THE 1962 VINTAGE TUNG SOL EI – 4 CAPACITIVE DISCHARGE IGNITION FROM MOTION INC.

Dr. H. Holden, March. 2014.

INTRODUCTION:

The purpose of this article is to document this unusual piece of automotive electronics history in such detail so as to allow it to be replicated by electronics engineers interested in Thyratron based CDI units and to fully document the unit's electronic design for future electronics historians.

Without this effort the extraordinary technology of the EI-4 could be lost to the sands of time.

The EI-4 represents a prototype capacitive discharge ignition system which in its essence was the basis for all commercial CDI units which followed, including those using SCR's (Silicon Controlled Rectifiers). In some respects the EI-4 was even more advanced than SCR units appearing in the few years afterwards because it did not need a free running transistorized DC:DC converter to operate, unlike the later SCR based units. On account of that it was far more efficient consuming only 1 Amp of current per 1000 RPM in an 8 cylinder vehicle. It also used a ferrite cored transformer ignition coil and had a number of other features.

Capacitive discharge ignition for automobiles had been experimented with in the 1950's by the Chrysler Corporation. However it was not until 1962 when Motion Inc of New Jersey in the USA produced the EI-4 CDI unit based on the Tung Sol cold cathode Rectifier & cold cathode Thyratron that a commercial unit or "add on CDI box" became readily available to the public. The uptake was rapid and they were fitted to high performance racing and "muscle cars" such as the Chevrolet Corvette. The name "Motion" gave the inspiration for the Baldwin-Motion company name, that came later, but this was a different company specialising in the engineering of racing Corvettes, however they used the EI-4 in a number of their performance cars.

The EI-4 described in this article came in its original condition complete with the manufacturer's instruction manual and the special mating transformer type ignition coil. It had seen some use as evidenced by heating of some of its internal components and wear on the handbook. The unit was a positive earth version and was temporarily converted to negative earth to allow adequate testing.

The EI-4 unit described here has been subject to a full laboratory analysis using test equipment designed for spark energy analysis (see www.worldphaco.net "spark energy test machine").

Also analysis of the circuit functionality is provided here along with detailed documentation of the three especially designed transformers it contains and the ignition coil. The data recovered includes the details of the transformer's electrical properties, including total number of turns, turns ratios, inductances, resistances and transformer core geometry and wire size where available. The laboratory method by which this transformer data was acquired without having to unwind or damage the transformers is explained in this article.

Prior to examining the actual EI-4 unit in detail, a copy is provided below of the manufacturer's handbook.

Note that the schematic shown on page 15 of the handbook is for the negative ground version.

In addition the polarities of the various transformer windings are not shown on the schematic.

Another interesting point is that the description of how the unit operates, as given on page 16 of the handbook under **Theory** "how it works" is not actually correct. For example the remark about the breaker points closing and stopping the primary current of T2 is incorrect. In fact the timing of the breaker points closing has no connection with the production of the spark generated by the unit and only provides a re-magnetization function at some non critical and variable stage during the operating cycle unless the rpm is so high that the contacts close less than 1.6mS after they have opened. Tests indicate the EI-14 can support an 8 cylinder engine to about 6000 rpm. The opening of the contacts is the important parameter. The contact breaker only needs to close to re-magnetise T1's (the input transformer) core for energy storage prior to the next cycle there and this does not relate to any part of the timing cycle of the events generating the spark unless the maximum rpm is exceeded and there insufficient time available to remagnetize T1. This is explained in the analysis below in the sections on circuits & transformers & operating theory.

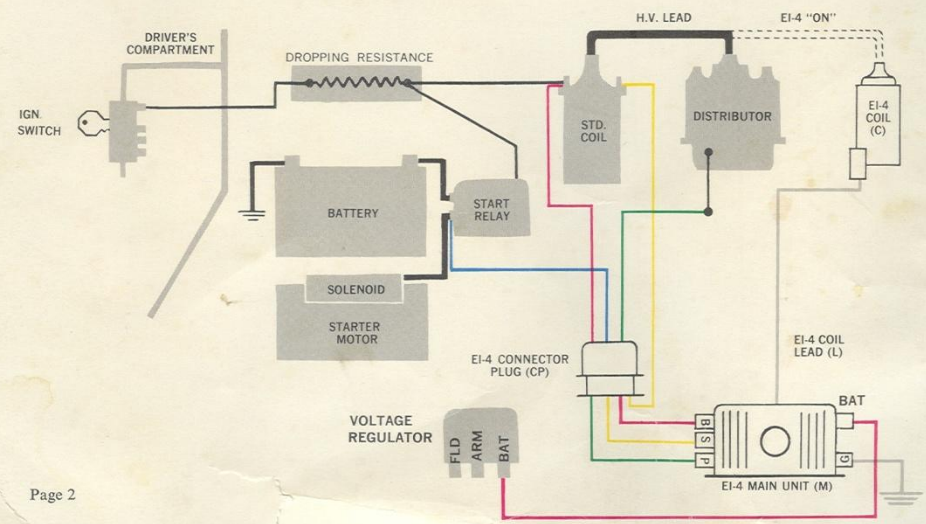
There is a typo on page 17, it says that the EI-4's spark lasts 3 millionths of a second (3 micro seconds), which is true and that an inductive spark lasts 150 millionths of a second (150uS or 0.15mS or milliseconds) which is not correct, it is usually about 1.5mS for an inductive discharge spark.

Below is a copy of the manufacturer's handbook:

CAPACITIVE DISCHARGE / **ELECTRONIC IGNITION**

INSTALLATION INSTRUCTIONS

FIGURE 1. EI-4 WIRING FOR ALL INSTALLATIONS — 6V, 12V, POSITIVE OR NEGATIVE



installation instructions

CAPACITIVE DISCHARGE ELECTRONIC IGNITION SYSTEM

MOTION INC. NEWARK 4, NEW JERSEY

CAUTION — FOLLOW INSTRUCTIONS EXACTLY AS YOUR WARRANTY DOES NOT COVER DAMAGE DUE TO IMPROPER INSTALLATION.

Be sure your EI-4 Unit has the correct voltage rating (6V or 12V) and correct polarity rating (POS. or NEG.) for your application. This can be determined from the Serial number on the end cap of MAIN UNIT (M).

12 volt negative ground	S/N numbers only	*ie. 645*
12 volt positive ground	S/N numbers followed by letter "P"	*ie. 123-P*
6 volt negative ground	S/N numbers followed by letter "V"	*ie. 721-V*
6 volt positive ground	S/N numbers followed by letters "VP"	*ie. 891-VP*

pre-installation procedure

Best results from the EI-4 Ignition System will be assured if the following steps are taken before installation.

STEP 1 Install new breaker points. Be sure the ground lead connecting the points to the distributor is tight at both ends.

STEP 2 Set dwell angle and timing as specified by the engine manufacturer.

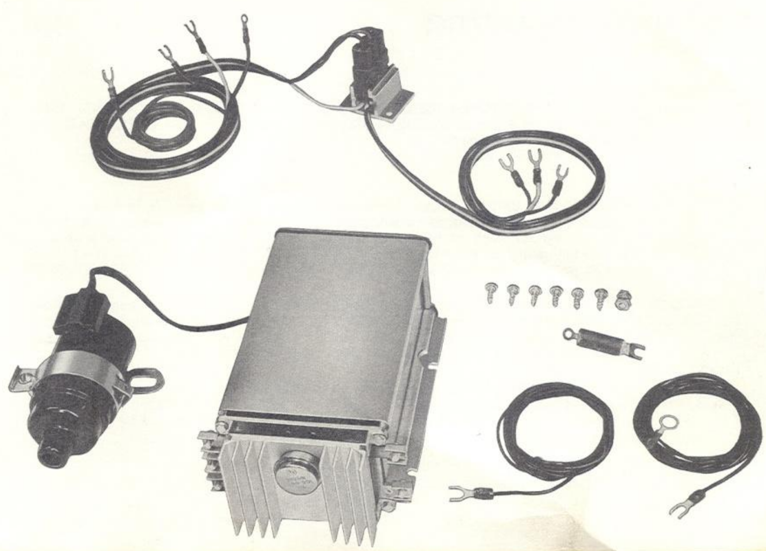
STEP 3 Check spark plugs for fouling and electrode erosion and replace if in poor condition. New extended tip plugs of proper heat range, gapped to .040" are recommended for optimum results.

STEP 4 Be sure high voltage leads from distributor to plugs are not cracked with age or excessively dirty. (New leads may be needed if the old ones have seen more than 20,000 miles or 500 hours of service.)

STEP 5 Be sure distributor cap and rotor are clean and free from cracks.

STEP 6 Start engine to be sure it is performing well.

THE EI-4 CAPACITIVE DISCHARGE ELECTRONIC IGNITION SYSTEM



location and mounting

Read STEPS 1, 2 and 3 carefully before mounting the EI-4 Unit. Choose locations for MAIN UNIT (M), COIL (C), and CONNECTOR PLUG (CP) as instructed, making certain that the six foot COIL LEAD (L) will reach without splicing before mounting the parts.

STEP 1 **MOUNTING MAIN UNIT (M):** Locate in the engine compartment away from heat sources, such as exhaust manifold, and away from areas subject to heavy water splash. Select a sturdy surface such as bulkhead, firewall, or fender side to minimize vibration. Locate and drill four mounting holes (#27 drill; 0.144"). Using the #10 sheet metal screws provided, attach MAIN UNIT (M) securely.

STEP 2 **MOUNTING COIL UNIT (C):** Locate near the distributor so that the high voltage lead from the distributor will reach the EI-4 COIL (C) tower without exceeding 18" in length. Using the extra coil bracket provided, bolt the COIL UNIT (C) into position. Make sure the connectors on COIL (C) are accessible for COIL LEAD (L) connector.

STEP 3 **MOUNTING CONNECTOR PLUG (CP):** Locate on a sturdy surface being sure the molded 3 wire lead will reach for connection to terminals (B), (S), and (P) on MAIN UNIT (M). Drill two mounting holes (#27 drill; 0.144") and using #10 sheet metal screws provided, screw the bracketed female connector into position.

wiring

CAUTION: Loose connections or wrong wiring can destroy the transistor.

BASIC WIRING IS ILLUSTRATED IN FIGURE 1: (inside front cover)

Read Steps 4 through 10 before beginning hook-up, referring to Figure 1. as you read. Note especially Step 9 IDIOT LIGHTS.

CONNECTOR PLUG (CP) wiring is shown in Figure 2. (inside back cover). The plug is assembled at the factory in the EI-4 "OFF", Standard System "ON" position.

CONNECTIONS TO MAIN UNIT (M)

STEP 4 **(B), (S) and (P) TERMINALS MAIN UNIT (M):** There is a three foot length of molded 3 wire cable connected to the base of the CONNECTOR PLUG (CP). Connect the green lead to (P), the yellow lead to (S) and the red lead to (B) on MAIN UNIT (M) Refer to Figure 1.

STEP 5 **(BAT) TERMINAL MAIN UNIT (M):** Connect the single red lead provided to the Battery terminal on the voltage regulator and to the (BAT) terminal on MAIN UNIT (M). Refer to Figure 1. Where alternators are used the voltage regulator may not have a battery terminal or the regulator may be built into the alternator. In this case connect to the battery terminal on the alternator. (This connection provides battery voltage to the EI-4 Unit at all times.)

STEP 6 **(G) TERMINAL MAIN UNIT (M):** Select a small bolt (such as the bolt holding the coil bracket) on the engine as a grounding point. Clean the contact surface carefully and using the black wire provided connect this point to (G) on MAIN UNIT (M). Refer to Figure 1.

CONNECTIONS TO VEHICLE

There is a four foot length of molded 4 wire cable connected to the CONNECTOR PLUG (CP), 3 wires being connected to the removable portion of the plug and 1 wire being connected to the plug base. See Figure 2. (inside back cover). The ends of these wires are connected as follows:

STEP 7 **BREAKER POINT AND COIL CONNECTIONS:** Remove the small lead, connecting the distributor to the standard coil from the coil. Connect the green wire in the 4 wire molded cable to the free end of the removed lead using a nut and bolt and taping to insulate.

Connect the yellow wire in the 4 wire molded cable to the distributor side of the conventional coil.

Connect the red wire in the 4 wire molded cable to the other terminal (ignition switch side) on the conventional coil leaving in place any other wires connected to this terminal.

STEP 8 **START CONNECTION:** Connect the blue wire in the 4 wire molded cable to a point on the start relay or start solenoid which provides battery voltage only when the start switch is in the "ON" position. See Figure 1.

The start connection (S) is provided to assure cold weather starting when battery voltage has dropped down. On some engines, particularly 4 cylinder imported makes, a mechanical start system is used and there is no convenient way to make use of the start (S) connection. In these cases simply tape the end of the blue wire in the 4 wire molded cable and leave unconnected.

STEP 9 **IDIOT LIGHTS:** On installations equipped with a generator indicator lamp on the dashboard instead of an ammeter, it is necessary to insert the small diode provided in the kit in the lead connecting this indicator lamp to the voltage regulator. See Figure 3. (inside back cover). Be sure to insert diode as instructed, otherwise the engine will not shut off.

STEP 10 **COIL LEAD (L):** Connect COIL LEAD (L) to COIL UNIT (C) being careful that the connector is tight and seated properly.

If the instructions have been followed correctly, the engine will start and run on conventional ignition. Try it.

To convert to EI-4 electronic ignition turn off the engine and take the following steps:

STEP 11 **H.V. LEAD:** Remove the H.V. lead connecting the distributor to the standard coil from the coil and insert in the EI-4 COIL (C). See Figure 1.

STEP 12 **CONNECTOR PLUG (CP):** Disconnect the plug, rotate 180° and reconnect. See Figure 2.

The engine will now start and run on EI-4 electronic ignition.

To return to conventional ignition reverse STEPS 11 and 12.

APPLICATION INFORMATION

ignition analysis

Oscilliscope ignition analyzers will not show a recognizable trace when checking plugs and wiring because of the capacitive discharge spark which is too fast for the equipment. This is one of the reasons the EI-4 is designed as a dual installation. Standard test equipment may be used in analyzing engine conditions by converting the ignition system to conventional for engine analysis. When the engine is perfect for conventional ignition it will be right for the EI-4 ignition.

dwell meters

Oscilliscope analyzers may be used to measure dwell angle while the engine is operating on the EI-4 system. Standard dwell meters cannot be used while the engine is operating on EI-4 as neither the meter nor ignition will perform satisfactorily. The dwell meter may be used while cranking.

tachometers

Most electric and electronic tachometers operate from a signal produced at the breaker points. This type of tachometer will continue to work with EI-4, although it may be necessary to disconnect the condenser from the distributor.

Some types of tachometers are hooked in series with the ignition coil and may not work unless hooked in series with the "red lead" connected to the (BAT) terminal on EI-4 MAIN UNIT (M).

carburetion

For maximum performance with the EI-4 system carburetion should be good. For this reason the condition of the carburetor, fuel pump and fuel cleaner should be checked. If there is any indication of dirt, these items should be cleaned carefully. Often a full degumming treatment will improve carburetor performance.

no load misfiring

It is characteristic of the EI-4 that in some few automotive installations misfiring will be audible when the engine is revved-up while in neutral. This is not cause for concern and is not related to road load performance. While this occurs on standard ignition, due to lean fuel-air mixture conditions in the combustion chamber, it is accentuated by the short spark duration characteristic of the EI-4 system.

lean mixture surge

Some engines have an ignition characteristic known as lean mixture surge which is generally inherent in the combustion chamber design. This surge will show up as a hesitation under light load conditions which occurs while decelerating or while cruising at constant speed. If such a condition exists, however slight, it will be accentuated by the EI-4 system.

Lean mixture surge can usually be eliminated or greatly reduced by the following corrective steps. Try the steps in the order shown and test between each step.

A Be sure carburetor is clean.

B Check vacuum line and carburetor gaskets for possible air leaks.

C Install extended tip spark plugs.

D Adjust carburetor idle mixture control.

E Open spark plug gap to .040".

F Retard spark one or two degrees.

spark plugs

Plugs which have been operated for long periods of time on conventional systems are likely to have the sharp edges of the center electrode eroded away leaving a rounded surface. Such plugs may not perform properly with the EI-4 system. Since the EI-4 system reduces electrical erosion of plugs due to short spark duration this rounded condition will not develop with the EI-4 system in operation.

rubbing block wear

Wear of the rubbing block which activates the breaker points will change dwell angle and timing settings. For this reason it is wise to check dwell angle and timing after the first 1000 miles and then periodically each 5000 to 10,000 miles.

Nylon rubbing blocks often have a soft surface layer. Filing away .002" to .003" of the bearing surface will avoid early wear and help maintain proper dwell angle during the initial running in.

leaking H.V. harnesses—rotor—distributor cap

Faulty H.V. harnesses, rotors or distributor caps, can cause rough operation due to flash over of voltage to ground, resulting in plug misfire. If this situation develops, clean these items carefully and check for cracks and arcing tracks. Be sure H.V. leads are at some distance from metal objects or water lines. Observation under darkened conditions will make the detection of arc-over easier.

At night or in darkened areas a bluish glow may be observed around the high voltage harnesses and distributor body. This is corona and characteristic of the capacitive discharge system. It is not cause for worry.

loose connections

Loose connections can cause poor operation. Check H.V. lead connections and all connections made to the EI-4 unit and parts. Check the ground connection in the distributor carefully.

radio interference

In general the EI-4 will produce the same or lower radio noise conditions in radio receivers, as will conventional systems. Standard suppressive measures may be used with the EI-4 system. Do not attempt military type shielding.

distributor condenser

The EI-4 system will operate with or without the distributor condenser, though it may be necessary to disconnect it to make electric tachometers work with EI-4 as explained under "TACHOMETERS". The conventional system will operate satisfactorily only with the condenser in place.

Should the condenser short out, neither conventional nor EI-4 will work. Removing the condenser will allow the EI-4 system to operate.

Should the condenser open up, EI-4 will still perform, whereas conventional will not.

If the condenser is removed from the distributor and hooked on between the distributor side of the coil and ground, it will perform its normal function with the standard system, and eliminate tachometer problems on EI-4 as well as preventing ignition failure on EI-4 due to shorting out of the condenser.

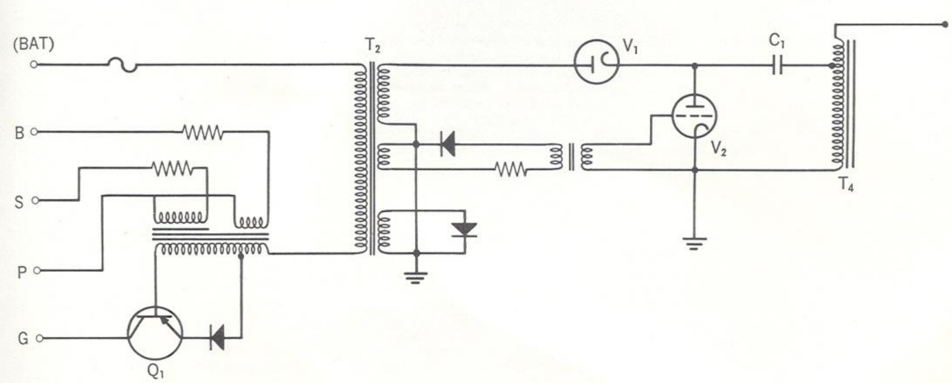
high performance engines

The EI-4 has an inherent advance characteristic as compared to conventional ignition of 50 to 100 millionths of a second. Above 4000 RPM on 8 cylinder engines or the equivalent on 4 and 6 cylinder engines, this advance may often be observed with a timing light. Generally this inherent advance will not deteriorate acceleration on high speed performance but may produce missing under deceleration or light load conditions. It may be compensated for by retarding static advance a degree or two or modifying the advance curve to suit the EI-4 system.

Many high compression performance engines require the use of hot plugs for engine warm-up with conventional ignition, cold plugs being inserted when the engine is warm. With EI-4 the engine will start and warm up on the colder running plugs so that plug change is unnecessary.

Many performance engines use a plug gap of .018" to .020" with conventional ignition. With EI-4 it is necessary to use a gap of .025" minimum. A gap of .035" may improve performance and generally is satisfactory for the conventional system as well.

EI-4 CIRCUIT DIAGRAM



THEORY

how it works

During the first engine revolution when starting, the EI-4 circuit begins to function when the breaker points open. When the points open, current flows through the primary of transformer T_2 momentarily building up a magnetic field in the transformer core. When the breaker points close, current flow through the primary is stopped, the magnetic field collapses and induces a high voltage in the transformer secondary which voltage is transferred through rectifier V_1 to capacitor C_1 where it is stored until the breaker points open again. When the breaker points open the second time the current flowing through the primary of T_2, in addition to building the magnetic field in the transformer coil, produces a voltage on the secondary. Part of this secondary voltage is applied to the grid of Thyratron V_2 causing it to conduct. The energy previously stored in the capacitor C_1 is then discharged through V_2 into the spark plugs through EI-4 coil T_4.

what it does

Eliminates Electrical Wear of Breaker Points

The primary circuit of the EI-4 system uses a transistor to carry and switch the heavy current flowing from the battery or generator through the main transformer so that the breaker points carry only a small control current of approximately one ampere. This results in elimination of pitting and bluing of breaker point contact surfaces so that electrically they will operate indefinitely, without replacement.

Fires Fouled Spark Plugs and Reduces Gap Erosion

At the moment the breaker points open the EI-4 system raises the plug voltage to firing potential in one millionth of a second which is 50 to 60 times as fast as conventional or transistorized inductive systems. The EI-4 spark lasts about three millionths of a second whereas the inductive type of spark lasts about 150 millionths of a second.

The very rapid voltage rise time of the EI-4 system gives it the ability to fire severely fouled spark plugs and wide gap plugs because there is not sufficient time before firing the gap to permit energy to leak away across resistive deposits on the ceramic nose of the plug center electrode. This ability reduces chance of misfire under all speed conditions.

The short spark duration of EI-4 reduces electrode erosion so that plug gaps do not enlarge with use.

Performance Improvement

Engine dynamometer tests conducted by independent concerns have shown a consistent five to six percent increase in BHP output over the engine RPM range on new engines. In addition many individuals have reported a feelable increase in acceleration performance in automobiles, sport cars, boats and trucks. Performance is particularly good with fuel injection or supercharging.

Fuel Economy

Superior mileage performance over a relatively long period of time will result due to the EI-4 maintaining a new-tuned ignition condition in the engine. This new-tuned condition is a result of keeping breaker point contacts clean and unpitted and the ability to fire temporarily fouled plugs.

In tests, extending over 30,000 miles, it has required 5% to 15% less gallons of gasoline to operate on the EI-4 system than on the conventional system.

An immediate increase in MPG may not result. In fact, if the improved performance abilities described previously are taken advantage of, mileage may drop for the obvious reason that it takes more fuel to accelerate faster.

Easy Starting

Under cold temperature conditions battery voltage can drop to approximately half the normal value. The EI-4 is designed to compensate for this through the "start" connection so that during starting,output to the spark plugs will be 25KV even at half battery voltage.

Lowered Battery Drain

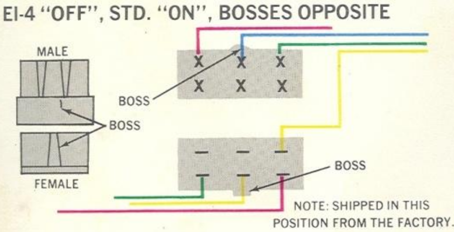
Under cranking or starting conditions, the EI-4 draws 0.5 amperes maximum compared to 3 to 4 amperes on the standard ignition systems and 4 to 8 amperes on transistorized systems.

With the engine stopped and the ignition key left on, current drain will be 0.25 amperes maximum with the breaker points closed and 0 amperes with points open on the EI-4 System. Standard systems will draw approximately 6 amperes and transistorized systems will draw 10 to 12 amperes with breaker points closed.

During engine operation current draw will be approximately 1 ampere per 1000 RPM on 8 cylinder engines and proportionately less in 6 cylinder and 4 cylinder engines.

FIGURE 2. CONNECTOR PLUG (CP) CIRCUIT DIAGRAM.

EI-4 "OFF", STD. "ON", BOSSES OPPOSITE



EI-4 "ON", BOSSES TOGETHER

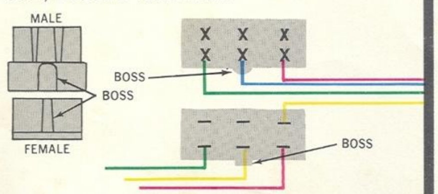
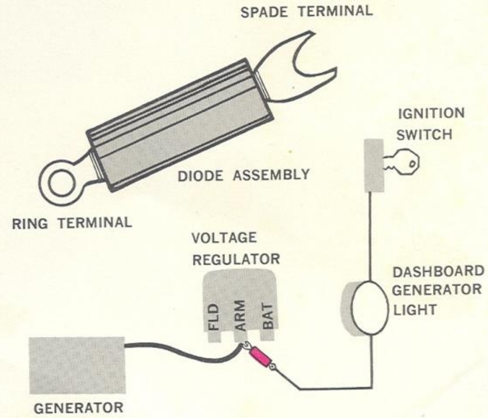


FIGURE 3. (IDIOT LIGHT CONNECTION) See STEP 9

There will be two leads connected to the (ARM) or (GEN) terminal on the voltage regulator. The lighter weight or thinner lead, which connects the indicating light to the voltage regulator, must be cut. The free end should be connected to the ring terminal of the diode assembly. The spade terminal of the diode assembly should then be connected to the voltage regulator at the (ARM) or (GEN) terminal.

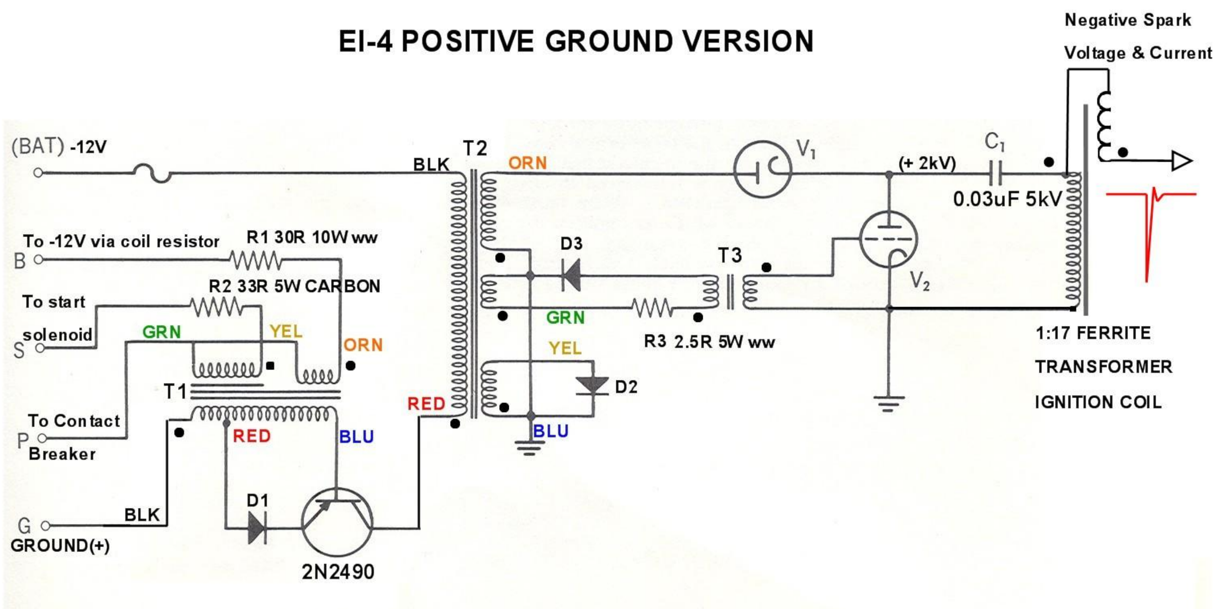


CIRCUIT & TRANSFORMERS:

As shown above the handbook was fairly detailed. The section on Theory and the function of the unit was glossed over and incorrect. However before going into a detailed circuit analysis and oscilloscope waveforms, the designs of the transformers, including the ignition coil are shown below.

The entire function of the EI-4 is very dependent on the design of its transformers. Every effort has been made to document these as accurately as possible. The wire sizes were measured where possible. The turns ratios & total number of turns were measured by threading some turns of wire around the core and testing with applied AC voltages. (Note when doing this it is important to apply a low impedance generator output voltage to the longest winding on the transformer or transformer self resonances will corrupt the results).

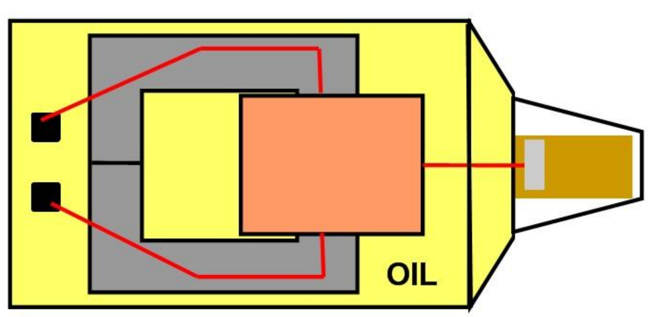
The schematic below shows the circuit re-drawn to include the transformer winding polarities and of the positive ground version. All of the circuitry on the secondary side of T2 is identical in both the positive and negative ground versions, including the way the ignition coil is drawn. It was specifically configured to have a negative going initial spark voltage and current common to all automotive spark generating systems. The primary winding of T2 is simply configured so its red wire is supplied by positive or the black by negative via the fuse with either the positive or negative ground versions respectively. T2 electrically isolates the secondary circuits which are the same in both + or – ground units.

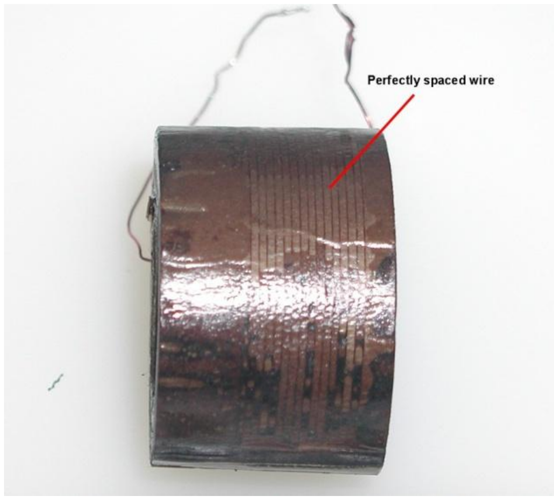


The coupling transformer T1 is not interchangeable between the + and – ground EI-4 units due to the winding polarities of the primary windings needing to be different and the way the transformer connections to the green wire of T2 were made common to the two primary windings before exiting the transformer winding. This means that the winding connections to the primary windings could not easily be reversed. So the two units EI-4 either + or – ground would have used a different T1.

Starting with the ignition coil removed from its case for repairs:

EI-4 TRANSFORMER IGNITION COIL

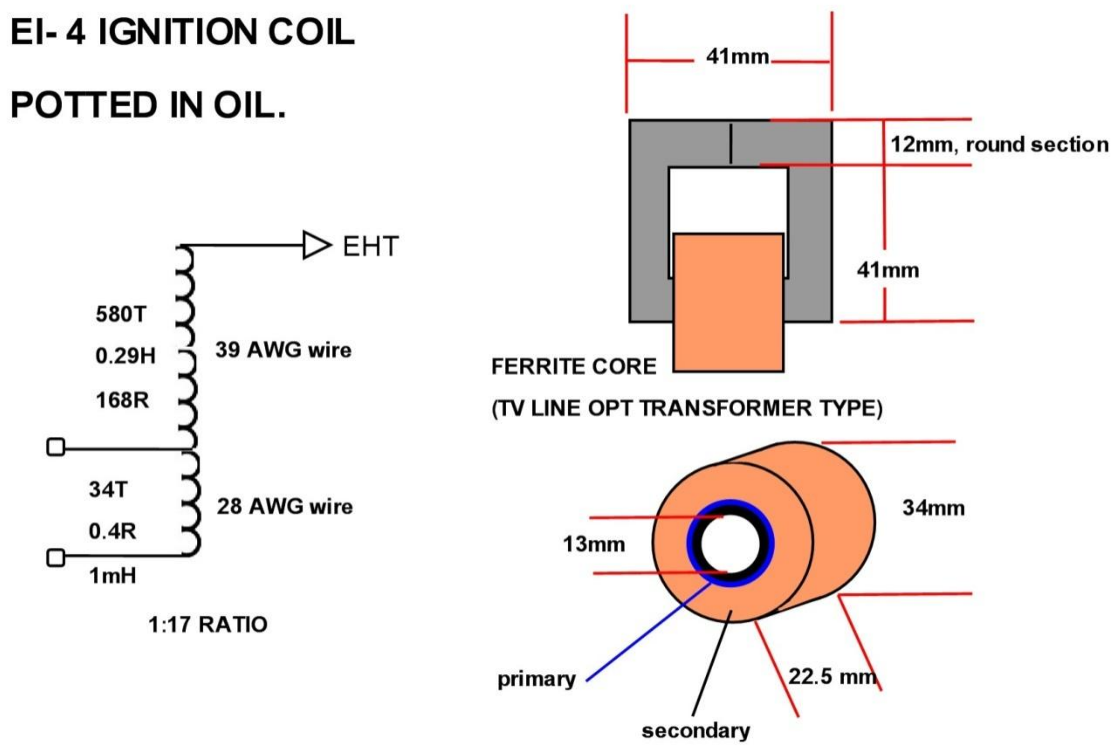




The secondary winding is very precisely wound in individual layers, but not only that the 39 AWG wire is precisely placed with a gap between each turn.

The designers of the EI-4 appreciated the importance of a transformer ignition coil. Standard ignition coils for Kettering systems are not very suited to CDI use. This particular coil required opening up and repairing as it was breaking down with internal arcing and it was therefore not possible to measure the CDI's peak off load output voltage without repairing it.

So this repair gave the opportunity to acquire the coil data.

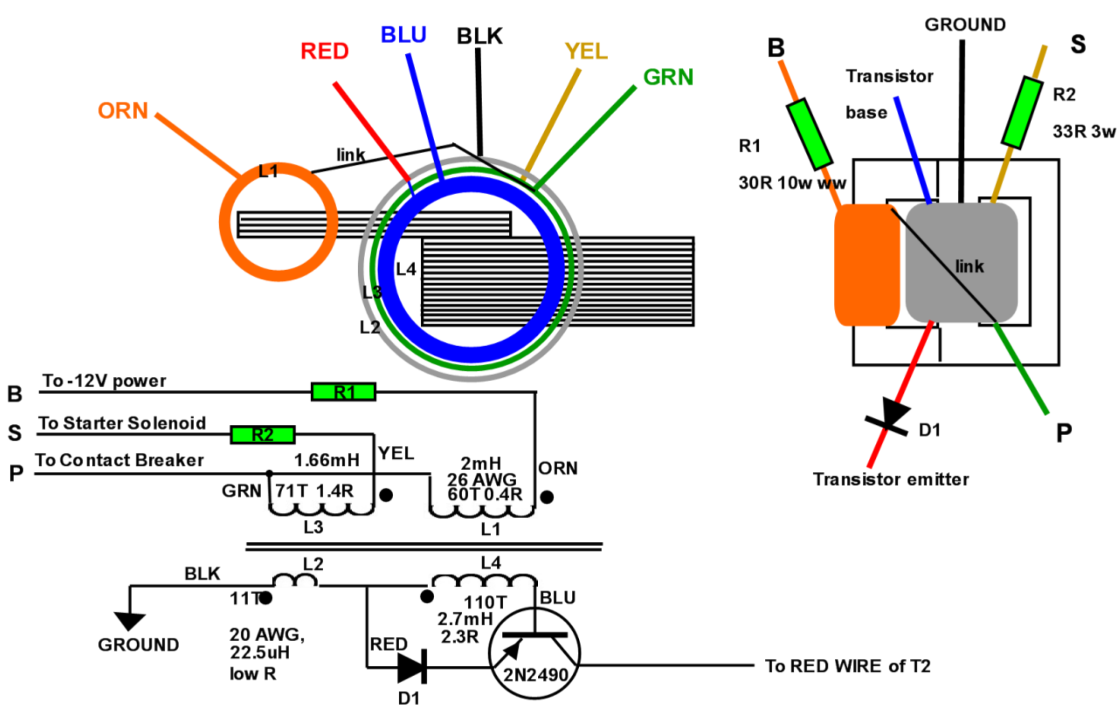


This ignition coil's ferrite core appears identical to the types used in TV line (horizontal) output stages of the time. The ratio is 1:17. The 0.03uF capacitor in the unit is charge to 2200V before the Thyratron triggers, applying the charged capacitor to the ignition coil's primary. The peak secondary voltage would therefore be expected to be around 39kV and have no difficulty initiating spark ionization (see recordings later).

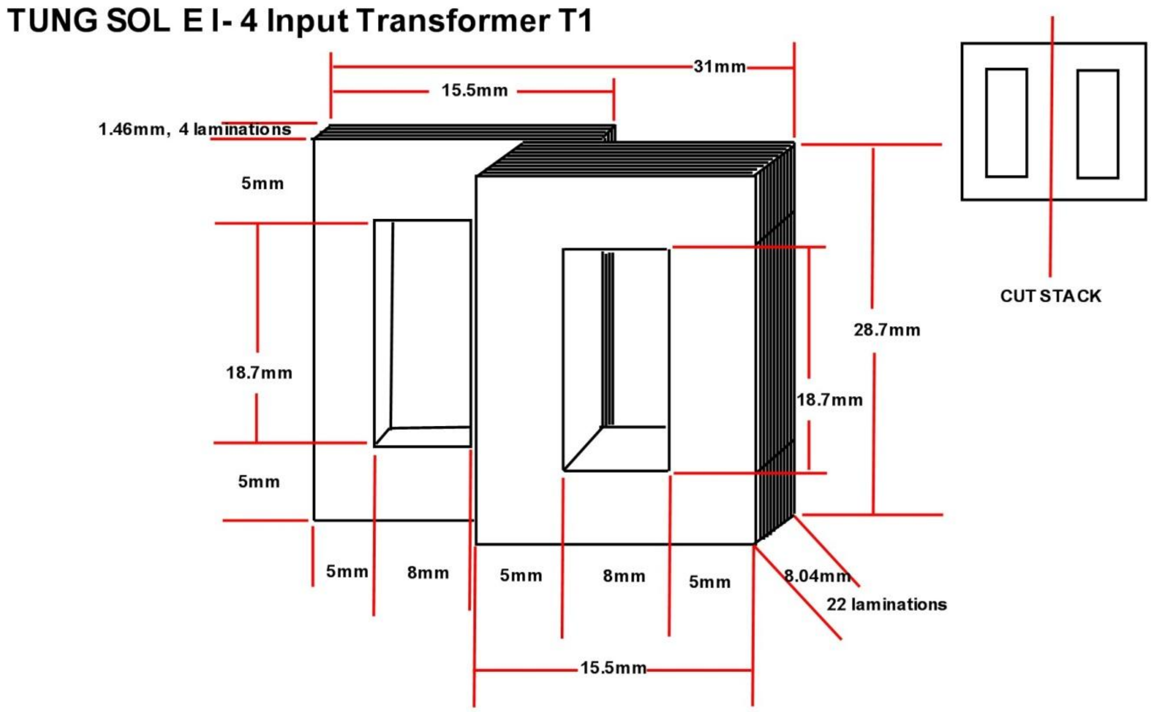
DRIVER TRANSFORMER T1:

T1 is the input coupling transformer which interfaces the transistor to the contact breaker. When the contacts are closed the magnetic field is climbing in T1's core and the transformer's polarities are such that this ensures the transistor is in a non conducting state. When the contact breaker opens, T1's field begins to collapse and the forward biases the diode D1 and the transistor's base-emitter junction, turning on the transistor. The transistor's collector-emitter current (which passes via the primary of T2) assists this switching process via the additional winding L2. However this is not enough to sustain transistor conduction on its own as ultimately the rate of change of flux in winding L2 drops off and so does the induced voltage driving the base circuit. Therefore after a period, about 1.6mS in this case the transistor drops out of conduction again. This circuit therefore provides a near fixed length 1.6mS switching interval to apply the 12V power supply voltage to the main transformer T2. The closing of the contact breaker occurs later and does not control the timing over which T2 is switched on and the dwell time has no effect on the operation of the unit unless its at the maximum rpm level. The 2N2490 is a very similar transistor to the much more common 2N174. T1's core is made from E-I laminations which have been cut to create the interesting core geometry:

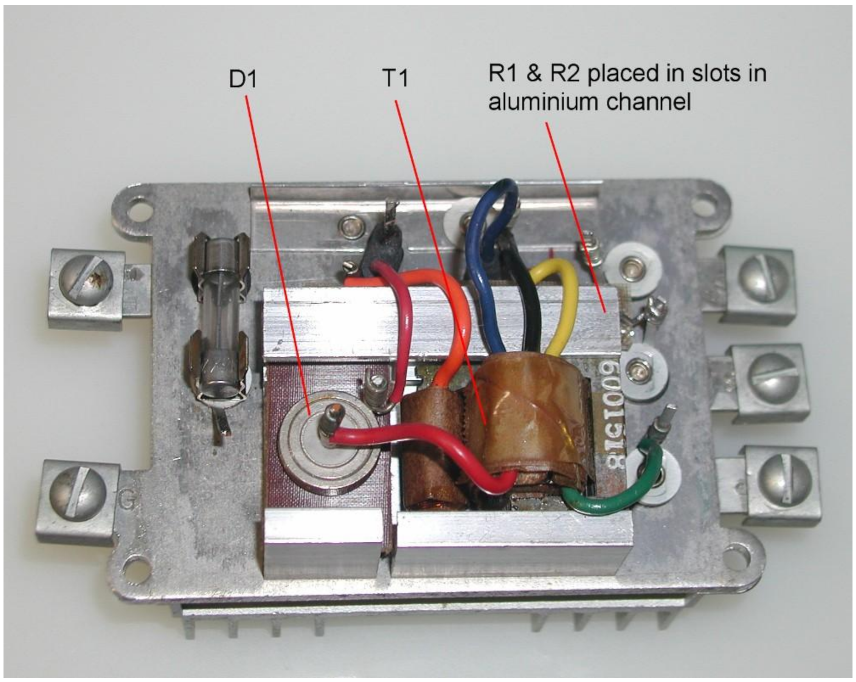
TUNG SOL E I - 4 POSITIVE GROUND VERSION T1:



The additional winding L3 connects to the 12V supply which is present during starting to help ensure adequate energy storage in T1's core if the battery voltage sags down on starting. The following diagram shows the laminated core of T1 in more detail:



The photo below shows the rear of the heat-sink where T1 is located:

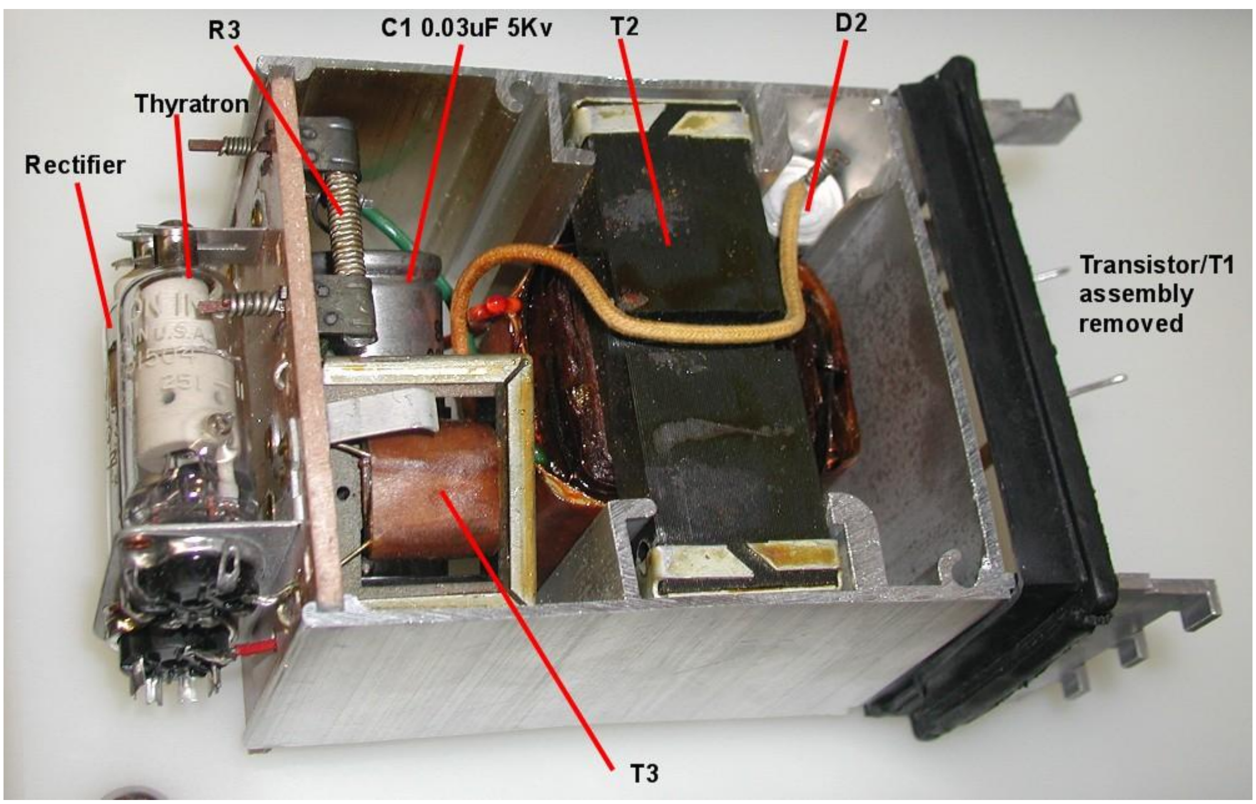


Of particular note is the use of “WIRE WRAP” as a technique to avoid soldering. The wires are wrapped around square pins to obtain a secure connection. There is some soldering in the EI-4 unit but most of the connections are done with wrapping.

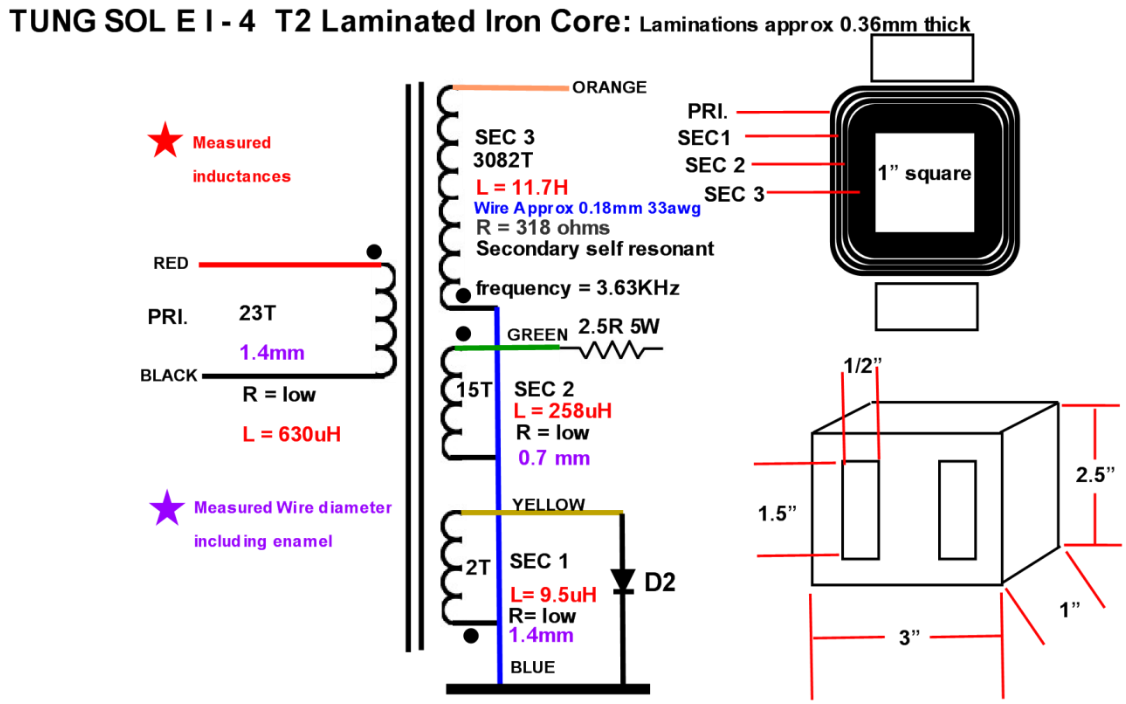
MAIN TRANSFORMER T2:

The main transformer is the heart of the unit and isolates the input and output side of the system but the manufacturers chose to make the earth common as the spark current must be relative to the cars earth potential. It meant however the entire secondary side of T2 and the circuitry there could be the same in both the positive and negative ground units and only the reversal of the primary of T2 and reconfiguration of the transistor wiring and T1’s windings would be required to keep the polarities the same on the secondary side of T2.

The photo below shows T2 along with the other components. The chassis of the unit is made from extruded aluminium, as is the outer casing it slips into. Diode D3 is pressed into the same section of channel as D2 but on the opposite side:



The diagram below shows the construction details of T2

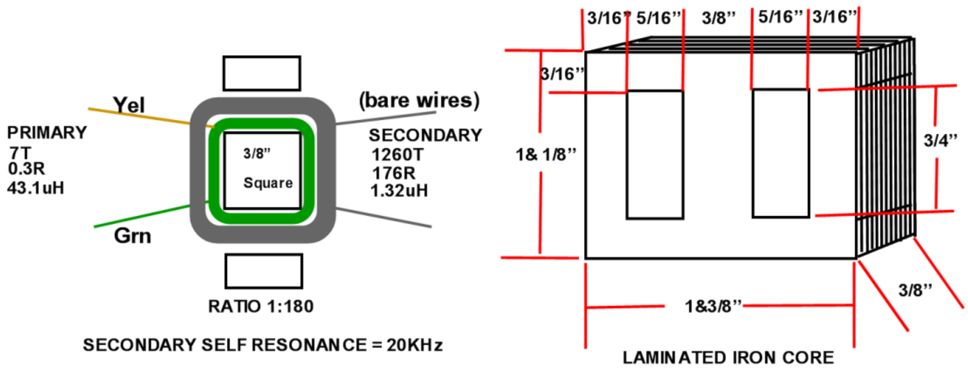


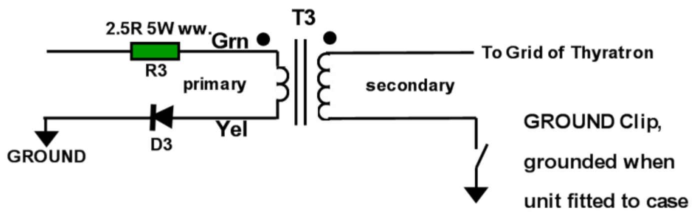
T2 is switched on for 1.6ms immediately after the contact breaker opens.12V is applied to the primary winding. When the transistor switches off, T2's field collapses releasing the stored energy and as it does a high secondary positive going positive voltage is produced on the orange wire from the main secondary winding. To avoid this climbing too high D2 (a power silicon rectifier) conducts limiting the voltage on the 2 turn secondary winding to one volt, the effect of this is to limit the peak voltage on the orange wire or main secondary output to the cold cathode gas rectifier to about 2200v. Therefore even with climbing battery voltages the capacitor charging voltage remains stable. More about these features will be explained in the operating theory section below.

TRIGGER TRANSFORMER T3:

T3 is a very high ratio step up transformer to get the Thryatron trigger voltage up to a high level. Anytime the contact breaker opens the polarity of the voltage on the 15 turn winding of T2 is such that when the trigger transformer T3 is driven by this, via the green wire and the 2.5R resistor (R3) and the rectifier diode D3 the polarity is such that the trigger pulse applied to the Thyratron's grid is a positive going voltage.

TUNG SOL E I - 4 Pulse Transformer T3:

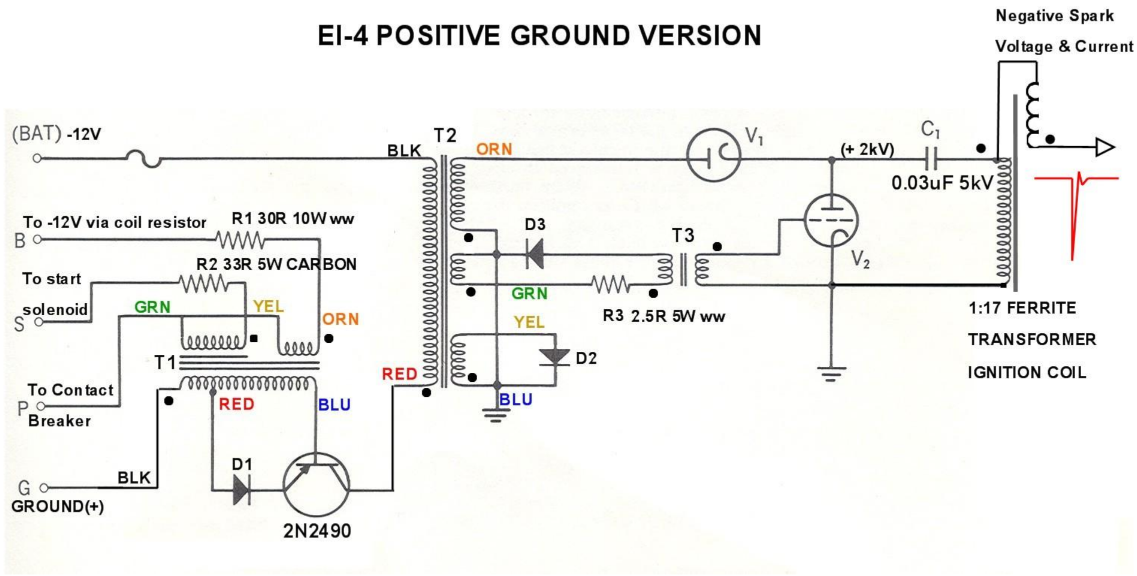




Therefore the Thyratron only triggers on after the contact beaker opens. The diode D3 ensures that trigger voltages can only occur on the correct polarity signal from T2. T2 steps the voltage down from 12 to about 7.8V due to the 15/23 turns ratio, then T3 steps the pulse up to about 1400V due to the turns ratio of T3 at 1260/7. This is enough to trigger the Thyratron into operation causing it to conduct heavily and dump the charge in the 0.03uF capacitor into the primary of the ignition coil.

OVERALL OPERATING THEORY & OSCILLOGRAMS:

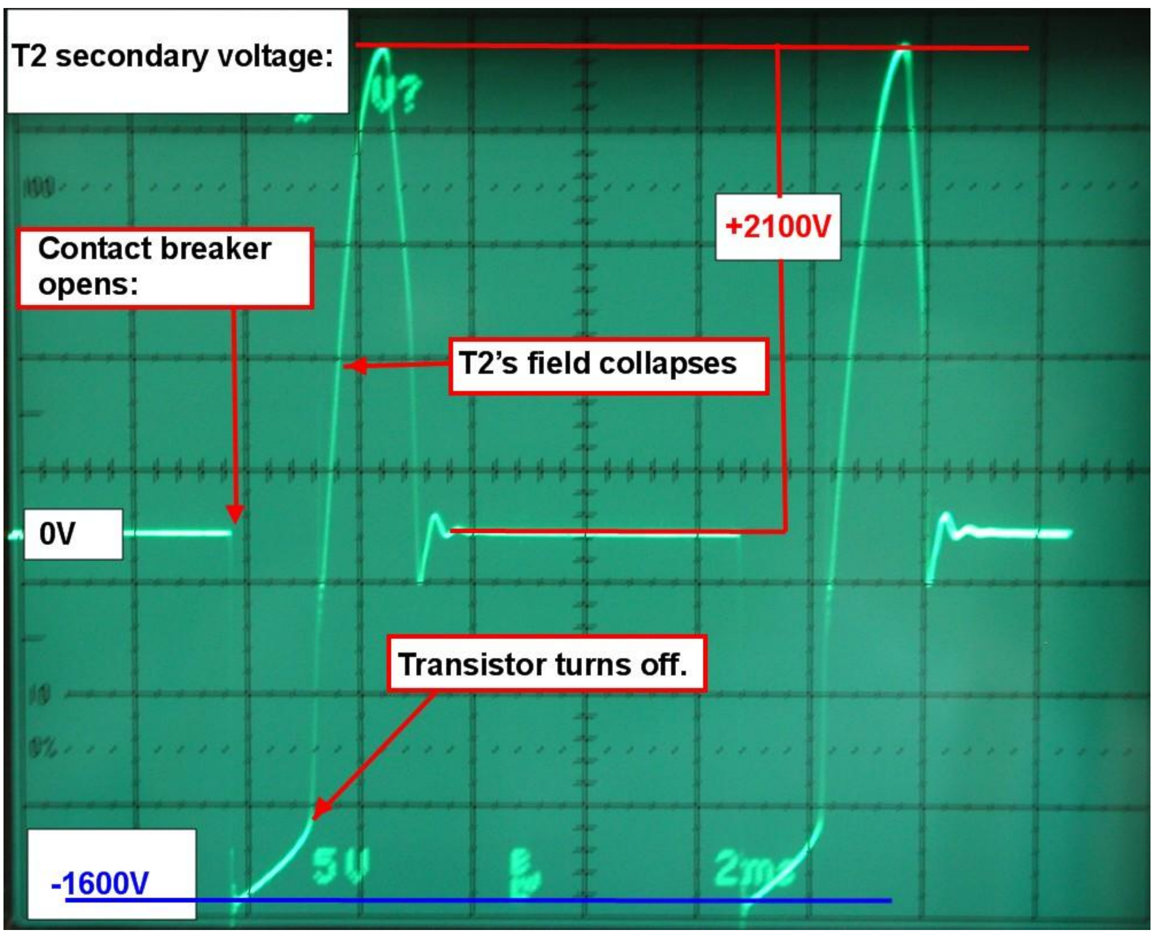
Repeating the Schematic:



When the contact breaker is closed current via R1, the 30R resistor, and primary winding (Orn + Yel) of T1 magnetizes T1's core. That is all it does because the polarity of the voltage induced across the red and blue wires on the secondary is positive on blue and negative on red which reverse biases D1 and the base-emitter junction of the 2N2490 transistor keeping them both in a non conducting state. When the contact breaker opens the magnetic field in T1 collapses. The polarity of the voltage induced across the secondary is now positive on red and negative on blue. This forward biases D1 and the transistor's B-E junction causing current to flow via the black wire of T1 via short winding of T1 (between black and red wires) the transistor's emitter-collector junction to the red wire and the primary winding of T2. This commences magnetisation of T2. The current in the short winding between the black and red wires of T1 reinforces the initial conduction of the transistor to give a brisk turn on process. However this is only for the turn on transient, as any sustained DC current is unable to induce a voltage in the windings of a transformer.

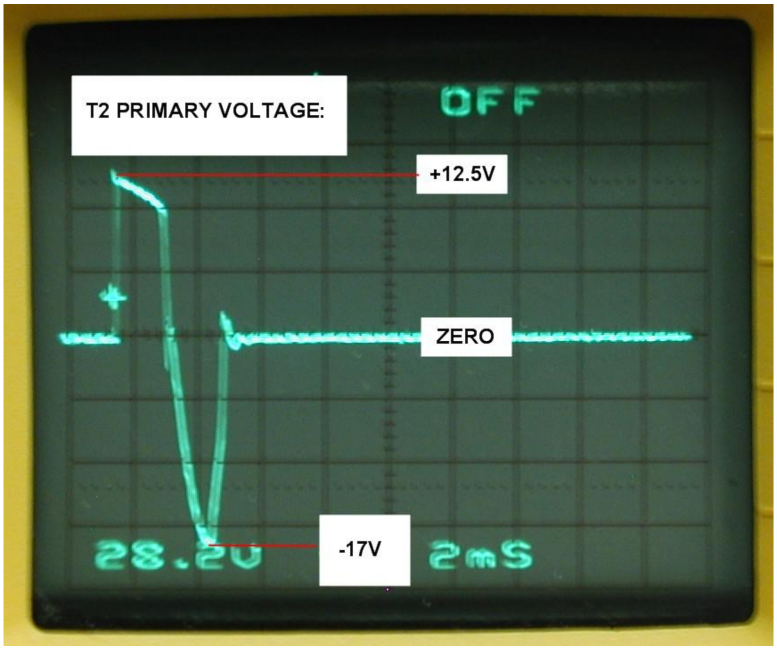
After a time, approximately of 1.6mS, the magnetic energy in T1 is dissipated and the rate of change of current in T2's primary is falling and the transistor turns off. This produces a sudden drop in current in the primary circuit of T2 and the collector emitter circuit of the transistor and in the short winding of T1 between the black & red wires. This assists rapid turn off of the transistor and the transistor's collector emitter circuit effectively becomes suddenly open circuit. The purpose of the short winding on T1(between the black and red wires) is to assist in the rapid turn on or turn off of the transistor. Once the transistor turns off, this lets the magnetic field of T2 to collapse, only limited by the loads on T2's other windings, because the primary winding is completely unloaded. This produces a +2100 to +2200V peak voltage to appear on the secondary (orange wire) of T2. This peak voltage causes the gas discharge rectifier V1 (which acts exactly as a diode) to conduct, and the capacitor fully charges to 2000V *with just one peak.* It does not require a series of pulses to fully charge the storage capacitor like a conventional CDI design with the HAM radio style DC:DC converter (Royer Oscillator) which followed the EI-4 a few years later.

These processes are shown below for the negative ground unit, initially looking at T2's secondary voltage on the orange wire with respect to ground:



The transistor is held on by T1 for about 1.6mS generating about 12V across the primary winding, this is transformed up to -1600V on the transformer secondary due to the 23:3082 turns ratio. After the 1.6mS has elapsed the transistor turns off, and the voltage generated by the collapsing field of T2 peaks to a stable 2100V to 2200V, due to the fact that the diode D2 across the 2 turn secondary limits the peak voltage to 1V on that winding. Because the coupling between the windings is not 100%, the voltage, rather than being limited to 1541V as predicted by the 3082/2 turns ratio, in practice limits to about 2150V.

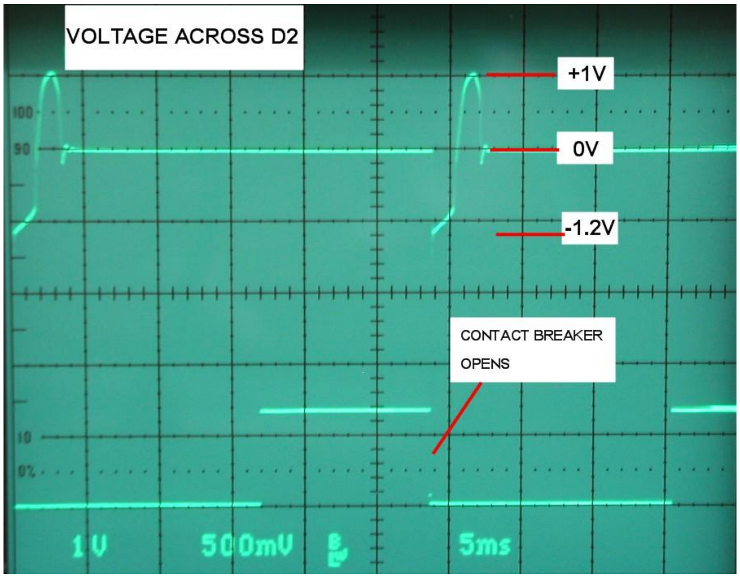
T2's primary voltage recording was taken with a different method. A fully isolated oscilloscope (Tek 222PS) was connected across the primary winding with negative of the scope input connected to T2's black wire and positive to T2's red wire. This avoids any confusion about the recorded voltage applied to the transformer as it eliminates the average power supply voltage from the recording:



As can be seen the transistor switches +12V for about 1.6mS across the primary just after the contact breaker opens. When the transistor switches off (coordinated by the energy stored in T1's field) the field in T2 suddenly collapses inducing a reverse polarity across T2's primary. This would be a very high voltage negative pulse if it were not for the damping effect of D2 limiting the voltage across the 2 turn winding of T2 to 1 volt. This limits the primary voltage to a theoretical value of 23/2 x1v or -11.5V. However again due to the imperfect coupling of the 2 turn winding providing this damping the peak primary voltage is higher than calculated. In effect diode D2 acts as a voltage stabilizer to make sure that as the power supply (battery voltage increases) the peak output voltage from T2 becomes stable because it effectively clamps the primary voltage and secondary high voltage to a fixed value after T2 switches off. This prevents the voltage being applied to the 0.03uF storage capacitor and the thyratron being exceeded, and the voltage levels off over a large range of battery voltages to around 2150V.

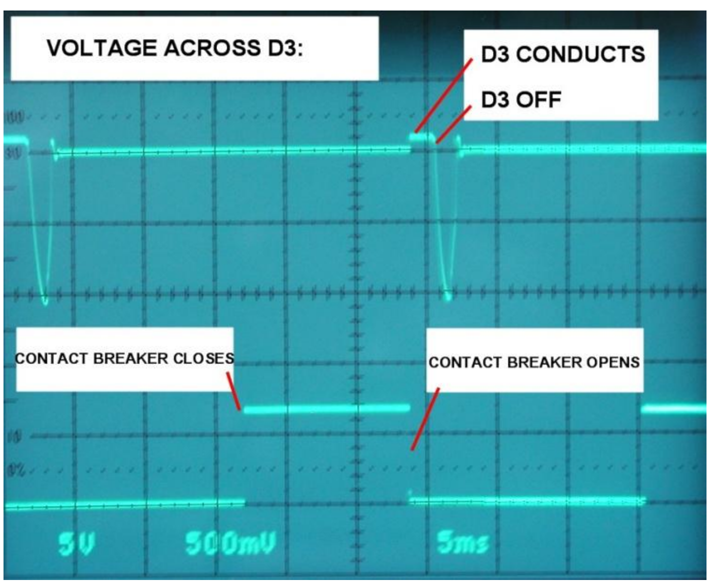
During the time that T2 is switched on, the transistor's collector current is increasing and it Collector-emitter voltage drop increases a little accounting tor the downward tilt on the waveform from about + 12.5V to about +10V just before the transistor turns off.

The recording below shows the voltage across D2:



During the time the transistor is turned on D2 is reverse biased by about -1.2V then when T2's field collapses the voltage is limited to about 1V peak by D2's current and the peak current would be fairly high at this time. Therefore D2 is certain to be a silicon power rectifier.

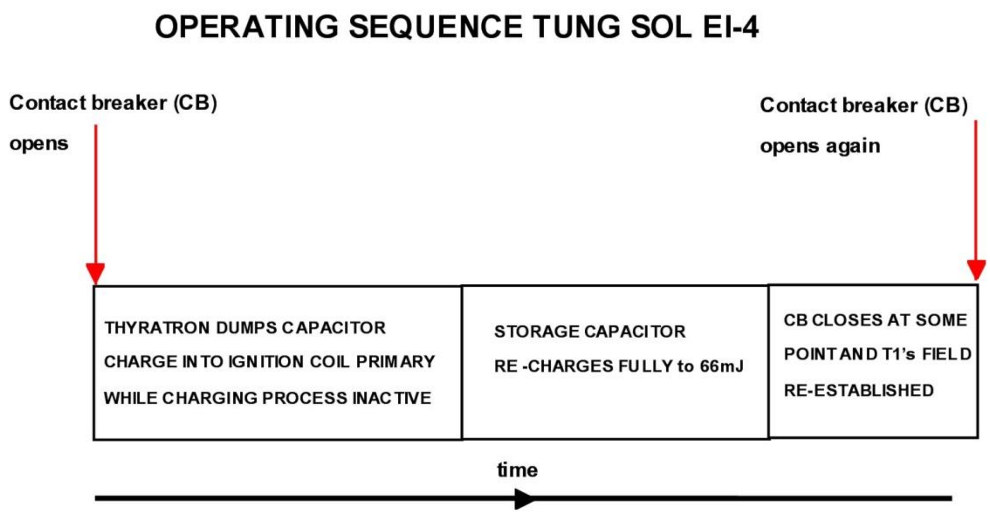
Due to D3, current only flows into the thyratron trigger transformer T3 at the moment (actually just a little after) the contact breaker opens. A recording of the voltage across D3 is shown below. The scale is 5V/large division (cm):



D3's forward voltage drop again is about 1V similar to D2 suggesting it is also a silicon rectifier. As noted in the diagram above, the timing of the closure of the contact breaker is an irrelevant feature of the operation of this CDI uni t (except perhaps at high RPM's when time for opening & closing is limited)

Another interesting and clever feature is that the trigger transformer T3, and the Thyratron, are only driven into conduction during the time in which the voltage output from T2's high voltage winding is negative and the gas rectifier not conducting and the storage capacitor not charging. This is completely unlike the situation in many CDI units where the discharge of the storage capacitor loads the DC:DC converter at that time.

The basic operating sequence is shown below:



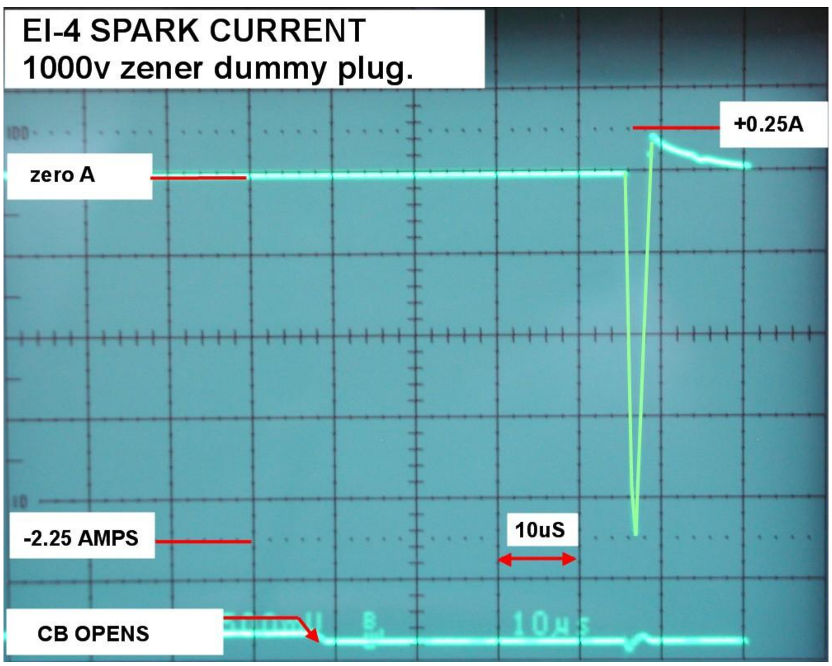
Therefore, before the unit starts working, the first contact breaker opening during engine starting is ignored because it has to pass through the cycle once to charge the storage capacitor. In practice this is not a problem. The dwell time, or period which the contact breaker needs to be closed is only enough to re-establish the small transformer's (T1's) field before the contact breaker opens again and the cycle repeats.

EI-4 SPARK VOLTAGE, SPARK CURRENT, SPARK ENERGY AND SPARK PULSE POWER (SPP) & DISCUSSION OF THE EI-4 VS OTHER CDI SYSTEMS AND INTRODUCING THE CONCEPT OF *SPARK PULSE POWER* or SPP:

The following measurements were performed on the EI-4 with the aid of the SPARK ENERGY TEST MACHINE and a FREQUENCY COMPENSATED HIGH VOLTAGE PROBE and a Tek 2465b oscilloscope and its delay time-base functions. (see www.worldphaco.net for the details of this apparatus)

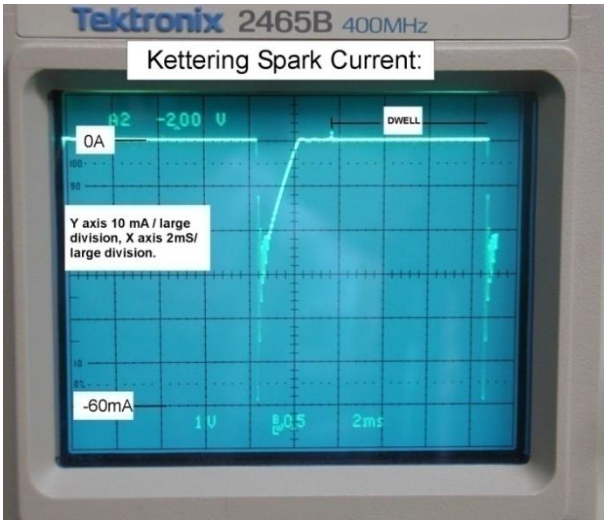
SPARK BURN TIME (PHASE 2) SPARK CURRENT:

The recording below shows the phase 2 (burn time) spark current profile produced by the EI-4 loaded into a 1000V dummy spark plug. It is completely unlike the spark current profile of CDI ignitions systems which followed it and completely different to a Kettering system spark current. It has more in common with the spark current profile produced by Exciters used in the Aviation industry. The recording was drawn over (touched up) to help see the waveform which was very low brightness on the scope face and photograph:



The step in the lower trace corresponds to the time that the mechanical contact breaker opens (Though this is a signal from the synthetic distributor in the spark energy test machine).The rise time of the spark current is in the order of 1uS or less. There is about a 40uS delay between the contact breaker opening and the EI-4 producing the spark. The current peaks to an astonishing -2.25 Amps for a brief period, the base of this wave as seen on the recording is only 3uS wide.

Then there is a positive spark current of triangular shape peaking at about +0.2A and decaying away over about 12uS. So this is a very brief spark compared to standard CDI's which came later, such as the Delta 10 unit, and very brief compared to Kettering spark currents which often have a maximum peaks of only 60mA and decay away over 1 to 2 mS. Typical spark burn time currents for Kettering & CDI (Delta 10 example) are shown below for comparison, taken from my CDI vs MDI article:



As can be seen from the recordings of the phase 2 (spark burn time currents), the Kettering spark in this case is nearly 2ms long and has a peak current of -60mA. The burn time spark energy, per spark, here is approximately 30mJ.

The Delta 10 CDI which conforms to a fairly standard transistorised DC:DC converter & SCR based unit of the mid 1960's produces a bipolarity spark of shorter duration than Kettering but higher peak currents of -140mA and + 80 mA and each spark current is about 100uS wide at its base and the spark burn time energy total is 9mJ in the first negative peak and 6mJ in the positive peak = 15mJ total spark energy.

In the case of the EI-4, the spark current as noted above is only about 3uS wide at the base of the first negative going peak, but a very high current at -2500mA (or 2.5A). The positive peaks to +250mA and is about 11uS wide. The spark burn time energy here is about 3.5mJ in the negative peak and about 1mJ in the positive peak.

It was widely known that the EI-4 was a good performer in racing Corvettes. How could this be when the *spark energy* is only 13% of Kettering and about 30% of the Delta 10 CDI?

The answer is that sparks cannot be compared on the basis of their energy alone, or the spark current alone or the spark duration alone for effectiveness in igniting fuel. The key feature in igniting fuel is the spark temperature. The spark temperature relates to peak spark power.

How to calculate peak spark power for a better comparison of three completely different spark profiles:

Peak power is a measurement which is the product of peak voltage and peak current at some instant when one or both values peak. Peak power therefore has units of V.A or Joules per second. Peak spark power is proportional to the spark's temperature or ionised gas temperature and the higher the ionised gas temperature the better the surrounding gas ignition.

"Peak Powers" for the three types of sparks described above would be:

Kettering: 60mA x 1000V = 6 watts

Delta 10: 140mA x 1000 = 140 watts

EI-4 : 2500mA x 1000V = 2500 watts

Yet in the concept of "peak power" there is no actual time interval involved in an instantaneous value. Any Physicist would agree that no physical process can take place in zero time (except perhaps in a singularity where there is no time but a process, the Big Bang, did begin), or less than one Planck interval if you like. Peak power numbers are in fact a "nonsense concept" because units of power are Joules/second but the "instantaneous power" concept actually has no time domain parameter.

Peak power numbers have been used in many industries for marketing purposes mainly, involving audio and RF work to make the values seem large and impressive. For example consider a 5 Volt rms sine wave applied to a 1 ohm resistor. The rms current is 5 Amps and there is 25 Watts rms (heating) power. The peak current is 7.071 Amps and the peak voltage 7.071 Volts and the peak power value (number) is 50 watts to impress the reader with a bigger number and make an amplifier for example seem more powerful than it really is.

However for any physical process to take place, including igniting gas, there must be a time over which the process occurs. To solve this dilemma and apply it to the spark testing problem, then the concept, perhaps for the first time is introduced here, is that of SPARK PULSE POWER or **SPP**. Spark pulse power is the spark's burn time energy divided by the time over which this energy was delivered, or the spark burn time itself. This value has units of Joules/second or power (Watts) and it accounts for both the spark's energy (which is the sparks voltage x current and time integral) and the spark's duration. This statement is expressed mathematically below:

SPARK PULSE POWER - SPP

$$SPP = \frac{\int_{0}^{tspk} V.I.dt}{tspk}$$

So using **SPP** to compare the three sparks:

Kettering: 30mJ/2mS = 15 watts (only a negative peak)

Delta 10: 9mJ/100us = 90 watts (first negative peak)

EI-4: 3.5mJ/3uS = 1166 watts (first negative peak).

So it is likely the reason why the EI-4 was such a good performer in that it has a very high SPP, which is much higher than Kettering or the Delta 10 CDI unit.

Apart form the fact that a gas thyratron has a limited life compared to a semiconductor, and might have to be changed every 30,000 miles, this analysis suggests that the supposed design improvements of the traditional CDI which followed the EI-4 in history were in some respects a step backwards.

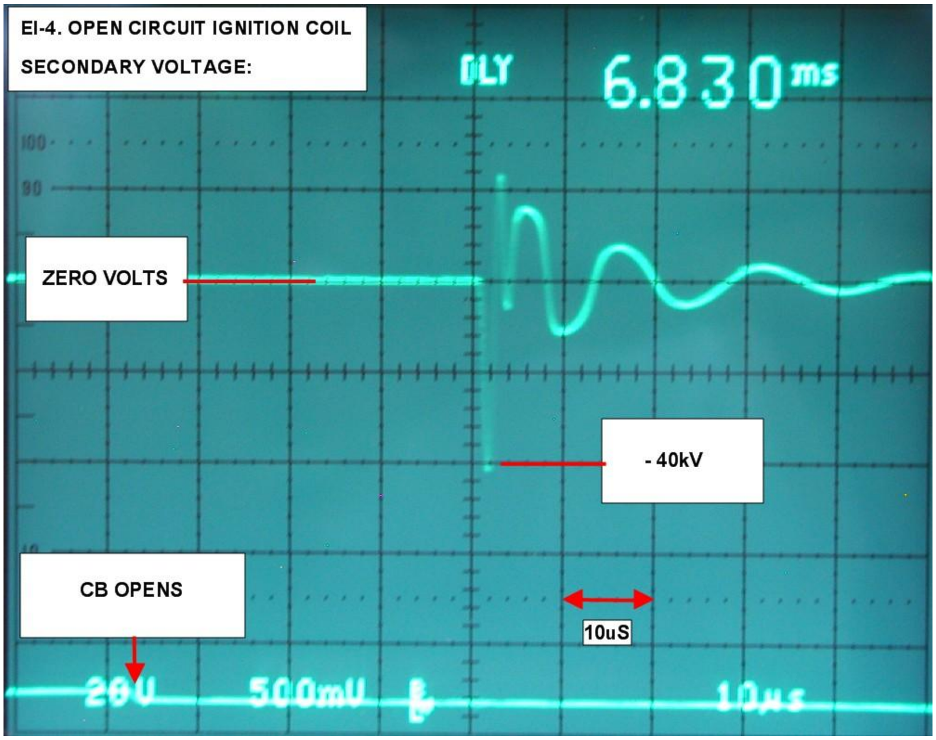
Another way to think about SPP is to imagine what happens to an object when a bolus of energy is delivered to it. The spark itself is a physical object of sorts with the physical properties of a gas and the electrical properties of a conductor like a metal. It can receive energy and heat up or cool down by losing heat & other frequency spectrum electromagnetic radiation & light to its surroundings. The easiest conceptual example to explain SPP is to think of another object like an aluminium heat sink in equilibrium with the environment with a resistor thermally connected to it and delivering heat to it. The heat sink properties are expressed by its thermal resistance or degrees C temperature elevation above ambient temperature per Watt of applied power. The spark too, as an object, will also have a thermal resistance. Therefore the temperature that the heat sink rises to above ambient temperature depends on the applied power, or heat, in units of Joules per second or watts. If the energy delivery is higher, eg a greater numbers of Joules per second, the heat-sink (or spark plasma) will get hotter. Therefore, considering a single isolated spark alone, with some number of Joules of energy, if it is delivered in a shorter time frame, this will create a hotter spark, than the same amount of energy delivered over a longer time frame. This is why SPP is an appropriate measure to compare spark temperature (and gas ignition ability) than any other single parameter such as voltage, current or spark energy alone. SPP in fact contains all this data plus the spark duration, so all the parameters are accounted for in one measure.

Of course if a sequence of sparks is delivered, this also influences gas ignition ability because the probability of ignition extends beyond that of a single spark.

The peak spark current is very high in the EI-4 and one might wonder if this could cause erosion of the spark plug's electrodes. It was stated in the manual above however that there is less spark plug electrode wear with the EI-4 than the standard system, because the sparks are shorter (pg17 handbook).

OPEN CIRCUIT OUTPUT VOLTAGE EI-4

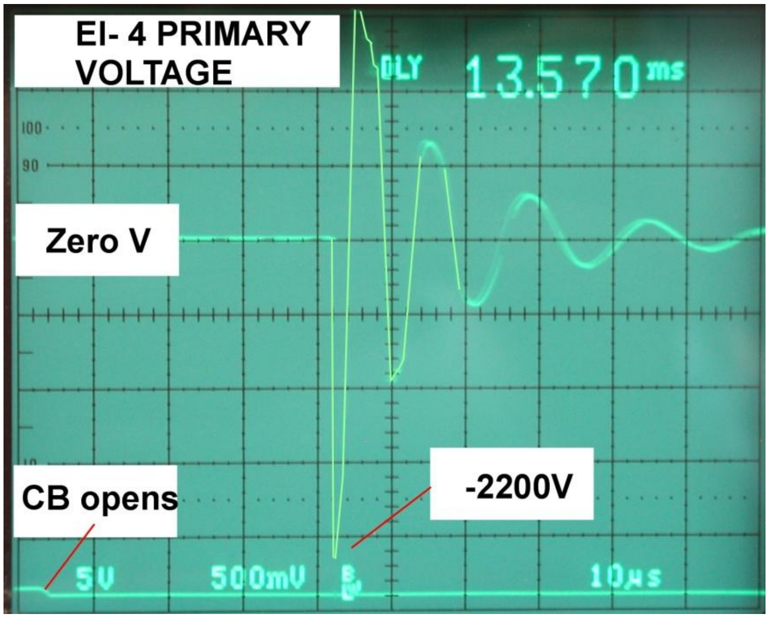
The recording below shows the output voltage of the ignition coil feeding the x 1000 high voltage probe. No sparks or corona discharges are occurring:



The recording is quite remarkable and shows a number of interesting features. Firstly the extremely high peak voltage of -40kV. With 2100 to 2200V applied by the storage capacitor to the primary, and a 1:17 turns ratio coil (measured from the coil) one would expect an initial negative peak of peak of 37.4kV + 2.2kV because the transformer is acting as an autotransformer and the voltage supplied to the primary is added to the secondary with respect to ground, so a peak of 39.6kV is expected. The actual recording with a calibrated probe shows it to be just over 40kV. After the initial discharge the residual coil magnetic field energy, and energy stored in the coil's distributed capacity decays away in an oscillatory manner due to the self resonance of the ignition coil.

(NOTE – the above finding indicates that with CDI systems such as this, which are very similar to many Aviation CDI's, it is a perfectly reasonable proposition, if one is not able to measure the open circuit output voltage on its first peak, to assume that the ignition coil's open circuit output voltage is the storage capacitor's charging voltage multiplied by the turns ratio of the ignition coil)

The recording below shows the voltage recorded with a x100 probe on the primary in the open circuit condition. The trace was faint on the photo so it was traced over in places for clarity:

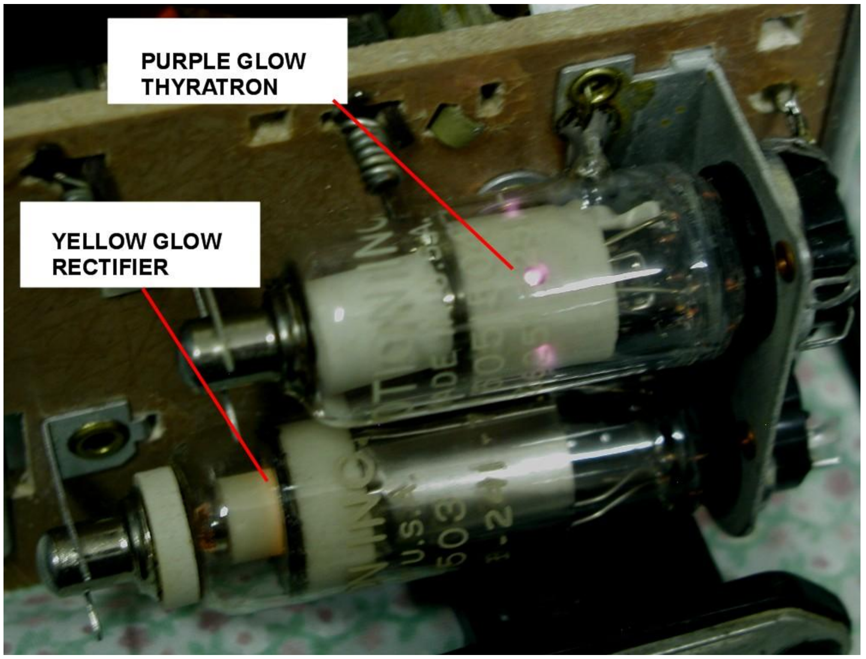


PHASE 1 SPARK CURRENTS:

The brief phase 1 or spark ionisation current (not measured by the spark energy test machine) results from the discharge of the system capacitance which has been charged to a high voltage for a brief time immediately prior to spark ionisation. The capacitance of the ignition coil secondary is about 68pF in this case and the wiring and spark plug body add another 20pF.When spark ionisation begins this capacitance rapidly discharges via the spark plasma formation. Assuming for example this occurs at a voltage of 10kV then energy of this discharge is around 4mJ (due to the capacitance stored energy) and the brief initial current can be as high as 60A.This current “transient” is significantly reduced if resistor HT cable or 5k ohm resistor spark plugs are used as this isolates most of the system capacitance (coil + wiring) from the spark plug’s electrodes. The spark plug itself has a capacitance of about 10pF. The discharge peak ionisation current is limited to a few amps only with a resistor and most of the 4mJ is dissipated in the resistance.

It is possible that initial or phase 1 spark ionisation currents could ignite fuel on their own with no actual significant spark burn time being needed, however it is an unreliable proposition. In many systems with resistor spark plugs and resistor HT wiring the brief initial ionisation currents are much lower and it is always the spark burn time responsible for igniting the fuel-air mix. One idea from the past was to increase the spark plug’s capacitance to increase the ionisation or phase 1 current but this idea did not prove to be too successful and was not widely adopted. Generally it is best to think of the phase 1 current as initiating the spark, while the burn time or phase 2 current creates the actual spark duration and is responsible for air-fuel ignition.

Finally, the photo below shows the Thyratron and gas rectifier in operation at 2000rpm. At low rpm they flash on and off. They clearly contain two different gasses as they glow different colours:



These are the numbers printed on the tubes along with “MOTION INC USA” logos:

THYRATRON numbers 6051504 3226251-251-11

GAS RECTIFIER numbers 6051503 3226243-241-7

SUMMARY:

The Motion Inc. EI-4 was a futuristic & brilliantly conceived masterpiece of automotive electronics. Many of its features including is low power consumption and high spark pulse power remain unmatched by any other type of CDI which followed it. It also has a unique operating cycle where it is able to fully recharge a 0.03uF storage capacitor to 2200v during the ignition cycle and when the Thyratron & spark deploys the charging system is automatically inactive. This is unlike the CDIs which followed it some years later where the spark discharge shorts out their DC:DC converters causing energy loss & converter recovery delays. Due to its design, the EI-4's power consumption is simply proportional to the RPM at 1A/1000 RPM.

The EI-4 has more in common with Aviation ignition exciters than any other device. In these units the storage capacitors generally charge to around 2000V and are dumped into a ferrite cored ignition coil by a gas discharge tube, which is not dissimilar to a gas cold cathode thyratron except they do not have a trigger electrode.

The designers also had the wisdom to know that standard ignition coils used for Kettering systems are not suitable for CDI use, so they designed a ferrite cored transformer coil to go with the EI-4. They also had to go down that road anyway because their coil required a relatively low turns ratio compared to a standard ignition coil. When CDI's such as the Delta 10 were introduced in the following years, the manufacturers clamed they did not need special ignition coils and that Kettering coils were fine. This was for financial & marketing reasons, as a transformer coil gives a significant (nearly twice as good) improvement over a standard coil with CDI. Sales would have been lower if the buyer had to buy the CDI box plus a new ignition coil as well.

I suspect that the technology in the EI-4 was simply overlooked by the developers of CDI units which came in the years later. Or perhaps they kept away from it because of patents or unfounded worries about the reliability of the Thyratron. Also the SCR's of the time had more limited voltage ratings than the Thyratron and wouldn't lend themselves well to an EI-4 circuit. Like many brilliant and clever designs, I think it was ill understood and not studied or documented well enough by others. The basic schematic diagram in the handbook did not reveal many of its secrets at all.

As explained above, the purpose of this paper is to document this unique piece of equipment for future electronics historians and for those who like to design and build their own CDIs. It is possible for example to use this design concept with a group of high voltage SCR's to achieve a similar design in a solid state format and thereby improve on existing CDI systems. Another option is the newer range of trigger-able gas discharge tubes applied to this design and making use of more modern transformer cores and high voltage silicon rectifiers such as those used in aircraft exciters.

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