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ION SENSE TECHNOLOGY FOR ENGINE DIAGNOSIS

BACHELOR'S THESIS

supervised by Dr. Javier Martínez García Tenorio

Double Bachelor's Degree in Electrical Engineering and Industrial Electronics and Automation Engineering

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This project has been developed on behalf of BRP-Rotax as an internship.

It is classified as confidential.

Supervisor at BRP-Rotax: Dipl.-Ing. Patrick Waldl

Foreword

Without knowing at first, I ended up living and working 30 minutes away from Mauthausen concentration camp where my great grandfather was one of the 4427 Spanish murdered. My family came to visit me but also to finally make it to the Mauthausen Memorial.

This BSc. Thesis is in memory of ***Joaquín Burjalés Gas***
(Xerta, 1905 – Mauthausen 1942).

This has been possible thanks to the European Union, local, and private support that has made this possible. Thanks to my university, as a member of the Aurora Alliance, for granting me with the Aurora Traineeship scholarship.

Thanks to Rotax for allowing me to develop this project on his behalf with the equipment and resources needed, from the software to the hardware. It wouldn't have been the same without the Hardware Electric development team headed by Dipl.-Ing. Manfred Möseneder. It has helped me to move on in life both professionally and personally.

This project and internship would not have been the same without the mentoring and support from Dipl.-Ing. Patrick Waldl. At the start of this project, I knew little to nothing regarding combustion engines, but his knowledge made it a learning experience day after day. Wish him all the best in the Project he has underway.

Also, the help from the RC-LowCAP project was extremely appreciated especially from Dipl.-Ing. Gabriel Gruber from TU Graz.

I must also thank Dr. Javier Martínez García Tenorio for his support when I needed it and making it so easy for me to carry out this dissertation in remote but also in person whenever I was in Catalonia.

And the most important of all, all the people who have put up with me during the completion of this work: relatives, friends from Catalonia and especially the international ones to whom the having to put up with me day to day was outsourced; especially Gabriel, Juan, Lidia, Rose (my fellow Austrian), and Valeria in Austria. Hope our lives merge together in the future. Without your moral support it would not have been possible.

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Abbreviations

TDC	Top Dead Center
ATDC	After TDC
BTDC	Before TDC
BDC	Bottom Dead Center
ABDC	After BDC
BBDC	Before BDC
IC	Internal Combustion
LPF	Low-Pass Filter
IMEP	Indicated Mean Effective Pressure
CA	Crank Angle
FFT	Fast Fourier Transform
COP	Coil on Plug

Abstract

This Bachelor Thesis focuses on the implementation of the Ion Sense technology. This implementation is made for the four-stroke Rotax engines. Future regulations in the market space will force an implementation of sensing technology to ensure and monitor the quality of the ignition that is directly linked to the emissions of the engines.

In the 90s this measuring method was developed, and sensing possibilities appeared. Misfire detection, one of the possibilities that was found is the main objective of this Thesis.

The implementation path chosen is based on the TU Graz research conducted in the past years that led to a sensing circuit design. It was validated and used for thermodynamic evaluation of the combustion, an early-stage study for misfire determination was also conducted.

A huge variety of factors had to be considered to implement it at Rotax, such as: higher rotation speeds, different ignition coils and all and all a different combustion chamber that could potentially affect the shape of the ion sensing. Because of that, this Thesis will show the trials and tribulations associated to achieve misfire detection.

Resum

Aquest Treball Final de Grau (TFG) es centra en la implementació de la tecnologia “Ion Sense”, sensat d’ions. Aquesta implementació es fa per als motors Rotax de quatre temps. Les futures regulacions al mercat obligaran a la implantació de tecnologia de sensat de la qualitat de la combustió per a garantir i controlar la qualitat de la ignició. Aquesta està directament relacionada amb les emissions nocives dels motors.

Als anys 90 aquest mètode de mesura va ser descobert i desenvolupat i van aparèixer possibilitats de detecció de la combustió. L’objectiu d’aquest treball és treballar en una d’aquestes possibilitats que es van obrir com és el que es coneix com “misfire”, no ignició.

El camí d'implementació triat es basa en la recerca que TU Graz ha dut a terme en els últims anys que va conduir a la creació d’un circuit de mesura. El disseny es va validar i es va utilitzar per a realitzar un estudi termodinàmic de la combustió. També es van fer passos per a detectar cicles sense combustió.

Es va haver de considerar una gran varietat de factors a l’hora d’implementar-lo a Rotax, com ara: una velocitat de rotació més alta, una bobines d'ignició diferent, en definitiva un motor diferent amb una cambra de combustió que podria afectar potencialment les lectura de l’”Ion Sense”. Es per això que en aquest Treball s’exposaran els problemes i solucions aportades per a la implantació de la tecnologia i a la detecció de problemes en la combustió.

1. Introduction

Nowadays the development of electric powertrains is making regulations for petrol-based engines tighter [1].

Although the transformation of the powertrain industry is happening already, a skeptic market makes the petrol engines still an excellent competitor. As it can be seen in Figure 1 the market share of the petrol engines is still dominant.

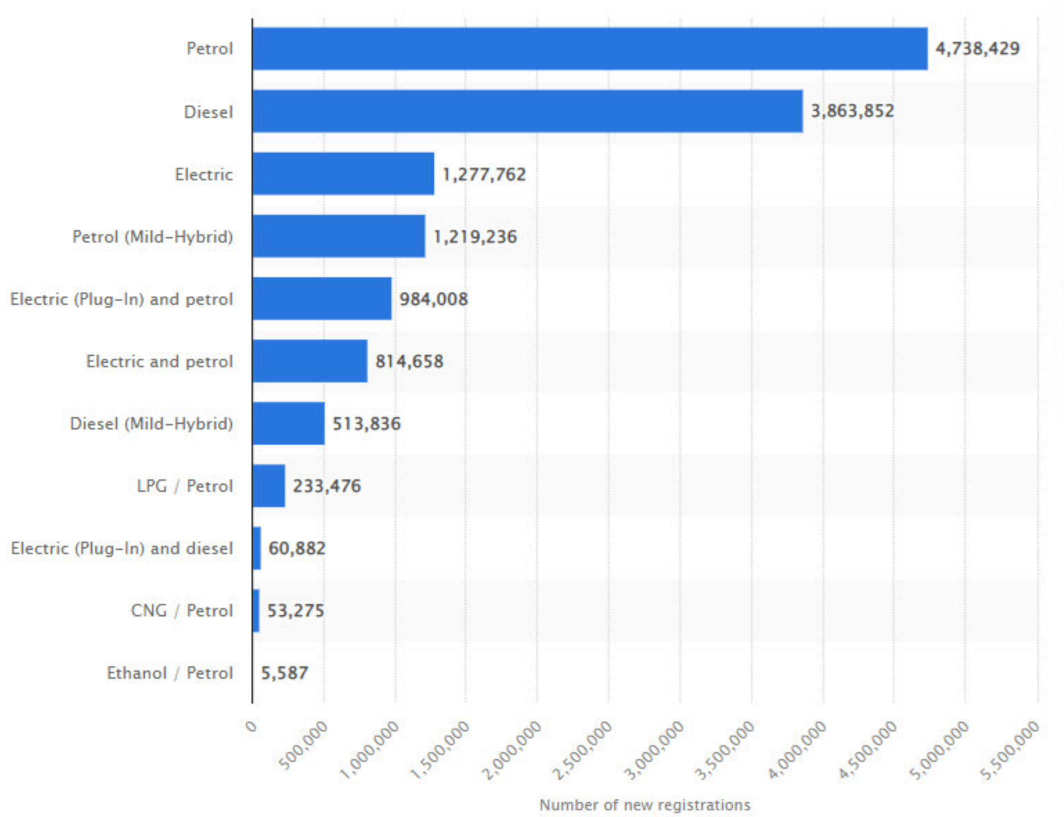


Figure 1 Commercial vehicle and passenger car registration in the European Union in 2021, by leading powertrain [2]

The ion sense technology, first researched in the 70's [3] finding in the 90's possibilities for combustion analysis [4]. It has been used in the past for some engine manufacturers but is not well spread as research needs to be carried out to understand the readings. This has been analyzed and proven in the past, but the cost sensitive sector did not implement it, some examples could be pointed out [5], [6] and [7].

At Rotax different vehicles are developed that are subject to different emission regulations but overall, a better sensing of the engine combustion is to be implemented to allow for a better control that directly leads to a reduction of emissions.

In the past the RC-LowCAP (Research Centre for Low Carbon Special Powertrain), a research center from TUGraz university, worked in the ion sensing technology. Rotax was a company sponsor of that research. Major thermodynamic research for two-stroke ion sensing has been carried out in the past with positive outcomes that lead Rotax to be interested in bringing home this research outcome [8]. Although the technology was proven from the fiscal standpoint, development was needed to really understand the outputs of the sensing device.

A good correlation between the ionization signal and combustion parameters has been found: in-cylinder pressure [9], burning rate [10] and [11], knock intensity [9] and [12] and air-fuel ratio [13], [14].

Most of the research in the past has been focused on the two-stroke engines, but nowadays with the increase of the market share for four-stroke engines.

TU Graz developed a sensing device only with passive components that will be used in this Thesis [15]. The implementation of this device brings along some issues that need to be fixed.

The ignition system, as seen in Figure 2, integrates an ignition coil and a spark plug. These two elements generate a spark that ignites the fuel mixture inside of the chamber.

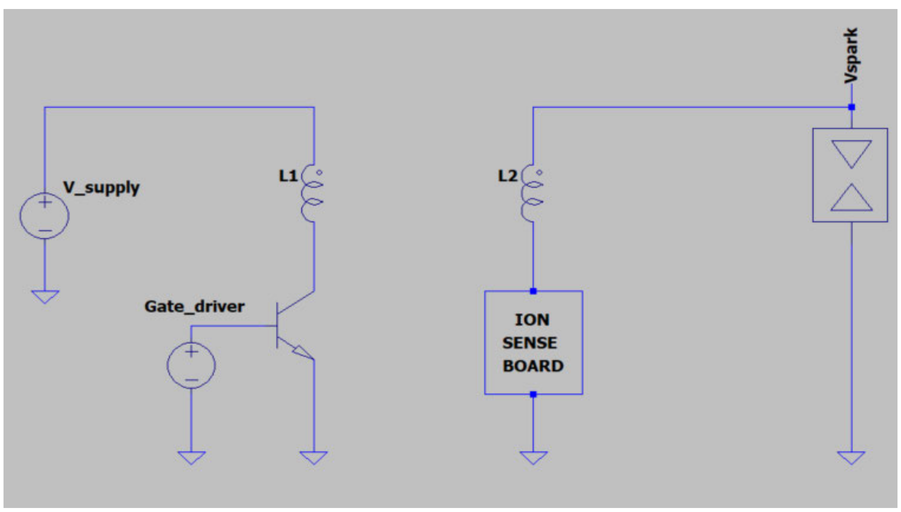


Figure 2 Ignition circuit

Ion sense uses ion concentration for combustion analysis. This ion concentration is proportional to the ion current through the spark plug gap. By measuring the current through the secondary side, we can determine the diagnostics of the engine.

An important disclaimer needs to be made. Ignition systems are not required for diesel engines which rely on compression to ignite the fuel/air mixture. That means that this method cannot be used in this type of powertrains.

1.1. Targets

The targets of this BSc are listed below:

- Study the ignition system for four-stroke engines
- Understand the current methods for engine quality determination
- Implementation of an Ion Sense circuit
- Conduct tests and evaluate the results
- Establish realistic uses of the technology

1.2. Structure

This BSc thesis includes in ‘2 Engine operation’ a basic explanation of four-stroke engines and in ’3 Ignition system’ an explanation of the major parts involved in the ignition system. Secondly, in section ‘4 Ion sense’ an explanation of the Ion Sense will be written together with the opportunities that it brings for engine diagnostics, see ‘5 Combustion issues’. Thirdly, the TU Graz research development will be explained in section ‘4.2.1 TU Graz design’. Finally, the industrialization carried out will be explained in section ‘6 Industrialization of the ignition system with ion sense technology’.

2. Engine operation

This project is based on the analysis of ion sense in 4 stroke engines. In this chapter an explanation of 4 stroke engines will be given.

Four-stroke cycles consist of four piston strokes with every revolution of the crankshaft. This Every stroke has its function:

1. Intake: The piston begins at Top Dead Center (TDC) and moves downward till finishing at Bottom Dead Center (BDC). During this movement suction brings fuel and air into the chamber takes place.
2. Compression: Beginning at BDC and finishing at TDC the piston compresses the air-fuel mixture in preparation for ignition during the power stroke. To achieve a great pressure in the chamber valves, need to be closed.
3. Combustion: By this point the first revolution of the crankshaft has been concluded and the mix is ignited with the spark plug. The energy generated with the combustion generates the desired mechanical work and pushes the piston downwards.
4. Exhaust: during this last stroke the piston goes back to TDC, original position, and by doing that expels the air and remaining mix in the chamber.

In terms of thermodynamics 4 processes can be described in the points before as seen in Figure 3:

- 0-1: During this intake phase the volume increases so we have an isobaric process.
- 1-2: Compression can be described as an adiabatic compression as there is a small increase of temperature and pressure, but no heat is transferred.
- 2-3: Here is where combustion happens, and a lot of heat is generated in a high-pressure chamber. This is an isochoric process.
- 3-4: This thermal energy brings the piston down generating power with the adiabatic expansion.

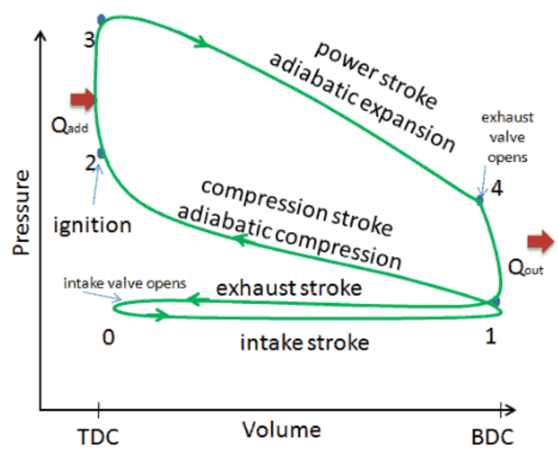


Figure 3 Thermodynamic cycle

To see the cycle, we can check the in-cylinder pressures as shown in Figure 4. All and all the thermodynamics of an engine is a world on its own.

We will see that the pressures are centered around the 0, being the left limit -360˚ and the right 360. It means that the combustion happens after the first revolution. Since it is a 4-stroke combustion engine (CI), it means that there are two crankshaft revolutions per cycle. However, an engine can have more than one cylinder, in this case the ignition phase will be shifted. In our case we have 3 cylinders connected to the same shaft. This topology will have ignition according to equation 1:

$$IG = \frac{720°}{n_{cd}} \quad \textbf{(1)}$$

Where IG stands for Ignition and n_{cd} equals the number of cylinders.

In our case combustion will take place at CA: -240˚, 0˚ and 240˚. Although there are 3 cylinders tests have always been conducted at the middle cylinder so all plots will be centered around 0˚ CA.

The idea is to understand the performance of the engine at different operational points to be able to understand the combustion. To do that different tests at different speeds and loads have been conducted.

Pressure at different speeds:

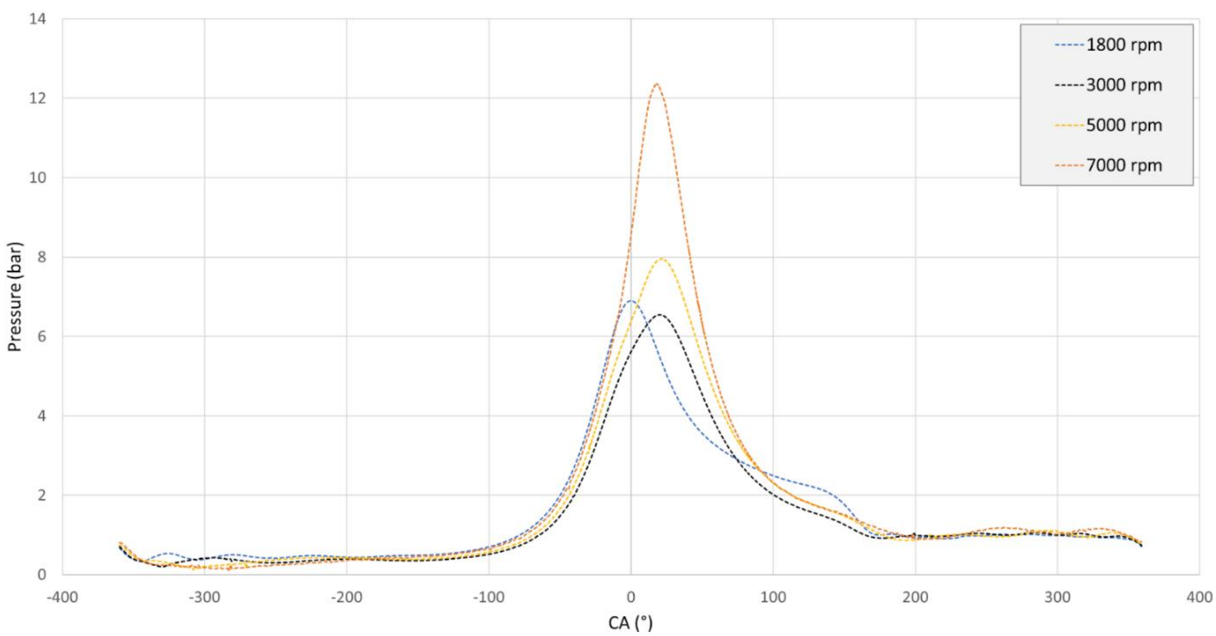
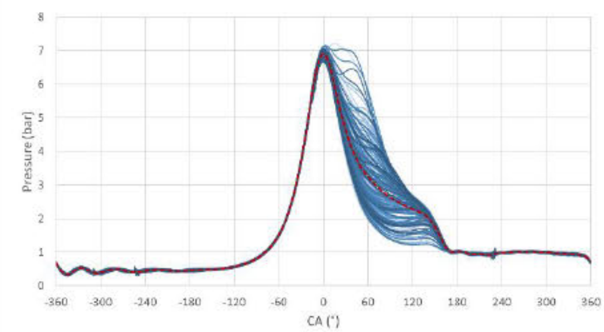
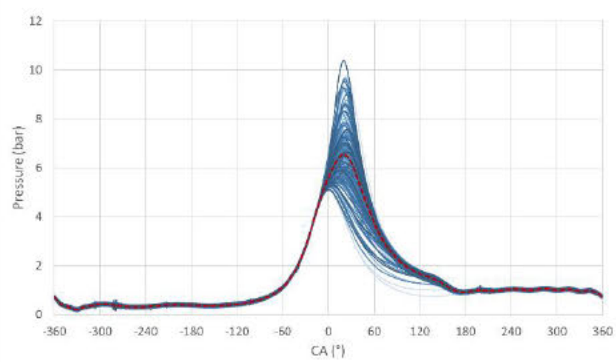
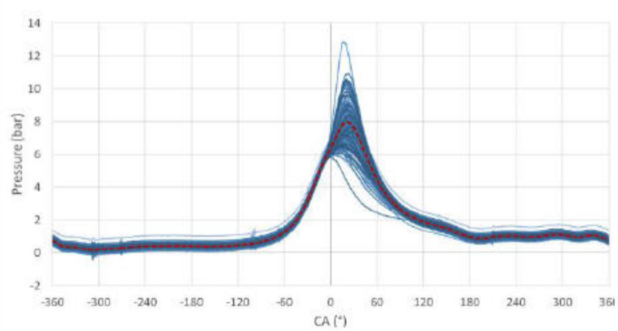


Figure 4 Pressures at no load (average of 200 cycles)

Figure 4 shows the average pressure of 200 cycles from different speeds at no load. As expected from thermodynamics, greater speeds turn in greater in-cylinder pressures. In the Figure 4 it is not exactly the case. We can see that the 1800 rpm average should have a smaller pressure pic. This is due to the high fluctuations caused by the low load. It would be clear at higher load points. This will also create a fluctuation on our measurements.

Table 1 shows how the scattered is the pressure at no load. Every figure of Table 1 shows the 200 cycles in blue and the average value is presented in red. This average corresponds to the pressures presented in Figure 4.

Speed [rpm]	Measurement
1800	
3000	
5000	

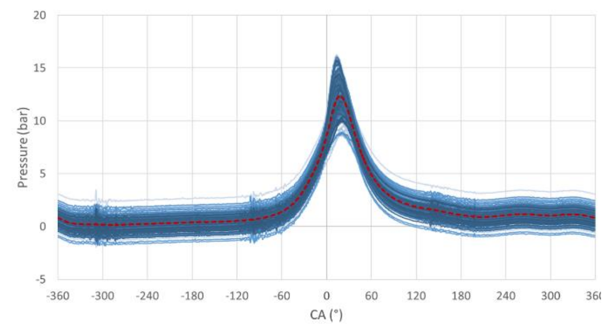
7000	

Table 1 200 cycles with red average

In Figure 5 we can see the different pressure lines corresponding to tests at different loads but with constant speed. Lines are an average of 200 cycles.

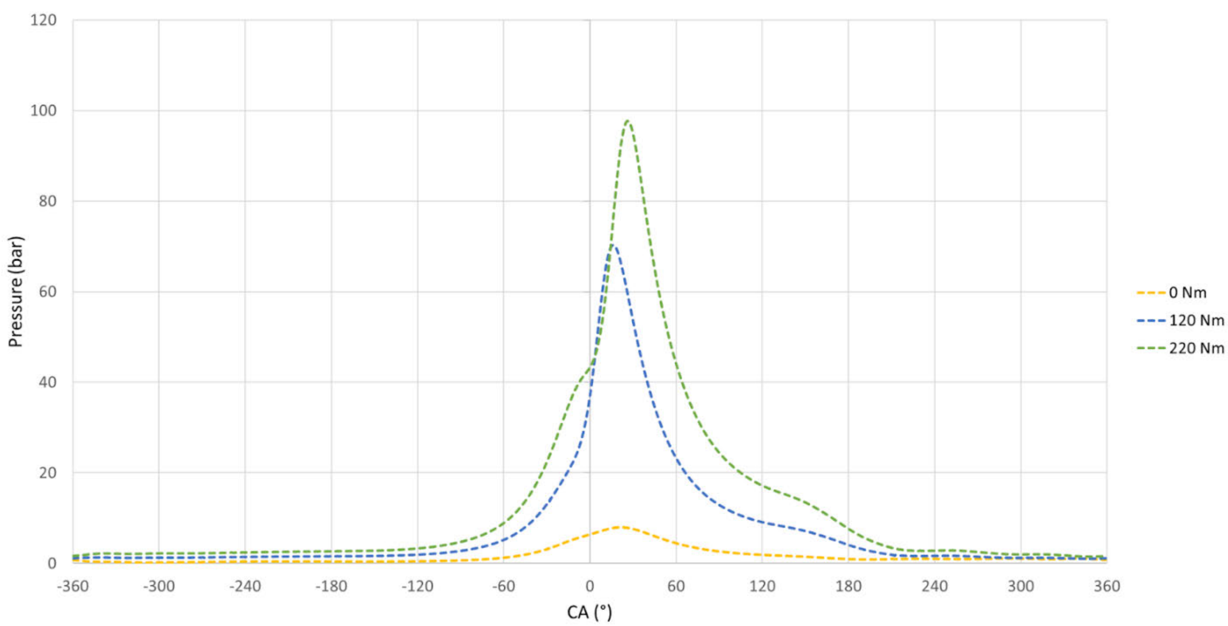


Figure 5 Different pressure lines from different loads at 5000 rpm (average of 200 cycles)

We can see that more lad means more pressure. In Table 2 see how fluctuations are more intense at low loads and pressures are more constant at high loads. This will mean that measurements at high loads will follow a more stable shape.

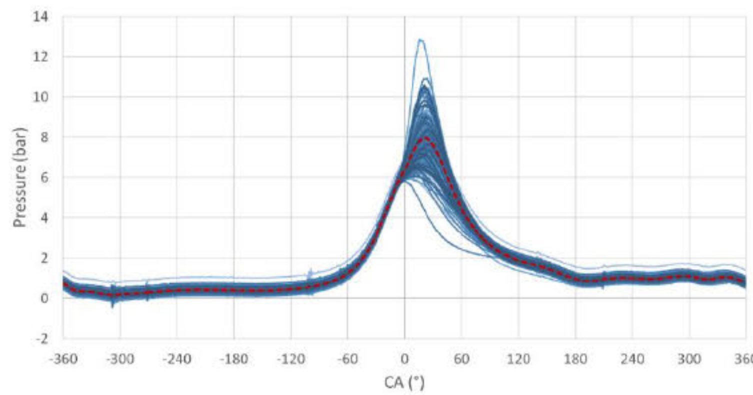
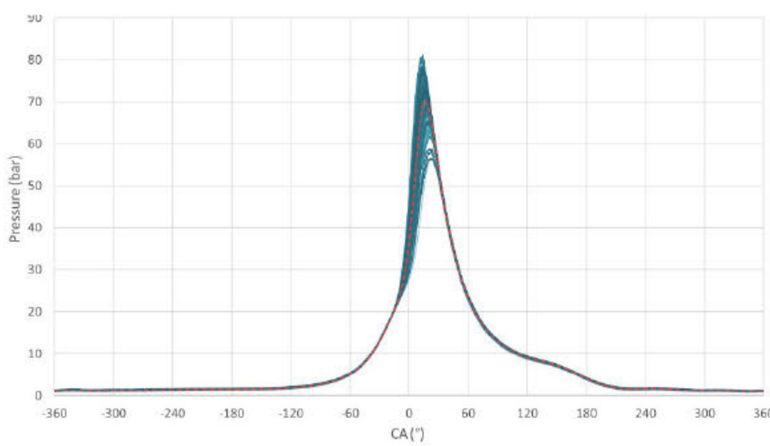
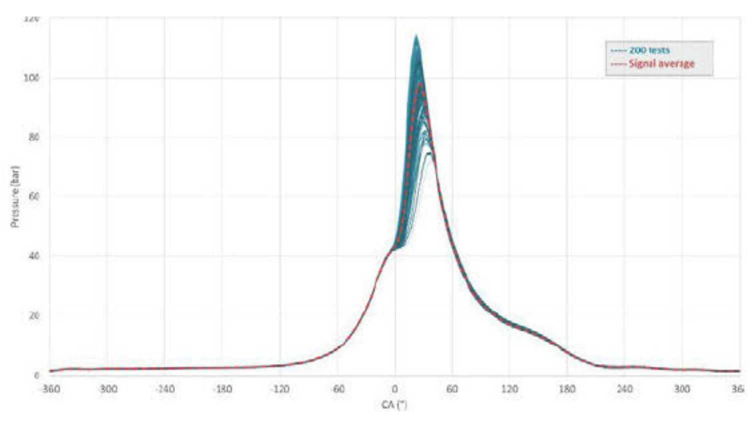
Speed: fixed at 5000 rpm Different loads [Nm]	Measurement
5	
120	
220	

Table 2 Pressures at different load with constant speed for scattering analysis (average in red)

3. Ignition system

3.1. Operation

Figure 6 shows the topology of a commercial ignition circuit. The basic circuit is composed of four elements. First the MOSFET or IGBT that oversees the charging of the ignition coil (dwelling). Second the ignition coil, which basically is a transformer. A diode is placed at the output of the ignition coil. Finally, the spark plug which is where the spark that ignites the mixture and makes the engine run should be happening.

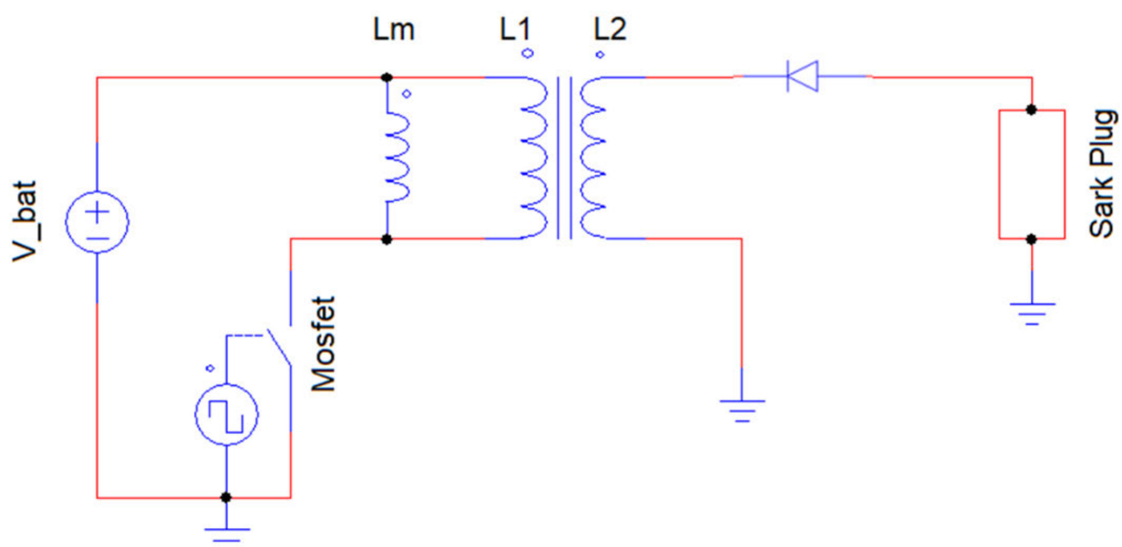


Figure 6 Ignition circuit

The ignition is made of two phases:

1. **Charge/Dwelling:**

   Figure 7 shows the charge of the ignition coil, also known as dwelling. In this phase the switch closes and creates a path that charges the magnetizing reactance of the coil. In this phase it can be seen the use of the diode; a voltage is built up in the secondary side and the diode block the possibility of having a spark (and a current flow). As desired, no flow causing a spark can happen as the diode is against that flow direction.

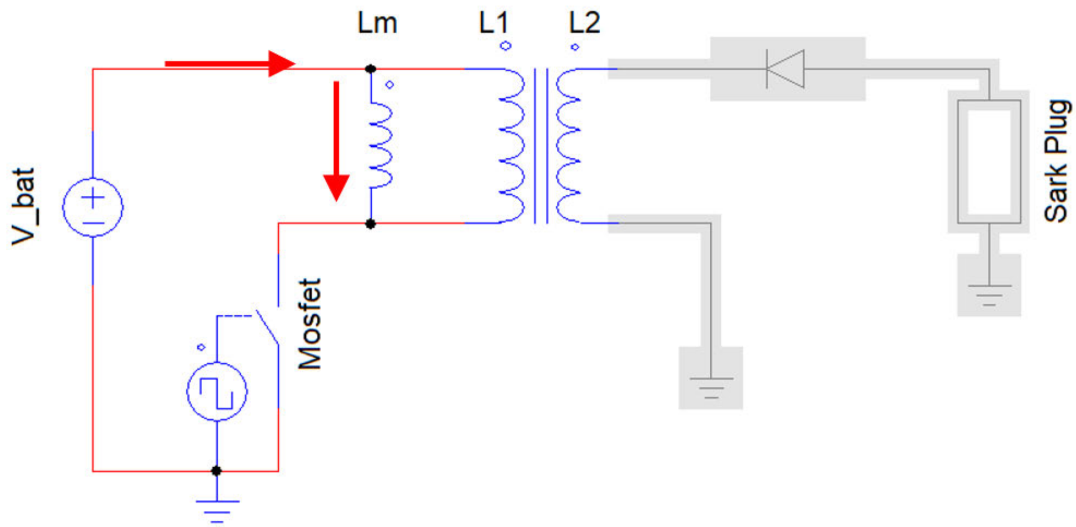


Figure 7 Charging of the coil

In case the diode is not installed the circuit would be like in Figure 8.

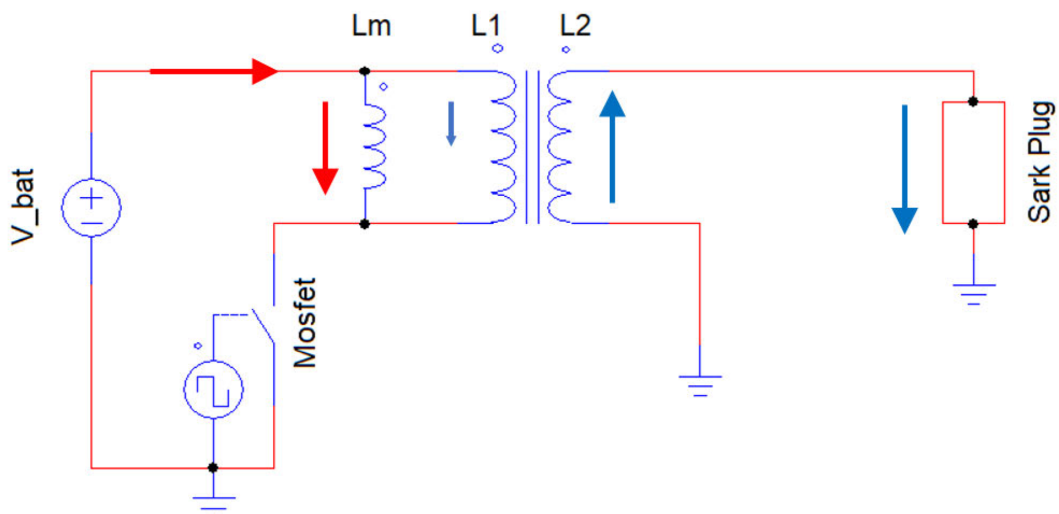


Figure 8 Charge of the coil without using diode

In this case it could happen that a voltage in the secondary side of the coil could generate a spark creating the blue current flow paths, as seen in Figure 8. This is not the desired case as an early ignition would lead to a malfunction of the engine. The dwelling is synchronized so ignition takes place when CA is around TDC - 10˚. This point can be depicted in Figure 9. When ignition happens the in-cylinder pressure rises. The ignition point happens when the charging of the coil is completed and the MOSFET opens as seen in Figure 10. This current is a ramp since the battery voltage is constant, as seen in Figure 11.

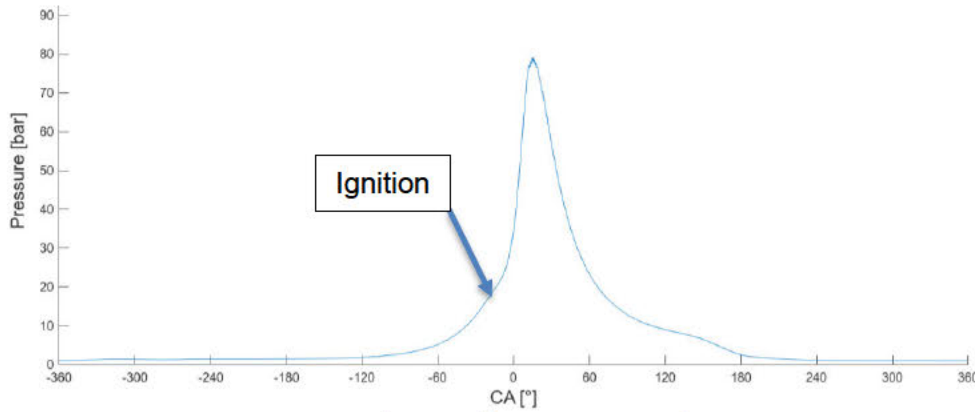


Figure 9 Typical pressure line at 3000 rpm and 106 Nm

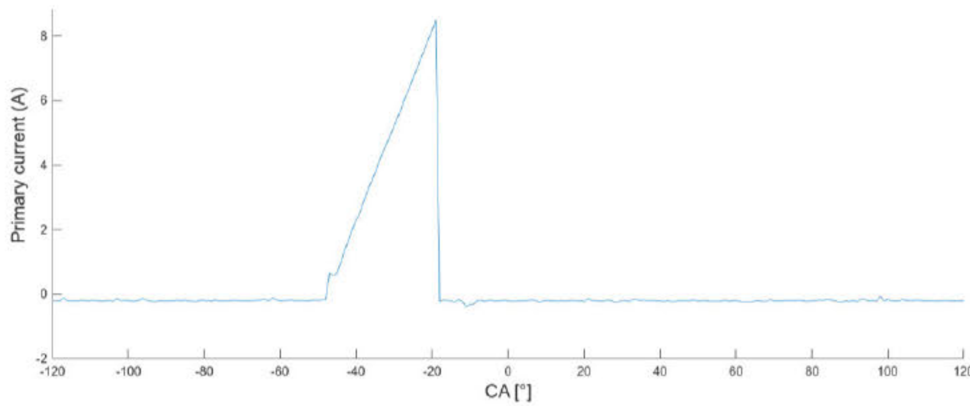


Figure 10 Current from the power supply at 3000 rpm and 106 Nm

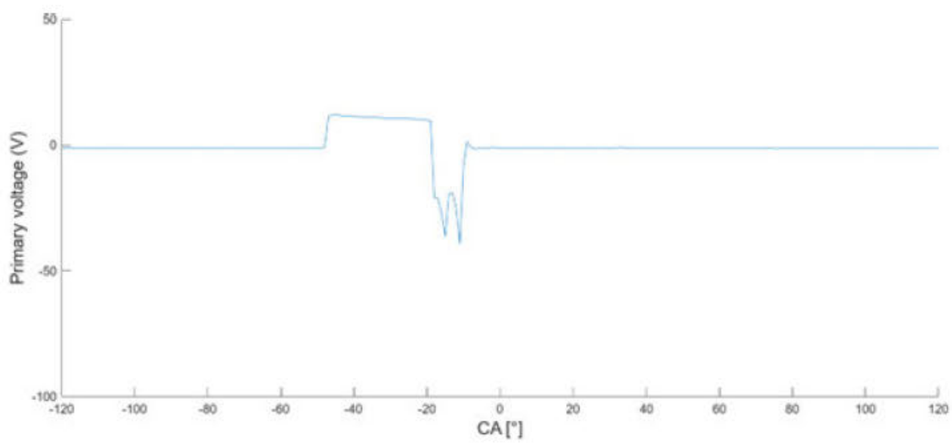


Figure 11 Primary voltage at 3000 rpm and 106 Nm

2. Discharge/Ignition:

When the charge of the primary side of the transformer is done the switch opens and the energy from the magnetizing inductance is transferred to L1 and subsequently to L2. The energy in the secondary side generates a voltage that breaks the airgap and ignite the mixture. The current flow in this case is shown in Figure 12.

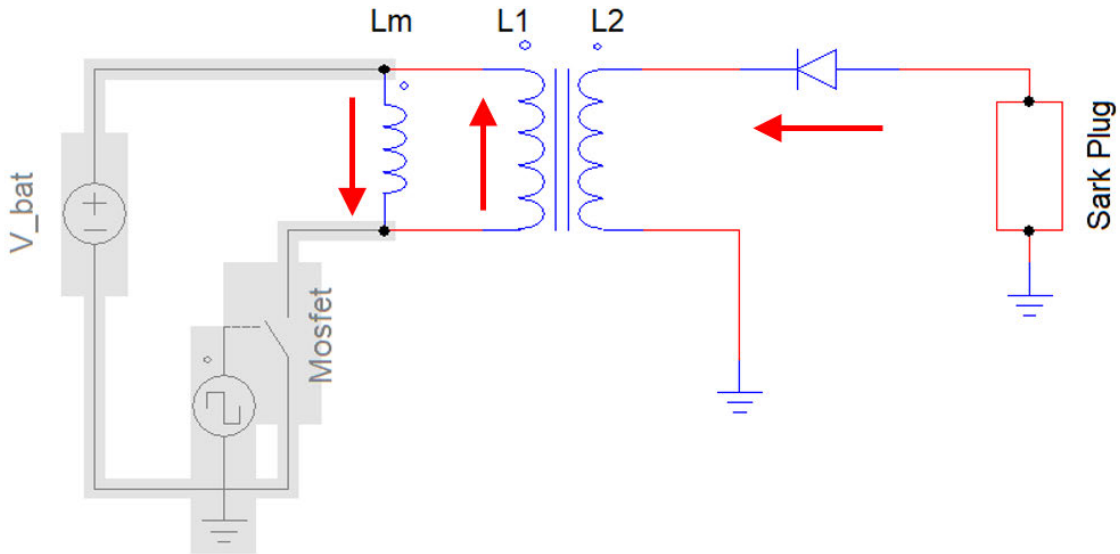


Figure 12 Discharge circuit

As it can be seen in Figure 12, the current in the primary side flows from low to the high side voltage. The high side voltage is negative and smaller than the voltage in the spark. In this way, the diode is forward polarized. At this point the electrons jump the airgap and flow through the secondary mesh.

An important point that should be mentioned that what generates the ignition is the heat transferred from the spark to the mix.

3.1.1. Spark energy

The spark energy is a very important factor, since spark intensity and burn time are related. From a power balance perspective, spark energy is coming from the magnetic energy stored in the magnetic reactance. Magnetic energy is directly related by the time that the MOSFET is conducting. Since the magnetizing current is a ramp dwelling time should be enough to store enough energy capable of igniting the mixture.

The most standardized way of setting the correct dwelling time is by replacing the spark plug with a Zener diode as seen in Figure 13 Coil energy test circuit. The voltage during the spark will be equal to the reverse voltage of the Zener. Recommended Zener voltages are around 800V, which can be achieved by placing a set of zeners in series. The Shunt resistor value was chosen to be 10 ohms. A low resistance value would reduce the quality of the measurement as the voltage would be too small to measure. On the other hand, a big resistance value would have a negative impact on the measurement, as it would make the current too small.

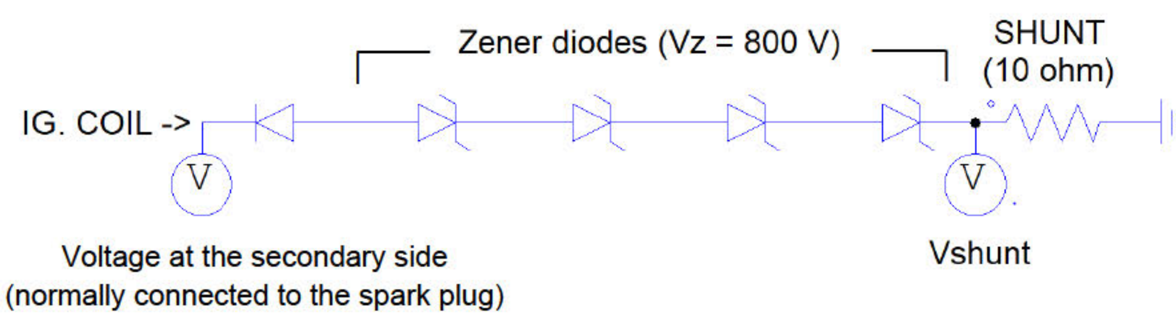


Figure 13 Coil energy test circuit

According to the datasheet of the ignition coil tested for this experiment, the Ion Sense coil, the energy of the coil should be at least 30 mJ at 13,5 V and 3 ms. The value obtained by the manufacturer at his conditions is 35 mJ, higher to ensure the minimum required.

We see in Table 3 that the energy is more a less than what the datasheet says, a possible reduction of the energy could be attributed to the testing losses.

	Dwell time [µs]							
	1000		2000		3000		4000	
V primary [V]	spark time [µs]	Coil energy [mJ]	spark time [µs]	Coil energy [mJ]	spark time [µs]	Coil energy [mJ]	spark time [µs]	Coil energy [mJ]
5	228.7	1.1	443	2.9	530.4	5	590	5.7
7	422.8	2.7	644	7.2	711.2	9.5	818.6	12.9
9	557	4.9	805.1	12.4	905.7	17.4	972.8	20.9
11	657.2	7.7	932.2	18.2	1047	25.1	1060	26.9
12	717.9	9.1	986.2	22	1070	27.6	1062	27.4
13	771.6	10.9	1040	25.2	1078	29.2	1055	24.6
13.5	790	11.8	1067	26.5	1084	29.92	1013	23
13.8	795	12.3	1069	27.3	1100	29.94	1005	22.2
14	811.5	12.6	1069	27.9	1100	29.8	992.6	21.7
15	866.5	14.6	1100	29.8	1080	28.7	960	19.4

Table 3 Spark time and coil energy depending on primary voltage and dwell time

What can be observed in Figure 14 is that when increasing the supply voltage and dwell time the energy increases, however, it can be observed that this is not the case in the last values of the 3 and 4 ms measurements. This is due to the saturation of the primary side of the transformer. When the core of the transformer isn't wholly demagnetized, a buildup of energy can occur, and eventually the core saturates, and the pulse no longer can pass through the transformer [16].

It is especially interesting to observe the 4 ms case, as we can see that when increasing too much the supply the energy reaches a maximum, and when increasing it more, it decreases the energy.

The same phenomenon we had with the energy happens with the spark duration in Figure 15. This means that a good dwelling timing is needed to achieve a great energy transformation and a good ignition. As explained in the '3.1.1 Spark energy' section, energy demand will fluctuate based on the operating conditions of the engine.

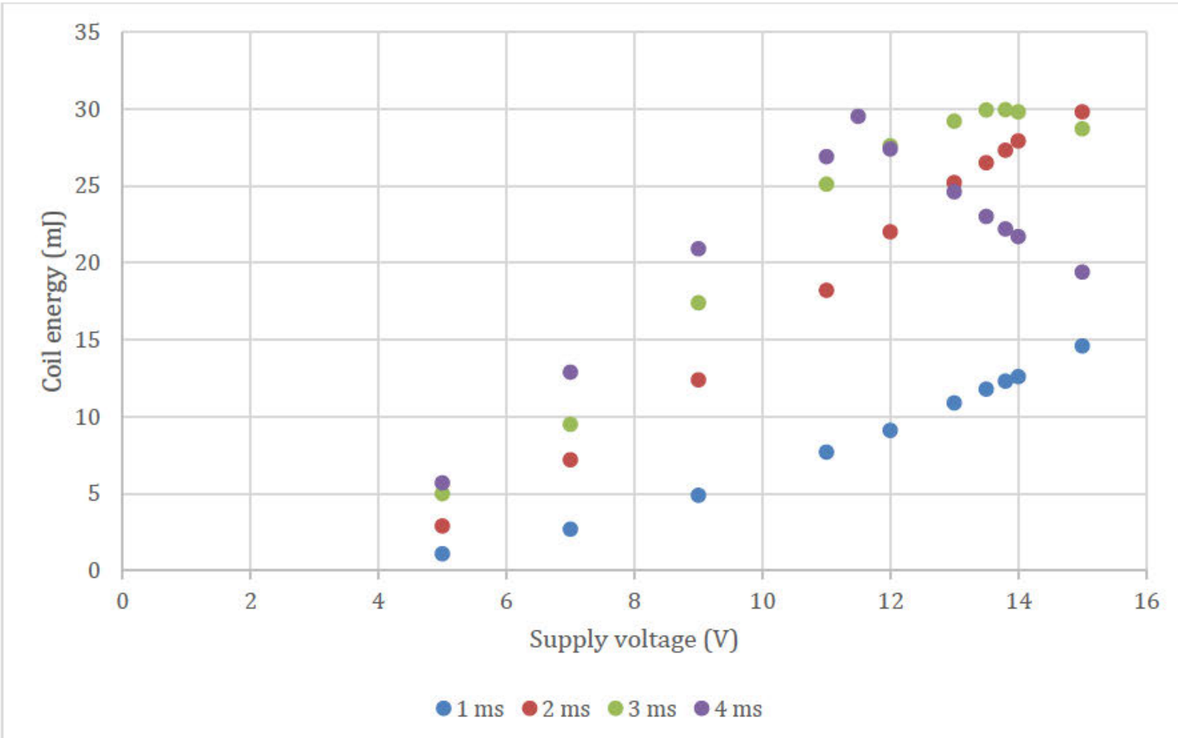


Figure 14 Coil energy (supply voltage, dwell time)

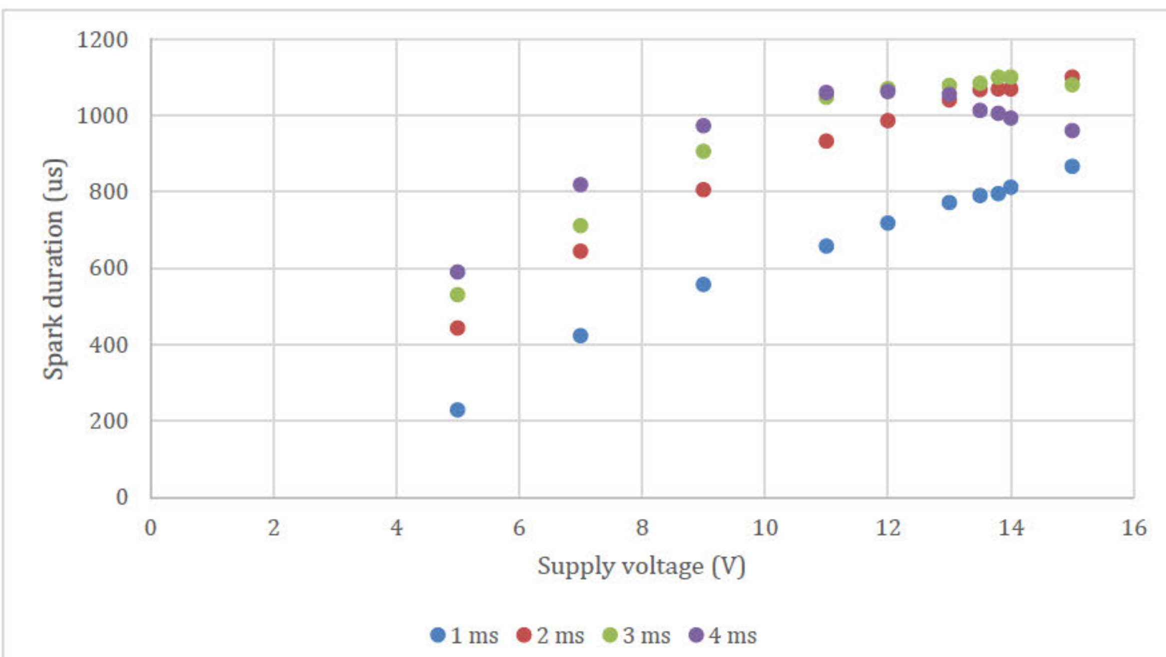


Figure 15 Spark duration (supply voltage, dwell time)

3.2. Components

3.2.1. Spark plugs

Spark plug is a device that is installed into the combustion chamber to initiate burning. It converts the high voltage generated by the ignition coil into a spark between a pair of electrodes, igniting the air and fuel mixture inside of the motor chamber to power the motor.

Effective combustion is the foundation for power and fuel efficiency and the correct selection and usage of the spark plug is needed to achieve great results.

OPERATION

As explained the spark plug generates a spark induced by the high voltage generated by the ignition coil. As current flows from the coil, a voltage develops between the central and ground electrodes. Initially no current can flow because the fuel and air in the gap acts as an insulator, but as the voltage rises further it begins to change the structure of the gasses between the electrodes. Once the voltage exceeds the voltage breakdown of the dielectric the mix becomes ionized. The ionized gas becomes a conductor and allows current to flow across the gap.

Temperature

The heat range of a spark plug is the temperature range in which the spark plug works well thermally. This influences the quality of the combustion. On the one hand, if the firing end temperature of a spark plug drops below its self-cleaning temperature, carbon accumulates on the firing end. This causes the voltage supplied by the ignition system to short circuit resulting in either no spark or a very weak one that may not ignite the fuel mix resulting in misfire.

On the other hand, when the firing end temperature is excessive, the air/fuel mixture in the combustion chamber can pre-ignite which is not desirable as a big part of the ignition power will not be in use and a lower efficiency will be obtained. This will also have a negative impact on the operation life.

Due to the high dependence on temperature for proper thermal operation, there are different spark plug ratings, but the basic concept is outlined in the two types.

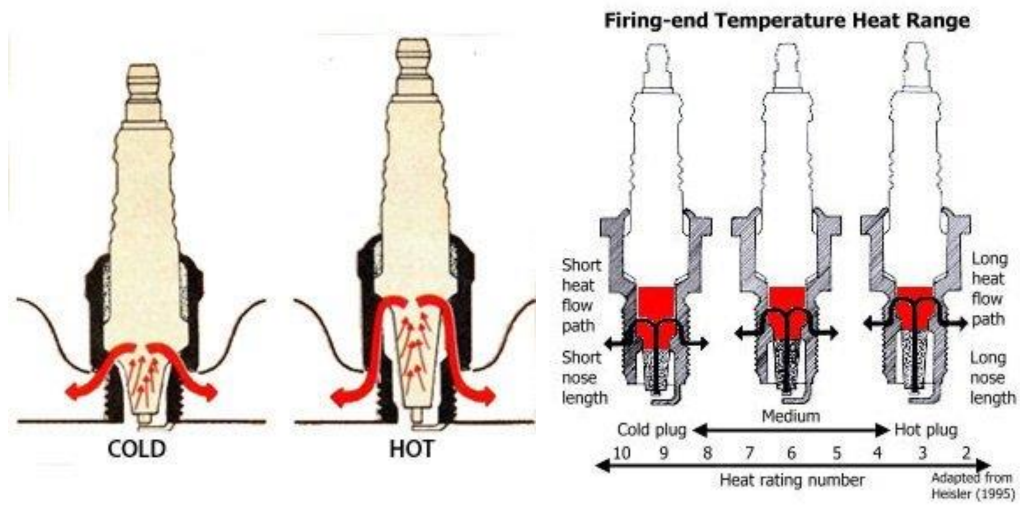


Figure 16 Spark plug heat range [17]

A hot type of spark plug is designed to maintain a temperature at the insulator nose high enough to provide a long heat flow path for the dissipation of heat. A cold-type spark plug is designed to avoid pre-ignition and burn-out of the firing end. They permit faster dissipation of heat through a short flow path.

Cold type is interesting for stressing performance motors such as racing vehicles or the ones for heavy loads because of the faster dissipation. However, the hot type should be used as the higher temperature is able to burn off oil and carbon deposits. This phenomenon describes what is called Self-cleaning characteristics.

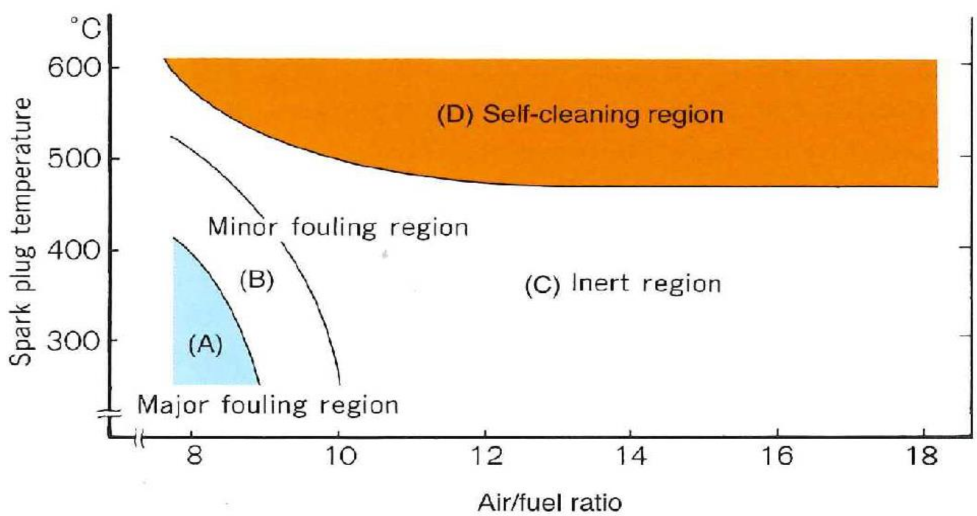


Figure 17 Fouling and self-cleaning regions

As seen in Figure 17Figure 16, air/fuel ratio has an impact on the number of lees that accumulate on the nose and that is the reason why high temperatures are needed for proper elimination of the lees at higher air/fuel ratios.

Voltage

As explained in the operation of spark plugs the spark takes place when the voltage rises. Having a lower voltage than needed is what is known as misfire as voltage leaks along the carbon leakage path.

Typical voltage ranges vary between 12 and 25 kV although they can reach 45 kV depending on the application. Because it will be important for future analysis, the main variables that influence the voltage are to be explained.

It is important to note that during tests without the motor the spark plug will have low voltages compared to operation, this is due, mainly because of the pressure difference.

Figure 18 shows the waveform of the spark plug voltage. The negative pic value seen in Figure 18 depends on both rotational speed and load. Table 4 presents the peak voltages for different running conditions.

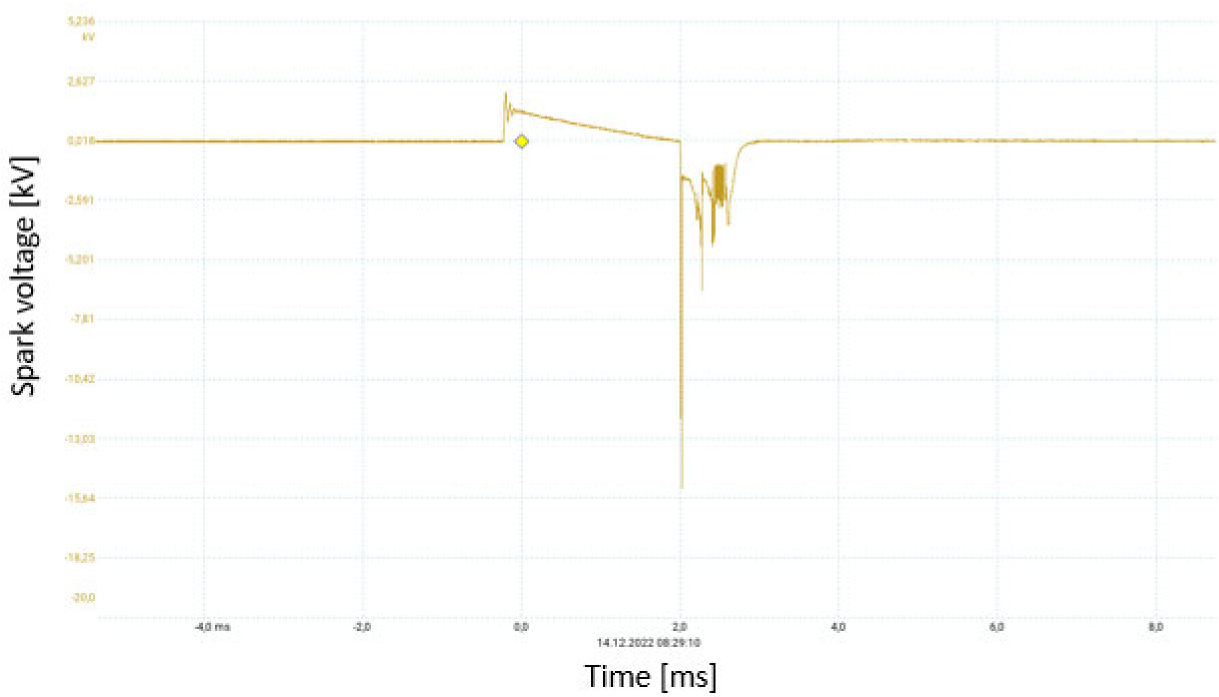


Figure 18 Spark voltage waveform

	1800 rpm	3000 rpm	5000 rpm	7000 rpm
Full load	8,43 kV	15,18 kV	17,85 kV	21,47 kV
No load	6,82 kV	8,482 kV	-	-

Table 4 Spark voltage at different running loads and speeds

As soon as the load of the engine is constant, there is a linear trend between rotational speed and peak voltage. This correlation can be seen in Figure 19. The reason for this effect can be linked to an increase of pressure as soon as the rotational speed increases.

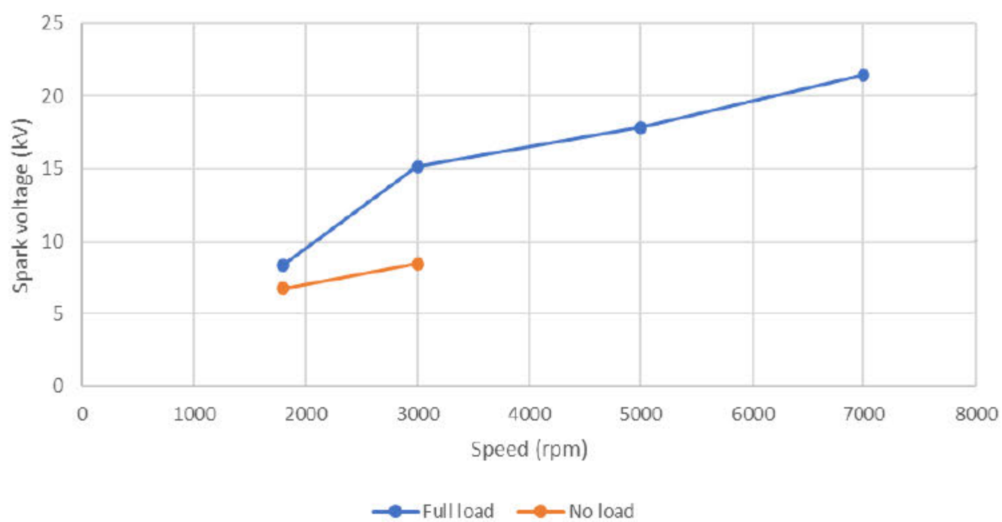


Figure 19 Spark voltage (voltage)

This effect matches with what can be seen in Figure 21, extracted from [18].

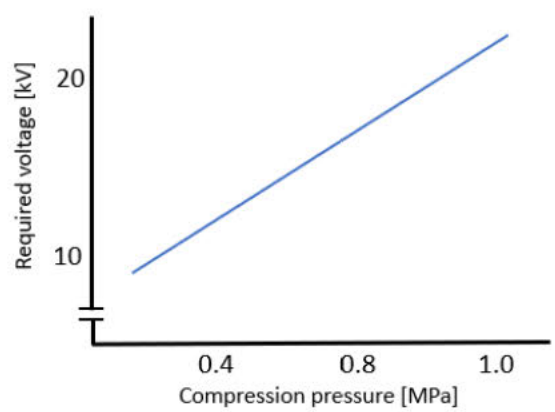


Figure 20 Pressure - Peak voltage [18]

Internal structure

The spark plug has different elements as seen in Figure 21.

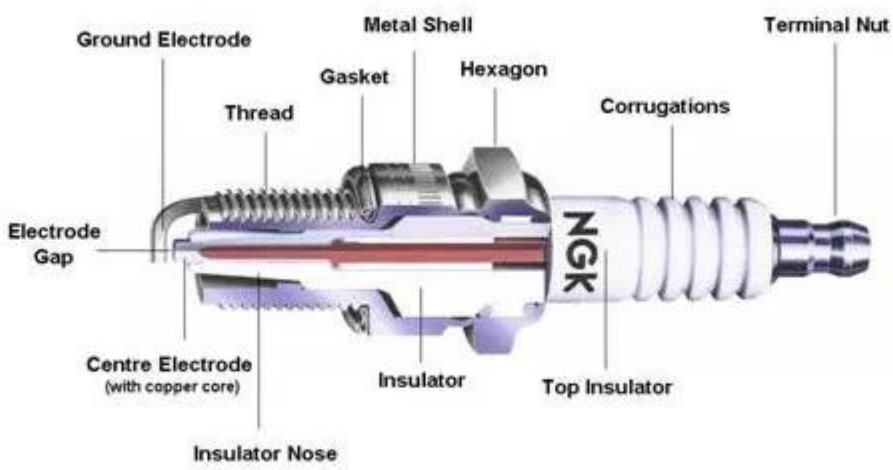


Figure 21 Spark plug internal structure [19]

The main components are the following:

Terminal

The top of the spark plug contains a terminal to connect to the ignition system. Over the years variations in the terminal configuration have been introduced by manufacturers and nowadays we can find 2 types: the removable or solid type connections. The ones used in this project are removable.

Insulator

Insulators are mainly made of highly pure alumina (aluminum oxide) ceramic, which offers heat conduction used for the reduction of the tendency for the insulator to glow with heat and so light the mixture prematurely. It is a corrosion-proof material with high electrical insulation and thermal shock resistance.

The bottom part has a ribbed design that lengths the surface between the high voltage terminal and the grounded metal case of the spark plug, the physical shape of the ribs functions to improve the electrical insulation and prevent electrical energy from leaking along the insulator surface from the terminal to the metal case. Because of that, it helps reduce the flash-over phenomena.

Electrodes

The central electrode can be made of a combination of copper, nickel-iron, chromium, or noble metals. It is connected to the terminal through an internal wire and commonly a ceramic series resistance to reduce emission of RF noise from the sparking. Non-resistor spark plugs, commonly sold without an "R" in the plug type part number, lack this element to reduce electro-magnetic interference with radios and other sensitive equipment. iridium and platinum plugs that have longer lifetimes than copper have become more common.

Spark plug gap

It's the area to be ionized. Spark plugs in automobiles generally have a gap between 0.6 and 1.8 mm depending on the motor. The gap will have a huge impact on the performance of the spark plugs and tests regarding this technology will be conducted to better understand the current shape of the ion sense.

3.2.3. Ignition coils

CONCEPT

An ignition coil is an induction coil that forms part of the ignition system of a vehicle used to step up the voltage of the battery, with a typical value of 12 V, up to thousands of volts to produce a spark able of igniting the mix thanks to a spark plug. In contrast with previous eras, the ignition coils now are connected directly to the spark plug in the cylinder head. This means that no high voltage cables are needed but an ignition coil is needed for every cylinder.

Ignition coils work as if it was a transformer. They basically consist of a primary winding, a secondary winding, the iron core, and a housing with isolation material, most commonly speaking a two-component epoxy resin. The windings are the following:

The primary winding is made of thick copper wire with approx. 200 windings (diameter approx. 0.6mm). The secondary winding is made of thin copper wire with approx. 20000 windings (diameter approx. 0.063 mm)

As soon as the primary coil circuit closes, a magnetic field is generated in the coil. Induced voltage is generated in the coil by self-induction. At the time of ignition, the coil current is switched off by the ignition output stage. The instantaneously collapsing magnetic field generates a high induction voltage in the primary winding. This is transformed on the secondary side of the coil and converted in the transformance ratio.

Ignition coil typical specifications and characteristics can be found in Table 5:

CHARACTERISTICS	RATING
Primary voltage	12–14.7 V
Primary current	6–20 A
Charging time (dwell time)	1.5–4.0 ms
Secondary voltage	25–45 kV
Spark duration	1.3–2.0 ms
Spark energy	10–60 mJ (but could reach 120 mJ)
Number of primary windings	100–250 (0,3–0,6 Ohm)
Number of secondary windings	10.000–25.000 (5–20 kOhm)

Table 5 Typical ignition coil parameters

In the following part the different types of ignition coils used in the project will be shown, regarding circuits and shape.

Circuit:

There are different circuit implementations for an ignition coil but at the end of the day is simple. A transformer to step up the voltage. A simple implementation would be like the one in Figure 22.

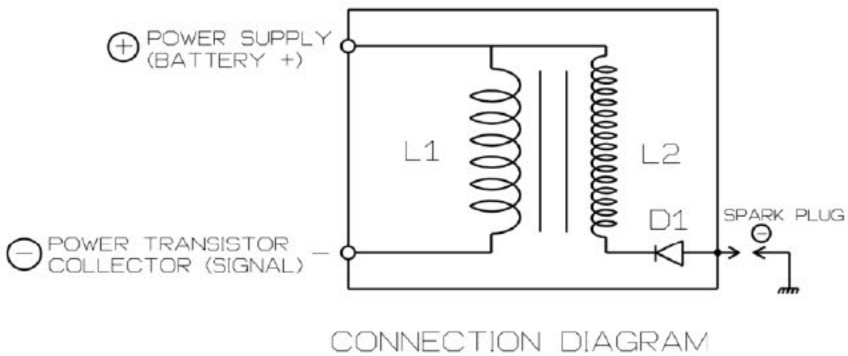


Figure 22 Coil schematic

This is the previous generation of coils used in the company. Only the two windings are in place together with the high voltage diode.

Thigs have improved and the need for a better design was clear. One of the main reasons being the EMIs that the coil was generating. To reduce them a filter in the primary side of the coil was putted in place as can be seen in Figure 23.

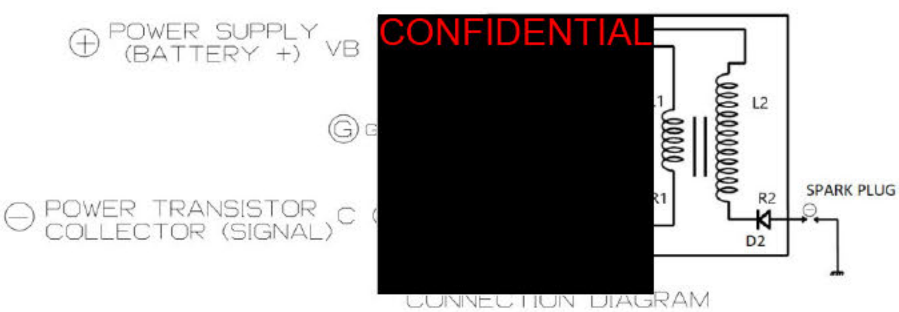


Figure 23 Coil with EMI filter schematic

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In the '3 Ignition system' chapter it will be mentioned the reason of having a coil without high voltage diode. This leads to the need of having a modified coil, and the diagram can be found in Figure 24.

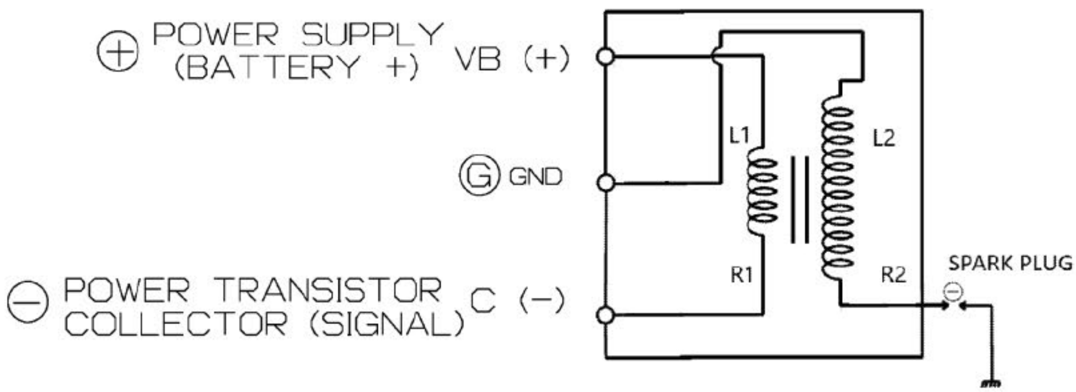

Figure 24 Ignition coil for ion sense (no diode)

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Typology:

External:

This type of coils are the ones they used to be common in the past. You have a transformer, and a high voltage cable connects the coil to the spark plug. This allow the design to be as big as it needs to be but high voltage cables are needed.

Figure 25 Photo of an external coil

Coil on plug:

This is the type of coils used in this project. As the name suggests they have the coil on the plug which is inserted inside of the engine and means that no high voltage cabling is needed from the ignition coil to the spark plug. It is due to that reason that in recent years the use of this kind of coils has increased a lot.

For concept photography one of these coils can be found Figure 25.

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[redacted]

Figure 26 Photo of s coil on plug ignition coil

Figure 26 shows a COP coil, but two main implementation approaches have been made. As we see in the image on top the coil is placed on the top, what is called the boot. From there a spring connects the coil to the spark plug. This coil is designed in a similar way to the independent ignition system shown in Figure 25.

Pencil coil:

This is the other main approach to an ignition coil implementation is by designing a coil that uses the ignition channel space. That way less space is needed at the top and no spring is needed. Figure 27 shows the internal arrangement of the coil.

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[redacted]

Figure 27 Photo of a pencil coil

4. Ion sense

4.1. Concept and theory

The spark plug is made of two different electrodes. When the electrodes are excited, an electric field is created and the ions and electrodes in between lead to a current flow, this current flow is what will be called ion current. As what is sensed is the ionization by the ion current intensity this technology is called ion sensing.

Once ignited, a voltage is applied to the spark plug as studies have shown that there is a proportional correlation between current (created with the voltage) and the ion concentration [20]. This proportionality exists for voltages between 100 and 500 V [8] (page 20) as can be seen in Figure 28.

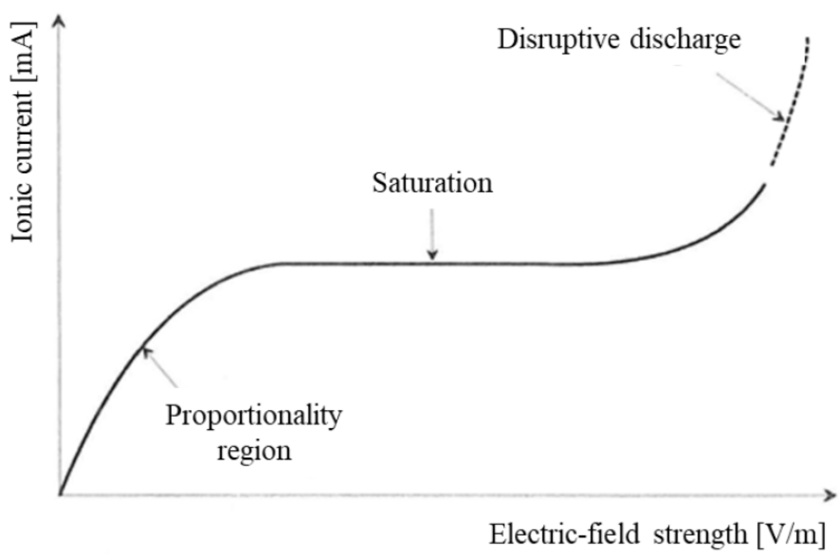


Figure 28 Ionic current intensity trend [21]

Figure 29 represents the ion current measured with the circuit design that will be used in the dissertation. A couple of points should be stated:

- The literature always flips the signal in the x axis. This will not be done to preserve the measurement and not disturb the comparison with other signals.
- We are talking of current as it can be seen in the following graph. In the graphs of this dissertation there will be no transformation between the voltage reading of the shunt resistors to current.

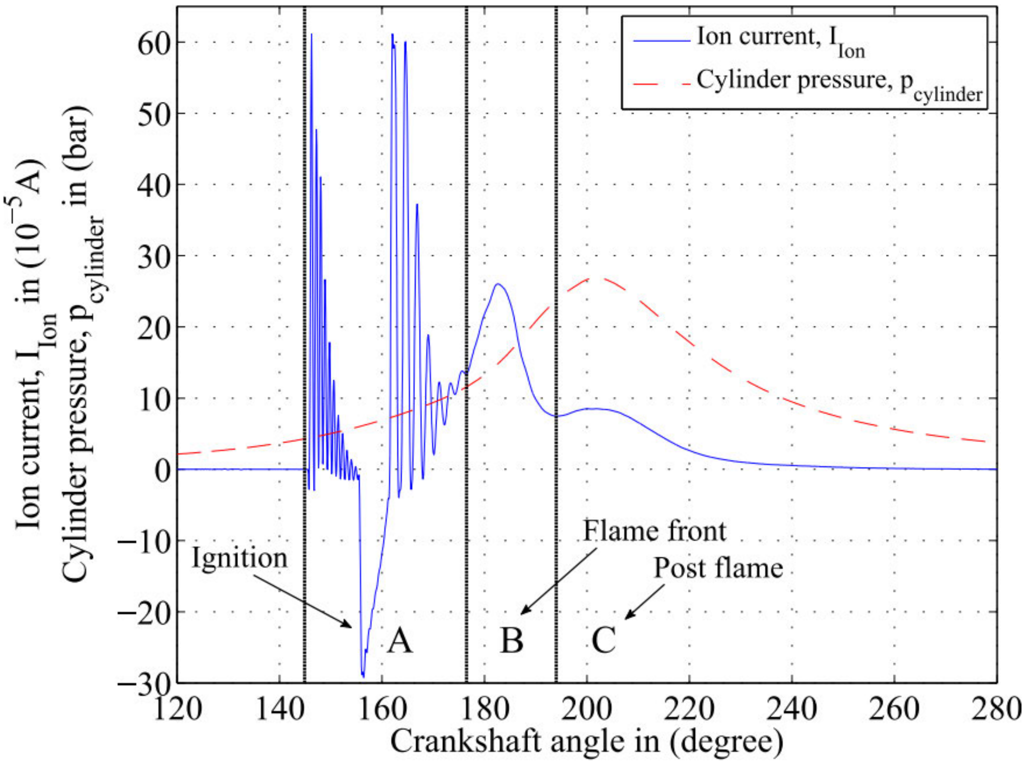


Figure 29 Ion sense reference shape [22]

From the Figure 29 the following 3 following phases:

Ignition Phase:

The ignition phase covers the influence of the ignition on the ion current signal [8] (page 27).

In section ‘6.1.1’ of [8] it is pointed out that Information regarding the wear conditions of the ignition system can be drawn but no corroborations have been conducted in our side.

We found that the determination of the ware is a very complicated parameter and that no reference table that would lead to wear determination has been drown. It should also be pointed out that different spark plug design would perform differently. A good reference table research would open the door for this estimation. Nevertheless, it is important to point that as engine manufacturers we do not care much about the little wear that a spark plug could have, and we are focus on the performance of the engine. This means that effort needs to be centered in the detection of engine malfunctions. In case a spark plug starts to have an irregular performance, misfire detection should be able to detect it.

Flame front phase:

This is the so-called chemical ionization phase.

During the combustion hydrocarbon oxidation generates a lot of reactions happen and a lot of electrically charged molecules and electrons are generated by the combustion reaction in the combustion chamber.

The three main reactions are the following [23]:

$$CH + O \rightarrow CHO^{+} + e^{-} \quad \textbf{(1)}$$

$$CHO^{+} + H_2O \rightarrow H_3O^{+} + CO + e^{-} \quad \textbf{(2)}$$

$$CH + C_2H_2 \rightarrow C_3H_3^{+} + e^{-} \quad \textbf{(3)}$$

"There are two ions (CHO^{+} and $C_3H_3^{+}$) which are generated by elementary reaction leading to free electron release. Ion H_3O^{+} is the most persistent during the combustion since it has a high reaction-rate. Therefore, H_3O^{+} is the ion thought to be measured since the other ions recombine faster" [8] (page 27).

After this, the equation 4 reaction happens leading to a drastic reduction of ionic current.

$$H_3O^{+} + e^{-} \rightarrow H_2O + H \quad \textbf{(4)}$$

This first area (the front flame) and its timing correlates with the flame speed [23].

Post Flame Phase:

This is the so-called thermal ionization phase. Models such as Saitzkoff (1996) [24] and Yoshiyama (2000) [25] have been developed but they will not be studied in this thesis.

Literature has found that an in-cylinder pressure estimation could be carried out as a proportion pressure-ion pic in this area has been found [26].

4.2. Implementation

4.2.1. TU Graz design

This circuit was developed by the Institute of Electrical Measurement and Sensor Systems at Graz University of technology having in mind that one of the premises for this automotive sector is the economy of the measurement devices [4] and [6]. Due to that, the circuit is made from resistances, diodes, and Zener's.

The capacitor is used as a limited voltage source for generating the ion current. This is a common implementation [4]. The capacitor is charged to the maximum reverse voltage of the Zener diode.

There have been ion sense different circuit approaches in the past, but Rotax decided on using TU Graz design as it is one of the most recent developments, it has no active components and also because of the support they have provided.

The circuit is made with the component arrangement shown in Figure 30 Ignition system with the ion sense circuit Figure 30.

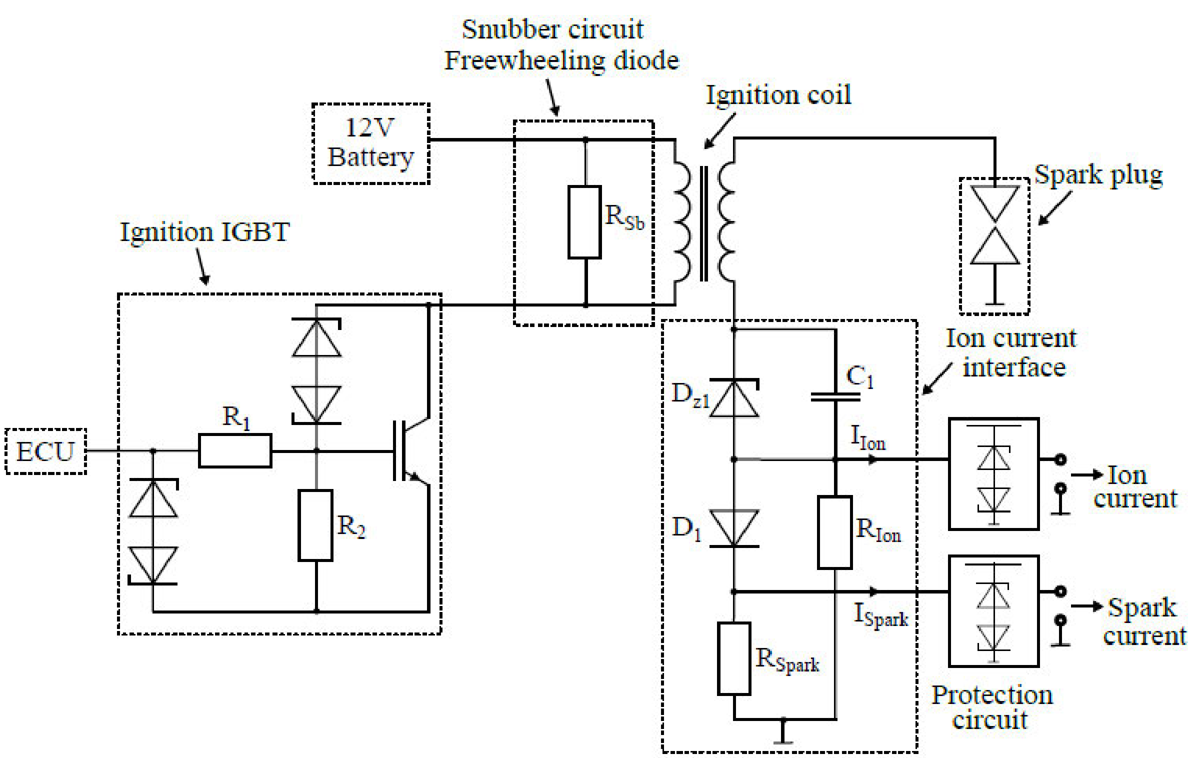


Figure 30 Ignition system with the ion sense circuit [8]

For now the implementation has been done with a protorype board, as can be seen in Figure 31. As it can be seen in the right side there are two BNC output connectors, one for the ion current and the other one for the spark current mesurements. BNC are used in automotive prototyping as they have a better mechanical performance against vibrations. A female bannana connector can also be seen. It will be used for puntual mesurements of the capacitor charge in order to ensure a correct operation of the circuit.

Figure 31 Test board

IGNITION SYSTEM SIMULATION

For a better understanding of the ignition system, a simulation based on the model developed by the Institute of Electrical Measurement and Sensor Systems at Graz University of technology was carried out.

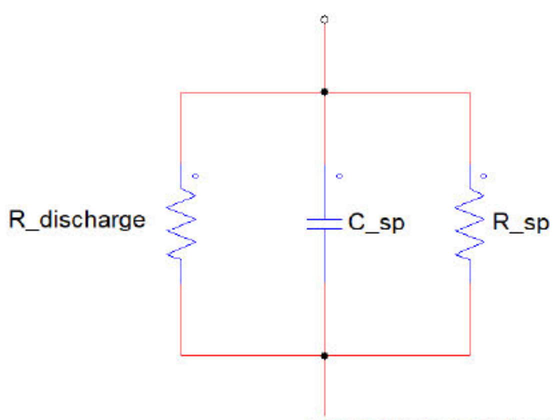
The simulation described in [27] paper presents an analysis that will represent our first approach on how to design robust ion current based ECU control systems.

This simulation is done using LTSpice software and it is based on the measurement of the impedance of the spark plug during ignition. This resistance will simulate the ionization of the chamber causing the spark and a current flowing through the spark plug.

The model consists of the following parts:

- Ignition coil: represented by the two inductors acting as a transformer, together with their series resistance and leakage reactance.
- Control unit (ECU): controlling the charge of the primary by the bipolar transistor.
- The ion sensing circuit: the one explained during the Ignition with ion sense chapter (4.2.2 Ignition with ion sense).
- The spark plug which is composed of these different elements connected in parallel:
    - A variable resistor that uses real values extracted from laboratory tests. These tests are the bases of the paper as a real modeling of the spark plug was needed.
    - A small capacitor.
    - A conditional impedance is used for determining the moment when the spark plug is creating the spark. When the resistance takes the 1GΩ value, the current can be neglected. On the other hand, as soon as the value drops to 1 kΩ there is a transient where the previous capacitance plays an important role.

This method of modeling a spark plug is one of the most used in literature [28] as can be seen in Figure 32.



R_discharge: discharge resistance

R_sp: flow resistance of the spark plug

C_sp: self-capacity of the spark plug

Figure 32 Typical characterization of a spark plug

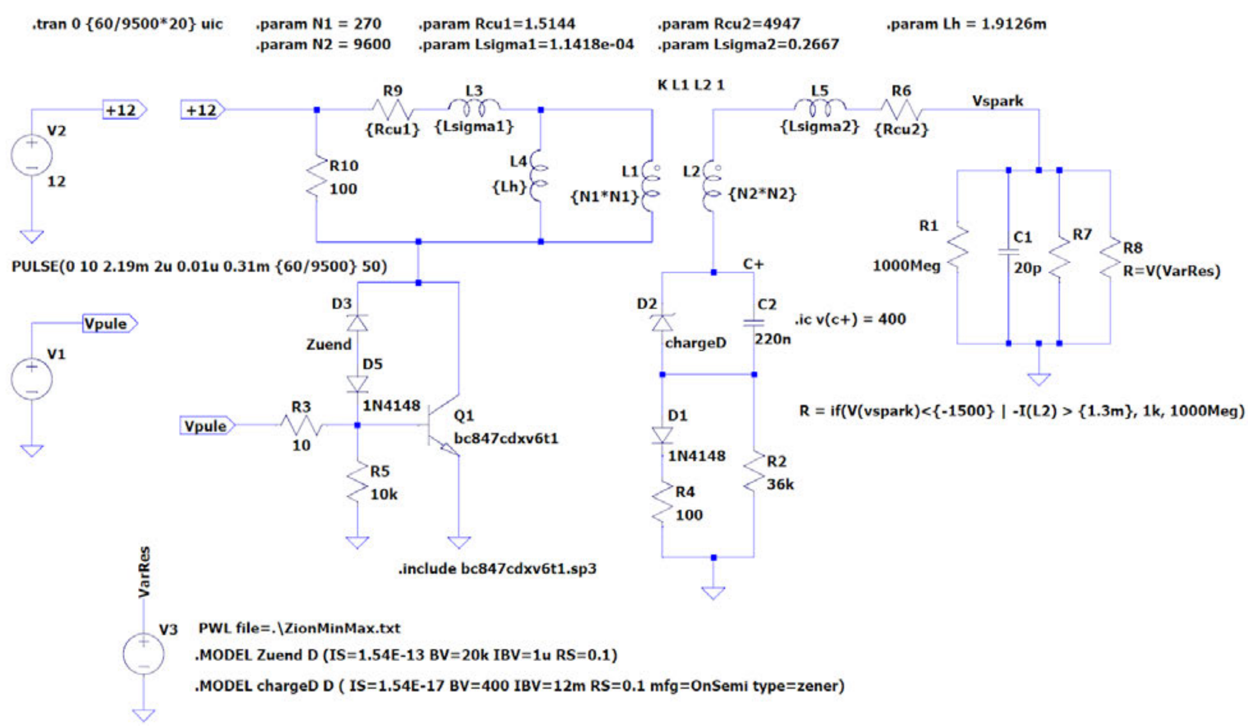


Figure 33 LTSpice diagram

It has allowed us to understand better the circuit and how the currents flow some plots extracted from the simulation, will be used, in other chapters of this dissertation, along with real-life tests to corroborate both.

4.2.2. Ignition with ion sense

The Ion sense circuit is composed of a capacitor protected by the Zener, a couple of resistors and a diode. In the following section the different phases will be explained. The basic concept of the implementation has no diode in the high side, between the ignition coil and the sparkplug, that would protect against a spark happening during dwelling.

Charge/Dwelling:

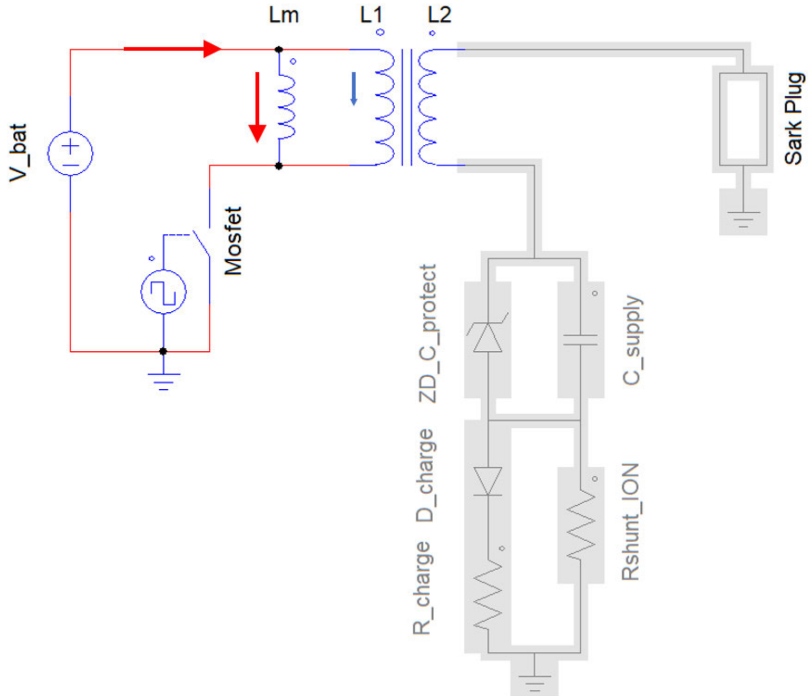


Figure 34 Charge phase with ion sense

The first step can be seen in Figure 34. It is the same as in a normal ignition circuit without ion sensing equipment. As stated, no protection against spark during this phase is in place. This principle means that the small blue arrow could transfer energy to the secondary side if chamber conditions would allow the spark to happen. During the charging, as it can be seen in Figure 35, the voltage builds up in the secondary side where this voltage is measured. The charging phase is highlighted in green.

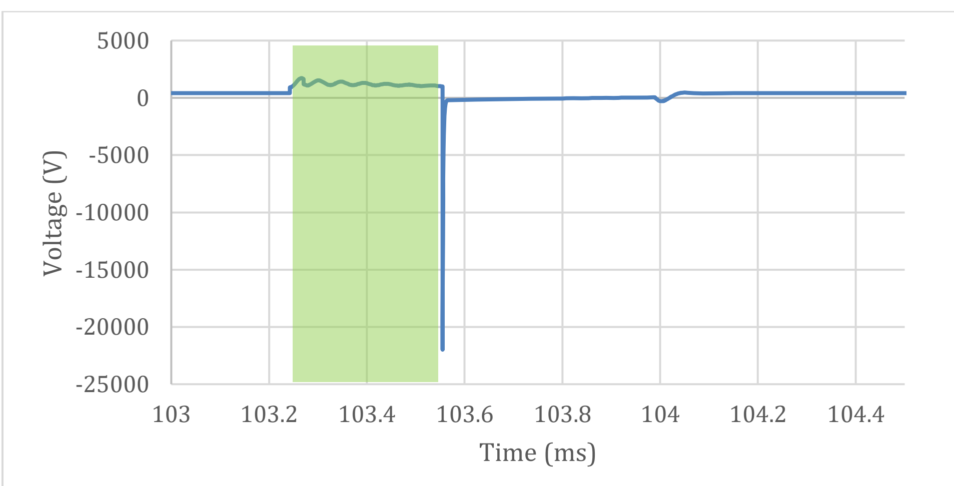


Figure 35 Spark voltage

Spark:

This phase starts when the dwell is done. At the precise moment that the switch in the primary side opens energy is transferred to the secondary side and voltage builds up as a negative voltage in the top side of the secondary side of the transformer generates a spark, as seen in Figure 36.

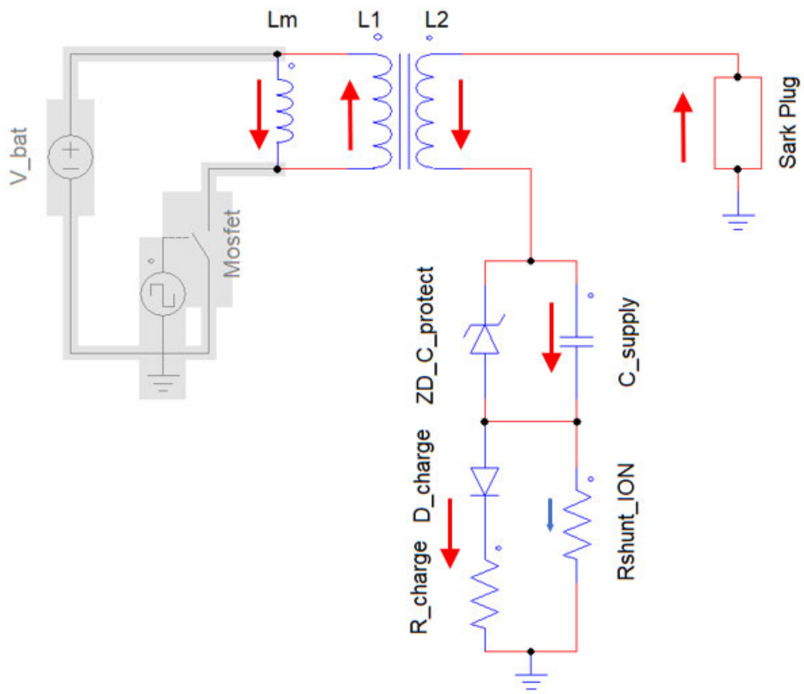


Figure 36 Discharge with ion sense

When the spark happens inside of the chamber, a current flow through the spark plug. This current is used for the charging of the capacitor. A diode with resistor path is placed in parallel with the $R_{\_Shunt}$ and have a greater current flowing and charging the capacitor. Further tests should be carried out to assess the need of this Branch as preliminary studies show that the capacitor is charged enough without this parallel Branch (blue arrow), and a couple of components could be saved up. In fact, preliminary tests showing positive results have been conducted.

An example of the voltage between the terminals of the capacitor, extracted from the simulation and shown in Figure 37 below:

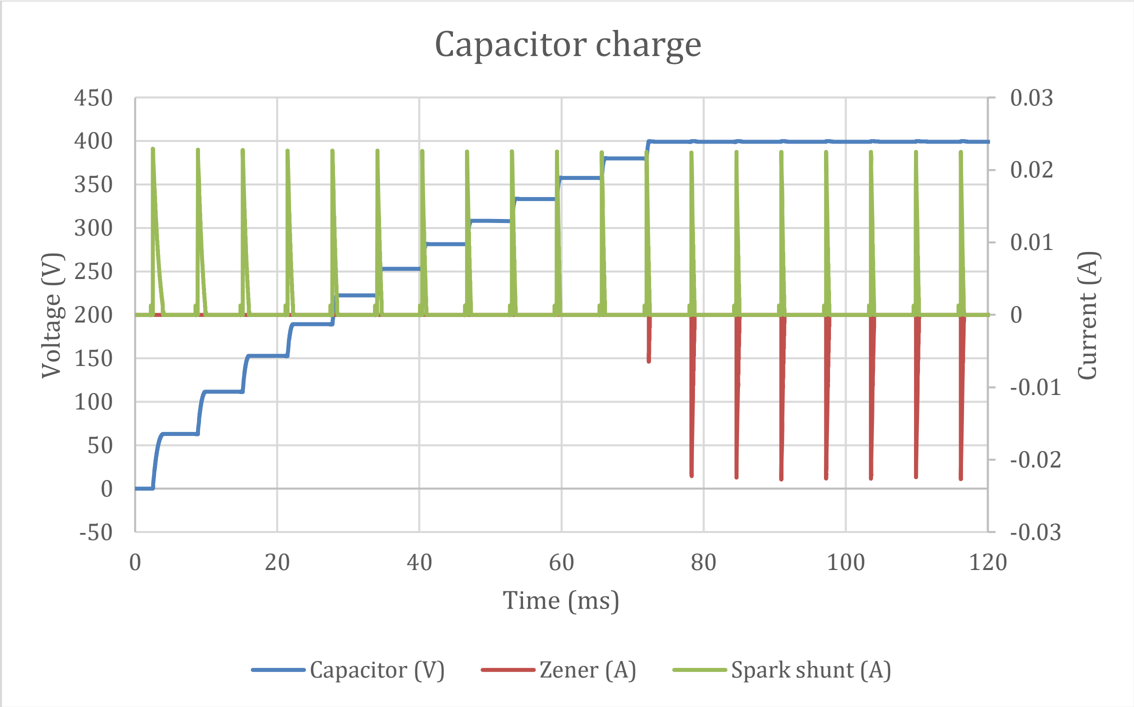


Figure 37 Charging of the capacitor (simulation)

The Zener serves as protection for the capacitor to ensure that it does not exceed the maximum voltage rating. It has current flowing when the capacitor is fully charged.

The current that charges the capacitor is the spark current. The current flows through the spark plug during the spark, meaning that the spark current is a measurement of the duration of the spark (see Figure 38 for the simulation result and Figure 39 for the experimental corroboration).

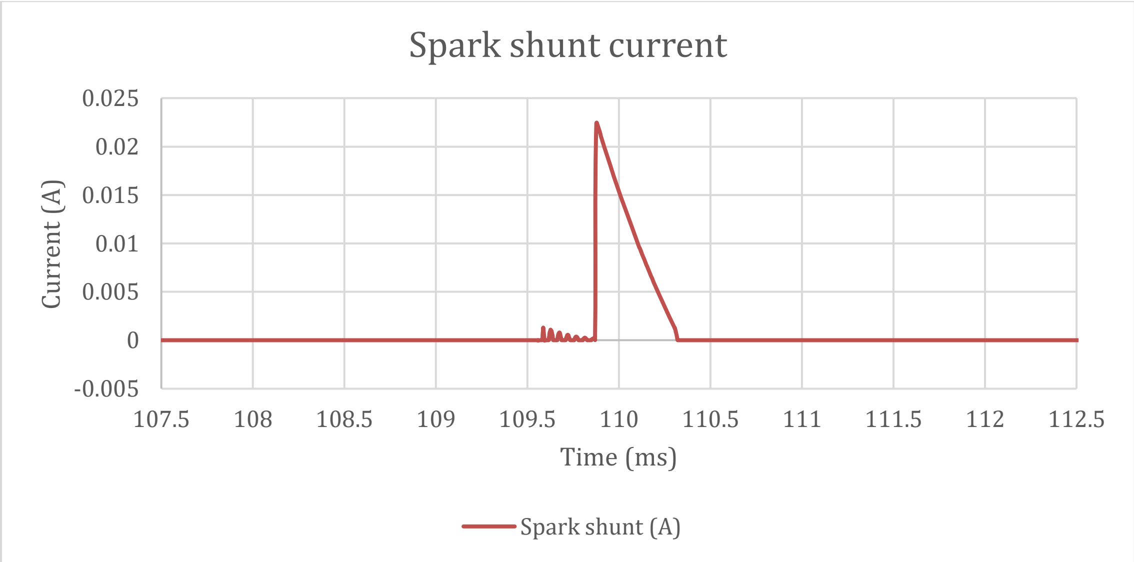


Figure 38 Spark current (simulation)

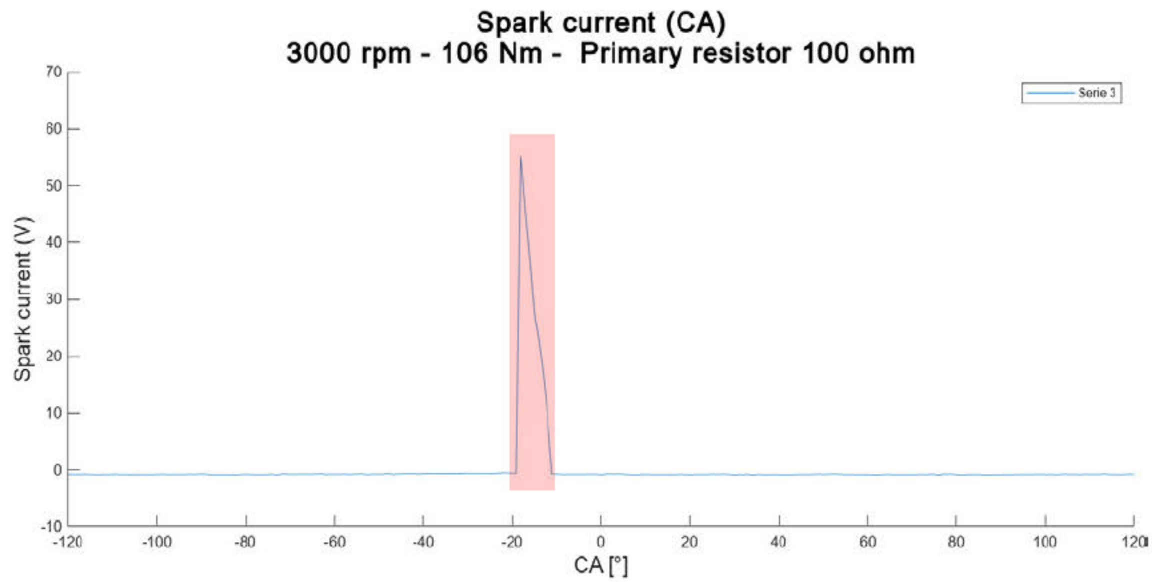


Figure 39 Spark current (experimental)

We can also appreciate it through the $R_{\_shunt}$ in simulation Figure 40 and in experimental in Figure 41. We can also see the spark and what is called ringing, an oscillation caused by the capacitance of the spark plug in parallel with the coil.

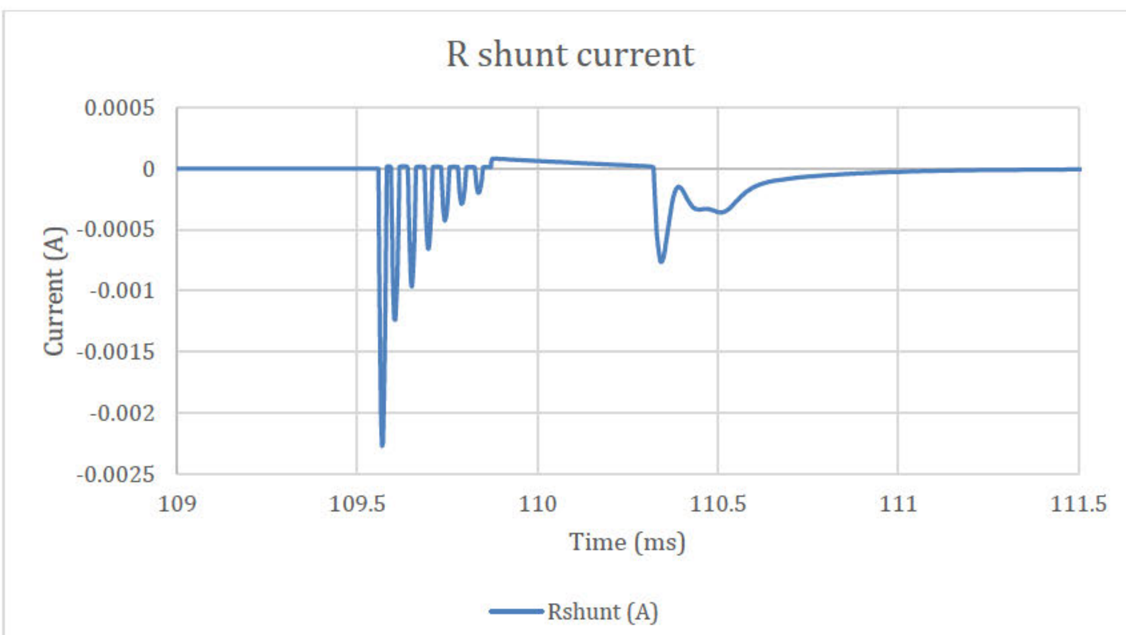


Figure 40 Ion current (simulation)

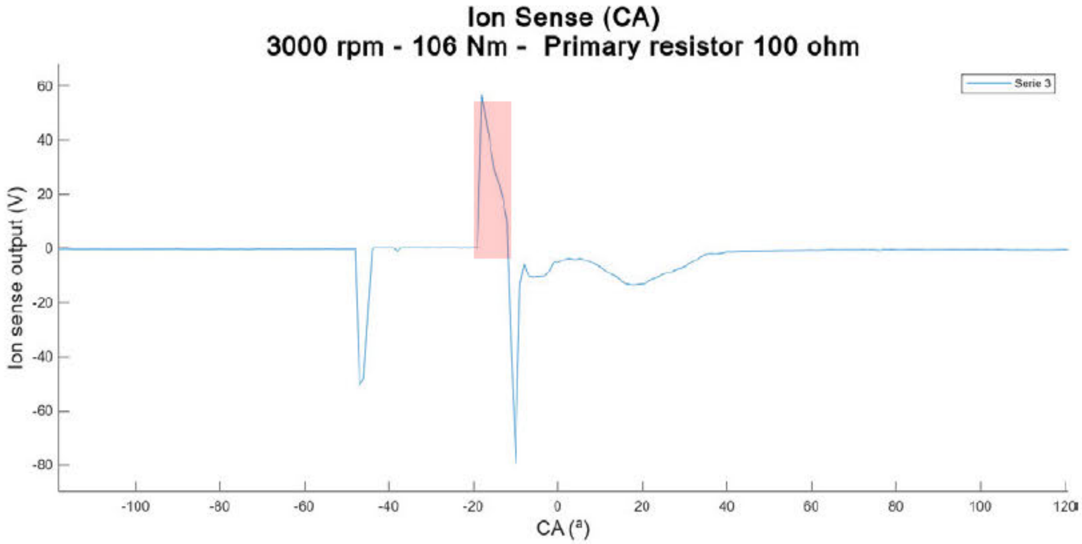


Figure 41 Ion current (experimental)

Flame front:

When the spark takes place, a point is reached when the capacitor discharge current is stronger than the current formed from the energy remaining in the ignition coil. This happens in the front and post flame. When the capacitor discharges onto the spark plug is because it still has ions in the airgap and can have a current flowing as explained in the ion sense '4.1 Concept and theory' section. To sum up, the capacitor is used as a voltage source. When it discharges onto the spark plug a determination on the ion concentration can be done through the voltage drop on the Shunt resistor.

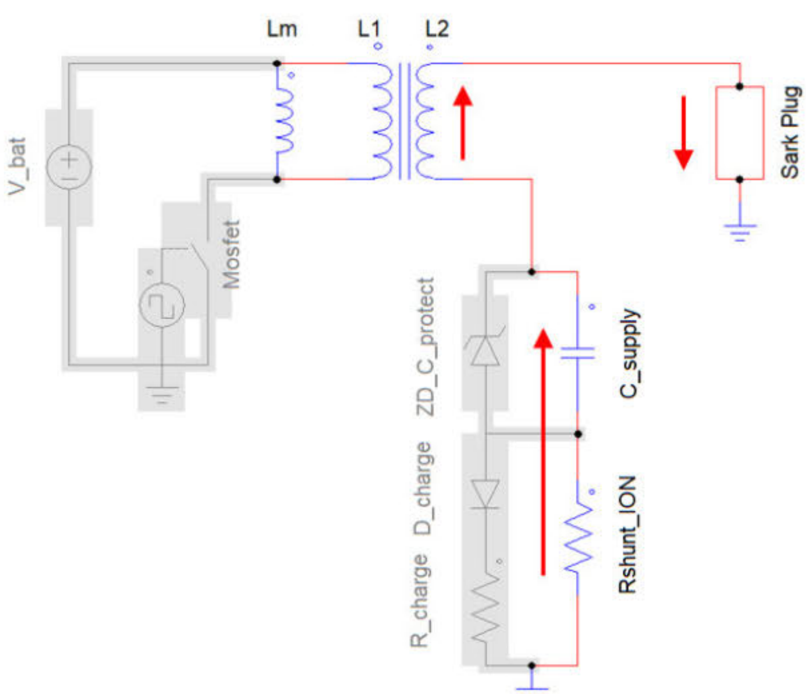


Figure 42 Discharge of the capacitor to read ionization

An example of the reading of the voltage at the Shunt can be seen in Figure 43.

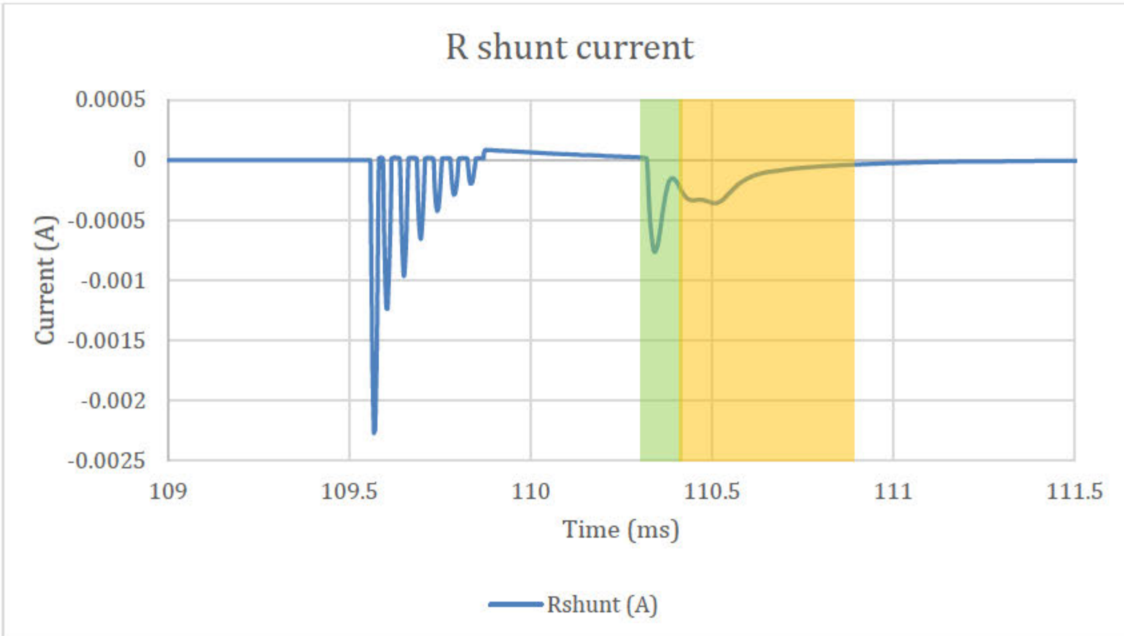


Figure 43 Ion sense (simulation). In green the spark and in yellow the ion reading

In Figure 43, the green what is called Front Flame in literature. The yellow part is called Post flame, as explained in the '4.1 Concept and theory' section. The same can be seen in the experimental measurement, Figure 44.

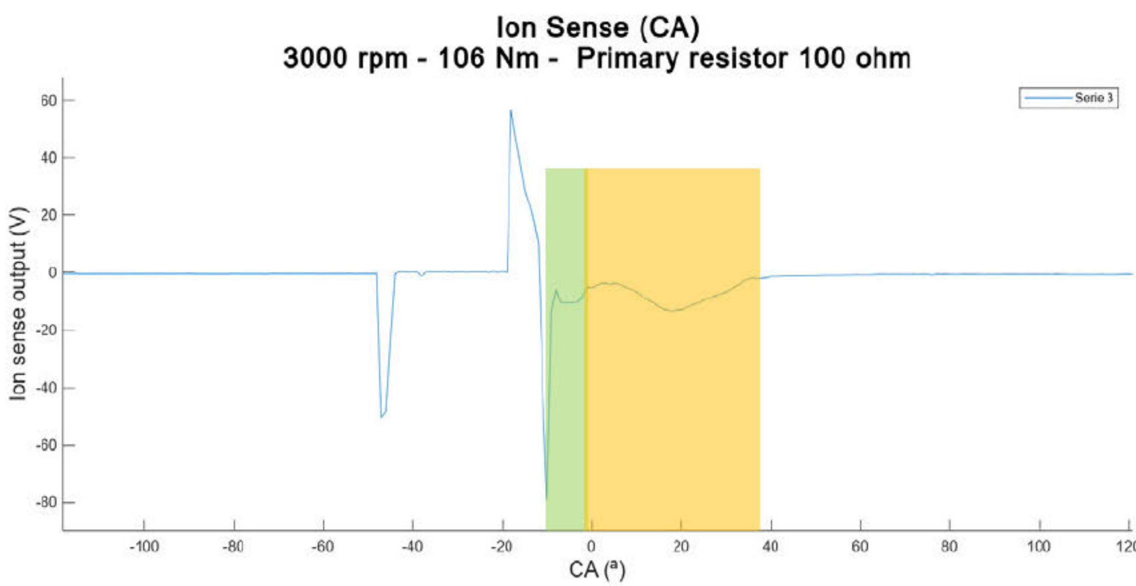


Figure 44 Ion sense signal (experimental)

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5. Combustion issues

5.1. Misfire

Misfire is a phenomenon that happens when the energy (a voltage pic) is not able to generate a spark in the spark plug gap able of igniting the mixture. When no combustion occurs in the chamber, before the exhaust opening, we have what is known as misfire.

There are multiple factors that could lead to a misfire enent. One of them being that the fuel mix is not rich enough. In this chapter the electrical causes will be discussed.

5.1.1. Electrical misfire causes

Corona discharge leading to flash-over:

Corona discharge is due to the phenomenon called ionization which occurs when gas molecules separate into free electrons and positively charged ions. If the air is highly ionized, its insulation ability is reduced, and partial discharge occurs. This phenomenon results in a pale blue light (see Figure 49). Corona discharge occurs in wet conditions or when the insulator surface is dirty. It can be a minimal persistent effect with a minimal and neglectable effect on the engine.

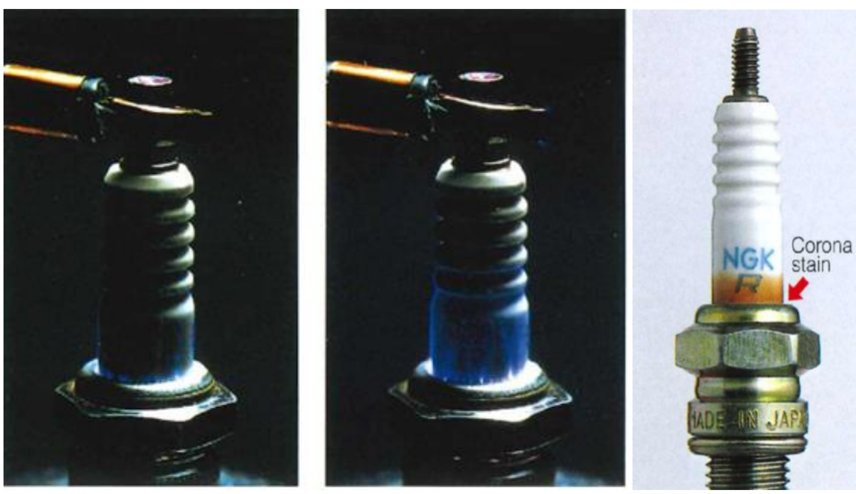

Figure 49 Corona discharge phenomenon and result [18]

As it can be seen in Figure 49, the corona stain is an indicator of this effect. When this effect is severe, it is called flash-over. In this case the discharge reaches the terminal stud, allowing flash-over to the metal shell, causing the engine to misfire. To reduce this effect, dents are in place to create a longer path.

In this case as it can be seen in Figure 50 burned lines are seen in the spark plug if the flashover is persistent. The corona stain can also be seen as it is a first step for the flashover to happen.

Figure 50 Flashover phenomenon and result (Left: [18], Right: [30])

Carbon accumulation:

Due to the running of the engine, carbon from the fuel can accumulate in the tip of the spark plug creating a current path. When the path has less resistance than the airgap, the spark will leak instead of jumping to the electrode as it can be seen in Figure 51.

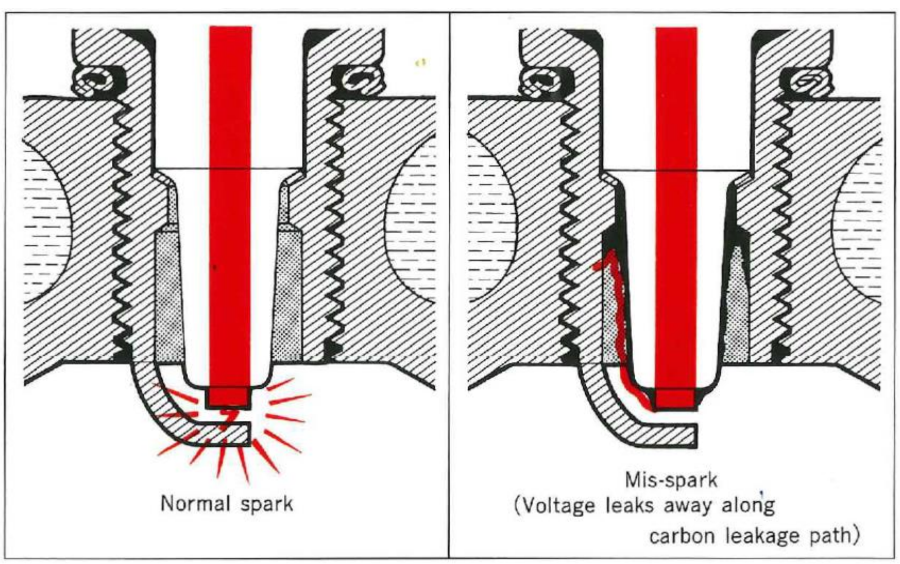

Figure 51 Leakage path formed by carbon accumulation [18]

Quenching:

Quenching is caused when the heat generated by a spark is absorbed by the center or ground electrodes instead of igniting the air/fuel mixture. As we know, what ignites the mix is the heat produced by the spark [31].

The quenching means that there is a spark, but this spark is not able to ignite the mix as the heat energy is transferred to the electrode. This phenomenon is a design fault and current designs reduce this effect by having small electrodes. The solution, as stated, is clear but a compromise needs to be made as in case, they are very small, corrosion or melting could lead to a generation of a bigger gap that the energy of the coil is not able to jump. It is important to mention that it can be defined as Quenching when there is mix inside of the camber.

5.1.2. Reasons for misfire detection

Although no direct association has been found linking the outcome of the analysis with the cause of the misfire events. During the tests, we can stipulate that multiple factors are affecting the performance of the engine:

- Wear of the spark plug, as seen in the '3.2.1 Spark plugs' chapter, many factors are affecting this deterioration that are also linked to the misfire events.
- Release of pressure in the chamber that reduces the compression pressure.
- A bad air/fuel ratio.
- Quality or type of fuel
- Temperature and pressure of the mixture during expected ignition.

The side effects that misfire has are:

- **Safety.** In terms of safety, it is important to ensure that misfire events can be detected because when the combustion is not happening inside of the chamber the exhaust valve opens, and the flammable gas (the mixture) is driven to the catalyst system. Combustion may happen there.
- **Noxious emissions**. As can be expected, when the mix is not ignited the fuel-air mix is expelled out of the engine. This is extremely important for small two-stroke engines as stricter regulations have been placed. When running in idling operation, ignition coil charging parameters are changed for speed control. This leads to an increment of the misfire rate (about 35% and 50 % of the cycles) so the detection is needed for ensuring a good speed and injection of fuel.

5.1.3. Methods for misfire evaluation

In the past indirect measurements in the shaft of the motor have been developed. Based on an accelerometer, a determination can be made. When in one of the cycles the speed of the shaft is reduced, the acceleration has a drastic reduction. The engine will not produce torque in this cycle, but the shaft would not stop rotating as it has a high moment of inertia.

When sensing the chamber pressure, the Indicated Mean Effective Pressure (IMEP or PI) and cylinder pressure are the greatest way of determining the misfire events. For this research, the pressure of the chamber and one method embedded in INCA (Rotax measuring tool) developed by the AVL company. A visual determination can be extracted from Figure 52.

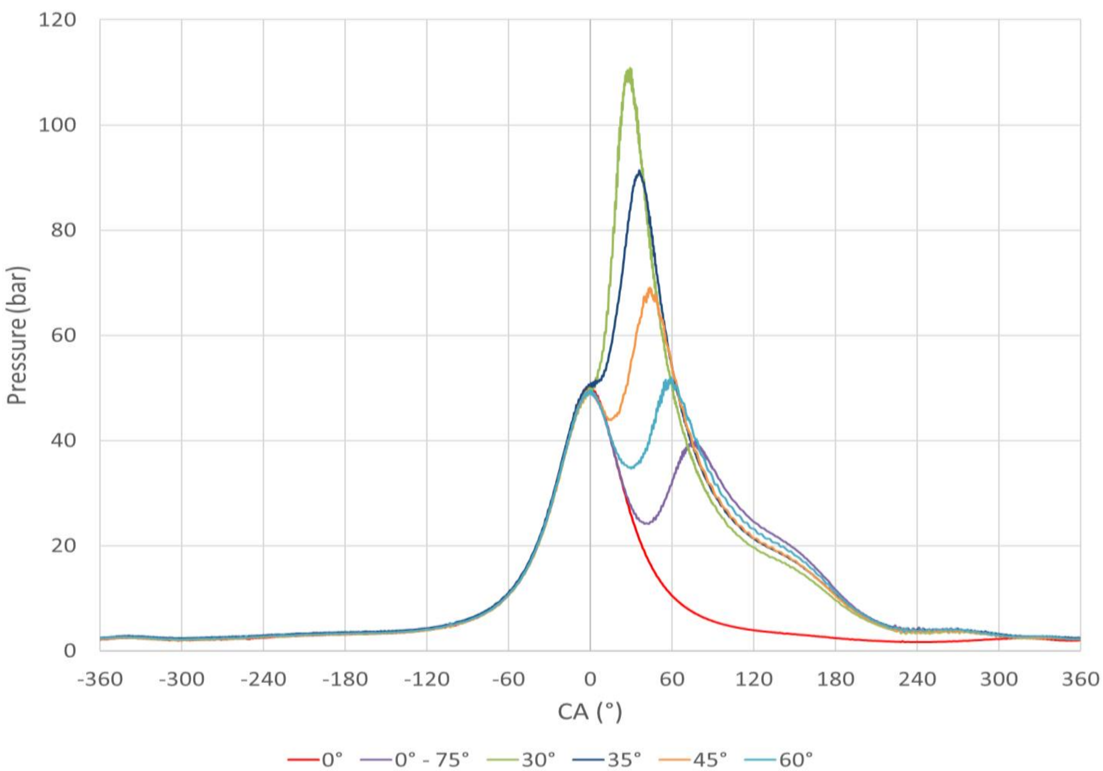

Figure 52 Pressure lines for misfire and late burn determination

The red line represents a cycle without combustion, where only the chamber pressure is reached. This happens at a CA of 0° and it is what is called misfire.

Some other curves were obtained out of the normal pressure lines. Those having a maximum pressure out of the normal running range and the ignition of the mixture, point at where the maximum pressure of the chamber is reached. This phenomenon is called late combustion, and when operating in this state the efficiency of the engine is reduced due to its malfunction indicated by the pressure. Although it is not desired in terms of efficiency and pollution, this phenomenon should not cause a high deterioration of the engine.

Another common method of determining the quality of the combustion is using IMEP or PI. In the case of IMEP the combustion of all the engine chambers is analyzed. In the case of the PI the analysis is based on the pressure of each chamber. The value will come out of the integral of the pressure graph and divided by the rotation per cycle. In the case of the four stroke engines there are two rotations per cycle, so 720°. From the description it can be expected that it will represent the average of all pressures, although this method is not good for measurements with a variable step time, as it is the case for a more precise measurement around the combustion area.

By using the results of IMEP calculations, as reference values, the Ion Sense will be evaluated. A direct relation between the ion sensing technology and the quality of the cycle would be interesting to understand the late combustion and predict misfire.

Tins is the method used for the determination with the AVR software. After this calculation the software gives you an average of the misfiring. This percentage comes from the triggering of the IMEP calculation result, when a value is below a certain low limit the percentage is increased.

5.1.4. Ion sense misfire detection

More information regarding the shape of the ion sense measurement in the Ion sense '4.1 Concept and theory' chapter.

In this chapter, an explanation on how the misfire is detected, is explained. In Figure 53, we can see the ion sense shape.

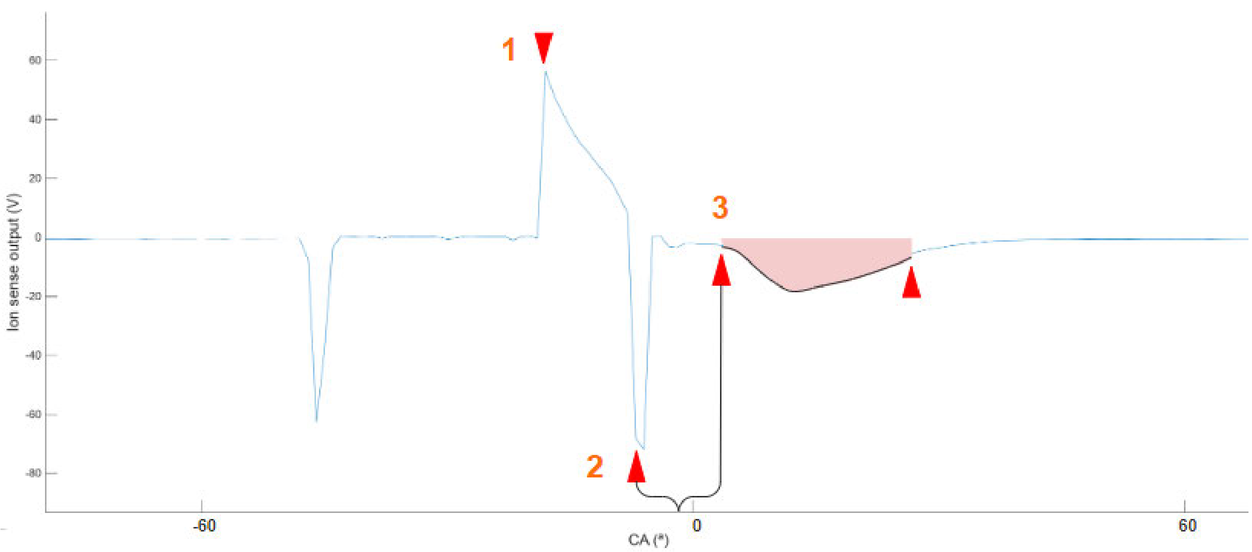

Figure 53 Misfire determination

Point 1 represents the ignition. From point 1 to 3, we have what is called Spark duration and according to [8], this can lead to a study of the wear of the spark plug but no studies have been made. Point 2 represents the discharge of the capacitor. Point 3 represents the start of the front phase. From this point to the end of post flame, point 4, the misfire is detected.

If there is an area, marked in pink, it means that there are ions inside of the chamber, so combustion has happened. In case there is no area, and it is a straight line in zero, it means that misfire has happened.

To determine this area, the applied method is the following:

1. Detect the discharge point (number 1)
2. Detect the negative pic after discharge (number 2)
3. Get the CA of point 2 and add 10˚ CA. This will be point 3.
4. From point 3 to point 3 + 10˚ CA we do the integral of the ion sense signal.
5. If the area is negative, we have correct combustion.

5.2. Knocking

Knocking is a spontaneous combustion of the air/fuel mixture caused by the spark plug, see Figure 54. This is produced by induced heat caused by the combustion pressure. It happens at high-speed when combustions, as intensive gas vibrations, are generated inside of the combustion chamber.

Figure 54 Knocking representation

It can be detected by hearing the engine running as if there was a hammer knocking the interior walls of the chamber. This is the reason for its name.

At present, there are two ways to measure the knocking effect. The indirect measurement uses the vibration of the motor to detect when knocking is happening, as it is obvious that knocking generates a huge amount of vibration. However, this method has some disadvantages:

- Contamination of the measurements. As other parts of the car may generate vibrations with similar frequencies.
- It is a costly system, as a sensor per cylinder is needed to achieve a good reading.

Texas Instruments developed a microcontroller to apply this technique in 1995 [32]. Results of this implementation have not been analyzed as a couple of tuned, resonant, or broadband vibration sensors are needed for the system to work, and it is not an option for Rotax.

CONFIDENTIAL [redacted] CONFIDENTIAL [redacted] based on literature published on this topic:

The pressure signal is filtered through a LPF (see Figure 55). After this first step that could be suppressed a FFT analysis of the signal is carried out. Having magnitude peaks would indicate that knocking is happening.

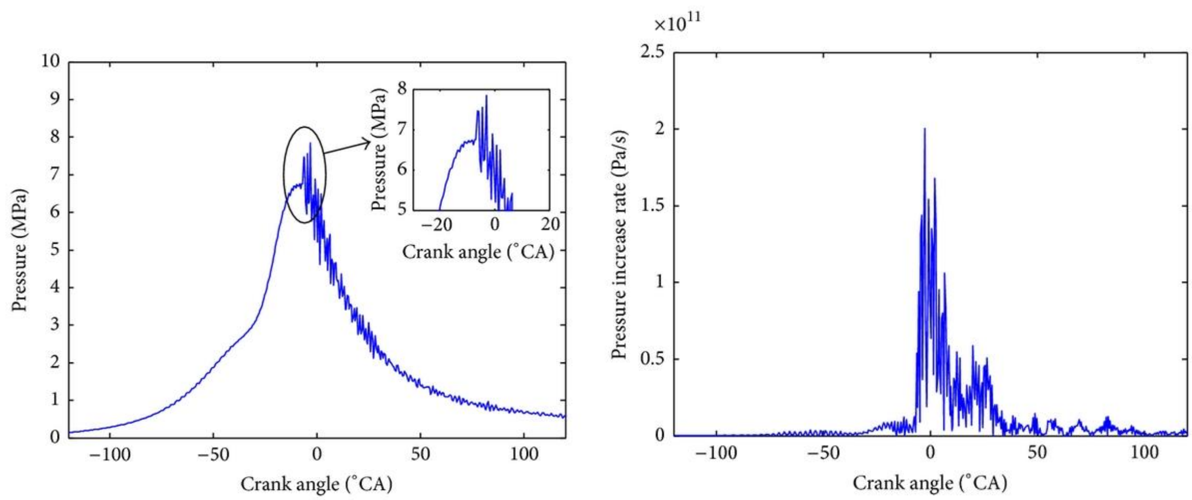

Figure 55 Knocking evaluation representation [33]

This phenomenon is more likely to happen just after the combustion and a window from 10-70° ATDC [4]. This was experimentally corroborated in our dyno as it can be seen in Figure 56.

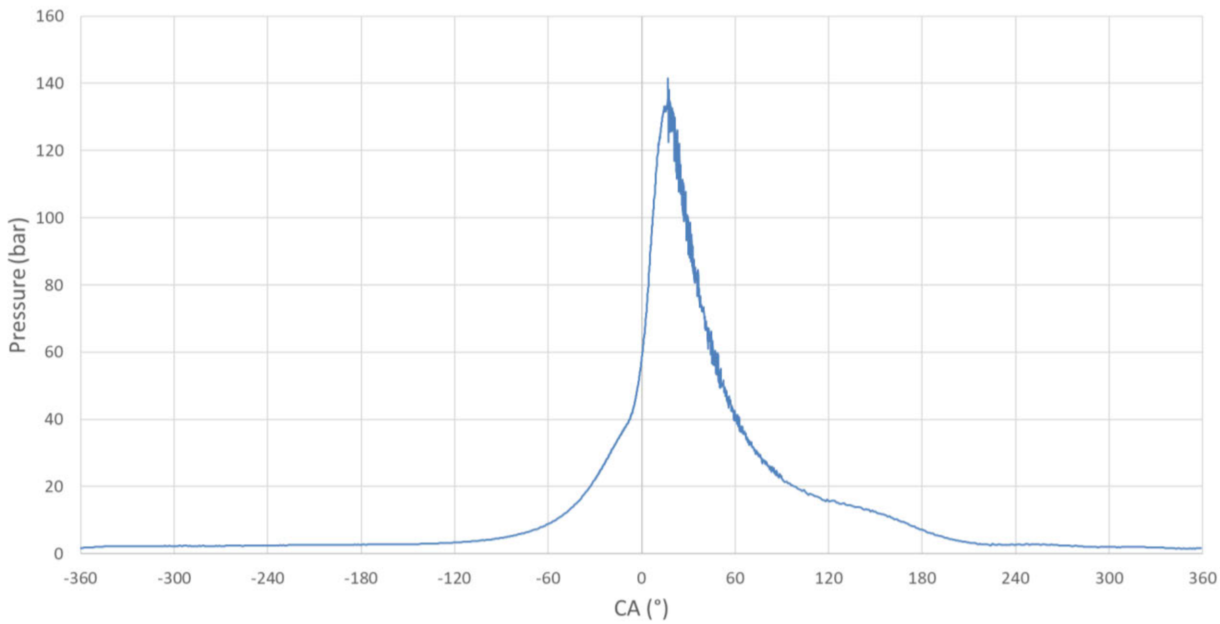

Figure 56 Pressure with knocking at 6000 rpm and 220 Nm

Some preliminary tests have been conducted with "noise" in the signal that would indicate that the chamber is experimenting knocking, in orange in Figure 57. This ringing was expected to happen also during the same crank angle window as the pressure [4]. More explanations will be given at the '6.4 Current state' chapter.

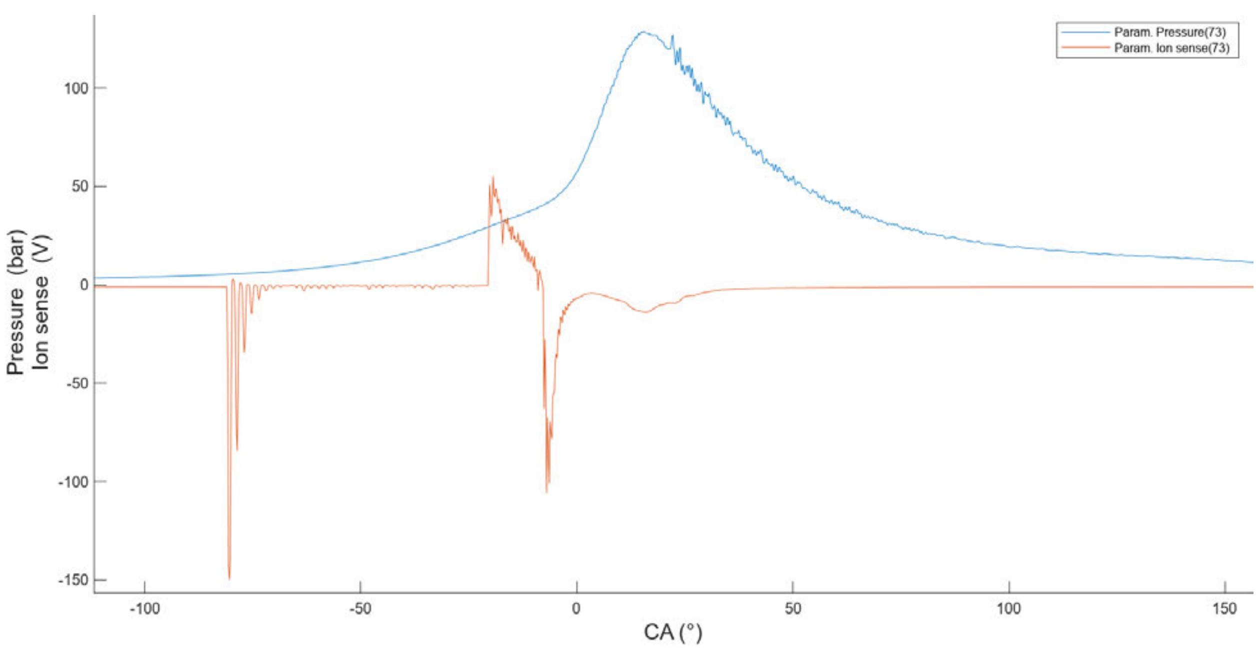

Figure 57 Knocking test and knocking measurement at 5000 rpm and 140 Nm

6. Industrialization of the ignition system with ion sense technology

In this section the steps for industrialization of the TU Graz preliminary board design will be explained. Issues and solutions will be explained, and the misfire results obtained shown.

In Figure 58 the schematics of the ignition system is shown with the measuring equipment in green as a reference for this project figures.

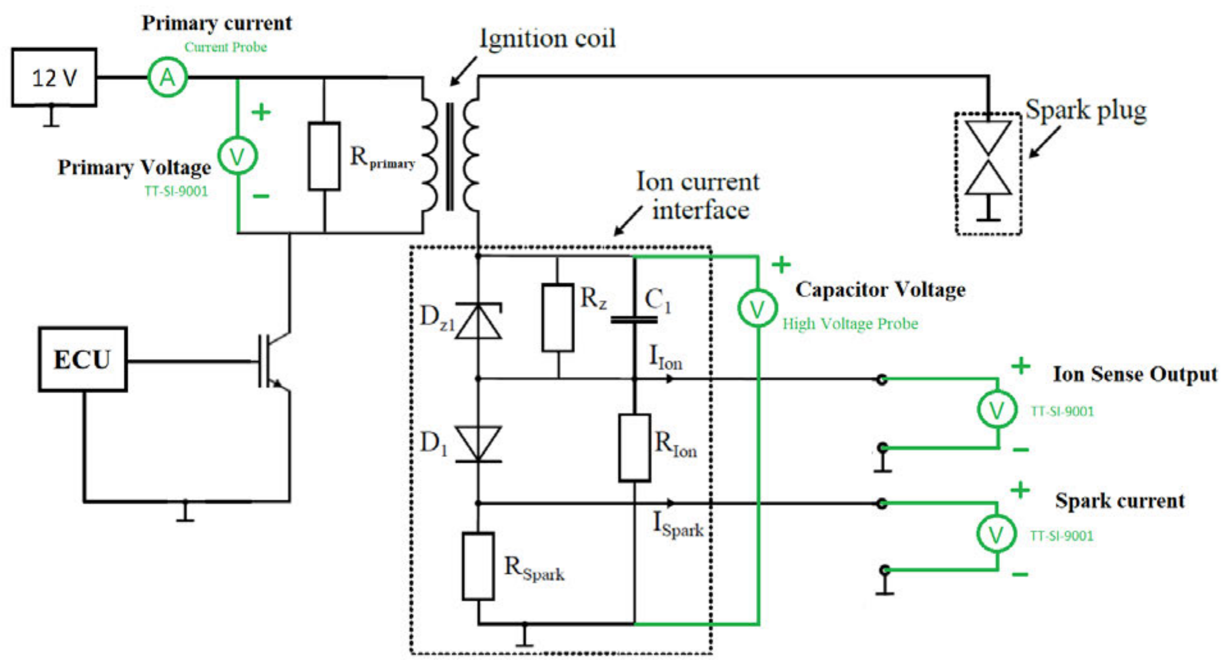

Figure 58 Measuring points and measuring equipment used

An explanation of the software used for engine control and data acquisition can be found in the Appendix A Data acquisition flow. For data plotting and analysis, a Matlab GUI has been developed with appearance. This tool makes the analysis of the tests way easier, not only for this project but for other data that needs to be plotted. The steps to make it work are explained in Appendix A Data acquisition flow. The code written can be found in Appendix B Matlab GUI code.

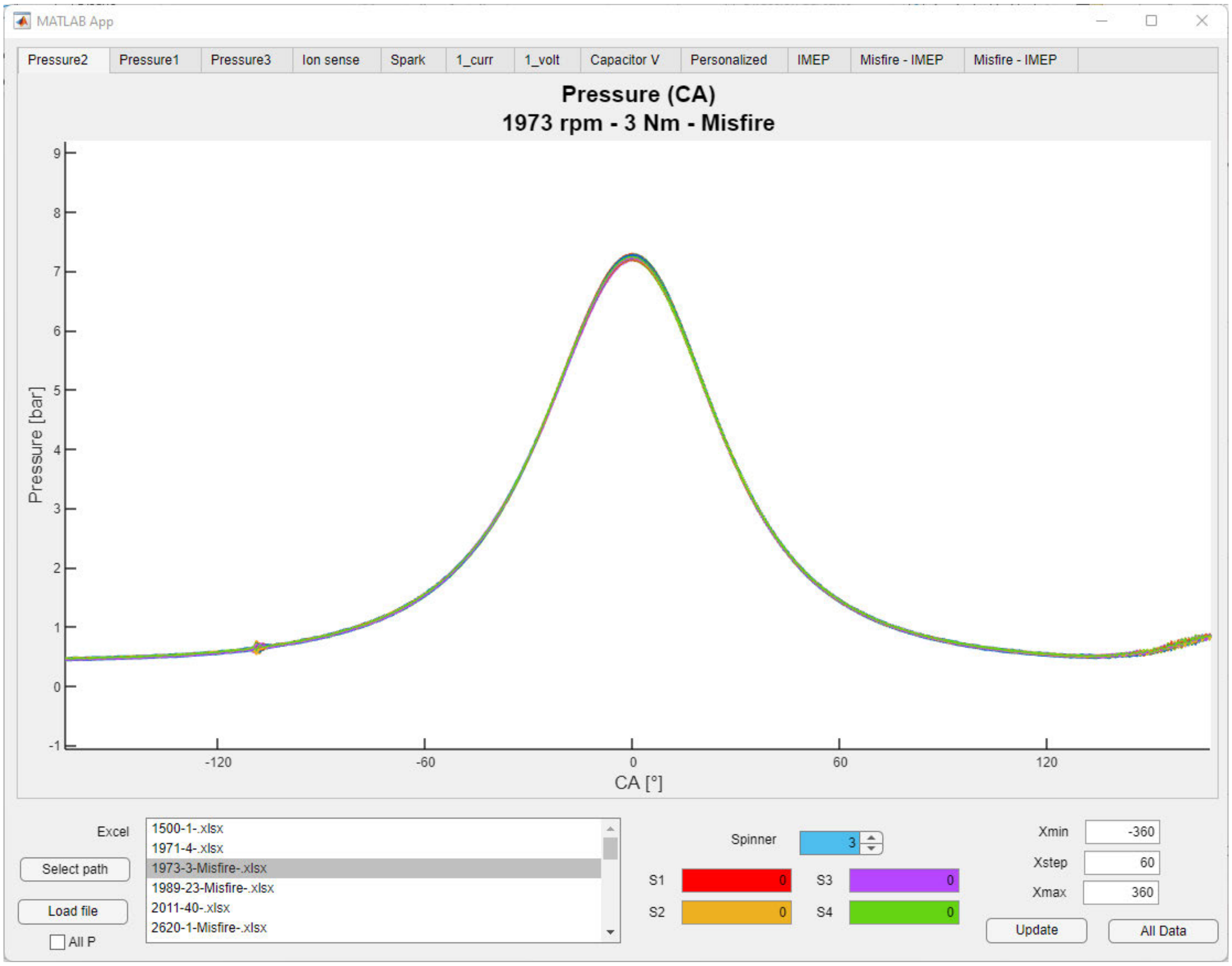

Figure 59 Matlab GUI for ploting

6.1. Coupling capacitance

This phenomenon is created in the transformer (coil) and creates a current path between the 2 coils, to be precise, from the low side of the coils. It means that a part of the energy is lost.

In standard operation this is not a problem, but when implementing the Ion Sensing device from TU Graz it was found that this effect was disabling the possibility of getting any result.

At first, on the Rotax side, we had some issues with the charging of the capacitor. After some trial-and-error strategies it was discovered that this issue was caused by the coupling. This issue was not found during the development of this measurement circuit.

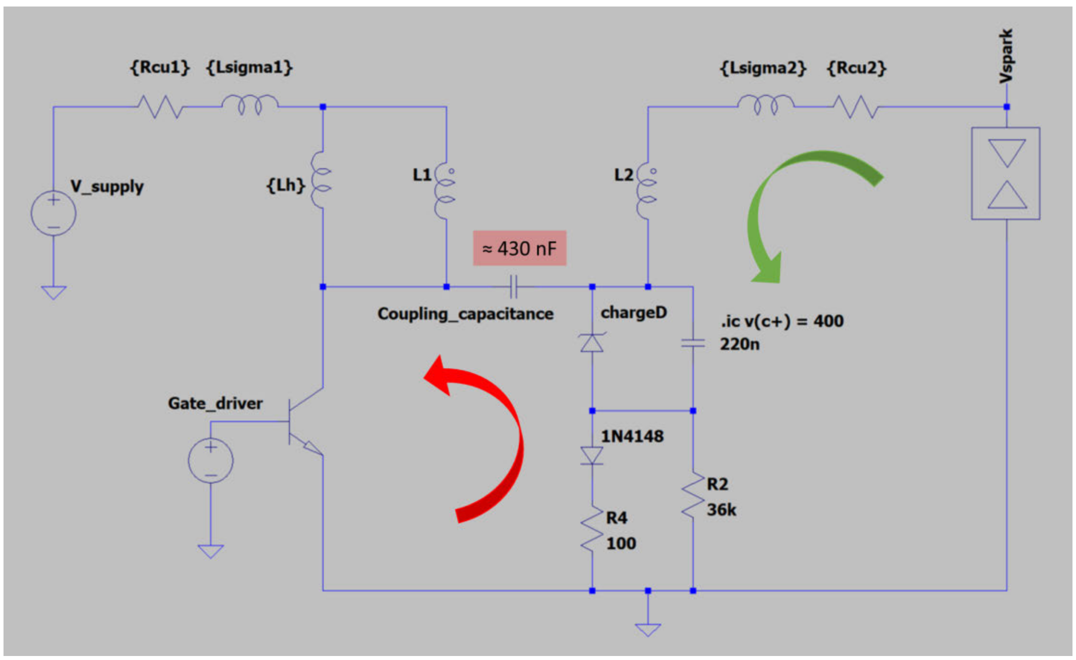

Figure 60 Coupling current path

As it can be seen in Figure 60, the current path that is meant to charge the capacitor, the green one, should flow through it to charge it. The issue with the coupling capacitance is that this capacitance generates a current flow through the coupling capacitance. To make the Ion Sense work, a big enough current through the capacitor should flow to charge it. In this case the coupling capacitance, in red in Figure 60, is predominant, and the capacitor is not charging enough.

At first, it was thought of modifying the circuit to avoid this issue, but no solution was found. This meant that a new coil with a lower coupling capacitance needed to be used. A coupling capacitance was carried out and results shown in Table 6 found.

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Table 6 Different coils coupling capacitance measurement

The tests from then on were conducted with the 45 mJ COP coil. The value in the previous coil is approximately between 7000-8000 times bigger. This can be linked to the constriction of the coil; the previous one has the secondary side of the coil surrounding the primary side. This means that the surface for both sides is way bigger than what we would have with the typical allocation of the coils.

6.2. Excessive ringing

When conducting the measurements, it was encountered that the ringing, an effect that is expected during the ignition turbulence in the chamber, was happening also during the post flame window leading to the loss of information when misfire events were happening.

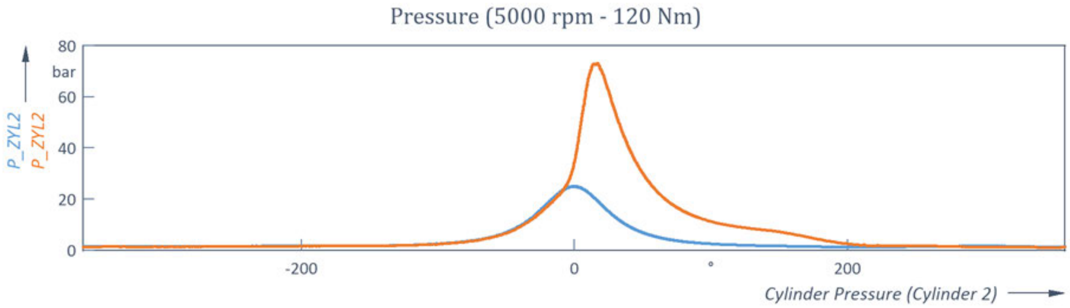

Figure 61 Pressure with and without misfire

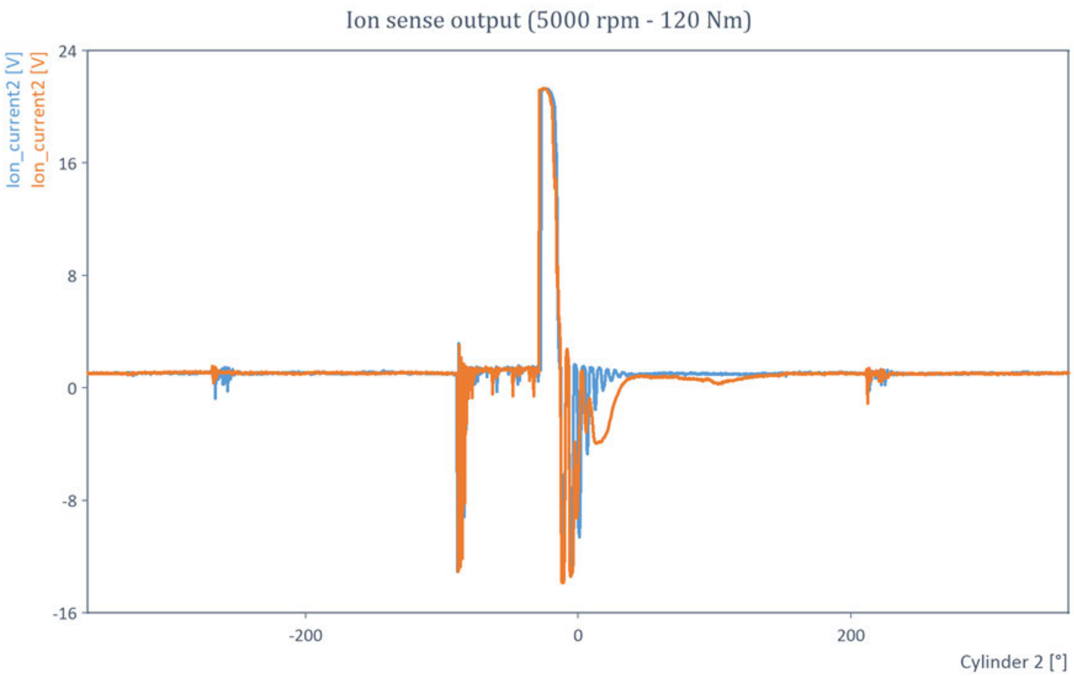

Figure 62 Ion sense output at misfire and no misfire (with too much ringing)

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As it can be seen in Figure 61, the blue cycle can be considered as a misfire event. The maximum pressure in the chamber is reached at 0º CA, and the pressure reached is way less than the typical; 80 ± 10% bar. The issue that can be observed here is the prolongation of the ringing, due to the need for dissipation of the coil energy when the energy is not used for ignition.

As we can see in the blue signal of Figure 62, the ringing is complicating the reading of misfire. This event should have no current during post flame. This phenomenon has been encountered in the past and a solution has been found using a snubber circuit that is able to reduce voltage transients in electrical systems [8]. In our case, a snubber resistor system has been used in the primary side of the coil.

This resistor allows the primary coil to discharge, so the main path is going to be the secondary coil but also some is going to this resistor. When the ignition has happened, the remaining energy is drained through the resistance added. This leads to a reduction of the unused energy that generates the unwanted ringing.

In the next graph, it can be seen how the resistor has helped the reduction of the issue.

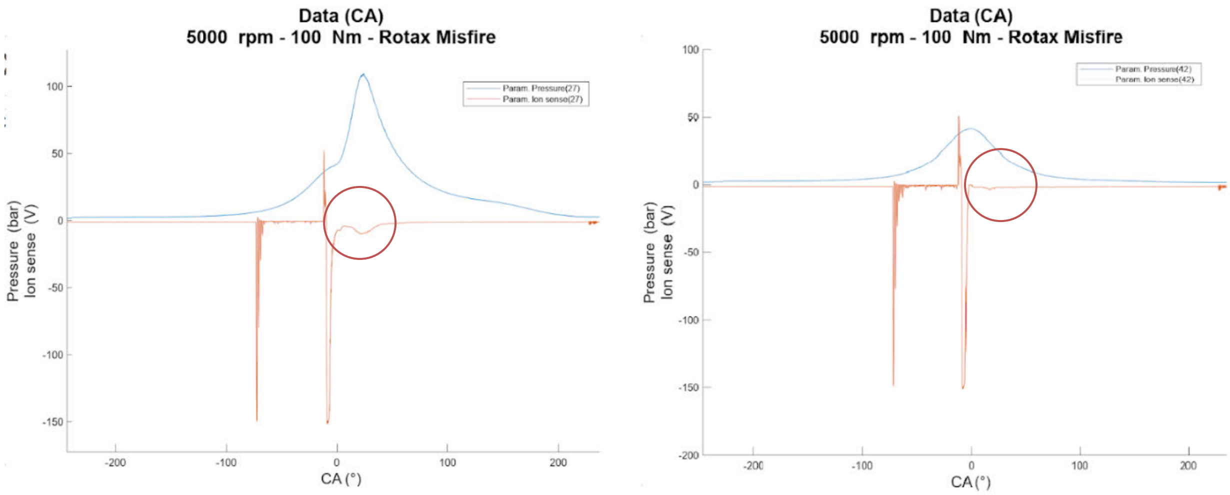

Figure 63 Misfire determination without ringing (resistor in parallel with the primary coil)

In the left of Figure 63, it can be seen that in the case of normal combustion and in the right a misfire event that as we can see has little to non-ringing.

A test to determine how big is the current flowing through the resistor has been carried out, see Figure 64. In Figure 65 the current that flows through the snubber resistor is relatively small. Only the 3.7 % of the pic current. The current through the resistance during charging is constant at around 0.25 A. At the start of the ignition, we have a negative pic, because of the spark in the secondary side of around -1.5 A. After this event it stays at around -0.25 A during front flame and post flame.

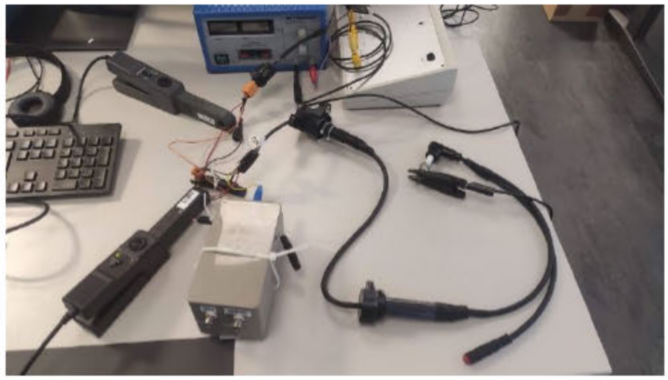

Figure 64 Test for measuring the current through the snubber resistor

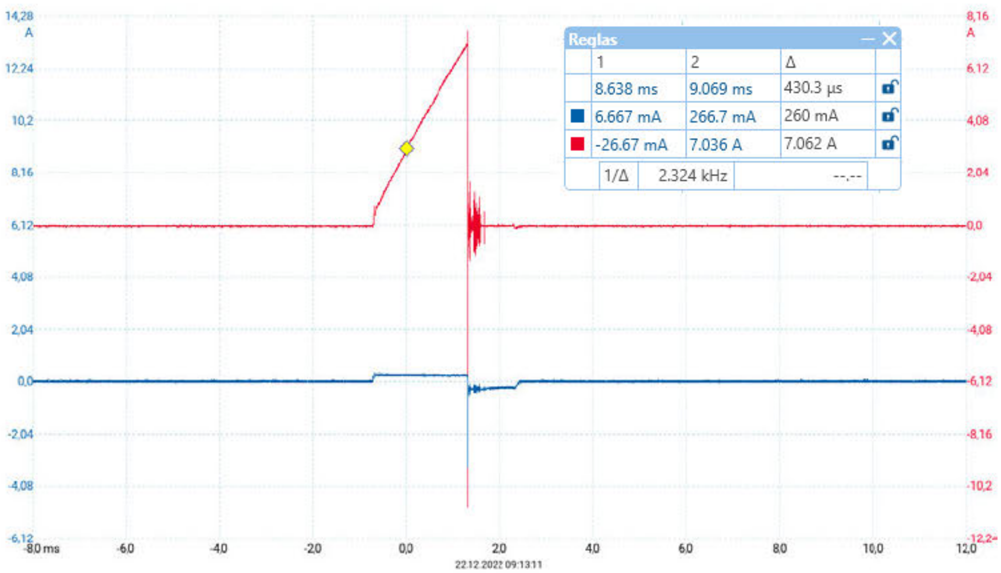

Figure 65 Current through the snubber resistor

Further tests should be carried out to ensure that the ignition snubbed will not have a negative effect on the ignition of the engine.

6.3. Charging of the coil

Another problem that has been found during this development is the abnormal behavior of the primary side of the coil for low load running conditions. The primary current, where the issue can be diagnosed, can be seen in Figure 66 in comparison with normal operation that can be seen in Figure 67.

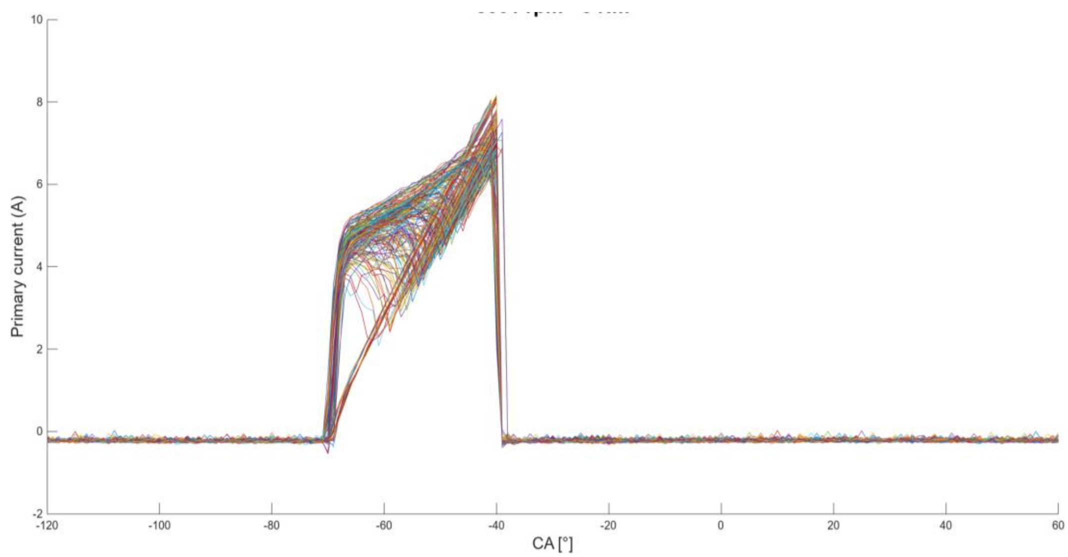

Figure 66 Primary current at 3001 rpm - 6 Nm - Typical operation – Facing issues

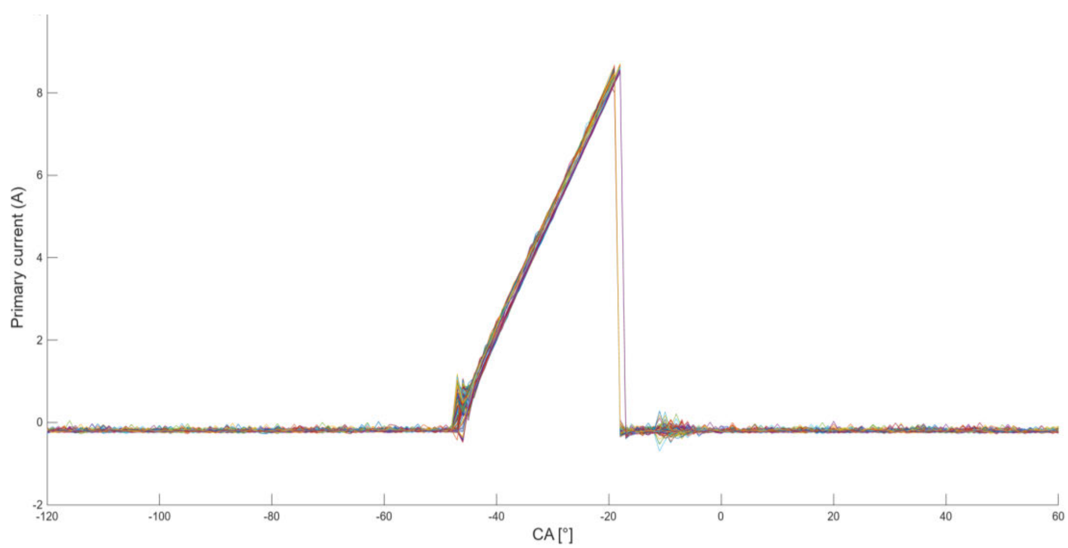

Figure 67 Primary current at 3000 rpm - 106 Nm - Typical operation

As it can be seen the current has a non-constant waveform. It is not related to misfire. In Figure 66 and Figure 67 cases of typical operation are shown. Moreover, the same tests were conducted with misfire events to see whether the misfire would affect our results and as it can be seen in Figure 68 and Figure 69 is persistant.

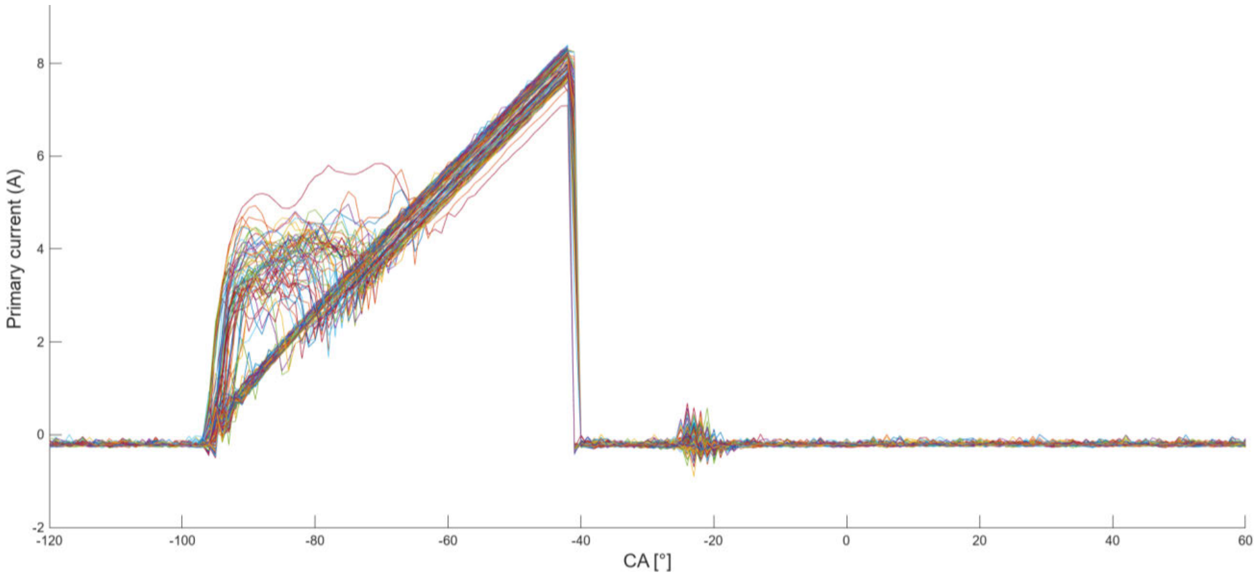

Figure 68 Primary current at 5488 rpm - 2 Nm - Misfire - Facing charging issues

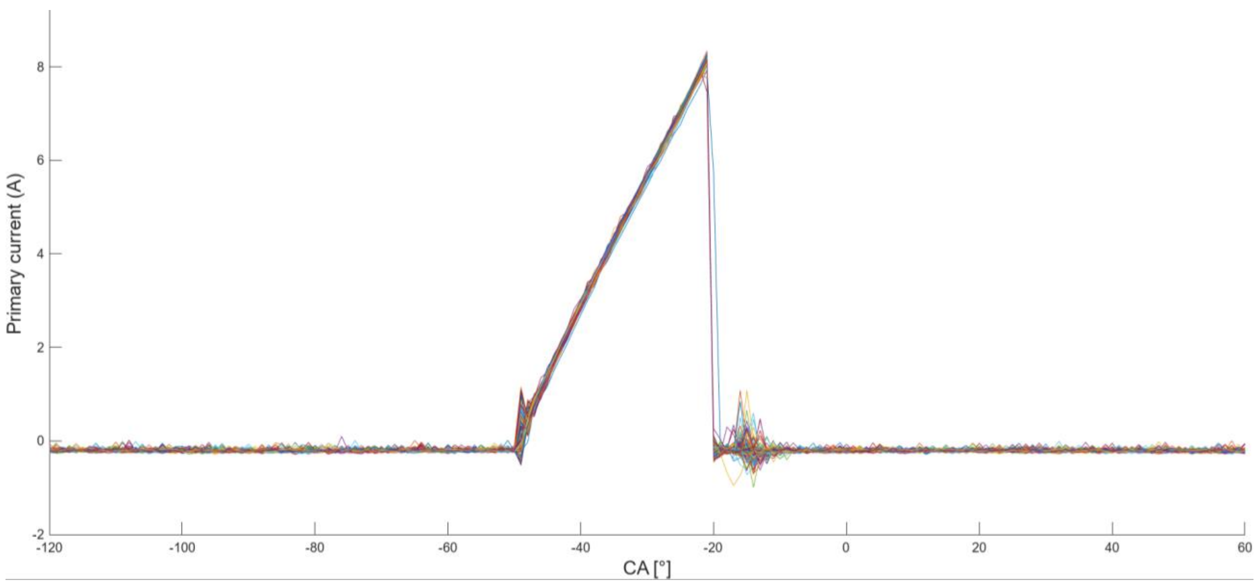

Figure 69 Primary current at 3000 rpm - 110 Nm - Misfire - Not facing charging issues

As it can be seen there is an issue related to the load of the engine which means that we have two situations normal charging and the abnormal one. These two cases are shown in Figure 70.

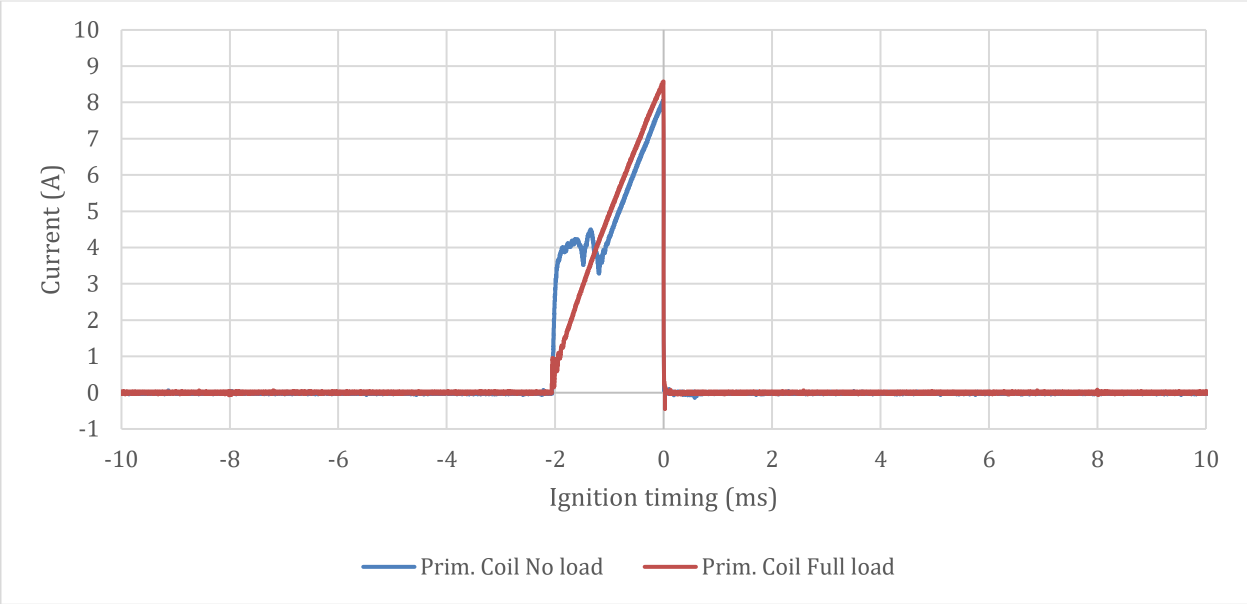

Figure 70 Normal and abnormal primary coil charging

Measurements needed to be conducted to see where the energy was coming from. The first thing that needed to be studied is the capacitor as it stores energy so it could inject it to the system.

With a high voltage probe the voltage in the capacitor was measured and can be found in Figure 71 overlapping the charging current.

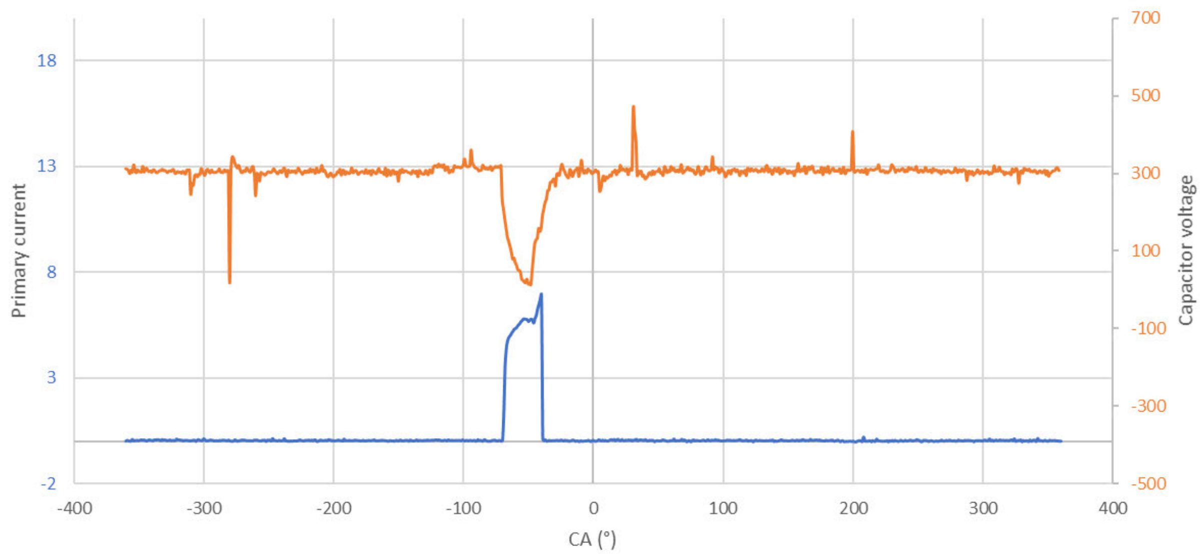

Figure 71 Capacitor voltage (in orange) and primary current (in blue)

As it can be seen at first glance, the capacitor discharges onto the primary coil and after the coil discharges onto the capacitor. After some discussions it was established that the energy that leads to the primary comes from the capacitor in the secondary side.

To have this happening the secondary side must be closing and forming a close mesh during changing. Because of that, a current path could be expected in the secondary side. One of the first things that were analyzed were the ion and spark current signals.

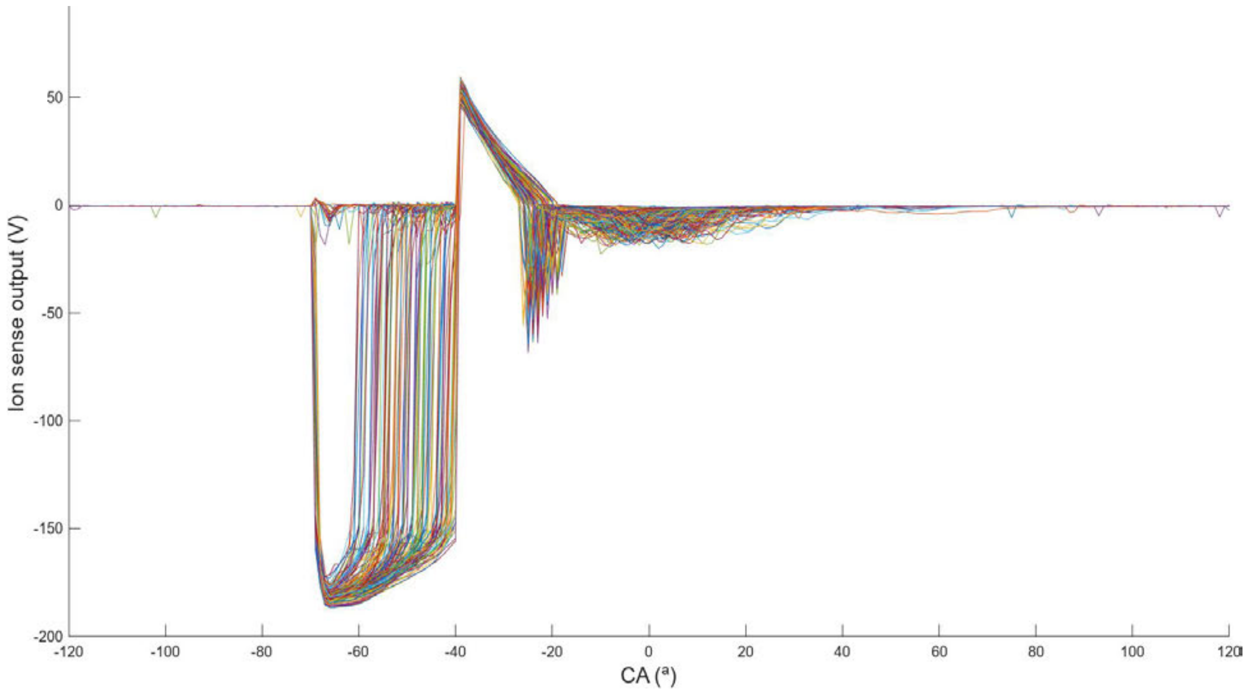

Figure 72 Ion sense measurement at 3000 rpm - 5 Nm - Experiencing the charging problem

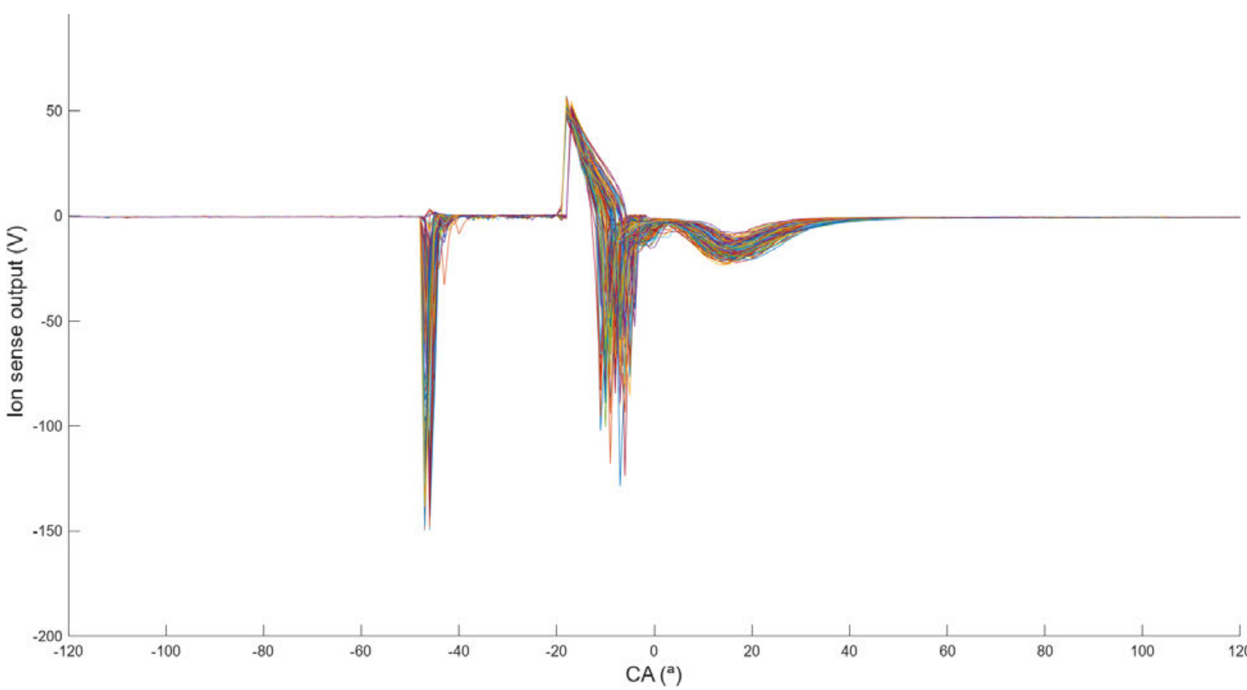

Figure 73 Ion sense measurement at 3000 rpm - 106 Nm

As it can be seen in Figure 72 the current that discharges through the capacitor is generating a voltage drop in the ion sense signal (from -70 to -40) during the charging of the coil. This was also the case on the spark signal. This is not happening when running at higher speeds as it can be seen in Figure 73.

The first possible explanation was that there was a current flow formed by the coupling capacitance as issues had been experimented before with this parameter.

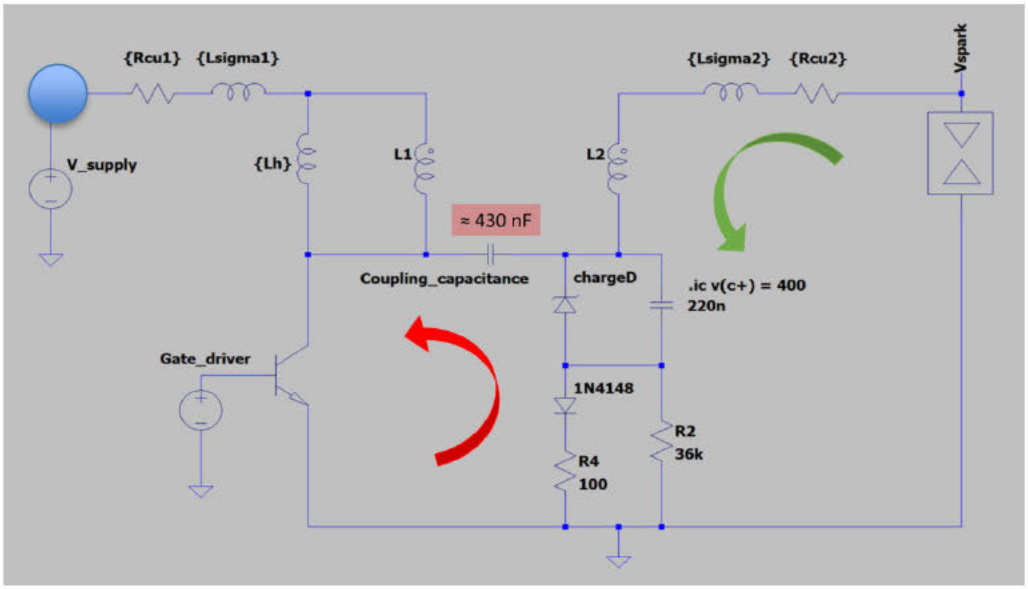

Figure 74 Coupling capacitance current path

The red arrow from Figure 74 would indicate that path. This is not a possible explanation as the current was appearing on the top, low side of the ignition coil (blue dot in Figure 74).

Nevertheless, a test was conducted to assess the current flow through the primary side. Both currents, top and low connections of the primary coil, were measured and it was seen that the current on the top side and the current on the bottom side were the same. They are represented in Figure 75 in red and green.

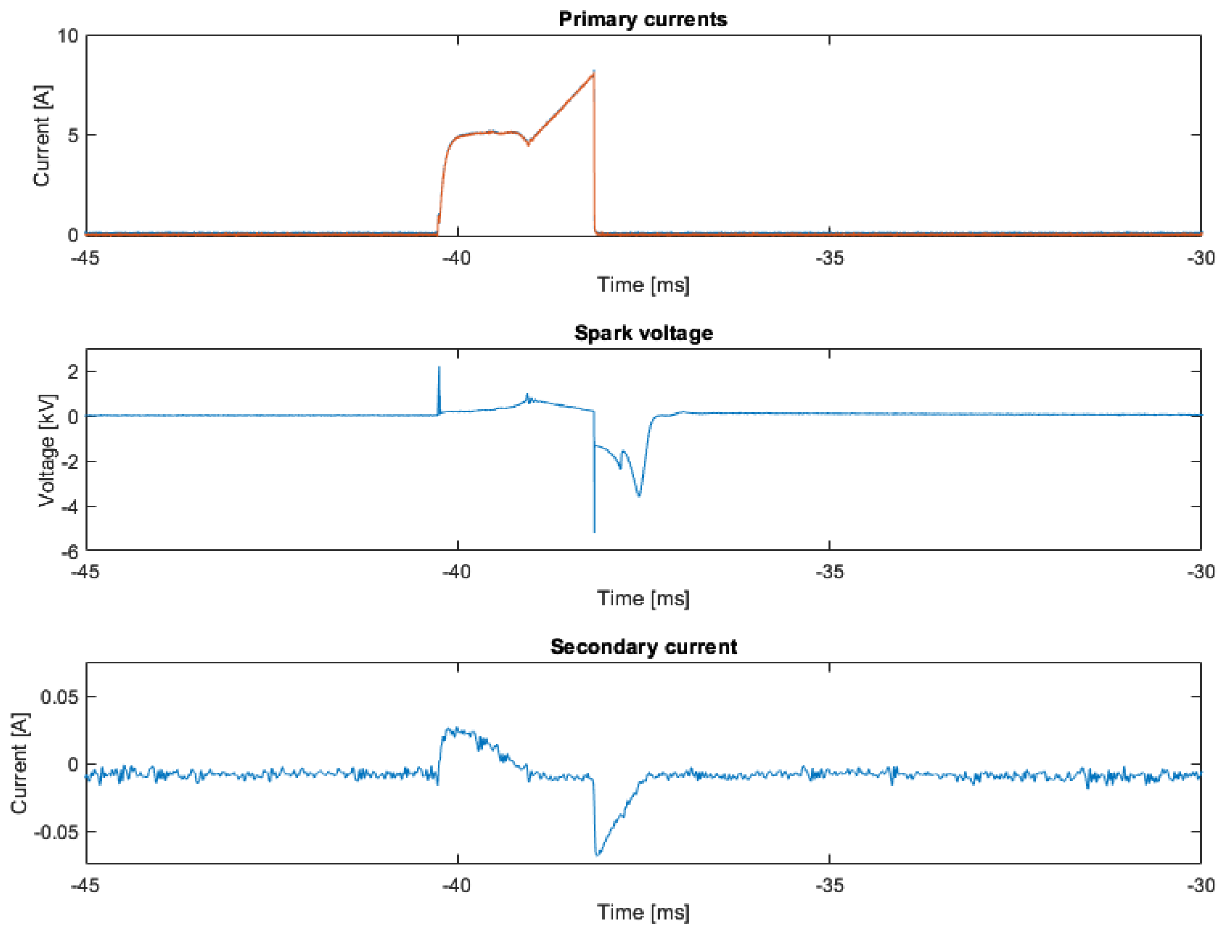

Figure 75 Measurement of currents and secondary voltage - with charging issue

This means that, according to the universal knowledge of the mesh analysis, no current was added so the coupling capacitance can be neglected in this case. Next test was to measure the secondary side top voltage. To be able to measure the high side of the secondary coil, an adapter and a modified coil had to be used. The real coil is the one on the bottom and the top one is a fake one that only connects to the spark plug.

Figure 76 Adapter for high side output measurement

With the Figure 76 adapter, the voltage in the high side was measured (in the middle plot in Figure 75) and the secondary current in the low side of the coil was also measured (in the bottom plot in Figure 75). In Figure 77 it can be seen how this is not happening when running at higher loads.

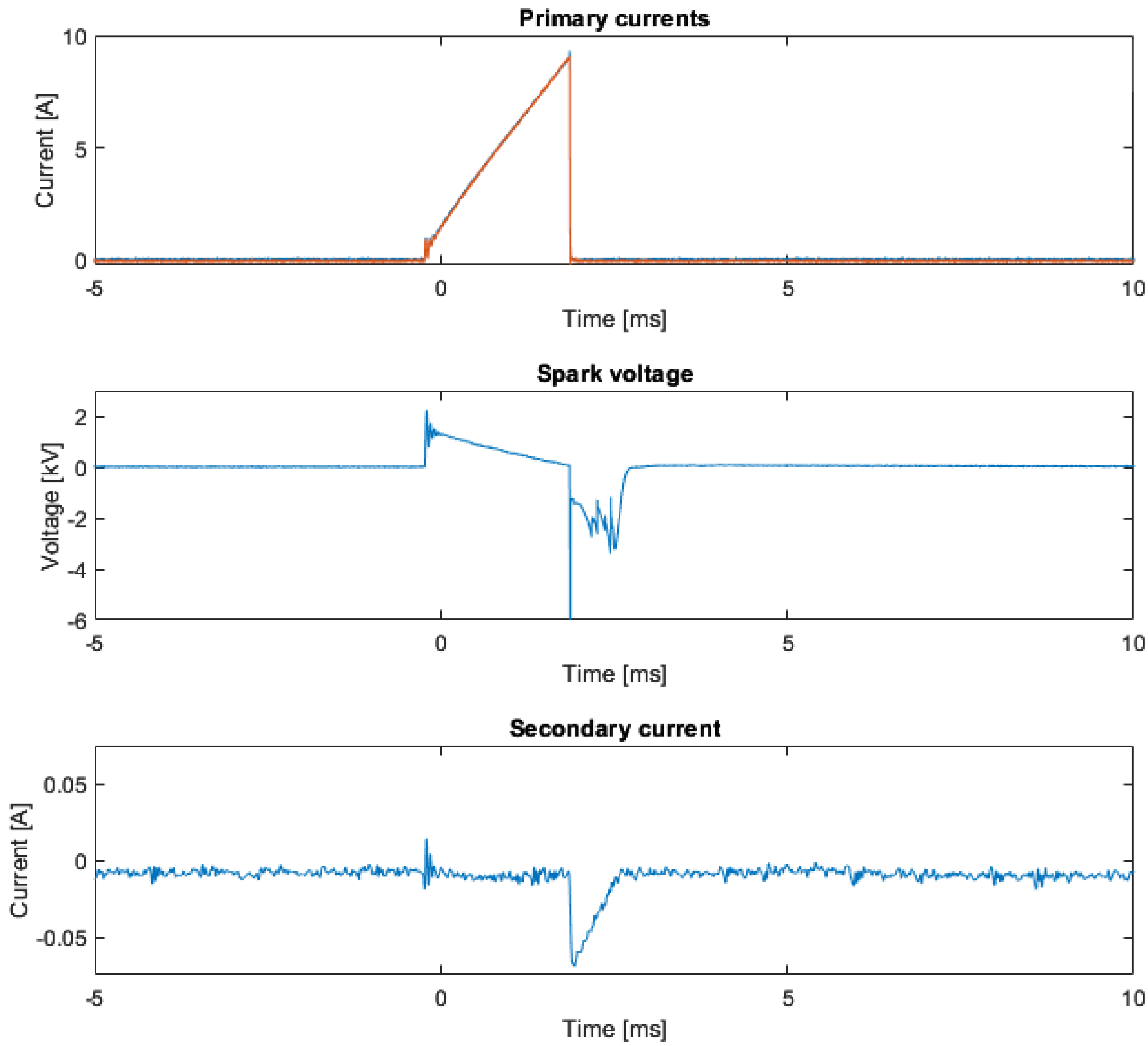

Figure 77 Measurement of currents and secondary voltage - without charging issue

As it can be seen in Figure 77, there is a current flowing on the secondary side. This means that there must be a spark in the spark plug so in this way there is a current path that allows the capacitor energy to flow onto the primary through the magnetic coupling of the transformer.

Thermodynamic experts from RC-LowCAP project and Rotax were consulted, and it was confirmed that this spark was not generating any combustion, which is a good thing because in this case it combusted it would be generating early ignition. Early ignition is a phenomenon that causes degradation in the engine and a decrease in the performance.

Although there is not an apparent effect on the combustion (that would be appreciated in the pressure signal) this is a negative effect that cannot be avoided.

After discussing this issue, it was agreed that this issue is happening because there is no diode in the secondary side blocking the current that could happen during charging when a positive voltage could generate a spark as explained in '3.1 Operation' section.

The reason for the event to happen only at low loads is that, as explained in '3.2.3 Ignition coils' section, when the load is low, the pressure inside of the chamber is lower meaning that less energy is needed to jump the spark plug airgap.

We know according to what is explained in '4.2.2Ignition with ion sense' section that we cannot just put the diode as no current will flow and charge the capacitor. This means that a switch needs to be installed. The easiest way of doing it is by adding a protected IGBT at the low side of the ion sense circuit as no need of driver will be needed (meaning that we will not have to step up the gate voltage to drive it).

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There would be two options of positioning the switching device (a semiconductor technology has not been decided but a well-protected Power-Transistor could be a possible option) that would be able to control bidirectionally the current in the secondary side (see 2 options: Figure 78 and Figure 79). One thing that is clear is that it must be connected to GND. The effect would be the same in other places of the secondary mesh but putting it down means that no gate voltage step-up is needed.

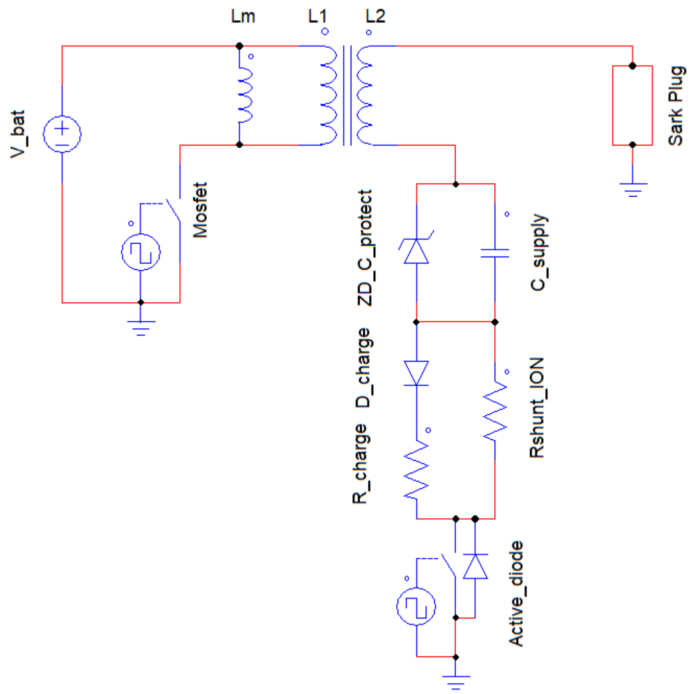

Figure 78 Possibility with orientation: cathode of the anti-parallel diode up

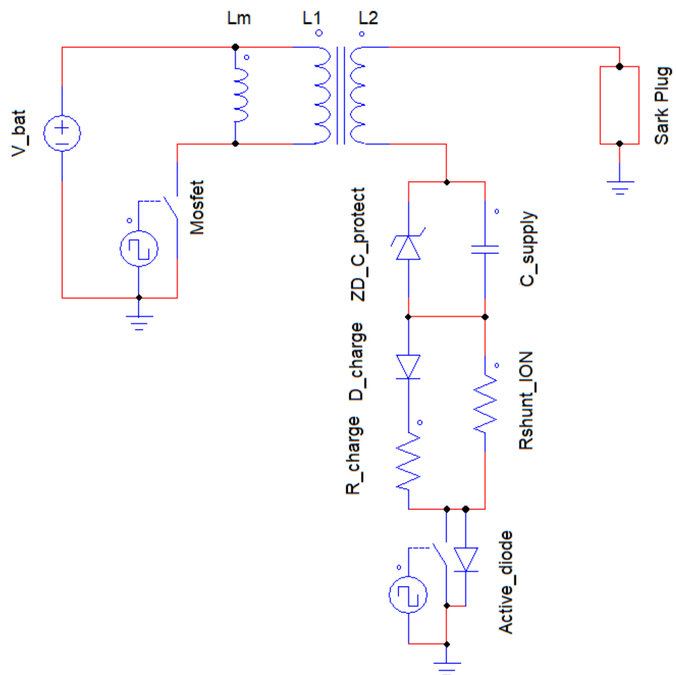

Figure 79 Possibility with orientation: cathode of the anti-parallel diode down

Table 7 summarizes the difference of operation between Figure 78 and Figure 79.

	Switch	Diode	Activation time
Figure 78	When activated the spark during charging will be blocked	Will be always allowing the charge of the capacitor (not a problem)	During dwelling (charging of the primary)
Figure 79	When activated the current that charges the capacitor will flow	Like in a traditional coil. It will block the spark during charging	During the ignition spark so the capacitor can be charged

Table 7 Active diode orientation differences

At first it looks like both options would work and most likely they would. However, we have to build safe circuits and from that standpoint it makes more sense to choose Figure 79 as in case the switching device stops working the ignition will still work (it would not be the case of the ion sense). CONFIDENTIAL [redacted]

6.4. Current state

At current the misfire detection, objective of this dissertations work is working but there has not been time enough to improve the circuit to avoid the charging issue.

Nevertheless, misfire detection has been found possible and misfire events have been detected in the Table 8 engine running conditions.

Speed (rpm)	Load (Nm)
1800	5
1800	30
1800	60
3000	6
3000	50
3000	100
5000	5
5000	90
5000	160
7000	8
7000	90
7000	180

Table 8 Running conditions where misfire detection has been evaluated

As seen, it means misfire detection has been found possible in all engine speed and loads (no load, mid-load and full load). Some examples of that being Figure 80 and Figure 81.

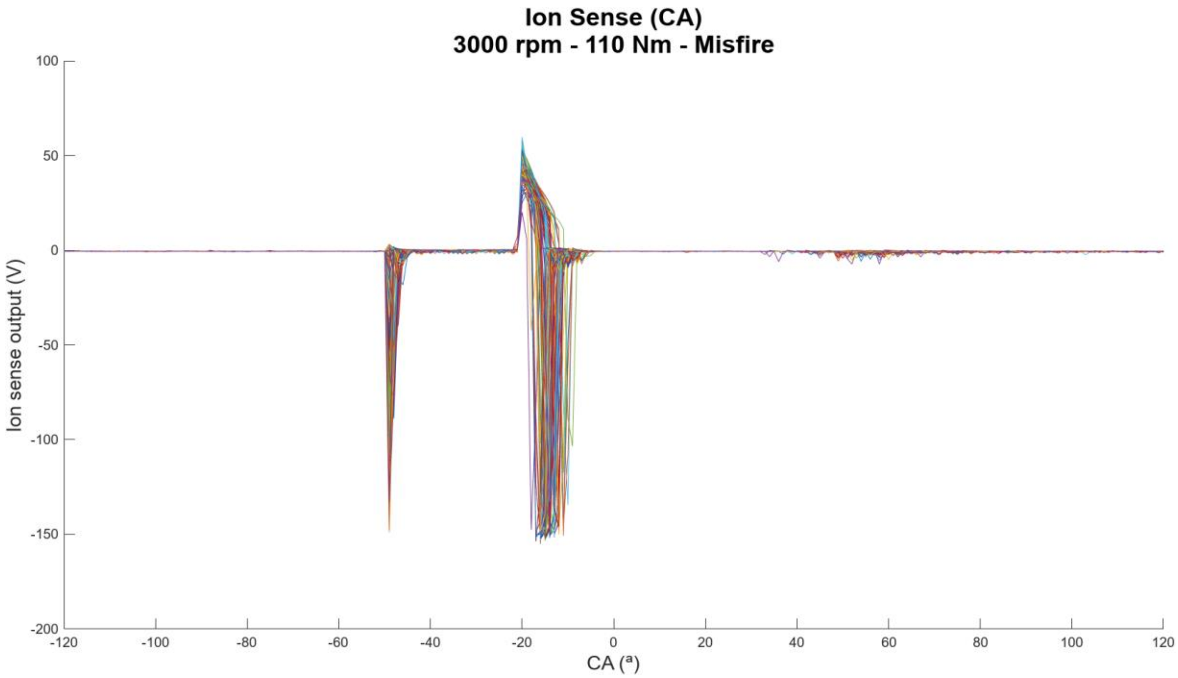

Figure 80 Ion sense signal. Misfire at 3000 rpm - 110 Nm

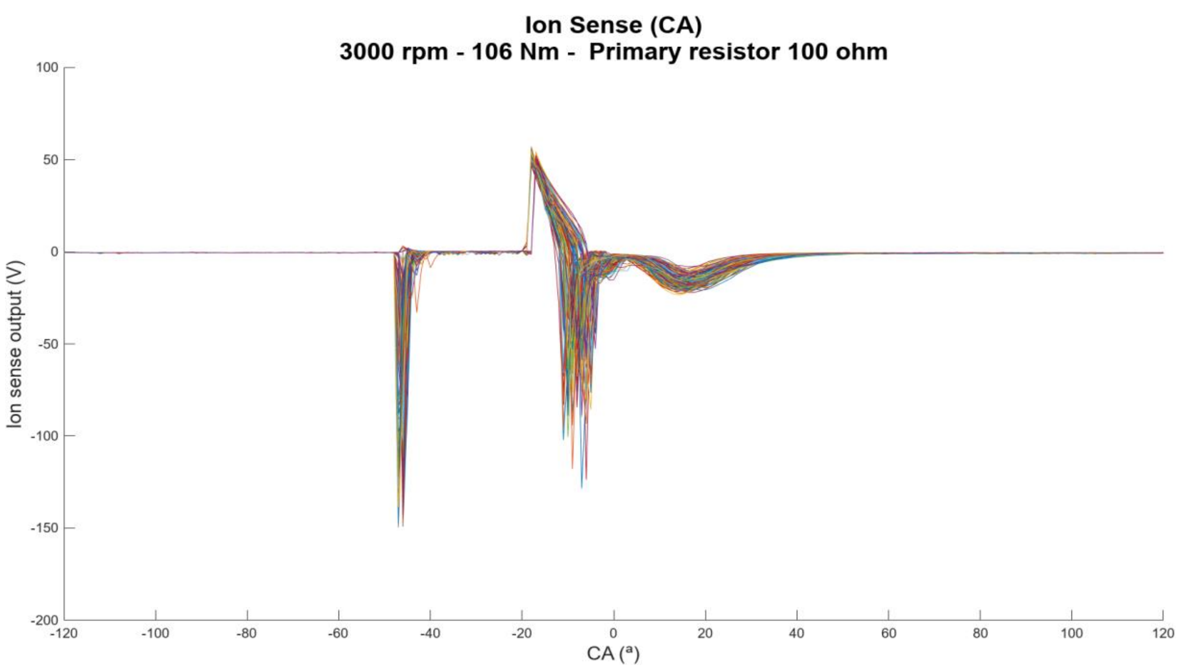

Figure 81 Ion sense signal. No misfire at 3000 rpm - 110 Nm

A basic determination has been established. The integral of the flame front and post flame area is carried out and based on that the determination is carried out. If the integral is less than the minimum value established misfire is detected. In the right side of Figure 83 it can be seen the misfire case and, in the left, the no misfire case. As it can be seen IMEP is used as a validation method as it indicates if combustion has happened through the pressure readings, see with the 200 cycles seen in the right side of Figure 83.

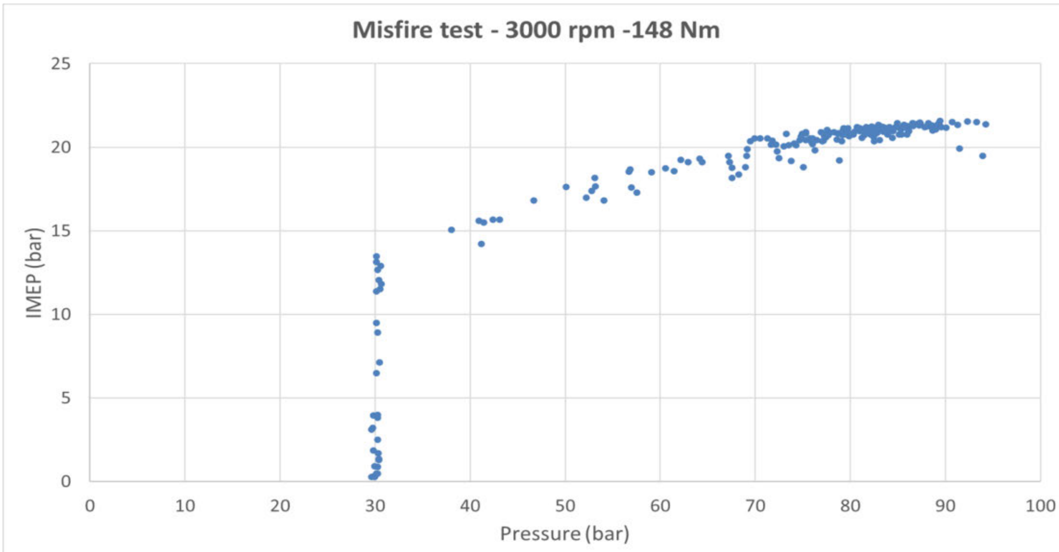

Figure 82 IMEP- Pressure

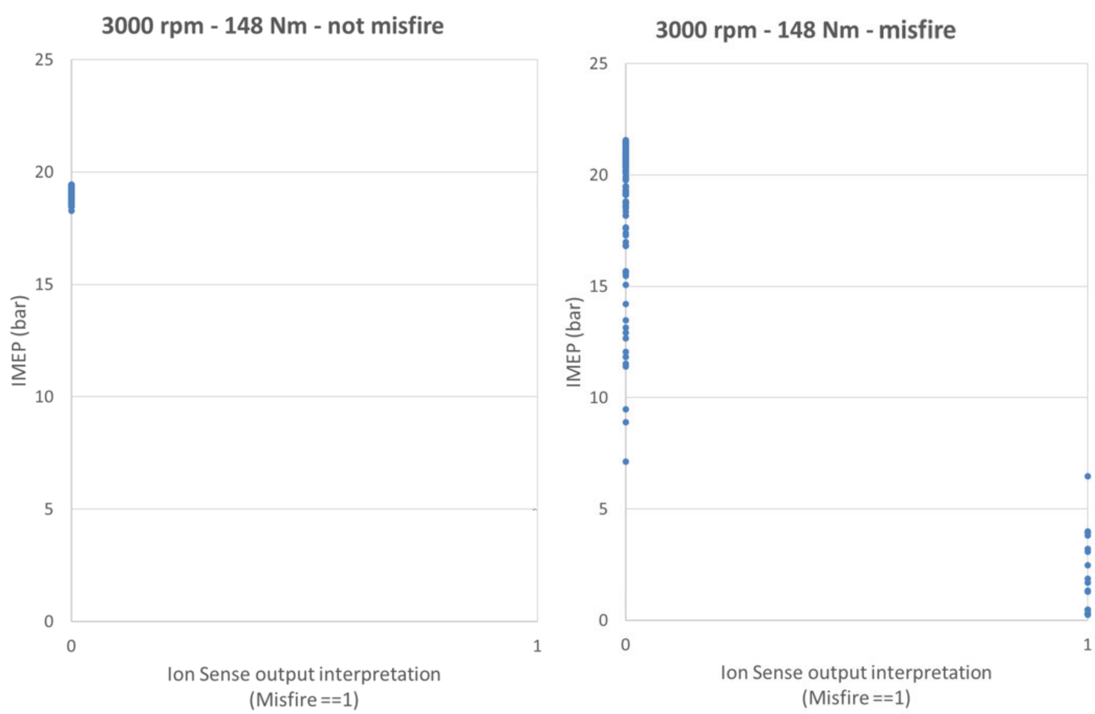

Figure 83 Misfire and no misfire determination (comapred with IMEP)

It has been found that detection in low loads is not as “strong”. This is since at low loads conditions inside of the chamber make it hard for thermal ionization to happen and only the chemical (created by the combustion is present. As it can be seen in Figure 84 when no combustion takes place no ions are detected during the front and post flame, see area marked in Figure 84 where misfire is detected. On the other hand, when combustion is detected like in Figure 85, we see a big area that indicates a strong ion concentration is present. As stated before, in low loads the ionization is not that strong leading lo a measurement like the one in Figure 86.

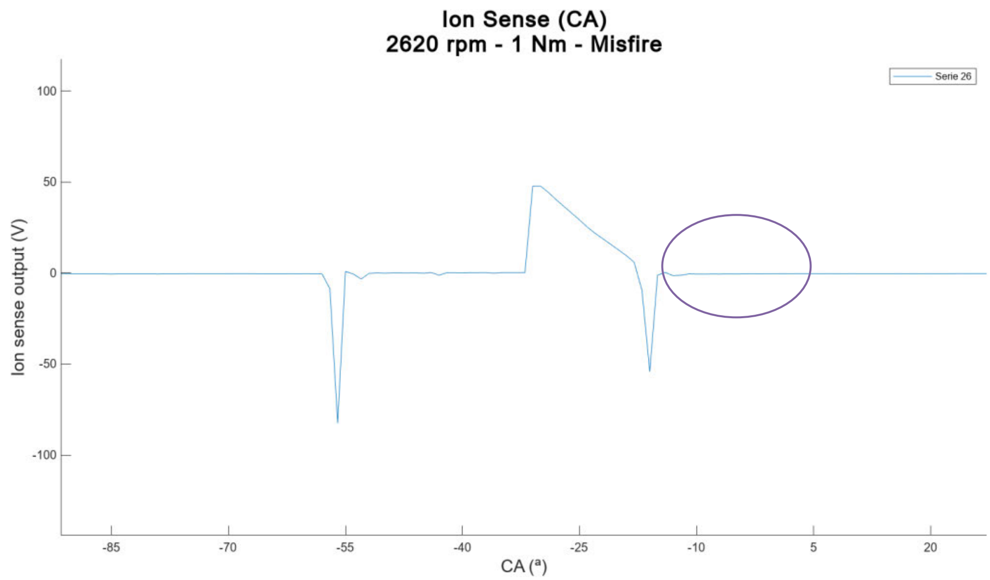

Figure 84 Misfire at low loads

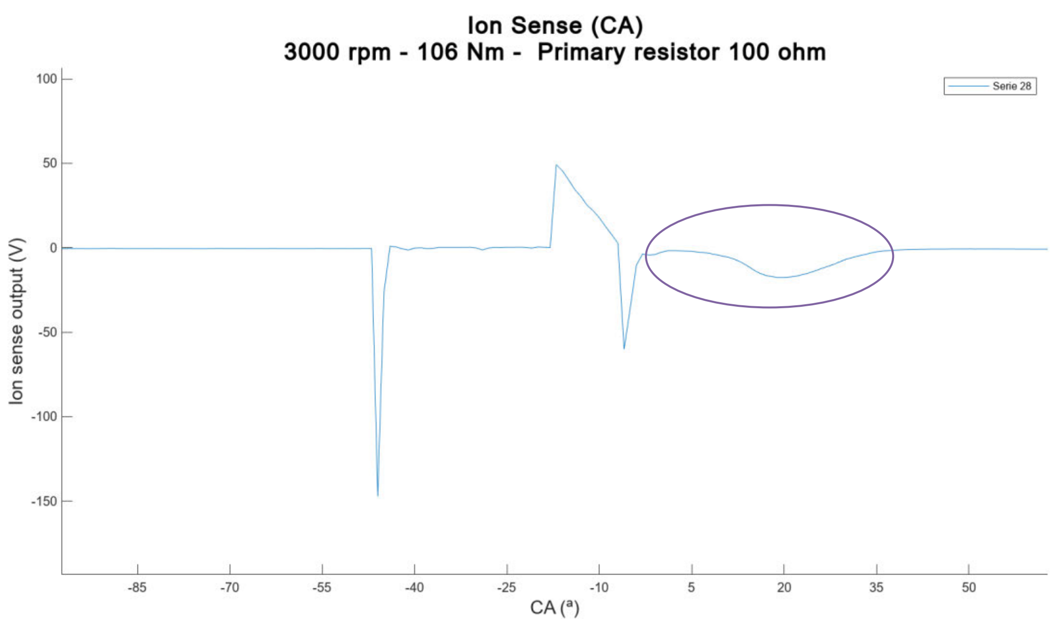

Figure 85 Combustion at high loads

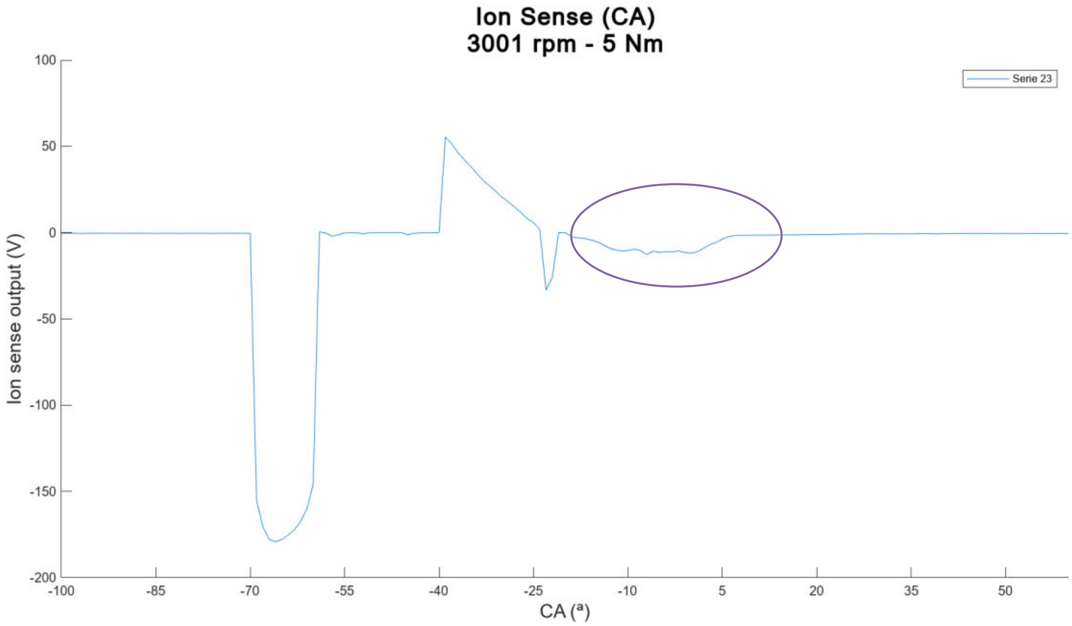

Figure 86 Combustion at low loads

7. Conclusions

A good understanding of engine combustion has been presented focusing on misfire detection, a key element for secure and green combustion. Misfire causes have also been explained to develop in the future engine diagnostics.

In this project, a working ion sense industrialization is presented. Problems faced, not found during previous development, and the solutions applied have been discussed to improve the readings.

An explanation on how the circuit works and the method for misfire determination have been explained. It has been proven that misfire detection is working reliably at different speeds and loads. At low loads the detection is not as sharp due to the lack of a strong thermal ionization leaving only the chemical one. At current, misfire detection is conducted on deferred basis, where more processing tools can be used.

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An issue regarding the charge of the primary coil has been found to the design, and in this dissertation a preliminary solution has been found.

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Appendix

A. Data acquisition flow

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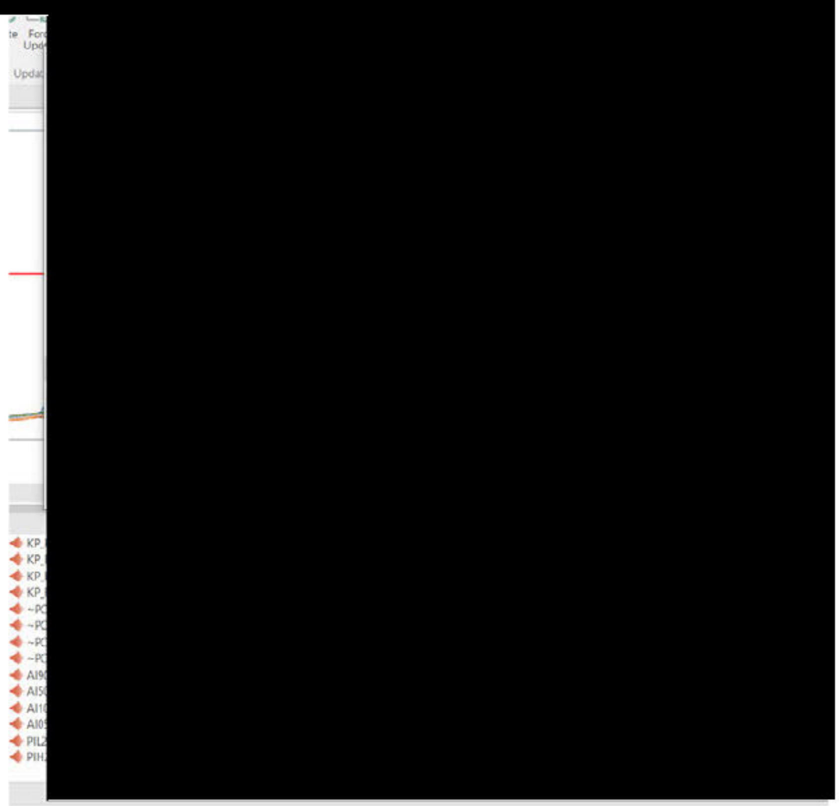

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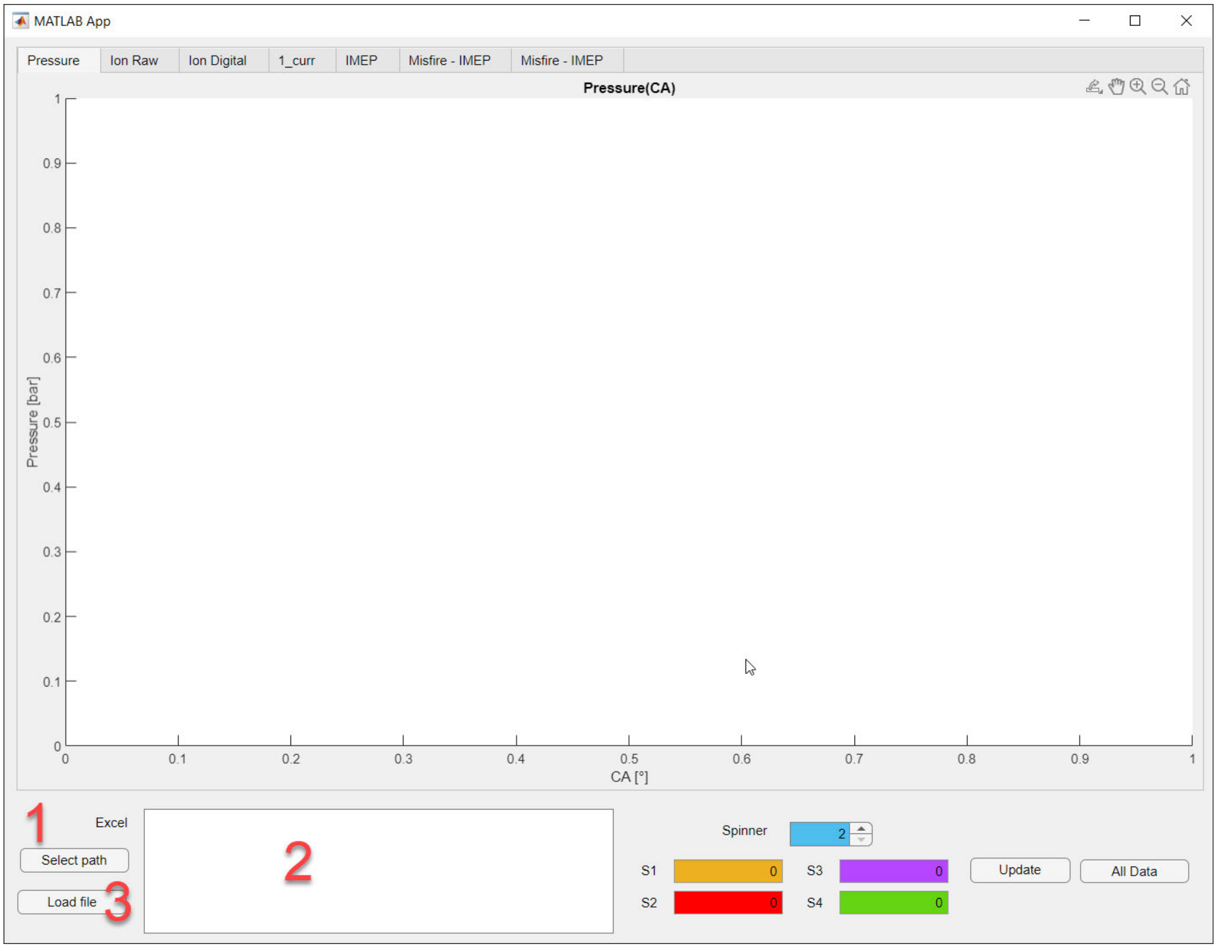
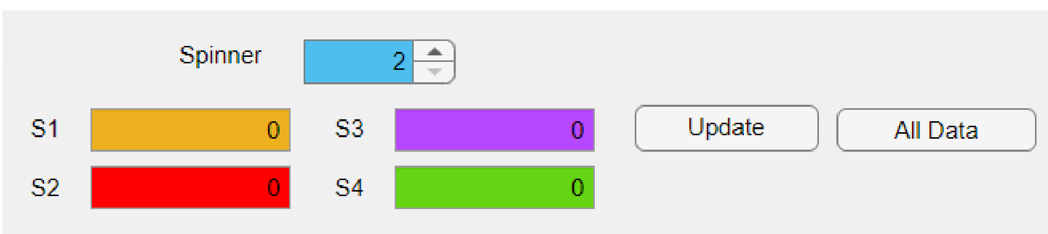
USE OF THE MATLAB TOOL

First: to make it work you need to have MATLAB working in your PC.

If you just want to use it without editing just double click. If you want to edit it, you have to open Matlab and modify it there.



1: Select the path. The folder where all the .xlsx
2: Select the file (test) you want to plot
3: Load the file



With the “All Data” you plot the 200 tests
With the “Spinner” you can change the cycle you want to see. If you want to fix one of the cycles you have to write that number in the “S1”, ”S2”, ”S3” and ”S4” and then press “Update”. You can only plot in order so if you want to use the “S” plotting first the “S1” then “S1” and “S2” and so on. You can still use the “Spinner”. This will update all the plots at the same time.

B. Matlab GUI code

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