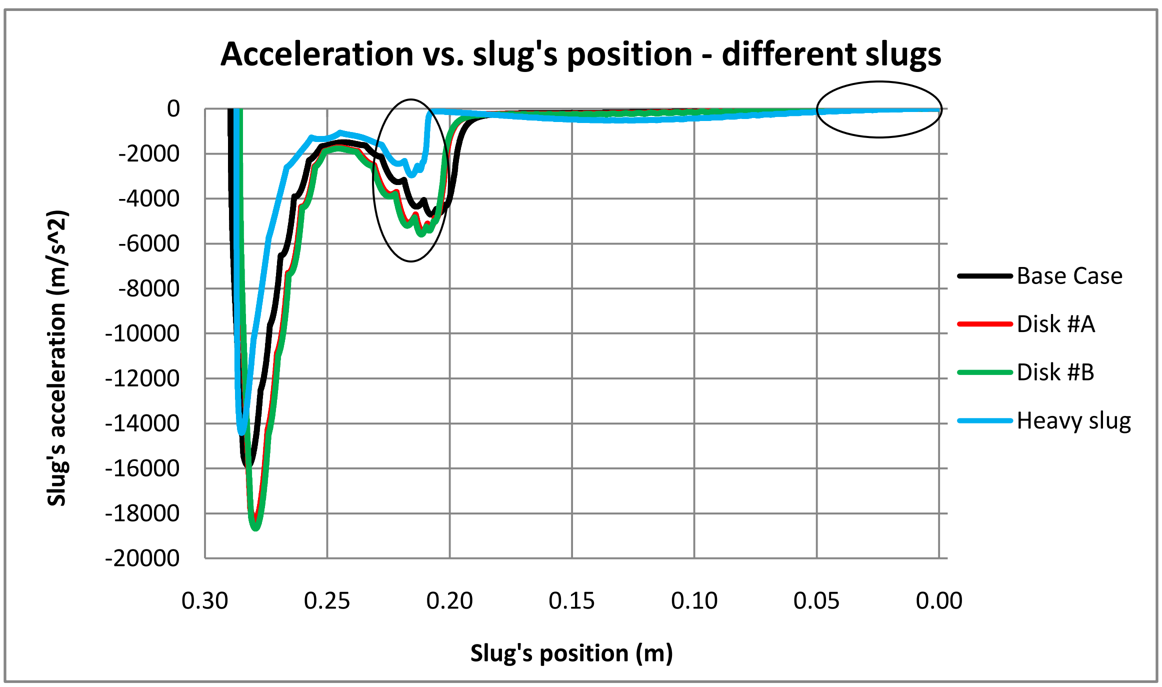
Increasing the diameter of the slug, while keeping its mass the same, increases the final speed and the efficiency of the energy transfer. The implication of this is that the core diameter of the coil should be as small as possible or, stated alternatively, that the slug should occupy as much of the diameter of the coil as possible.

Now, look at the results for the heavy slug. It weighs more than four times as much as the basic slug (and Disk A and Disk B, as well) yet received almost three times as much energy. The efficiency of the heavy slug is very high – 69.78%. It did not get quite as much speed as the base case, but did get much more energy. The implication is that a coil gun can be more efficient the heavier the mass of the slug. Perhaps we should be designing for a 48-calibre instead of a 38-calibre gun.

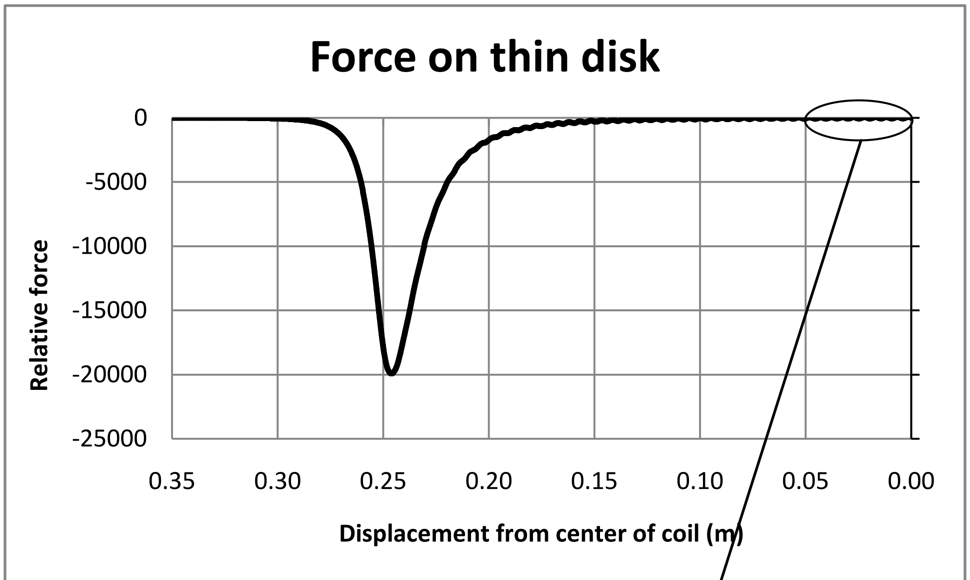
The following graph shows the current with respect to time in these four cases.



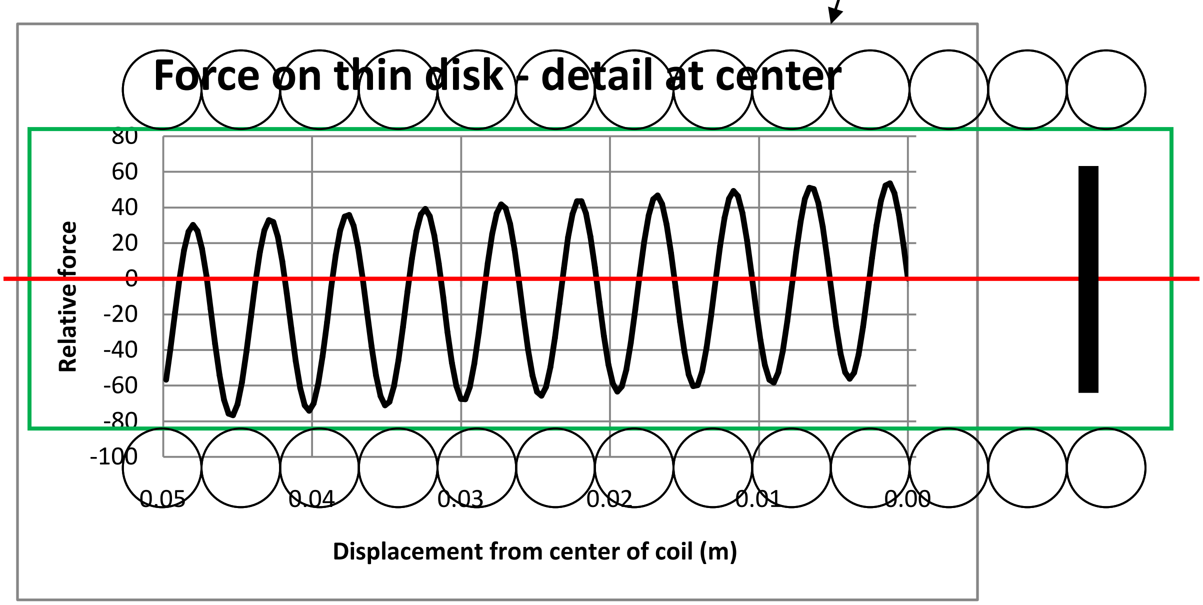
The first three cases, in which the slug weighs 9.9879 grams, have current waveforms like those we have seen before. Of course, the bigger the diameter, the faster the slugs passed through the gun. The current for the heavy slug is interesting in that the current shows two separate peaks, on either side of the moment at which the slug passes through the face of the coil. The following graph shows the acceleration of the slug with respect to the slug's position during the runs.



I have highlighted with ellipses two areas on the graph. The cusps in the acceleration, which are most apparent in the ellipse on the left, arise because of the physical spacing of individual turns of wire in the coil. The cusps become more pronounced as the diameter of the slug increases, so that its outer surface comes closer to the innermost turns of wire. The second ellipse highlights the five centimeters of the coil which are just to the left of the coil's center. I highlighted this distance because my first encounter with this phenomenon occurred when the numerical integration procedure failed when slugs entered this region. To understand this matter, consider the following graph. It shows the force on thin disks which have a diameter of 15 mm. Since the core radius of the coil is two centimeters, or 20 mm, the circumference of such thin disks are 2.5 mm away from the inside of the innermost layer of turns. Seen as a whole, there is nothing unusual about the force curve.



It looks similar to ones we looked at in Part III of this paper, where we began our investigation into the spatial distribution of the force field. However, the following graph shows the detail from that last five centimeters on the active side of the center of the coil.



I have superimposed on this graph a scale diagram of the configuration. The outline of the coil's core is shown in green. The axis of the coil is shown in red. The coil's core measures 20 mm in diameter, that is, from top to bottom in the graph. Since the horizontal axis of the graph is five centimeters long, it follows that the part of the coil shown is about eight centimeters long. The thin disk is shown in cross-section as the black rectangle. Seen face on, the thin disk is a circle, with a diameter of 15 mm. The wires in the innermost layer are shown as well. Recall that the wire has a diameter of 5.189 mm, which is relatively large compared with the diameter of the coil. Furthermore, there are four layers of wire in the coil, but I have shown only the innermost layer. It can be seen that the force acting on the thin disk depends on its exact position with respect to the central axes of individual wires. This is less of an issue when the thin disk is located further and further from the center of the coil, because the magnetic fields set up by the current in the individual wires "smears" together. But, near the center of the coil, the effects from the two ends tend to cancel one another out, giving more importance to the local turns.

The numerical integration routine, as I had originally written it, failed because I assumed that the force acting on a thin disk would always be attractive when the thin disk was located to the left of the coil's center. But, this is not so. Over the last five centimeters or so of the active side of the coil, the force can be repulsive.

The effect of initial speed

In all the runs up to this point, we have assumed that the slug starts from rest. In this section, we will look at what happens when the slug has an initial speed, directed towards the center of the coil. This is, in essence, a first look at the second stage of a coil gun, where the first stage accelerates the slug prior to it entering the second stage. In this section, we will consider only the base case slug, with a 9 mm diameter and a 20 mm length. The following table shows the results when the slug has initial speeds of 0, 10, 20, 30 and 40 meters per second.

Initial speed →	**0 m/s**	**10 m/s**	**20 m/s**	**30 m/s**	**40 m/s**
Capacitor	11 mF	8.8 mF	6.6 mF	4.4 mF	2.2 mF
Initial voltage	46.500 V	54.073 V	63.603 V	76.107 V	96.710 V
Initial energy	11.892 J	12.865 J	13.350 J	12.743 J	10.288 J
Starting position	0.28950 m	0.30350 m	0.31275 m	0.31650 m	0.31975 m
Ending speed	31.189 m/s	35.399 m/s	41.111 m/s	47.103 m/s	52.061 m/s
Slug's ending energy	4.858 J	6.258 J	8.441 J	11.080 J	13.535 J

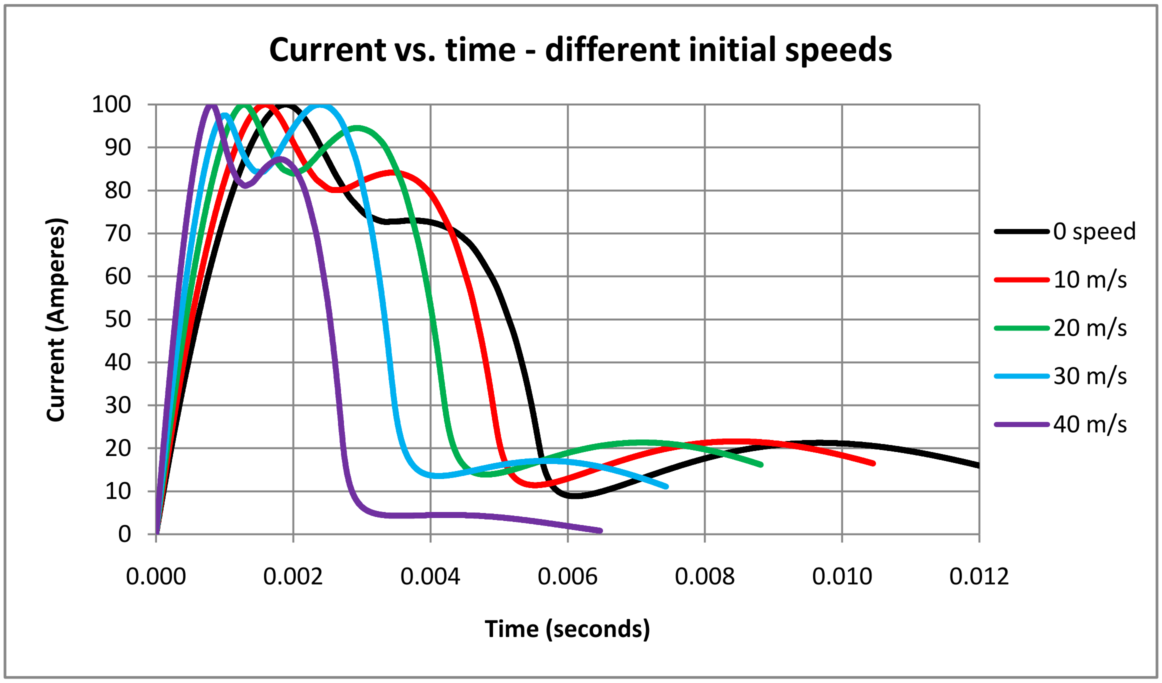
As the initial speed of the slug increases, the capacitance must be decreased – since the slug passes through the coil more quickly, the current pulse must be shorter. I should point out that the label "Initial energy" in this table refers to the initial energy stored in the stage-two capacitor. On the other hand, the label "Slug's ending energy" refers to the kinetic energy of the slug when it leaves the second stage, including the energy it had at the end of the first stage.

It is useful to separate out the effect of the second stage from the outcome of the first stage. The following table does this. For each of the initial speeds, this table shows the additional speed imparted to the slug (labeled "Extra speed"), the additional kinetic energy imparted to the slug (labeled "Slug's extra energy"), the initial energy in the stage-two capacitor (labeled, as before, "Initial energy") and the efficiency with which energy from the stage-two capacitor was imparted to the slug.

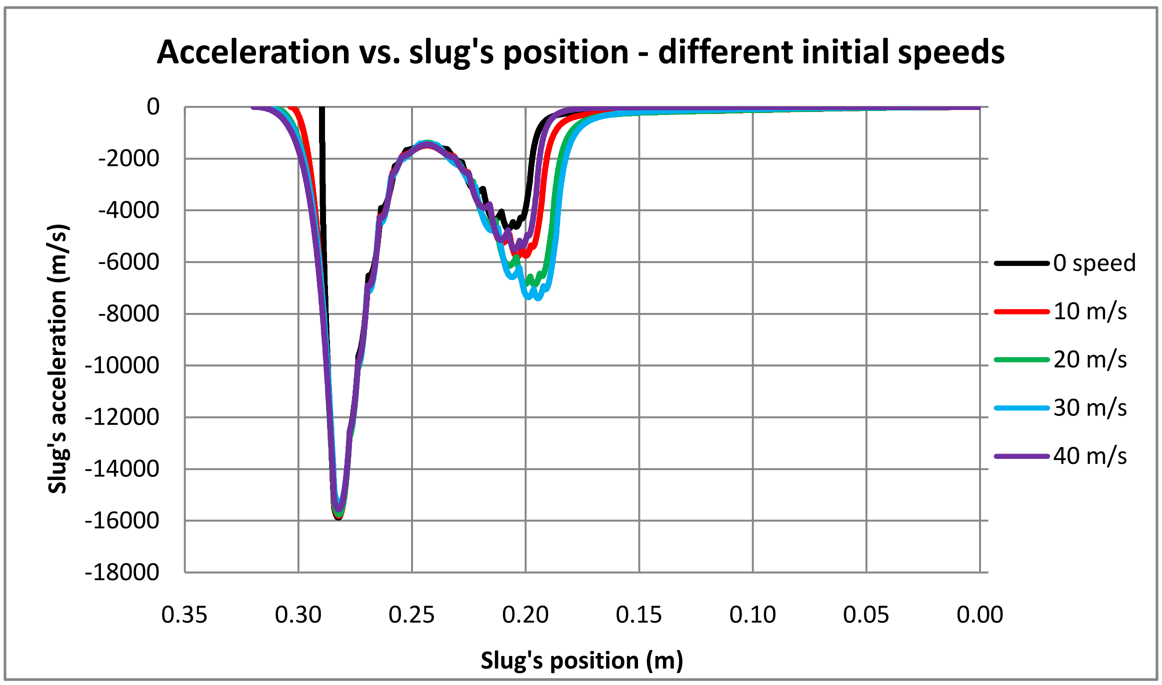
Initial speed →	**0 m/s**	**10 m/s**	**20 m/s**	**30 m/s**	**40 m/s**
Extra speed	n/a	4.224 m/s	9.922 m/s	15.914 m/s	20.872 m/s
Slug's extra energy	n/a	5.759 J	6.443 J	6.585 J	5.545 J
Initial energy	n/a	12.865 J	13.350 J	12.743 J	10.288 J
Efficiency	n/a	44.76%	48.26%	51.68%	53.90%

The zero-speed column is not applicable because, by definition, if the slug starts with zero speed it is in the first stage. What is remarkable is that, the higher the speed of the slug going in to the second stage, the greater the efficiency with which the energy stored in the stage-two capacitor is converted in kinetic energy of the slug. This will be helpful when making a multi-stage coil gun.

The following graph shows the current with respect to time for these five cases.



The following graph shows the slug's acceleration as a function of its position during transit.



We are still a long way from having a coil gun that could be considered to be a success. My personal goal is to design one that is at least as effective as a “Saturday night special”, by which I mean one that can shoot the base case 9 mm slug at a speed of more than one thousand feet per second. One thousand feet per second is approximately equal to 305 meters per second. The 30 m/s second speeds which are typical of the runs we have been getting from one stage is only ten percent of the required speed and even less, only one percent, of the required energy.

However, we have identified a number of topics which deserve individual attention, before starting a complete re-design. I will examine these issues in subsequent addenda.

Jim Hawley
September 2012

An e-mail setting out errors and omissions would be appreciated.