Extension of Operating Window for Modern Combustion Systems by High Performance Ignition

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Abstract. Upcoming legislation motivates further development of modern combustion systems and engine designs to achieve a reduction of fuel consumption and emissions. Increased power density, charge motion and dilution drives requirements of the ignition system. Bosch prepared a high performance ignition device focused on high energy output and long spark duration while providing high flexibility to select relevant performance parameters. The ignition concept furthermore is designed as a plug and play solution in order to fit to established hardware interfaces and offers high energy efficiency.

Based on this technology several engine tests were completed at global OEMs and inside Bosch. The following paper summarizes the main test results which cover extension of EGR rates, lean limit and reduction of emissions as well. Based on this results possibilities how the benefits can be used in real applications are derived and discussed.

Investigations were performed on different engines representing diverse combustion concepts especially with regard to charge motion level. The concluded tests also confirm that increased ignition performance only in combination with parameters of the combustion concept itself can lead to the desired benefits on engine level.

Besides the review of mentioned engine tests a new advanced ignition system called CEI (Controlled Electronic Ignition) is introduced. The main properties of the used high ignition device are described including a comparison to the visible market trend for ignition requirements.

1 Introduction

Current development trends for combustion systems in spark ignition engine focus mainly on exhaust gas recirculation and/or on air dilution (e.g. [24]) as possible approach for increasing the engine efficiency, Fig. 1. For homogeneous lean combustion concepts enleanment needs to be strongly expanded in order to reduce raw nitrogen oxide emissions to make this approach a valuable solution also in terms of costs for exhaust gas after treatment.

However, increasing inert gas fraction also means more severe conditions for the ignition and combustion system itself. The negative influence of the rise in air dilution is reflected in the form of cyclic variations at engine operation. Therefore, in practice,

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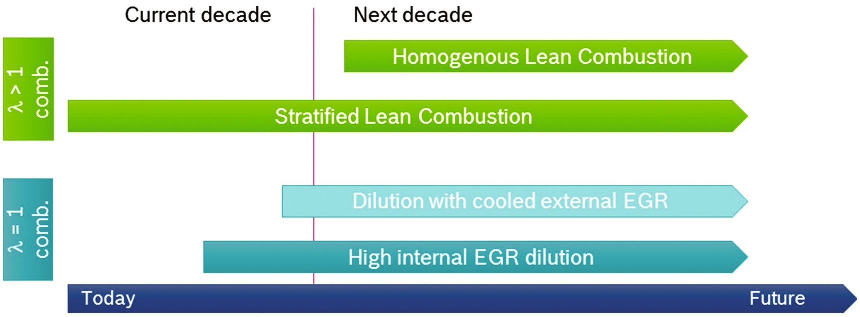


Fig. 1. Roadmap combustion concepts

further mixture dilution is not applicable when exceeding a smooth running limit of about 3–5 % (COV, Coefficient of Variance). The disturbance in running smoothness is mainly caused by cyclic variations in the in-cylinder flow field, mixture homogeneity and flame kernel formation [1, 2]. This leads to sporadic cycles with delayed combustion or even misfires. In order to stabilize the initial stage of combustion in diluted mixtures a wide number of ignition concepts and systems were proposed over time, recently leading to frequent discussions in expert groups. Figure 2 summarizes the variety of different proposals using a main classification based on how the flame kernel volume is activated during the ignition process. For more details about single ignition proposals see [3, 4] or latest IAV Conference Proceedings [5, 6].

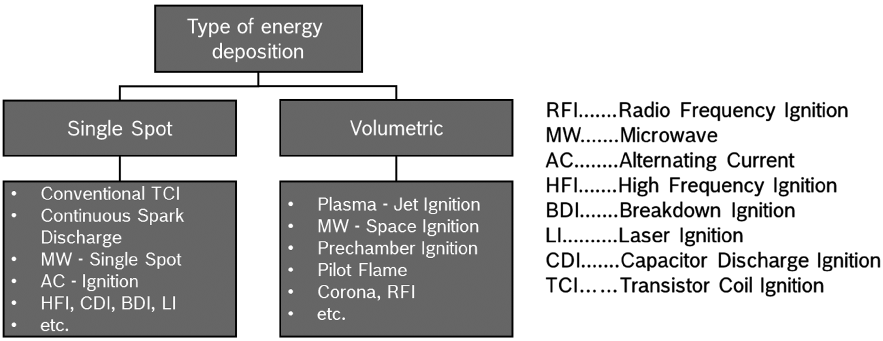


Fig. 2. Classification of ignition systems

“Single spot ignition” strictly means the deposition of ignition energy within a fixed location inside the combustion chamber, whereby the energy distribution is not actively controlled by the ignition system itself. Nevertheless, a spark volume is defined by the spark channel and even enlarged by charge motion, e.g. by deflecting the ignition spark, which essentially leads to an activation of a flame volume. This is one of the key factors, which yields the potential to ignite diluted mixtures using spark ignition systems.

"Volumetric" ignition concepts, such as corona or plasma-jet ignition actively provide a flame kernel volume even in low charge motion conditions at ignition timing.

Despite of the tremendous variety of ignition concepts and their competition, the TCI (Transistor Coil Ignition) is still the dominating product in series application of passenger cars. Its simplicity, low cost and proven robustness, especially compared to innovative, often complex systems made TCI to an unrivaled product. However, the ignition of diluted mixtures using TCI-Systems gets more severe and the question arises how further potential for spark ignition concepts can be accessed. To address these challenges Bosch is about to extend the spark ignition portfolio by proposing new high performance products as shown in Fig. 3.

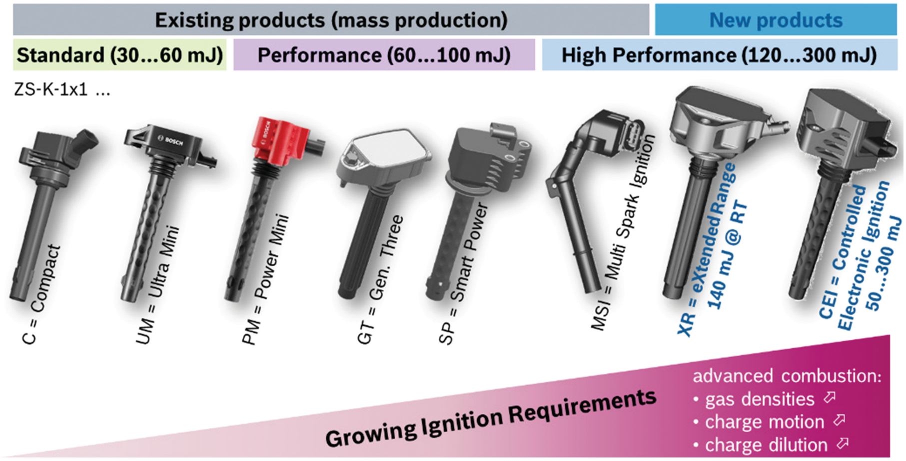


Fig. 3. Spark ignition portfolio incl. extension by new high performance products XR and CEI

A straightforward method to promote the ignition process is to boost the ignition energy by increasing spark current and/or spark duration. For conventional TCIs this approach is typically limited as negative side effects do increase e.g. spark plug wear, low ignitability in low spark current phases, size and weight of the ignition device and the electrical efficiency (ratio of output spark energy to input energy delivered from the board net). Investigations showed efficiencies in the range of 20–30 % under real engine conditions [7]. Due to the described conflict it is assumed a conventional TCI can be designed for a spark energy of some 140 mJ but not significantly higher. This is covered by a new proposed XR coil (see Fig. 3).

To solve some of the drawbacks as listed above connected with conventional TCIs and also to avoid the negative impact of decreasing spark current over time on flame kernel formation a new high performance ignition approach called CEI (Controlled Electronic Ignition) is described in this paper. This includes in a detailed way: identification of requirements for advanced combustion concepts (main aspect: highly diluted mixtures), discussion of target requirements for high performance ignition, review of present state of the art ignition systems, description of CEI with key properties, summary of test results and benefits for different engine/combustion types. At the end of the article short summary and final remarks are presented.

2 Requirements on Ignition System for Modern Combustion Concepts

2.1 Requirements for Efficient Combustion

Depending on the combustion concept and engine operation point different requirements on ignition system may arise. For stratified combustion one of the key factors is to cover the temporal and geometrical tolerances with regards to local mixture composition at spark plug location [8, 18]. A particular importance is assigned to the injection process, in order to create a preferably stoichiometric mixture in the vicinity of the spark plug. However, temporal fluctuations in the mixture formation process need to be covered, which can be achieved by long spark durations. Similar requirements on the ignition system apply at catalyst heating operation, so called homogeneous split injection (HSP). As mentioned before, long spark durations are limited when using conventional TCI. Even though in-house tests showed advantages of CEI for stratified operation the focus was put on homogeneous combustion concepts to derive requirements, since no market indication is obvious implying stratified operation as a mainstream trend.

At full load operation main requirements arise from high gas densities at ignition timing, leading to high ignition voltage demands of up to 40 kV. After spark breakdown the conditions to promote the flame kernel formation are more favorable than at low load conditions, since high gas densities and high flow velocities are present, leading to efficient energy transfer into the surrounding mixture. One straightforward method to decrease the ignition voltage demand would be to decrease the electrode gap distance. However, this would result in negative consequences at low load conditions due to quenching losses, especially with higher dilution of the mixture. Here, ignition

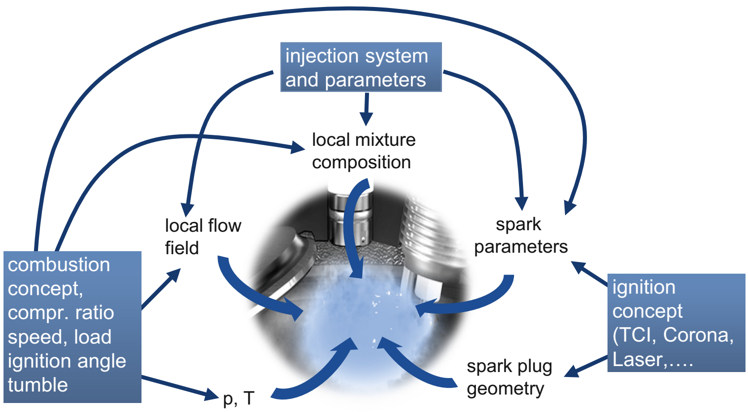


Fig. 4. Influencing factors on flame kernel formation

voltages are rather low but the requirements on ignition system to promote the flame kernel formation are high. Besides the influence of ignition system, the initial stage of combustion is influenced by many other factors, see Fig. 4.

To exploit further potentials of spark ignition systems at diluted engine operation, the interaction of all shown parameters needs to be considered. Despite global homogeneous operation, local mixture inhomogeneity may arise at spark plug location. These can be covered by long spark durations [16]. The local flow field is of particular importance, since it affects the spark deflection. High local flow velocities lead to long plasma arcs, which help to distribute the thermal spark power in the mixture. This leads to high energy transfer efficiencies [9, 17].

Basic investigations in an optical combustion vessel showed disadvantages with regard to maximum spark deflection when using a TCI System with its typical decreasing shape spark current. Figure 5 shows the evolution of spark length as function of time at local flow velocity of 10 m/s for 50 consecutive cycles (gray lines) and two different spark current profiles (left & right). The spark length was determined by optical analysis of captured high speed images. Based on single cycles and on mean spark length it can be observed that for current levels below approximately 40…50 mA the spark length steadily decreases. The reason for this is the steady increase of the number of so called “restrikes” with the decreasing spark current. A restrike occurs if a certain value of spark length is exceeded, leading to formation of a short circuit arc between the plasma channels. In this case the deflection process is interrupted and the channel length is abruptly shortened [10]. Single restrike events can be identified in the waveforms (gray lines) showing steep spark length gradients. With regard to ignition at engine operation it can be expected that below a certain current level the ignition plasma remains in the immediate vicinity of the spark plug electrodes preventing good access to fresh mixture. Furthermore, higher heat losses from the flame kernel to the relatively cold electrodes are promoted [10]. The right picture of Fig. 5. shows the evolution of spark length if the spark current is kept constant over the entire discharge duration. This shape was achieved by using a laboratory ignition system. The number of restrikes decreases significantly, leading to stable spark deflection. Therefore,

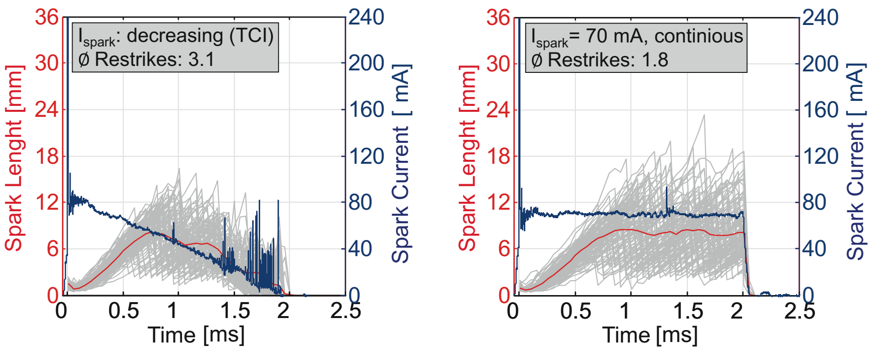


Fig. 5. Evolution of spark length for a decreasing (left) and continuous (right) spark current for 50 cycles (gray lines) at v = 10 m/s. Red line indicates mean spark length.

an ignition system with continuous spark current level would be favorable. The maximum spark deflection also depends on local value of flow velocity.

High flow velocities lead to long plasma arcs. However, the deflection process cannot be sustained endlessly, since a restrike becomes more probable as the plasma arc becomes longer. The reason for that is the increasing spark voltage (burn voltage) with spark length, leading to high electric field strengths between the plasma channels [9]. Engine measurements at different operating points revealed, that restrike voltages higher than 6 kV are less likely. However, at highest flow velocities a so called "spark blowout" is possible. In such cases the spark plasma can detach from the electrodes, therefore requiring new spark breakdown between the electrodes. The ignition system therefore needs to establish high voltage build up and provide a new spark breakdown within a short time after spark blowout.

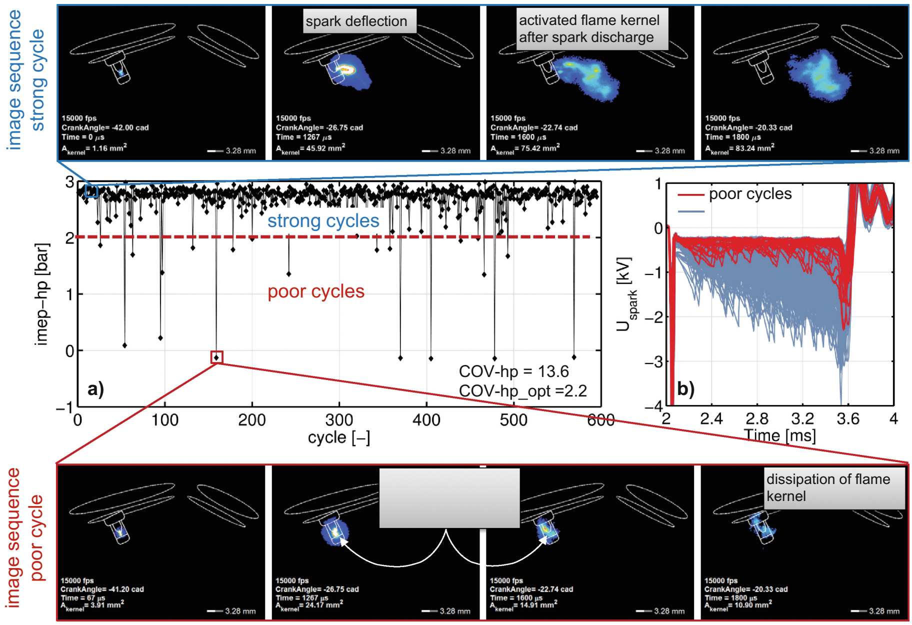


Fig. 6. (a) imep-hp as f(cycle #) at IgnAng = 42° before TDC (Top Dead Center), dashed line separates poor cycles from strong cycles, (b) U_{spark} as f(t). Image sequence at the bottom: formation of a misfire. Image sequence at the top: flame kernel formation in case of strong cycle

The meaning of flow velocity at spark plug location on spark deflection and flame kernel formation in condition of lean combustion had been discussed in recent paper by Schneider et al. [10]. Based on optical measurements on a single cylinder research engine it was shown, that misfires and delayed combustion cycles refer to low velocity of air-fuel-mixture in the vicinity of spark plug. Figure 6(a) shows the indicated mean effective pressure imep-hp (high pressure loop) at lean limit (λ = 1.6) for 600 cycles, spark timing being at 42° cad before TDC (Top Dead Center). A continuous spark current profile was used for the measurement. A limit (imep-hp = 2 bar) is defined to indicate the delayed combustion cycles and misfires (dashed line). The cycles below this limit are classified as “poor” cycles. The COV-hp (COV of high pressure loop) includes all 600 cycles, while COV-hp_opt includes only those cycles being above the defined limit (“strong” cycles), see figure legend. Figure 6(b) shows the corresponding spark voltage waveforms. Poor cycles (red lines) clearly indicate low spark voltages and so can be referred to cycles with low flow velocities. The image sequence at the bottom shows how a misfire develops. The reduced flow leads to static arcs which in turn lead to high quenching losses. It has to be pointed out that in such conditions, spark ignition systems cannot release their potential, even if ignition energy is increased, either by high spark current levels or long spark durations. According to these findings requirements for the ignition system and also for the Operating Point: imep = 2 bar, n = 2000 rpm, λ = 1.6 [10]. Combustion system can be derived [10]. Furthermore, when evaluating the dilution limit one has to consider the temporal phases of the combustion process, consisting of flame kernel formation (mfb0-5), first half of combustion (mfb5-50, duration in [cad] from 5 % till 50 % of total mass fuel burned) and the last half of combustion (mfb50-95). The COV, often used as criterion for evaluating ignition systems or ignition parameters contains the variation of all three phases. Figure 7 shows the described phases of combustion obtained from pressure trace analysis as function of in cylinder residual gas fraction.

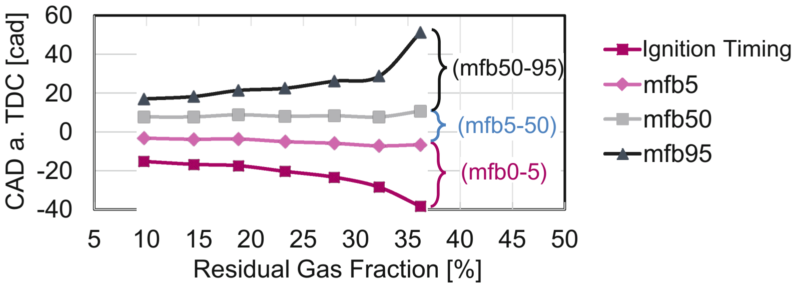


Fig. 7. Different combustion phases as function of residual gas fraction. Operating Point: imep = 3.5 bar, n = 2000 rpm, ext. EGR sweep, High Tumble

The optimum of isfc (indicated specific fuel consumption) is obtained when the combustion phasing (mfb50) is approximately at 6–8 cad a. TDC. The dilution of mixture leads to lower laminar burning velocities and therefore longer overall burn durations. Figure 7 shows, that most time of the combustion process is consumed for flame kernel formation (mfb0-5) and the second half of combustion (mfb50-95). The shortest time is consumed for mfb5-50, since this combustion phase takes place around TDC, where, especially for high tumble concepts, highest TKEs (Turbulent Kinetic Energies) are present. The biggest trade-off in combustion of diluted mixtures arises between the phase mfb50-95 and mfb0-5. The best ignition performance is achieved in case of late ignition timing (typically near TDC), where high gas temperature and high flow velocity are present. However, retarding the ignition timing towards TDC will shift the main combustion phase (mfb5-95) and especially the mfb50-95 as well, leading to delayed combustion cycles. Consequently, the COV increases. The ignition system is only capable to shorten the first phase of combustion (mfb0-5).

However, for spark ignition systems this means that high flow velocities at ignition timing must be present in order to achieve maximum energy transfer efficiency. Since ignition timing cannot be shifted towards TDC for the reasons stated above, the main alternative is to shorten the burn duration (mfb5-95), by e. g. higher tumble level or higher compression ratio [11, 23], which in consequence will allow later ignition timing. Therefore, when evaluating the COV, attention must be laid on the whole combustion process, especially when comparing different ignition systems. Strong fluctuations in the main combustion phase may either mask the potential of ignition systems or can lead to unfavorable ignition conditions in case of long burn durations. In the latter case substantial improvements of spark ignition systems may not be possible. Nakata et al. [11] show that increasing spark current can lead to significant improvements with regard to flame kernel growth if velocities at spark gap are increased by engine set-up. If the above mentioned requirements for combustion system are met, high performance spark ignition systems can provide stable flame kernel formation even in diluted conditions. To sum up, the following requirements for spark ignition systems can be defined:

- Spark current level above 50 mA over the entire discharge duration to stabilize spark deflection by avoiding frequently occurring restrikes in strong flow fields.
- Spark duration of 3 ms at low engine speed (1000–2000 rpm) to provide high spark energy level and to cover possible mixture inhomogeneity at spark plug location.
- Ignition voltages of 40 kV to provide secure ignition at high loads.
- The ignition system must sustain spark voltages (burn voltages) of at least 6 kV, at conditions where high spark elongation is present.
- Fast re-ignition capability in case of spark blowout, typically occurring in strong flow fields.

2.2 Derived Component Requirements

Taking a conventional ignition transformer (so called ignition coil) as a reference, the following requirements for a new ignition component are derived:

1. Target performance values acc. to findings in Sect. 2.1:
   (a) Spark duration: 3 ms
   (b) Minimum spark current: 50 mA
   (c) Secondary voltage (depending on load): 40 kV
2. Definition of spark energy and secondary voltage offer independent from each other: Demand for both parameters has different reasons. In case of conventional ignition coils, both parameters depend on each other since both are delivered from the same inductive energy store. That means for a given value of stored energy the available spark energy is influenced by the energy consumption needed to establish

the breakdown voltage at the spark plug electrodes which further depends on cylinder pressure, spark gap and spark plug fouling.

3. Spark current trace with optimized energy content: A triangle shaped spark current typical for conventional ignition coils represents only 50 % compared to a rectangular trace. Ways to increase total spark energy in conventional coils usually are limited with respect to increased spark plug electrode wear or increasing the low current area not contributing to an efficient combustion process.
4. Definition of spark duration and spark current level independent from each other: acc. to above requirements, a long spark duration with a spark current above a certain threshold enables ignition of diluted mixtures. In the same way high spark current levels/peak values can be limited only for challenging operation conditions of the engine and beyond that be avoided in order to minimize spark plug electrode wear.
5. Spark stabilization: enable spark to withstand turbulences or in case of blowout enable quick re-ignition.

   Besides the requirements for secondary performance driven by the combustion concept there are further aspects to be considered in view of mass production engines:
6. High energy efficiency: important in order to really contribute to reduce fuel consumption and also limiting heat dissipation for high energy ignition. The latter becomes more severe in combination with engine concepts connected with high ambient temperatures for the ignition device.
7. Fit to established hardware and software interfaces: of course this is not an absolute must, but seen as a success factor for acceptance and project implementation. Reasons: ignition components are mainly handled as “commodity”; high requirements for adaptation of a complete new system will lower the chances for market entry.
8. Small package size/high energy density: growing packing density or downsizing trends realized in modern engine concepts will most probably not allow that package size of the ignition device can proportionally grow to the increase of performance output.
9. Robustness and durability: mandatory requirements anyway but efforts to safeguard robustness and durability are expected to be tremendous in case of completely new technological approaches due to technological challenges or risks on component and system level.
10. Cost: Definitely one of the all-time key parameters in the highly competitive market of automotive ignition. In terms of high performance ignition, additional costs for this higher performance usually need to be balanced with according benefits for the combustion system and have to consider implementation efforts in the system environment (see also requirement no. 7).

2.3 Requirements Development vs. Ignition Solutions

Conventional ignition coils clearly dominate the automotive market segment of passenger cars. A rough differentiation may separate clusters acc. to spark energy

- 30…60 mJ used in PFI applications for several decades
- 65…90 mJ used in DI applications for some 20 years
- approx. 100 mJ appearing in latest DI applications with increased requirements.

Besides these standard solutions Bosch started early to work on solutions with higher performance output:

(a) Proposal for a high power conventional ignition coil with 140 mJ spark energy: Over many years (since 2007) only built as a laboratory sample – known as "PowerPlus" – and widely spread in the community as enabler for testing of new combustion concepts due to the outstanding high spark energy. Results were published acc. to a study [4] where PowerPlus was rated as a reference ignition system representing conventional technology. Meanwhile Bosch started a study to prepare industrialization of an ignition coil with 140 mJ nominal output at room temperature, now called XR (=eXtended Range) coil. Focus here is also on providing a reasonable high output of min. 120 mJ at high ambient temperatures. In contrast to CEI, the XR coil can be optionally available with or without integrated power stage/electronics. Motivation is a high number of applications having the power stage placed in the ECU, since high ambient temperature for the ignition device make integration of electronics difficult or even impossible.

(b) First industrialization of MSI (multi spark ignition) for lean stratified DI applications (realized in 2009): Based on a standard ignition coil regularly providing ≈70 mJ in single spark mode, a special closed loop control for multiple discharge and recharge enables a significant increase of spark duration and spark energy output while keeping the small package size unchanged. MSI functionality is achieved with an electronic control inside the ignition coil. Significant fuel consumption benefit could be realized for a serial engine supported by MSI technology [12].

Further progress in development of new high performance ignition concepts in general can be separated in two segments:

- Concepts mainly based on conventional technological approaches, extending the basic idea of MSI but avoiding the spark interruption during the recharge phase.
- Concepts with a significant different technological approach like high frequency, microwave, Laser or Corona ignition (see Fig. 2).

Recent publications [6] report progress in both segments with regard to high performance output and according combustion benefits. In view of the derived component requirements listed in Sect. 2.2 this article is mainly focused on the first segment of conventional concepts. Although own evaluations have been performed including samples from the second segment of concepts, the received results do not indicate that these approaches will be relevant for introduction in mass production for automotive passenger car applications within the next 5 to 10 years.

With respect to the first segment the proposed solutions are connected more to a potential industrialization. In order to allow a continuous, uninterrupted spark, long spark duration and as a result scalable, high spark energy output, main proposals include

- DCI (Dual Coil Ignition) [13],
- DCO (Dual Coil Offset) [14] and
- CMC (Coupled Multi-Charge Ignition) [15].

All three are based on repeated recharge and discharge of an inductive store. Therefore (similar to MSI) there is no limitation to spark duration and spark energy due to the working principle itself. Limitation due to self-heating vs. maximum ratings of used components is of course a relevant aspect.

Brief description of concepts:

- DCI [13]: Combining two ignition coils being charged and discharged alternating and by superposing of both high voltage outputs an uninterrupted spark is achieved.
- DCO [14]: Basically similar to DCI but additionally aiming on reduction of overlapping of secondary current traces coming from two ignition coils.
- CMC [15]: Basically similar to above described concept with two ignition coils but in addition a step-down converter and a more advanced control procedure is used to achieve further reduction of high secondary current peak duration and reduced voltage load for high voltage diodes.

Main pros and cons:

Pro (DCI, DCO, CMC):

- technical feasibility
- high and scalable secondary performance.

Con:

- high spark current peaks: DCO: >0.4 A measured with sample, CMC: 0.2…0.4 A,
- high primary current: DCO: 20 A measured with sample, CMC 35…70 A,
- necessity of high voltage diodes (40…50 kV) for DCI and DCO to decouple ignition coils secondary circuits
- big package size and weight due to double coil design (expected to be significantly higher compared to CEI (Sect. 3)).

Though a lot of good results have been collected in the ignition community, the remaining cons connected to the described solutions above motivate to look for further solutions. A new Bosch approach is described in the following chapter.

3 CEI Working Principle and Sample Status

3.1 CEI Working Principle

Based on the set of requirements above and evaluation of alternative approaches known from publications and own studies a new proposal for high performance ignition is presented in the following. The essential idea for the design is the separation of the two main functions of an ignition device, which is to provide …

- high breakdown voltage and
- spark energy

The name CEI = Controlled Electronic Ignition is chosen according to the working principle. The basic approach is more an evolutionary one, based on technical design components which are in general available and already proven in other applications. This includes:

(a) ignition coil optimized for high voltage generation,
(b) step-up converter to generate the spark energy,
(c) electronic unit to control operation of (a) and (b) triggered by ECU input.

All three functional elements are combined in one package and represent the CEI device (Fig. 4).

The selected functional design shows the benefit of high performance output, which in terms of spark energy and spark duration is not limited due to the working principal. Of course, in practical applications a limitation has to be considered based on heat dissipation, component maximum rating and ambient temperature. Main features of CEI based on the shown design and related to a standard conventional coil are (Fig. 8):

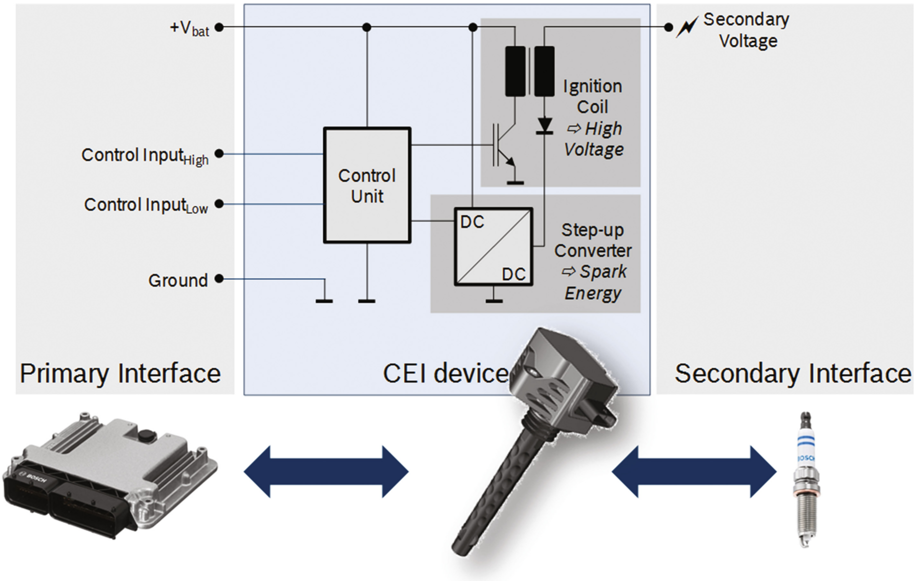


Fig. 8. Block diagram of CEI (Controlled Electronic Ignition) and interface structure suitable for operation with established ECUs and spark plugs

- Widely extended range for applicable spark energy and spark duration.
- Increased ignition voltage and electrical efficiency.

- Flexible spark performance data and ignition voltage applicable on demand and independent from each other.

A more detailed comparison between the performance of a standard conventional ignition coil and CEI is summarized in Fig. 9. Especially the change of the spark current shape by means of the functional principle of CEI leads to several benefits like high performance and the flexibility of selecting the single performance values independent from each other. The electrical performance data are defined acc. to internal evaluations of requirements connected with combustion concepts as discussed above (Sect. 2.1).

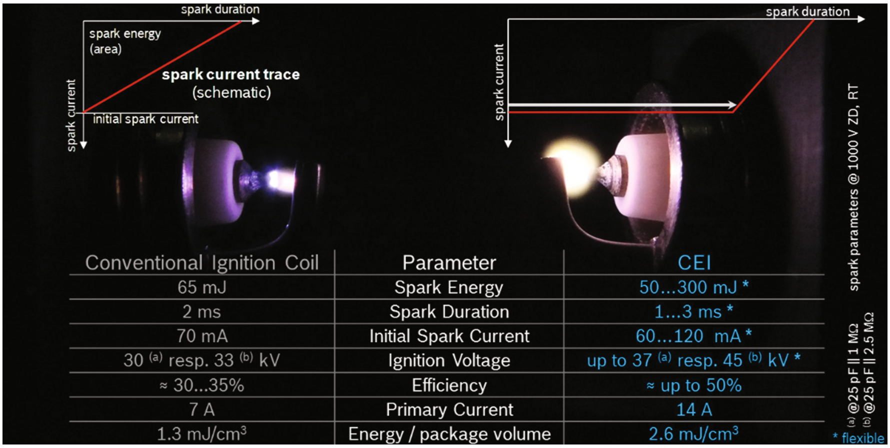
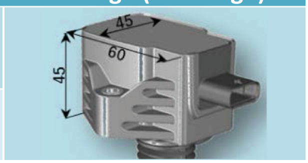


Fig. 9. Performance data: CEI vs. conventional ignition coil, incl. comparison of spark current traces (schematic view)

In addition to the secondary performance, the geometrical design parameters shown in Table 1 are relevant for the application. Dimensions refer to the functional volume without connectors and fixing point, since these elements usually are specific to their application.

Table 1. CEI Packaging dimensions and weight

#	Parameter	Value for CEI	Package (A3 design)
1	Dimensions (W x H x L)	45 x 45 x 60 mm^3	
2	Weight	≈300 g	

3.2 CEI Sample Status and Performance Measurement Results

Bosch activities with CEI are running as a study based on an idea created in a brainstorming session in 2012. Besides theoretical considerations, simulations and measurements were started in the early beginning to verify the idea of CEI. On this bases the development and buildup of samples were realized. Figure 10 shows the sample history.

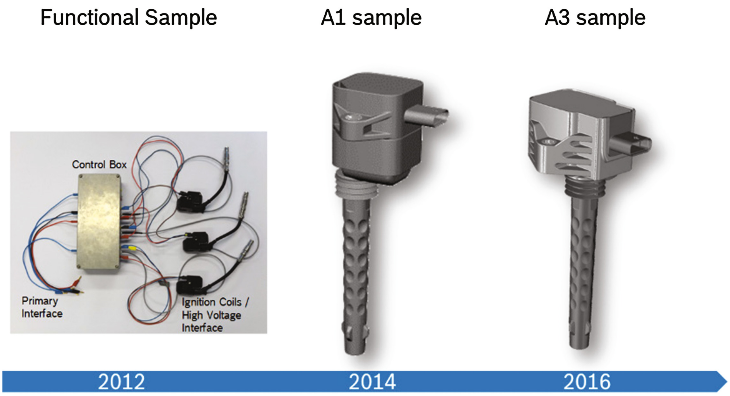


Fig. 10. CEI sample development and present status

Measurements of secondary performance data are presented in Figs. 11, 12 and 13. Figure 11 starts with measurement results for the spark current showing the flexibility to achieve very long spark duration (variation achieved by changing the control signal) and very high spark energy values. In addition the spark current level can also be

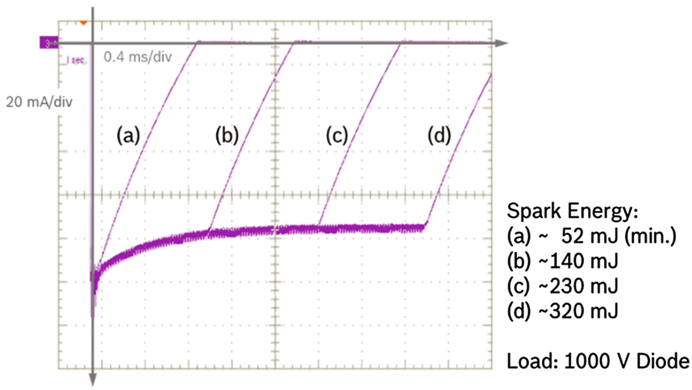


Fig. 11. Measured CEI spark current traces and resulting spark energy levels obtained by variation of input control signal: with CEI spark current is kept at high level for long spark duration

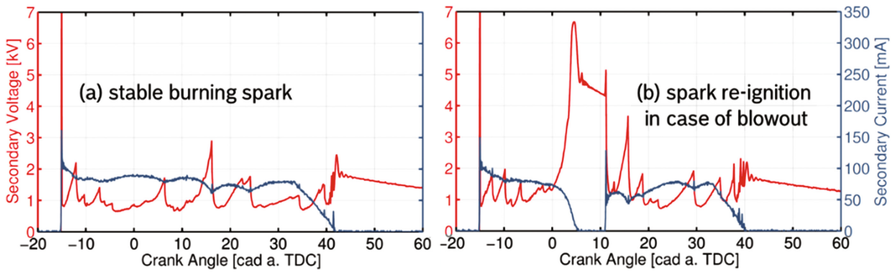


Fig. 12. Measured CEI spark current and voltage traces at imep = 10 bar, n = 2000 rpm showing behavior at (a) moderate and (b) strong turbulence with (a) stable burning spark and (b) spark re-ignition in case of blowout due to special feature of CEI

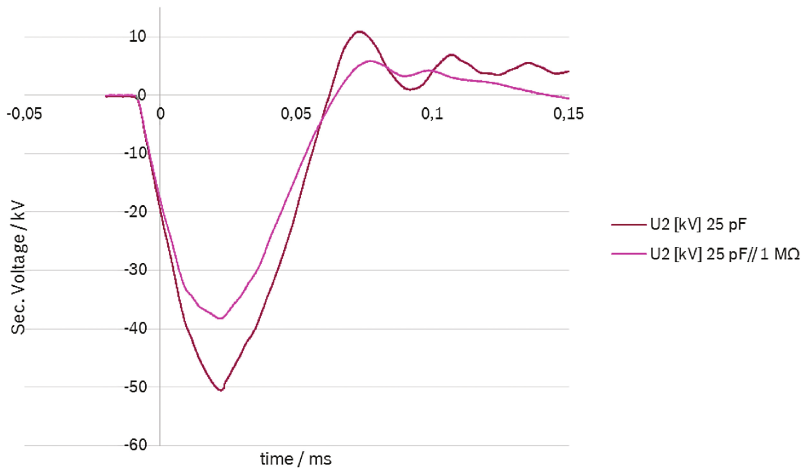


Fig. 13. Measured CEI secondary voltage traces at laboratory load conditions as indicated

adjusted in a flexible way approx. between 60 mA and 120 mA to allow spark energy performance on demand and avoid unnecessary spark plug wear and heat dissipation in the CEI device itself.

As an additional feature - besides showing a reasonable good spark stability - CEI provides the ability of quick re-ignition in case of spark blowout. This is illustrated in Fig. 12 comparing two spark current traces at imep = 10 bar/2000 rpm, one without (a) and one with re-ignition feature.

Finally Fig. 13 shows secondary high voltage offer of CEI acc. to different load conditions in laboratory.

4 Engine Results

Performance tests with CEI have been evaluated on many engines over the last years, to study the impact of continuously fed high ignition energy under different cylinder flow respectively charge motion conditions. A summary of these results will be presented in this section to show the bandwidth of the achieved increase of engine performance.

Tests have been carried out mainly for EGR and homogenous lean combustion process but also for stratified lean and special catalyst heating modes. Nevertheless the focus in this paper will be on EGR and homogenous lean combustion since EGR dilution is already widely used and homogenous lean combustion tends to be a promising development step for gasoline engines.

Table 2 lists the different engines used for evaluation of the CEI potential. All engines are modern turbocharged (T/C) engines with inlet-/outlet cam-phasing (D-VVT), direct injection system (DI) but differ in the charge motion. All engines are equipped with central mounted injector except engine D where a side mounted injector is applied. Mounting position of the injector has some impact on the spark plug position, typically engines equipped with central mounted injectors have a spark plug with a slight offset to the combustion chamber center. Even for tumble charge motion concepts this can affect the flow field in the vicinity of the spark plug. Furthermore, the investigated engines follow different charge motion layouts from medium to high level.

Table 2. Engines used for CEI performance investigation

Engine	Fuel system	Air system	Charge motion
A Full engine	GDI central	T/C, D-VVT + VVLin Int. EGR	High
B Single cyl.	GDI central	T/C, D-VVT Ext. EGR	Medium
C Single cyl.	GDI central	T/C, D-VVT Ext. EGR	Medium - High
D Full engine	GDI side	T/C, D-VVT Ext. EGR	Medium

Typically dilution by EGR respectively air is limited when the combustion stability becomes worse which in general is described by the CoV of the mean effective pressure (CoV_{pmi}). A typical limit of CoV = 5 % for single cylinder engines and CoV = 3 % at full engine application (in view of series application) is chosen. This covers the fact that at full engine CoV is evaluated as a mean value over all cylinders. With the lower CoV limit for a full engine it is ensured, that a single cylinder (e.g. due to cylinder-cylinder variation of charge and flow) not exceeds values of CoV > 5 %. It is widely known [19–22] that by an increase of ignition energy combustion stability limits can be shifted to higher dilution ratios. Current study therefore focuses on the potential of CEI extending the dilution limits compared to conventional TCI Systems.

4.1 Potential Study for EGR Combustion Concepts

First evaluations of the CEI potential have been carried out on single cylinder engine B with external EGR. Since engine B is equipped with a variable charge motion system (tumble flap) it is possible to study also the effect of charge motion on combustion and ignition. An operating point (2000 rpm/2 bar_i) critical for ignition has been chosen. CEI is compared with two transformer coils, providing 90 mJ resp. 140 mJ nominal ignition energy. The 140 mJ coil is the formerly known PowerPlus prototype from Bosch [17]. Furthermore the 140 mJ coil was operated at different energy levels between 96 mJ and 167 mJ.

Figure 14 shows results with active tumble flaps which would be applied for this operating point if a variable tumble flap is installed. The application of gas exchange analysis allowed for estimation of residual gas fraction at inlet valve closing. The x-Axis therefore indicates the total in-cylinder residual gas fraction. Following the rule of CoV limit = 5 % for single cylinder engines it can be observed that CEI enables highest internal EGR rates. Compared to the nominal operation of 140 mJ, the EGR-rate can be increased by roughly ΔEGR = 5 %, whereas compared to the nowadays typically standard energy level of around 90 mJ the shift of combustion limit is even higher ΔEGR ~ 8 %. Only the overloaded 140 mJ coil providing an ignition energy of 167 mJ allows an extension of the combustion stability limit close to the CEI performance. Nevertheless this operation would not be possible under vehicle respectively series conditions with this coil.

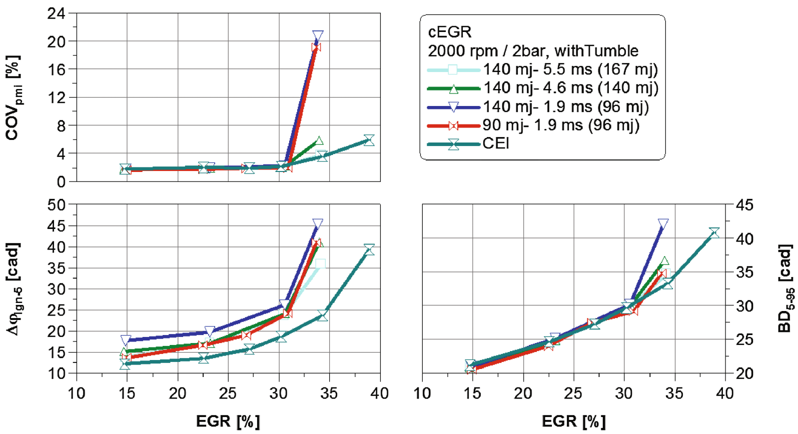


Fig. 14. External EGR variation and stability limits on engine B with activated tumble flap at 2000 rpm/2 bar_i. x-axis indicates total in cylinder residual gas fraction.

Additional to the CoV evaluation ignition delay values ($\Delta\phi_{ign-5}$) are plotted in the lower left plot. Clearly lowest values can be observed with the CEI system, a more detailed discussion will follow below. On the other hand it can be observed that the effect of the investigated ignition systems on the combustion duration ($BD_{5\text{-}95}$) is small until corresponding combustion stability limits are reached. Since the spatial influence

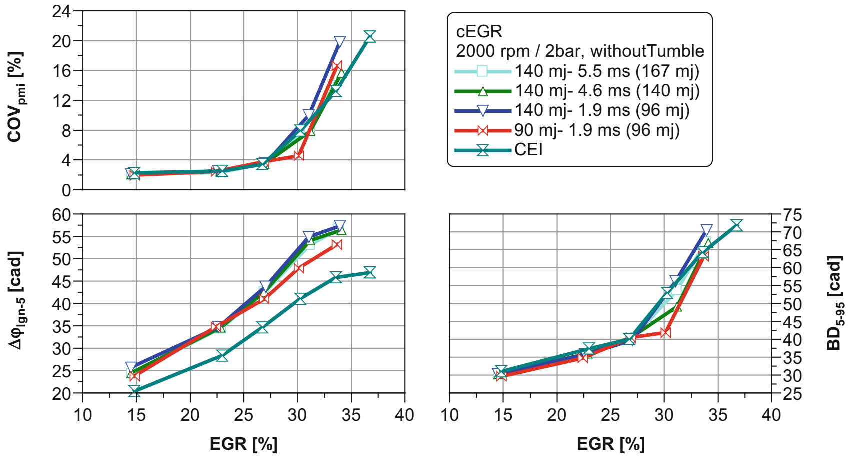


Fig. 15. External EGR variation and stability limits on engine B with not active tumble flap at 2000 rpm/2 bar$_i$, x-axes indicates total in cylinder residual gas fraction.

of spark plug ignition systems is limited to a small volume (see Sect. 2.1) this behavior is expected. More investigations have been carried out on engine B with deactivated tumble flap. Results for the same operation point are summarized in Fig. 15. Here combustion stability limit is reached at much lower internal EGR values $EGR_{Limit\sim 28\,\%\ \mathrm{compared\ to\ EGRLimit}}$ 32 % … 38 % for the case with active tumble flap. In addition the impact of the ignition system on stability limit is rather small. It is assumed that this behavior relates to the rather low charge motion values in case of deactivated tumble flaps. Spark elongation by the flow field in the near field of the spark plug is very small. At such conditions a large ratio of ignition energy provided to the spark plug is lost via the spark plug electrodes (see Chap. 2.1).

Evaluating ignition delay times ($\Delta\phi_{ign-5}$) also shows on average a slower flame kernel growth compared to the active tumble flap case. Nevertheless also here CEI shows significant faster flame kernel growth. This in general leads to stabilization of the combustion process but due to the very long burn durations in case of the deactivated tumble flaps the CoV value indicates, that the overall stability of the combustion cannot be significantly improved by higher ignition performance.

As mentioned at the presentation of results on engine B with active tumble flaps, a detailed view on the combustion stability will be discussed in terms of combustion statistic plots shown in Fig. 16. The data corresponds to the operation point with EGR-rates ~ 33 % in Fig. 14. Investigations have been carried out using standard ignition transformers (TCI) with nominal energy levels of 96 mJ respectively 140 mJ as well with CEI. The statistic plots show the cycle individual values of indicated mean effective pressure (high pressure loop, imep-hp) and the ignition delay defined as the interval between ignition timing and 5 % heat release (fhr0-5). Increase of ignition energy applied by standard transformers results only in a slight decrease of the ignition delay whereas CEI leads to significant reduction of ignition delay. The continuous feeding of high energy provided by the CEI system enables a faster establishment of

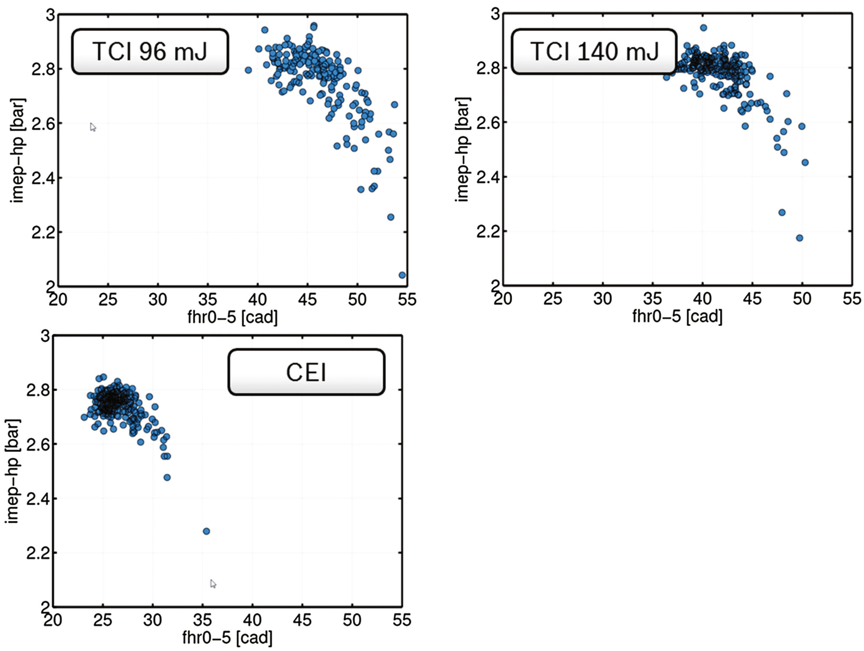


Fig. 16. Combustion statistics on engine B for different ignition systems for operation point 2000 rpm/2 bar_{i}/EGR ~ 33 %, activated tumble flaps

the flame kernel. Assuming a constant combustion phasing (50 % heat release mfb50) at mfb50 = 8 °CA, this results in later ignition timings for the CEI system. Later ignition timing then profit from improved ignition conditions, clearly indicating a considerably lower scatter band width CEI.

Full engine results are shown for engine A in Fig. 17 for the operation point 1000 rpm/2 bar_{i}. Fuel consumption is plotted in terms of inlet and exhaust cam timing position, whereby timings are given with respect to the gas exchange TDC (top dead center). Variation of cam timings results in different internal EGR rates. Highest internal EGR ratios are achieved with late outlet and early intake cam timings resp. high valve overlap. Combustion stability limits for different ignition systems are included (solid lines) as well as the series calibration point (dashed circle) as function of valve timings.

Stability limits based on CoV < 3 % are plotted for the series coil with 90 mJ, the 140 mJ PowerPlus coil and the CEI system. In the relevant area stability limits of series coil and PowerPlus coil behave quite similar. However CEI shifts the stability limit to significantly higher valve overlap which means higher internal EGR rates. Series calibration for valve train target positions is somewhat away from the stability limit which reflects the safety margin needed to cover tolerances in the system (engine resp. valve train tolerances, transient behavior …). If an identical safety margin is applied to CEI (red solid circle), the series calibration point (dashed circle) can be shifted towards higher EGR rates respectively larger valve overlaps. Fuel economy benefit accounted for this operating point was around $\Delta b_e = 11$ g/kWh which corresponds to roughly 3 %.

It should be mentioned that additional test have been carried out with a reduced electrode gap ($\Delta l = 0.2$ mm). In general reduction of electrode gap leads to even worse ignition conditions especially at low engine speed and low load, where charge motion is weak. With CEI it was possible to maintain the stability limit found for the series coil with the larger electrode gap. Smaller electrode gaps in general reduce the requirements of ignition voltage demand.

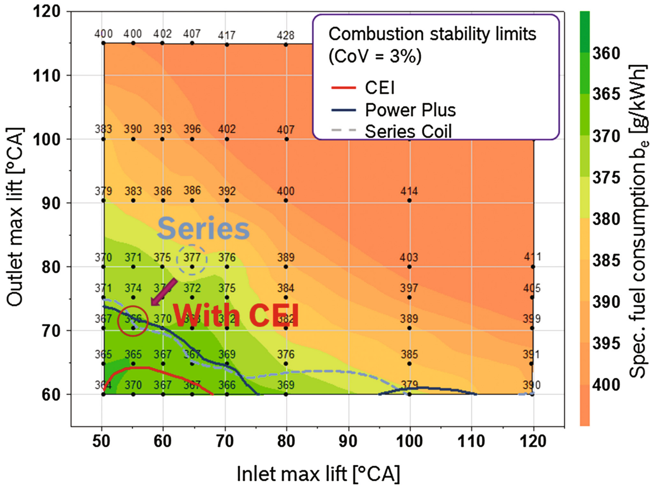


Fig. 17. Cam timing variation and stability limits achieved with different ignition systems on engine A at 1000 rpm/2 bar

Modern and especially future engines tend to have increased charge motion level. Hence experiments have been carried out on single cylinder engine C to investigate also the performance of CEI for higher charge motion levels on representative D-VVT engines. Here for the operating point 2000 rpm/3 bar_i a variation of the external EGR was investigated. In these tests CEI is compared against the MSI-System (Multi Spark Ignition) and the series coil with 90 mJ. Here CEI enables a significant shift of the combustion stability of $\Delta EGR = 12$ % compared to both the MSI and the series system. In this case the stability limit reached with CEI is in the range where fuel consumption already starts to increase again. This is related to due to increasing burn durations. However, also here safety margins need to be considered (shaded areas in left figure). If the target EGR rate is at minimum fuel consumption, applying the safety margin leads to fuel consumption benefit with CEI of roughly 1 % (dashed vertical lines in right figure). Furthermore with the increased EGR limit also NOx raw emissions are reduced but this is not main topic for stoichiometric homogenous operation (Fig. 18).

More benchmark results based on measurements on full engine D are presented for the operation point 1500 rpm/3.2 bari in Fig. 19. Here a comparison between

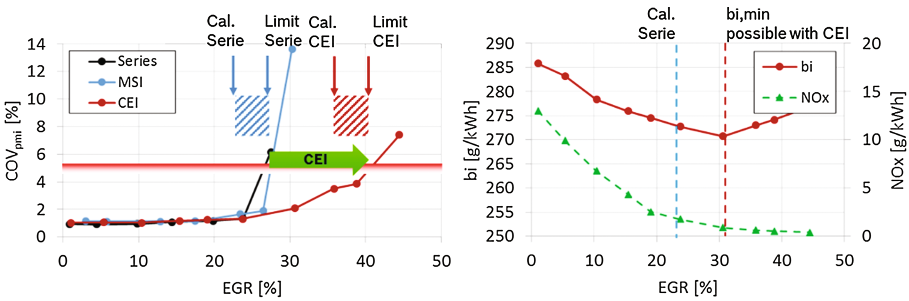


Fig. 18. External EGR variation on single cylinder engine C at 2000 rpm/3 bar$_i$; combustion stability, fuel consumption and NOx raw emissions

a conventional transformer coil operated at two energy levels, CEI and a DCO system is shown. DCO system has been introduced in Sect. 2.3. It offers a quite high energy of 450 mJ but also shows very high spark current pulses which need to be considered when evaluating spark plug wear. An external EGR variation was performed to study the influence of the ignition systems on combustion stability limit. CEI as well as DCO enables shifting the stability limit by around ΔEGR = 5 % applying a COV limit of 5 % but benefit vanishes compared to the 80 mJ case if the full engine COV limit of 3 % is chosen.

Nevertheless CEI and DCO show a benefit when evaluating which safety margin need to be applied. This will be evaluated based on the LNV value [20]. Evaluating a certain number of cycles (200 … 500) LNV is defined as:

$$LNV = \frac{\min(\text{imep})}{\text{mean}(\text{imep})} 100\,\% \tag{1}$$

This property is of great importance for transient operation, since it reflects better the driver feeling during acceleration. During transient operation, increased tolerance of the cylinder charge can be observed since the gas exchange flow varies from stationary conditions. Temperatures as well as pressures relevant for the gas exchange are away from their equilibrium state. This can lead to EGR-rate overshoots nevertheless a continuous evolution of the torque is expected. Typically the LNV value should drop below 80 %.

Above presented results for EGR combustion concepts can be summarized as follows:

- Depending on engine combustion concept and load point EGR can be increased up to ΔEGR = 12 % compared to a nowadays ignition system ranging between 70 … 90 mJ.
- Operating points and engine types have been observed, where the impact of a more powerful ignition system is rather small. However, considering system tolerances higher robustness can be achieved with CEI.

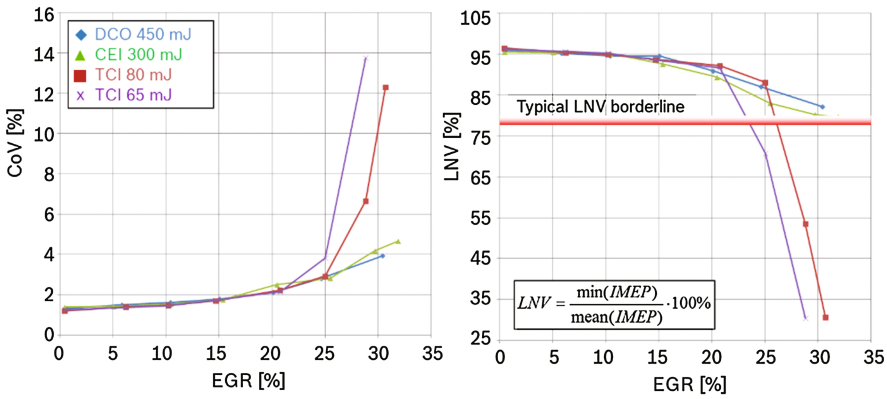


Fig. 19. External EGR variation on engine D at 1500 rpm/3.2 bar_i

- Higher charge motion levels generally lead to higher benefits, since spark is elongated stronger and the ratio of spark energy lost via the spark plug electrodes is reduced.
- Especially at low load conditions, improved combustion stability limits enable increased EGR rates allowing fuel economy benefits typically around 1 %, up to 3 % at specific operating points and engines.

4.2 Potential Study for Lean Combustion Concepts

In the future, homogenous lean combustion concepts will play a much more significant role than today. Therefore investigations have been carried out evaluating the impact of the CEI ignition system on the air dilution limits.

Since conventional 3-way catalyst does not allow sufficient high conversion rates of NOx at lean operation conditions, optimization of NOx raw emissions to lowest values is of great importance. The level of NOx raw emissions defines what type of NOx aftertreatment must be applied to fulfil emission legislation. Hence, additionally to the design of the combustion process itself, a powerful and suited ignition system enabling high dilution rates is a key technology to allow simple exhaust gas treatment e.g. passive systems for lean combustion engines.

Results for lambda variation on engine B are presented in Fig. 20. Here, for CEI different spark durations between 1.5 and 3.5 ms are chosen, a PowerPlus coil operated at 140 mJ is used as reference. It can be found that CEI enables highest lambda (air-fuel equivalence ratio) values. Compared to the PowerPlus coil, lambda can be increased by $\Delta\lambda = 0.1$. It should be mentioned that comparing against todays coils with around 80 mJ the benefit would be even higher.

Additional study of the CEI potential for homogenous lean combustion concept was performed on single cylinder engine C and is presented in Fig. 21. This engine has a higher charge motion level than engine B used for the investigation shown in Fig. 20. On engine C CEI was benchmarked against MSI and the series coil. With CEI it was

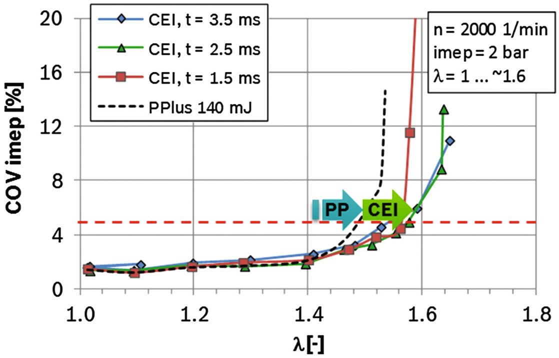


Fig. 20. Lambda variation for engine B at operating point 2000 rpm/2 bar$_i$

possible to significantly increase the lambda limit. Compared to the other ignition systems, a gain of $\Delta\lambda = 0.17$ was found and a remarkable lambda value around $\lambda = 1.9$ has been achieved for the operating point 2000 rpm/9 bar$_i$. Indeed, also the other ignition systems enable an operation close to optimal fuel consumption (b_i-best point) since the b_i-curve becomes quite flat in this range. Nevertheless, as described above, NOx raw emissions are of big interest for lean combustion concepts. In this case with CEI it was possible to reduce the NOx raw emissions by 50 % compared to series coil as wells as the MSI system. These results confirm the basic investigations presented in Sect. 2.1 that a continuous energy fed into the spark is beneficial to achieve a long and stable spark elongation which finally leads to improved ignition of lean mixtures.

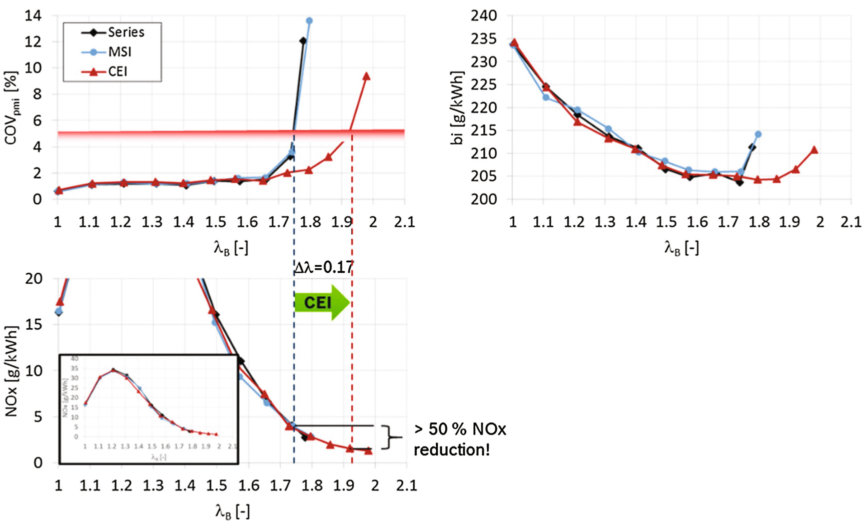


Fig. 21. Homogenous lean combustion lambda variation on engine C at 1250 rpm/9 bar$_i$

Considering that for series calibration the target values for lambda would be chosen with a certain safety margin to the stability limit, the impact on NOx would be even higher since the gradient dNOx/dλ increase for lower lambda values.

Nearly the same benefit in terms of enleanment extension as well as raw NOx decrease was found at engine C for other operation points e.g. 2000 rpm/3 bar_i.

Above presented results for lean homogenous combustion concepts can be summarized as follows:

- Depending on engine combustion concept and operating point the lean limit can be extended by up to $\Delta\lambda = 0.17$ compared to conventional TCI-Systems ranging between 70 … 90 mJ and MSI.
- A continuous energy fed into the spark is essential for reaching highest air dilution values.
- Even if benefits in terms of fuel economy at some operation points are small, the main focus is put on significant reduction of the NOx raw emissions. Those significantly determine, if a simpler/cheaper NOx aftertreatment can be chosen.

5 Summary

CEI (Controlled Electronic Ignition) as a new approach for high performance ignition is presented; being derived from generic analysis of requirements driven by from market and combustion trends but also considering aspects of industrialization for automotive high volume products. CEI offers high performance up to 300 mJ spark energy and also high flexibility to select a set of secondary performance parameters. Further benefits are high energy efficiency, a balanced package size and weight resulting in an outstanding value of energy density as ratio of spark energy per package volume. Present samples of CEI allow operation at engine test bench and are prepared for vehicle testing as well.

Basic requirements on ignition and combustion system were described, in order to extend the dilution limits. Measurements in a flow combustion vessel have shown that the decreasing spark current profile of TCI-Systems leads to frequently occurring restrikes if the spark current level drops below 50 mA. Restrikes shorten the plasma channel, which impede further deflection. Therefore, the current threshold must be considered when designing high performance spark ignition systems. However, besides electrical spark parameters the combustion system must provide adequate boundary conditions at ignition timing. Optical measurements on a single cylinder engine revealed, that the reduced flow velocity at ignition timing lead to inefficient energy transfer from spark to mixture increasing the probability of misfires and delayed combustion cycles. Furthermore, attention must not only be paid to ignition but also to the entire combustion process when evaluating the lean limits. The ignition system is specifically capable to influence the very early phase of combustion (typically up to 3…5 % heat release point). The acceleration of second half of combustion (mfb50-95) is one of the key factors to extend the lean limits.

Several engine tests have been carried out on different engines to benchmark the CEI system against standard transformer type coils as well as against the MSI system.

Here the main focus was on evaluating the benefit in terms of higher dilution rates for EGR and for homogenous lean combustion concepts.

Variations of internal and external EGR rates show in general an increased combustion robustness enabling higher EGR rates. Depending on engine and reference ignition, EGR rates could be extended with CEI by ΔEGR 5…12 %. This in general enables fuel economy benefits of around 1 % but at some specific points up to 3 %. Compared to MSI a benefit was observed which supports the conclusions made in Sect. 2.1, that a continuous feeding of high spark energy is necessary to create a stable spark providing further elongation in the flow fields. Nevertheless, it must be mentioned that besides the ignition system the layout of the combustion concepts (charge motion) influences the inflammation significantly and is limited for extended EGR rates.

Evaluations carried out to analyze the potential of CEI for homogenous lean combustions concepts also showed promising results. Depending on engine and reference ignition system it was possible to increase the air dilution in the range of $\Delta\lambda = 0.10 \ldots 0.17$. While fuel consumption is already close to optimal values for the investigated operation points with the reference ignition systems, NOx raw emissions are further reduced by 50 % using CEI. This is of big interest since NOx raw emissions determine which type of NOx aftertreatment becomes necessary. Hence, a powerful ignition system as CEI is a key technology to enable homogenous lean combustion concepts with cost optimized NOx aftertreatment.

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