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# Spark Ignition - Searching for the Optimal Spark Profile

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**Abstract.** The impact of different spark designs on the ignition and combustion stability is studied using a 13-liter CNG fueled heavy duty spark ignited engine to search for the “optimal” spark design. Experimental results show that robust ignition can be achieved using a significantly shorter spark duration and lower energy than expected. A capacitive discharge ignition (CDI) system enabled to separately control the available spark voltage, current and duration (FlexiSpark® CDI) was compared to a standard CDI system without spark control and an inductive discharge (IDI) ignition system. Typically, a robust ignition can be provided using only 5% of the spark duration and 17% of the spark energy compared to that required by an IDI system to accomplish an equivalent ignition and combustion stability. By applying control of the spark, a robust ignition can be provided which is optimized for the fuel, the engine design, the engine operating condition, and the condition of the spark plugs. This offers a potential to significantly reduce the spark-plug wear and the total cost of ownership without compromising engine performance. The results are especially interesting in the view of hydrogen fueled SI-ICE, where the required available spark voltage is high, but the required spark energy is low. It is desirable to use a spark design with just enough voltage and power to initiate a sustainable combustion, but with minimal energy not to excessively wear and heat the spark plug electrodes to avoid pre-ignition.

**Keywords:** Spark ignition, ignitability, internal combustion engine, renewable fuel.

## 1 Introduction

Spark ignited internal combustion engines (SI-ICE) using alternative and/or renewable fuels are vital to reduce emission of greenhouse gases. Substantial effort is dedicated to make such engines a viable complement to electrification. However, the fuels in focus, e.g., bio- and natural gas, hydrogen, ammonia, and alcohols have different properties that need to be considered when designing the control system and optimizing the performance.

The paper presents novel results from an ignitability study using different spark designs, performed on a HD natural gas fueled SI-ICE. In the study, the spark ignition performance was measured as the combustion stability ($COV_{IMEP}$) at different engine operating conditions when applying different spark designs. Sparks from both inductive and capacitive discharge ignition (CDI) systems were tested. When using an inductive discharge ignition system (IDI), the spark is DC and the available control parameter is the dwell time, which controls the available spark voltage, current and duration. An increase in available spark voltage increases the spark current and duration, i.e., the spark energy is increased.

When using a capacitive ignition system design, the spark is AC and the spark can be controlled from the ECU if the ignition system is enabled to provide such a flexibility. Hereby the available spark voltage (ASV), the spark current, and the spark duration can be adapted to the fuel and engine properties. The ignition system provider SEM has developed a flexible CDI system denoted FlexiSpark® and a prototype was made available to the Dep. of Energy Sciences, Division of Combustion Engines, at Lund University. The ignition performance of the FlexiSpark® CDI prototype was compared to a standard CDI system without spark control and to a standard IDI system.

The paper is organized as follows. First, the spark ignition process is summarized. Second, the results from the ignitability investigation are presented. Third, preliminary conclusions and ongoing/future research is described.

## 2 The spark ignition process

Spark ignition is an energy-exchange phenomenon, where electrical (spark) energy is converted to thermal energy in the air-fuel mixture locally around the electrode gap, increasing the temperature to several thousand degrees Kelvin, exceeding the auto-ignition temperature of the fuel, initiating a self-sustained exothermic combustion process [1, 2].

The sparking process can be described by three phases: Breakdown, arc, and glow. The breakdown phase consists of the formation of a conductive plasma channel between the spark plug electrodes. It is characterized by a short timescale (tens of nanoseconds) and requires a high voltage (10 kV or more) [11]. At the onset of the spark, the voltage across the spark plug electrodes rapidly increases and the randomly existing free electrons gain kinetic energy, accelerating towards the anode. When the applied electric field reaches sufficiently high values (50-100 KV/cm), the electrons have such high kinetic energy that they may ionize the fuel-air molecules by collisions, generating additional electrons and ions, like an avalanche, also known as the impact ionization effect [2, 3]. The temperature of the plasma hereby formed between the electrodes at the breakdown reaches up to 60.000 K. The current during the breakdown is high, in the range of 100 A. The voltage required for breakdown is linearly dependent on the in-cylinder gas pressure and the gap between the spark plug electrodes, according to Paschen’s law [3, 4].

After the breakdown the arc phase follows, which is characterized by a highly conductive thin medium of plasma, where gas along with electron temperatures are in thermal composure and the temperature drops down to below 10.000 K. During this phase, the electrons are primarily emitted from the cathode through field emission and the high temperature [9]. The electrode wear is expected to be high, due to the high electrode temperature which leads to evaporation of molten metal. The current during the arc phase is in the range 10-20A and mainly supplied by the spark plug and ignition coil extension capacitances. When the charge in the spark plug and coil extension capacitances have discharged, the current decreases to a lower value, typically in the range of 10-200 mA. Then the electron emission mechanism switches from thermionic emission to secondary emission of electrons due to bombarding ions and photons, and the spark discharge takes on the characteristic of a more diffuse glow discharge. The current supply during the glow phase is from the ignition system (primary and secondary coil windings). A strong enough spark current is required to sustain the plasma. In the presence of turbulence, the plasma channel is “stretched”, forming a bow-shaped trajectory. A higher current can sustain a longer plasma elongation than a weak, increasing the flame kernel area, which in turn is expected to enhance the capability to trigger a self-sustained combustion [5, 6, 7, 8].

The spark generates a flame kernel. The laminar flame speed of the flame kernel is determined by the property of the air-fuel mixture (pressure, temperature) between and around the spark plug electrodes. When the diameter of the flame kernel has reached a few millimeters, the flame initiation has come to an end, and the ignition process has played out its role. The rest of the combustion process is determined by the turbulence and other in-cylinder properties as determined by the fuel property and engine design.

It has been estimated that the spark discharge phases transfer different fractions of energy to the spark plug electrodes; breakdown ~ 5%, arc discharge ~ 45%, and glow discharge ~ 70% of the total electrical energy in each phase [8]. The energy not absorbed by the electrodes is absorbed by the gas. Hence, it is expected that the breakdown phase is the most efficient to transfer energy to the fuel mixture, followed by the arc and glow phases, respectively. If this is true, then it can be expected that a very short spark should be sufficient to ignite – provided that the property of the fuel mixture around the electrodes is favorable as is expected at medium and high load conditions. During idling conditions and/or highly diluted fuel mixtures, however, the fuel mixture may be less homogenous, and the ignition process is expected to require a longer spark duration for the spark to hit a favorable fuel mixture.

It is well known that the ability to ignite a fuel mixture depends on the spark characteristics, which in turn depends on the ignition system that generates and controls the necessary voltage and electrical charge released during the spark. To clarify how the ignitability of natural gas fueled SI-ICE depends on the spark characteristics, a measurement campaign was conducted at Lund University in cooperation with SEM, an ignition system provider. The results are presented below.

## 3 Ignitability Study

The focus of the study was to clarify how the ignition performance depends on controllable spark characteristics. In the search for the “optimal spark”, it was assumed that a spark with lower energy will wear the electrodes less than one with higher energy, provided it has the same basic characteristics (AC or DC, current, duration)[1].

The controllable spark characteristics will, most probably, lead to different rate of wear on the spark plug electrodes. The break-through and arc phases are short (in the order of $10^{-9}$ and $10^{-6}$ seconds) and mainly determined by the spark plug and coil extension properties and cannot be controlled by the ignition control system. Therefor, if there is a favorable fuel mixture close to the spark plug gap, it will most probably be ignited by the break-through and arc phases of the spark. Since the glow phase does not transfer heat to the fuel mixture as efficiently as the other, it may be a waste of energy unless a long spark duration is required to increase the probability to hit a favorable fuel mixture, e.g., when the fuel mixture is inhomogeneous and/or highly diluted. A short spark with just enough energy to provide a robust ignition (combustion) is expected to outperform a spark with longer duration and the same spark energy, because the longer spark must have a lower power in the break-through and arc phases than the short to have the same total energy. It is obvious that spark energy is not a good measure of the capability of an ignitions system.

The objective of the measurement campaign was to clarify and provide indicative answers to the following questions w.r.t. ignitability:

1) Is a long spark better than a short?
2) What is the minimum spark energy and duration required to ignite at different EOP and dilution rates?
3) Can the combustion stability be improved by applying a more powerful spark than that with minimum power to initiate a combustion?
4) Is DC (inductive) better than AC (capacitive) sparking?

To clarify this, the engine performance was measured for different spark characteristics at different EOP characterized by RPM, load and dilution by EGR as described below.

## 3.1 The engine

The experiments were conducted on a CNG fueled HD SI-ICE provided by Volvo Penta. The engine specifications are provided in **Table 1**.

**Table 1.** Engine specification

| | |
|---|---|
| No. of Cylinders | 6 |
| Fuel Type | CNG |
| Injection Type | Port Injected |
| Arrangement | Inline |
| Bore | 131 mm |
| Stroke | 158 mm |

---

[1] The assumption needs to be verified and is the topic for current research at Lund University, Dep. of Combustion Physics.

| | |
|---|---|
| Length of Connecting Rod | 267.5 mm |
| Compression Ratio | 12.4:1 |
| A/F Ratio | Stoichiometric (Lambda = 1) |
| Displacement Volume | 12.8 litres |
| Maximum Power | 330 KW |
| Maximum Torque | 2200 Nm |

## 3.2 The ignition systems

Three different ignition systems were used in the measurement campaign as described in **Table 2**.

**Table 2.** Ignition systems used in the measurement campaign

| ***System*** | ***Discharge type*** | ***Spark control parameters*** | ***Spark type*** |
|---|---|---|---|
| ***Standard IDI*** | Inductive | Dwell time | DC |
| ***FlexiSpark ®*** | Capacitive | Available spark voltage (ASV), current, duration. | AC |
| ***Standard CDI*** | Capacitive | - | AC |

For a more detailed description of inductive and capacitive ignition system designs, see [10]. Here, we focus on the control parameters available to shape the spark and the spark characteristics as such.

ASV denotes the maximum voltage the ignition system can provide. The ASV is an important feature of an ignition system because it determines the maximum electrode gap over which it can generate a spark, i.e., how long a spark plug can be used before it needs to be replaced. Clearly, a vehicle using an ignition system with a high ASV can use the spark plugs longer before a service is needed, which in turn reduces the TCO and down-time of it. Note that the ASV is not the same as the break-through voltage, which of obvious reasons must be lower, otherwise a spark would not be released.

A new J-type tri electrode spark plug with 0.1 mm gaps electrodes was installed before starting a measurement campaign with a new ignition system type in-order to minimize any possible impact of spark plug wear from the previous measurement campaign.

### Standard IDI system

In a standard inductive ignition system, the energy to be released in a spark is stored in a magnetic field through a primary and secondary coil. The standard IDI offers only one control parameter which is the dwell time. The **dwell time** is the amount of time in which a current is drawn from the supply (battery) through the primary coil. It is a measure of how much energy that is charged into the magnetic field and later discharged, typically as a DC spark, as illustrated in **Fig. 1**. The available spark voltage, the current and duration are all determined by the dwell time and cannot be controlled individually. The performance of the coil is shown in **Fig. 2**, which shows the dependence of ASV, current and duration on the current through the primary coil, which in turn is a result of the supply voltage and dwell time as shown in **Fig. 3**. The supply voltage was 24 V.

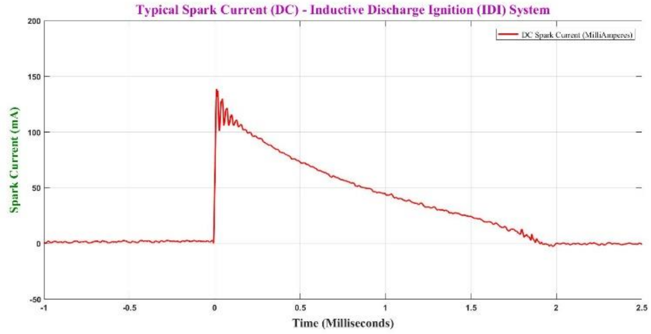

**Fig. 1.** The typical shape of a spark generated by an inductive system. It is a DC spark with decaying spark current. The available spark voltage, duration and current are determined by the dwell time and cannot be controlled individually.

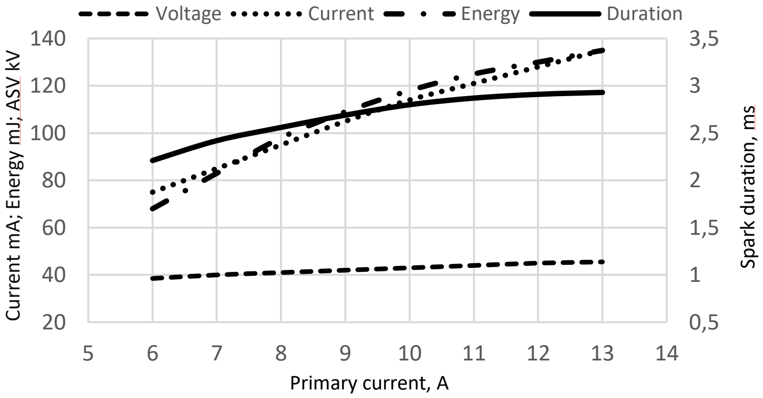

**Fig. 2.** The spark characteristics when using the standard IDI system. The available spark voltage (dashed), current (dotted), energy (dash-dot) and duration (solid) are controlled by the dwell time, which together with the supply voltage determine the primary coil current (x-axis).

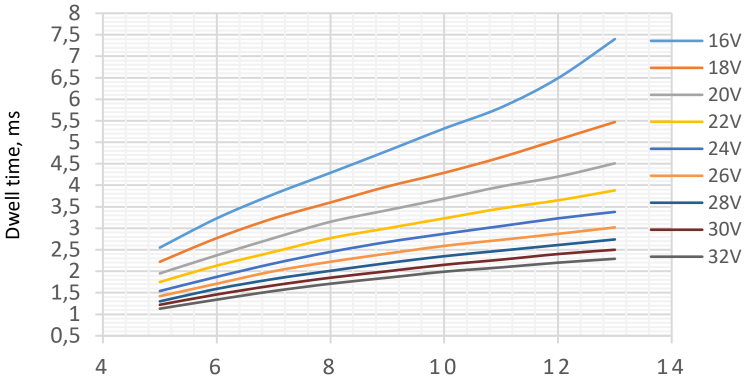

**Fig. 3.** The relationship between dwell time (y-axis) and primary coil current (x-axis) at different primary coil voltages for the standard IDI, c.f. **Fig. 2**.

## Standard CDI system

A standard CDI system was used for reference. In a capacitive ignition system, the energy is stored in a capacitor and the spark is typically an AC. The standard CDI system provided to the measurement campaign was configured with a "standard" spark characterized by a fixed spark duration of ~360 µs and peak current ~230 mA ($I_{RMS} \sim 120\ mA$). The spark characteristics was not changed[2] throughout the measurement campaign. A spark from the used standard CDI system is shown in **Fig. 4**.

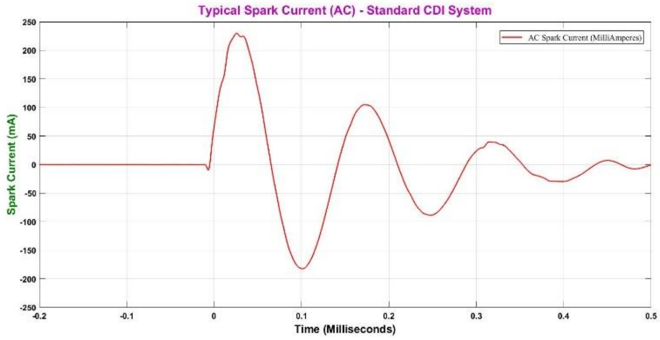

**Fig. 4.** The typical shape of the spark current generated by a standard CDI system used for reference. It is an AC spark with decaying spark voltage. The spark characteristics could not be controlled: ASV ~42 kV, peak current ~230 mA ($I_{RMS} \sim 120\ mA$) and duration ~360 ms.

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[2] Standard CDI on the market may enable re-strikes and variable ASV as well as other diagnostic functions which are not evaluated in this study.

## FlexiSpark® CDI system

The FlexiSpark® CDI is a system under development by SEM with a high degree of freedom to separately control the ASV, current (after break-through and arc) and duration. The degrees of freedom to control the spark is achieved by a patented µ-processor controlled embedded power-electronic system, using a configuration of switches and capacitors to form a spark of duration from only a half AC wavelength up to as long as desired. Typical spark characteristics are shown in **Fig. 5** for the cases of 70 µs and 500 µs spark durations, respectively.

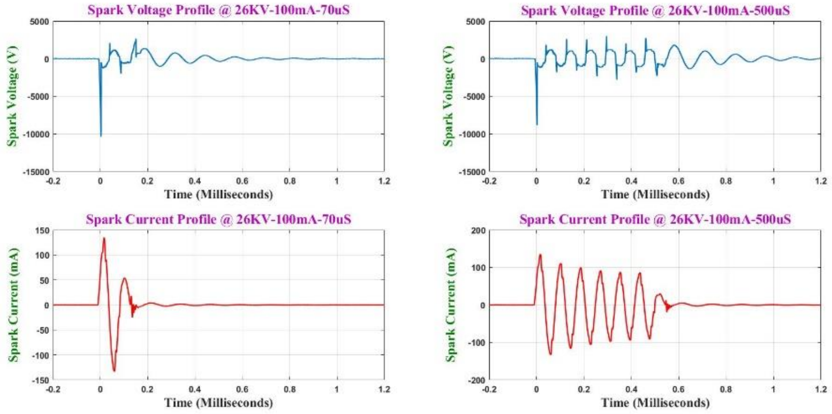

**Fig. 5.** The typical shape of spark currents generated by FlexiSpark® CDI system: Top row voltages and bottom row currents for duration 70 and 500 µs, respectively, for ASV=26 kV. Using a FlexiSpark® system, the ASV, duration and current can all be controlled separately from the ECU using CAN communication.

Note that the current in the beginning of the 500 µs spark is slightly higher than in the latter part. The initial current depends on the demanded ASV. An increase in ASV will increase the current during the first 10 or so microseconds. Of practical reasons, the Flexispark® CDI provided for the experiment had a set of pre-set spark control values[3] as given in **Table 3**.

**Table 3.** FlexiSpark® ICD pre-set spark control values.

| ***Available spark voltage (ASV)*** | ***Current amplitude mA*** | ***Duration*** |
|---|---|---|
| *{26, 36} kV* | {100, 150, 200} mA | {70, 200, 500, 1000} µs |

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[3] Later versions of FlexiSpark® ICD prototypes provide a significantly wider range of ASV, spark durations and currents, which are controlled from the ECU, cycle by cycle, using CAN communication.

### 3.3 Experiment design

The objective of the measurement campaign was to find the “optimal spark” when varying the spark characteristics using the standard IDI and FlexiSpark® CDI, respectively. An “optimal spark” was defined as the spark control parameter setting, that can robustly ignite the fuel mixture at a given EOP with the least energy. By “robust ignition” was defined that $COV_{IMEP} < 2.5\%$. Clearly, when the spark approaches a limit of being too weak to ignite the fuel mixture, then the combustion will occasionally become unstable, which leads to an increase in the $COV_{IMEP}$. By finding the spark characteristics with the least energies that robustly ignited the fuel mixture over a variety of EOP, a base for comparison of the standard IDI and the FlexiSpark® CDI was created. Also, as reference, the ignition performance for the standard CDI was recorded for comparison. The engine operating points chosen for the measurement campaign are described in **Table 4**

**Table 4.** Engine RPM and load used in the measurement campaign.

| ***Engine Speed (RPM)*** | ***Brake Torque (Nm)*** | ***Engine Load*** |
|---|---|---|
| *1000* | 1780 | 80 % |
| *1500* | 1000 | 45 % |
| *1000* | 150 | 6 % |

The experiments were conducted as follows. At each EOP, characterized by stoichiometric AFR and constant {RPM, load, EGR, ST for MBT}, the spark control parameter was successively decreased from high to low energy level, until the engine performance was below an acceptable level. The level for acceptable engine performance was set to $COV_{IMEP} < 2.5\%$. The spark control parameter corresponding to the lowest spark energy for which $COV_{IMEP} < 2.5\%$ was recorded together with the corresponding engine performance parameters.

The results from the measurements are summarized in the sections below. First, the results for the standard IDI is presented, followed by the FlexiSpark® CDI, and finally a comparison of all ignition systems is presented, including the standard CDI as benchmark.

### 3.4 Ignitability using standard IDI

To investigate the ignitability when using the standard IDI, the EGR level was increased from 0% to 15% in increments of 3%. At a constant EOP, the dwell time was changed in discrete steps: {3.38, 3.23, 3.05, 2.87, 2.68, 2.45, 2.18, 1.87, 1.54}ms. The measured spark duration, current and total energy, respectively, are shown in **Fig. 6**.

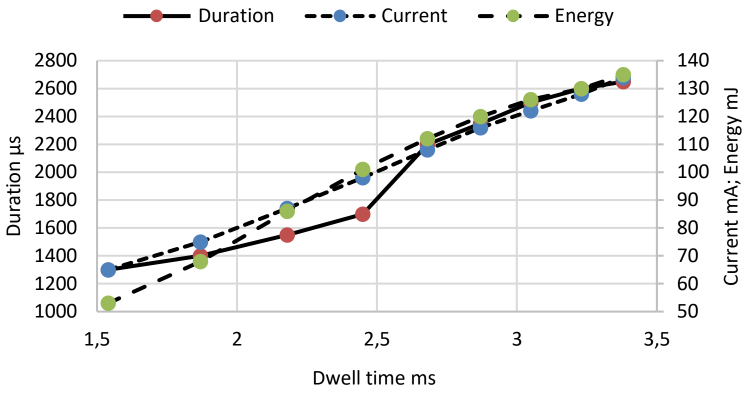

**Fig. 6.** Measured spark duration, current and energy vs dwell time.

The dwell time was decreased until $COV_{IMEP} > 2.5\%$, i.e., when the performance of the engine was degraded due to insufficient ignition, and then the corresponding engine performance was recorded. The measurement procedure was repeated using a new EGR level such that the span {0, 3, 6, 9, 12, 15} % EGR was covered. The required minimal dwell times (spark energy) to achieve $COV_{IMEP} < 2.5\%$ are shown in **Fig. 7** for the EGR levels under consideration. At light load conditions (1000 RPM, 6% load) the dwell time (and spark duration, current and energy) needed to be increased already at 9 % EGR, for medium load (1500 RPM, 45% load) at 12% EGR, whereas for the high load condition the minimum dwell time was sufficient to ignite robustly for all EGR levels tested. In this study, the minimum dwell time was set to 1.54 ms during the experiment. Probably the ignition would have a good performance for shorter dwell times as well, but the main point has been made – *at difficult EOP:s (low load and highly diluted) a longer dwell time, i.e., longer duration and higher current resulting in higher spark energy, is required*. The key question is if it is the duration or current that does the job, or is it the combination of the two? The answer to that will be apparent when using a spark where the duration and current can be controlled separately, as with the FlexiSpark® CDI system.

Another key question is if the combustion stability and/or HRR can be improved by using a more powerful spark? Consider **Fig. 8** which show the $COV_{IMEP}$ vs dwell time for 1500 RPM, 45% load and 12% EGR. From the figures it is seen that *the combustion stability is not decreased when using more powerful sparks*. Since the combustion stability is not affected by a more powerful spark once an ignition has been achieved, it is expected that the time from ST to MFB10 and time from MFB10 to MFB90 will not be affected either. Indeed, this is the case as seen in **Fig. 9**. Once ignition has been achieved, the CA(ST-MFB10), CA(MFB10-90) nor the $COV_{IMEP}$ decrease with increasing spark duration, current, and energy. The same results hold for the other EOP:s that were studied.

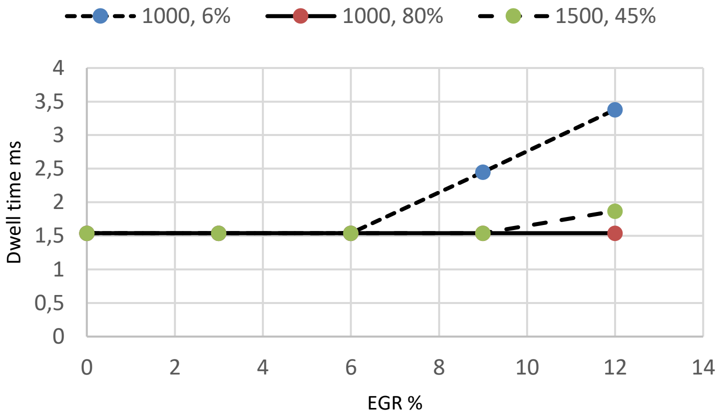

**Fig. 7.** Required minimal dwell time to achieve $COV_{IMEP} < 2.5\%$ at different EOP:s. A longer dwell time is required at low loads and high EGR levels.

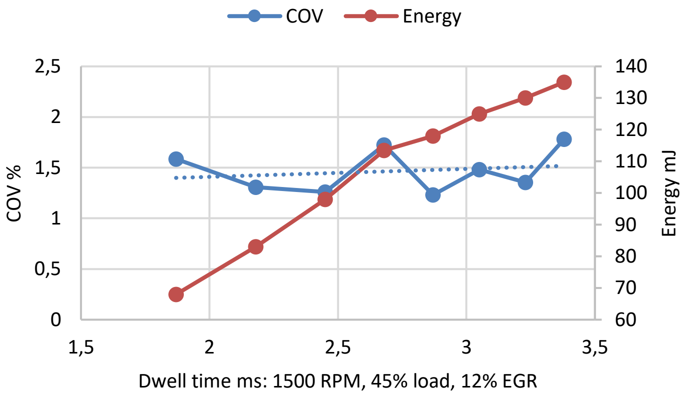

**Fig. 8.** COV vs dwell time (duration, current, energy) at 1500 RPM, 45% load and 12% EGR. The combustion stability is not decreased when using more powerful sparks.

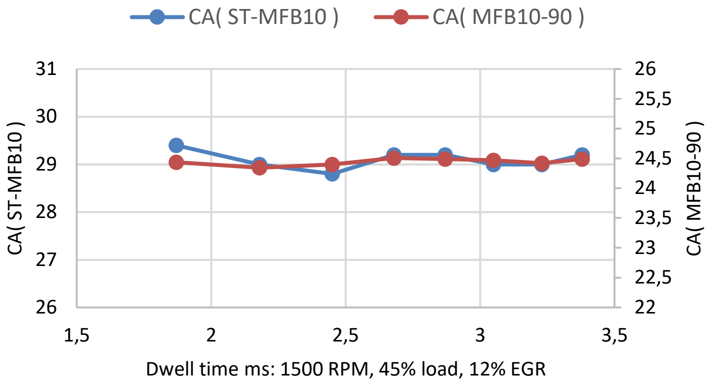

**Fig. 9.** CA from ST to MFB10 (flame kernel development) and CA for MFB 10-90 at 1500 RPM, 45% load and 12% EGR. Neither the initial flame development nor the HRR is affected by the power of the spark.

### 3.5 Ignitability using FlexiSpark® CDI

The combustion performance when using the FlexiSpark® CDI system is shown in **Fig. 10**, where the Initial flame propagation and HRR is shown vs the applied spark current for two spark durations (70 µs and 200 µs) at 1000 RPM, 80% load and 12% EGR. Once a combustion has been ignited, neither the initial flame propagation nor the HRR are improved by increasing the spark current or spark duration (spark energy increased 290%, from 9 to 26 mJ). The EOP 1500 RPM at 45% load and the $COV_{IMEP}$ show the same behavior, and plots thereof are omitted.

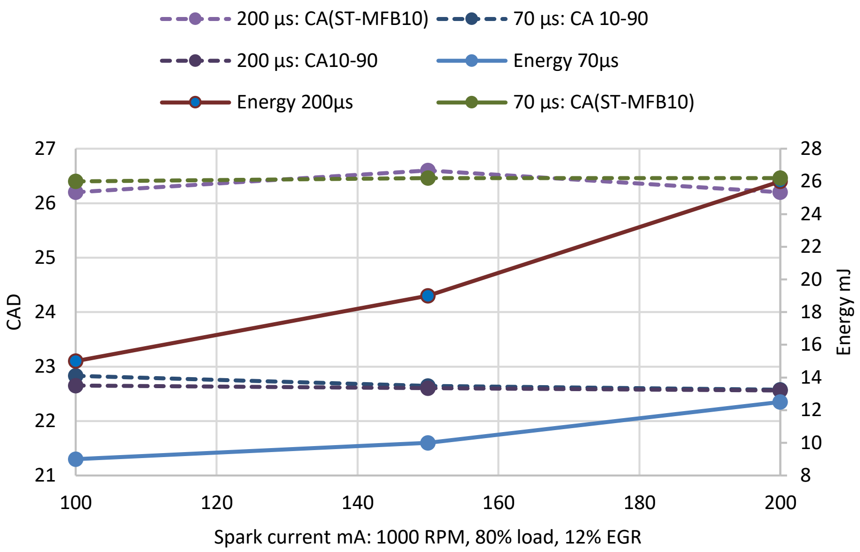

**Fig. 10.** Initial flame propagation (CA(ST-MFB10)) and HRR (CA(MFB10-90)) vs spark current for two spark durations (70 µs and 200 µs) at 1000 RPM, 80% load and 12% EGR. The initial flame propagation nor the HRR are improved by increasing the spark current or spark duration.

The impact on ignitability when using the spark control provided by the FlexiSpark® system becomes apparent when comparing the three systems, which follows in the next subsection.

### 3.6 Comparison of standard IDI, standard CDI, and FlexiSpark® CDI

The ignition systems were compared in search for the "optimal spark", i.e., sparks that provide robust ignition with the least spark energy (expected least electrode wear) such that $COV_{IMEP} < 2.5\%$.

When using the FlexiSpark® CDI system, no improvement was noticed when the ASV was increased from 26 kV to 36 kV. Apparently, the ASV needs to be high enough to generate a spark break-through, but there seems to be little to gain from an ignitability perspective to increase it more than necessary. On the contrary, increasing the ASV more than necessary will probably just add to the spark plug electrode wear. However, being able to increase the ASV is of great importance to maximize the usable life length of the spark plugs. It is preferred to slowly increase the ASV with the wear of the electrodes, enough to robustly generate spark breakthroughs but not more to avoid excessive wear, until the maximum ASV is reached, and the spark plugs need to be replaced. All measurements presented here were collected using ASV=26 kV. The ignitability results for each EOP are summarized in the following.

## Evaluation at 1000 RPM, 80 % load

From **Fig. 11** it is seen that the FlexiSpark® CDI robustly ignites the fuel mixture for all levels of EGR using only 5% of the duration and 17% of the energy, as compared to the standard IDI system; and only 20% of the duration and 26% of the energy, as compared to the standard CDI system.

Consider **Fig. 11** top left, showing $COV_{IMEP}$ vs EGR. It is seen that $COV_{IMEP}$ increases with EGR for all ignition systems as expected. At high EGR levels, the $COV_{IMEP}$ when using the standard CDI appears to be slightly greater than that for the other. The increase in $COV_{IMEP}$ is, however, not statistically significant. Consider **Fig. 11** bottom left, showing $I_{RMS}$. The current is lower when using the standard IDI, but the duration (bottom right) is significantly longer.

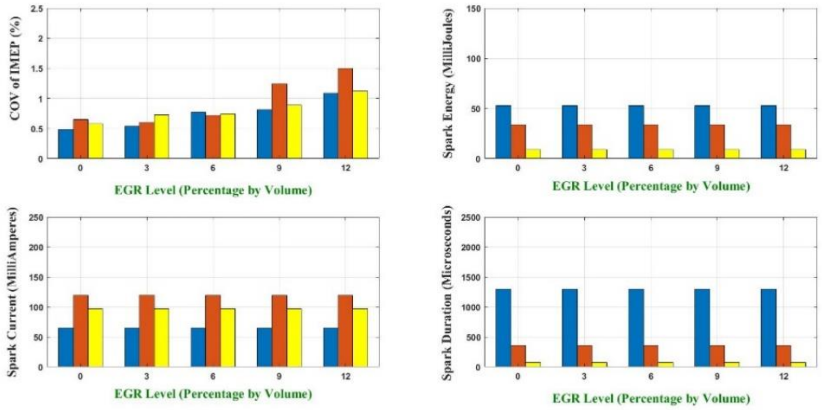

**Fig. 11.** Comparison of the ignition systems at 1000 RPM and 80% load for varying EGR levels. Blue=Standard IDI, red=standard CDI, yellow=FlexiSpark® CDI. The current shown in the bottom left subplot is the RMS value to enable a fair comparison between the systems, and ASV=26 kV.

## Evaluation at 1500 RPM, 45 % load

From **Fig. 12**. it is seen that the FlexiSpark® CDI robustly ignites the fuel mixture for EGR up to 9% using only 5% of the duration and 17% of the energy, as compared to the standard IDI system; and only 20% of the duration and 26% of the energy, as compared to the standard CDI system. At 12% EGR, the FlexiSpark® system ignites using only 15% of the duration and 47% of the energy, as compared to the standard IDI system; and only 55% of the duration and 74% of the energy, as compared to the standard CDI system.

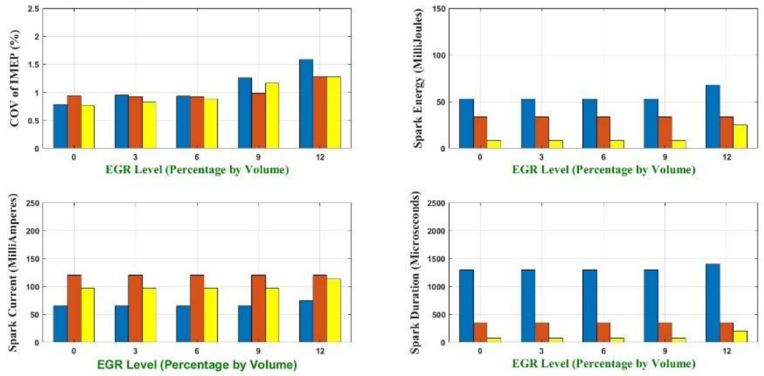

**Fig. 12.** Comparison of the ignition systems at 1500 RPM and 45% load for varying EGR levels. Blue=Standard IDI, red=standard CDI, yellow=FleciSpark® CDI. The current shown in the bottom left subplot is the RMS value, and ASV=26 kV.

## Evaluation at 1000 RPM, 6 % load

From **Fig. 13**, top left, showing $COV_{IMEP}$, it is seen that the standard ICD could only provide a stable combustion up to 6% EGR. This is explained by the relatively short spark (360 µs as compared to 1300 µs for the standard IDI and 1000 µs for the FlexiSpark® CDI). During low load and idling conditions, when the fuel mixture is inhomogeneous and has a relatively low swirl, a long spark duration is needed in order for the spark to hit a favorable fuel mixture and initiate a sustainable combustion. Indeed, at 12% EGR, it is seen that the FlexiSpark duration of 1000 µs is not enough. For 12% EGR a 3750 µs long spark was required as delivered by the standard IDI. From **Fig. 13** bottom left showing $I_{RMS}$, it is seen that the current did not have a significant impact on the ignitability. It is the duration that appears to be the most important.

Note that the spark duration was limited to a maximum of 1000 µs in the FlexiSpark CDI system provided to the experiment. In later versions the duration can be much longer, and shorter, than the prototype used here.

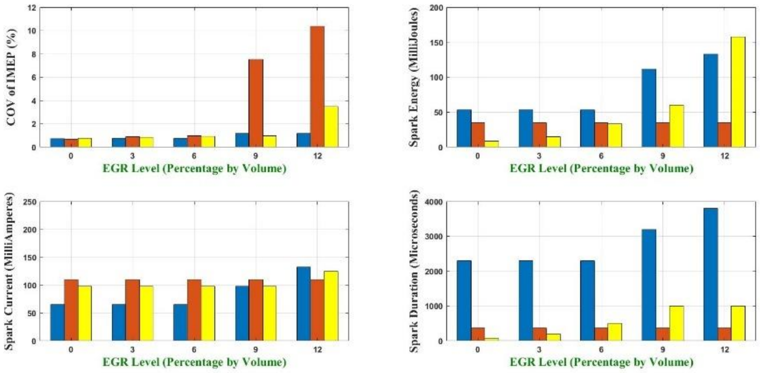

**Fig. 13.** Comparison of the ignition systems at 1500 RPM and 45% load for varying EGR levels. Blue=Standard IDI, red=standard CDI, yellow=FlexiSpark® CDI. The current shown in the bottom left subplot is the RMS value, and ASV=26 kV.

## 4 Concluding remarks and future research

Robust ignition can be achieved using a significantly shorter spark duration and lower energy than that achieved when using a standard IDI. However, the degrees of freedom of the ignition systems used in the experiment were limited. Therefore, the lower limit of spark duration was not challenged, using shorter dwell times for the standard IDI system and shorter duration when using FlexiSpark®. The results presented here should be regarded as preliminary. There is an on-going research project investigating the limiting spark characteristics at varying EOP, especially w.r.t the dwell time and the control parameters available in a FlexiSpark® CDI system that can provide spark durations as short as 50 µs. Nevertheless, the observations support the following preliminary conclusions:

**Conclusion 1: Enough is enough.** Once a combustion has been initiated, any additional sparking does not improve the combustion stability and is a waste that will lead to an excess spark plug electrode wear, with an increase in TCO as a result.

**Conclusion 2 - Duration:** A very short spark is enough at most EOP:s. Longer duration is typically needed at idle and very low load condition and/or high dilution.

**Conclusion 3 - Current:** The spark current does not have a significant impact on ignitability provided it is high enough to sustain a plasma (spark) between the electrodes. In high turbulence a high current may be needed to avoid spark blow-outs. The current shall be kept as low as possible to avoid excessive electrode wear.

**Conclusion 4 - ASV:** The available spark voltage, ASV, needs to be high enough to enable a spark break-through, but should not be higher. A high maximum ASV is advantageous because it extends the lifetime of the spark plugs.

**Conclusion 5 – Energy:** Spark energy is not a relevant measure of the capability of an ignition system. It is the combination of ASV, current and duration that together defines the capability, which need to be controlled separately to optimize the ignition performance over the lifetime of a spark plug.

The conclusions imply that an ignition system with diagnostic capabilities is beneficial to monitor if a spark has been released (sufficient ASV), the breakthrough voltage (electrode condition) and if a spark has been blown out (sufficient current). By using such diagnostic information, it is possible to not only adapt the spark to the EOP, but also to the spark plug condition, hereby optimizing the ignition performance while keeping the electrode wear to a minimum.

The results are especially interesting in the view of hydrogen fueled SI-ICE. In hydrogen applications, the required ASV is high, but the required spark energy to initiate a combustion is low – two contradicting requirements. Since the electrode temperature in hydrogen SI-ICE applications tend to become very high, special attention must be paid to hot spots and electrode wear. Recent investigations on hydrogen fueled HD SI-ICE have shown that a spark duration of 50 µs is sufficient even at highly diluted fuel mixtures, except at idling conditions when longer sparks are required. It is reasonable to assume that such short sparks with minimized current (energy) will mitigate excessive electrode wear and heating of the electrodes. In cooperation with Department of Energy Sciences, Division of Combustion Engines, and Department of Physics, Division of Combustion Physics, Volvo, Scania and SEM have an on-going research project focusing on the basic combustion properties and ignition when using a direct injected HD hydrogen fueled SI-ICE application.

There is a need to gain a deeper understanding of how much the spark phases (breakthrough, arc, glow) erode the spark plug electrodes. Such research is on-going in cooperation between the research partners. In the research, novel laser spectroscopy measurement techniques are being developed that, if successful, will give time- and spatially resolved information on the erosion during single spark events. Hereby the dependence of erosion on the spark characteristics for specific electrode material will be clarified, enabling a design of spark with a minimal wear and robust ignition.

Finally, consider AC vs DC sparks. More research is required to investigate which is the most advantageous w.r.t. ignitability and electrode wear. Such research is on-going, as mentioned above.

## Abbreviations

| | |
|---|---|
| AC | Alternating Current |
| ASV | Available Spark Voltage |
| CDI | Capacitive Discharge Ignition |
| CNG | Compressed Natural Gas |

| | |
|---|---|
| DC | Direct Current |
| EOP | Engine Operating Point |
| HD | Heavy Duty |
| HRR | Heat Release Rate |
| ICE | Internal Combustion Engine |
| IDI | Inductive Discharge Ignition |
| SI | Spark Ignited |
| ST | Spark Timing |

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