High Voltage Pulsers and Spark Generators

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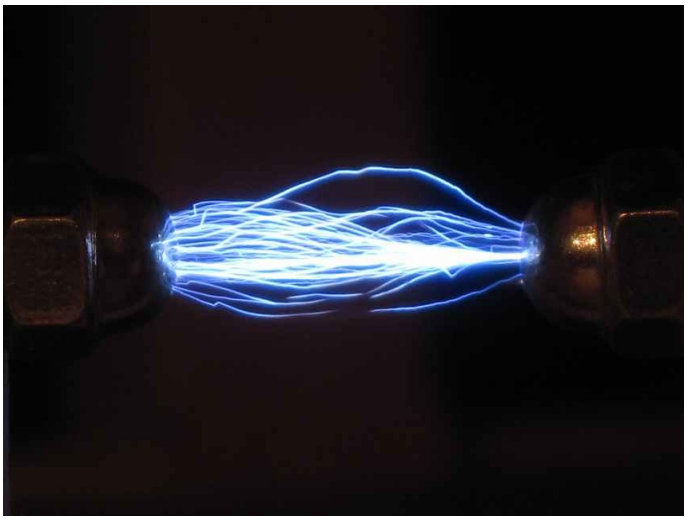
(updated 9/23/14)

This page describes the construction of two types of high voltage spark generators used for a variety of science experiments. The first is a modern version of the Kettering system originally used for automobile ignition. The second is a Capacitive Discharge system useful for automobile ignition experiments, laser spark gap firing, igniting fuel-air mixtures or other physics experiments involving high voltage discharges.



Time-lapse photo of the Capacitive Discharge pulser driving a spark gap consisting of a pair of rounded brass electrodes, separated by 22 mm.

1. Modern Version of a Kettering Ignition Coil Pulser - Kit #106

This device produces high voltage pulses of approximately these specifications:

Peak voltage: 20 kV (with 12 volt supply)
Polarity: Negative with respect to ground
Stored energy: 5 millijoules
Repetition rate: up to 50 pulses per second

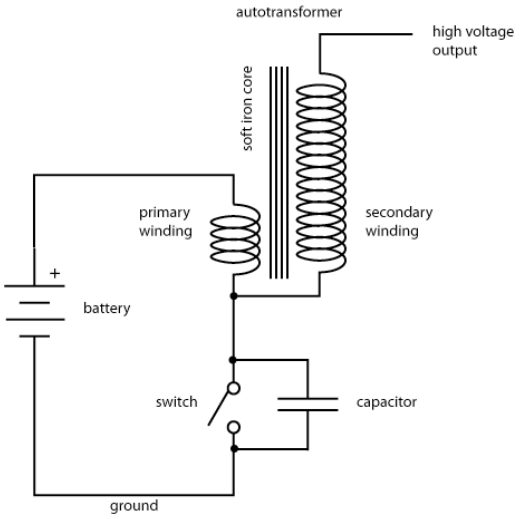
Other specifications:
Power source: 9-15 volts, 12 volts recommended
Overall size, including ignition coil and battery pack: 6.5" x 2.5" x 2"
PC board can be reduced to 2.5" x 2.5" when used with external ignition coil and power source.

1.1 Operating Principles

How It Works

Here is the original Kettering ignition system, dating from 1910.

Two coils of wire are wound onto a "soft" (magnetically and mechanically) iron core, consisting of a *primary* and *secondary* winding, (connected as an autotransformer) with roughly 1:100 turns ratio. The primary is connected to a battery in series with a mechanical switch, resulting in a primary current that rises from zero and reaches a maximum value depending on the DC resistance of the transformer primary, and at a rate (amps per second) determined by the magnetizing inductance of the ignition coil. When the switch is opened, the magnetic field encompassing both the primary and secondary windings collapses rapidly, inducing a high voltage in the secondary winding (between the high voltage output terminal and ground). In principle, the opening of this switch causes the primary coil current to be interrupted instantaneously. That would imply an infinite back EMF generated across the switch, which would cause an arc to form at the switch, dissipating most of the energy stored within the magnetic field. Instead, a capacitor is place across the switch. Then, as the switch opens, primary current will continue to flow through the capacitor, albeit rapidly decreasing at a controlled rate, and inducing the desired high voltage at the secondary, and simultaneously inducing a rapidly rising voltage across the capacitor. Energy flows back and forth resonantly between the magnetic field in the coil and the electric field in the capacitor, with a period given approximately by 2 pi x Sq. Rt. (LxC), the energy decaying rapidly as energy is transferred to the secondary side spark and to the wiring resistance. Therefore, a *series* of

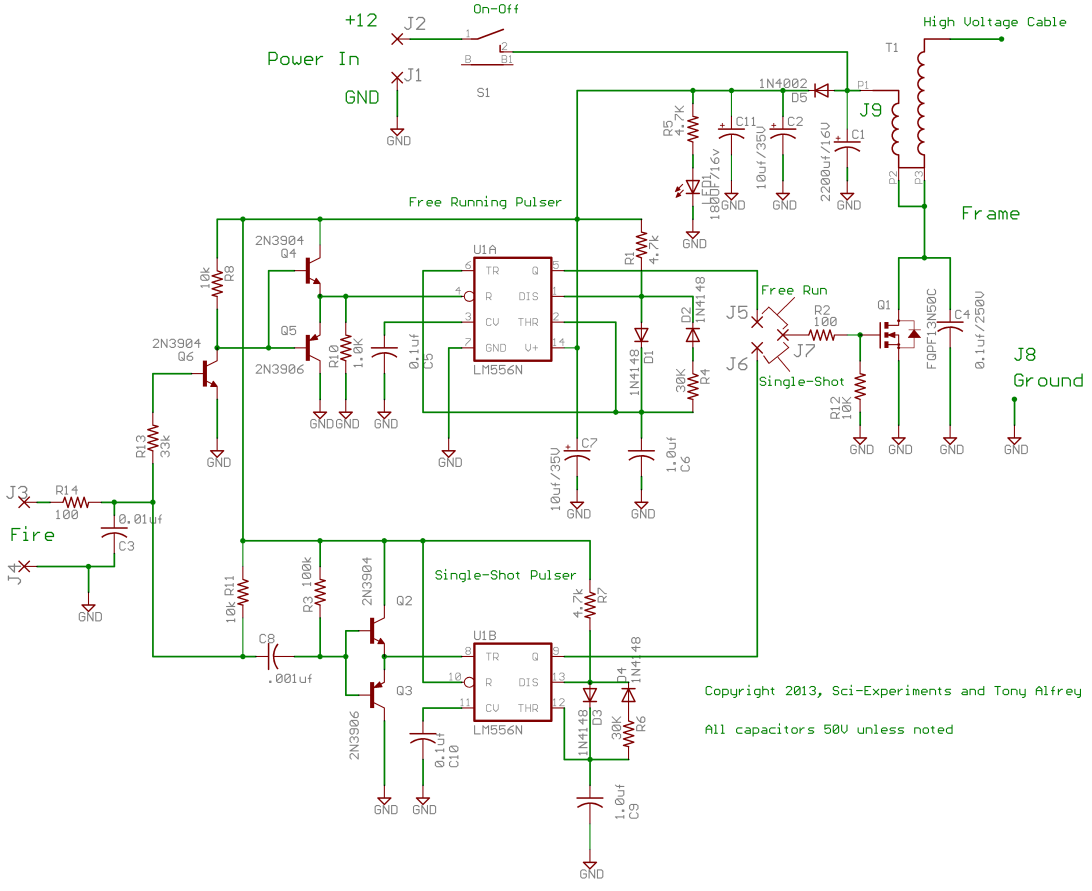


decaying high-voltage pulses appears between the high voltage output and the ground terminal.

The modern version of this system replaces the mechanical switch with a semiconductor (MOSFET or IGBT) switch, and includes a pulser circuit to turn the semiconductor switch on and off in such a way as to maximize the stored magnetic energy while minimizing the wasted DC primary current that serves only to heat the ignition coil and MOSFET. When this circuit is used with the recommended ignition coil and 12 volt battery pack, and when the MOSFET is turned on, the current will rise to a maximum value of about 7 amps in approximately 2 milliseconds, limited by the DC resistance of the ignition coil primary of 1 ohm, the on-resistance of the MOSFET and the current capacity of the power supply. The MOSFET switch is then opened, and the current through the primary rapidly decays and oscillates at a rate determined by the magnetizing inductance of the ignition coil and the capacitor in parallel with the MOSFET, the capacitor and the magnetizing inductance of the ignition coil forming a resonant circuit. The energy originally stored in the magnetic field of the ignition coil will be transferred to energy stored in the electric field within the capacitor. However, unlike the original Kettering system, the MOSFET switch places a diode (the so-called 'body diode') across the switch which will prevent the charging of the capacitor with a negative polarity with respect to ground. This yields only one high voltage pulse from the ignition coil (a simplification which ignores the parallel capacitor that exists across the primary winding resulting from the distributed capacitance of the windings themselves). Much of the residual energy is thereby transferred back to the battery (and filter capacitor in the version described below).

An LM556 (a dual version of an LM555) timer is use to create a train of 3 millisecond long pulses that turns the MOSFET switch on and off at a nominal 50 Hz rate, or to deliver a single pulse of the same width.

Schematic Diagram, Detailed Circuit Function



Click on the schematic to download.

MOSFET switch and ignition coil

An EMGO #24-71532 ignition coil (T1) with a 1 ohm primary winding on a laminated iron core is wired in series with Q1, a Fairchild FQPF13N50C MOSFET switch. The Fairchild part is a nice component because it has a low gate threshold voltage, a fairly low on-resistance for a 500 volt MOSFET, good maximum current specs, and is inexpensive.

C4 is placed across the MOSFET switch to control the rate of current collapse in T1: a larger capacitance for C4 slows the rate of collapse and yields a lower voltage output pulse while a smaller capacitance yields a larger back EMF across the MOSFET. The maximum allowed voltage drop across the FQPF13N50C is 500 volts and the 0.1uf capacitor in combination with the selected ignition coil yields a maximum back EMF spike of 200 volts. The laminated core of the ignition coil is used as the common electrical connection for the primary and secondary windings.

The large diameter high voltage output wire leads directly from the ignition coil and is about 2 feet in length. It is best to use the Frame of the ignition coil itself as the opposite spark terminal, but ground may also be used. Be careful not to ground the ignition coil frame!

LM556 pulse generator - free running mode

One-half of U1, an LM556 timer, is used to generate a free-running stream of gate pulses for Q1. The 'on' time is about 0.7*R1*C6 (time in microseconds for R in ohms and C in microfarads), while the 'off' time is determined by 0.7*R4*C6. When the MOSFET switch is turned on, the power supply voltage (nominally 12 volts) is applied across the primary winding. The current rises at a rate equal to the applied voltage divided by the magnetizing inductance (plus the leakage inductance) of the ignition coil, in this case at a rate of about 6 amps in 3 ms, after which time the power supply voltage begins to sag considerably, and primary current reaches a plateau because of the coil resistance and on-resistance of the MOSFET. Therefore, the 'on' time is selected to be about 3 ms, after which time the MOSFET is shut off, allowing the magnetic field to collapse, generating the high voltage pulse. After about 17 ms, the process is repeated, yielding a pulse rate of 50 Hz (20 ms start-to-finish). The LM556 timer is started by pulling pin 4, the /RESET pin, to the power supply voltage through the use of the buffer consisting of Q4 and Q5 and inverter Q6.

The normally-open pushbutton switch is connected to J4 and J3 to serve as a *Fire* control; long leads may be used so that the fire control can be placed a long distance from the pulser circuit. For the free-running mode, pins J5 and J7 are jumpered to direct the pulse stream to the power MOSFET Q1.

LM556 pulse generator - single-pulse mode

The basic circuitry for the single-shot pulse generator is the same as that for the free-running pulser, except that this time, a single pulse is generated by the LM556 by momentarily bringing the Trigger pin low. This is achieved through the use of a differentiator consisting of R3, R6 and C8, followed by a buffer consisting of Q2 and Q3. In this mode, J6 and J7 are jumpered to direct the single pulse generated each time the pushbutton is depressed to the power MOSFET.

In all cases, note that the high voltage pulse is generated at the *very end* of the 3 ms MOSFET 'on' time. So, in single-shot mode, the high voltage pulse occurs 3 ms *after* the *Fire* button is pressed, and in the free-run mode, the high voltage pulse train starts 3 ms *after* the *Fire* button is pressed.

In the free-run mode, the firing rate may be *decreased* by *increasing* the value of R4, but R4 should be no smaller than 30k ohm.

An important note: There are CMOS equivalents of the LM555/LM556 timer chip. DO NOT use them as they are much more susceptible to electrostatic damage and high-voltage spikes that can result from corona discharge created by the ignition coil.

Battery and power supply capacitors

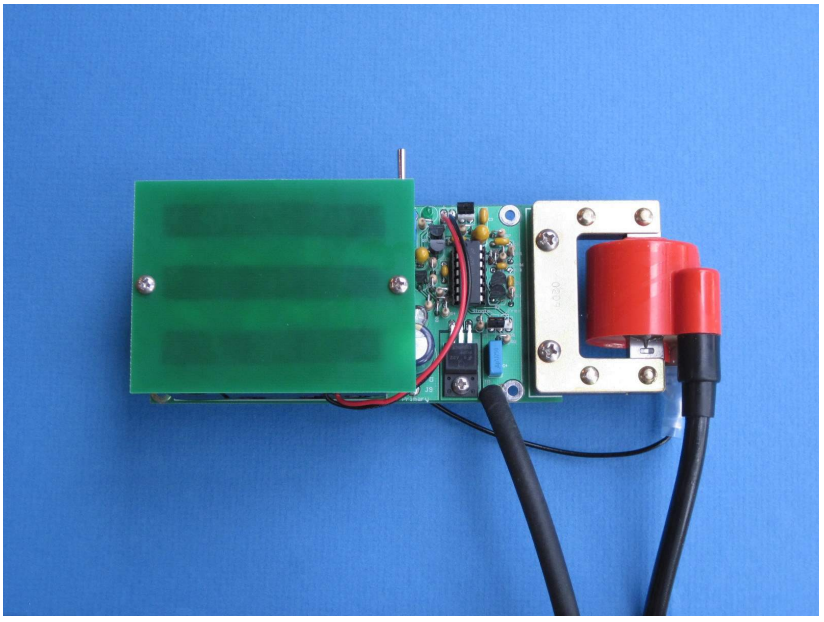
For an application in which the pulser will be operated only intermittently (firing a potato cannon, briefly demonstrating high voltage breakdown, or demonstrating a Hertzian transmitter and receiver), a power source consisting of a pair of 9 V batteries in parallel will be sufficient. A substantial improvement will be to use 8 "AA" batteries in a holder to provide 12 volts. The AA cell holder is provided on the printed circuit board in our suggested layout, and provides higher voltage and more energy per spark. For an hour of continuous sparking, the user should instead consider a pair of 6 V lantern batteries in series. C1, C2, C7 and D7 are used to provide some buffering for the power supply voltage, as the heavy current surge of each primary winding pulse temporarily draws down the power supply voltage which can lead to unpredictable operation of the LM556. The capacitors also help minimize high voltage transients that might damage the LM556. The absolute maximum allowed power supply voltage is 18 volts.

1.2 Assembly and Operation

Kettering Pulser Kit

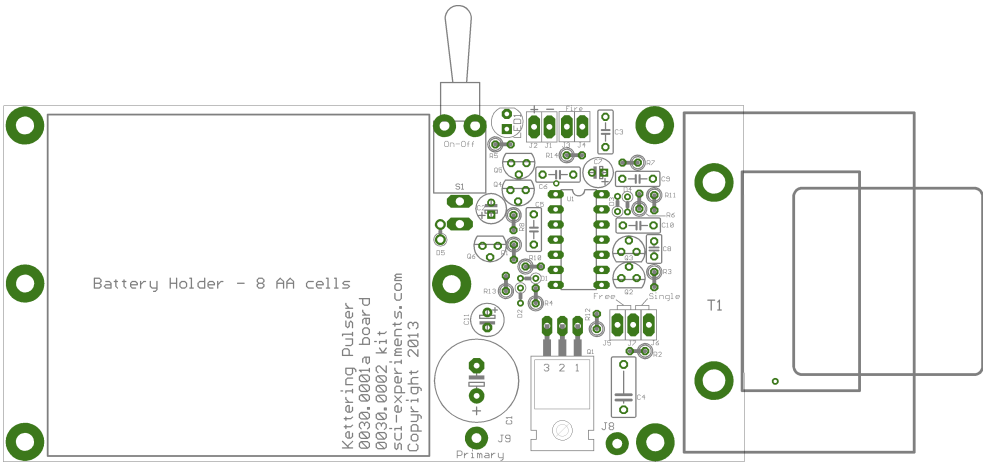
The Kettering pulser is available as a complete kit, #106, or the printed circuit board is available separately, #107. The kit consists of all of the components listed below in the parts list, except for the "AA" cells, and is shown below in assembled form. In the assembled figure just below, the circuitry is in the middle of the board, the ignition coil is mounted on the right side, and the 8-cell battery pack is hidden beneath an additional board on the left.

Ordering - Go here to get pricing or to place an order.
Assembly - Go here to get the assembly instructions for this kit.
General Kit Instructions that apply to all of our kits can be found here.
On rare occasions, we've been asked to provide a pre-assembled version. Please contact us directly for this.



Refer to the following information if you'd like to build your own circuit on protoboard material, or if you'd like to collect your own parts and use our circuit board.

Printed Circuit Board Layout



Many of our printed circuit boards use through-hole components, allowing easier assembly for the hobbyist (although this board is densely loaded, with resistors mounted end-up). The battery pack and ignition coil comprise the bulk of the circuit board footprint, so little is gained by using surface mount parts. J1 is the negative battery terminal, J2 is the positive battery terminal, and J3 and J4 are the connections for the pushbutton firing switch. J5, J6 and J7 are the connections for the header that allow mode selection. The primary winding of T1 is connected to J9, and the companion connection on the ignition coil is made with a female spade connector. Make sure that the ignition coil frame is securely fastened to the mounting holes on the circuit board; these holes provide the electrical connection to the common primary-secondary terminal of the ignition coil.

Important. Because the ignition coil frame is the common autotransformer connection (see 'FRAME' on schematic), it CANNOT be used as a ground. So if the pulser is installed into any type of metal enclosure, take great care not to use the ignition coil mounting frame as a mechanical connection to the enclosure. Instead, use the corner holes provided on the printed circuit board to mount the board. The battery holder and batteries are held to the board with a simple piece of circuit board affixed with #4-40 screws.

Parts List

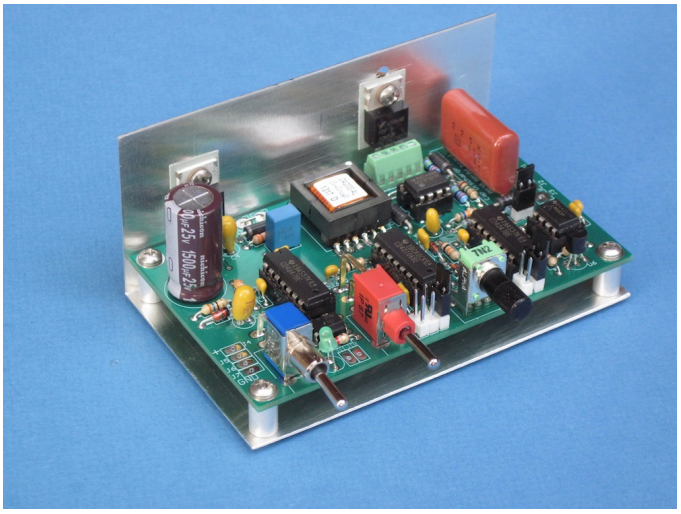
Please download this pdf file of the parts list.
We've suggested specific vendors for most of the parts, but certainly other vendors and parts manufacturers are possible. We suggest using the specified ignition coil because it is compact, fits the printed circuit layout, and provides a good compromise of output voltage, minimal primary current, high magnetizing inductance and price. But if you wish to experiment, see the list of Recommended Ignition Coils below.

This parts list is chosen to match the printed circuit layout, but other parts may be selected if a protoboard layout is used or if you are being creative. In the parts list, we've included a pushbutton firing switch that is intended for use with up to 50' of speaker wire so that the pulser can be operated from a safe distance from an ignition hazard. For other high voltage applications, you may choose not to use this long cable to the pushbutton.

2. Capacitive Discharge (CD) Ignition Coil Pulser - Kit #108

Improved for 2014!

Here is the assembled board for the capacitive discharge pulser (ignition coil included, not shown). Battery or other power supply connections are on the left, and connections



to the ignition coil are on the right. Controls along the lower edge of the board include: power, multiple or single-shot firing and rate control. Jumpers allow the selection of different operating modes.

Recent improvements:
- Isolated computer control input option.
- Easy MOSFET switch replacement and upgrade.
- Improved heat sinking.
- Selectable capacitor charging voltage.

This device produces high voltage pulses with an exponentially-decaying, ringing waveform of roughly these specifications:

Peak voltage: 45 kV
Output Polarity: Negative with respect to ground
Stored energy: 175 millijoules or 100 millijoules (selectable)
Capacitor Charge Voltage: 300 or 400 V (selectable)
Repetition rate of up to 300 pulses per second with 12 volt supply
Power source: 9V - 18V, battery or other supply.

See a video here of the pulser being used with a 12 volt battery and a spark gap of 22 mm; the photo at top of this page was taken with this pulser. The accepted value for electric field breakdown in dry air is 3.0 kV/mm, so the 22 mm gap corresponds to a voltage of roughly 60 kV. But because the radius of the electrodes is smaller than the gap itself, the electric field is most certainly enhanced near the electrodes, leading to an overly optimistic measurement of voltage. Measurements with large spherical electrodes indicate that 45 kV is reached with this pulser . The pulser will deliver full output voltage with a single, fresh 9 volt battery, but at a lower repetition rate.

Uses:

1. As an igniter for fuel-air mixtures, including potato cannon firing, gas furnace firing, or experiments with electronic ignition for automobiles or other internal combustion engines.

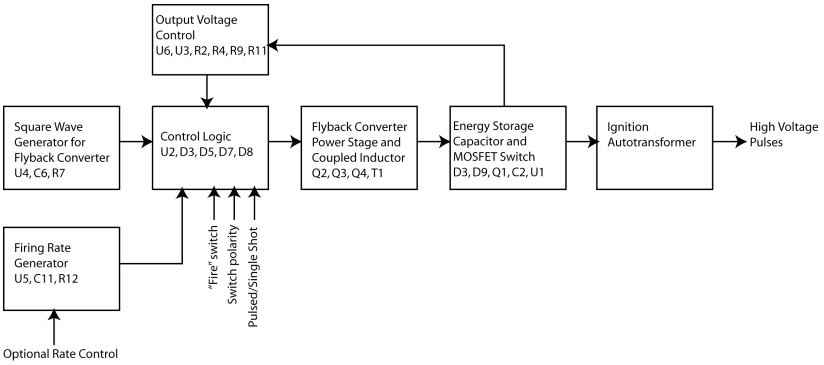
2. As a trigger for high-energy spark gaps that are typically used for flashlamp-pumped lasers, nitrogen lasers or Marx banks.

3. For various demonstrations of pulsed high voltage, including dielectric breakdown strength of insulating materials, and the breakdown strength of dry and moist air.

2.1 Operating Principles

The Kettering pulser stores energy in the *magnetic field* of the step-up transformer core. The Capacitive Discharge pulser stores energy in the *electric field* of a capacitor and rapidly discharges it into the primary coil. In both cases, the magnetic field in the transformer is rapidly changing as the current is rapidly changing, inducing a high voltage in the secondary. However, in the Kettering pulser, the high voltage is created during the rapid *fall* of the ignition coil current, while in the Capacitive Discharge pulser, the high voltage is generated during the rapid *rise* of ignition coil current. The development of inexpensive components (for charging the flash capacitor in digital cameras) for providing the several hundred volts needed to charge the capacitor have made this approach practical.

Block Diagram

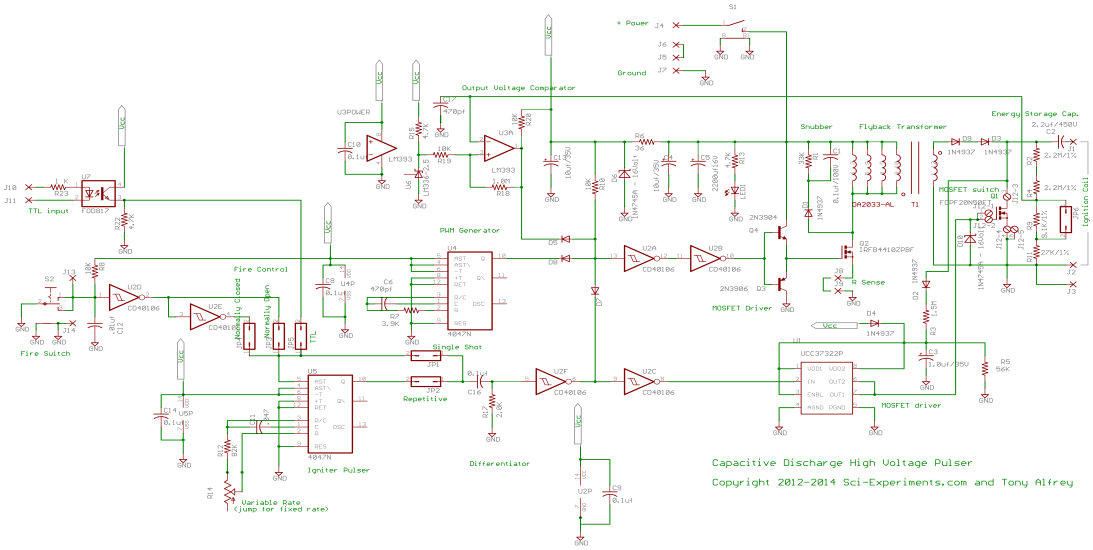


A Flyback Converter, consisting of a simple 100 kHz square-wave oscillator, MOSFET switch, a coupled inductor with 1:10 turns ratio, and rectifier is used to rapidly charge an Energy Storage Capacitor of 2.2 uf to 300-400 volts. After charging, the capacitor is then discharged into the primary winding of a conventional motorcycle or automobile Ignition Autotransformer through the use of a high voltage MOSFET transistor. The MOSFET may be fired manually with a simple switch closure (such as a pushbutton), or switch opening (such as a set of automobile ignition points). The manual switch can be used to produce single pulses, or a continuous pulse train. The repetition rate of the pulse train is adjustable up to 100 pulses per second, but may be changed to any value between 0.1 and 300 pulses per second by changing the value of a resistor/capacitor pair. Various jumpers on the printed circuit board set the operating mode of the circuit. These jumpers may be connected to external switches, allowing the user to build the pulser into a flexible, user-controlled installation. The use of through-hole packages means that simple soldering tools can be used for assembly (as opposed to smaller surface-mount

components), making the design more suitable for the hobbyist or student.

This circuit uses the 4000-series CMOS logic family that allows a wide operating voltage range without the need for special power supply voltage regulation. Some manufacturers have discontinued making this series, although there are still several sources for these chips; for example, Texas Instruments provides both commercial and high-reliability military versions of this logic family.

Schematic Diagram, Detailed Circuit Function



Click on the schematic to download.

Flyback Converter

The heart of the pulser is the Flyback Converter (refer here for a detailed description of the theory of a flyback converter used as a capacitor charger) consisting of U4, U2, Q2, Q3, Q4, T1, D1, D3, D9 and C1. U2A receives a square wave pulse train from U4. U2B, Q3 and Q4 serve as a low-impedance driver for the high-capacitance gate terminal of the MOSFET switch Q2. This driver insures that the gate pulse delivered to Q2 has a short rise time, improving the efficiency (reducing the time during which the drain-source resistance of MOSFET Q2 is high). When Q2 is switched on for a period of about 5 microseconds, current flows through the primary of T1, building up a magnetic field in the air gap within the core of T1. Diodes D3 and D9 are reversed biased for the EMF induced in the secondary during the magnetic field build-up and therefore pass no current during this time. Next, Q2 is switched off for another 5 microseconds, during which time the magnetic field within the air gap of T1 collapses, generating an induced EMF in the secondary of T1. The polarity of the induced EMF forward biases diodes D3 and D9, and the energy storage capacitor C2 is charged through the primary of the external ignition coil autotransformer connected between J1 and J2. The value of the induced EMF is elevated by the 1:10 turns ratio of the flyback transformer. While the capacitor is charged in only a few milliseconds, this charging rate is too slow to induce any appreciable output voltage from the external Ignition Coil.

A word about MOSFET Q2 is important. First, the gate drive voltage must be sufficient to fully turn on the MOSFET, otherwise the primary current to the flyback transformer will be limited, thereby reducing the stored energy in the flyback transformer core. So the MOSFET has been carefully chosen to be a "logic-level" MOSFET with a low gate turn-on voltage. Other MOSFETs may be used, but only if higher battery supply voltages (such as 12 volts) are available. Second, a "sense resistor" connection is provided in series with the MOSFET source lead. This may be used to monitor the MOSFET source current when the MOSFET is switched on to insure that the current through the flyback transformer primary increases linearly and does not saturate. If the circuit, especially the timing components C6 and R7 used with U4, is used with the recommended flyback transformer, then the sense resistor (typically 5 milliohms) will be unnecessary, and the sense resistor connections must be shorted. Inquire of sci-experiments.com if you would like to add this resistor to enable a more thorough examination of the circuit operation.

Flyback Converter MOSFET Pulse Generator

The MOSFET pulse generator consists of U4, C6 and R7. U4 delivers a square wave pulse train of period 10 microseconds, through an OR gate consisting of D5, D7, D8 to the MOSFET driver. The period in microseconds is given approximately by one-half the product of C6 in microfarads and R7 in ohms. Ideally the duty cycle of the pulse generator should change as C2 is charged. While the "on" time of Q2 is determined by the primary inductance of T1, the saturation current of T1 and the battery voltage, the "off" time of Q2 is rather long (several tens of microseconds) at the beginning of capacitor charging, and short (a microsecond or two) as C2 reaches full charge. In higher power applications that require optimum efficiency, a driver with an adaptive "off" time is important. But in this simple charger, a fixed duty cycle does not drastically affect the efficiency (but affects the charging rate). A larger version of this same device incorporates adaptive duty cycle charging, and will be described on a future page.

Energy Storage Capacitor, Autotransformer, and the MOSFET switch

The high-voltage output of T1 charges capacitor C2 to 300 volts or 400 volts (selectable). When Q1 (the MOSFET switch) is turned on by a pulse from the control logic (consisting of the remainder of U2, U1 and U5), capacitor C2 is rapidly discharged through the primary winding of the external Ignition Coil autotransformer, thereby generating a high-voltage pulse in the Ignition Coil secondary of a width approximately determined by the square root of the product of the ignition coil primary inductance and the energy storage capacitance C2.

We find that some that choose to build the CD pulser investigate other ignition coils or install the CD pulser into other innovative circuitry. But sometimes the load attached to the CD pulser is too severe for Q1, possibly causing its failure. Unsoldering Q1 can irreparably damage the circuit board. So, in our most recent upgrade of our popular CD pulser, we have added a special terminal block to allow easy replacement of Q1, a relatively inexpensive part. An even higher power MOSFET is available as an option for a few dollars more.

Voltage Divider and Comparator Voltage Control

A voltage divider consisting of R2, R4, R9 and R11 divides the voltage across C2 by a factor of 2.5/300. Therefore, if the voltage to which C2 is charged is 300 volts, the output at the junction of R4 and R9 will be 2.5 volts. This voltage is compared to the 2.5 volt reference generated by R15 and U6 by the comparator U3. When the voltage at the junction of R6-R5 reaches 2.5 volts (i.e. the output voltage of C2 reaches 300 volts), the pulse train from U4 is disabled until C2 is discharged by an igniter firing pulse. C17 acts as a filter to reduce noise sensitivity, and some hysteresis is introduced by R18 and R19 for the same reason.

If a jumper is installed at JP6, the voltage divider values are changed. This will result in C2 being charged to 400 volts.

The rate at which C2 is charged will be influenced by the use of a 9 volt or 12 volt battery. A 9 volt battery will charge C2 less quickly, but still to the same final voltage. But the use of a 9 volt battery will thereby limit the maximum firing rate of the pulser.

Firing Pulser and Control Logic

C11, R12, R14, C15, R16 and U5 serve to generate a pulse train of short spikes which are sent through the jumper JP2, U2F, U2C and U1 to fire the MOSFET Q1, which provides a high voltage pulse train at a rate of approximately 100 Hz, determined by 1/(C11 in farads and R14+R12 in ohms). To yield a continuous pulse train, jumper JP2 is installed; to provide single pulses, jumper JP1 is installed. JP3 is installed if the controlling switch is a Normally Open switch (such as a typical pushbutton), JP4 is installed if the controlling switch is a Normally Closed switch (such as a set of ignition points in a typical automobile ignition circuit of pre-1980 vintage) and JP5 is installed if a TTL input (possibly from a computer) is desired. The layout as shown includes S2, a SPDT switch, wired as Normally Open, with a fixed On position when pressed down, and a momentary On position when pressed up. Depending on your application as described below, you may choose to not include either S2 or R14.

MOSFET Drive

Because Q1 is a high-voltage MOSFET, its required gate drive voltage is larger than that of a lower-voltage MOSFET, such as the MOSFET Q2 used in the flyback converter. When the pulser is used with a single 9 volt battery that might be a little weak, insufficient gate drive may be available to fully turn on Q1, resulting in weak high voltage pulses from the ignition transformer. To solve this problem, we "borrow" some of the high-voltage output from T1 to charge up C3 to about 15 volts. So even when the pulser is used with a weak 9 volt battery, there will still be plenty of gate drive available for complete turn-on of Q1, resulting in good spark energy. This technique will actually increase the rate at which the 9 volt battery is depleted, but at least it will make a weak 9 volt battery useful. But this boost scheme will not provide sufficient charging current for C3 when the pulser is used at a high repetition rate with a weak battery. A 12 V or two 9 V batteries in series is required for high repetition rates; as the repetition rate rises, diode D4 takes over to charge C3 directly from the battery.

A Texas Instruments (actually the Unitrode division of TI) UCC37322 integrated circuit MOSFET driver U1 is used to drive Q1. It provides high current for the high-capacitance gate terminal of Q1 and works with a large range of supply voltages. The same circuit can be easily implemented with a collection of discrete transistors which removes some of the mystery of this chip, but the layout then becomes more crowded, and the additional cost of the chip is not prohibitive.

If a 9V battery is fresh, U2 will actually drive the MOSFET Q1 fairly well at moderate repetition rate, eliminating the need for U1 and all of the other components associated with it, thereby reducing the complexity of the circuit.

A Final Circuit Comment

All of the functions associated with U2A, U2B, U3, U4, Q2, Q3, and Q4 can be found in single chips offered by a variety of companies such as Linear Technology, Texas Instruments and Maxim Integrated. While these chips are great for finished products, they don't allow the student access to the circuit, making it more difficult to study circuit operation or make modifications.

2.2 Assembly and Operation

Caution!

This project is not a toy! There is high voltage present on this circuit board when the power is supplied to the circuit, yet no sparks are being generated by the ignition coil. Project assembly and operation should not be attempted by children without the supervision of an adult familiar with the hazards of working with high voltage.

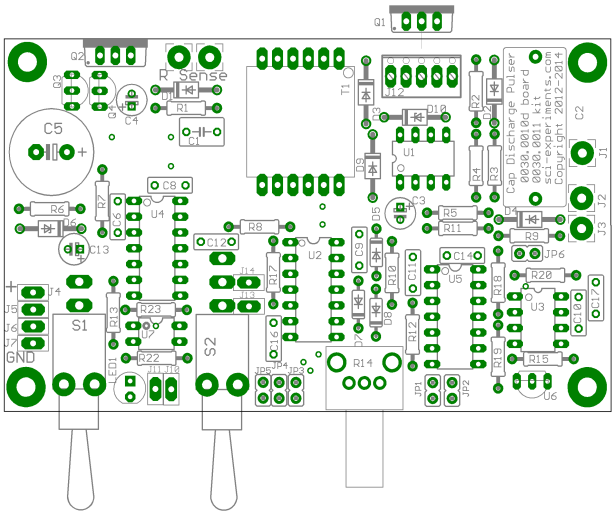
CD Pulser Kit

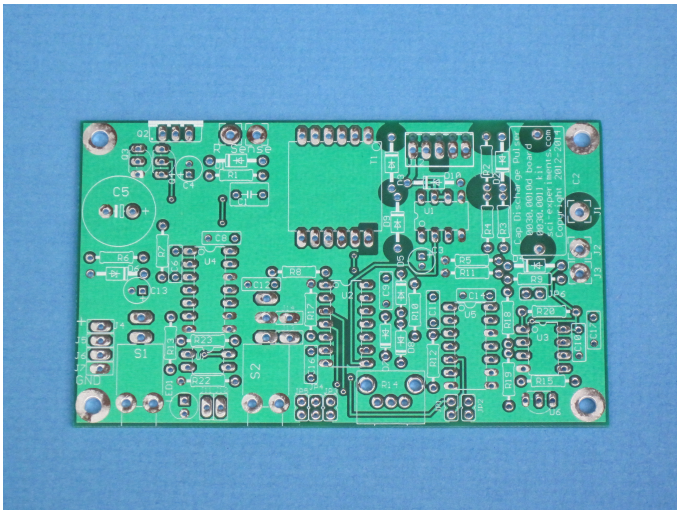
The CD pulser is available as a complete kit, #108, or the printed circuit board is available separately, #109. The kit consists of all of the components listed in the parts list below, including the ignition coil. The printed circuit board is shown here in assembled form. You'll probably want to use an enclosure or other mounting scheme (not provided in the kit) to hold the battery or power supply of your choice, and include a way to mount the ignition coil.

Ordering - Go here to get pricing or to place an order.
Assembly - Go here to get the assembly instructions for this kit.
General Kit Instructions that apply to all of our kits can be found here.
On rare occasions, we've been asked to provide a pre-assembled version. Please contact us directly for this.

Refer to the information below if you'd like to build your own circuit on protoboard material, or if you'd like to collect your own parts and use our circuit board.

Printed Circuit Board Layout





Board Design

The printed circuit board is a two-layer board with the top side dedicated to component mounting and ground plane, while the bottom side is dedicated to providing most circuit connections. The ground plane is useful for reducing the interference caused by the large current spike from the discharge of C2. For ease of assembly, through-hole components are used for most parts. The Flyback Transformer is a surface mount device; the pins on the device may be bent to conform to the holes provided on the printed circuit board, or the transformer may be surface-mounted to the oval pads. The size of the circuit board could be reduced somewhat through the use of all surface mount components, but this reduces the flexibility of the layout for experimenter modifications.

Unlike the Kettering Pulser circuit board on which we've mounted the battery pack and ignition coil, we've left these for the user to mount within their own enclosure for greater flexibility. Also, unlike the Kettering Pulser, the ignition coil autotransformer frame, if it has an exposed iron core, may be bolted to an enclosure ground connection. This board has switches and a rate potentiometer mounted directly to the board, but the experimenter can leave these components off of the board and use their own controls that might be better suited to their custom application.

You really want to use sockets for the CMOS integrated circuits. Although these chips are fairly robust in static discharge environments, they are not invincible. When you are experimenting with various circuit layouts and ignition coils, it is easy to put sparks where you don't want them. Replacing a dead 50 cent chip takes seconds if you use sockets, yet creates a frustrating mess if you don't.

A "socket" (we provide a screw terminal block) is essential for Q1.

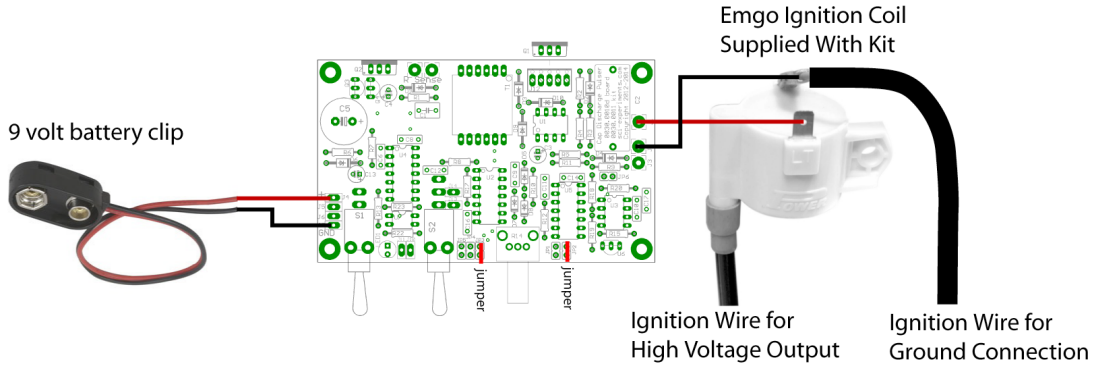
Parts List

Please download this parts list as a pdf file.
These parts are all a proper fit for the printed circuit layout, but other parts may be chosen if a protoboard layout is used or if you are being creative. We've suggested a few specific vendors for most of the parts, but certainly other vendors are possible as are other parts manufacturers. We strongly suggest using the specified flyback transformer T1, simply because it works so well, and is inexpensive. However, if you'd like to experiment, a small, conventional 120V to 12V transformer may be wired in reverse (the 12V winding becomes the primary). You will have to experiment a bit to get the phasing correct (that is, which of the 12V winding leads goes to Q2 and which goes to "power").

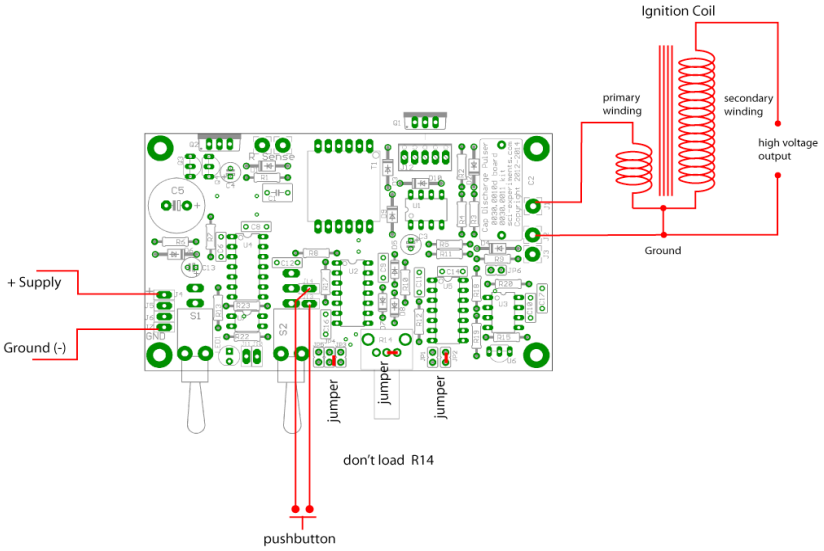
Selecting the Operating Mode

Energy Storage Capacitor Voltage.
The voltage to which the energy storage capacitor C2 is charged will, for a given ignition coil, determine the *open circuit* (no spark gap) peak output voltage from the ignition coil. Installing a jumper at JP6 will set the charge voltage to 400 volts; no jumper at JP12 sets the charge voltage to 300 volts. As per these precautions, this can help to limit the maximum output voltage from the ignition coil.

Basic Wiring - Just making sparks.
This pictorial drawing shows how to connect a 9 volt battery clip and the basic Emgo 24-71536 ignition coil that is supplied with the parts kit. As described in the Assembly Manual, the Power switch is to the left, the Mode switch (single/multiple pulses) is center-left, the Rate control is center-right. A jumper is placed in JP2 and JP3. Sparks are drawn between the two ignition-style wires. After stripping the insulation off of the ignition wire ends and possibly attaching some electrodes of your choice, some means of holding the wire ends at a fixed spacing between 1-10 mm should be utilized.



As an igniter for a gas furnace or potato cannon.
In this application, multiple sparks are sometimes needed to ignite a fuel-air mixture. Typically the switch that might be available for firing the igniter is a simple normally-open pushbutton switch. In this case, install the jumpers at JP2 and JP3 and connect the push-button or external computer-controlled switch to the pins shown instead of using S2. Jumper the pins otherwise occupied by R14 to hold the pulse rate fixed when used in the free-run mode. Connect a 9 volt battery or 12 volt battery to J4 (+) and J7 (Gnd). With the jumper in place of R14 attached as shown in the figure below, the repetition rate is at a maximum and a weak 9 volt battery will not be enough to deliver sparks. If instead, the jumper is replaced with a 470 kohm resistor, the repetition rate will be low and a single 9 volt battery will be acceptable. Finally, if the full repetition rate with 9 volt batteries is desired, go to the section "Power Supply Requirements" below for information on using *two* 9 volt batteries in series.

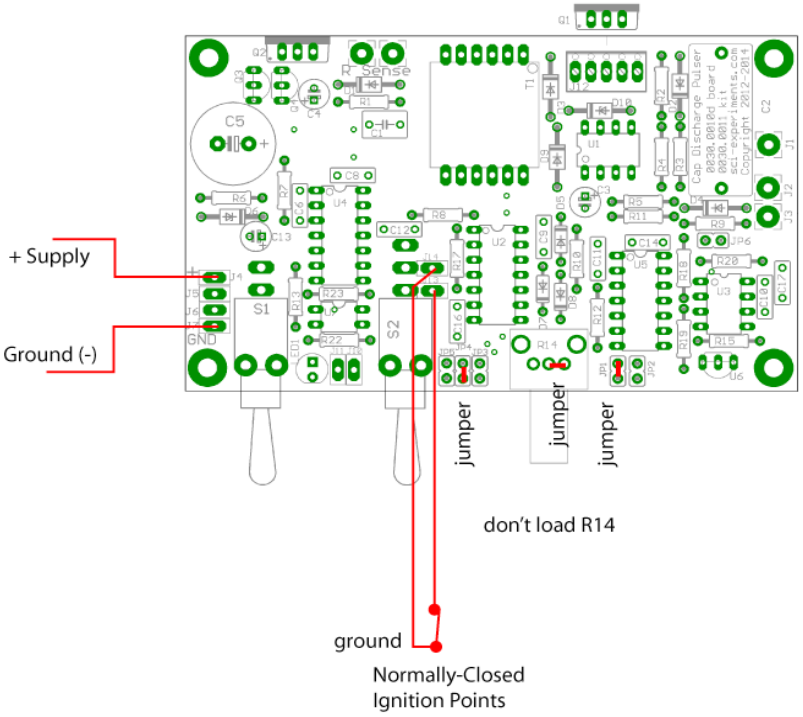


As an electronic ignition

In this application, a single spark is needed on each opening of the normally-closed ignition points in an internal combustion engine in a classic car. For that application, use jumper JP1 and JP4; pads J13 and J14 are used to connect to mechanical ignition points, and S2 is left in the "off" position. Connect a 12 volt automobile battery to J4 (+) and J7 (Gnd).

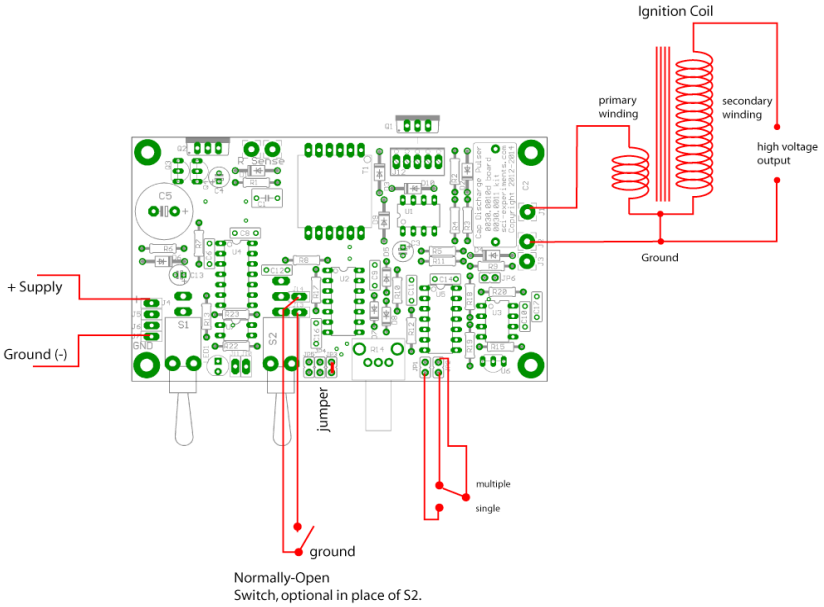
You will need to be able to operate at very high repetition rates for use as an electronic ignition. For a four-cylinder engine, there are two sparks per engine revolution. Therefore, at 8000 r.p.m. you will need to operate the pulser at 266 pulses per second, which implies a charging time for C2 of only about 4 milliseconds. This is faster than the current implementation will charge. However, the energy per pulse that is currently set up (175 millijoules) is much greater than is needed for auto ignition purposes. In most electronic ignition systems, a 1.0 microfarad capacitor is charged to only 300 volts, or 45 millijoules. If the pulser is reconfigured for 300 volts/1.0uf energy storage, the charger will work well for a four-cylinder engine. However, we recommend using this version of the pulser only for experimenting; we will offer a substantially more robust and powerful version specifically for electronic ignition in classic cars.

For experimenting with electronic ignition, you'll have to first change C2 to 1.0 uf/400 V. Use Panasonic ECQ-E4105 (mouser.com part # 667-ECQ-E4105). Next, change R9 to 27K ohm/ 1% and R11 to 10K ohm/1%.

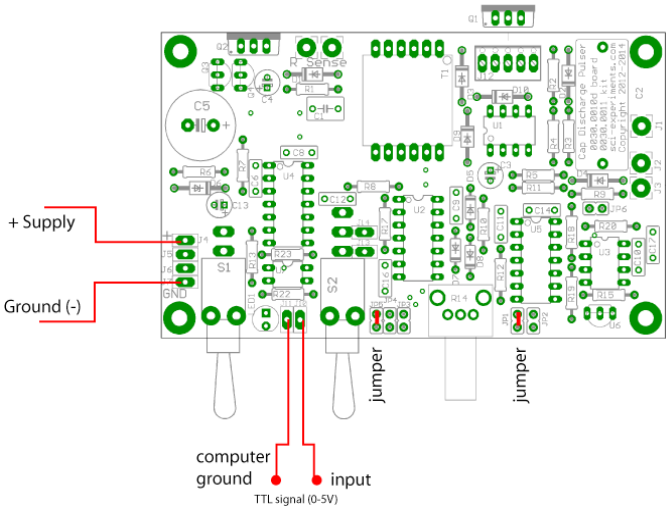


As a high voltage pulse generator for triggering a laser spark gap.

In this application, the user may wish to operate the pulser in both Single Shot or Repetitive modes. In this case, a single-pole/double-throw switch will be added to the connections at JP2 and JP1. R14, a 1 Meg potentiometer is installed to allow an adjustable and lower repetition rate. Usually a normally-open switch will be used to trigger the pulser, so a jumper should be used at JP3. If an external panel-mounted switch is used for firing the pulser, S2 is left off of the circuit board and connections are made as in the figure below. A repetition rate of 10 hertz will require less than 5 watts of power; see the section "Power Supply Requirements".



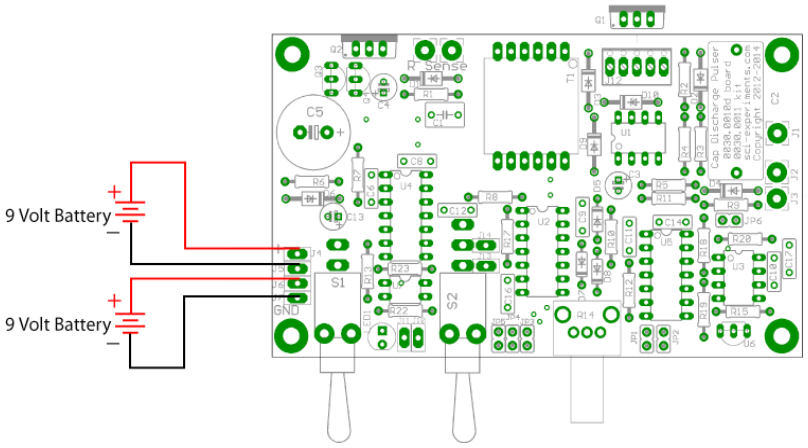
Computer control.
A TTL-level signal (0-5 volts) may be applied to the *isolated* TTL input as shown below. The ground at your computer is not actually tied to the ground at the CD Pulser, thereby reducing the possibility of damage to the computer from ESD; an opto-isolator is used to couple your computer output to the control circuit. Install a jumper at JP5; the toggle switch will not function in this mode. Jumpers may be used at JP1 or JP2 to select single or multiple pulses respectively; the action of the pulser will be identical to that when used with the toggle switch, except that a TTL-level pulse (of a millisecond width or less for a single pulse, or a constant TTL-level "high" for multiple pulses) will be required.



Power Supply Requirements

Stored energy per pulse is less than 0.2 joules. To determine the power supply requirements, simply multiply 0.2 joules by the repetition rate in hertz to yield the power requirements in watts. For example, *continuous* operation at 100 Hz will require 20 watts and will require a more substantial battery than a simple 9 volt battery. At any continuous power output over a few watts, additional heat sinking of Q1 will be required.

At high repetition rates, a small 9 volt battery will be "loaded down" and its output voltage will decrease. This affects both the rate at which the energy storage capacitor C2 can be charged and, more importantly, it reduces the gate drive voltage to Q1; both of these problems reduce the energy output per spark. However, it is still possible to get high repetition rates at full output voltage with 9 volt batteries by using *two* 9 V batteries in series. An extra set of pins has been provided on the circuit board to allow the use of two 9 V battery clips. Refer to this figure below for use with two 9 volt batteries; the red and black wire connections correspond to the red and black wires used on the typical 9 volt battery clip.



3. How to Choose

Here is a list of characteristics that can help you make a choice as to which pulser kit might be best for your project.

	Kettering Pulser	Capacitive Discharge Pulser
Cost	Lower	Higher
Voltage Output	Lower	Higher
Flexibility	Lower	Higher
Complexity	Lower	Higher
Triggering	Multiple Mode, from pushbutton.	Multiple Mode, from pushbutton or external electronics.
Pulses	Fixed Rep Rate, 50 Hz	Single/Multiple pulses, wide rep. rate range, up to 300 Hz
Power Source	Best at 12 volts	Tolerates a range of supply voltages
Ignition Coil Type	Needs high primary inductance	Tolerates different coil styles
Packaging	All parts contained on one circuit board	Power source and ignition coil separate from circuit board

In general. the Kettering pulser is best for the application requiring a simple, fixed rep rate source of high voltage pulses in a self-contained package with battery, circuitry and ignition coil all on a single board. The Capacitive Discharge pulser should be considered for applications in which the user may install the circuit board and ignition coil into a custom enclosure that may include mode switches, rep rate adjustment control and panel-mounted connectors. Its higher output voltage and spark energy is an important consideration.

4. Recommended Ignition Coils and Ignition Coil Comments

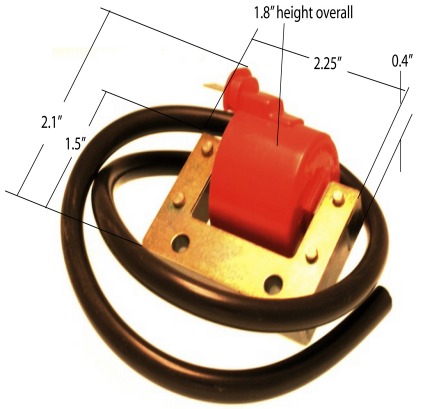
Our parts lists above show specific ignition coils, but many others will be satisfactory; the common feature is that they must be single coils (as opposed to the dual coils common in newer motorcycles, or the in-line coils commonly used on modern automobiles). Coils can be found at a typical auto supply parts store (simply ask for the ignition coil for any American or Foreign car older than approximately 1980), purchased at an auto salvage yard, or on-line. Here are several possible on-line sources:

An appropriate coil for the Capacitive Discharge pulser is Emgo part number 24-71536, offered by Oemcycle.com as their part number 2102-0030.
http://www.oemcycle.com/Item/product/900105885

or this vendor:
http://www.cheapcycleparts.com/products/192351

It appears to have a small ferrite rod core, instead of a closed, laminated soft iron U-I core.
Approximate measured parameters:
Primary resistance - 0.5 ohms
Secondary resistance - 4.9 kohm
Turns ratio: 1:100 (published spec; our measurements show that it is slightly higher)
Magnetizing inductance - 0.11 mH
Leakage inductance - 0.05 mH
While the low primary resistance might allow high currents, primary current in the Kettering pulser is limited more by the on-resistance of the MOSFET switch. So the lower inductance stores less energy, making this coil more useful for Capacitive Discharge uses, and impractical for the Kettering Pulser.

A more conventional ignition coil, the Emgo 24-71532, with Oemcycle.com part number 2102-0029, with a laminated soft iron core, has been tested on the Kettering and Capacitive Discharge pulsers.
Approximate measured parameters:
Primary resistance - 1.0 ohm
Secondary resistance - 6.4 kohm
Turns ratio - 1:75
Magnetizing inductance - 6.2 mH
Leakage inductance - 0.4 mH



The core in this transformer begins to saturate at an applied volt-seconds of 0.012 volt-seconds so will not store quite as much magnetic energy as would be expected for the measured inductance as the primary current rises above about 2 amps.

In the event that the parts from Oemcycle are not available, try these links:

http://www.motorcycle-superstore.com
http://campfireculinarian.com/links/atv-parts/

http://www.oldbikebarn.com Kawasaki Ignition Coil #21121-1186
A very nice coil; most (but not all) of the frame, which is the common autotransformer connection, is not so accessible to physical contact, thereby reducing the shock hazard. But it's rather expensive.

http://www.texaslawnmowerparts.com Briggs & Stratton Ignition Coil #1779
A fully-encapsulated coil at a moderate price, but without mounting holes.

Important!

These ignition coils listed above are convenient, small and inexpensive. But neither coil will tolerate output voltages much above 30 kilovolts. Above that, the insulation will break down within the coil itself. In the case of the Emgo 24-71536 coil used with the CD pulser, if the output voltage is allowed to rise too high, sparks can actually be seen through the translucent shell that surrounds the coil. And why is this important? Because if a spark develops between the primary and secondary, it can destroy the MOSFET Q1. Hence we have made Q1 easily replaceable.

The way to prevent overvoltage is to operate these ignition coils with a maximum electrode gap that will limit the maximum voltage rise at the secondary. Once a discharge starts, the output voltage will be clamped, rise no further, and fall to a value of only about 1 kV. The problem is that the correlation between electrode spacing and initial breakdown voltage is highly dependent on the electrode shape. So until you gain some experience with the pulsers, start with a 5 mm spacing between whatever electrode arrangement is used at the ignition coil secondary. Increase the gap spacing until you see that some pulses are missing, and then back off a few millimeters.

Comments about specifications.

The specifications for the typical auto ignition coil advertised in the retail marketplace, or on the web, are often inaccurate. A quick review of the products available will yield the typical "canister"-style coil, advertised at "40,000 volt" output for $29, or will yield a very different E-frame style coil with similar output voltage rating at 5 to 10 times the price. When both are connected to the typical modern spark plug with a 1 mm gap, the voltage across the spark plug will never rise much above 3 kilovolts before the spark discharge begins, clamping the actual output voltage across the spark discharge to as little as 400 volts. What can make a considerable difference in performance is the secondary winding resistance which is in series with the spark discharge and which can limit the energy deposited in the spark. We'll have more to say about this in a separate web page.

5. A Word About "Ground".

The high voltage output of these pulsers is developed across the secondary winding of the ignition coil, one side being connected to the "ground plane" of the circuit boards (or in the case of the Kettering pulser, connected to the ground plane by a varying "flyback" voltage as the spark is generated). But unless the "ground plane" of the circuit boards is actually connected to Earth ground, the potential of the ground plane on the circuit boards can "float" as the high voltage pulse appears at the output of the ignition coil. And it can do so by several hundred volts, enough to give a spark *to your finger* as you operate the toggle switches; a spark roughly equivalent to what you might feel from the static charge picked up when rubbing your shoes across a carpeted floor. So one should either connect a ground wire from the ground plane of either circuit board to a suitable Earth ground, or enclose either pulser in a conductive box, and the ground plane to that box, so that the capacitance of the enclosure is sufficient to define the enclosure itself as "Ground" for the short length of time that the high voltage pulse appears.

6. Some Experiments.

Here is a link to our pulser experiments page where we try some simple things that can be done with our high voltage pulsers. We'll add new experiments as time permits.

7. Circuit Comparison - Some Math for the Technically Inclined

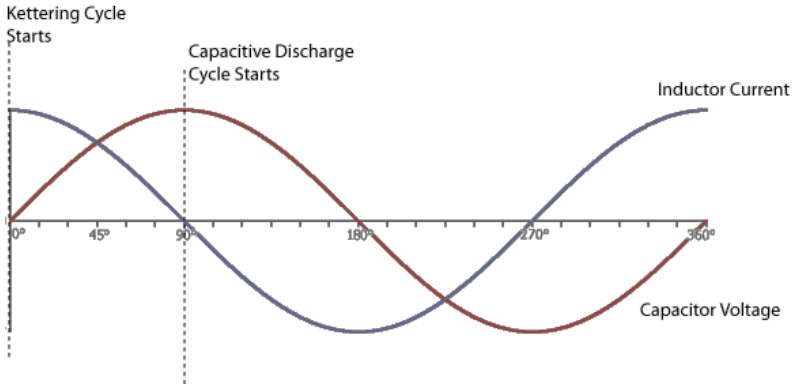
You won't need to study this to build these pulsers, but some experimenters may like to study these circuits more thoroughly.
Let's examine the difference between these two circuits. In many respects, they are exactly the same: both involve the dampened, sinusoidal, resonant transfer of energy between an inductor and capacitor. In the Kettering pulser, the energy is initially stored in the magnetic field of the inductance of the ignition coil transformer and transferred to the capacitor placed across the MOSFET switch. In the Capacitive Discharge pulser, the energy is initially stored in the electric field of the capacitor, and transferred to the inductance of the ignition coil transformer. We'll see that this difference can be important.

In an undamped parallel resonant circuit consisting of a capacitance C and inductance L, the time-dependence of the current is given by

$$I = I_o \cos\left(\frac{1}{\sqrt{LC}}t\right) \qquad (1)$$

where Io is the maximum current, and L and C are the inductance and capacitance of interest.

Here is a graph of the undamped sinusoidal inductor current and capacitor voltage, indicating where each cycle starts. In both cases, the voltage output from the ignition coil transformer peaks at the point where the slope in the inductor current is greatest, that is, where the inductor current goes through zero.



For reference, 360 degrees on the graph is equal to a time period of 6.28xSquareRoot(LC) .

If the resonant transfer of energy back and forth between inductor and capacitor is lossless, the maximum current may be found by assuming that the energy stored in the capacitor at zero current,

$$E_{electric} = \frac{1}{2} C V_0^2 \qquad (2)$$

where Vo is the maximum voltage across the capacitor C,
is the same as the energy stored in the magnetic field of the inductor at maximum current,

$$E_{magnetic} = \frac{1}{2} L I_0^2 \qquad (3)$$

The peak output voltage at the transformer secondary is given by

$$V_{out} = N L \frac{di}{dt} \qquad (4)$$

where N is the primary-to-secondary turns ratio of the ignition coil transformer. So we may solve equations 3 for Io in terms of energy E and substitute into equation 1. Then we may differentiate equation 1 with respect to time, maximize the time derivative, and substitute *that* result into equation 4, which finally yields the peak output voltage:

$$V_{peak} = N \sqrt{2 \frac{E}{C}} \qquad (5)$$

So the peak output voltage depends only on the transformer turns ratio, the stored energy E, be it magnetic or electric, and the capacitance. Let's see the results for both cases.

Kettering Pulser

Magnetic (inductive) stored energy is given by equation 3. The maximum current is about 7 amps, and the measured inductance is 0.24 mH, with a turns ratio of 1:75. The stored energy is then 5.8 millijoules. Inserting these data into equation 5 yields an output voltage of 25 kilovolts.

Capacitive Discharge Pulser

Electric (capacitive) stored energy is given by equation 2. The stored energy in the 2.2 uf capacitor in the CD pulser, charged to 400 volts, is 176 millijoules. Even though the capacitance in the Capacitive Discharge pulser is 20 times larger than that in the Kettering pulser, the predicted output voltage is then 40 kilovolts when using a 1:100 turns ratio ignition coil transformer. This process is readily scaled to substantially higher voltages with different components.

It is interesting to simply substitute equation 2 into equation 5. The result is that the peak voltage is simply the voltage initially stored on the capacitor times the transformer turns ratio. So then what is the need to worry about the value of the capacitance or the magnetizing inductance? Why not just use a tiny capacitor and a one-turn primary wrapped around a few hundred turns of wire for a secondary? Because this simplified analysis ignores the finite resistance and capacitance of the MOSFET switch and ignores the massive current that would flow with little or no distributed resistance in the circuit. So the objective is to select L and C so that *they* determine the circuit current (not the other components like the switch or wiring) and that *they* are the dominant reactive components in the circuit (not the distributed reactances of other components like the switch or the distributed capacitance of the transformer windings).

Conclusion

It is easier to store electric field energy in a capacitor charged to a high voltage than it is to store energy in a magnetic field "charged" to a high current. When Kettering invented his system in 1910, there was no compact and inexpensive way to produce the 400 volts needed for charging the capacitor in the Capacitive Discharge pulser. In fact, the earliest Capacitive Discharge auto ignition systems did not appear until the early 1960's even on an experimental basis (while one might justly claim that Tesla created bulky versions of such devices in the late 19th century). Now, partly driven by the need for compact high-voltage supplies for the flash units in portable digital cameras, such a power supply can be obtained for under 100 dollars.