## Motors Inc Training

## What is an Oscilloscope?

An oscilloscope is an electronic instrument used to visualize and measure electrical signals over time. It displays waveforms on a screen, showing how voltage changes in a circuit as a function of time.

## Basic Components of an Oscilloscope:

1. **Display**: Shows the waveform of the signal.
2. **Vertical Controls**: Adjusts the voltage scale (Y-axis).
3. **Horizontal Controls**: Adjusts the time scale (X-axis).
4. **Trigger**: Stabilizes the waveform, ensuring a consistent start point.
5. **Probes**: Used to connect the oscilloscope to the circuit under test.
6. **Time Base**: Determines how much time is represented on the X-axis (e.g., seconds per division).
7. **Voltage Scale**: Determines how much voltage is represented on the Y-axis (e.g., volts per division).

## Getting Started:

1. **Connect the Probe:**
   - Attach the oscilloscope probe to the circuit, usually by connecting the probe's clip to ground and the probe tip to the signal of interest. Typically the probe has a x1 and x10 switch, normally leave it on x1
2. **Adjust the Vertical Scale:**
   - Set the vertical scale (volts/div) to a value that lets you see the full amplitude of the signal.
3. **Adjust the Horizontal Scale:**
   - Set the time/div control so that you can clearly see one or more cycles of the signal. Typically signals in automotive use will be in milli second range. For example the injector pulse will be say 10ms, while a a Pulse Width Modulating (PWM) driver to say a Pressure Control Solenoid will be at around 1 kilo Herz (kHz). 1kHz means 1000 cycles per second , therefore the signal comes On and Off every ms.
4. **Use the Trigger:**
   - The trigger is important for stabilizing the waveform. Set it so that the oscilloscope "captures" the signal at a consistent point each time (e.g., at the rising or falling edge of a waveform).
   - Trigger can be Auto: meaning oscilloscope will show a screen shot of the captured signal but with no defined reference to the signal itself, this may lead to see the signal move horizontally.
   - Trigger can be on Normal: Meaning oscilloscope will show the captured signal keeping a predefined reference point (negative or positive edge slope) in the y axis (vertical) and also a predefined point in the horizontal x axis (time axis). In normal mode the display will be

refreshed repeatedly with new measurements if these are available but will show the last capture if the trigger condition is not satisfied any longer.
    - Trigger can be on Single:  Meaning Oscilloscope will capture just one screen shot of the signal that satisfy the trigger condition.  This is very helpful in understanding and trouble shooting things that occur once or repeat very slowly.  The Oscilloscope will have to be “told” to take a new capture every time a new screenshot is desired. This might be called Run on the push buttons.
    - Trigger can also be External, through a BNC connection on most desktop oscilloscope.  However this is rarely used.
    -

5. **Fine-Tuning:**
    - You can adjust the **Position** knobs to move the waveform on the screen so it’s easier to analyse.
    - Play with the **Time Base** and **Voltage Scale** to zoom in or out of the waveform.

## Types of Waveforms:

- **Sine Waves**: Regular, smooth oscillations; common in AC signals.
- **Square Waves**: A wave that switches between high and low states; often used in digital circuits.
- **Triangle Waves**: Linear rise and fall in voltage.
- **Pulse Width Modulating waves**: Similar to square waves but with a varying duty cycle.

## Reading the Oscilloscope:

1. **Amplitude**: The height of the waveform (vertical axis) shows the voltage.
2. **Frequency**: The number of cycles per second (horizontal axis) shows how often the waveform repeats.
3. **Peak-to-Peak Voltage**: The total voltage difference between the highest and lowest points of the waveform.
4. **Period**: The time it takes to complete one full cycle of the waveform.

## Common Tips:

- **Start with Known Signals**: If you're just getting started, practice with a known, simple signal like a sine wave from a signal generator.  Actually almost all oscilloscopes have a built in signal generator, typically a 3Volt 1 kilohertz square wave for this purpose to make sure probe and settings are properly set.
- **Be Patient**: It can take some time  to get used to how the different settings affect the waveform display. (it took hours for the author of these notes to learn the use of a new oscilloscope)
- **Use the Autoset Function**: Many oscilloscopes have an automatic setting feature that tries to adjust the controls for you, however the undersigned advocates that you should be patient and be able to set up the oscilloscope

yourself based on what you know you expect the signal to be like in voltage magnitude (y axis) and horizontal time x axis.

- 

## Safety:

- Always ensure that your oscilloscope probe is correctly connected and that the probe's ground is connected to the circuit's ground.
- Never use an oscilloscope on high-voltage circuits unless it's rated for such use.

**Automotive relevance**

The Cam and Crank signals are best analysed by an oscilloscope. Their signal is not sinusoidal but still of an oscillating nature. The amplitude varies with RPM.
The signal should be a hill first followed by a valley. The triggering time is the zero crossing going negative. If the polarity is wrong the ECU will still lock to a zero crossing but it will be offset in crank angle meaning the ECU will not properly know the engine angle. It may also issue a fault if it can check with something else, example cross check between cam and crank sensors.

The function of the crank and cam sensors is to provide knowledge of angular position and speed of the engine to the ECU. The ECU requires knowledge of angular position of the engine crank so that spark and fuel are generated at the desired crank angle.
Usually these sensors are inductive type, two wire (or three wire) and operate on the principle that a voltage is generated in a coil when iron (a tooth) goes past the sensor at some speed. Other types of position sensing is sometimes used such as optical triggering or hall effect (hall effect requires use of magnets).

The two wire sensor gives an output that is AC, that is the voltage goes above and also below zero. The amplitude of the signal depends on the rpm, the gap between sensor and wheel and the sensor itself. The amplitude may be in the range of 0.1V peak to peak at low rpm but will go to a couple of volts at high rpm. If the amplitude needs to be increased, the gap might be reduced, or if lower voltage is desired, gap is increased. The proper connection of the sensor should give the positive voltage hump first, then goes through zero volts and then goes negative see **Figure 1**. The sensor and tooth are aligned perfectly at the zero crossing.

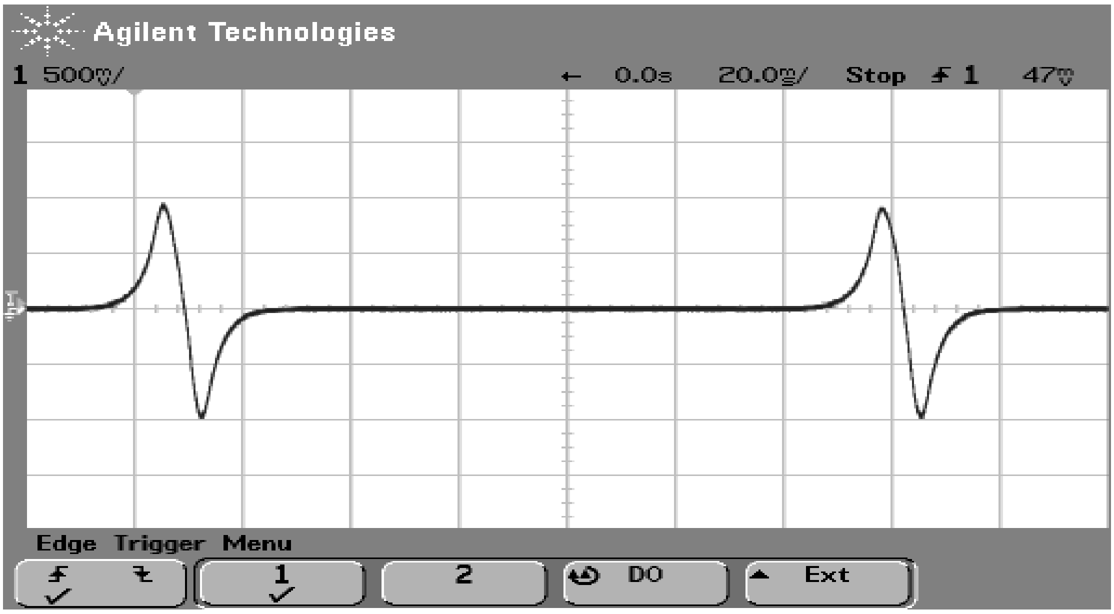



**Figure 1  Signal from a two wire sensor, with proper ground and signal connection**

If the two wires from the sensor are swapped the signal will be upside-down, see **Figure 2**.  The position when the sensor is lined up with tooth will correspond to the zero crossing from negative voltage to a positive voltage (which is opposite of the typical).  If the ECU internally is looking for strictly a positive to negative zero crossing is will find one which is in the gap between the teeth.  However this zero crossing is not very well defined in crank angle (as can be seen in **Figure 2**) and the ECU will not be very accurate in determining angles.

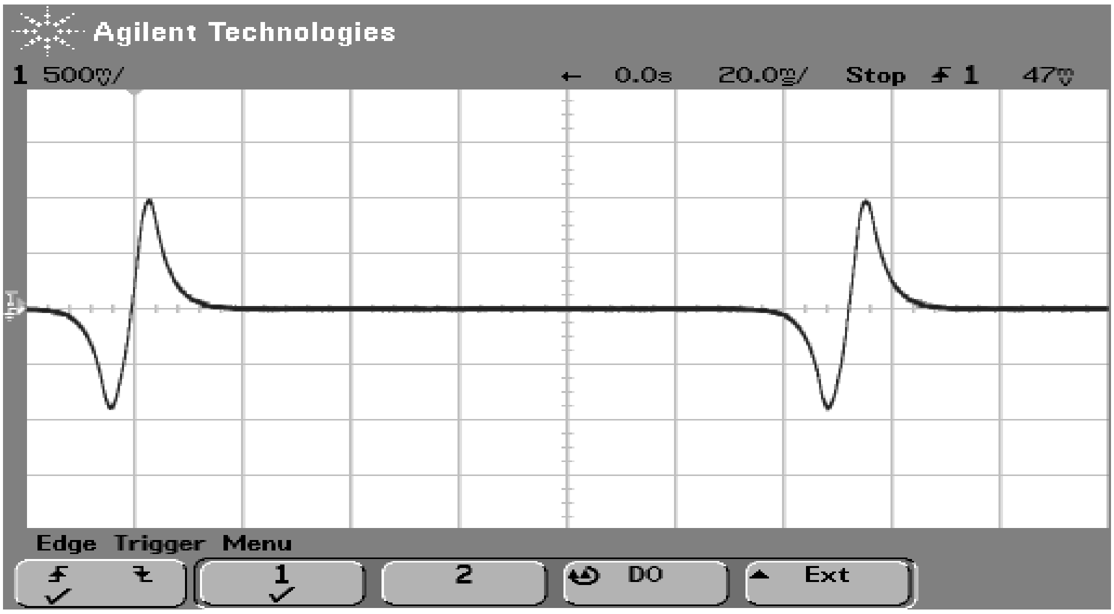



**Figure 2  Signal from a two wire sensor with swapped ground and signal connections**

The cam and crank signals (if both are used) can be seen in **Figure 3**.  It is noted here that the positive to negative zero crossing of the cam sensor is located to a gap between the teeth of the crank teeth.  This is a good feature to have in the mechanical orientation between the cam and crank signals and it is advised to implement this if one is setting up the triggering wheels himself.

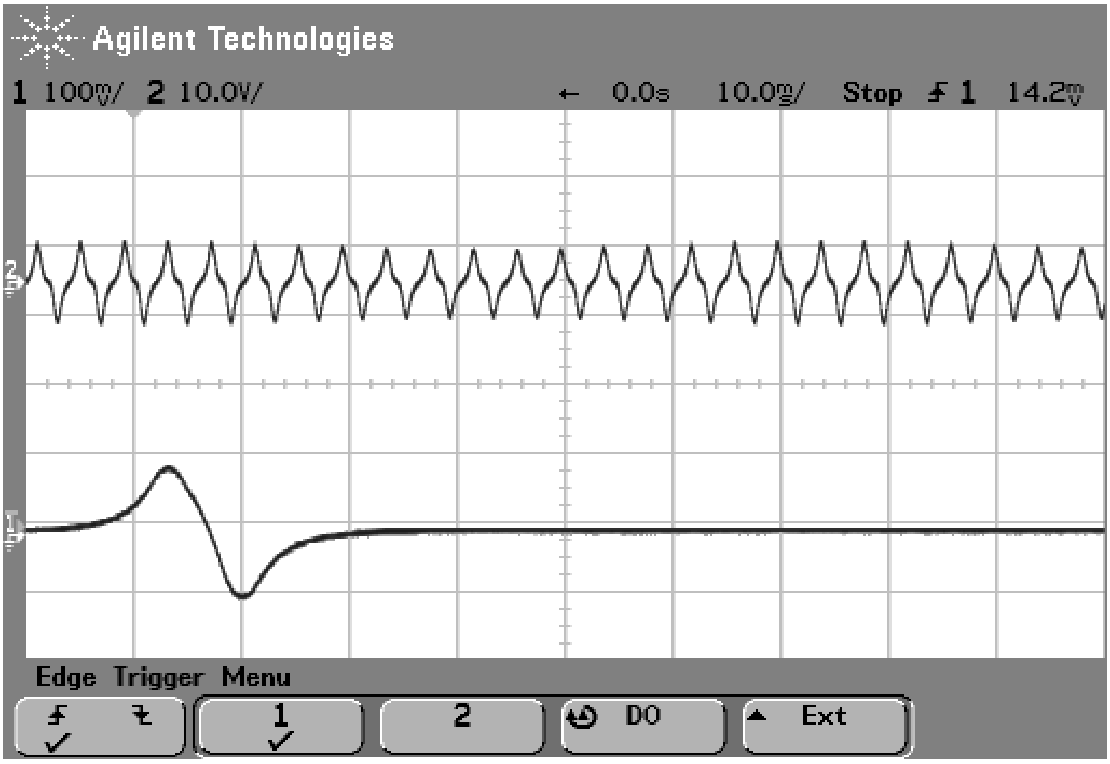



**Figure 3  Signals from Cam and Crank sensors**

Three wire sensors are typically also inductive type pickups but they also have electronics in them so that the raw signal (which is the same as the two wire described above) is converted into square pulses.  The sensor internal electronics will look for the zero crossing and turn on the signal output for a period of time.  The "on" time will be calculated on the time interval between the teeth.  The three wire sensors will have Ground, Signal and Supply connections.  The signal might be having a voltage output on it, or it can be a transistor output which needs to have a load connected to it to have a voltage change (this is technically called "open collector" output and is similar to the transistor used for injector and ignition drivers).  One significant difference of the three wire sensor is that it is able to hold the on or off states indefinitely (that is forever).  That is the 3 wire will say remain high if the sensor is aligned to the tooth with the engine stopped.  However the two wire sensor will give zero volts when the engine is stopped regardless of whether the sensor is aligned or not with the tooth.

***Injectors and Injector Impedance***

Injectors have been evolving over the last decades.  The first fuel injection systems on street cars were single-point type, that is one injector that was properly sized for the whole engine.  These injectors where quite big in physical dimensions and the internal coil that opened the spindle was also quite big.  Thus the coil required quite a bit of current to operate and the impedance (or resistance) was low, 1 Ohm or less.  Such low impedance made the current consumption of these injectors quite large.  By Ohm's Law, V = IR, the current is I = V/R, and for a 12V battery and 1 Ohm injector this would give a current I = 12A.  Such a current is quite high, in fact if the power

associated with it is calculated, P = IV, this is 144W. The high current is a requirement due to the large and heavy injector internals that would need to be physically pulled open by a magnetic field to open fuel flow. However the current required to keep the coil energized with enough magnetic flux to maintain the electromagnet strong enough to keep the injector open is much lower than the initial current required. Therefore peak and hold injector drivers were used on these low impedance injectors. The peak and hold circuit supplies full battery voltage to the injector until a certain current is sensed to flow in the injector and then reduce the current supply to the injector to typically a quarter of the initial current limit, refer to Figure 4. The initial current limit should be enough to pull the injector internals open at the highest fuel pressure. High flow injectors, typically associated with high performance applications, may still be low impedance and hence require a peak and hold injector driver. Recently we noted that AdBlue injector on Renalut 1.5 DCi is also peak and hold.
The curves shown in Figure 4 are for tests on a TrickFlow 120lb/hr low impedance injector without any fuel flow, that is dry operation of the injector. The upper curve shows current through the injector, while the lower curve shows the voltage at the collector of the transistor. The current was measured by means of a 0.1 Ohm resistor connected between the emitter and ground of the switching circuit. Since the resistance was 0.1 Ohm, the current for each division (100mV per division on the oscilloscope) translates to 1 Amp. Hence from the upper curve of the figure, it can be seen that the current starts flowing in the injector slowly from an initial value of zero. The current then reaches the highest value of current, approximately 4 Amp, say around 1.4ms after being switched on. The injector driver than limits the current in the injector to approximately 1 Amp. The 4 to 1 Amp strategy is a function of the injector driver and different current strategies are sometimes cited and required. The lower current is enough to maintain the injector open and for most of the 10ms DOI shown in the figure, it is the lower current that is supplied to the injector.

The voltage supplied to the injector is shown in the lower part of Figure 4. The voltage at the collector of the transistor is shown in this curve. When the injector is initially off, the collector voltage is high, that is 12V due to the fact that the transistor is switched off and therefore both sides of the injector would be pulled up to 12V (the zero Volt or ground is shown by the earth symbol close to number 1 on the lower left corner of the figure). When the transistor is switched on, the collector is pulled to ground, and hence the injector would have a 12V differential voltage across it. This voltage difference initiates current flow. However current start flowing in the injector slowly due to the fact that the injector coil is an inductor which does not like abrupt changes in current. When the current reaches the 4Amp target, the injector driver lowers the voltage difference across the injector by raising the voltage of the collector such that a current target of 1 Amp is made. As can be seen from the voltage trace the change from 4Amp to 1Amp induces quite a bit of voltage spikes. Once the lower current target (approx 1 Amp) is achieved, both voltage and current are stable. Turning off the injector at the 10ms point once again generates voltage spikes due to the fact that the coil would resist the current change and the coil would continue to flow current through the transistor safety diodes until the magnetic flux is consumed.

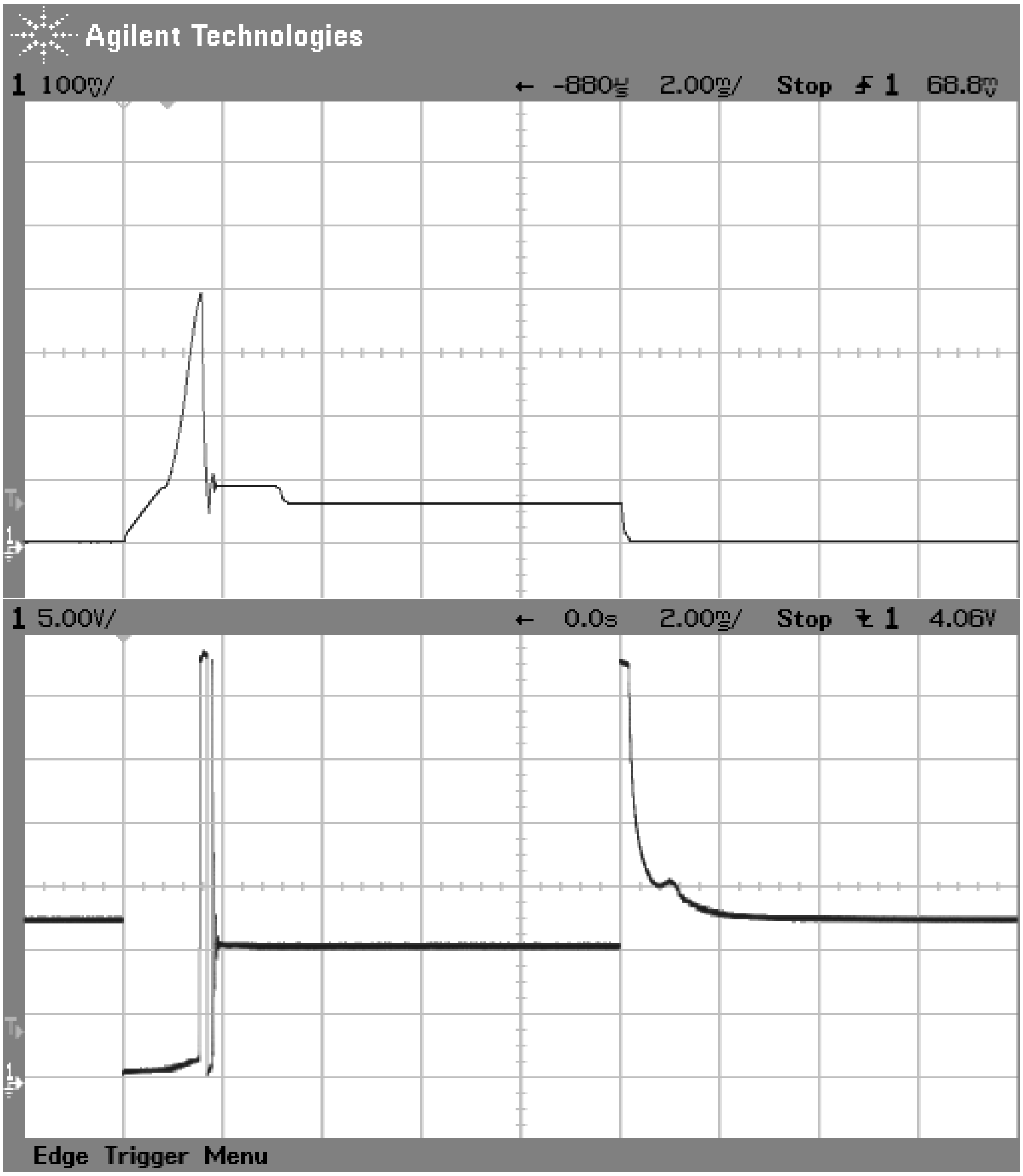



**Figure 4  Current and voltage curves of low impedance 120lb/hr injector, DOI 10ms**

The DOI shown in Figure 4 is 10ms, but as we now have established much lower DOI's are required at low load operation.  Figure 5 shows the current and voltage curves for a DOI of 2ms.  It can be noted that the curve's initial portion is identical to that of Figure 4.  However on reaching the DOI of 2ms, the injector driver switches off the injector, meaning that the transistor collector goes back to 12V.  It is noted here that the DOI of 2ms is just after the coil driver transitioned from the 4 to 1 Amp scheme and hence the injector might not work linearly if a DOI of less than 2ms is required.

Going back to the injector historical evolution, after a short spell of single point injection the port fuel injection became predominant in street cars and this drove the fuel injection technology to become more streamlined and low cost.  The Bosch injector body style is very popular and many manufacturers produce injectors in this style.  Injector fuel flow sizes are also found in a wide range.  When the industry went from single point to port fuel injection, the fuel flow per injector was reduced and hence the injector internals became smaller and could be opened by smaller electromagnets.  Hence the coils became smaller and having higher impedance (resistance).  Thus the port fuel injector on street cars are usually high impedance injectors, 12 Ohms and above, and do not require a peak and hold driver.  When an injector does not require a peak and hold feature it is said to be operated in saturation. That is full battery voltage is applied and the current would increase from an initial value of zero to the saturated value of current.  The associated electronics in the driver are simpler and the injector can be given 12V supply even manually to check for operation.  Low impedance injectors cannot be manually connected to a 12V supply as they will get damaged by the prolonged high current that will pass through them. The higher flow rate injectors are still today low impedance and hence require a peak and hold circuit.  However the highest flow rate of high impedance injectors is quite high already and would probably keep increasing in the future.

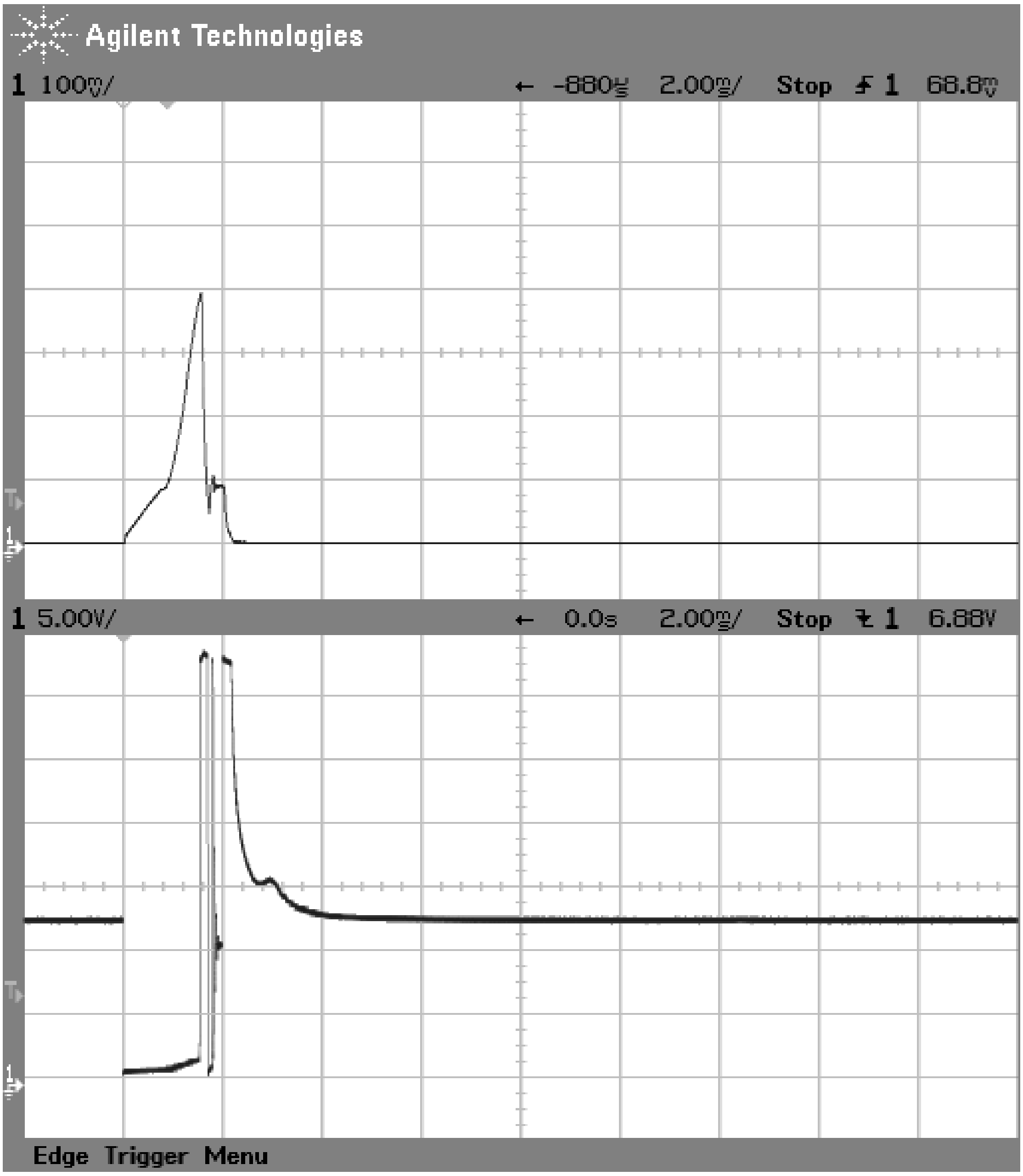



**Figure 5  Current and voltage curves, DOI 2ms, low impedance injector**

Figure 6 shows the current and voltage curves for a saturation injector. The curves shown are for a test without any fuel of a Ford production injector. Once again the current is noticed to increase slowly from zero amps. The current reaches a saturation current of around 0.8Amp just after the 2ms mark (the vertical division is 50mV, the current sensing resistor is 0.1 Ohm, hence 1 division equals 0.5Amp). The injector is switched off at 3ms and the current is shown to decay quickly, but not instantaneously, to zero. The voltage curve shown in the lower part of Figure 6 shows that the full 12 volts are applied to the injector for the whole duration of the injection time. The same injector driver as for Figure 5 is used in this case but since the current never reaches the initial target of 4Amps, the injector driver stays in the initial strategy of applying full supply voltage for the whole duration of the injection cycle.

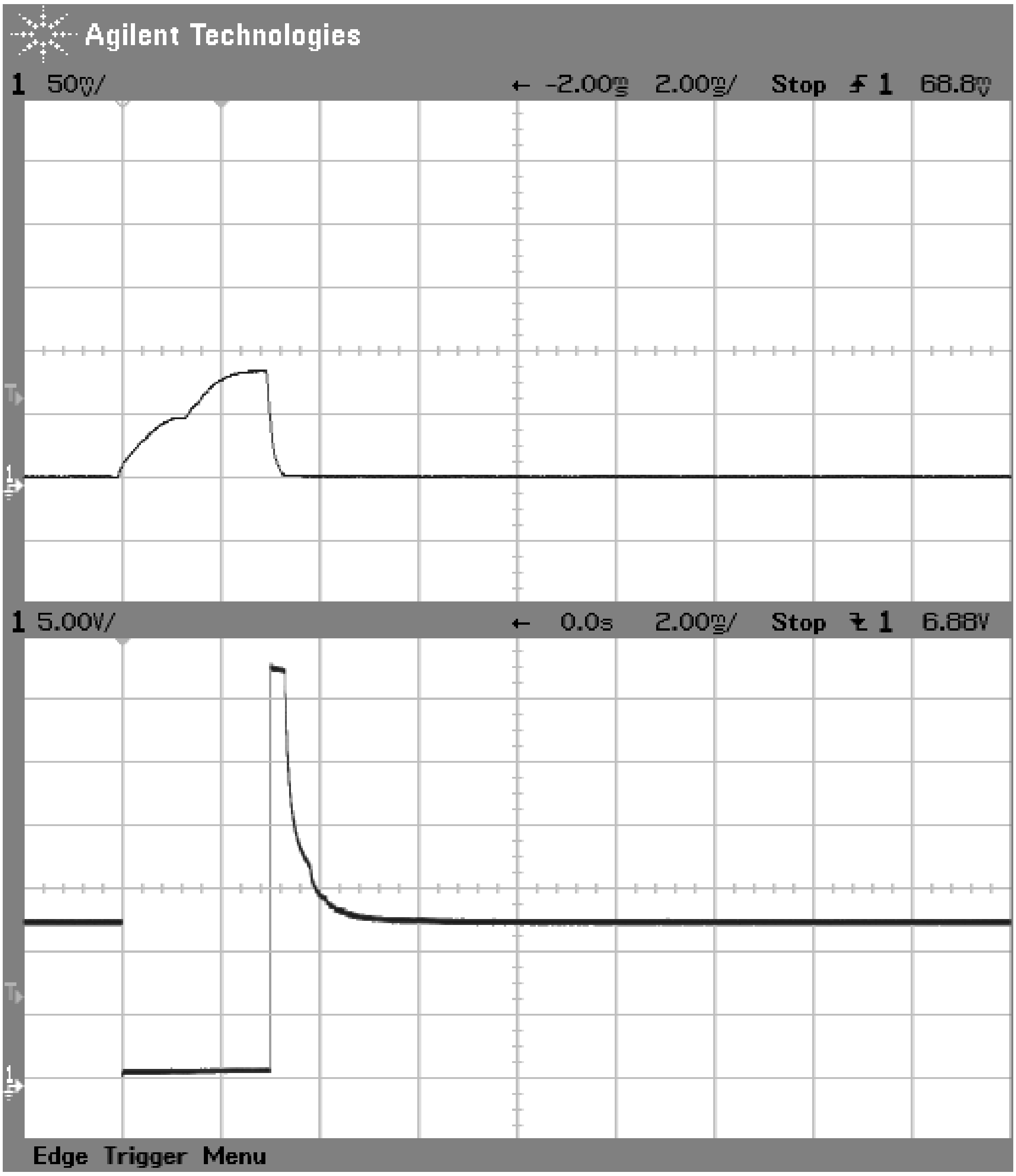
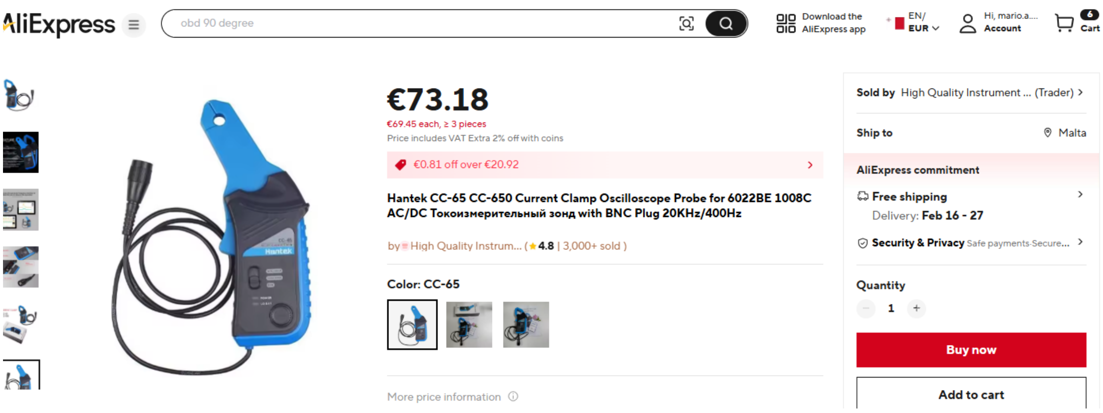


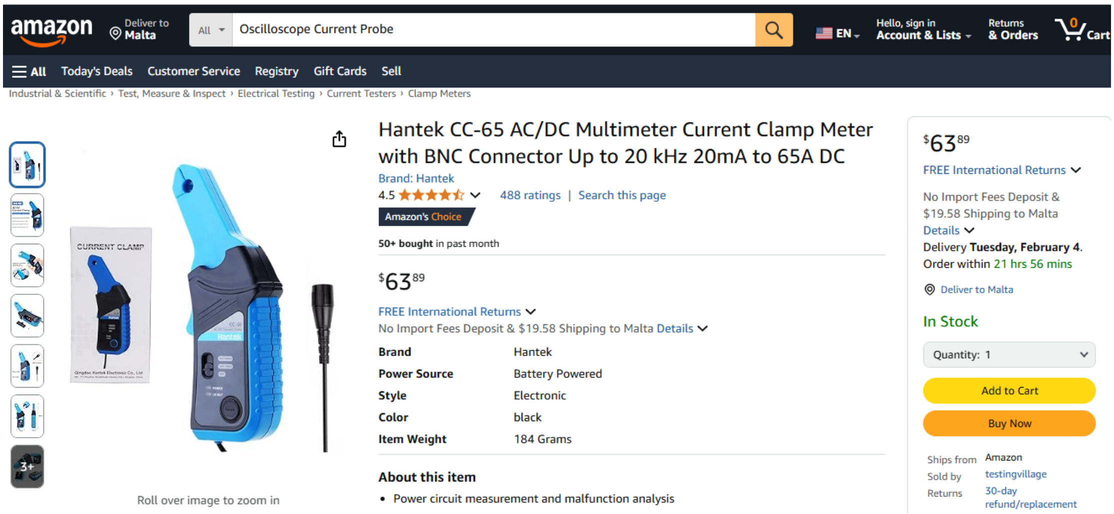

**Figure 6 Current and voltage curves, high impedance injector 3ms DOI**

Looking at the voltage curve in Figure 6, the voltage is noticed to spike upwards on switch off.  This is due to the fact that the injector is an inductor and does its utmost so that current continues to do what it was doing before.  On switch off, current will continue to flow in the coil but since it finds a closed passage through the transistor, the voltage would rise until the protection diodes in the transistor circuit open as a means of protecting the electronics from too high voltage spikes.  It is noted here that the saturation current is not reached before 2ms DOI.  Hence it should become even more apparent that too short DOI's cannot and should not be imposed on injectors.  At 2ms, not even the current has enough time to reach its ultimate value and therefore the mechanical movement of parts is also probably requiring similar values of time.  Therefore the dead or delay time mentioned earlier can also be linked to the current delay of the injector.

Gasoline Direct Injection GDI uses injectors that are also operated in peak and hold mode as the pressure of the fuel is quite high.
Diesel injectors also operate in Peak and Hold mode but are supplied in peak mode with a 70 or 80 V supply to make the current go up very fast.  Diesel injectors need to open and close in a very fast manner and example the longest pulse of a diesel injector is just around 1ms. Modern Diesel ECU will operate the injector in multiple pulses, in Pilot and Main mode and hence the pilot can be appreciated to be very small say 0.2 or 0.3 ms.

Injector signals can be checked by the oscilloscope because they are low voltage. However appreciate that there will be some flyback voltage spike at the opening instance (by opening here is meant transistor opening meaning switch off of current). The low voltage signal going from the ECU to the spark plug coils is better if not read directly by oscilloscope as the low voltage of the could still goes to 300 or 400V which may be beyond the oscilloscope capability.  A voltage divider by say connecting 1k and 10 K resistors in series and reading off across the 1k resistor is a good way to read the low voltage side of the coil.  However a much safer and more practical way is to use a current clamp connected to the oscilloscope.
Signals operating solenoid valves such as EGR, pressure control solenoid, AdBlue injector, fuel pump, etc can all be monitored safely and without cutting any cables using the current clamp connected to the oscilloscope.  The oscilloscope connection is called BNC .






## ***Ignition Coil Switching***

The ignition coil generates a spark on the high tension side when the low tension current is turned off. The coils would initially be un-magnetized. Then the ECU will turn on the current to the coil by means of switching the low side transistor on. However since the coil is an inductor, the fact that the transistor (or switch) is turned on, does not mean that current will start flowing immediately with a constant value. Inductors resist the change of current and hence the coil will start allowing current to go through very slowly. Eventually the current will reach the maximum value that can go through, but this will take some time. The maximum current that can be reached is called the saturation current, and is a function of the supply voltage and the resistance of the coil. The time it takes for the current to reach saturation is a function of the inductance of the coil. Coils are not identical and both the resistance as well as the inductance can vary. That is coils can draw different quantities of current, examples of very distinct current consumptions are the 12V coil and the ballast (6V or 9V) coil. The time to reach saturation can also be quite different, examples of distinctive coil reaction times are the “usual” vs “racing” coils (racing coils are expected to reach saturation quicker), refer to Figure 7. The racing coil needs to be faster because typically racing engines go to higher rpm, and since the available time at the higher speed is less, the coil needs to act quicker. The coil saturation time is a time not an angle. The fact that in the older make and break system the coil was turned on for a portion of the revolution determined by the cam profile and contact breaker gap, was only because it was mechanically feasible. In an ECU it makes more sense to turn on the current to the coil for enough time to reach saturation but no more than that (so that the coil heats up less and consume less electrical power). Therefore the time (in ms) that the coil needs to be turned on needs to be specified in the ECU. The coil on-time will occupy a much larger proportion of the revolution at higher speeds. Hence it is also important to appreciate that using sequential ignition alleviates the burden from coils as the coil will have the time of two revolutions if need be, while if wasted spark is used, it will only have the time for one rev as the maximum allowable.

In Figure 7 it is noted that the Motorcraft coil reaches a very distinguishable saturation current after say 2.6ms, the Ducellier coil and the Honda double ended coil do not show such a prominent saturation current but are surely slower than the

Motorcraft. However it is noted that the Motorcraft coil consumes a much greater current, approximately 8Amps (100mV per vertical division being sensed across a 0.01 Ohm current sensing resistor connected between the emitter and ground). The Ducellier consumes around 4Amp while the Honda around 5Amp. It is noted that the Honda coil comes from a 12000rpm engine but due to the fact that it is only required to generate spark for two rather than 4 cylinders, it can take advantage of longer charging times as if it were responsible for a 6000rpm engine.

Note that the word “charging” of the coil was avoided in the above because charging is a good word to use with batteries and capacitors due to the fact that they store charge. Inductors do not store charge hence the word charge is not a proper match. Batteries and capacitor (which store charge) try to keep their voltage (and charge) constant. Inductors (coils) which have magnetic field in them and the associated magnetic flux, try to keep the flux constant. Due to the fact that the maintainment of flux requires a current to flow, the inductors would hence try to keep constant current flowing in them. The flow of current in the coil for longer than the saturation time does not build (or strengthen) the flux any further. The same spark will be obtained from the high tension side regardless of the duration of current beyond the saturation time. Therefore, allowing current to flow in the coil beyond the saturation point will only heat up the coil and consume more electrical power. Hence it makes most sense to turn on the coil for the required time only and leave it off for all the rest of the available time.

As mentioned earlier, the coil tries to keep the magnetic flux constant in its magnetic core. When initially there is no magnetic flux the coil would resist the building up of the flux and this opposition to the building up of the flux would be manifested by the impedance (resistance) that the coil would have initially. Subsequently, when an appreciable or the saturated level of current is flowing, the flux would be at a high level. The coil would also like that flux remains constant, in this case a high value, which would require the current to continue to flow. The ignition coil actually has two sets of windings, the low tension winding and the high tension winding. The flux is built by supplying current to the low tension winding. When the low tension current is turned off, the coil would try whatever it takes to keep the flux constant, hence is tries to keep the current flowing in the primary winding and it also tries to keep the flux constant by initiating a current in the high tension winding. This is what generates the spark. That is on turning off the current in low tension side, the coil would find an easier way to support its internal magnetic flux by making a current to flow in the secondary winding. The secondary winding has many more turns than the primary, so with the level of flux available, a much higher voltage is generated which can make a spark bridge the spark plug gap.

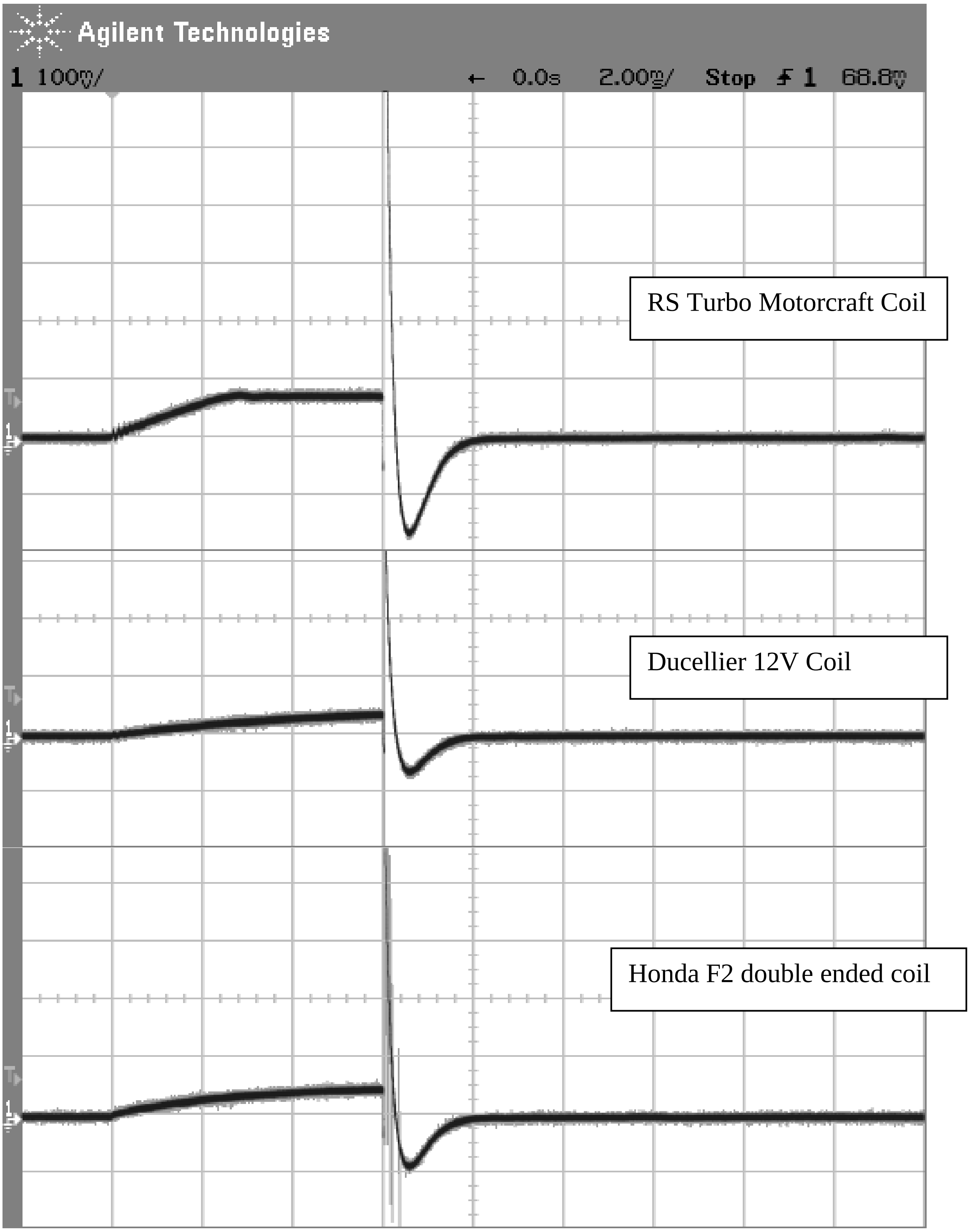


**Figure 7  Current curves through various 12V ignition coils**

For Automotive use the slow speed and hence cheap oscilloscope is enough. Two examples from local suppliers are