THE CHAMPION 305013 EXCITER MYSTERY AND RE-CREATING NASA’s MODIFIED 3050131 CHAMPION UNIT FOR ANALYSIS.

Dr. H. Holden. Updated-2025

I became interested in Aircraft & Rocket motor Exciters after being asked an opinion on how they worked and how to design one. It is an interesting area, of which there is very little good detail on the internet. In addition I came across a NASA paper that evaluated a range of Exciters for Spark Energy output. This was also an interest area of mine, because I had previously designed a Spark Energy Test Machine for Automotive applications to measure the Spark Energies of CDI and MDI (magnetic discharge ignition systems)

I didn’t know it initially, but ultimately I would figure out why NASA ran into a problem which prevented them from evaluating a Champion Exciter Unit for its Spark Energy and they had to abandon the analysis of the Champion unit.

The notion that there could be an issue with the Champion Exciter unit intrigued me too, because most Champion ignition products I have seen have been very good and usually excellent.

“Exciter” is a term from the Aviation and Rocketry industry for an electronic unit or Capacitive Discharge Ignition (CDI) unit which generates high voltage so as to create a spark or plasma to ignite gases in gas turbine engines or rocket motors.

Turbine engines typically run from kerosene based fuel and air, rocket motors from liquid oxygen and liquid methane. “Igniters” are merely the term for the specialised spark plugs.

One interesting thing is that the equipment to perform an analysis of Spark Energy has to be much more complex if the spark current contains high frequency oscillations (in the region of 100kHz to a few MHz) and is “bipolar”. Compared to the case where there is enough resistance in the load (Igniter circuit) to damp the oscillations out. In that case the spark current is a longer time frame event and a “uni-polar” exponential decay and very easy to integrate with time and in conjunction with the spark’s voltage drop, determine the spark’s energy.

A diagram below was taken from a Champion Aviation Catalog AV-14 below shows a typical Igniter. Note the series resistor it contains, more about this will be said later.

These resistors are critical to suppressing oscillations in the spark current during the spark time, ***if it is desired that they should be suppressed.***

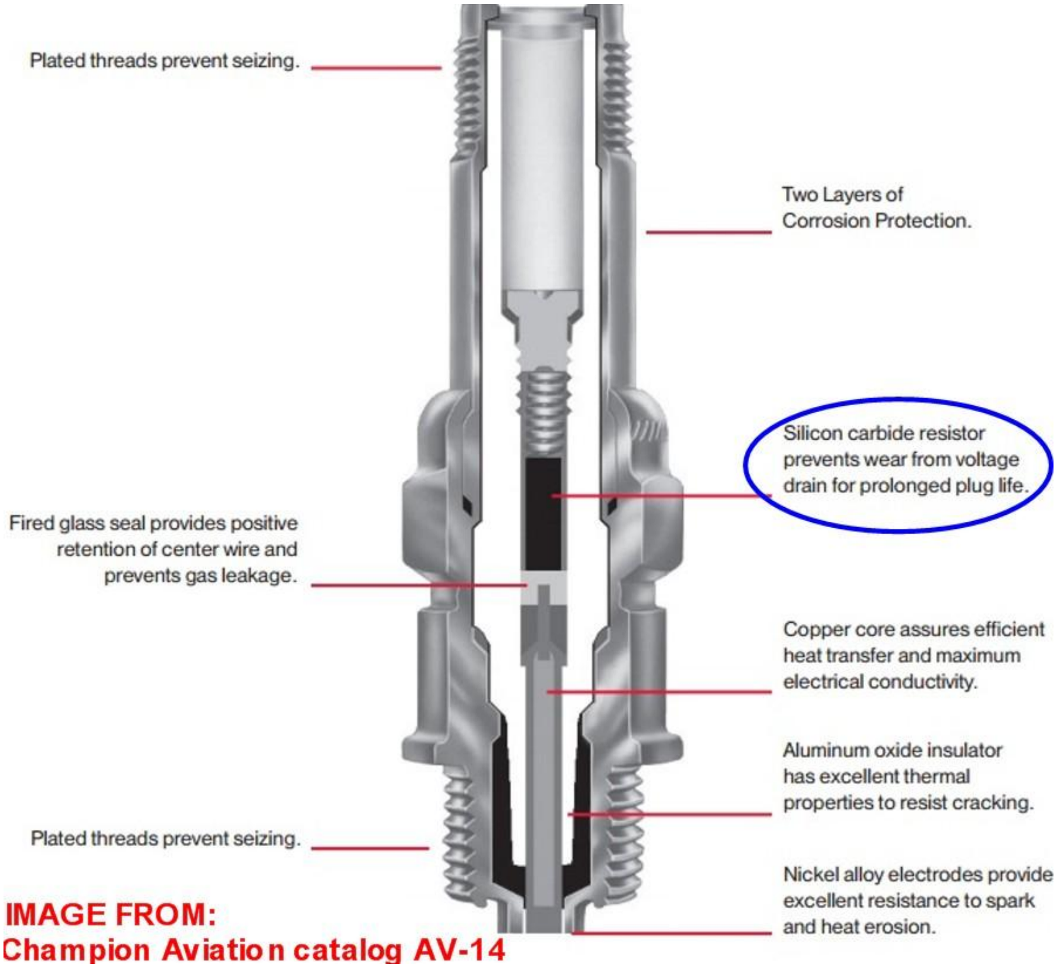


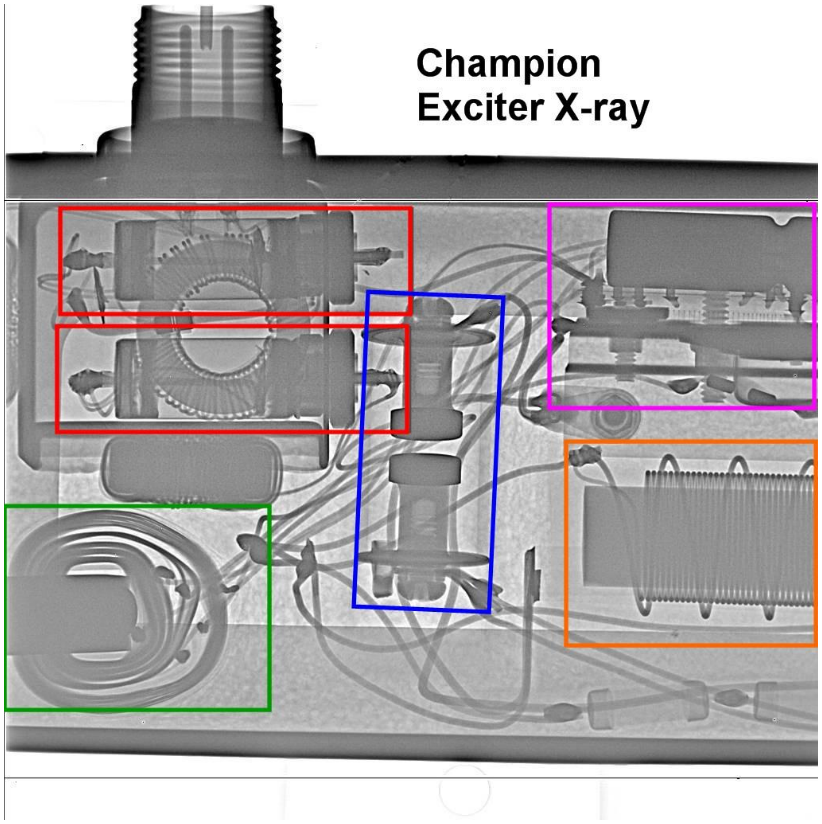
IMAGE FROM:
Champion Aviation catalog AV-14

Igniters project into a combustion chamber where the gases are spark ignited.

Igniters are connected to the Exciter unit typically by a shielded extra high tension (EHT) cable. Unlike automobiles, the extra high tension spark plug cables in Aeroplanes are shielded. This is to prevent external corona discharges and fires, but also to shield the rest of the craft's electronics from RFI (EMI). It is common for these cables to have a core made from spiral wound Nichrome resistance wire of about 10 Ohms per foot.

One might think that the Exciter units used in aviation applications would be similar to automotive CDI (Capacitive Discharge Ignition) units. In fact they are quite different for a number of reasons. Firstly there is generally gas only in the combustion chamber area of the gas turbine engine or ignition area of the rocket motor and no piston. Therefore the timing of the ignition does not have to be synchronised with the rotational angle of any moving shaft, as it is in the automobile. Secondly the characteristics of the Igniter and the spark itself need to be such that high gas flow velocity across the Igniter's electrodes will not extinguish the spark plasma.

Another thing that intrigued me was the notion of the flashing Gas Discharge tube used in the typical Exciter unit. Also, I saw some X-rays of an unknown model of Champion Exciter unit and attempted to work out what the internal parts were and even the reconstruct the schematic. Below is one of the X-rays:



I worked out that the items in the red rectangles were power supply feed through filter capacitors. Also in that area there was a toroidal common mode choke to help filter the DC power supply fed to the unit. And just below that was another toroidal core in the input filter area and another one just nearly out of the image on the left side. These input filters are as much about preventing these switch-mode devices putting radio frequency interference on the 28V DC supply as they are about keeping keeping interference out of the unit.

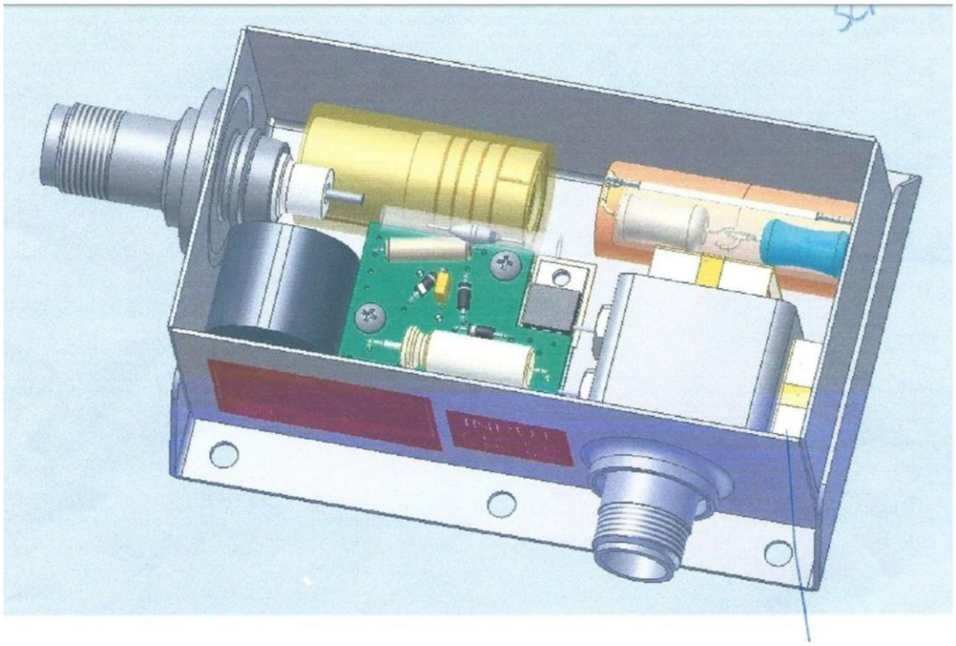
In the lower left corner, in the green rectangle, is a Flyback Transformer. The unusual object in the blue rectangle is the GDT (Gas Discharge Tube) and up in the right top corner is the control electronics with a 100uF Filter Capacitor.

In the orange rectangle the output coil (ignition coil) which appears to contain a Ferrite core and under that a couple of resistors can be seen. However, the X-ray did not readily show that there were two rectangular High Voltage rated Mica Capacitors in there too.

I also imagined what it might be like for an Astronaut pressing a button and hoping that an Exciter and Igniter of some sort would fire the craft's Engine. And if it did not, what the failure modes of that could be.

Hunting around on the internet I was able to find a sort of "pictorial diagram" of what was inside a typical Champion Exciter unit. Not in any detail though, but enough to indicate the basic parts assortment that they contain. Although it was a little odd in that the output coil was not in line with the output connector and that the transformer was not a realistic diagram of one, or the Gas Discharge Tube not present. I realized that it was a sort of "Artistic Impression" of what might be in there.

The thing is, very few people except for the manufacturer find out what is in these units, because the entire assembly is filled with a difficult to remove high density foam like potting compound.

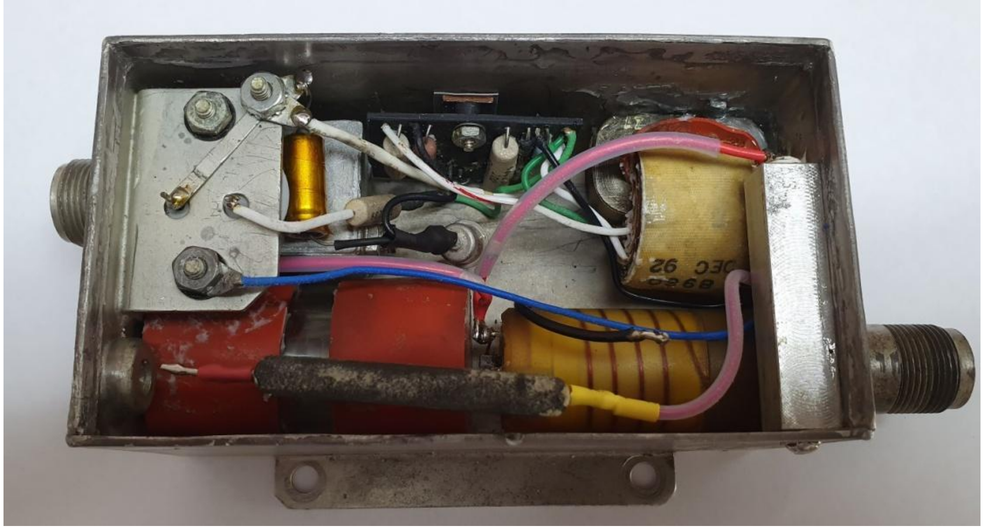


Given my curiosity level I bought a used defective Champion Exciter unit on eBay, Model Number 305013 and disassembled it.

It was a difficult job in that the top required unsoldering and the potting- filler material very slowly removed very small chips at a time. I could not find a suitable solvent that would have not have affected the components.

Also on searching I came across a Paper authored by NASA that included a modified version of this Exciter, a Model No. 3050131 and this increased my interest level mainly because of difficulties they had with it.

The photo below shows my unit after it was completely disassembled, the insulating high density foam removed from everything and the unit reassembled. Not shown (so as to give a better view) are the main Storage Capacitor and Ionisation Capacitor removed for the photo:



Generally, you won’t see a picture of a unit like this above where the major working parts are visible.

The glass body GDT is sitting between the two red rubber caps in the lower left corner.

The Flyback transformer is in the upper right corner. Its tape wound iron core was simply glued to the side of the housing as was the 3k power resistor which had been placed in a custom machined section of Aluminium bar that was 3/8” x 3/8” and 2” long.

Other parts such as the series reverse polarity protection input diode and the 100uF filter capacitor were floating free, but they were suspended in the foam filler of course and couldn’t actually move around.

The DC input connector is part of a box shaped assembly that contains the common mode DC power rail filter. I did not open that as I could see its essential style of construction from the X-ray of the other unit.

The circuit board and a TO-220 cased transistor on it, is held to the the side of the case with a screw and insulator for the tab. The EHT rectifier (High voltage rectifier) is seen as the long rectangular stick below sitting over the GDT and part of the output/ignition coil.

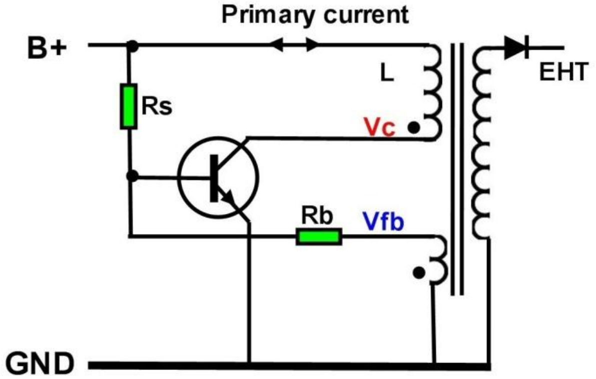
Once the components were removed, I was also able to document the schematic, work out its operating principles and repair it. The unit is a self oscillating flyback generator.

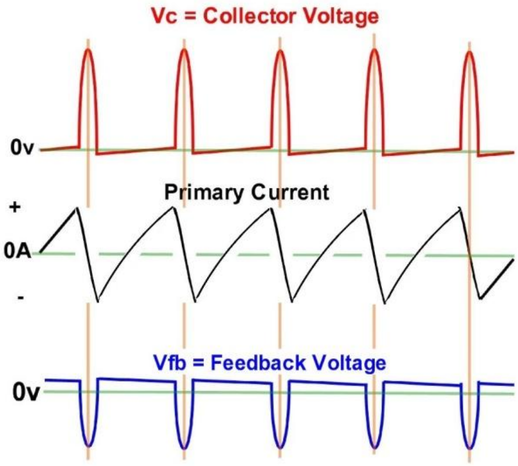
This circuit has near identical operating principles to the typical flyback supply in most TV’s and VDU’s, which is a sawtooth current generator and a high voltage pulse generator, except for the fact it is self oscillating and not oscillator driven. This confers some additional properties to it.

In the oscillator driven case, in typical CRT TV’s & CRT VDU’s, the Transistor is not turned on until after about 1/3 of the period after the flyback pulse, therefore a diode across the transistor’s collector to emitter is required to return the magnetic field energy to the power supply on the negative half of the current wave. However, in the self oscillating circuit’s case, with the BJT, the diode is not required and the BJT performs this task too as it can conduct current in both directions.

The diagram below and very simplified schematic shows the principle of operation of the self oscillating flyback supply:

BJT FLYBACK GENERATOR





Paying close attention to the sawtooth current: After flyback the rate of change of current with time, in the inductance of the primary L, is highest at the beginning of the sawtooth ramp and tapers off a little toward the next flyback pulse. As a consequence the voltage across the transformer’s primary and the feedback winding has a small tilt on it, because the induced voltage for an inductor is proportional to the rate of change of current with time.

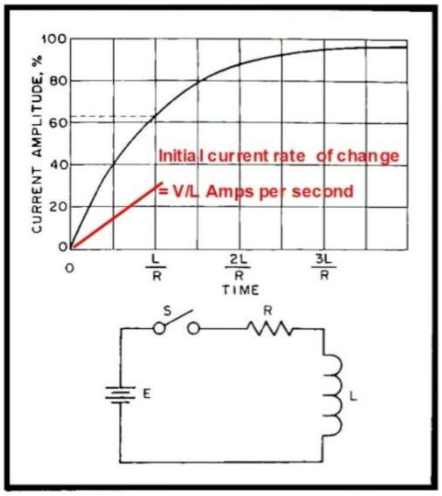
Generally there is a Start Resistor Rs, to get the circuit started. Once running though the base drive to the transistor, from the transformer’s feedback winding, takes over control of the transistor. The Base current is limited by Rb. Lower values of Rb affect the operating frequency because the transistor is held on longer per cycle before coming out of saturation.

Starting from the position that there is a low primary current and the transistor is switched on (saturated) the current in the transformer primary starts to rise. Due to the positive feedback via the transformer this also provides base current.

When an inductor L is switched across a DC power source V, the initial rate of rise of current is V/L Amps per second.

As time passes, the ***rate of change of current with time*** *(tangent to the ARRL graph below)* drops off and ultimately, if left alone with no other interventions, the current itself would settle on V/R where V is the power supply voltage and R is the resistance of the inductor and after that long time frame, ***the rate of change of current with time is zero***.

Most are familiar with the usual inverted exponential current profile of an inductor switched across a DC supply. From the ARRL Handbook: The diagram below shows the circuit, the graph and the relevant equation describing the inverted exponential current with time profile:



The current at any time after the switch in Fig. 41 has been closed can be found from

$$I_{(t)} = \frac{E}{R}\left(1 - e^{\frac{-tR}{L}}\right)$$

where

I_t = current in amperes at time t
E = power supply potential in volts
t = time in seconds after initiation of current
e = natural logarithmic base = 2.718
R = circuit resistance in ohms
L = inductance in henrys

However, the voltage induced in the feedback winding (or the primary winding) is proportional to the ***rate of change of current with time*** and on the primary it opposes the applied voltage. This is the relationship for the inductor:

$$V = -L\frac{dI}{dt}$$

This states that the voltage across the inductor's terminals is proportional to the inductor's rate of change of current with time dI/dt and that the proportionality constant is the Inductance L (in Henries). And the negative sign indicates that the induced voltage opposes the applied voltage.

A the moment the switch S is closed and the voltage is applied, the current is zero at t=0 (if you make t=0 in the ARRL equation above then I equals zero) because at that moment the induced voltage is exactly equal to the supply voltage and no current is flowing.

However the ***rate of change of change of current with time*** is not zero at t=0.

If the ARRL equation is differentiated and solved for the rate of change of current with time (the tangent to the graph) at t=0, the solution is V/L amps per second. The resistance does not feature in that solution. Obviously too, if the rate of change of current with time was not a value greater than zero at t=0, the current would never start to rise after t=0.

As time passes after t=0, the rate of change of current with time (or the tangent to the ARRL current graph) starts to taper off, the feedback voltage on the feedback winding terminals is reduced and this happens in conjunction with increasing collector current. Ultimately this pulls the transistor out of saturation.

As can be seen from the sawtooth current wave in the diagram of the simple flyback generator above, the rate of change of current with time after flyback is greatest initially and then is slowly tapering off (the sawtooth current is not a straight line it is an inverted exponential as the ARRL equation predicts) Though it may appear as a fairly linear sawtooth ramp in some circuits on oscilloscope examination, if only a small section of the initial inverted exponential is responsible for it, prior to the flyback.

Sooner or later the transistor is always dragged out of saturation. When that starts to happen, it is a positive feedback effect, as the induced voltage falls more rapidly and the transistor is quickly cut off. This is the start of Flyback. It is called “Flyback” because when this style of sawtooth current generator is used as the basis for a Horizontal scan circuit in a magnetically deflected CRT based TV or VDU, the quick reversal of the magnetic field takes the CRT’s beam from the right side of the screen to the left side of the screen. This obviously requires a reversal of the direction of the magnetic field and the direction of the deflection Yoke’s current.

Prior to the transistor switching off there was energy stored in the magnetic field of the transformer that is proportional to the square of the primary’s peak current value, just before flyback.

Once the transistor switches off, that magnetic field begins to collapse. The arrangement then is an un-damped tuned L-C circuit with the self capacitance of the transformer. Some flyback supplies have added lumped capacitance on the primary.

After 90 degrees of a sine wave cycle, the voltage on the transistor’s collector has peaked, and now the stored energy is in the form of the electric field of the self capacitance of the transformer (and any added lumped capacitance) and the inductor current is zero. This is halfway through flyback.

After another 90 degrees of oscillation the voltage across the capacitance is again zero and the current and the magnetic field direction has *reversed* in the inductance, but, aside from losses, the total energy is now back in the magnetic field of the transformer.

At that point the voltage on the collector of the transistor attempts to swing below ground or common. However, at that point the transistor has been driven on again with a high base current and because a BJT can conduct in both directions, it clamps the primary voltage to the power supply again acting as a switch, but conveniently carrying current now in the opposite direction from the transformer primary back to the power supply.

Hence the other name for these supplies known as “Efficiency Supplies” because of the returned current to the power supply and the low average current consumption.

The inductor energy, then in a near linear fashion (but actually inverted exponential form) is returned to the power supply. Due to the fact the self capacitance of the transformer can be quite low, the voltage peak on the collector without additional capacitance added, can be very high, easily in the order of 10 to 30 times the power supply voltage. Adding parallel capacitance lowers the voltage peak and widens its base because the resonant frequency of the half cycle of oscillation drops to a lower frequency. And for any fixed or constant amount of energy stored in a capacitor’s electric field, a larger value of capacitance will have a lower terminal voltage, the terminal voltage being inversely proportional to the square root of the capacitance for some fixed stored energy value.

In many flyback circuits, but not all, there there is a Diode, often called a Damper diode, though a better name is an Energy Recovery Diode, connected across the transistor’s collector to emitter to carry the damped current for the negative part of the sawtooth current returned to the power supply. The diode is essential in Tube versions of the circuit because the Tube, unlike a BJT, cannot conduct in both directions. And in most TV Horizontal scan stages where the output transistor is driven by a separate oscillator, the transistor is not switched on immediately after flyback, there is a delay, so the diode must also be there to return the damped current to the power supply after flyback.

Also, due to the fact that the collector voltage pulse (or emitter pulse if the load was placed on the emitter side) is often very high in the Flyback supply, when set to see the flyback pulse on a scope’s screen, the baseline voltage between the pulse looks almost flat and close to zero volts, but there is a small tilt there as shown in the diagram which can be seen when the scope’s vertical amplifier gain is increased.

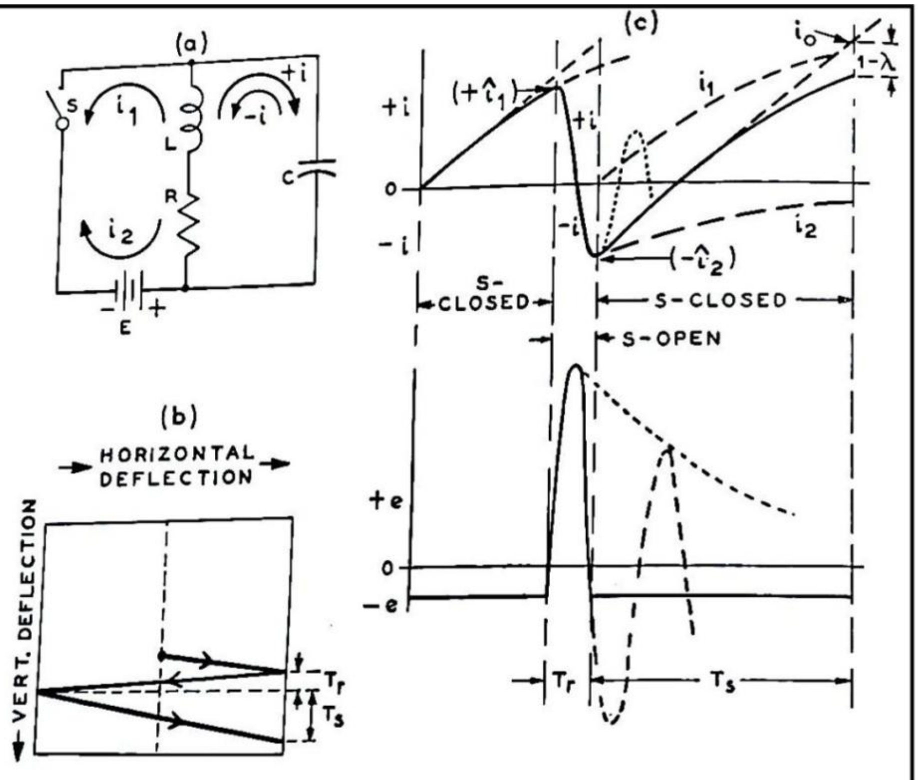
With flyback there is a rapid rate of current reversal with time, being most rapid when the current wave crosses zero. Since the induced voltage on an inductor’s terminals is proportional to the rate of change of current with time, it becomes obvious that this is why the voltage peaks at that time. The voltage waveform in the Flyback Supply is the inevitable result of switching the inductor on and off the DC power supply with the correct timing provided by the feedback winding and transistor in the self oscillating supply.

The Flyback design was recognised very early as the basic method to generate a sawtooth current scan to suit magnetically deflected CRT's in TV sets.

The diagram below, from RCA's research papers published in 1947 shows the method was well understood then.

Otto Schade at RCA had figured out that if you had an ideal switch, which operated at the correct time (closed for the production of the sawtooth ramp and open for flyback) you could generate a sawtooth current wave and also obtain a high voltage pulse as well.

Little did he know at the time that transistors which could very easily do this were just around the corner. Still, he managed to do it with Tubes.



Otto Schade: MAGNETIC DEFLECTION CIRCUITS FOR CATHODE RAY TUBES; RCA VICTOR TUBE DEPARTMENT. Volume V, 1947-1948

One of the first Commercial TV sets to employ a Flyback Sawtooth Generator & combined High Voltage Pulse Generator was the RCA model 621TS in 1946. The design of the horizontal scan output stage was due to Otto Schade.

Generally, due to the fact that in the Flyback condition, the high voltage pulse is the result of undamped resonance, it makes it useful for a very low current high voltage supply, to power a CRT's electrodes and the CRT's final Anode in a TV.

You cannot draw too much current and power during flyback time or the amplitude of the voltage pulse drops sharply because the resonant circuit gets damped.

However, during conduction time of the tube or transistor (+/-Damper diode if present) the transformer is operating in a "transformer mode" and the voltage on any winding is basically rectangular in character between the flyback times and can be rectified and easily smoothed to make a high power capable supply. This is done in TV's and VDU's to power circuits such as the Video Amplifiers.

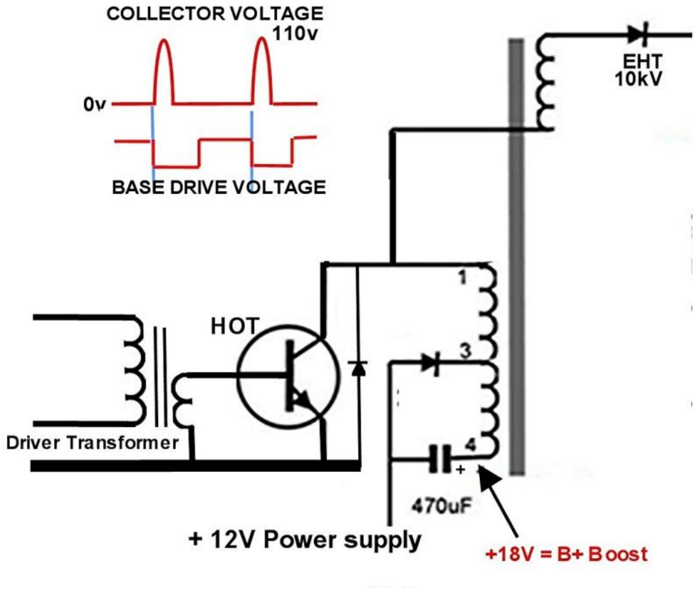
However there is another interesting use of the rectangular voltage pulses. It is like the notion of pulling yourself up by your boot laces. Some rectified power can be placed in series with the the DC power feed to the Flyback transformer's primary. In TV work this is known as the "B+ boost voltage" or just boost voltage. This enables the horizontal output stage's transformer primary to be powered by a voltage higher than the B+ supply already present in the set.

This boost idea was done in tube TV's and commonly done in transistor TV's and VDU's which ran from 12v supplies, in that latter case to gain a 6V additional boost so that the primary of the flyback transformer became powered by 18V.

Of course no extra energy is created it just results in some factors being improved. With a higher supply voltage the circuit resistances have less of a significant effect for the same amount of scan power transferred because the currents are lower. In magnetic Horizontal deflection systems, the circuit resistances always degrade the scan linearity which was another thing Otto Schade discovered. It is easier to obtain better scan linearity from sets with a higher B+ voltages than a lower ones.

A typical partial circuit below is an oscillator driven flyback supply from a TV or VDU shows this arrangement. It appears as though the rectified voltage on the primary goes nowhere, however it powers the transformer primary with an additional 6V giving an 18V supply on pin 4 of the transformer. During the flyback time, neither primary side diode is conducting.

Only the EHT diode conducts on flyback pulses, to power the CRT's final Anode.



There is another interesting thing about oscillator driven Flyback supplies aside from the fact they must always have the the energy recovery diode due to the switching timing of the HOT (Horizontal Output Transistor) It is that the drive to the HOT's base is normally via a small transformer driven by a single transistor driver stage and:

The polarity of the drive to the HOT's Base-Emitter junction is such that active conduction in the transistor driver stage switches the HOT OFF, not ON.

The HOT is only switched ON by the energy stored in the magnetic core of the driver transformer which was acquired when the driver transistor was conducting in the previous part of the operating cycle. When the driver transistor turns off, the collapsing magnetic field in the small driver transformer's core delivers the Base-Emitter current to the HOT. Also this limits the total amount of time that the HOT can be held on for in a fault condition, due to the limit of the magnetic field energy that can be stored in the small driver transformer's core.

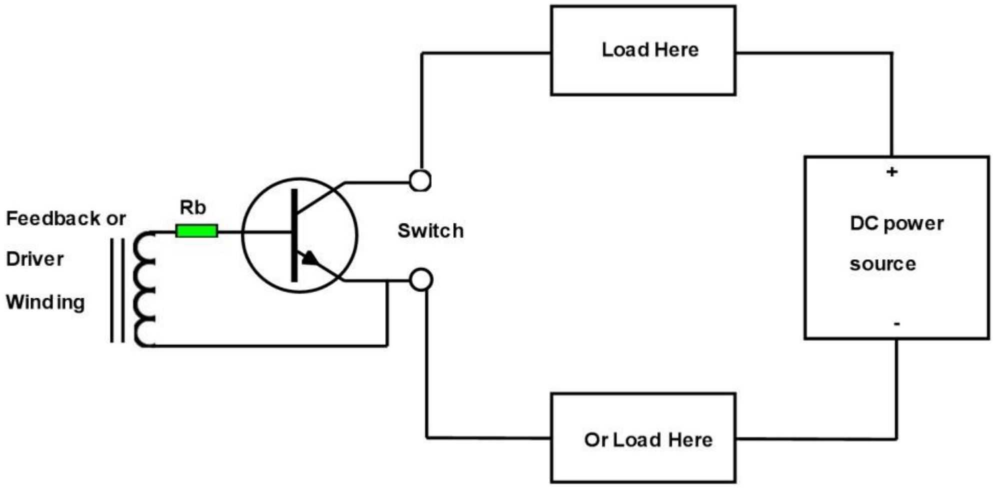
The above fact is only evident on some TV & VDU schematics where the polarity of the driver transformer's windings has been documented by the manufacturer. Often they don't bother to document it and this point is not often mentioned books on transistor horizontal scanning. It was done to actively deplete the transistor's base current and help it switch off rapidly for flyback. If one of the driver transformer's windings is accidentally reversed the circuit malfunctions. Also, Transistors, to play the role of the HOT generally have special properties such as high collector voltage ratings and very low storage times.

One other difference between self oscillating flyback supplies and oscillator driven supplies: In the case that their output is shorted out or overloaded; in the self oscillating case, the feedback is diminished and the oscillations stop, making these self overload protected. This is not the case for an oscillator driven supply.

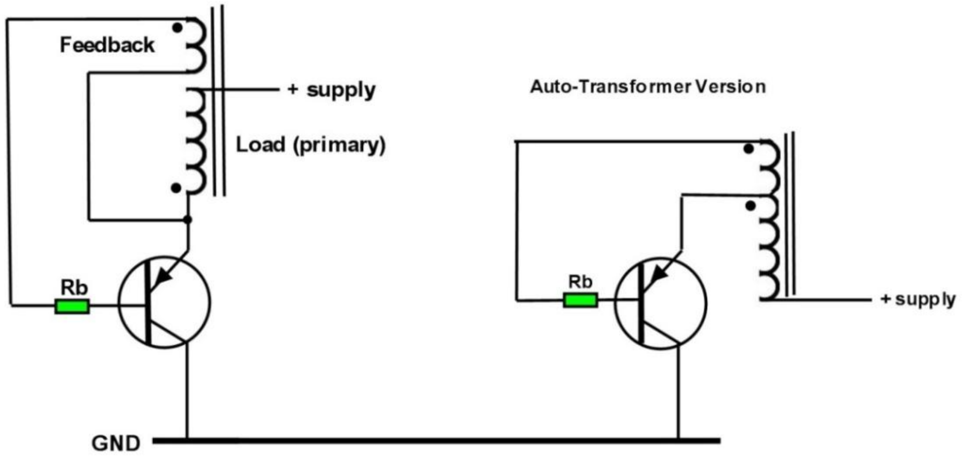
OTHER FLYBACK CIRCUIT VARIATIONS:

One issue is (ignoring the issue of injecting some base-emitter current to start the self oscillating circuit) is that when a transistor is driven from a transformer winding, to provide a source of base-emitter drive current, that this is a form of isolation which converts the transistor's collector and emitter connections into an isolated "Two Terminal Switch"

This means that the load, wherever it is placed in series with the power supply, can *appear* to be in the emitter or the collector circuit. Unfortunately this has led some to believe that in cases where the load is in the emitter circuit, that the transistor is acting in an Emitter Follower role, when it is not. It is still acting as a saturated switch. The diagram below explains this:



This can result in some advantages. For example, if a PNP transistor is used in a Negative Ground system and the load placed on the emitter side, it means that the transistor's collector (metal body) can be connected to ground with no insulators, just thermal paste, which not only saves money it gives a better thermal contact. Also in this configuration, the transformer can be made as an auto-transformer which is more efficient:



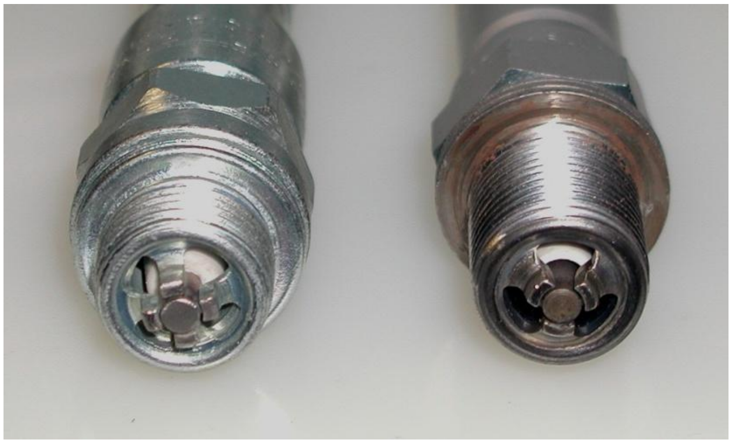
Yet still more refinements to a Flyback circuit can be made. One is in the area of better and more efficient methods than just a starting resistor Rs, to inject current into the base-emitter to get the self oscillating circuit started up, or re-started for that matter.

In Aircraft & Rocket exciters and their self oscillating Flyback supplies, when the output circuit fires, this transiently shorts out the output of the converter during the spark time and the Flyback supply can stop. Therefore, in these cases, it is very important that the Flyback supply is able to re-start quickly again automatically.

As will be seen, Champion did an interesting job arranging the start and re-start circuitry in their self oscillating Flyback converter in the Champion Exciter.

IGNITERS:

Some are shown below. These are very robust compared to automotive spark plugs and have a very narrow gap on the order of 0.6mm. One is a Champion RHM83N for use in a piston engine and the other an AC273. The end on photo shows the narrow gap and the configuration of the electrodes. Some types of Igniters simply have a narrow annular gap:



As previously noted, some Igniters contain internal series resistors. The one in the champion unit was an NTC (negative temperature coefficient resistor) while the other had a plain 160 Ohm resistor.

EXCITERS:

Once the typical Exciter is switched on it produces a fixed rate of sparks, this can be as low as 1 spark per second to 150 sparks per second depending on the design of the particular exciter unit.

The spark burn time currents are very high, often peaking briefly to over a few hundred Amps depending on the Igniter’s internal resistance and any resistance internal to the Igniter body in the cable leading to it.

The resistance, if present, in the Igniter body limits the peak current, but it also suppresses oscillations in the current and radio interference.

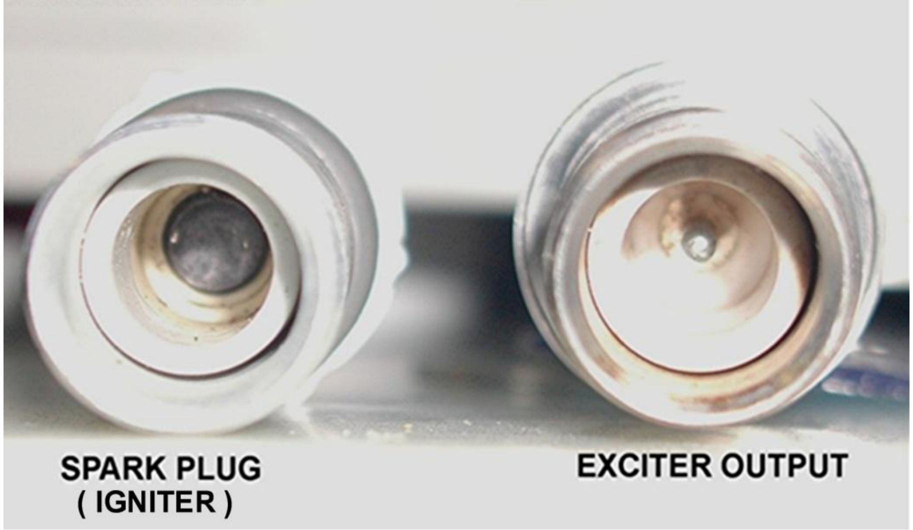
However the resistance, with respect to the storage capacitance in the Exciter and Output (ignition) coil's Inductance has to be high enough to create an over-damped situation, or the spark burn time current becomes oscillatory. This is not necessarily a disadvantage with spark ignition of gases, but, it creates a significant problem trying to measure the Spark's Energy.

As will be explained below, this is what happened when NASA attempted to assess the spark energy output from a modified Champion Exciter unit. The oscillating spark current, which had components both around 1.8MHz and 100kHz, could not be accurately assessed by their National Instruments test setup and it fouled up the calculations which attempted to integrate the Spark Current x Spark Voltage product.

Therefore attempts to calculate the spark energy value for the Champion unit were abandoned by NASA, which was a shame because there was an easy fix, as will be explained.

Generally many types of Exciters have a 24 to 28V DC input on a two pin input connector.

The EHT (extra high tension) output connector on an Exciter unit is very similar to the connector on a ¾ inch diameter aviation style Igniter except instead of being a blind ended hole where a spring from the spark plug cable connects it has a central 3/32" metal pin. This is shown in the photo below:

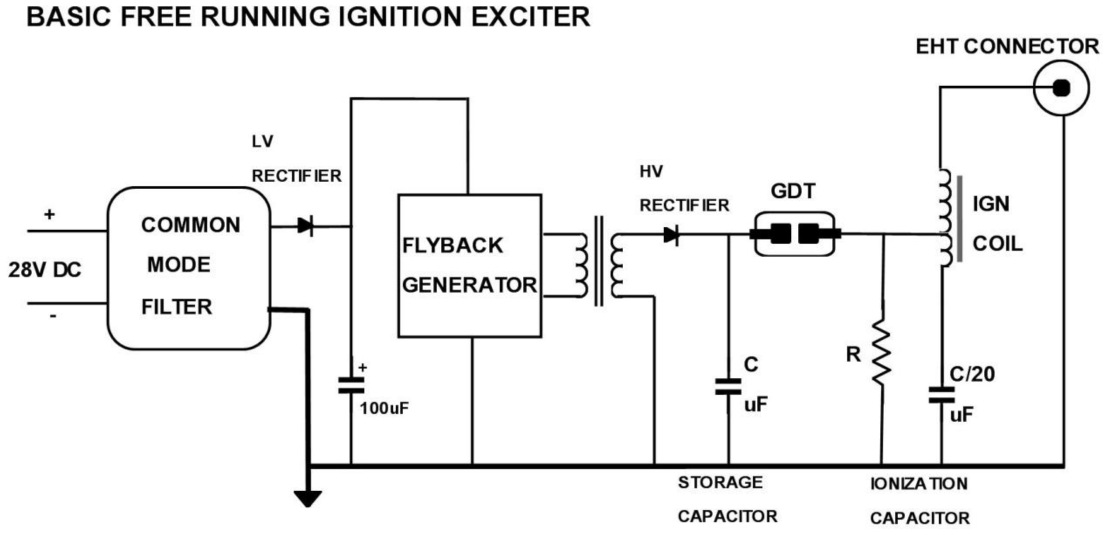


Exciter units are usually housed in metal cases which are soldered together. The connector shells are also soldered to the case. They are completely sealed units but can be opened for repairs. Due to the potting compounds, that is not easy at all. Some types used for very high altitude or Space applications are rated to withstand a continuous Vacuum and are hermetically sealed.

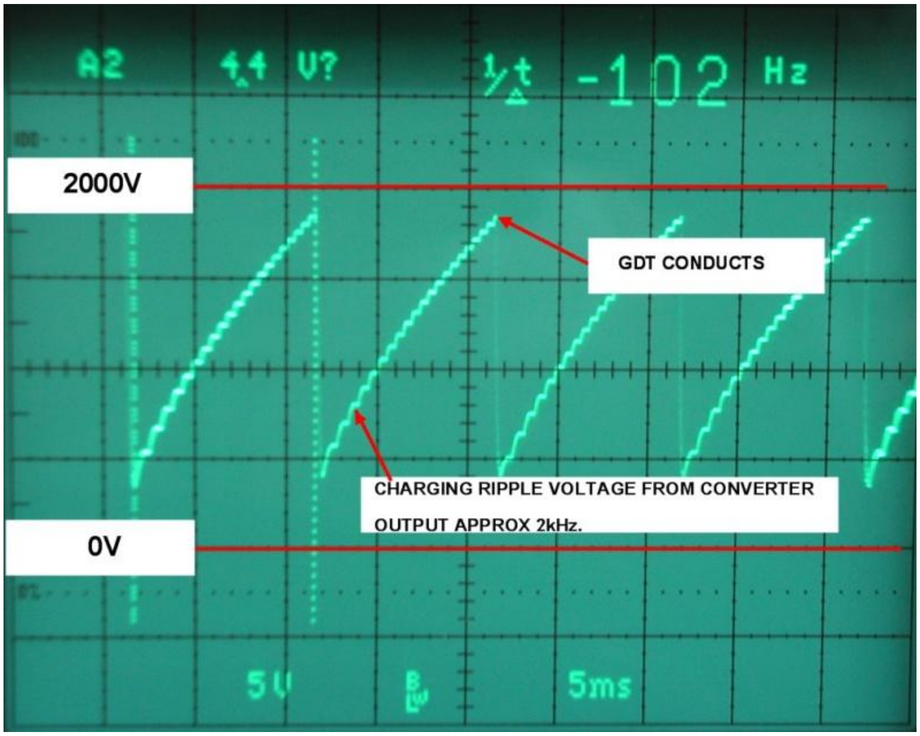
The common mode filter on the DC power input usually consists of the two pin DC input connector and a small enclosed metal housing which contains two windings on a powdered iron toroidal core and feed through capacitors to exit the metal housing. This keeps RFI out of the unit and prevents signals generated by the Exciter getting on to the aircraft's DC supply line.

Typically the running frequency of the Flyback supplyis around 1kHz to 2.5kHz. In some vintage pre-transistor era exciters the job of the transistor circuits is done by a mechanically vibrating reed running at a lower frequency, much the same as used in vibrator power supplies in vintage car radios.

The high voltage peaks on the secondary of the transformer charge the "storage" Capacitor Cs via the high voltage (HV) rectifier. The voltage value climbs with each positive peak of charging voltage until the breakdown voltage of the Gas Discharge Tube (GDT) is reached, which is typically in the range of 1800V to 3000V depending on the particular GDT.



An example oscilloscope recording of the storage capacitor's voltage below shows an **experimental exciter unit** with a storage capacitor of 0.05uF and an ionization capacitor of 0.0025uF and an 1850V GDT and the EHT output loaded into the AC273 Igniter:



The spark rate with this configuration is around 102Hz and the DC:DC converter is running around the 2kHz mark, though it speeds up a little as the loading drops as the storage capacitor charges. The small ripples from each charging peak are seen in the charging voltage waveform of the storage capacitor.

The GDT is called a ***spark gap switch*** (more about these below) which is a type of heavy duty switch. The GDT, when it fires, suddenly connects the storage capacitor onto the 3k load resistor and via the ignition coil primary to the ionization capacitor. The storage capacitor then starts to share charge with the ionization capacitor and that charging current passes via the output coil’s short primary winding and a stepped up voltage appears on the secondary winding and output connector.

The GDT also connects the storage capacitor via the ignition coil’s secondary winding directly to the Igniter too.

When the Igniter has fired, this essentially shorts the exciter output out, or to a low resistance if present in the igniter itself or EHT cable, because the spark voltage drop is relatively low and fairly constant at around 25 to 30V during the spark time. The spark itself behaves as a negative resistance. Then the 0.05uF storage capacitor discharges via the Igniter circuit.

In the example above the voltage on the storage capacitor's terminals falls to around 400V and at that point the current in the load and the applied voltage cannot maintain GDT conduction and the GDT extinguishes (drops out of conduction) and the storage capacitor re-charging process begins again.

Whether there are oscillations in the discharge current (spark current) during the spark time, depends on the proportions of L,C and R in the output circuit.

The Model 305013 Champion unit I bought, shown in the photos above was designed to have a low frequency spark rate at around a few Hz or less. To achieve this low spark rate, it has a very large storage capacitor of 0.53uF and an ionization capacitor of 0.026uF and a 3kV GDT. In this instance the initial charge in the storage capacitor prior to the GDT conducting is 0.53uF x 3000V = 1.59mQ (milli-Coulombs) and has a stored energy value of 2.385 Joules.

Most of this Charge is passed to the external load (Igniter circuit) with a small percentage passed via the internal 3K resistor during the spark burn time at the Igniter. The bulk of the charge passes the potential of the spark gap (25v to 30V) of the Igniter so the individual spark energy is very approximately 25V x 1.59mQ = 39mJ, ignoring (for now) the loss in the 3K resistor. Also in this instance, testing with a 0.5uF value indicated that with each deployment of the GDT the storage capacitor was discharged from 3kV to a voltage within 150 volts of zero.

The ratio of spark energy at the Igniter to energy in the storage capacitor prior to the spark is low at about 0.039/2.385 = about 1.6%.

Therefore, although some Exciter product might be marketed as say a "2 Joule" unit based on energy stored in the storage capacitor, the energy per spark for the actual individual spark burn time may only be around 2% to 20% of that value depending on design factors and the spark plug's voltage drop. The same is true of automotive CDI's where the energy in the storage capacitor was often quoted in marketing, but the energy per spark is always considerably less.

THE OUTPUT (IGNITION) COIL:

These usually have a turns ratio in the approximate range of 1:5. Also some are wound on a 1.5 to 2 inch long and ½ inch diameter ferrite rods (completely unlike an automotive ignition coil). They are typically two layer coils with the small primary on the outer surface. The primary winding can have very few turns in the range of 3 to 11. The secondary turns are usually in the order of 40 to 60 turns and they are connected as an autotransformer. Sometimes these coils have no core and are effectively “air cored” a photo below shows some examples of these ignition coils:

The yellow coil in the middle of the photo above is from the 305013 Champion unit and was found to be air cored. The other two types are from Simmonds Exciters and have round ferrite cores. The Champion coil appears to have a primary inductance of around 0.4uH to 0.6uH and a secondary inductance of roughly 7uH to 10uH range and a turns ratio of around 1:4.

On the other hand the other two coils with Ferrite cores have primary secondary inductances that are 7 to 10 times higher, but a similar turn’s ratio in the range of 1:4 to 1:6.

One interesting thing was the X-ray of the unknown model Champion unit, showed a high density object in the output coil that was probably a Ferrite core. No core existed in the Champion coil from my 305013 unit shown above. It looked like it may have been designed to receive one, but its central core was only a plastic material. I drilled into it to be 100% sure this was the case. So a core in this coil may have been optional. This will be discussed more in the case of the modified 3050131 unit that NASA tested.

Consider a 1:5 ratio coil for the discussion:

When the GDT conducts the terminal voltage of the storage capacitor is applied to the load resistor and the tap on the ignition coil. This transiently raises the voltage on the ignition coils tap to close to the storage capacitors voltage (which is close to the GDT’s breakdown voltage). This voltage is applied, transiently at least, to the small primary winding, because initially, the ionization capacitor has near zero charge and a near zero terminal voltage.

Charging current then flows via the ignition coil's primary, charging the ionization capacitor. Therefore, initially at least, the voltage applied across the transformer's primary is the storage capacitor voltage. This is transformed up by the ignition coil's turn's ratio.

If the voltage applied was 3000V and the ratio of the coil 1:5 the output voltage is transiently 3000 + (3000 x 5) = 18kV. This is because the voltage on the ignition coil tap adds to the induced voltage because the ignition coil is acting as a step up autotransformer during the spark ionisation process. In practice the induced value will be a little less due to leakage inductance between small and larger coils.

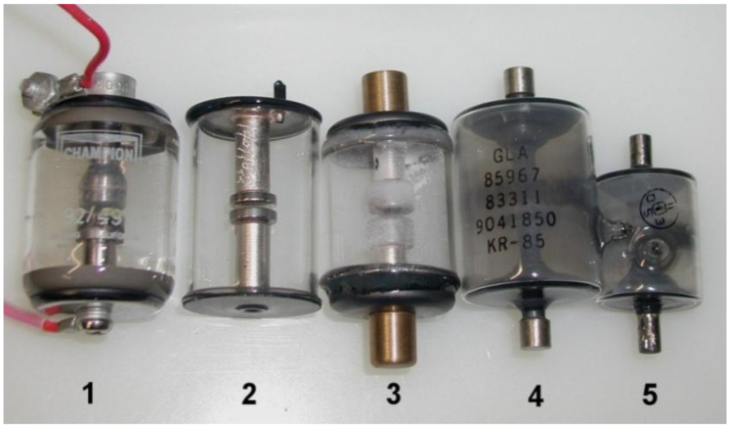
This high voltage peak initiates spark formation or *spark ionisation* known as Phase1 of the development of the spark in the Igniter. Once the spark is initiated at the Igniter and due to the fact the spark between the Igniter's electrodes has a very low resistance and low voltage drop, the output of the ignition coil is very heavily loaded. The spark thickens in its cross sectional area as the current increases and it acts as a negative resistance, or a very effective low voltage clamp, regardless of the increasing current. This allows the remaining charge and the bulk of the energy stored in the larger storage capacitor, and also any accumulated charge in the ionization capacitor, to discharge via the ignition coil secondary and continue the spark plasma for the *spark burn time* or Phase 2. In the end the applied voltage and current falls low enough that the spark cannot be maintained and it extinguishes.

The spark burn time therefore is dominated by direct discharge of the storage capacitor via the low resistance pathway of the single layer ignition coil secondary and any external series resistance. The secondary coil has a very low resistance typically less than 0.5 Ohms and a low inductance in the order of 6uH to 10uH in an air cored coil and 75uH to 100uH in a ferrite cored coil.

The high spark currents which result create a thick (broad cross sectional area) and robust plasma between the Igniter's narrow electrode gap (0.6mm). This plasma or arc is extremely resistant to being "blown out" by gases rushing past the narrow gap electrodes. The spark current flows and decays away in an exponential manner (or can be oscillatory see below) as the storage capacitor discharges.

(The actual Spark rate is determined by the value of the storage capacitor combined with the output voltage and the internal resistance of the flyback generator charging the storage capacitor. It is not significantly related to the properties of the output coil or load because the sparks relatively quickly discharge the storage capacitor compared to the time it takes to recharge it)

The photo below shows some typical GDT's (spark gap switch tubes):



The tube labelled 1 is a 3kv tube recovered from the 305013 Champion unit.

The tubes 2 & 3 are 2kV units were manufactured for me by Ruilongyuan Electronics for experimental purposes and are very good quality and worked exactly to specification.

Tube 4 is a 3kv tube from a Simmonds exciter unit and tube 4 is a smaller 2kV unit.

Tubes 4 & 5 contain Kr(85) Krypton 85, the gas composition in the Champion tube is unknown probably Kr(85) and the units from Ruilongyuan use H(3) which is Tritium.

Tritium, known as "Hydrogen 3" contains 1 Proton and 2 Neutrons. It decays to produce β (beta) rays or a steady state population of free electrons. Kr(85) on the other hand breaks down to produce β rays and Y (gamma) rays. Gamma rays are very high frequency electromagnetic waves in the order of 10^{19} Hz which are very penetrative radiation and quite difficult to shield. The purpose of these gases inside the spark tube is to provide an abundant source of electrons.

When voltage is applied to the tube initially it requires some free electrons in the gas to be released, this creates a delay. Then the tube goes into a glow phase, like a gas discharge lamp. After that a fine "streamer" or filament forms, which is a conducting channel in the gas and the spark inside the tube begins. When it does the voltage across the tube drops to a very low value, to only around 20V even with massive peak currents of 1kA or more.

Without the added source of β rays the initial electrons can be provided by cosmic rays or even the photoelectric effects making the tube susceptible to light and therefore having variable performance. The radioactive gases stabilize the performance of the tube. It is also possible to gain some electrons to help the function of the tube from secondary emission from electrons striking the tube's Tungsten electrodes.

Adding a powder to the tube such as MgO, BaO or SrO coats the electrodes and improves this effect. Some spark tubes, not all, contain powder for this reason. Metal halides can be added to the tube such as CsCl or KCl and they liberate electrons from the light produced in the tube (photoelectric effect) and are used in some spark tubes.

All spark tubes have a fixed life and the electrode material (which is conductive) is evaporated onto the inner glass walls. In the end this effectively shorts out the tube. As the tube ages the breakdown voltage usually drops below its unused or new value.

In some spark gap tubes, there can be an initial random delay before they fire the first spark and some electrons become more abundant. If this is a problem it would be better to move to a triggered device such as an SCR or triggered spark gap tube.

Storage & Ionisation Capacitors:

Most of the capacitors I have found inside Exciters are Custom Mica capacitors. A photo of these types of capacitor is shown below. They are often very flat and compact for the voltage rating and capacity:

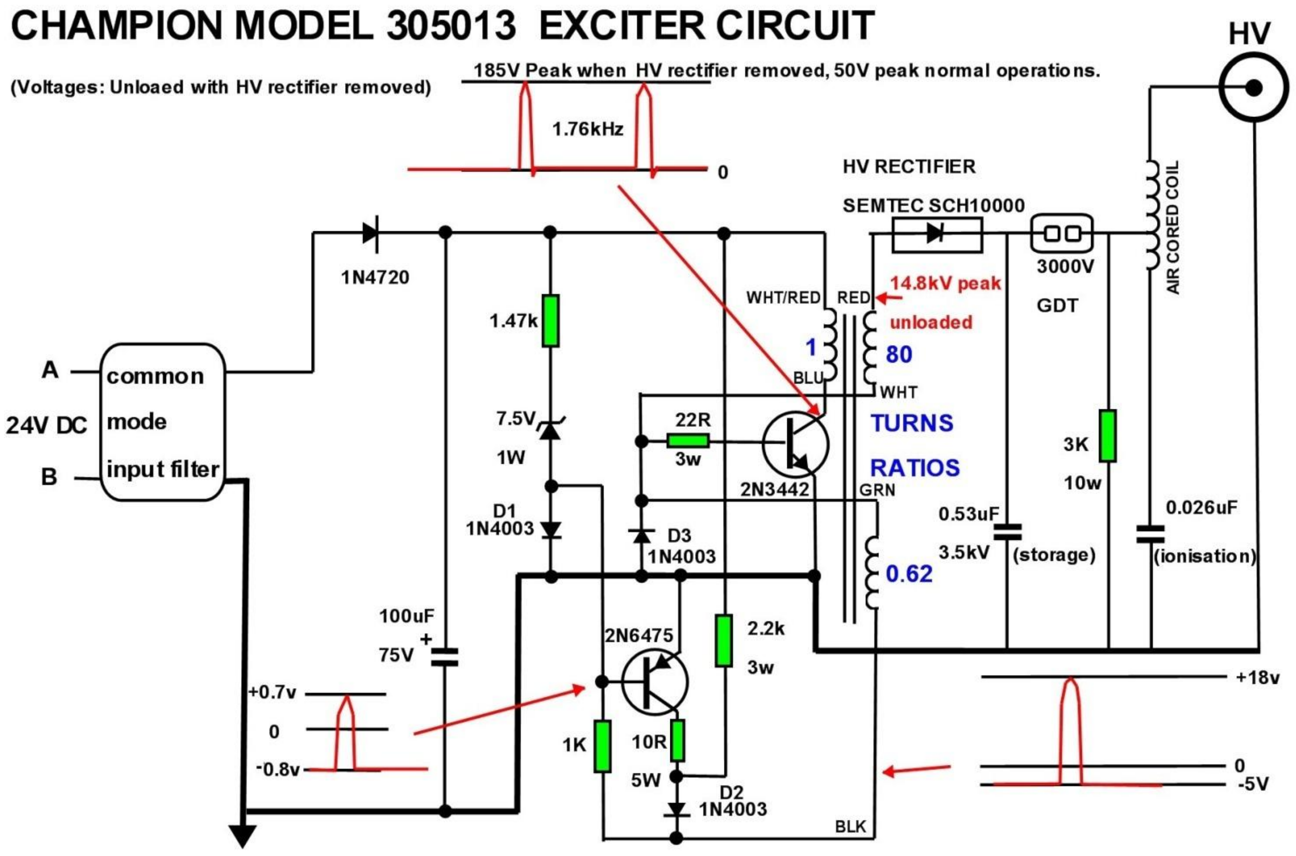
The 0.53uF was the storage capacitor used in my Champion unit. The other capacitors are similar types of different values, all made by the same company. These sorts of capacitors are still available from Surplus Sales in Nebraska.

High Voltage Rectifiers:

The high voltage rectifiers in exciters are usually rated at 0.5 to 1A and have 10,000V piv ratings at least. Typical rectifiers are the SCH10000 or the 1N6519 from VMI (Voltage multipliers Inc).

Very similar rectifiers are used in microwave ovens, typically 10kV 0.5 to 1A rated devices. Since the storage capacitor is only charged to approximately 3kV before the discharge tube breaks down one might wonder why a 10kV rated rectifier is used. Clearly this is a wide safety margin.

However, I was very surprised to find that with the rectifier removed from my Champion Exciter unit, the peak voltage appearing on the DC:DC converter’s secondary winding was around 14kV. In practice it never reaches this value because the discharge tube fires at 3kV and this also protects the 3.5kV rated storage capacitor. However, if there was a significant delay in the GDT firing for the first time, this could be problematic.



The Champion model 305013 exciter schematic (recovered from the unit) has refinements over the simple arrangement with two resistors, so as to make the starting and re-starting functions more efficient.

When the 2N6475 PNP transistor is conducting drive current to the base-emitter junction of the 2N3442, the circuit pathway includes the 10R and the 22R resistors and D2 and substantial drive current can be applied from the feedback winding. D3 prevents excessive reverse bias on the 2N3442's base-emitter junction.

After DC power is applied, the collector current in the primary winding reinforces the base-emitter drive current because the polarity of the voltage induced across the feedback winding is such that positive is on the base circuit of the 2N3442 transistor.

In the condition of the power supply voltage being more than about 8V (or during flyback time) the 2N6475 transistor is in a cut-off condition. This makes it easier for the start up circuit via the 2.2k resistor and D2 to inject current into the 2N3442's base circuit, to get the oscillator started, or re-started. The unit starts up with about 8 to 9V DC input voltage.

This overall arrangement may have been to help the flyback supply re-start more quickly when the output on the high voltage side was effectively heavily loaded by the GDT firing and overloading the flyback supply's output. As noted before, when these supplies are overloaded, they can shut down because the feedback voltage is diminished, making this type of supply self overload protected (this is not the case of course for an oscillator driven flyback generator) The Champion arrangement in the 2N3442's base circuit, would likely result in better starting and re-starting after the GDT fired than just a simple single start resistor in the 2N3442's base circuit.

Also, interestingly, they placed the ground return of the high voltage winding to the base circuit of the 2N3442. Pulses of current here during the flyback voltage pulse when the storage capacitor was charging, would also assist the transistor in staying out of conduction then, but it is not necessary for the circuit to work and the high voltage secondary winding can be returned to ground instead.

With this circuit it is also helpful to have a Flyback transformer core with an abrupt bend in the B-H curve because this results in a fairly abrupt increase in collector current over a certain value. However these flyback circuits still work with Iron or Ferrite cores of many types.

Also if the EHT rectifier fails, or is disconnected, the peak voltages (as noted on the diagram) climb to very high values. 185V appears on the 2N3442's collector in the unloaded state, which is not ideal because its collector breakdown voltage is 140v. After noticing these issues I only performed “unloaded tests” on the flyback generator with low power supply voltages in the range of 8 to 10 Volts.

Due to the fact that a fairly fixed amount of energy is stored in the flyback transformer core, prior to each flyback, then with varying power supply voltage, the peak output voltage is fairly stable, only the frequency of operation of the flyback converter changes to any significance with varying supply voltage. This is because as the supply voltage is increased the collector current climbs at a higher rate to the point where it reverses. This is due to the previously mentioned V/L relationship for the inductance that is the transformer primary.

SPARK CURRENT AND SPARK ENERGY RECORDINGS AVIATION EXCITERS

The results obtained in terms of ***peak igniter spark current and spark length*** are roughly inversely proportional and depend on the resistance in the Igniter cable and Igniter body.

For different Igniter’s with different internal resistors the spark burn time ***energy*** (phase 2 energy) is roughly constant, although the phase1 (ionisation) currents are lower with resistor plugs and decrease with higher resistances.

I took spark current measurements with two Igniters, one the Champion RHM83N (an aircraft spark plug) which contains a NTC internal resistor which is easily removed to make a zero Ohm unit. The other plug an AC273 which contains a 160R resistor and 1 foot of shielded aviation ignition cable connecting the exciter to the Igniter. This cable had a resistance of 10 Ohms.

Experiments with aviation Igniters on a free air test indicated that the spark voltage drop with these narrow gap (0.6mm) igniters during the spark burn time is very low, in the order of 20 to 30V.

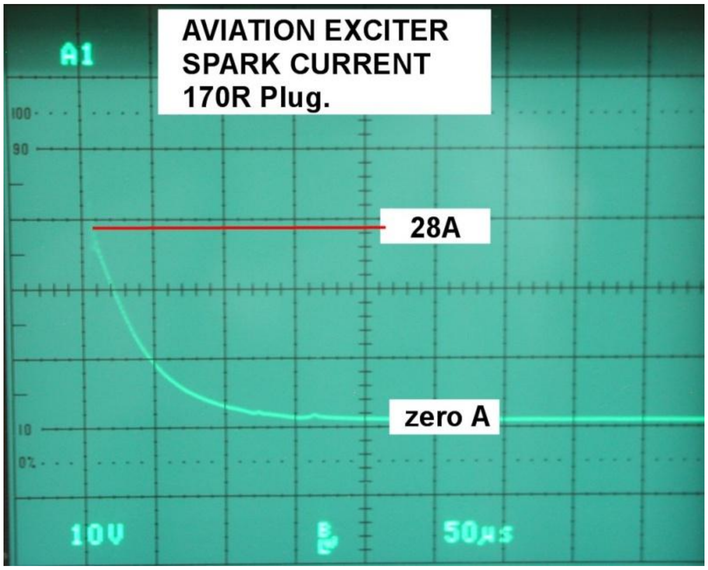
A Zener dummy plug was also created using a 24V power Zener diode .The Zener is superior to the actual spark plug for this testing because it snubs off the extremely high voltage transient prior to actual spark formation. The early phase 1 currents as the capacitances of the ignition coil, wiring and spark plug discharge at the moment of spark ionisation with the real spark plug can produce high transients. These can be many hundreds of amps and generate very high peak voltages even across a 1 ohm current sensing resistor placed in series with the Igniter’s earth connection. These are destructive to laboratory instruments, such as oscilloscopes, so the Zener “dummy plug” method was used to assist recordings.

Prior to running tests & Spice simulations, some Igniters were investigated. During experimentation with a Champion RHM83N Igniter, it was observed on the recording that the initial spark currents were low, and then they climbed at a gradual rate with time as the Igniter warmed up. This indicated a temperature dependence in the actual Igniter.

Looking on Champion's website they include a diagram of an Igniter which shows that it contains a series resistor. It says that it "prevents wear from voltage drain". However, this resistor actually limits the peak current in the early phase of the spark time and prevents electrode wear that way. The resistor is a NTC (negative temperature coefficient resistor or *thermistor*). At room temperature the resistance is very high at around 20k Ohms but as it heats up the resistance drops to a few hundred ohms.

The resistor was removed from the RHM83H Igniter and is shown below:

One other Igniter tested was the AC-273 which on measuring contains a fixed resistor of about 160 Ohms. So combined with about 10 Ohms from the one foot length of Igniter cable used provided a load to the exciter output of about 170 Ohms. The following recording was obtained using a 24V power zener shunting the AC-273's electrodes and a series 1 Ohm resistor.

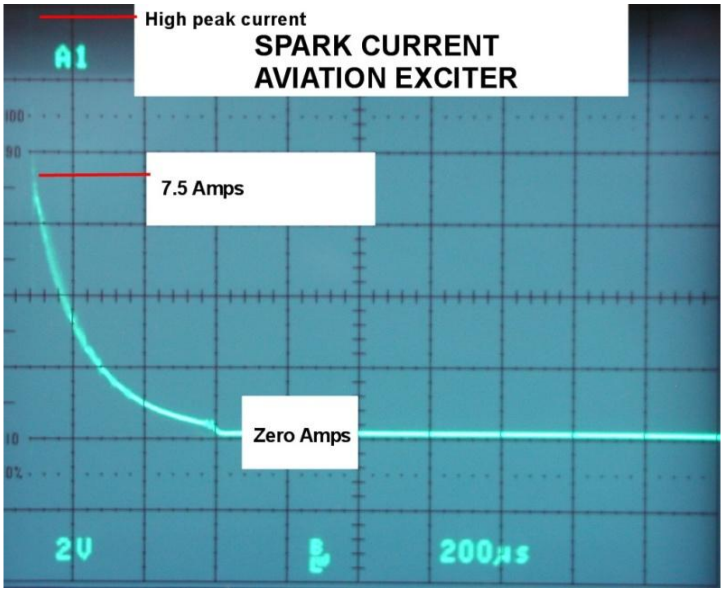


As can be seen from the recording above, there is a very fast initial rise in current. The experimental 0.3uF storage capacitor (which was charged to 3kV) initially discharges along with the ionisation current to create the high peak current on the leading edge. The discharge pathway includes the inductance of the coil secondary coil, which for the trial coil was 100uH, the DC resistance of the coil (low at <0.2R) the resistance of the Igniter at 170 Ohms and a 24V power zener. There are no high frequency oscillations seen. For the output circuitry to be oscillatory, the load resistance has to be less than twice the square root of the L/C ratio which is 36 Ohms. So with the 170 Ohm load, no oscillations are seen, just exponential decay.

It will be seen below how the current is indeed oscillatory with a 10 Ohm load.

The bulk of the recording is the storage capacitor discharging with a typical exponential decay and time course determined by the value of the of the storage capacitor and load resistance of 170 Ohms the RC time constant being close to 50uS. As can be seen in this instance the time course of the spark current itself would around 150uS or three time constants.

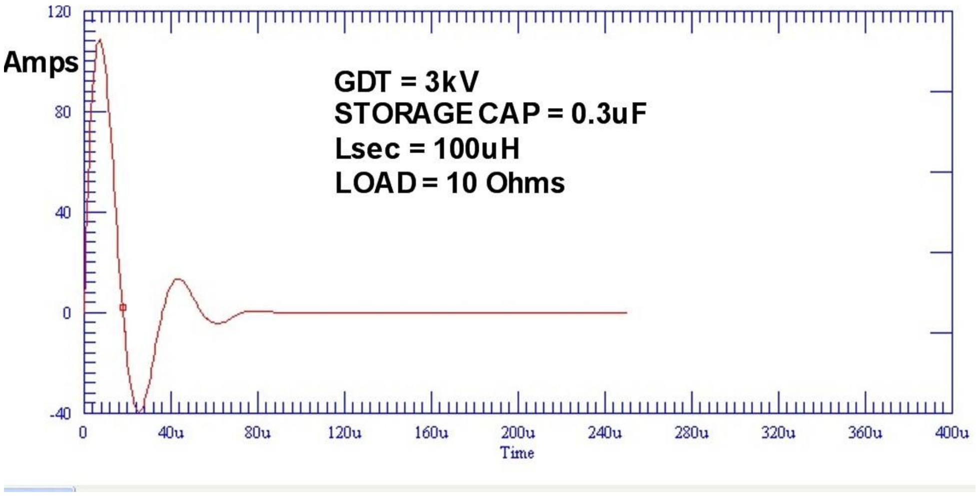
Using the Champion Igniter, the following recording was obtained when the Igniter was hot and the NTC resistor within it had dropped to a value in the order of 500 Ohms:



As can be seen from the above (Champion Igniter), with the higher load resistance the discharge (or spark) takes place over a longer time frame of around 500uS and the peak current, as expected, is lower.

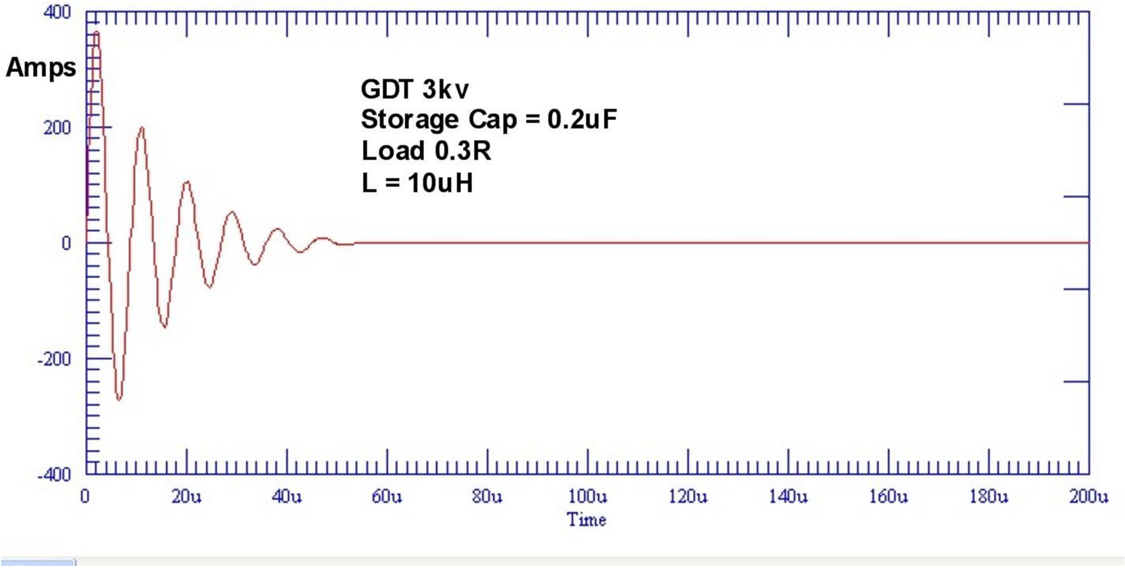
If the load resistance is very low and the Igniter is a zero Ohms type, there is just the resistance in the Igniter cable as the load. In this case, if that value is 10 Ohms as it is in my test cable, the peak currents are very high and the system is oscillatory.

The following recordings were made in a Spice simulator and they agree with the practical recordings with different load values. In this case the ionisation capacitor was not used in the Spice simulation, merely the 0.3uF storage capacitor (charged to 3kV) discharging via a 100uH ignition coil secondary, into the zener dummy Igniter with various series load resistances to observe the effects:



As can be seen with the 10R load the spark current becomes bipolar (oscillatory) as expected and the peak currents are very high at around 110A.

Altering the values in the simulator, it is obvious how oscillations in the spark current occur with low output resistance loads, depending on the values of L & C of the particular ignition coil secondary and the storage capacitor.



NASA attempted to measure this basic current profile on a modified Champion Exciter in an article comparing the spark energies of three different units, a Unison Unit, Champion unit and a VEE unit in a rocket motor system using liquid oxygen and liquid methane. The article was once available on a Google search of those terms and was also found at:

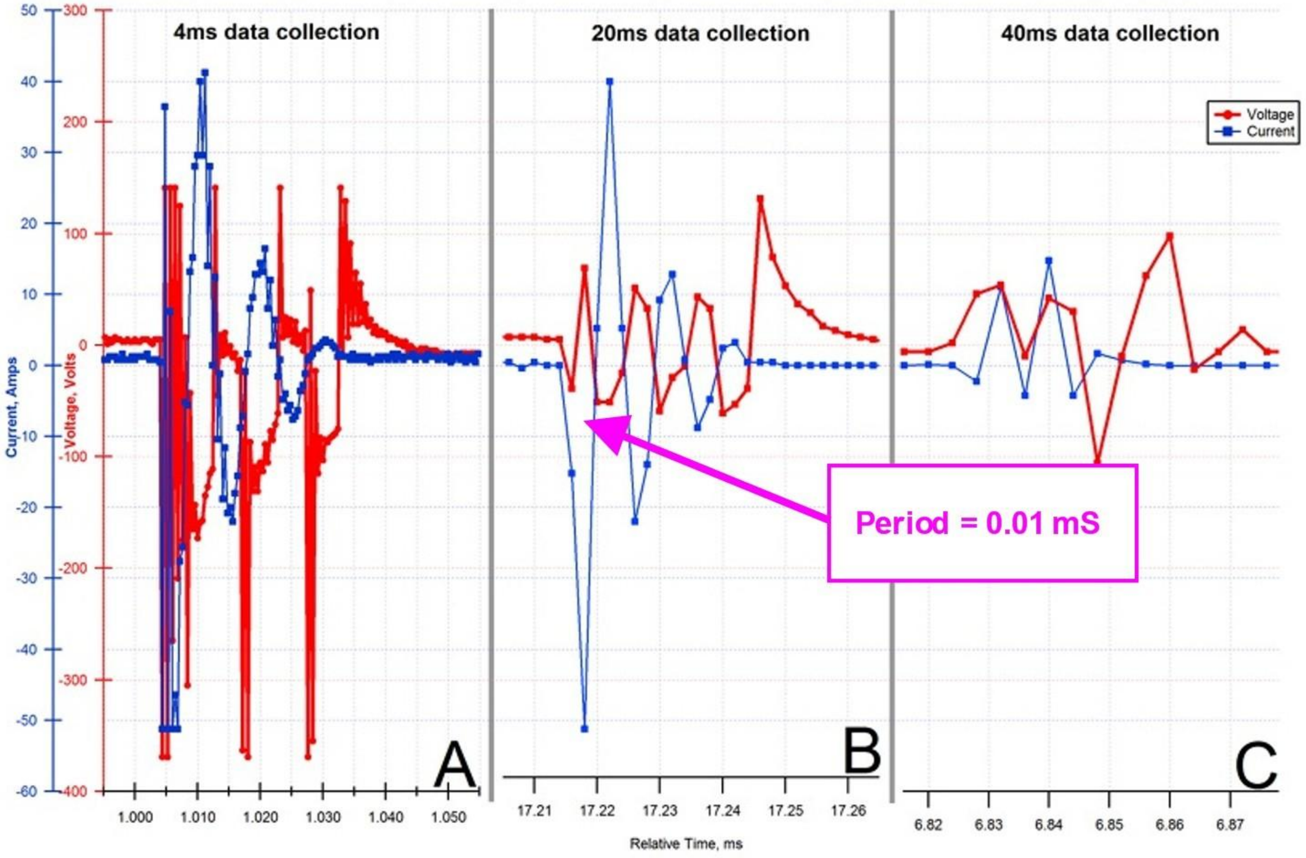
https://www.yumpu.com/en/document/view/16313895/experimental-investigation-of-augmented-spark-ignition-of-a-lo2-

I noted at the time that NASA's recordings indicated a bipolar (oscillatory) spark current at a frequency around 100KHz for the Champion unit. This brief oscillatory profile from the Champion unit proved very difficult for NASA to sample and record and assess for spark energy. They described the Champion unit as being "bipolar" referring to the bipolarity spark.

But the technical report above, number 16313895 appears to have been removed by NASA now from the internet and I don't have a copy of the original .pdf handy. However, another NASA paper with Exciter test data comes up on searching instead:

https://ntrs.nasa.gov/api/citations/20120011145/downloads/20120011145.pdf

And the Oscillations in the Champion unit were again mentioned. A graph from this paper is shown below and again it indicates 100kHz oscillations in the output of the Champion unit they were testing. The Pink writing on it is mine:



Second NASA paper number 20120011145
Champion unit has 100kHz oscillations as shown
in original deleted paper number 16313895

Period = 0.01 mS

Figure 14: Examples of dry spark waveforms from the Champion exciter.

Also of note in the left figure with the 4mS data collection, there are some much higher frequency oscillations. These are expected and around 1.8MHz (The reason for both of these oscillations is explained below).

This time there was also interesting detail which has enabled me to work out what Champion did to modify the 305013 exciter for NASA into the 3050131 unit, so as to convert it from a unit that produces a very low spark rate of a few sparks per second, into a unit that produced 100 sparks per second.

From NASA’s 20120011145 paper:

The Champion exciter (model number CH92111, which was a modified 305131 single channel design) was a hermetically sealed, vacuum-compatible, capacitive-discharge unit. Operable from a 26 to 30 Vdc input, it generated bipolar sparks from a capacitor with 94 mJ of stored energy. Delivered spark energies were 12 mJ, as measured at the spark gap in room air conditions. The unit produced a spark rate of 100 sparks per second (sps) as it periodically generated ionization pulses rated for 20 kV, but reduced to 9 to 10 kV at the spark plug due to ignition cable loading.

If Champion started out with their 305013 model unit, what would they have to do to convert it from a unit that produced a few sparks per second to a unit that produced 100 sparks per second that NASA wanted ?

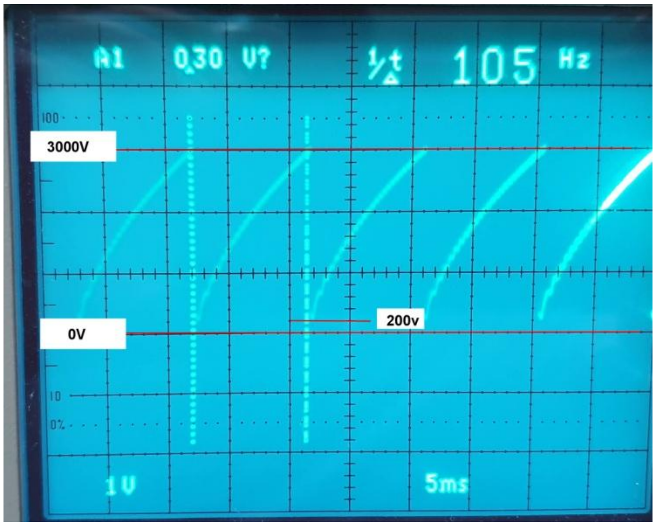
The determinant of the spark rate *all else equal* is the value of the storage capacitor. Other things affect it, however there would be no logic in altering any other parameter, except perhaps proportionally reducing the Ionization capacitor value. Lowering the GDT threshold value would be counter productive, as the energy stored in a capacitor is proportional to the square of the voltage, and it is more detrimental to lower the GDT's firing voltage than lowering the storage capacitor value. Also, a completely different flyback converter with a lower output resistance would help recharge the storage capacitor more quickly, but that would require a larger Flyback transformer and there is little room in the housing for that change.

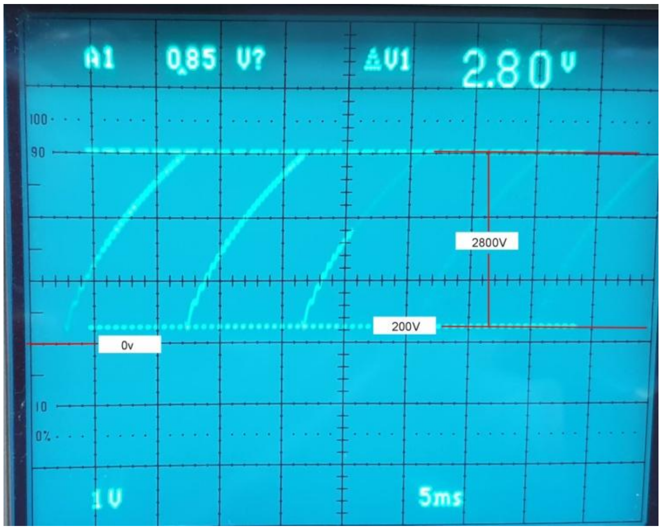
After studying the problem for a while, my calculations suggested that the Storage Capacitor would have to be changed from a 0.53uF part which was in the original 305013 unit, to a capacitor in the order of 0.02uF to get the spark frequency to the 100Hz region.

Then I noticed that there was already a near suitable 0.0264uF capacitor in the 305013 unit, deployed as the ionization capacitor. So initially I concluded that Champion simply re-connected that to be the storage capacitor and added another smaller value ionization capacitor. Later though I determined that they likely left the original ionization capacitor in place and simply changed out the 0.53uF storage capacitor for a capacitor close to 0.022uF.

To test this theory I modified my Champion unit by replacing the 0.53uF storage capacitor with a 0.025uF capacitor.

Below is the result, on testing the unit, it ran well at 105 Hz with 28V applied. With 26V applied it ran exactly on 100Hz. The 1000:1 TEK high voltage probe is connected to the storage capacitor:





As can be seen, these changes resulted in the Champion unit running close to 100Hz.

NASA also remarked in their paper that the Energy in the storage capacitor in their 3050131 Champion unit was 94mJ. The energy in the 0.025uF (now storage capacitor) peaks when charged to 3000v. This (from CV^2/2) is 112.5 mJ, a little higher than the 94mJ NASA noted. A 0.022uF capacitor with 3kV applied stores 99mJ. That may have been the value Champion used. Still, this meant that I had determined the required value to make my Champion unit run at the 100Hz spark rate.

Was the ignition coil changed too? As noted, some coils in Exciters contain a ferrite core and some don’t.

The X-ray of the other unknown model Champion unit appears to have a core in the output coil. This unit may well be a 3050131 unit, but I had no way to know for sure. However my 305013 unit did not have a core in the coil. Though, the coil construction in my unit looked like a ½” diameter ferrite core might have been “optional”

If the coil has a Ferrite core it does not affect the spark rate to any significance, but it would, in conjunction with the values of the storage capacitor Cs and the Ionization capacitor Ci values, determine the resonant frequency of the output circuit when the spark fired and during spark time (under the condition that the total resistance in the load was low enough to support an oscillatory state.)

My calculations suggested that much like the X-ray of the unknown Champion unit (but unlike my 305013 unit) NASA’s modified 3050131 unit must have had a Ferrite core in the transformer.

The reason being that for the Air (or plastic) cored coil, the inductance is far too low to support 100kHz oscillations, being well under 1uH for the small winding and around 7uH for the long winding.The values needing to be at least 7 to 10 times that in association with a 0.025uF storage capacitor and a similar value ionization capacitor. Therefore, in the final step to convert my 305013 unit to behave in the same way as NASA’s 3050131 unit, I fitted a 2 inch long ½ inch diameter type 77 Ferrite rod into the Champion coil:

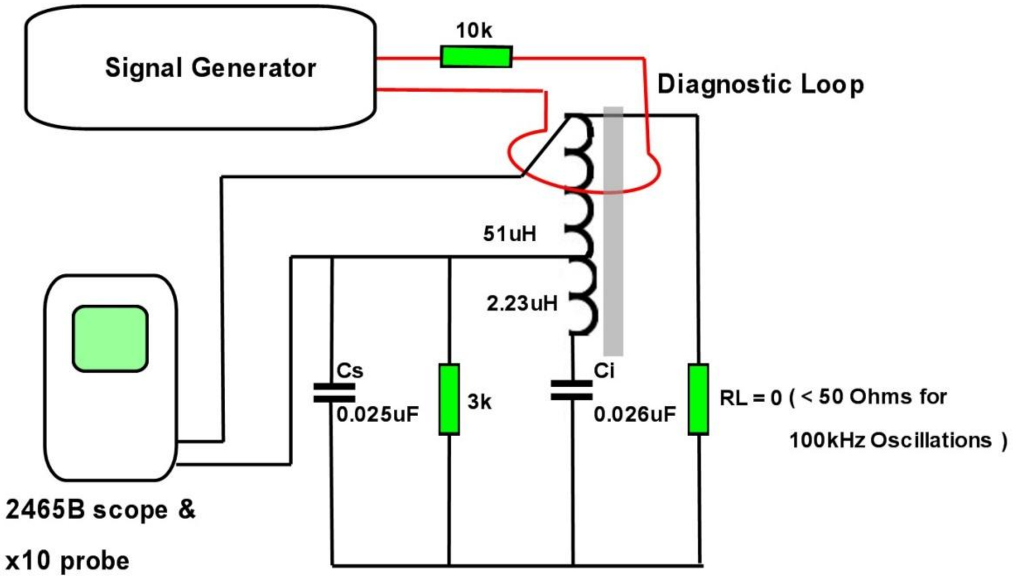
After this was done I performed some resonance tests on the modified coil led me to another conclusion, about the the last unknown:

What approximate value did Champion use in the modified unit for the Ionization capacitor Ci ?

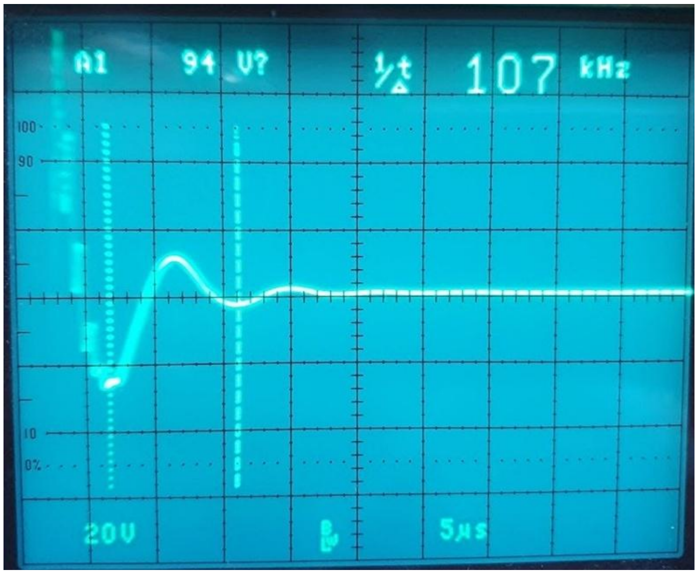
The value of the Storage capacitor Cs was worked out from the 94mJ specification for the 3050131 NASA unit, being close to the 0.022 to 0.026uF range when charged to 3kV, which in conjunction with the Flyback converter and standard GDT, yields the correct spark rate of 100Hz too, helping to verify its exact value.

One way to analyse the output coil is to perform a test with a loosely coupled generator with a lightly damped single turn loop and the scope. The 0.025uF capacitors swamp out the small input capacitance of the x 10 probe and the coil's self capacitance. It was found that with the modified Champion coil, when both the storage capacitor Cs and the Ionization capacitor Ci, had near the same value and the output load resistance was low enough to support oscillations, the resonant frequency was 100kHz (actually measured 101 kHz) and 1.8MHz. From this I concluded that Champion, not only used their output coil version with the Ferrite core, but they very likely used a 0.026uF Ionisation capacitor, which was the same value as in the original 305013 unit.

Modified Champion Output Coil with Ferrite core added.
Main Resonant Frequency 100kHz. High resonant frequency 1.8MHz
Equivalent Circuit: GDT Conducting & Ignitor conducting:



A brief calculation suggested that the load resistance would have to be less than 75 Ohms to see oscillations. On testing it appeared to be around 50 Ohms. On powering the Exciter and with a 10 Ohm resistance of the cable to the Igniter and the Igniter shorted out to obtain a cleaner waveform, the two oscillations (as expected were visible) one at around 1.8MHZ, the other near 100 kHz. These were recorded from a sense coil placed around the output coil to avoid damage to the oscilloscope. The high frequency oscillations of around 1.8MHz are seen on the leading edge of the 100kHz oscillation.



The NASA recordings also showed the higher frequency oscillations as well as the main one in the 100kHz region.

The inductances shown are those of the short and long windings measured separately. Because they are on the same core though, the total inductance of the two in series is higher than their sum, because of Mutual inductance and their coupling coefficient which helps determine that. Testing across the full coil length yielded close to 65uH.

In addition, whenever there are two tuned circuits of different frequencies on the same core, another resonance always appears that that is much higher than the main resonance.

This relates to the imperfect coupling between the two tuned circuits (k<1). In this case the high frequency resonance appeared at 1.8MHz. The equation that describes these two frequencies is very difficult to obtain, the only place I have seen it is in a rare book by Page & Adams. There is a simplification of it in Terman’s book for the case that the two tuned circuits have the same resonant frequency Wo:

From Terman’s Radio

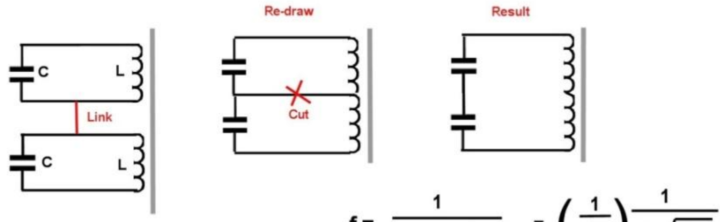
Engineers Handbook:

$$\omega_0' = \frac{\text{Wo}}{\sqrt{1 + k}},$$

$$\omega_0'' = \frac{\text{Wo}}{\sqrt{1 - k}}.$$

As can be seen from the Terman equations, if there were two identical resonant circuits on the same core and if the coupling coefficient *k* was unity, the high frequency $\omega o''$ vanishes and the resonant frequency would simply be $1/\sqrt{2}$ of the frequency of each single resonant circuit on its own.

Let us see if this makes intuitive sense. Consider two resonant circuits on the one core:



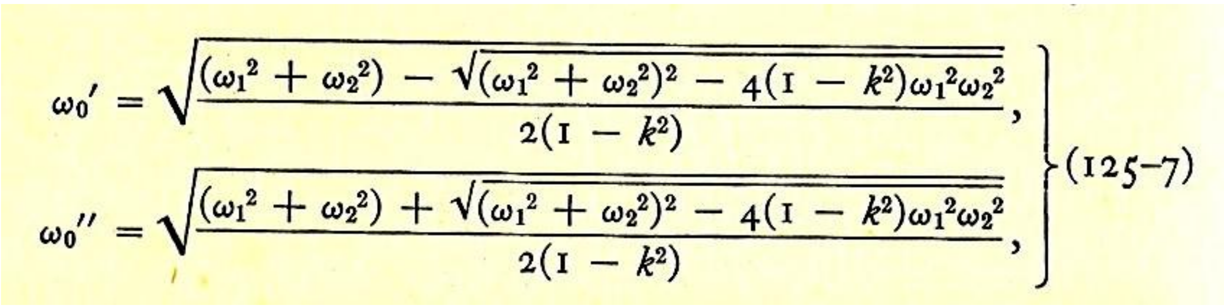
$$f = \frac{1}{2\pi\sqrt{\left(\frac{C}{2}\right)(4L)}} = \left(\frac{1}{\sqrt{2}}\right)\frac{1}{2\pi\sqrt{LC}}$$

A link is added, zero current flows in that link, the circuit re-drawn , a link is cut (because there is zero current in the link) and a new circuit results. Because the turn’s numbers of the inductance have now doubled and the fact that inductance is proportional to the square of the number of turns, the inductance has increased by a factor of 4. The total capacitance value has halved as they are in series. Therefore, the resonant frequency, on account of having the two identical tuned circuits on the same core has dropped by a factor of $1/\sqrt{2}$), or by a factor of 0.7071, compared to what it would be if there were just the one resonant circuit on the core agreeing with Terman’s equation.

In practice though *k* is always less than 1 so a leakage inductance related high frequency resonance always appears in practical transformers.

However, when the two resonant frequencies of the two tuned circuits on the same core are not the same, and they are $\omega 1$ and $\omega 2$ respectively the solution is much more complicated.

The equation solution (hard to find) is from Principles of Electricity by Page and Adams, Chapman Hall, London, first published in 1931:



$$\left.\begin{aligned} \omega_0' &= \sqrt{\frac{(\omega_1^2 + \omega_2^2) - \sqrt{(\omega_1^2 + \omega_2^2)^2 - 4(1 - k^2)\omega_1^2\omega_2^2}}{2(1 - k^2)}}, \\ \omega_0'' &= \sqrt{\frac{(\omega_1^2 + \omega_2^2) + \sqrt{(\omega_1^2 + \omega_2^2)^2 - 4(1 - k^2)\omega_1^2\omega_2^2}}{2(1 - k^2)}}, \end{aligned}\right\} \quad (125\text{-}7)$$

CONCLUSION:

In NASA’s tests on their modified Champion unit, there was not enough resistance in the load to suppress the oscillations in the spark current. The tests on my modified Champion unit give the same results as theirs.

This made the assessment of the spark energy by NASA impossible to easily assess for the Champion unit. The voltages and currents were oscillatory with components at around 1.8MHz and 100kHz.

The Champion unit really required a resistance in the order of to 40 Ohms or more added in series with the feed to the Ignitor to damp the oscillations out and make the spark current a simple exponential decay, or a unipolar spark current, as was seen with the Unison unit.

NASA indicated they used 3.65 meters of plain wire for their tests feeding the Igniter. And the internal resistance of their Ignitor was not specified, it may have not had a resistor of any value added. In this case the setup guarantees that the Champion unit would have aggressive initial 1.8MHz and then 100kHz oscillations in the spark current, which is exactly what is seen on NASA’s published recordings.

Why were oscillations not observed with the Unison Exciter?

I think the answer is fairly simple. Firstly the Unison unit had a larger value Storage Capacitor at 160mJ. All else equal, assuming similar charging voltage and ignition coil design, this proportionally larger storage capacitor uF value lowers the required resistance value in the load to support oscillations compared to the Champion unit.

However the main likely factor here is:

NASA mentioned in the test setup in their 20120011145 paper: The Unison unit had “a welded length of 1.37m (or 4.5 feet) of shielded ignition cable that was spliced into the unshielded facility cable”

Highly likely that Unison cable was Aviation style shielded resistance cable of 10 Ohms per foot. With these factors the output of the Unison unit was simply over critically damped and therefore no oscillations were seen in the recordings, which is direct evidence that the output circuit for the Unison unit was critically or over critically damped.

To make it a fair comparison with the Champion unit and be able to accurately measure the Champion unit’s Spark Energy output, the Champion unit should have had an identical cable section, or enough of a cable section, as the Unison unit had, added to its output in series with the Igniter, to ensure that the spark current was aperiodic and suitable for measurement.

In any event, it is clear that the presence of oscillations in the spark current, or not, in Exciter systems, simply relate to the proportions of L,C and R in the output circuit.

A video of my modified Champion unit running at 100Hz is seen in this short video:

https://www.youtube.com/shorts/xidy_6CcNf8

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