# High magnetic field generation using a modified, portable single turn coil apparatus

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**Abstract**

We examine a method to generate high pulsed magnetic fields, the single turn coil method. This is a destructive method, giving rise to pulsed magnetic fields in a timeperiod of about 100 $\mu$s. It is unique amongst the destructive methods in that there is no destruction in the actual sample space. For our experiments, we used a small, portable testing apparatus, powered by a capacitor of 400 $\mu$F at 850 V, capabale of producing fields in excess of 2 T. We modified the apparatus by adding current and coil voltage sensing probes. The effects of the geometry of the coil and the materials of which it is composed on the peak field were examined. The added measurement capabilities also allowed us to examine a variety of effects such as the coil inductance, coil deformation, plasma conduction and power dissipation in coil and plasma.

## 1 Generation of magnetic fields

### 1.1 History

Magnetic fields are of the utmost importance to the experimental physicist. For example, they are widely used to resarch the proporties of various solids, often in conjuction with cryostatic temperatures.

Thus, various techniques have been invented to generate strong magnetic fields. There are basically three classes of techniques: continuous, pulsed non-destructive and pulsed destructive field generation methods. Various techniques have been summed up in table 1 together with their strongest produced fields [6] [1].

Iron core electromagnets can only be used for fields up to 2 tesla, because the material saturates at these flux densities. For this reason, most coils are used without a core. The strongest permanent magnetic fields are generated using superconducting electromagnets or a hybrid of both resistive and superconductive magnets. When even higher fields are needed, superconductors become unavailable because their conductive properties are lost as the field crosses a critical value. Thus, to deal with the extremely high heat that is generated, pulsed fields are used. Valuable data ought to be collected in the small moment the magnetic field is present. [4]

### 1.2 Single turn coil

The method for generating magnetic fields we researched is the “single turn coil” method. As the name says, the coils used consist of a single loop of metal. A capacitor (bank) is used to

**Table 1:** Various magnetic field generation methods and their maximum attainable field

| Method | Field (T) |
|---|---|
| Permanent magnet | 1.3 |
| Resistive electromagnet | 36 |
| Hybrid electromagnet | 45 |
| Pulsed (non-destructively) | 89 |
| Explosive | 2800 |

store electrical energy which is released into the circuit. When operated at the ideal power level, Joule heating and magnetic stresses in the coil will cause it to disintegrate shortly after the peak field is reached. The metal of which the coil is composed evaporates and after a short pause, the plasma of metal vapour starts to conduct again. During the short period where coil stays more or less together, a very high field is generated in the measurement "chamber".

The single turn coil method is unique among the destructive methods as there isn't any destruction in the sample space. After the violent explosion of the coil, the material is driven outwards because of the Maxwell stress, directed entirely away from the sample space [3]. This makes repeated measurements possible as well as the possibility of using cryostats. The expelled coil fragments move at dangerously high speeds and care must be taken to protect apparatuses and personnel [2]. During the experiments we performed, about 50 shots were fired. The pickup-coil was protected by a thin sheet of Kapton that also served to insulate the coil. The sample space and coil suffered no damage at all.

### 1.3 RLC circuit theory

The circuit containing the coil and the capacitator can be approximated as an RLC circuit. A more in depth analysis would require solving the non-linear Maxwell equations, for example by finite-element analysis.[3]

The value of $C$, the capacitance, was determined to be 400 $\mu F$ with a multimeter, matching the given specification. The values for $R$ and $L$, respectively the resistance and the self-inductance of the circuit are very low and nigh impossible to measure directly. These values and will be computed in section 4 by fitting the model below to the measured data.

Preliminary measurements showed that the system is very underdamped ($\zeta \approx 0.1$), so we don't need to consider the critically and the overdamped case. The equation for the damped harmonic oscillator goes as follows [5]

$$Q(t) = V_0 C e^{-\zeta\omega t}\left(\cos\omega_d t + \frac{\zeta}{1-\zeta^2}\sin\omega_d t\right) \tag{1}$$

Where $Q$ is the charge in the capacitor in function of time, $V_0$ is the initial voltage, $C$ is the capacitance, $\omega$ the undamped natural frequency, $\zeta$ the damping factor and $\omega_d$ the damped natural frequency defined as

$$\omega^2 = \frac{1}{LC} \qquad \zeta = \frac{R}{2L\omega} \qquad \omega_d = \omega\sqrt{1-\zeta^2}$$

Differentiating this expression, one obtains the current

$$I(t) = \frac{\mathrm{d}Q}{\mathrm{d}t} = -V_0 C \frac{\omega}{\sqrt{1-\zeta^2}} e^{-\zeta\omega t}\sin\omega_d t \tag{2}$$

Using this expressions and the measured voltage over a shunt, we were able to determine with some precision the effective self-inductance and resistance of the circuit in section 4.

# 2 Apparatus

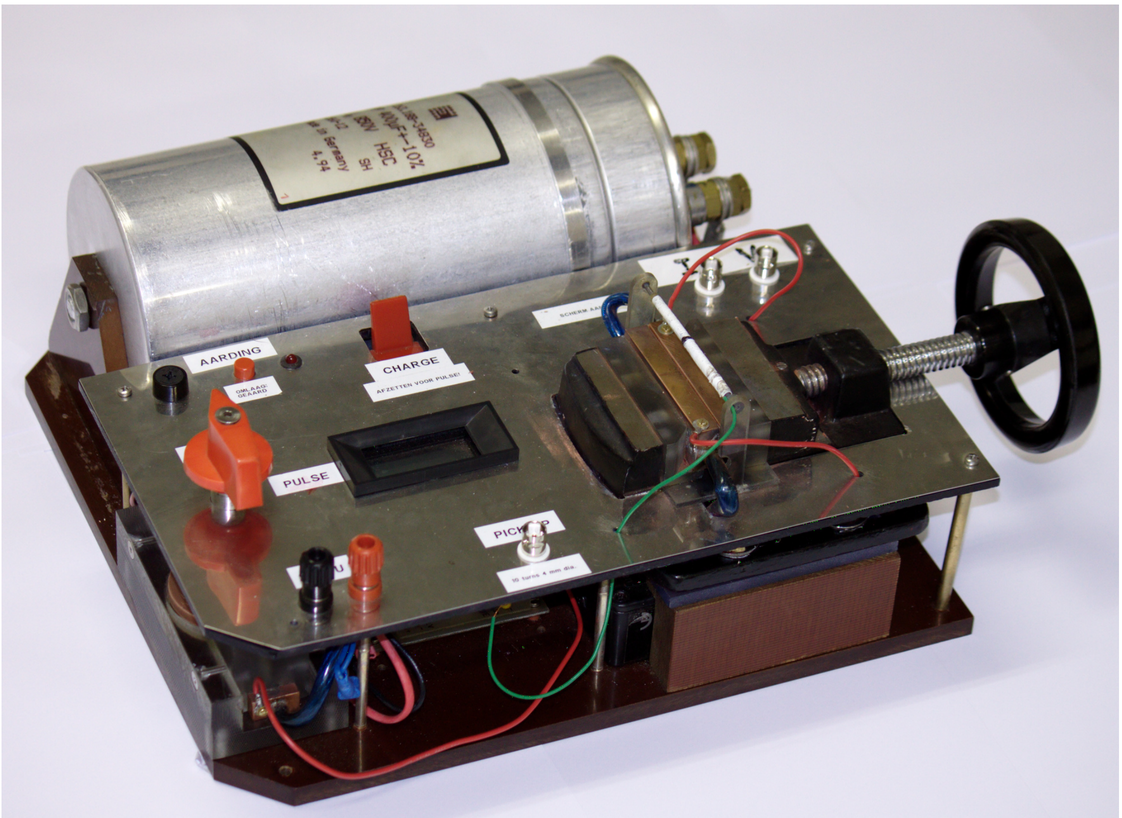


**Figure 1:** Overview of the apparatus

A photograph of the apparatus is given in figure 1. Its internals are sketched in figure 2. It consists of a power supply that charges a large capacitor (top). The energy in this capacitor gets dumped in the single turn coil (right) through a spring loaded, high current switch (left). The coil is mounted over the testsample.

## 2.1 Power supply

The apparatus has a built-in 12 V 1.2 Ah sealed lead acid battery to provide a portable power supply to charge the capacitor. Because of the age of the apparatus, however, the battery had gone dead and the power was provided by a 12V lab power supply. An inverter boosts the 12V to around 870V to charge the high voltage capacitor.

## 2.2 Capacitor

The capacitor used is a 850 V 400 $\mu$F bipolar capacitor that can store around 150 J of energy.

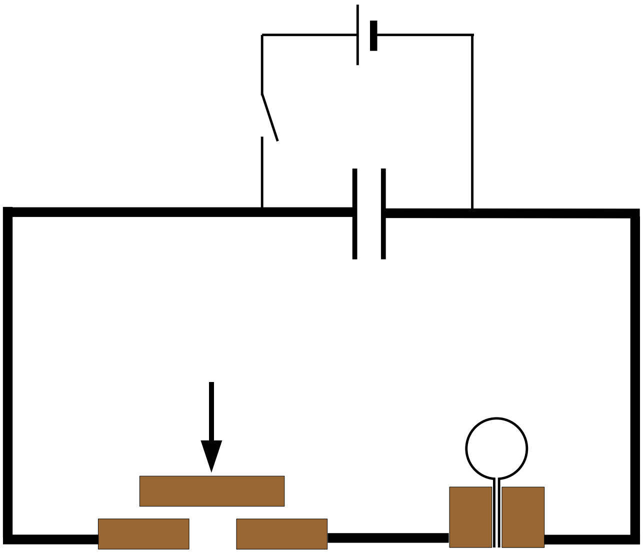

**Figure 2:** Schematic overview of the apparatus

## 2.3 Switch

Because of the very high current surges, it is unfeasible to use a standard switch to commute this current. Instead, a custom made spring loaded switch is used.

This switch consists of two copper bars, separated by a small distance. Suspended above these bars is a copper disk, which is mounted on a notched, spring loaded shaft. The notch slides over a small retaining screw. The switch is armed by pulling the shaft out and twisting it, so the screw is no longer aligned with the notch.

When the knob is then turned again, the notch lines up with the retaining screw and the spring pushes the shaft down. The copper disk is propelled towards the copper bars and upon impact the current can flow.

A photograph of the switch is shown in figure 3. The circular copper disk is clearly visible. The switch is armed in this photograph, ready to shoot downwards when the knob is turned to the right.

## 2.4 Coil

The apparatus is equipped with a (conducting) vice in which a variety of coils can be mounted. These coils are usually made of thin metal foil or sheeting. Most of our tests are conducted with coils of 0.5 mm thick copper foil.

An hourglass shape, as seen in figure 4, is cut from the sheet and bent into the required form. The feeder plates of the coil preferably have a large surface area for the high current to pass through. To ensure good conduction, the plates should also be sufficiently smooth and parallel. To prepare for a measurement, the coil is pressed firmly in the vice.

A piece of Kapton is inserted between the inside of the plates to electrically insulate them from one another and protect the sample space from any stray fragments or vapour.

Additionally, a small plastic clamp is used to pinch keep the coil together, as seen in figure 5. This increases the field by forcing the current to go completely round the sample. It also

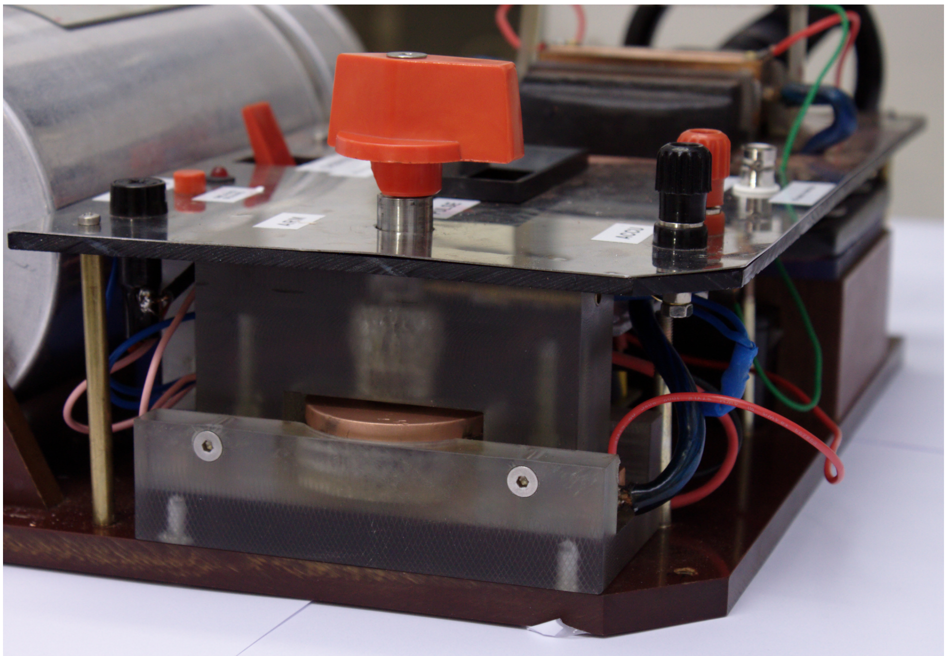

**Figure 3:** The spring loaded, high current switch

helps the coil withstand the high Maxwell stress that is exerted on the material.

We experienced that coils made from weaker materials, like aluminium foil, can get ripped apart by the magnetic forces before a considerable field has formed. Finally, a protective plastic casing is installed to protect ourselves and the instruments from flying debris.

### 2.5 Sample

In our case, the sample merely consisted of a small pick up coil to determine the generated magnetic field. This pick up coil is a 10 turn coil with a diameter of about 4 mm and a calibrated equivalent surface area of 136 $\mathrm{mm}^2$.

## 3 Modifications

We modified the original apparatus with extra measurement capabilities and gave it general revision and cleaning.

### 3.1 Maintenance

The apparatus already had a history of many high energy pulses, which meant it was time for some cleaning and maintenance. The plates of the spring loaded switch had gotten charred and rough from the frequent arcing when commuting the high currents. They were filed smooth and flush again[1].

[1]Interesting fact, the first few high current pulses after smoothing out the switch actually welded it shut. Both plates made contact within a very small tolerance and a large surface area stuck together.


**Figure 4:** Some of the coils used. Copper on the left, aluminium on the lower-right, nickel on the upper-right

The vice that holds the single turn coil also needed to get filed down, as it had gotten rough and showed several bumps, decreasing the effective contact area.

### 3.2 Replacement of pick up coil

During the maintenance and adding the extra measurement connectors, one of the brittle wires of the pick up coil got damaged beyond repair. This was the ideal opportunity to wind a new pick up coil that could be calibrated. The new coil was wound from a slightly thicker and less brittle copper wire. It has a diameter of about 4 mm and consists of 10 turns of wire. The total equivalent calibrated surface area reads $136\,\mathrm{mm}^2$.

### 3.3 Measuring current and voltage over the coil

The voltage over the coil can be measured straightforward by measuring over both sides of the clamping vice. The current measurement is more difficult. We opted for a simple and non-intrusive method. We measure the current by measuring the voltage drop over a connecting wire that acts as a shunt resistor.

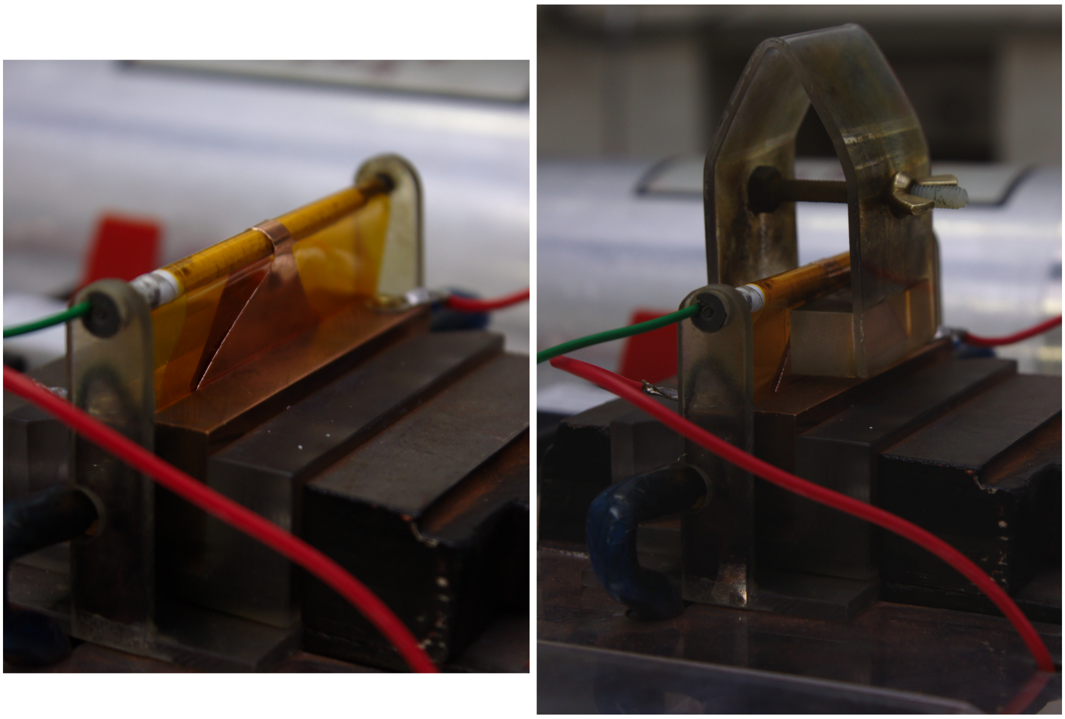

**Figure 5:** An unclamped and clamped coil

### 3.3.1 Motivation

Knowledge of both the current through and the voltage over the coil allows us to do measurements that weren't possible before. Multiplying both values gives us the power dissipated or generated in the coil. The new measurements also made it possible to analyse the current flowing through the plasma that is formed after the coil evaporates. Finally, by fitting the data with a simple RLC model, we are able to determine the characteristics of several electrical components of the apparatus. Values for the total resistance ($R$) and self-inductance ($L$) were figured out. This provides a way to improve the circuit, as the inductance and resistance ought to be as small as possible, as shown below.

### 3.3.2 Choosing measuring points

Care needs to be taken that both probe connections share the same ground. If they don't, the oscilloscope that is used to read out the signal will short out both grounds anyway. This will disturb the measurement and can potentially send very large currents through the scope.

Practically, the easy and tidy option was to choose both measuring points as depicted in figure 6. The voltage over the coil is given by $V_1$ and the current is proportional to (the negative of) $V_2$.

However, as will be shown in section 5.5, the (stray) inductance of the connecting wires is much greater than the inductance of the single turn coil. This means that the wire coming from the capacitor and leading to the coil, and the wire from the switch to the coil both have a much higher effect on the measured voltage than the single turn coil itself. The resistance of the wires (which we actually use as a shunt for the current reading!) also adds to the

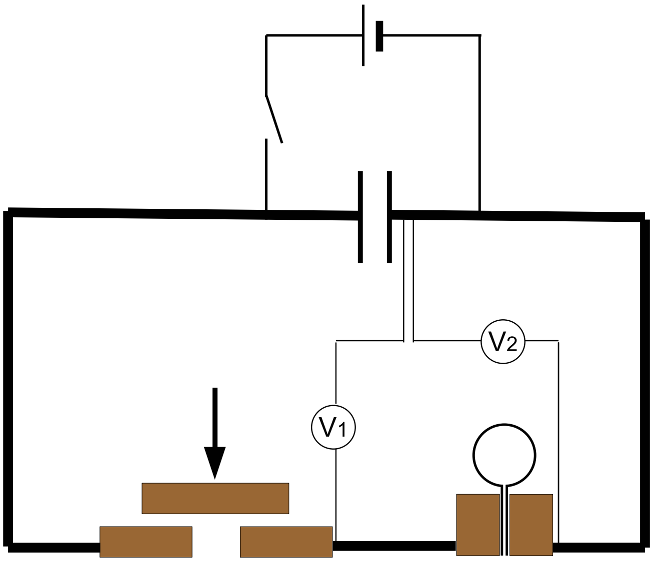


**Figure 6:** Initial setup of measuring probes

measured voltage.

This effect skewed the measurements and was mitigated by choosing a different placement of the probe connections. This setup is depicted in figure 7.

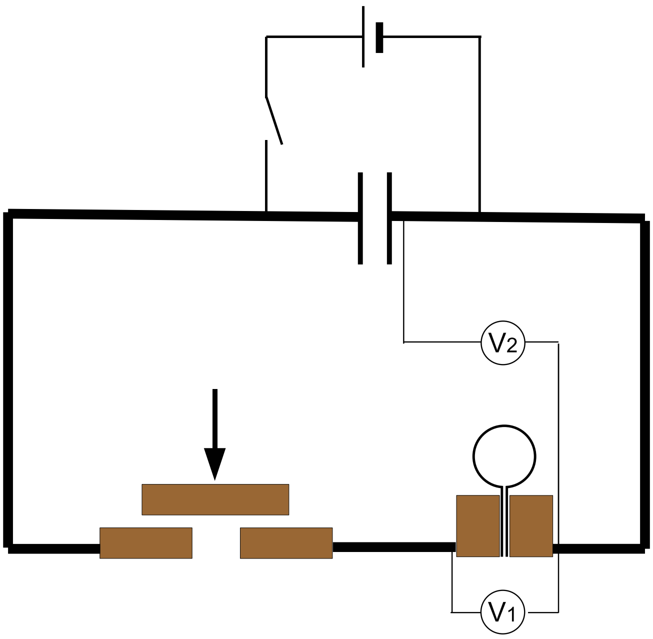


**Figure 7:** Improved setup of measuring probes

The voltage $V_1$ over the coil is measured with as little extra wire in between as possible. The voltage $V_2$ is measured over a wire that is as straight as possible, to minimize the inductance. This setup offered more reliable and correct measurements than the previous one.

### 3.3.3 Getting the voltage down

Because the capacitor gets charged to 850 V for the high energy pulses, the voltage over the measuring points can get very high. In order to safely measure this voltage, a custom voltage divider (figure 8) was added for both measuring points.

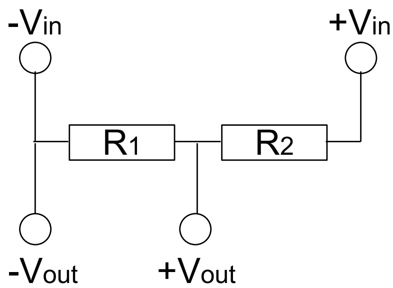


**Figure 8:** Voltage divider

At first, we used values of $R_1 = 120\,\mathrm{k\Omega}$ and $R_2 = 15\,\mathrm{M\Omega}$, leading to a $126\times$ reduction in the measured voltage.

At the highest possible voltage of 850 V, these resistors would dissipate about 0.06 W.

However, we noted some dampening effects when measuring via these voltage dividers compared to a direct measurement. We assume the internal capacitance (and in general the impedance) of the connecting coax cables was a bit too high for the given frequency and the (high) output impedance of the voltage divider.

We therefore choose to lower the values to $R_1 = 18\,\mathrm{k\Omega}$ and $R_2 = 820\,\mathrm{k\Omega}$. This gives a power dissipation of 1 W at peak voltage, still much lower than the power dissipated in the coil. The new voltage divider seems to mitigate the lagging and soft response of the old one. The new factor is thus 46.6, which we shall call $\xi$ from now on.

The input impedance of the used oscilloscope was $1\,\mathrm{M\Omega}$.

### 3.3.4 Effect of stray inductance on the measured current

The current reading can still be affected by the stray inductance on the wire that acts as a shunt. To estimate its effect, a seperate measurement of the current was made by measuring the (full) voltage over a piece of straight metal from the connector plate of the capacitor. This will certainly have a low stray inductance.

The result is shown in figure 9. The graphs were scaled so their resemblence is more noticable.

One notices that the graphs are very similar for high $t$, but in the beginning the voltage over the low inductance shunt is lower. In the beginning, there is a very rapid oscillation, with high $\mathrm{d}I/\mathrm{d}t$ hence the voltage over the high-inductance shunt will be relatively larger than over the purely resistive shunt.

There also appears a phase difference, where the low-inductance shunt precedes the voltage over the full cable. This is once again because of (complex) impedance differences between

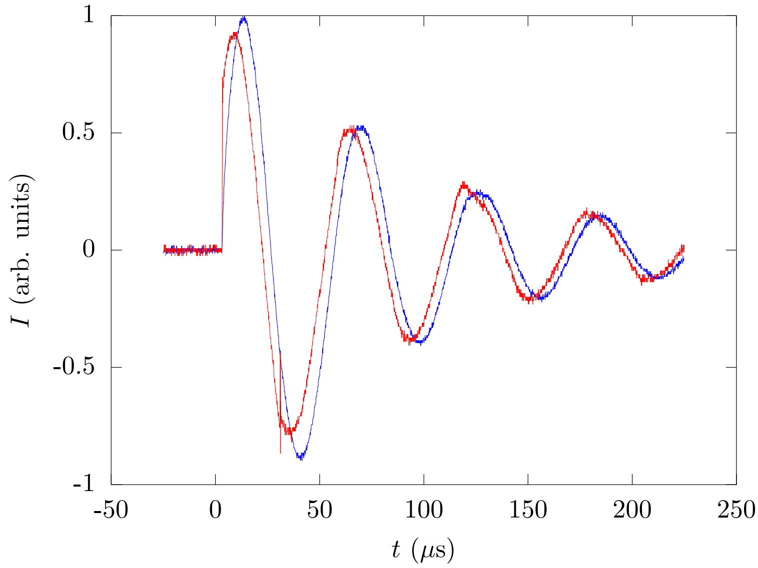


**Figure 9:** Comparison of the used (shunt) cable (blue) with a low-inductance shunt (red)

the two. It seems that it is *very* hard to get any reliable measurement of the phase between several signals on these timescales and in these environments with our available equipment.

Overall, we chose to continue using the shunt with this slight anomaly. A better way would be to use a dedicated low-inductance shunt, or to measure the current in another manner.

#### 3.3.5 Calibrating the current

Because the resistance of the shunt is unknown, the current value needs to be calibrated. We can do this by fitting the current of an RLC circuit to the measured signal.

This will also allow us to find other relevant parameters such as the total inductance and resistance of the circuit and hence is attributed a separate section below, section 4.

## 4 Calibrating the current and fitting system parameters

Sustainably producing currents of the magnitude of a typical pulse is not possible, so we cannot apply a known current and measure the voltage over the shunt to calibrate the current reading.

We can, however, fit the measured voltage to the expected current in an RLC circuit with a scaling factor that needs to be determined. This factor is composed of the resistance of the shunt, scaled by the voltage divider.

The measurement was made without a single turn coil present. The vice was just clamped together. Thus, the only inductance that played a role was the total stray inductance of the circuit. Several measurements were made with different initial voltages on the capacitor.

The function that needs to be fitted is thus

$$V_{\text{shunt}}(t - \Delta t) = R_{\text{shunt}} I(t)/\xi$$

with $\xi = 46.6$ the reduction of our voltage divider and $I(t)$ given by equation 2 where $C$ is known to be $400\,\mu$F and the initial voltage over the capacitor $V_0$ is known too.

We also incorporate a time difference to align the graph. The triggering of the oscilloscope (the measured point $t = 0$ for $V_{\text{shunt}}$) surely did not happen at the exact moment the current started flowing (the point $t = 0$ in the expression for $I(t)$). This $\Delta t$ is an extra factor that needs to be fitted.

The remaining factors that need to be fitted are $R_{\text{shunt}}$ the resistance of the shunt, $R$, the total resistance of the circuit and $L$, the total inductance of the circuit.

The fitting was done with a custom Octave script that does a $\chi^2$ minimization. The results we got are tabulated below, where the value of $\Delta t$ is omitted because it serves no meaning (it merely dependends on when the osilloscope is triggered).

| $V_0$(V) | $L$($\mu$H) | $R$(m$\Omega$) | $R_{\text{shunt}}$(m$\Omega$) |
|---|---|---|---|
| 71 | $0.83 \pm 0.06$ | $12 \pm 3$ | $43 \pm 8$ |
| 100 | $0.84 \pm 0.03$ | $9 \pm 1$ | $9 \pm 1$ |
| 200 | $0.82 \pm 0.01$ | $8.3 \pm 0.6$ | $5.3 \pm 0.3$ |
| 400 | $0.82 \pm 0.01$ | $7.1 \pm 0.6$ | $2.0 \pm 0.1$ |
| 800 | $0.82 \pm 0.01$ | $7.7 \pm 0.7$ | $1.12 \pm 0.09$ |

We find that the value of $L$ is constant throughout the voltage regime, as expected. The resistance of the circuit on the other hand, seems to decrease as the pulse becomes stronger (this is plotted in figure 10). Even more worrying is the fact that our $R_{\text{shunt}}$ exceeds the total resistance. This is likely caused by parasitic impedances in the cabling and the measurement circuit. The value of $R_{\text{shunt}}$ should therefore not be looked at as a real resistance, but merely as a factor that describes the total effect of various impedances on the amplitude of the measured voltage. This is all we need in order to calculate a current amplitude from a voltage amplitude reading.

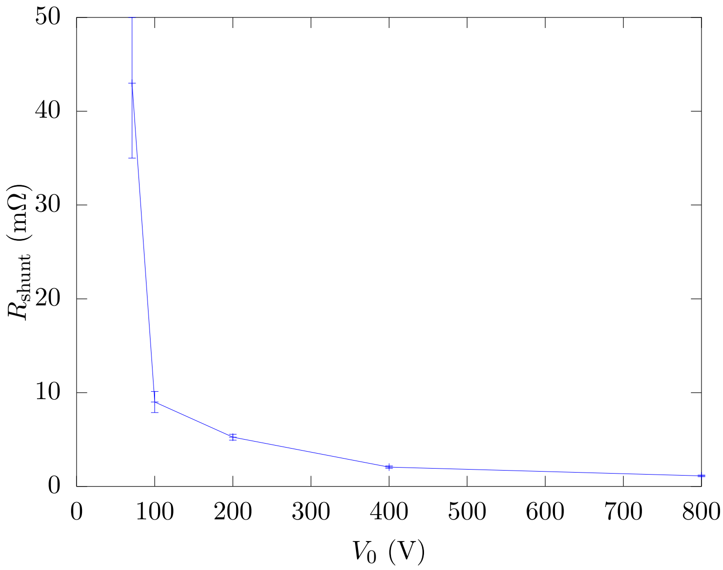


**Figure 10:** The “resistance” $R_{\text{shunt}}$ in function of bank voltage

In the measurements that follow, we have used the value of $R_{\text{shunt}}$ found for an initial voltage of 800 V for all pulses at the maximum energy. A graph of this measurement with the fitted curve is shown in figure 11.

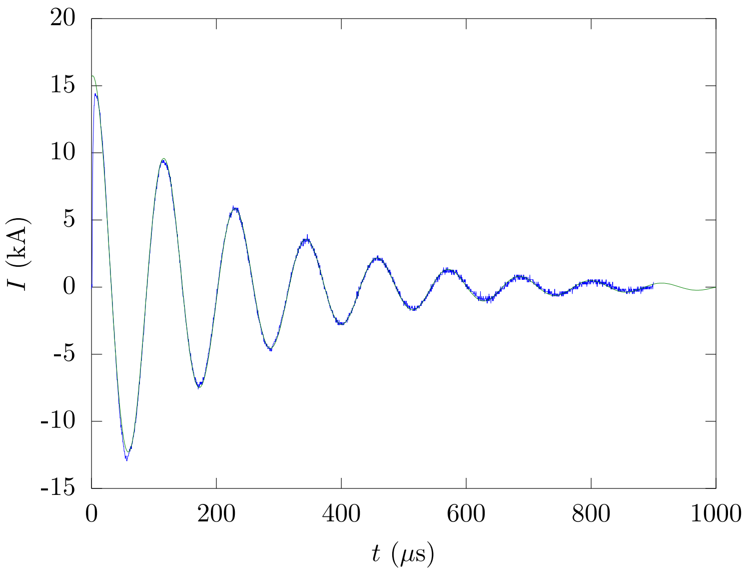


**Figure 11:** Measured current (blue) and fitted function (green, hard to see because of overlap) for an initial voltage $V_0$ of 800 V

It would have been better to use a low inductance shunt, such as the one used previously in figure 9. However, using that shunt it would be impossible to measure the current and the voltage at the same time because the ground of those measuring points is not shared. Thus we opted to continu using the slightly biassed shunt. Because of its non-linear characteristics, all the results derived from this current measurement should only be considered for their qualitative value, not their actual quantitative data.

# 5 Results

After having adapted the apparatus with the extra measuring capabilities, we performed some standard measurements of the maximum magnetic field. We also used the added $V$ and $I$ readings in an attempt to measure a few other phenomena such as the current conduction in the plasma after a coil breaks, the coil deformation and the power dissipated by the coil and plasma.

Because modifying the apparatus took up quite a bit of time, the measurements below are not as thorough as we preferred. We chose to touch several small topics, some of which are only possible after our modifications. These topics can be investigated further and in more depth in the future.

## 5.1 Magnetic field in function of the width of the coil

One expects to find an optimal value of the coil width. Too narrow a coil will experience a lot of Joule heating because of its high resistance. This can cause the metal to melt and evaporate before the maximum field strength is reached. A very wide coil will distribute its magnetic energy over a large volume, thus loosing efficiency.

The magnetic field of 28 measurements at maximum voltage was recorded. The results of these measurements are displayed in figure 12. The magnetic field is rendered in function of the width of the coil. Although we expected there to be an optimal coilwidth, we can discern no correlation between the field strength and the dimensions of the generating coil. We presume more measurements have to be performed under more strict conditions to determine any relation.

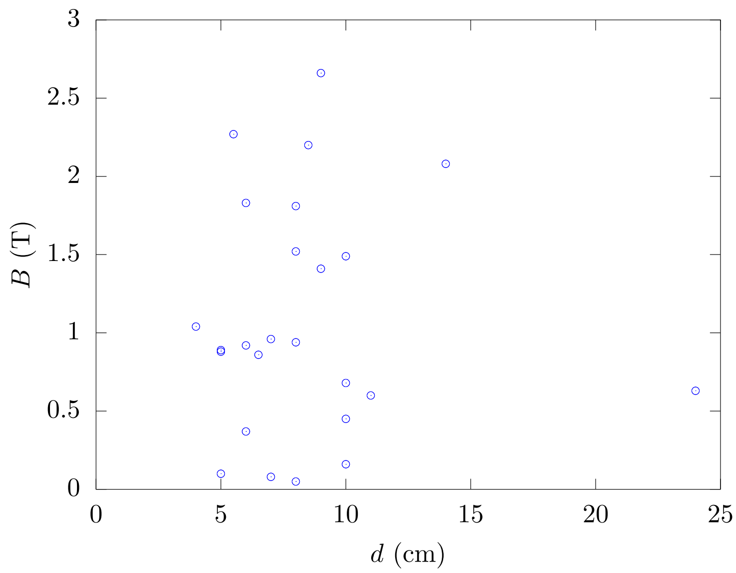


**Figure 12:** Magnetic field in function of the coildwidth

## 5.2 Magnetic field in function of the bank voltage

We also resarched the relationship between peak field and voltage of the capacitor bank. Measurements with a coil width of 6±1 cm were selected and rendered in figure 13. The peak magnetic field is displayed in function of the voltage of the capacitor. Although no real relationship can be determined, it is clear that a higher voltage usually results in a stronger field.

## 5.3 Peak field

In total, we did 28 measurements at maximum capacitor voltage. Of these, 10 reached magnetic field strengths of over 1 tesla. Because we couldn't sufficiantly research every parameter that could change the magnetic field, we didn't find a procedure to consistently generate such high fields. Although we lack some control, high fields were succesfully achieved in more than 60% of the experiments with a maximum at 2.7 T.

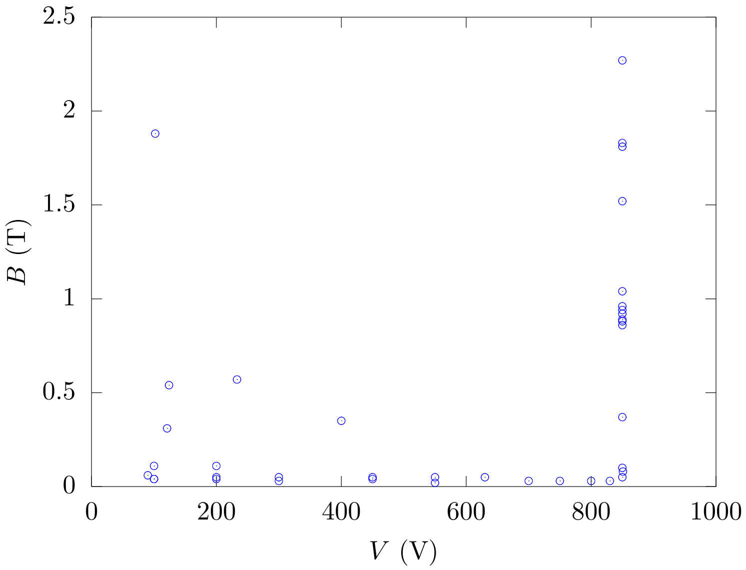


**Figure 13:** Magnetic field in function of the bank voltage

## 5.4 Choice of material

Coils made from copper (Cu) and aluminium (Al) were tested. The copper sheet was at 0.5 mm a lot thicker than the aluminium foil of only 15 $\mu$m. Nevertheless, the peak fields achieved with aluminium were as high as they were with copper, within the level of statistical uncertainty because of our small sample size.

The experiments with copper were a lot more consistent, though, as it seemed the brittle aluminium got tore off by the magnetic stress too soon, before peak fields were achieved. Evidence of this is visible in figures 16 and 17 (page 17). The field was still increasing and clearly hadn't reached it peak at the moment the coil disintegrated and a plasma was formed. Sadly, the plasma never was good enough a conductor or appeared too late for it to generate an appreciable field.

## 5.5 Inductance of the single turn coil and effect on peak field

Having the extra voltage and current readings, we can also try finding other interesting effects or phenomena. One such thing is that we are now capable of finding the inductance of the single turn coil by ftting the results to the model above.

Our choice was to fit the current measurement in a similar fashion as we did in section 4. The difference between the fitted inductance and the parasitic inductance of the apparatus found in section 4 should give the inducance of the single turn coil.

However, when plotting and fitting these curves, no significant deviation was noted from the curves found in section 4 (eg. figure 11 on page 12). The small inductance of the single turn coil is thus insignificant compared to the large inductance of the rest of the apparatus.

This has a few concequences regarding the peak field. For one, the energy available in the capacitor gets distributed over the magnetic energy in the single turn coil and the inductance of the rest of the circuit. Having such high a parasitic inductance severely limits the energy available to the coil.

Secondly, having such a high total inductance lengthens the time until the peak field is generated. This means the single turn coil has to stand up to the large stresses for a longer period of time. This can of course be mitigated by choosing a lower capacitance of the capacitor bank. In order to store the same energy, however, the voltage of this bank will have to rise. There is, however, a practical limit to this voltage [4]. Voltages of 50 kV and above become very difficult to handle.

In order to generate higher peak fields, it would be wise to try and limit the stray inductance of the circuit. It could also be beneficial to choose a capacitor with a smaller capacitance (but higher rated voltage). One remark here is that these operations both decrease the pulse duration, so that any measurements in the high magnetic field need to be very fast.

### 5.6 Plasma conduction

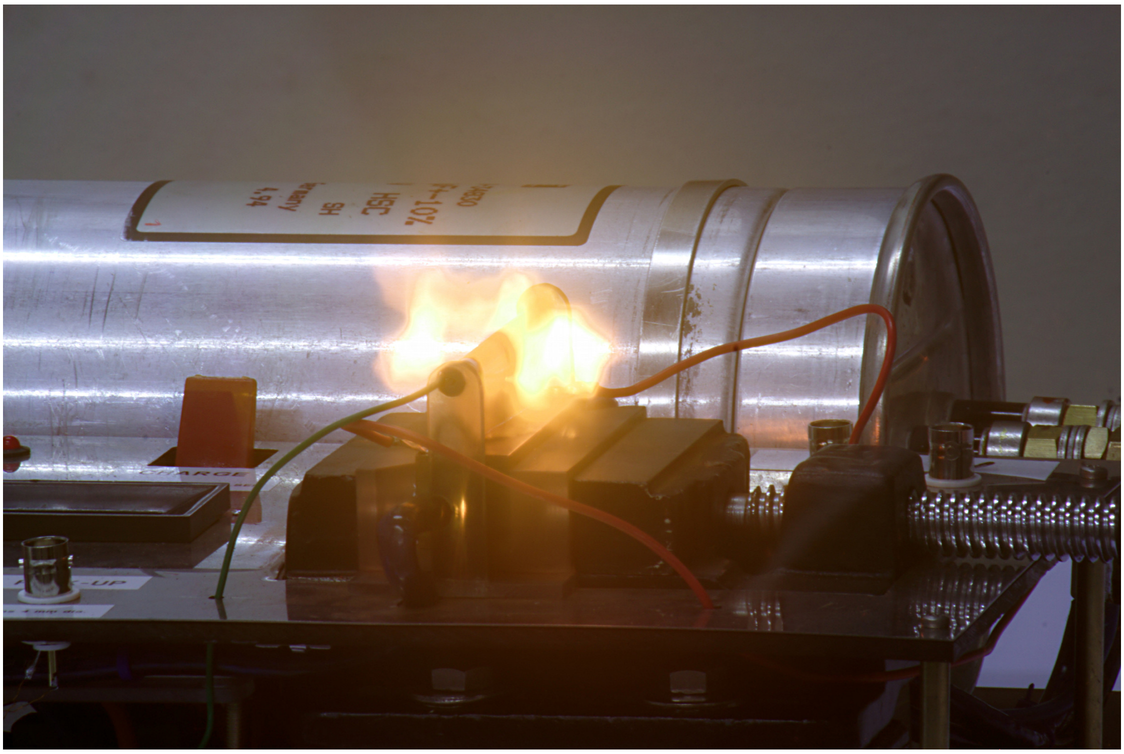

**Figure 14:** Long exposure of the plasma during a high energy pulse through an aluminum foil coil. The yellow colour of the plasma is due to the yellow plastic used to block excess light and protect the camera sensor.

A few microseconds after the coil is violently destroyed, a plasma is formed because of the strong electric field as photographed in figures 14 and 15. This plasma of metal vapour starts to conduct a short time later.

We have observed this phenomenon a few times and chose to examine it in more detail. The following results are obtained by using an aluminum foil coil with a width of approximately 8 cm.

An exampe has been plotted in figure 16. Around time zero, the magnetic field collapses as the coil disintegrates. The strong back emf turns the current around for a very short period. After that, the plasma current starts to flow. Notice that the magnetic field doesn't collapse as fast anymore as the new current keeps it up. The characteristic kink in the current is present. The magnetic field never gets as strong as it was before anymore because the resistance of the plasma is a lot higher and it is being blown away from the sample space, thus increasing the diameter of the "plasma coil", as can clearly be seen in 15.

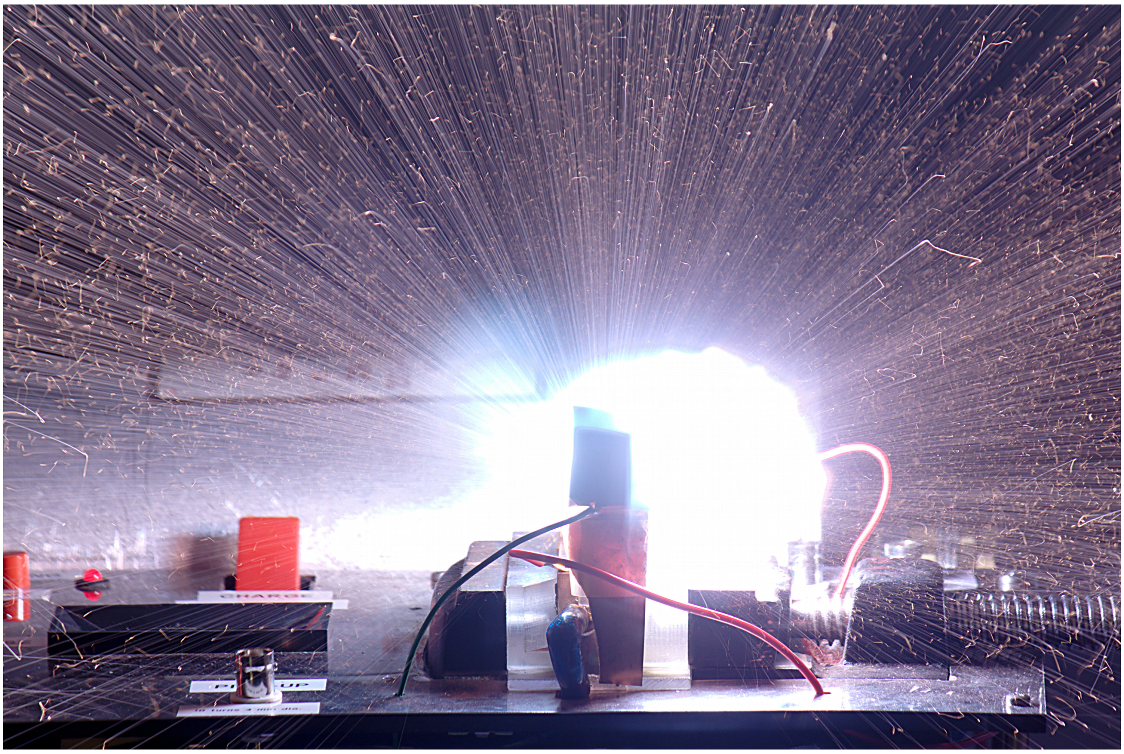

**Figure 15:** Long exposure of the plasma during a violent high energy pulse through an aluminum foil coil. No background light was added, all the light came from the plasma. Notice that the debris violently fly away from the coil and thus protect the sample space.

A similar plot is shown in figure 17, where the coil desintegrates at a field of 1 T. The current is once again kinked and the field follows a similar parttern as before. Note that the coil disintegrated well before the maximum field was reached, thus a great deal of potential was lost here. Of course, the coil was specially made from thin aluminum foil to examine the effect of the plasma, not to generate a high magnetic field.

### 5.7 Power dissipated in the coil and plasma, their resistance and coil deformation

Using the values calibrated in the previous section, one can easily calculate the power dissipated or generated in the coil (and later on, in the plasma) by multiplying them ($P = VI$). Doing so presents us with a plot like figure 18. This plot was generated by a full-energy pulse

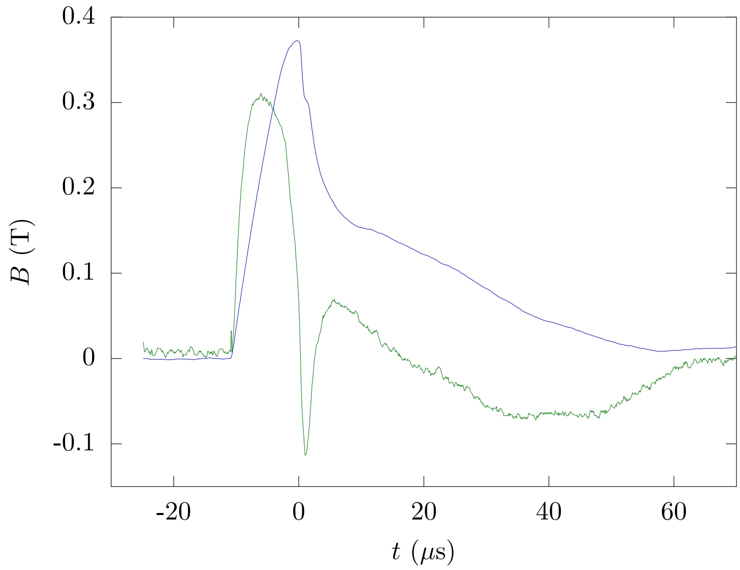


**Figure 16:** An example of plasma conduction. The magnetic field (blue) collapses slighty after $t = 0$ as the coil disintegrates. A few moments later, the plasma current (green) starts to flow, restoring some of the field. The current is in arbitrary units but the peak current is expected to be around 15 kA

through a copper coil of width 4 mm. The discontinuity around $100\mu$s is the moment the coil breaks, after which all current conduction occurs through the plasma.

At first sight, these results look sensible. The power dissipation of the plasma can be modeled an that of a resistor with a small inductance. Indeed, the power dissipated is mostly positive (because of the resistance), but has some negative peaks (where some enery is received from the magnetic field).

However, when we integrate the power over time to find the total dissipated energy, we find that it is a multiple (about 3 times) of the energy stored in the capacitor! As this is physically impossible, we have to conclude that either the voltage over or the current through the coil is measured incorrectly. Since the voltage is measured directly, the current is probably not completely right. Our experience showed that shifting the cables around a bit often could change the phase of the measured signal varies a considerable amount. Another problem is that the shunt used consists of a piece of wire that has some unnegligible self-inductance, meaning that it is not a linear component and thus can't be modeled as such.

Although we can only determine some qualitative behaviour, we're sure that if a method is used to determine the current with some degree of confidence, the power can certainly be determined as well.

Moreover, having a correct power measurement combined with a $\mathrm{d}B/\mathrm{d}t$ reading should allow us to get a rough estimate of the deformation of the coil (when this survives multiple periods of the pulse, before breaking).

Indeed, the energy in the magnetic field can be crudely approximated by $U_B = VB^2/2\mu_0$ (ignoring edge effects). Thus, power delivered to the coil can be linked to the change in energy of the magnetic field. This expected change in field strength can be linked to the measured

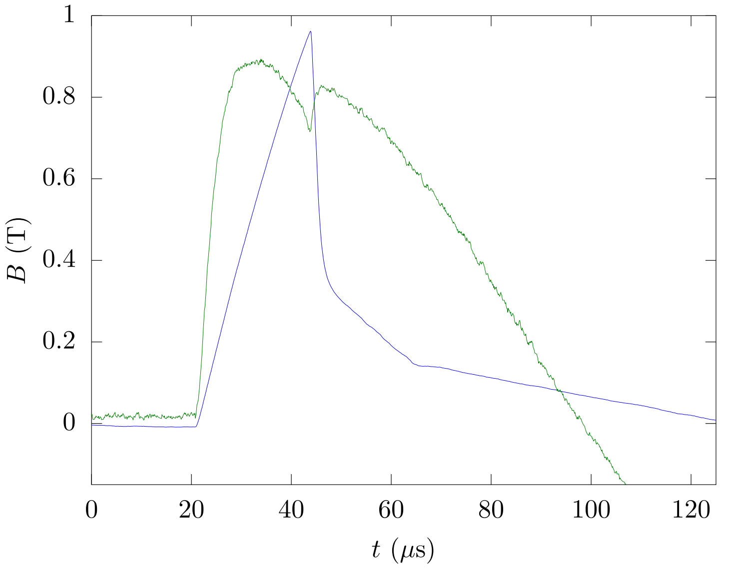


**Figure 17:** Another example of plasma conduction. The magnetic field (blue) is plotted against the time. Note the kink in the current (green). The current is in arbitrary units but the peak current is expected to be around 15 kA

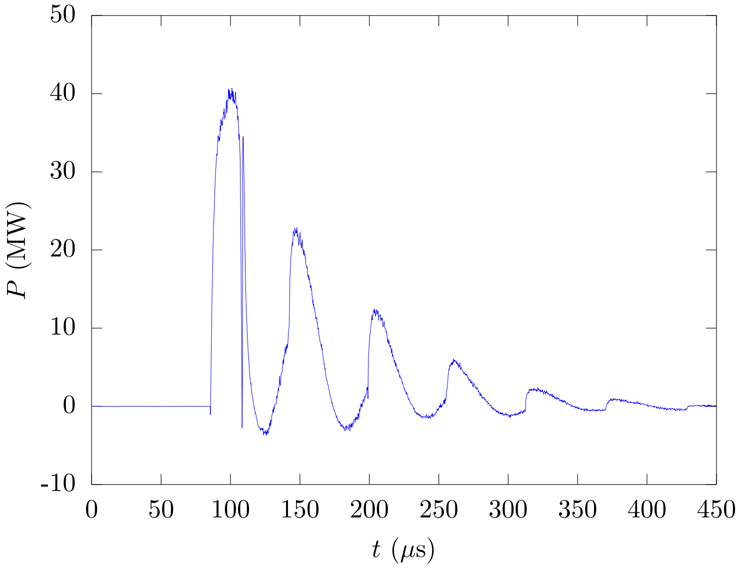


**Figure 18:** Power dissipated in the coil and plasma. The coil breaks after 100$\mu$s. Quantitatively incorrect because more energy is dissipated than is initially available in the capacitor

change. Any (downwards) deviations of the measured field from the expected field can be linked to a volume change (increase) of the coil, because $V$ is an explicit fuction of the time $t$, meaning that it also plays a role in $\mathrm{d}U_b/\mathrm{d}t$.

This could give some "first order" insight to the expansion velocity of the coil. However, because the lack of precision measurements, such results are not attainable with our setup.

## 6 Conclusions

With our small portable single turn coil apparatus, we were able to achieve fields in excess of 2 T. We did some standard measurements of peak field in function of the initial voltage over the capacitor and the coil material and geometry.

We could not, however, find any significant correlation in the limited amount of tests we have done. A great deal more measurements need to be repeated in order to confidently show a proper relation between these variables, for which we did not have the time.

Secondly, the added measurement capabilities showed some difficulties when working with high voltage, high frequency signals. Choosing an appropriate voltage divider isn't a trivial task and measuring on such low timescales leads to uncertainties in the phases of different measurements. Care needs to be taken to minimize and take into account any parasitic impedances in the measuremnt circuit in order to still have some confidence of the measured amplitudes and phases. In our case, we suffered from the effect of the impedances of the connecting coax wires and the inductance of our shunt that causes significant non-linear effects, meaning that our current measurements are only (roughly) qualitatively correct.

Using these new measurement capabilities, we could (qualitatively) show some interesting results such as the (neglectible) single turn coil inductance and the plasma conduction and power dissipation after the coil desintegrates. Using better measurements, it would also be possible to get a rough estimate of the coil deformation as a result of the Maxwell stress by measuring the power and the magnetic field. Given the limited accuracy and reliability of our measurements, this was out of our scope.

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