

GAS TURBINE ENGINES, AVIATION & ROCKET MOTOR EXCITERS.

Dr. H. Holden, April 2014.

“Exciter” is a term from the Aviation industry for an electronic unit or Capacitive Discharge Ignition (CDI) box 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 spark plugs. Igniters project into a combustion chamber where the gases ignite and are connected to the exciter typically by a shielded EHT cable. Unlike automobiles, the extra high tension (EHT) spark plug cables 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).

One might think that the Exciter units used in aviation applications would be similar to automotive CDI 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 apex of the bell 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 flows across the igniter’s electrodes will not extinguish the spark plasma. Spark plasmas produced from conventional automotive style CDI units with an SCR and 1 to 2uF capacitors charged to 400V and 1:50 to 1:80 ratio range ignition coils are not as suited to the application.

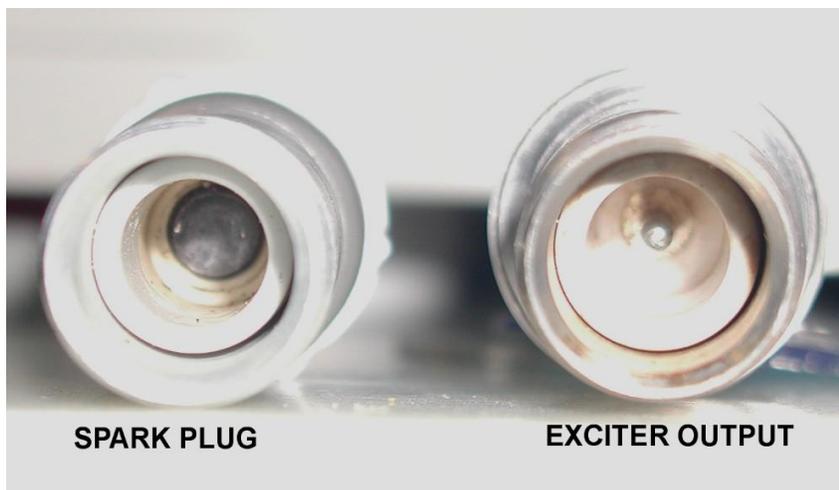
Once the typical Exciter is switched on it produces a fixed rate of sparks, this can be as low as 1 spark per second to 150 sparks per second depending on the design of the particular exciter unit. The spark burn time currents are very high, often peaking to over a few hundred Amps depending on the igniter cable resistance and any resistance internal to the igniter body. The spark durations are very brief compared to conventional Kettering (inductive) spark generating systems and also shorter than typical automotive CDI systems. Some recordings of these different systems will be shown in this article.

The photo below shows two different exciter units, the large one was removed from a DC10 aircraft, the other is a unit made by Unison which has similar artwork & colours to a packet of Stimorol chewing gum:

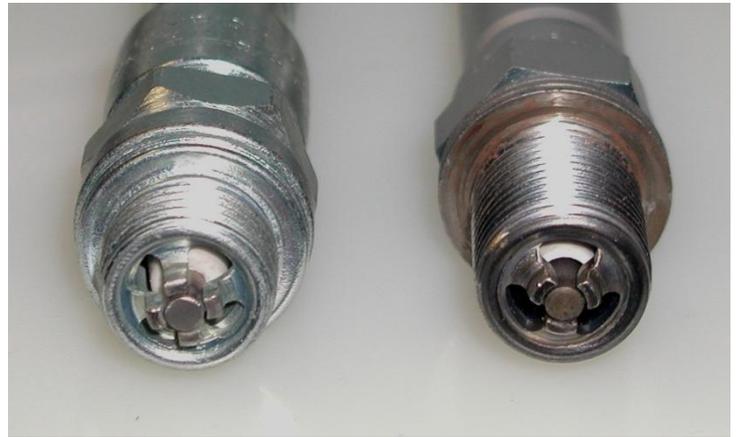


Generally many types have a 24 to 28V DC input on a two pin input connector.

The EHT (extra high tension) output connector is very similar to the connector on a 3/4 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:



The photo below shows two aviation style igniters. These are very robust compared to automotive 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 turbine igniters simply have a narrow annular gap:

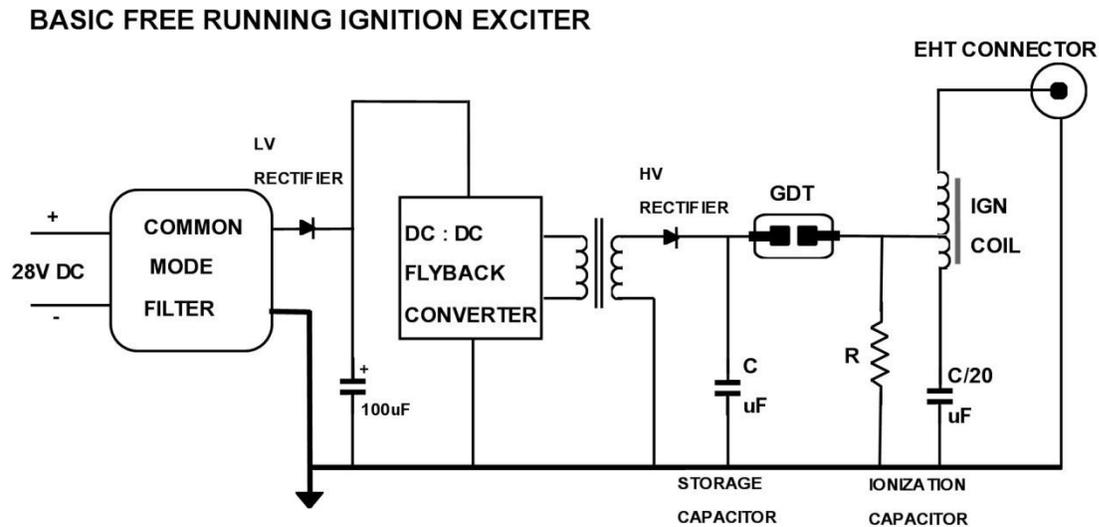


The photo below shows a Champion exciter Part number 305013, which is very similar to the Unison unit:



Exciters 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. Some types used for very high altitude or space rocket applications are rated to withstand a continuous vacuum and are hermetically sealed.

The block diagram below shows the basic arrangement of a free running aviation gas turbine exciter:



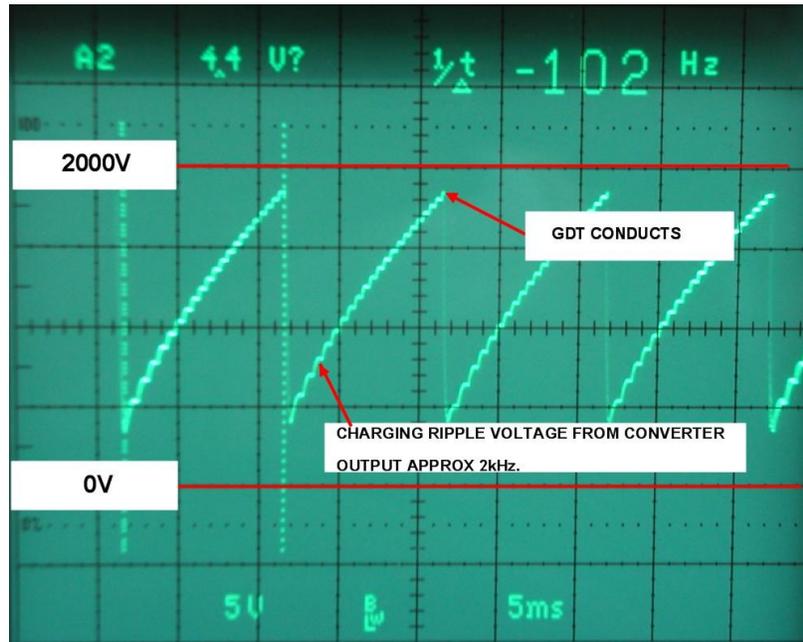
The common mode filter usually consists of the two pin DC input connector and a small enclosed metal housing which contains two windings on a powdered iron toroidal core and feed through capacitors to exit the metal housing. This keeps RFI out of the unit and prevents signals generated by the exciter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

The DC:DC converter is a self oscillating flyback style converter usually composed of one or two transistors. The main output transistor is normally held on for a significant period of the oscillation cycle, then switches off to produce a brief high voltage peak from the transformer's collapsing magnetic field, very similar to that seen from the Line (horizontal) output transformer in a CRT based television set. Typically the running frequency of the converter is 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 internal load resistor R is typically 3K Ohms in most exciters.

The high voltage peaks on the secondary of the transformer charge the "storage" Capacitor C 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 a test 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 peak are seen in the charging waveform.

Once the spark initiates inside the GDT it goes from being open circuit to a very low impedance. This type of heavy duty GDT is called a *spark gap switch* (more about these below). The GDT suddenly connects the storage capacitor onto the load resistor and via the ignition coil primary to the ionization capacitor, which has a typical capacitance value of about 1/10 to 1/20 of the storage capacitor. It also connects the storage capacitor via the ignition coil's secondary winding directly to the igniter. By the time the storage capacitor has discharged via the igniter circuit, in this example to around 400V, the current in the load has dropped to a value which cannot maintain GDT conduction and the GDT extinguishes and the charging process begins again.

The Champion unit shown in the photo above was designed to have a much lower frequency spark rate at around a few Hz. It has a larger storage capacitor of 0.53uF and

a proportionally larger ionization capacitor of 0.025uF and a 3kV GDT. In this instance the initial charge in the storage capacitor prior to the GDT conducting is $0.53\mu\text{F} \times 3000\text{V} = 1.59\text{mQ}$ (milli-Coulombs). 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) of the igniter so the individual spark energy is approximately $25\text{V} \times 1.59\text{mQ} = 39\text{mJ}$, ignoring (for now) the loss in the 3K resistor. Also in this instance testing with these values showed that with each deployment of the GDT the capacitor was discharged from 3kV to a voltage within 150 volts of zero.

The initial stored energy in the 0.53uF capacitor charged to 3kV is a large 2.4 Joules. The ratio of spark energy at the igniter to energy in the storage capacitor prior to the spark is low at about $0.039/2.4 = 1.6\%$. Therefore although an exciter might be marketed as say a “2 Joule” unit, the energy per spark for the actual spark burn time may only be around 1 to 2% of that value. However, despite the modest energy per spark values, the peak spark currents and spark powers in aviation exciters are very high compared to their automotive counterparts because the spark duration is very brief and more about this will be explained below. Some of this apparent missing energy is used in the spark ionization process (phase 1 current) which is extremely high and the remainder is lost as heat in the circuit’s resistances including the spark tube’s losses during the spark burn time.

Moving on to the ionisation capacitor and ignition coil; the ignition coil usually has a turns ratio in the range of 1:5 to 1:15. Also they are often 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. 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 where the short primary windings are wound on the outer part of the structure:



The coil in the middle of the photo above is from the Champion unit and is air cored. The other two types are from Simmonds Exciters and have round ½ inch diameter ferrite cores.

Consider a 1:6 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 was the GDT's breakdown voltage). Charging current then flows via the ignition coil's primary. Initially at least, the voltage applied across the transformer's primary is the GDT & storage capacitor voltage. This is transformed up by the ignition coil turns ratio. So if the voltage applied was 2000V and the ratio of the coil 1:6 the output voltage is transiently $2000 + (2000 \times 6) = 14\text{kV}$. 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 the primary and secondary windings. This high voltage peak initiates spark formation or spark ionisation (known as phase1). Once the spark is initiated at the igniter and due to the fact the spark between the igniter's electrodes has a very low impedance and low voltage drop, the output of the ignition coil is very heavily loaded. This allows the remaining and bulk of the energy stored in the larger storage capacitor to discharge via the ignition coil secondary and continue the spark plasma for the *spark burn time* or (Phase 2).

The spark burn time therefore is dominated by direct discharge of the storage capacitor by the low impedance pathway of the single layer ignition coil secondary. The secondary coil has a very low resistance typically less than 0.5 Ohms and a low inductance in the order of 10uH in an air cored coil and 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 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. By the time the storage capacitor has discharged to a value around 150V (in this instance with the 0.53uF storage capacitor) GDT drops out of conduction. At that point the DC:DC converter (which was transiently shorted out for the spark time) is unloaded and begins to recharge the discharged storage capacitor. The charge and voltage across the storage capacitor's terminals then builds up until the GDT fires again and the cycle repeats. Therefore the operating (spark) frequency is determined by the value of the storage capacitor combined with the output voltage and the internal impedance of the flyback DC:DC converter & rectifier charging the storage capacitor.

The photo below shows some typical spark gap switch tubes:



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

The tubes 2 & 3 are 2kV units were manufactured for me by Ruilongyuan Electronics 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 γ (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.

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 the Champion unit. The other capacitors are similar types of different values, all made by the same company.

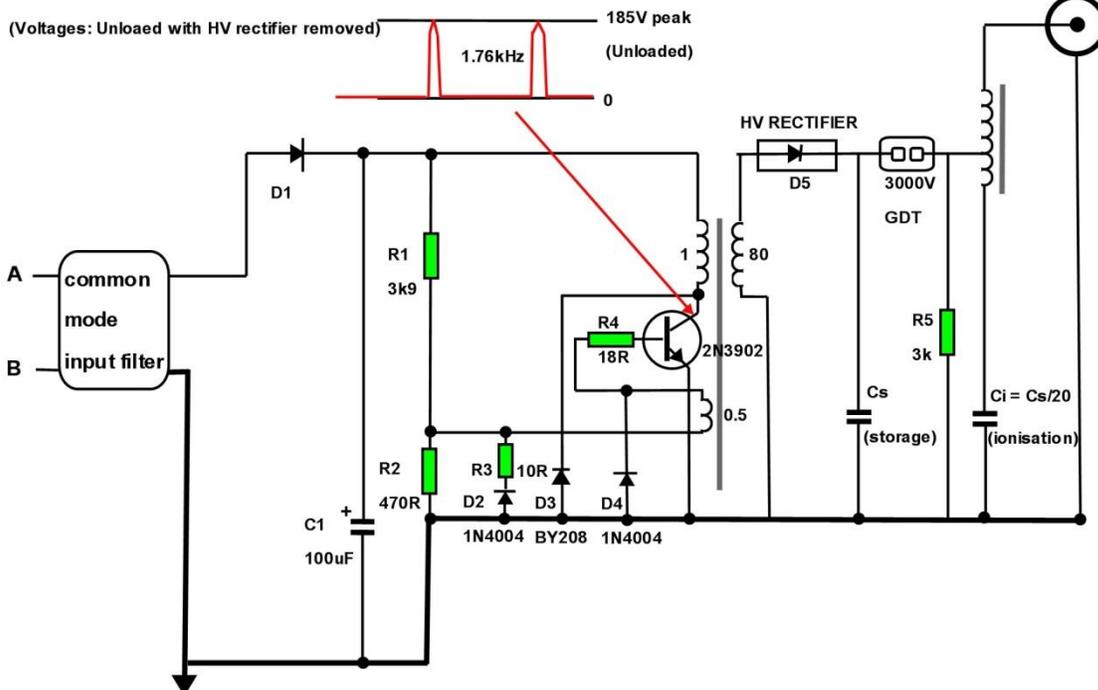
High Voltage rectifiers:

The high voltage rectifiers in exciters are usually rated at 0.5 to 1A and have 10,000V piv ratings. 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 surprised to find that with the rectifier removed from a test exciter unit, the peak voltage appearing on the DC:DC converter secondary winding was 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. The high voltage in conjunction with the series resistance of the rectifier and transformer secondary winding helps keep the capacitor's charging profile more linear and more brisk than it would be if the charging voltage was closer to the GDT's breakdown voltage. The charging wave shape to an extent still resembles an inverted exponential.

DC:DC Converters:

The circuit below shows a typical transistor exciter circuit. The voltages shown are those with the HV rectifier removed and the DC:DC converter unloaded:

TYPICAL EXCITER CIRCUIT



This is a standard type of flyback supply with a damper diode or efficiency diode on the collector of the transistor. For those interested in the evolution of the damper diode, see:

http://www.worldphaco.com/uploads/TELEVISION_LINE_OUTPUT_STAGES_AND_THE_EVOLUTION_OF_THE_DAMPER_DIODE_OR.pdf

When DC power is applied current flows via R1 and the feedback winding on the transformer and R4 to the base-emitter circuit of the 2N3902, this starts the circuit running. 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 transistor. The feedback winding circuit is a low impedance pathway to turning the transistor on via D2, R3 and R4.

As time passes with build up of the magnetic field in the transformer, the core begins to saturate. As a result the rate of change of current with time falls off. Induced voltage is proportional to the rate of change of current for an inductor or transformer. Therefore the feedback voltage from the transformer's feedback winding to the transistor's base circuit also drops off, further lowering the rate of change of current so the transistor abruptly turns off. This takes place when a fixed amount of magnetic field energy is stored in the transformer. When the transistor turns off, its base-emitter voltage reverses but it is clamped to -0.7V by D4. This is the "flyback time" where the flyback high voltage pulse is generated. The flyback peak represents half a cycle of the self resonant frequency of the transformer and its windings. Some transformers incorporate an added capacitor across the transformer primary to lower the frequency and amplitude of the flyback pulse.

In essence the magnetic field energy stored at the end of the transistor's conduction time is exchanged for electric field energy of the transformer's winding capacitances (and any added parallel capacitance on the primary winding). At the moment the voltage peak is highest, then the magnetic field energy of the transformer's core has been given to the electric field energy of the capacitances. Then this will return to magnetic field energy and so on. This would give a decaying sine wave oscillation, however only the first half cycle is permitted to occur because as the collector voltage attempts to fall below zero, D3 (the energy recovery diode) conducts as does the diode D2. This returns stored energy in the magnetic field of the transformer core to the power supply. This is why D3 is often called an "efficiency" diode. It also prevents the transistor's collector going negative which can be destructive to the transistor. The cycle then begins again with the transistor in a conducting state and building up magnetic field in the transformer. Sometimes the energy recovery and damping function can be performed by D2 alone which also conducts during the transistor's "on" time and the

damped current in the base-emitter circuit and the tight coupling between the transformer's primary and feedback windings is enough to prevent the transistors collector voltage from swinging too negative, without needing D3.

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 fairly stable, only the frequency of operation of the flyback converter changes to any significance with varying supply voltage.

SPARK CURRENT AND SPARK ENERGY RECORDINGS AVIATION EXCITERS VS STANDARD CDI & KETTERING AND THYRATRON BASED CDI:

The following recordings are from a typical aviation exciter. This experimental unit has a 0.3uF storage capacitor, a 3000V GDT and a 0.025uF ionisation capacitor and a typical ferrite rod cored 1:10 ratio ignition coil.

Importantly, 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. Many aviation ignition/igniter leads have a core of spiral wound nichrome like wire which has a DC resistance of about 10 Ohms/foot.

Spark current measurements were taken 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.

Experiments with aviation igniters on a free air test indicted 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. 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 ignition and 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. These can be many hundreds of amps and generate very high peak voltages even across a 1 ohm current detecting resistor placed in the

spark plug's earth connection and are destructive to laboratory instruments, such as oscilloscopes, so the zener "dummy plug" method was used to assist recordings.

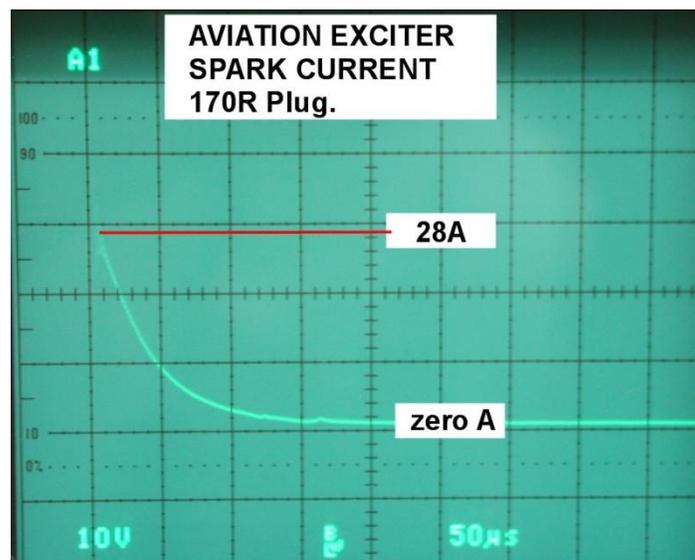
Prior to running tests & Spice simulations, some igniters were investigated. During experimentation with a Champion RHM83N igniter, it was observed on the recording that the initial spark currents were low, and then they climbed at a gradual rate with time as the igniter warmed up. This indicated a temperature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

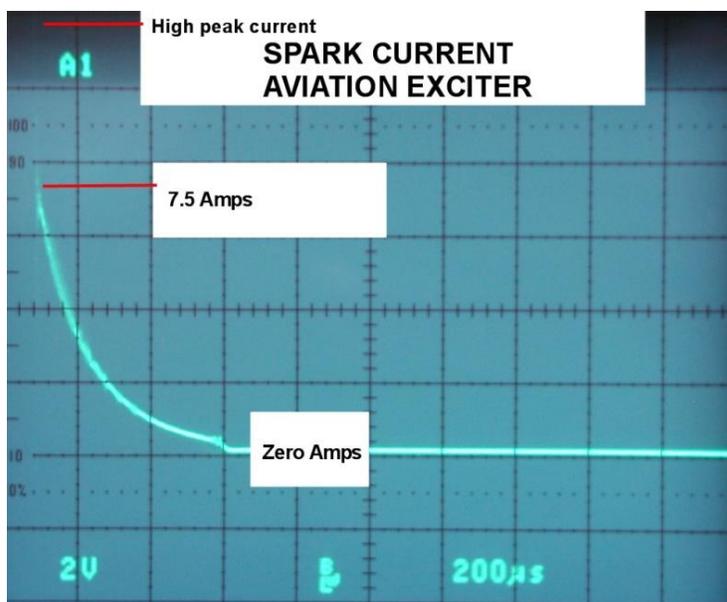


As can be seen from the recording above, there is a very fast initial rise in current. The 0.3uF storage capacitor (which was charged to 3kV) initially discharges along with the ionisation current to create the high peak current on the leading edge. The discharge pathway includes the inductance of the coil secondary(100uH), the DC resistance of the coil(low at $<0.2R$) the resistance of the igniter at 170 Ohms and a 24V power zener. 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. As can be seen in this instance the time course of the spark current is around 150uS.

Although the circuit consists of a capacitance C, discharging into a resistive load R with a series inductance L, there are no oscillations seen. This is because the ratios of L, C and R are such that the damping is well over critical damping. For the current to be oscillatory, the resistance must be less than twice the square root of the ratio of L/C.

L is 100uH and C is 0.3uF and the root of this ratio is 18.25, and twice this is about 36.5. So for the current to be oscillatory the total load resistance must be less than about 36 Ohms. It will be seen below how the current is indeed oscillatory with a 10 Ohm load.

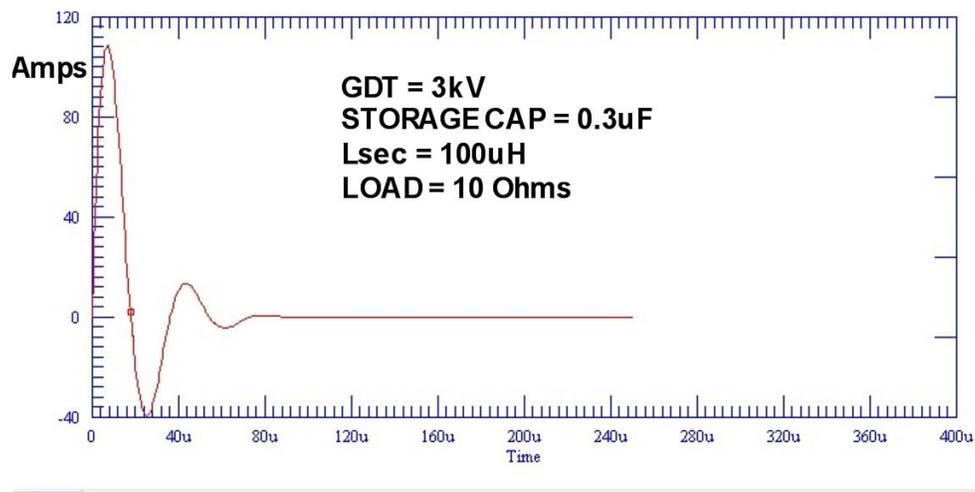
Using the Champion igniter, the following recording was obtained when the igniter was hot and the NTC resistor within it had dropped to a value in the order of 500 Ohms:



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, say 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 the 100uH ignition coil secondary, into the zener dummy igniter with various load resistances to observe the effects:

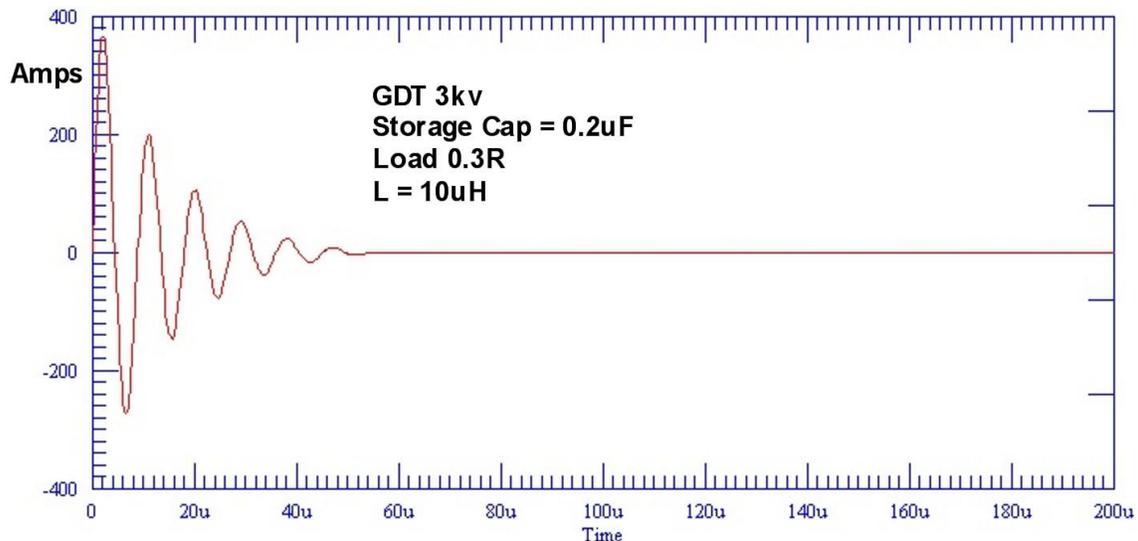


As can be seen with the 10R load the spark current becomes oscillatory (as expected) and the peak currents are very high at around 110A.

Air cored vs ferrite cored ignition coils:

In the instance where an air cored ignition coil was used, as it was in the Champion unit, the inductance of this coil is about 1/10 of what it is with a ferrite core. This pushes the system a little further away from resonance, all other factors equal. However repeating the simulation with a 10uH inductance (Champion coil) and a low DC resistance of the load (0.3R) which would be the approximate value for the secondary coil winding perhaps 0.1 Ohms plus igniter cable where no resistor was included the

system perhaps 0.2R. Also with a 0.2uF storage capacitor: This has critical damping at $2 \times$ the square root of $10\mu\text{H}/0.2\mu\text{F} = 14$ Ohms. So it will be oscillatory with a 0.3R load:



The current peaks initially to nearly 400A and the resonant frequency is about 120KHz. This sort of spark current profile can be very difficult to assess on practical testing for total energy.

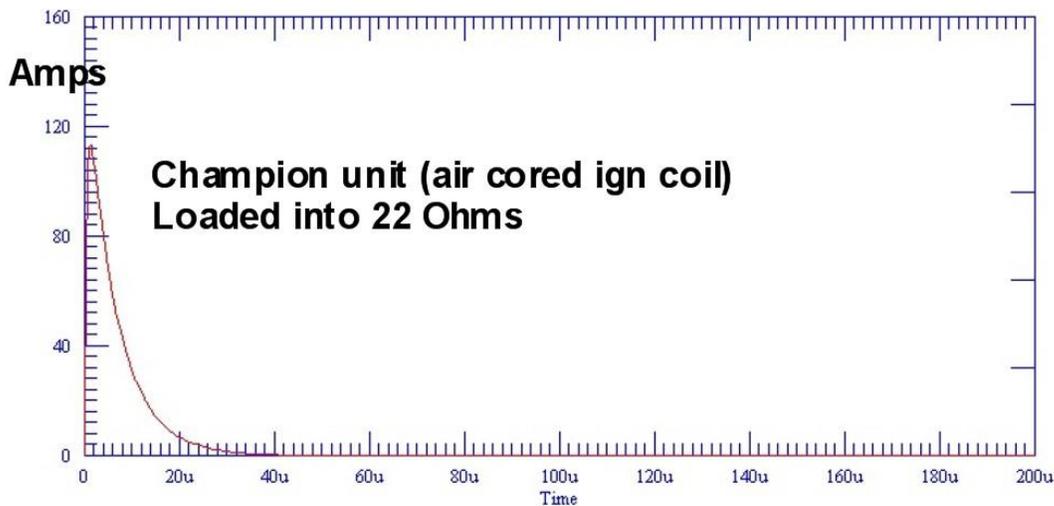
NASA attempted to measure this current profile on a Champion exciter in an article comparing the spark energies of three different units, a Unison Unit, Champion unit and a VEE unit in a rocket motor system using liquid oxygen and liquid methane. The article is available on a Google search of those terms.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

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

NASA's recordings show a spark current 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. The unit they tested was a 3050131, probably similar to the 305013 shown above in the photo which has an *air cored* ignition coil and my calculations suggest it would have had about a 0.1uF to 0.2uF storage capacitor and about a 2kV GDT as it operated at 100Hz. (This is why the simulation above was done with a 0.2uF storage capacitor). What is not clear is why the Unison unit they tested produced single polarity exponential decay spark current, suggesting that there was some load resistance, at least 10 to 20 Ohms in series with its output pushing it over critical damping and eliminating the oscillations. Perhaps this

resistance was inside the Unison unit. 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.

The recording below shows a simulation of my 1990's vintage Champion unit, running a 3kV GDT and a 0.3uF test storage capacitor with 22 Ohms igniter cable and this is enough to suppress the oscillations and convert it to a uni-polarity spark.

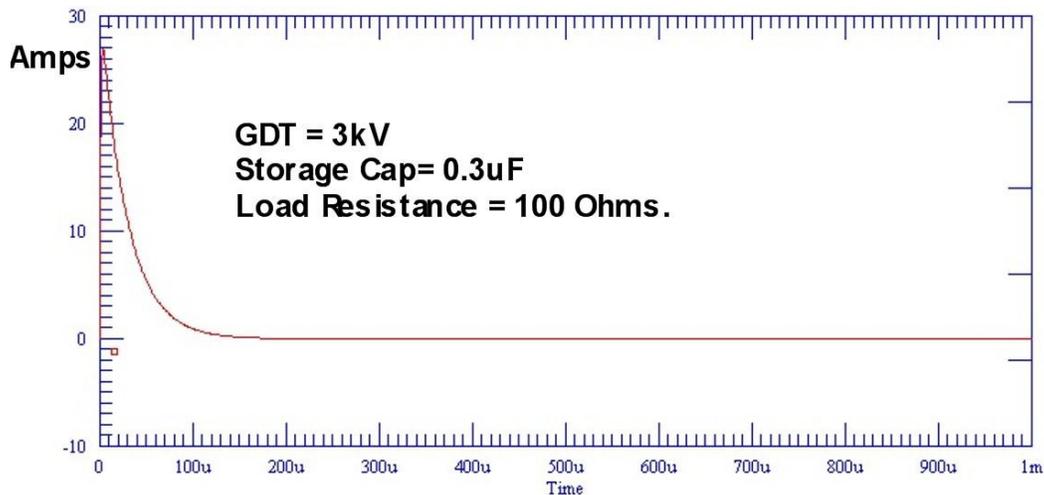


The charge transferred here is about 0.76mQ and the spark energy approximately $0.76\text{mQ} \times 25\text{V} = 19\text{mJ}$. The addition of the 22 Ohm resistor has little effect on the spark energy, only the spark peak current and spark duration, because the 0.76mQ charge is still transferred across the near constant spark gap of 25V simply over a longer time course of the spark burn time as the resistance is increased.

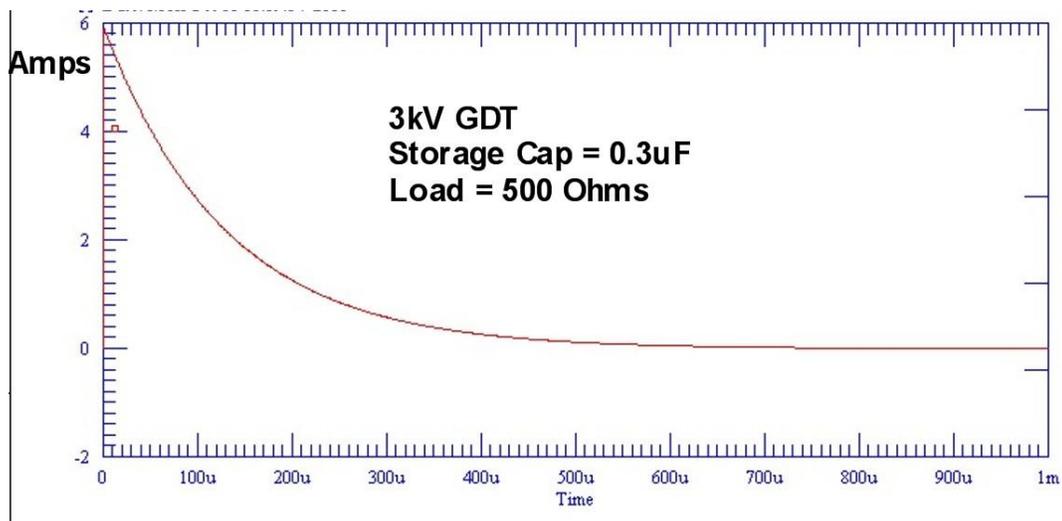
The solution therefore to “easily” measuring & comparing exciters for spark energy is to add enough series resistance at least to a value of twice the ratio of the square root of L/C in the exciter unit being tested (where L is the inductance of the ignition coil secondary and C is the storage capacitor value). This results in a much easier to measure uni-polarity spark current and this would have solved the dilemma faced by NASA measuring the Champion unit. The Unison unit in the NASA experiments must have had at least that value of damping, or the spark currents in those would have been oscillatory just like the Champion unit assuming they had identical igniters and igniter connecting cables during the experiments.

(It is possible to measure the energies of oscillatory spark currents, but it requires a wide dynamic range, wide bandwidth full wave rectifier and integrator system such as that used in the spark energy test machine as shown on www.worldphaco.net)

The simulation below shows a 100R load and 100uH ferrite cored coil and as expected the oscillations are damped out and the spark current lasts longer at around 100uS:



The recording below shows a 500 Ohm load and again 100uH coil the peak currents are lower but the spark time is longer at around 500uS:



Returning to the practical recordings, the peak amplitude and time course of the simulation above is very similar to the recording with the Champion igniter whose internal resistance (when hot) is just under 500 Ohms. The current peaks to around 6 to 8 amps and the spark last about 500uS.

Generally most of the discharge current passes via the external load (spark plasma) except for the losses in the 3K internal resistor in the exciter where the current is kept inside the unit. The lower the external load resistance value, the higher the percentage of charge from the storage capacitor passes via the external load and the lower the losses in the 3K internal resistor because the voltage is applied to the resistor for a shorter time frame for each spark.

Looking again at the Spice simulation above with the 500R load, the peak current is about 6 Amps. (In comparison to Kettering systems it is normally around 0.06A and automotive CDI around 0.25A). As the storage capacitor discharges directly via the internal 3K 10 watt power resistor and the ignition coil secondary and 500R load and 25V spark gap (zener), the current decays away as expected. The area under this graph of spark current vs time indicates the charge transferred across the external zener load (or a 25V spark plasma). The transferred charge can be estimated from the graph. The time for the current to fall to ½ its starting value, from the graph, is about 90uS.

Therefore the exponential decay constant, k is $\ln(0.5)/90 \times 10^{-6} = -7702$ or k is 7702.

So the equation describing the exponential decay of current with time (It) is close to:

$$(It) = 6. e^{-7702.t}$$

Integrating with time to find the charge transferred over the 500uS spark time:

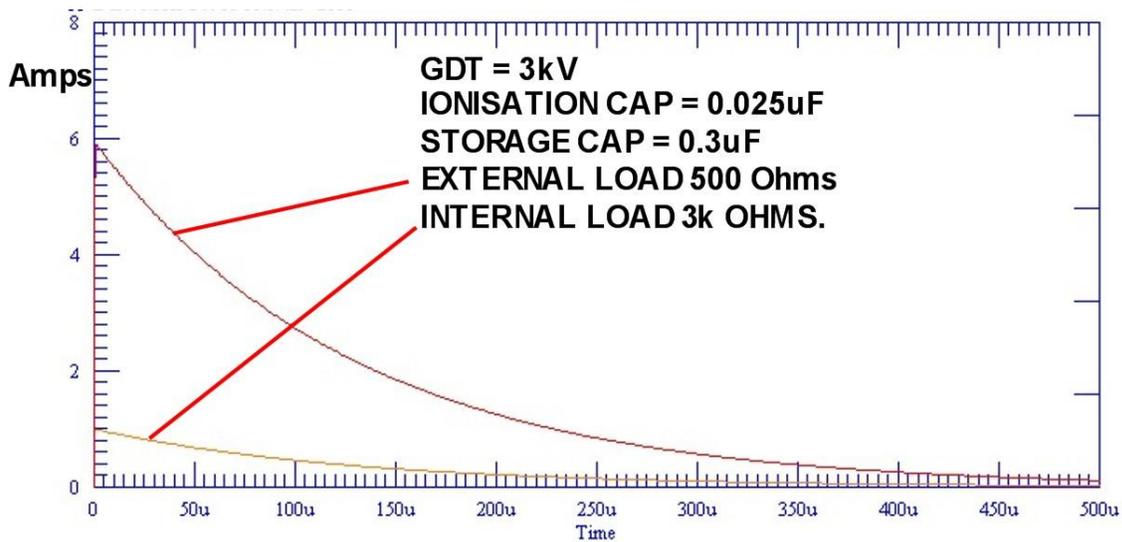
$$Q = \left[\frac{6}{-k} e^{-k.t} \right]_0^{500\mu\text{S}}$$

$$Q = (-1.66 \times 10^{-5}) - (-7.79 \times 10^{-4})$$

$$Q = 0.76 \times 10^{-3} \text{ Coulombs, or } 0.76 \text{ milli-Coulombs (mQ)}$$

Which from $Q = CV$ is approximately the charge stored in the 0.3uF capacitor charge to 3kV in the first instance as expected which is 0.9 mQ. The missing charge about 0.14mQ) passed via the internal 3k resistor. At least 0.76/0.9 or 84% of the initial stored charge exits a real exciter unit, even with the 500R load. This proportion is higher with a lower load resistance as the spark time is briefer and there are lower losses in the 3K internal resistor.

The graph below shows the currents in both the external load and the internal 3K resistor during the discharge process:



This data indicates, that even with a relatively high external load resistance of 500 Ohms, most of the charge is transferred from the storage capacitor via the external load and not the internal 3k Ohm load resistor in the exciter. And therefore most of the stored charge (but not energy) is delivered to the external load, especially when the load resistance is lower.

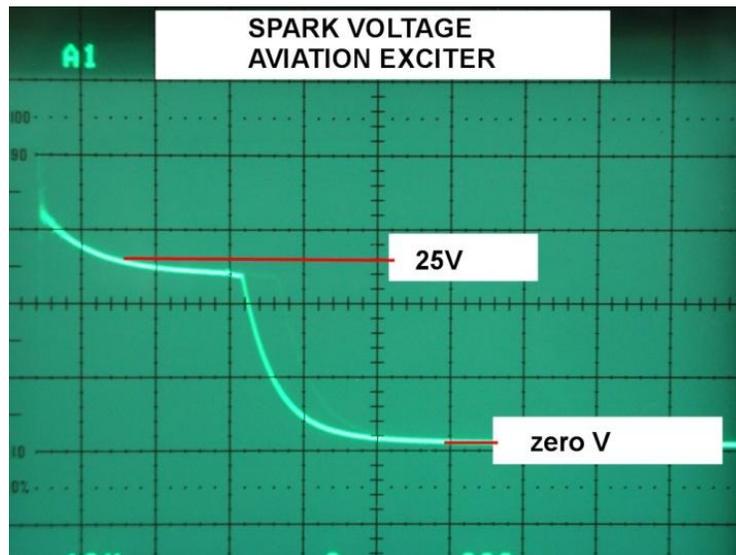
Despite that favorable charge transfer figure, due to the fact that the spark voltage is only around 25V in aviation igniters (as noted above) the spark energy can only be the product of the transferred charge and spark voltage, in this case 0.76mQ x 25V or 19mJ per spark even though the initial stored energy was 1.35 Joules for the 0.3uF capacitor charged to 3kV. (work done is always the product of the charge and the potential difference the charge passed between)

So it pays to remember that if an exciter is quoted as a "Something Joule unit" the actual Joules per spark will be around 1 to 2% of that figure. Unless the spark gap is

wider with a higher voltage spark drop than 25V and it will then be proportionally higher. However physically longer sparks are easier to blow out with high gas cross flows.

Spark burn time voltages with the dummy zener aviation igniter (spark plug):

The recording below shows the spark voltage during the spark burn time as measured across the dummy zener spark plug:



Very similar results are obtained with a real igniter except that the voltage clamping is a little better on the leading edge and it peaks up a little more with the zener in the early phase of the spark burn time.

Multiplying the charge of 0.76mQ by the near constant spark voltage of 25V yields the spark energy of 19mJ as noted. The spark pulse power or SPP is $0.019/500\mu\text{s} = 38$ watts. However, if the load resistance is lower, say using the 10 ohm load example and the total spark current burn time is around 60uS, the SPP is 317 watts.

(See notes below on how and why to calculate SPP).

IGNITER & CABLE RESISTANCES SUMMARY:

Resistance in the igniter wiring and igniter itself (if present) lowers the peak spark plasma temperature during the spark burn time and lowers the peak spark currents

while extending the spark burn time. This gives longer lasting igniters, but may reduce gas ignition efficiency as this is related to peak spark power (See below on how and why spark pulse power, or SPP, is calculated).

The total spark energy is not significantly affected by added resistance, unless it starts to become comparable to the internal load resistor value of 3k Ohms. Typical resistances though would either be close to zero (< 1 Ohm) or less than 500 Ohms in systems which used resistive igniters and/or resistive igniter cables. The reason why the total spark energy is not greatly affected by series resistance in the igniter circuit (which initially seems counter intuitive) is that even with a larger resistance, the same amount of total stored charge passes via the spark plasma at the igniter, simply over a longer time frame with added resistance. The spark's burn time energy is the product of its voltage drop and total charge passed during the spark time. Only a small percentage (1 to 2%) of the stored energy in the storage capacitor becomes actual spark energy.

To acquire the spark energy value with a recording system, the spark current must be integrated with time to yield the charge transferred and then multiplied by the spark voltage. Since the spark voltage is fairly stable over the spark burn time it is reasonable to use a constant 25V figure. This is the basic process in the spark energy test machine.

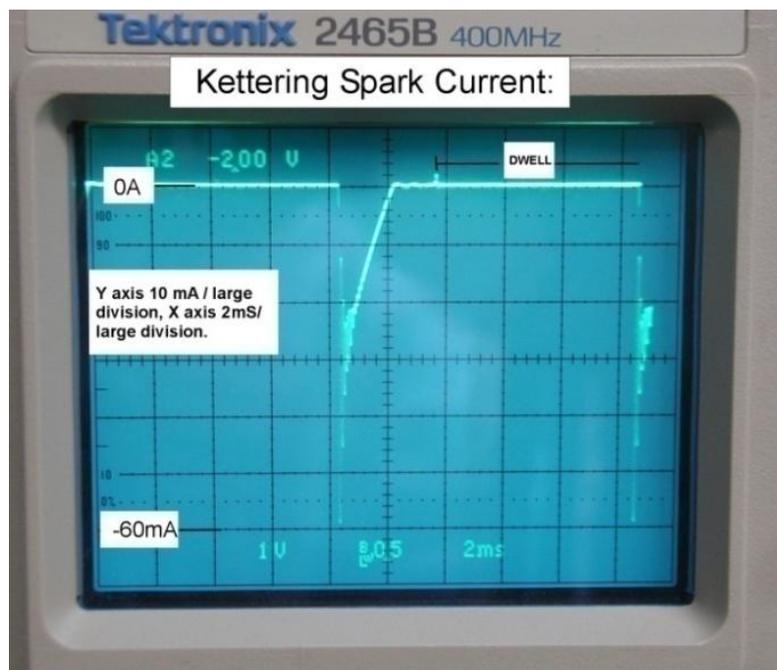
For any fixed cable and igniter DC resistance (if present), the spark currents may be bipolar or uni-polar depending on the ratios of L, C and R, where L is the inductance of the ignition coil secondary, C is the storage capacitor value and R is the resistance of the coil's secondary winding wire plus the resistance of the igniter cable (some cable types use nichrome wire about 10 Ohms/ft) plus the resistance inside the igniter itself (some igniters have internal resistors or NTC resistors or Thermistors). Once the resistance is above a certain value where the resistance is equal or higher in value than twice the ratio of the square root of L/C, then the spark currents are non oscillatory and "uni-polar" and have the typical exponential current decay profile.

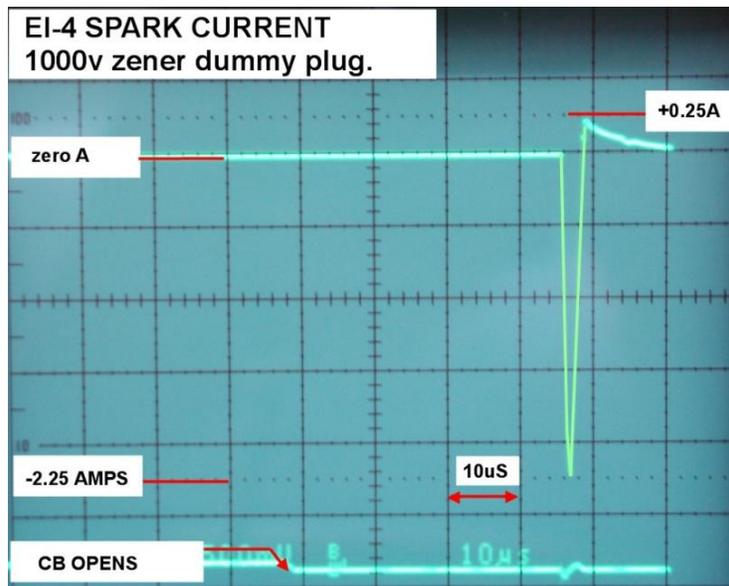
Aviation Exciter Units vs Automotive units & Spark Current Recordings:

From the overall energy perspective, the aviation exciter's single spark is not dissimilar to the overall energy of an ignition spark produced by typical Kettering or automotive CDI units at around 20mJ to 40mJ. However its character is completely different. The very high initial peak currents immediately after the discharge tube strikes and the igniter spark ionizes are on the order of many hundreds of amps. Then the storage capacitor discharges from about XkV/R amps where XkV is the gas discharge tube's breakdown voltage and R is the external load resistance (the igniter wiring & any igniter resistance) in the expected exponential manner during the spark burn time, or can be oscillatory as outlined above.

The spark voltage at the igniter during the spark burn time is much lower than automotive systems at around 25V (vs 1000V) and the high spark currents produce a very robust and thick spark plasma that is very resistant to being extinguished by fuel air mix flowing past the spark plug's electrodes in the gas turbine engine.

The recordings below for comparison show the spark currents from a typical automotive CDI (Delta MK10B) unit and from a typical Kettering system and also a recording from a Tung -Sol EI-4 Thyratron based CDI ignition system which is a little closer in its properties in terms of peak spark current, but is has a much shorter spark at only 3 μ S duration:





The Tung Sol EI-4 Thyatron CDI (spark current profile shown above) charges a 0.03uF capacitor to 2200V. This capacitor doubles as both the ionisation and the storage capacitor. The capacitor discharges via a gas Thyatron, which is not dissimilar to a spark tube, except that it has a trigger electrode and into an ignition coil. The peak burn time current is around 2.25A, much higher than Kettering or standard CDI, but is very brief at only 3uS duration.

Spark Pulse Power SPP notes:

How to calculate peak spark power for a better comparison of four completely different spark profiles from Kettering, standard CDI and Thyatron based CDI & Aviation Exciter:

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 ionized gas temperature and the higher the ionized gas temperature the better the surrounding gas ignition.

“Peak Powers” for the four types of sparks described above would be:

Kettering: $60\text{mA} \times 1000\text{V} = 6 \text{ watts}$

Delta 10: $140\text{mA} \times 1000 = 140 \text{ watts}$

EI-4 : $2500\text{mA} \times 1000\text{V} = 2500 \text{ watts}$

Aviation Exciter :

(0.3uF storage cap charged to 3kV, 100 Ohm load example): $27\text{A} \times 25\text{V} = 675 \text{ watts}$.

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

$$SPP = \frac{\int_0^{t_{spk}} V.I.dt}{t_{spk}}$$

So using **SPP** to compare the four different types of sparks:

Kettering: 60mJ/2mS = 30 watts (only a negative peak)

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

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

Aviation Exciter: Delivered charge = 0.76mQ, 25V, energy = 19mJ over 100uS = 190 watts (only positive peak as over damped).

With a 10 ohm load the charge delivery is faster and the current is oscillatory(under damped) and most of the energy is delivered in the first positive peak over about 18uS and the charge transferred through the 10 Ohm and 25V zener load here from the Spice graph(10 Ohm load example) is about 1.2mQ. Stopping right here, immediately this seems impossible as the capacitor has only stored CV (3kV x 0.3uF) or 0.9mQ in the first instance and some of this charge passed via the internal resistor, so how could more charge be transferred in the first peak than was stored in the capacitor? The reason is the circuit is now resonant and there is an exchange of electric field energy and magnetic field energy not happening in the other examples with the higher load resistances. The energy of this peak about 1.2mQ x 25V = 30mJ, so the SPP is higher at 30mJ/18uS or 1666watts and the spark plasma temperature higher than all the other sparks compared above. Therefore, in an Exciter, when the inductance of the output coil comes into play, when the proportions of L,C and R are such that resonance is occurring, it is possible to transfer more electrical charge through the load (spark plasma) than is stored in the capacitor alone on the first positive going peak. This occurs because a large proportion the capacitor's electric field energy which is very high is given to the magnetic field of the ignition coil, and the collapsing field of the coil

provides spark current and charge to the external load that way. The charge swings in both directions during the oscillatory cycle and averages to the value stored in the capacitor, but the peaks are higher than the average value.

Therefore, if the system is oscillatory, very high peak spark powers can be attained. Typically the load resistance has to be less than 20 Ohms. For systems with little resistance in the EHT wiring & igniter, less than few Ohms for example, the spark currents are always oscillatory and the SPP values very high.

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 EM 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, ie 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.

Finally, a spark energy and SPP meter is currently under construction specifically to measure aviation exciters as there appears to be a shortage of a useful tool like this in that industry.

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