Elastic breakdown via multi-core high frequency discharge for lean-burn ignition

Xiaoye Han, Xiao Yu, Hua Zhu, Linyan Wang, Shui Yu, Meiping Wang and Ming Zheng

Abstract
An advanced ignition technique is developed to achieve multi-event breakdown and multi-site ignition using a single coil for ignition quality improvements. The igniter enables a unique elastic breakdown process embracing a series of high-frequency discharge events at the spark gap. The equivalent electric circuits and current/voltage equations are identified and verified for the first time to explain the working principle that governs such an elastic breakdown process. Benchmarking tests are first performed to compare the elastic breakdown ignition with the conventional and advanced multi-electrode ignition systems. The elastic breakdown and spark events are thereafter analyzed through current and voltage measurements and high-speed imaging techniques. Finally, ignition tests in combustion chambers are performed to examine the effects on the ignition process in comparison with conventional coil-based ignition systems. The experiments show that, the elastic breakdown ignition can distribute multiple high-frequency breakdown events at all electrode pairs of a multi-electrode sparkplug while using only one ignition coil, thereby offering significant cost saving advantage and packaging practicability.

Keywords
Elastic breakdown, multi-event breakdown, multi-site ignition, spark ignition, sparkplug, ignition systems

Date received: 10 May 2021; accepted: 29 October 2021

Introduction
Ignition devices are widely used in propulsion applications primarily automotive gasoline engines. An ignition system serves the key purpose of providing a reliable ignition source at a desired timing, and it needs to guarantee reliable functionality over the entire engine operating range, in both steady-state and transient operations, and under all climatic and geographic conditions. An ignition failure can result in poor engine performance, high pollutant emissions, faulty powertrain maneuvers, and sometimes catastrophic hardware damages. Therefore, the research and development of ignition systems traditionally focus on hardware robustness and at low cost throughout the service life.

In recent decades, ignition products have evolved to offer continuous improvements in control precision and flexibility to address fuel economy and emission requirements. The ignition hardware design has advanced from mechanically timed ignition, for example, the break-point ignition, to electronic ignition control dedicated for each cylinder, for example, coil-on-plug ignition. Despite the incremental hardware upgrades, the fundamental mechanism of coil-based inductive ignition remains the same, and these coil-based ignition systems dominate the mainstream markets of spark ignition engines.

With regard to successful ignition, it is essential to secure flame kernel formation and sustain flame front propagation in an ignition event. As demonstrated by the authors previous studies and investigations from other researchers, ignition quality depends on many impacting factors, including but not limited to the ignition energy, electrode contamination, gap distance, gas flow, and mixture properties such as the air-fuel ratio, density, temperature, and the molecular structures.
The conventional ignition systems have been performing well for stoichiometric burn, naturally aspirated, and/or turbocharged gasoline engines. However, recent technologies enabling engine downsizing and diluted combustion aim to improve fuel efficiencies but inevitably alter the in-cylinder thermodynamic conditions beyond current boundaries, which poses substantial challenges on the ignition systems.\textsuperscript{10,11}

Downsizing demands a higher power density to deliver desired engine performance while meeting low load and idle quality requirements at the same time. The ignition system, therefore, faces a dilemma of sufficing both ends of a widened engine load range and the resultant greater span of cylinder pressure and temperature. For example, a common practice is to reduce the spark gap to ease the spark breakdown for a highly boosted engine at full load, but the ignitability at engine idle becomes a potential problem.

In the other aspect, the charge dilution naturally lowers the inflammation propensity when exhaust gas recirculation (EGR) and/or lean burn are applied. In a homogeneous mixture, the reduced ignitability near the spark poses challenges to reliable flame kernel formation and flame-front propagation development.\textsuperscript{12} In a stratified mixture, the injection strategy intends to create conditions in the spark gap favorable for ignition; however, the mixture properties exhibit fluctuations near the spark in both spatial and temporal domains, especially when strong charge motion is introduced to accelerate the burning of diluted combustion.\textsuperscript{13,14} As a result, conventional ignition systems face demanding requirements for delivering successful spark events, due to the lack of desired discharge duration and/or sufficient spark area/volume.

Active research programs around the world target to develop advanced ignition technologies to tackle the abovementioned challenges. When the spark energy is deposited through a single spark discharge channel, such as using a conventional ignition system, the research approach primarily relies on enhancement of the ignition energy\textsuperscript{15,16} and the breakdown power.\textsuperscript{17} At the same time, novel research has been conducted to extend the ignition duration and/or increase the number of ignition events via advanced techniques such as continuous discharge.\textsuperscript{18,19}

Other innovative ignition technologies also aim to produce ignition at multiple sites or in a larger volume to accommodate the spatial inhomogeneity of the air-fuel mixture. The multi-site and volumetric ignition technologies have been demonstrated to effectively improve the combustion stability of a diluted cylinder charge.\textsuperscript{20,21} For instance, research results have shown that corona ignition generates an array of plasma streamers to reach a large volume in the combustion chamber.\textsuperscript{22} Discharge along the ceramic surface is applied to form multiple ignition sites for racing applications.\textsuperscript{23} Double-spark ignition systems utilize a bridging electrode to form more than one plasma channels, thereby extending the overall arc length in a spark event.\textsuperscript{24,25}

Upon a spark command, electrode bridging allows multiple spark arcs distributed in the spatial domain, that is, between electrodes, but it cannot enable more than one breakdown events in the electrode gap.

Another innovative method patented by the authors’ group integrates multiple pairs of electrodes within a single sparkplug to enable multiple spark channels simultaneously.\textsuperscript{26} As shown in Figure 1, spark events of a multi-core igniter are compared with a production sparkplug during spark discharge. The multi-core igniter generates three spark channels in different directions and locations, which substantially increases the probability of successful ignition as the air-fuel mixture flows across the spark gaps. The multi-core igniter has been studied in a single cylinder research engine to extend the lean-burn and EGR diluted combustion limits,\textsuperscript{27} as well as demonstrated in a production engine to improve fuel economy.\textsuperscript{28}

Conventionally, a coil-based ignition system employs one set of ignition coil to generate one spark event upon receiving the spark trigger. Achieving multiple breakdown events generally requires a fast-charging coil and high-frequency spark triggers to repeat the processes of primary coil charging and secondary coil discharging within a short time window.\textsuperscript{29,30} In other cases, multiple coils are needed along with staggered spark triggers to sustain one prolonged discharge process.\textsuperscript{31,32} Similarly, the multi-core igniter requires a matching number of coils to drive multiple cores. It is desired to produce multiple breakdown events using only one ignition coil upon one spark trigger, which offers system simplification and cost reduction. Therefore, this research targets to demonstrate an innovative ignition mechanism to generate multiple breakdown events with one ignition coil triggered by a single spark command, and reveal the working principle in great detail to understand the elastic breakdown concept as patented by Zheng and Yu.\textsuperscript{33} In addition, the authors intend to combine such an innovative ignition mechanism with the multi-core ignition system to deliver spatially distributed sparks and, at the same time, sequentially generate multiple spark events at each spark gap using only one ignition coil, as shown in Figure 2.

![Figure 1. Spark event comparison between a production sparkplug and a multi-core igniter.](image-url)
Experimental setup

The advanced ignition research platform employs optical combustion vessels and high-speed imaging techniques to visualize the spark ignition and subsequent burning processes. As illustrated in Figure 3, the testbed comprises the high-precision control system, advanced ignition hardware, an optical combustion vessel equipped with gas exchange devices, and a high-speed camera and an image intensifier to capture direct images of the spark events. The ignition experiments use Schlieren imaging to visualize ignition and flame propagation. The specifications of the high-speed imaging equipment are given in Table 1.

A modular adapter at the top of the combustion vessel allows testing different sparkplug designs, including the multi-core igniter patented by the authors’ group.20 In previous studies,22 the multi-core igniter has demonstrated advantages of improving engine fuel efficiency operating under diluted gasoline combustion; each pole of the igniter generates one spark event per combustion cycle and in total 24 ignition coils are used for an eight-cylinder engine. Details of the multi-core igniter are documented in Hampe et al.20 and Burrows et al.22 This research, in contrast, deploys only one ignition coil along with separate in-line capacitors in the electrical circuits leading to individual electrodes.

The coil charging process is managed through an insulated gate bipolar transistor (IGBT) along with the control system encompassing a real-time (RT) controller with a field programmable gate array (FPGA) module. The RT-FPGA system provides desired speed and precision of the ignition command and offers controllability of varying charging durations and charging strategies. The selected IGBT V3040p has a turn-off slope of approximately 4.8 μs and serves as the ignition coil driver in the research setup. Upon receiving the ignition signal from the RT-FPGA system, the IGBT actuation generates a transient high voltage in the primary coil. The system therefore enables programmable generation of controlled charging durations and offers flexibility of experimenting unconventional ignition strategies. The control capability of the ignition research platform is essential to generate high-quality data and make fair comparisons when studying different ignition systems and charging strategies, as demonstrated in previous studies.5,14

The electrical circuit of an ignition system is redesigned to enable multiple breakdown events upon a single spark trigger. Among other configuration changes, a key enabler is the in-line capacitor integrated between the secondary coil and the spark gap. The electrical circuit of the elastic breakdown ignition is shown in Figure 4. Prior to the breakdown in the spark gap, the secondary coil, the in-line capacitor, and the parasitic capacitor form a series RLC oscillation circuit, similar to that in the conventional ignition system. The unique feature of this circuit design is the altered electric voltage interaction at the ignition coil and at the spark gap when breakdown occurs, which offers the possibility of enabling multiple breakdown events. In order to understand the electrical circuit behavior, the experimental setup includes current and voltage measurements at both upstream and downstream of the in-line capacitor. These electric measurements complement the high-speed imaging techniques to better understand the spark discharge process and its effects on ignition and flame development. The specifications of the electrical measurement devices are listed in Table 2.
The experimental investigation therefore leverages the sophisticated control and comprehensive measurements of the advanced research platform, and the working principle of the elastic breakdown concept is explained in subsequent sections with comparison against conventional and other advanced spark ignition strategies; the ignition capability of the new ignition mechanism is thereafter evaluated in optical combustion vessels to highlight the advantages of multi-event and multi-site spark discharge.

**Results and discussion**

Experiments are first carried out to benchmark conventional and multi-electrode ignition systems through electrical measurements and photographs of the discharge process. The discharge current and voltage profiles of the elastic breakdown phenomena are thereafter demonstrated with the multi-core sparkplug. Further experiments are conducted to examine the elastic breakdown mechanism in detail. Finally, the ignition capability of the new ignition technique is evaluated in optical combustion vessels.

| Type                  | Equipment          | Rated bandwidth/Sampling rate (MHz) | Rise time (ns) |
|-----------------------|--------------------|-------------------------------------|----------------|
| Electrical measurements| Tektronix P6015A   | 75                                  | ~4             |
| Voltage               | Pearson 411        | 20                                  | ~20            |
| Current               | PicoScope 4824     | 10                                  | 35             |

Figure 3. Ignition research platform with high-speed imaging capabilities.

Table 2. Specifications of electrical measurement devices.

Figure 4. Schematic diagram of the elastic breakdown ignition system.
Working principles of conventional and multi-electrode ignition systems

The electrical circuit of a common transistor coil ignition system is shown in Figure 5. There are also sparkplugs featuring additional ground electrodes (represented by the dashed lines in the electric circuit) to improve product durability. Despite the increased number of ground electrodes, the breakdown voltage only establishes a single spark channel connecting the central electrode to the ground electrode in the least resistance path. As the wear of the ground electrode lengthens the spark gap over time, the spark channel migrates to other ground electrodes, thereby enhancing the overall durability. However, the ignition capability is normally compromised because of the increased heat loss from the flame kernel to the multiple ground electrodes.

The working principle is the same for these coil-based ignition systems. The charged ignition coil stores sufficient energy prior to the spark event. The electronic ignition driver interrupts the magnetic field at the moment of spark ignition command, which induces a high voltage across the spark gap. A spark discharge between the electrodes occurs once the secondary voltage becomes high enough to breakdown the spark gap. A parasitic capacitor exists in parallel with the spark gap, inherently formed between the central electrode and the cylindrical metal shell due to the capacitive ceramic insulator. This parasitic capacitance provides the primary breakdown energy. Post breakdown, the spark discharge continues with a glow phase discharge with relatively low voltage (e.g. a few hundred volts) but lasting for a few milliseconds. The high-temperature plasma generated in the spark gap ignites the gas mixture that subsequently forms the flame kernel and develops propagating flame front.

In order to enable spark channels at every spark gap, the sparkplug with multiple ground electrodes can integrate a matching number of high voltage electrodes in its core, with careful insulation between each other. An example of the multiple spark sites is illustrated by the photograph and discharge current measurements in Figure 6. Each central electrode of the multi-core igniter is connected to an individual coil, thereby allowing independent control of each pair of electrodes. Such an innovative ignition system has demonstrated strong ignition capabilities. It is noted that, using a single coil connected to all central electrodes will result in a single spark channel established in the least resistance path, similar to that of a sparkplug with multiple ground electrodes. Therefore, the ignition flexibility offered by the multi-core igniter also requires complex control and increased cost, including a greater number of ignition coils and drivers, to operate such an ignition system.

The elastic breakdown technique developed in this research has a unique advantage of enabling
breakdown events at all electrode pairs using only one ignition coil. The modified electric circuit interrupts the direct connection between the ignition coil and spark gaps; therefore, the three electrode pairs work almost independently from each other. As shown in Figure 7, a single coil is used to drive the three-core igniter with additional in-line capacitors to enable elastic breakdown. The secondary voltage \( U \) starts to oscillate when the driver executes the ignition command on the primary coil side; the voltage measurement in each electrode branch \( U_a, U_b, \) and \( U_c \) respectively) manifests breakdown occurrences and discharge processes at all spark gaps. The working principle and basic characteristics are explained and discussed in detail in the next section.

**Characterization of elastic breakdown ignition system**

**Working principle of elastic breakdown.** In order to understand the working principle of the elastic breakdown ignition system, experiments are first carried out using a controllable electrical circuit setup that fundamentally represents a production spark ignition system with an addition of selected in-line capacitance of 100 pF. The ignition coil has an inductance of 5 mH on the primary side. Critical parameters of the ignition coil on the secondary side are characterized. As labeled in Figure 8, the secondary coil has an inductance of 30 H, a resistance of 3.26 kΩ, and a parasitic capacitance of 66 pF. The parasitic capacitance of the spark gap is approximately 18 pF. The charging duration is set to 500 µs in this test. Voltage and current profiles are both measured upstream and downstream of the in-line capacitor, respectively. At the first step, an electrical insulator is placed in the spark gap to avoid the breakdown event, and measurements are acquired to show the energy oscillation process.

An equivalent RLC circuit is formed by the in-line capacitor \( C_1 \), and the parasitic capacitor of the sparkplug \( C_2 \), and the secondary winding of the ignition coil with the secondary inductance \( L_s \), the parasitic capacitance of the winding \( C_s \), and the resistance \( R_s \). Based on Kirchhoff’s voltage law, the loop equation of the circuit can be written in equation (1), where, \( i_0 \) is the total current from the secondary winding, and \( C_T \) is
the total capacitance of the circuit, as can be calculated with equation (2).

\[ R_s \cdot i_0(t) + L_s \cdot \frac{di_0}{dt} + \frac{1}{C_T} \cdot \int i_0(t) \cdot dt = 0 \]  

(1)

\[ C_T = C_s + \frac{C_1 \cdot C_2}{C_1 + C_2} \]  

(2)

By solving the second-order differential equation (1), the total discharge current \( i_0(t) \), and the voltage upstream of the in-line capacitor \( U_{c1}(t) \), can be written with equations (3) and (4), respectively. \(^3^4\) Coefficients \( K_1 \) to \( K_4 \) are primarily dependent on the discharge current and voltage at the beginning of discharge, as well as the characteristic inductance, resistance, and capacitance of the circuit. Solution procedures to calculate \( K_1 \) to \( K_4 \) can be found in David and Nelms. \(^3^4\)

\[ i_0(t) = K_1 e^{-\alpha t} \cos \omega_d t + K_2 e^{-\alpha t} \sin \omega_d t \]  

(3)

\[ U_{c1}(t) = -R_s i_0(t) - L_s (K_3 e^{-\alpha t} \sin \omega_d t + K_4 e^{-\alpha t} \cos \omega_d t) \]  

(4)

where \( \alpha \) is the damping factor, as shown in equation (5); \( \omega_d \) is the damped angular frequency, which is determined by the natural frequency \( \omega_0 \) and the damping factor \( \alpha \), as shown in equations (6) and (7).

\[ \alpha = \frac{R_s}{2L_s} \]  

(5)

\[ \omega_d = \omega_0 \sqrt{1 - \left( \frac{\alpha}{\omega_0} \right)^2} \]  

(6)

The current upstream of the in-line capacitor \( i_{c1} \) and the spark gap voltage \( U_{c2} \) are primarily dependent on the capacitance in the circuit, as governed by equations (8) and (9).

\[ i_{c1}(t) = \frac{C_i}{C_T} i_0(t) \]  

(8)

\[ U_{c2}(t) = \frac{C_i}{C_1} U_{c1} C_i = \frac{C_1 \cdot C_2}{C_1 + C_2} \]  

(9)

where \( C_i \) is the total capacitance of the in-line capacitor and the parasitic capacitor of the spark gap. Equations (3), (4), (8), and (9) are the main governing equations for the current and voltage oscillations in the RLC series circuit. Figure 9 illustrates an overly comparison of the voltage and current measurements and calculations using the governing equations. The corresponding coefficients used for the calculations are shown in the Appendix.

The same experiments are repeated after removing the electrical insulator in the spark gap. Voltage and current measurements are placed upstream and downstream of the in-line capacitor. In order to have successful breakdown events, the charging duration of the ignition coil is set to 1 ms. In addition, these experiments incorporate high-speed imaging synchronized with the electrical measurements to better understand the experiment observations. A typical discharge process of the elastic breakdown is shown in Figure 10. Plots at the bottom right corner present the voltage and current profiles during the spark events, while plots on the left show the zoom-in views of voltage
measurements at upstream and downstream of the inline capacitor. At time zero, the RT-FPGA system sends the ignition command and triggers data acquisition at the same time. The high-speed camera is synchronized to start recording at 100,000 frames per second (fps) and an exposure time of 9 µs for each image.

As shown by the voltage measurements, both $U_{c1}$ and $U_{c2}$ start oscillating approximately 15 µs after the ignition trigger and increase in magnitude till around 30 µs time stamp. Prior to breakdown, the voltage pattern is very similar to that of the void discharge shown in Figure 8, and the current measurements also present a classical charging process of capacitors in-series under alternating current (AC). The current and voltage in this pre-breakdown stage are governed by equations (3), (4), (8), and (9), and the equivalent circuit is shown in Figure 11.

At the time stamp of 30 µs, breakdown occurs as $U_{c2}$ reaches the breakdown voltage threshold across the spark gap, and a plasma channel is established. The spark gap thereupon becomes conductive, and $U_{c2}$ stops following the trajectory governed by equation (9). Instead, $U_{c2}$ decreases in magnitude rapidly at the time of breakdown and then maintains a discharge voltage near $\pm 400$ V as the discharge process continues, as manifested by the voltage measurements in the time window of 30 to 110 µs. With the plasma channel established, the spark gap can be represented by a resistor, and the equivalent circuit is shown in Figure 12. It is important to note that $U_{c1}$ largely remains a sinusoidal

**Figure 9.** Comparison between measurement and calculation of the discharge profile for the elastic breakdown system in a void discharge event.

**Figure 10.** Electrical measurements and high-speed images of a typical elastic breakdown discharge.
waveform during this period, which presents a unique feature of separating $U_{c1}$ and $U_{c2}$ during the discharge process. Therefore, $U_{c1}$ is still governed by equation (4), but its oscillation frequency changes due to the changes in the equivalent circuit and coefficients need to be re-calculated.

After the first breakdown, the current magnitude shows a decreasing trend. When $U_{c1}$ reaches the valley at $\sim 110 \mu$s, the current traces cross zero and the spark gap becomes an open circuit, which marks the finish of the first discharge event. The ignition system returns to the equivalent RLC circuit as shown in Figure 11. After passing the valley, $U_{c1}$ continues to oscillate but with a positive slope, and $U_{c2}$ starts to rise from near $-400$ V toward the positive direction. The current flow also changes directions.

The voltage oscillation continues, and $U_{c2}$ keeps increasing till the positive voltage is high enough to result in another breakdown across the spark gap. It is noted that the amplitude of the breakdown voltage in the second breakdown event appears to be lower than that of the first event; the gas media between the spark gap may be more reactive after the first discharge event, which may contribute to the breakdown voltage difference. After the second breakdown, $U_{c2}$ maintains at about $400$ V till the end of the second discharge event. The equivalent circuit of the positive glow phase can also be represented as in Figure 12. It is noted, however, that the voltage polarity at the spark gap changes from negative to positive.

After solving the coefficients for each stage during the breakdown events, comparisons between the measured current and voltage waveforms and the calculation results are plotted in Figure 13. As shown, the governing equations can well capture the overall trends and characteristics of the breakdown events. The calculation details are included in the Appendix.

The breakdown and discharge processes are captured by the high-speed images. By convention, the ground electrode of the sparkplug is considered to have zero voltage potential. During the first breakdown and discharge process, the high voltage electrode works as a "cathode" since it has a negative voltage potential.
Discharge energy of elastic breakdown ignition.

Figure 14. Discharge energy of elastic breakdown ignition.

Inclusion of the in-line capacitor adds another variable in controlling the discharge energy. In conventional coil-based ignition system, the discharge energy is usually controlled by regulating the charge duration. In the elastic breakdown ignition setup, the in-line capacitance effectively determines the energy storage and charging profiles of the capacitor, and thus impacts the discharge energy released during the spark events. Figure 15 shows the calculated discharge energy as a function of the charging duration at three levels of in-line capacitance (plots on the left), along with the discharge energy profiles at 4 ms charge duration (plots on the right). Similar to conventional ignition systems, the elastic breakdown ignition delivers higher discharge energy when the charging duration is prolonged. Moreover, the use of a greater capacitance can also increase the discharge energy.

Elastic breakdown ignition to generate multiple spark events at multiple sites. As mentioned earlier, the multi-core ignition system requires a matching number of coils to enable spark events at all electrode pairs; however, the elastic breakdown technique offers advantage of using only one set of ignition coil. When connected to the multi-core igniter, the elastic breakdown circuit comprises a dedicated in-line capacitor for each electrode pair, thereby allowing the voltage at each spark gap to act almost independently from others, because breakdown occurrence at any electrode pair does not result in short circuit at any other pairs. An example of the experimental results is shown in Figure 16. Essentially, the breakdown and discharge process as described in the last section (Figure 14) takes place at each electrode pair of the multi-core igniter. The breakdown voltage varies among spark gaps and between breakdown events due to gap differences and condition changes, for example, the gap size and ionization activity, and therefore multiple breakdown events occur in a seemingly stochastic manner.

Although the individual voltage measurement receives noise interference from breakdown at other electrode pairs, the high-speed images are helpful to identify and correlate the breakdown events with the associated voltage waveforms. In this experiment, the optical setup leverages the image intensifier to enable clear imaging of breakdown and discharge with an exposure time of 9 μs. As shown in Figure 16, both negative and positive breakdown events are captured at all three spark gaps. The camera captures the first appearance of a plasma channel at 30 μs in spark gap “a”; the discharge sustains till 110 μs, as evidenced by subsequent high-speed images. The breakdown and discharge in spark gap “b” resemble those in spark gap “a” but occur ~20 μs later as shown in the image at 50 μs. The spark event in spark gap “c” is first observed at 40 μs, and the plasma channel disappears at 50 μs, manifesting a very short spark event. As the spark voltage turns to positive, the high-speed image at 290 μs, as an example, demonstrates spark occurrence at all three electrode pairs simultaneously.

With the voltage and current measurements, the discharge energy can be calculated using equation (10).

\[
E = \int_0^{t_d} P \, dt = \int_0^{t_d} U \cdot I \, dt
\]

where \(E\) is the energy in a discharge event, \(P\) is the discharge power, \(U\) and \(I\) are the measured discharge voltage and current, \(t_d\) is the discharge duration. The discharge energy is plotted in Figure 14 along with the discharge voltage and current in the exemplary case shown in Figure 10.

Inclusion of the in-line capacitor adds another variable in controlling the discharge energy. In
Performance of multi-site elastic breakdown ignition

Combustion tests under quiescent condition in the optical combustion vessel are carried out to examine the ignition capability of the multi-core elastic breakdown strategy. The experiments also include testing with a conventional spark ignition system for comparison. Methane and air are premixed at an excess air ratio of 1.4, and the combustion vessel is charged to a pressure level of 4 bar at 25°C. Although the temperature effect is not simulated, the density of the gas mixture in the combustion vessel is estimated to be equivalent to that of an engine cylinder charge at 10 bar during the compression stroke. The ignition setup uses the same ignition coil for fair comparison.

High-speed imaging is used to visualize the spark and flame, and the time instant of spark breakdown is assigned as “0 ms.” In Figures 17 and 18, comparisons...
of ignition and flame propagation are shown for charging durations of 1 and 6 ms respectively. Both ignition systems have successfully ignited the lean methane-air mixture. It is important to note that the multi-core elastic breakdown ignition generates more than one flame kernel near the sparkplug, thereby contributing to faster flame propagation. Such an effect becomes more obvious as the charging duration is increased from 1 to 6 ms.

Under the tested conditions, increasing the charging duration of the conventional ignition system results in minor improvements in flame kernel formation and flame propagation, whereas the multi-core elastic breakdown ignition forms a larger flame kernel and a greater ignition volume. The flame area is calculated for each case and the comparison is shown in Figure 19. Compared to the conventional ignition cases, the calculated flame area of the new ignition system increases by 50% and 100% at 1 and 6 ms charging time, respectively.

**Additional considerations and future work**

Experiments and analyses in previous sections show that the discharge duration of the elastic breakdown ignition is noticeably shorter than that of the conventional ignition mechanism. The in-line capacitor allows $U_c$ to continue oscillating while breakdown occurs downstream, thereby enabling possibilities of subsequent breakdown events; however, the in-line capacitor limits the energy passing to the spark gap during each discharge. As a result, the elastic breakdown ignition generally releases lower energy than that of conventional ignition systems. The success of ignition requires, among other things, that the delivered ignition energy meets the minimal ignition energy demand for self-sustained flame kernel formation. Nonetheless, once the minimal ignition energy requirement is met with a safety margin, additional spark energy makes diminishing contributions to ignition improvements, whereas increasing ignition volume and thus the initial flame kernel size become more effective to accelerate flame propagation. Therefore, the multi-core elastic breakdown can take advantage of the volume ignition at multiple sites, provided that it can deliver enough ignition energy. Further studies will be carried out to identify the ignition energy requirements for different fuel/air mixtures under different operating conditions, as well as methods to increase the discharge energy of the elastic breakdown.
spark ignition are expected to be more beneficial when mixture heterogeneity and strong flow exist near the spark plug, as the new ignition technique increases the chance of contact between spark channels and mixture pockets more favorable for ignition, in both temporal and spatial domain. Moreover, experimental results also show a potential of controlling the elastic breakdown duration via charging duration and capacitance matching. Strategies can thereafter be developed to predict and control the breakdown timing and the number of breakdown events.

Conclusions

In this research, the elastic breakdown ignition system is studied with detailed current and voltage measurements in systematic experiments to understand the electrical characteristics, in comparison with the conventional and advanced multi-electrode ignition systems. Analyses of the experimental results have revealed the working principle and identified the governing equations of the elastic breakdown process. A series of elastic breakdown events under one spark trigger command have been demonstrated via high-speed imaging techniques. In addition, elastic breakdown events at multiple electrode pairs of a multi-core spark plug have been established using only one spark coil. Ignition experiments in combustion chambers have proved the capability of the elastic breakdown ignition system to secure the ignition of the air-methane mixture. The major findings and contributions are summarized as follows.

1. Fundamentally, in order to enable multiple breakdown events, the voltage at the spark gap needs to reach the breakdown voltage multiple times. The secondary voltage oscillation in conventional ignition event finishes once breakdown occurs, and the secondary voltage magnitude reduces, resulting in only one possible breakdown occurrence within a single ignition event. The integration of an in-line capacitor into the secondary coil circuit preserves the secondary voltage oscillation upstream of the in-line capacitor while breakdown occurs downstream of the in-line capacitor at the spark gap, allowing the voltage at the spark gap to build up again after one breakdown and thus enabling subsequent elastic breakdown events. It is then possible to energize multiple spark gaps using a single ignition coil with single spark command.

2. The first breakdown event of the elastic breakdown ignition is similar to that of the conventional ignition, where a negative breakdown is typically enabled by the negative voltage at the spark gap. However, as the spark voltage builds up again in the elastic breakdown system, it is possible to generate positive breakdown events as the voltage changes polarity and the current flows in the opposite direction. The negative and positive spark events have been validated by matching high-speed imaging and voltage/current measurements.

3. This research has demonstrated multiple breakdown occurrences in an electrode gap upon one spark command. It is the first time that an ignition system uses only one spark coil with the multi-core igniter to enable a series of breakdown events at multiple sites.

4. The working principle of the elastic breakdown is explained in detail for the first time, with governing equations identified for each stage in the ignition process. The calculation of voltage and current can capture the overall trend and oscillation period of the elastic breakdown events.

5. In the preliminary combustion chamber tests, the elastic breakdown ignition with multi-core spark plug outperforms the conventional ignition system by offering faster burning of the methane-air mixture, mainly contributed by the multiple flame kernel initiated. As demonstrated by the high-speed images of the flame kernels, the flame area nearly doubles with the new ignition system with 6 ms charging duration.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.
References

1. Reif K. Fundamentals of automotive and engine technology: standard drives, hybrid drives, electronic brakes. Plochingen: Springer Nature, 2014.

2. Yu S and Zheng M. Future gasoline engine ignition: a review on advanced concepts. Int J Engine Res 2021; 22: 1743–1775.

3. Heywood JB. Internal combustion engine fundamentals. New York, NY: McGraw-Hill Education, 2018.

4. Bauer H, Dietsche KH, Crepin J, et al. Gasoline-engine management basics and components. 2nd ed. Stuttgart: Robert Bosch GmbH, 2001, pp.66–67.

5. K Reif. (ed.) Gasoline engine management: systems and components. Wiesbaden: Springer Vieweg, 2015.

6. Pera C, Knop V and Revellion J. Influence of flow and ignition fluctuations on cycle-to-cycle variations in early flame kernel growth. Proc Combust Inst 2015; 35: 2897–2905.

7. Zhen X, Li X, Wang Y, et al. Effects of the initial flame kernel radius and EGR rate on the performance, combustion and emission of high-compression spark-ignition methanol engine. Fuel 2020; 262: 116633.

8. Badawy T, Bao X and Xu H. Impact of spark plug gap on flame kernel propagation and engine performance. Appl Energy 2017; 191: 311–327.

9. Aleiferis PG, Taylor AMKP, Ishii K, et al. The relative effects of fuel concentration, residual-gas fraction, gas motion, spark energy and heat losses to the electrodes on flame-kernel development in a lean-burn spark ignition engine. Proc IMechE, Part D: J Automobile Engineering 2004; 218(4): 411–425.

10. Idicheria CA, Yun H and Najt PM. An advanced ignition system for high efficiency engines. In: Ignition systems for gasoline engines: 4th International Conference (ed M Günther), Berlin, Germany, 6–7 December 2018, p.40.

11. Corrigan DJ, Pasolini E, Zecchetti D, et al. Ignition system development for high speed high load lean boosted engines. In: Günther M and Sens M (eds) Ignition systems for gasoline engines. Cham: Springer International Publishing, 2017, pp.217–242.

12. Zhang A, Naber JD and Lee SY. An experimental study of flame kernel evolution in lean and diluted methane-air mixtures at engine-like conditions. Combust Sci Technol 2014; 186(8): 988–1004.

13. Aleiferis PG, Taylor AM, Ishii K, et al. The nature of early flame development in a lean-burn stratified-charge spark-ignition engine. Combust Flame 2004; 136(3): 283–302.

14. Wang Y, Han W and Chen Z. Effects of fuel stratification on ignition kernel development and minimum ignition energy of n-decane/air mixtures. Proc Combust Inst 2019; 37: 1623–1630.

15. Dale JD, Checkel MD and Smy PR. Application of high energy ignition systems to engines. Prog Energy Combust Sci 1997; 23(5–6): 379–398.

16. Yang Z, Yu X, Zhu H, et al. Effect of spark discharge energy scheduling on ignition under quiescent and flow conditions. Proc IMechE, Part D: J Automobile Engineering 2020; 234(12): 2878–2891.

17. Huang S, Li T, Ma P, et al. Quantitative evaluation of the breakdown process of spark discharge for spark-ignition engines. J Phys D Appl Phys 2020; 53(4): 045501.

18. Hese M, Tschöke H, Brenninger T, et al. Influence of a multi-spark ignition system on the inflammation in a spray-guided combustion process. SAE Int J Fuels Lubr 2009; 2(2): 376–386.

19. Weyand P, Lorenz F and Schilling S. Adaptive continuous spark ignition as enabler for high dilution EGR operation. In: 2nd international conference on ignition systems for gasoline engines, Berlin, Germany, 24–25 November 2014.

20. Hampe C, Kuback H, Spicher U, et al. Investigations of ignition processes using high frequency ignition. SAE paper 2013-01-1633, 2013.

21. Zheng M, Yu S and Tjong J. High energy multipole distribution spark ignition system. In: 3rd international conference on ignition systems for gasoline engines, Berlin, Germany, 3–4 November 2016.

22. Burrows J, Lykowski J and Mixell K. Corona ignition system for highly efficient gasoline engines. MTZ Worldw 2013; 74(6): 38–41.

23. Brisk Racing. Online referencing. https://www.briskracing.com/brisk-racing-premium-multi-spark-plugs (accessed 1 September 2021).

24. Astanei D, Munteanu F, Nemes C, et al. Electrical diagnostic of high voltage discharges produced by a new spark-plug. In: 2015 13th international conference on engineering of modern electric systems (EMES), Oradea, Romania, 11–12 June 2015, pp.1–4.

25. Hnaïtiuc B, Hnaïtiuc E, Pellerin S, et al. Experimental analysis of a double-spark ignition system. Czech J Phys 2006; 56: 851–867.

26. Zheng M, Yu S and Xie K. Multi-coil spark ignition system. Patent 9,441,604 USA 2016.

27. Xie K, Yu S, Yu X, et al. Investigation of multi-pole spark ignition under lean conditions and with EGR. SAE paper 2017-01-0679, 2017.

28. Han X, Yu S, Tjong J, et al. Study of an innovative three-pole igniter to improve efficiency and stability of gasoline combustion under charge dilution conditions. Appl Energy 2020; 257: 113999.

29. Piock WF, Weyand P, Wolf E, et al. Ignition systems for spray-guided stratified combustion. SAE Int J Engines 2010; 3(1): 389–401.

30. Poggiani C, Battistoni M, Grimaldi CN, et al. Experimental characterization of a multiple spark ignition system. Energy Proc 2015; 82: 89–95.

31. Alger T, Gingrich J, Mangold B, et al. A continuous discharge ignition system for EGR limit extension in SI engines. SAE Int J Engines 2011; 4(1): 677–692.

32. Alger T, Gingrich J, Roberts C, et al. A high-energy continuous discharge ignition system for dilute engine applications. SAE paper 2013-01-1628, 2013.

33. Zheng M and Yu S. System and method for elastic breakdown ignition via multipole high frequency discharge. U.S. Patent 9,828,967, 2017.

34. David J and Nelms RM. Basic engineering circuit analysis. 11th ed. Hoboken, NJ: John Wiley & Sons, Inc, 2014.

35. Loeb LB. Fundamental processes of electrical discharge in gases. Nature 1940; 146: 729–730.
Appendix

Governing equations and calculations of elastic breakdown ignition

An ignition system can usually be simplified as an equivalent RLC circuit. An impedance analyzer (Keysight E4990A) is used to characterize the inductance, capacitance, and resistance of each component. Table A1 summarizes the characteristics of the ignition system.

The equivalent circuit of the elastic breakdown ignition system is shown in Figure A1 that includes the secondary winding of the ignition coil, the in-line capacitor, and the spark gap.

During the ignition process, the equivalent circuit changes depending on the status of the spark gap. Prior to breakdown, the spark gap is equivalently an open circuit with parasitic capacitance formed by the ceramic insulator between the central electrode and the metallic shell of the sparkplug. When breakdown occurs and a conductive plasma channel is established between the central electrode and the ground electrode, the spark gap can be represented by a resistor whose resistance mainly depends on the spark gap conditions, such as the gap size and background pressure of the gas media.

In the following sections, equivalent circuits and governing equations are presented for the elastic breakdown circuit without spark discharge and with spark discharge, respectively.

Elastic breakdown ignition system without spark discharge

Without a spark, the spark gap in the secondary circuit of the elastic breakdown ignition system is simply treated as a capacitor \( C_2 \), as shown in Figure A2.

According to Kirchhoff’s voltage law, the loop equation for a RLC series circuit can be written in equation (A1).34

\[
R_s \cdot i_0(t) + L_s \frac{di_0}{dt} + \frac{1}{C_T} \int i_0(t) \cdot dt = 0 \tag{A1}
\]

\[
C_T = C_s + \frac{C_1 \cdot C_2}{C_1 + C_2} \tag{A2}
\]

Where \( i_0 \) is the total discharge current from the secondary winding; \( C_T \) is the total capacitance in the secondary circuit, as shown in equation (A2). By solving the secondary-order differential equation (A1), \( i_0 \) can be expressed with equation (A3), with two constant coefficients \( K_1 \) and \( K_2 \) which are mainly determined by the initial conditions of the discharge current \( i_{d1}(0) \) and discharge voltage \( U_d(0) \). The detailed solving process for \( K_1 \) and \( K_2 \) is provided in David and Nelms.34 The magnitude of the initial discharge current and voltage are mainly dependent on the ignition coil design and charging duration.

\[
i_0(t) = K_1 e^{-\alpha t} \cos \omega_d t + K_2 e^{-\alpha t} \sin \omega_d t \tag{A3}
\]

where \( \alpha \) is the damping factor, as shown in equation (A4); \( \omega_d \) is the damped angular frequency, which is determined by the natural frequency \( \omega_0 \) and the damping factor \( \alpha \), as shown in equations (A5) and (A6).

\[
\alpha = \frac{R_s}{2L_s} \tag{A4}
\]

\[
\omega_d = \omega_0 \cdot \sqrt{1 - \left( \frac{\alpha}{\omega_0} \right)^2} \tag{A5}
\]

\[
\omega_0 = \frac{1}{\sqrt{L_s C_s}} \tag{A6}
\]

Table A1. Electrical parameters of the elastic breakdown ignition system.

| Component          | Value       |
|--------------------|-------------|
| Ignition coil      |             |
| Primary inductance  | 5 mH        |
| Primary resistance  | 0.3 Ω       |
| Secondary inductance| 30 H        |
| Secondary resistance| 3.26 kΩ    |
| Parasitic capacitance| 66 pF    |
| Sparkplug          |             |
| Imbedded resistance| 4.3 kΩ      |
| Parasitic capacitance| 18 pF    |
| Spark gap size     | 0.86 mm     |
| In-line capacitor  |             |
| Capacitance        | 100 pF      |

Figure A1. Simplified secondary circuit of the elastic breakdown ignition system.
Based on the distribution of the capacitors in the secondary circuit, the discharge current upstream of the in-line capacitor $i_{c1}$ is expressed with equation (A7).

$$i_{c1}(t) = \frac{C_2}{C_T} i_0(t)$$  \hspace{1cm} (A7)

Where $C_t$ is the total capacitance of the in-line capacitor $C_1$ in series to the parasitic capacitor $C_2$, as shown in equation (A8).

$$C_t = \frac{C_1 \cdot C_2}{C_1 + C_2}$$  \hspace{1cm} (A8)

With $i_0$, the upstream voltage of the in-line capacitor $U_{c1}$ can be written in equation (A9).

$$U_{c1}(t) = -R_s i_0(t) - L_s (K_3 e^{-a t} \sin \omega_d t + K_4 e^{-a t} \cos \omega_d t)$$  \hspace{1cm} (A9)

The voltage downstream of the in-line capacitor $U_{c2}$ is mainly dependent on the capacitance ratio between the in-line capacitor and the parasitic capacitor of the spark gap, as shown in equation (A10).

$$U_{c2}(t) = \frac{C_1}{C_t} U_{c1}$$  \hspace{1cm} (A10)

Equations (A3) and (A9) are the primary governing equations corresponding to the oscillation of the discharge current and voltage of the equivalent RLC circuit. A comparison between the measurements and the calculation results for $I_{c1}$, $U_{c1}$, and $U_{c2}$ are shown with the calculation parameters and coefficients in Figure A3.

**Elastic breakdown ignition system with spark discharge**

Figure A4 illustrates the discharge current and voltage waveforms acquired upstream and downstream of the in-line capacitor ($C_1$) with a charging duration of 1000 μs. The equivalent circuit changes depending on the state of the spark gap. Therefore, the entire process of the elastic breakdown ignition is divided into six sub-sequences, as depicted in Figure A5.
The T1 stage is the pre-breakdown stage, starting from the ignition trigger to the moment prior to the first breakdown ($t = 13.7\, \mu s$). The equivalent circuit is the same as the one shown in Figure A2, governed by equations (A7), (A9), and (A10) to describe $i_{c1}$, $U_{c1}$, and $U_{c2}$, respectively. The coefficients of $K_1$ to $K_4$ are solved and summarized in Table A2.

**Table A2.** Coefficients and parameters to calculate the discharge current and voltage in T1.

| Coefficient/Parameter | Value  |
|-----------------------|--------|
| $i_{c1}(0)$           | -0.012 |
| $U_{c1}(0)$           | 830    |
| $K_1$                 | 0.032  |
| $K_2$                 | -0.0015|
| $K_3$                 | 648.3  |
| $K_4$                 | -24.6  |
| $\alpha$              | 54     |
| $\omega_d$            | 20.258 |
| $C_t$                 | 15.57  |
| $C_T$                 | 81.22  |

Upon breakdown ($t = 13.7\, \mu s$), a conductive plasma channel is established within the spark gap. The electrical energy stored in the parasitic capacitor ($C_2$) and the in-line capacitor ($C_1$) rapidly releases to the spark gap through the plasma channel within a short period, which causes a sharp decrease in both $U_{c1}$ and $U_{c2}$, as shown in the left-hand side of Figure A6. T2 ($13.7$–$14.7\, \mu s$) is thus defined as the capacitive discharge stage, in which the plasma channel is treated as a resistor ($R_2$) in parallel to the parasitic capacitor $C_2$, as shown in the right-hand side of Figure A6. The resistance of the plasma channel varies during the breakdown event, and $30\, k\Omega$ is used in the calculation based on voltage and current measurement results. At the end of T2, the discharge process enters to the glow phase, where $U_{c2}$ reduces to a voltage near $-400\, V$.

Based on the capacitor discharge process, $U_{c1}$ and $U_{c2}$ in the T2 discharge stage are written with equations (A11) and (A12) respectively.
\[
U_{c1} = U_{c1}(t = T_2) \cdot e^{-(t - T_2)/(C_1 \cdot R_2)} \tag{A11}
\]

\[
U_{c2} = U_{c2}(t = T_2) \cdot e^{-(t - T_2)/(C_2 \cdot R_2)} \tag{A12}
\]

**T3: Negative glow phase**

As the discharge process proceeds to the glow phase discharge, \(U_{c2}\) maintains around \(-400\) V. Within this period, \(U_{c1}\) continues to oscillate and \(i_{c1}\) reduces from a maximum value to zero, as shown in Figure A7. The T3 stage is defined from the end of T2 \((t = 14.7\) μs) to the moment when \(i_{c1}\) reaches zero \((t = 124.7\) μs). During the T3 stage, the spark gap is simplified as a resistor of 30 kΩ, and the equivalent circuit is shown on the right-hand side of Figure A7. The parasitic capacitance is effectively shortened by the conductive spark gap. Governing equations for \(i_{c1}\) and \(U_{c1}\) are equations (A7) and (A9) respectively, and new coefficients and oscillation frequency are solved and listed in Table A3.

**T4: Parasitic capacitor charging**

The conductive plasma finishes at the end of T3 stage, and the parasitic capacitance of the spark gap becomes effective again. The equivalent circuit (Figure A8) in the T4 stage is therefore essentially the same as that in the T1 stage, while the initial values of current and voltage and thus coefficients are different. Equation (A13) is used to calculate \(U_{c2}\), and the coefficients are calculated and summarized in Table A4.
Figure A8. Equivalent circuit of T4 discharge.

Table A4. Coefficients and parameters to calculate the discharge current and voltage in T4.

| Parameter | Value |
|-----------|-------|
| $i_c^1(0)$ | 0 |
| $K_1$ | 0.021 |
| $K_2$ | -1.14 |
| $K_3$ | 425.42 |
| $K_4$ | 2 |

\[
\Delta U_c^2(t - T4) = \Delta U_c^4(t - T4) \cdot \frac{C_T}{C_2} \quad (A13)
\]

T5: Positive breakdown

Similar to T2, T5 is defined as the positive breakdown stage ($t = 163.7 \mu s$). The equivalent circuit and voltage measurements are shown in Figure A9. In this stage, $U_{c1}$ and $U_{c2}$, are described with equations (A14) and (A15), respectively.

\[
U_{c1}(t) = -R_i i_0(t) - L_i (K_3 e^{-at} \sin \omega_d t + K_4 e^{-at} \cos \omega_d t) + U_{c1}(t = T5) \cdot (1 - e^{-t/T_5})
\]

(A14)

\[
U_{c2}(t) = U_{c2}(t = T5) \cdot e^{-(t-T5)/(C_2 R_3)}
\]

(A15)

T6: Positive glow phase

T6 represents the positive glow phase, where $U_c^2$ maintains at a quasi-constant value around 500 V. The same equivalent circuit of the negative breakdown phase is used, as shown in Figure A10. Using the same governing equations, the coefficients are re-calculated, as summarized in Table A5.

The calculated results and measurements are overlaid for the entire process in Figure A11.

Figure A9. Equivalent circuit of T5 discharge.
Table A5. Coefficients and parameters to calculate the discharge current and voltage in T6.

|     |     |     |
|-----|-----|-----|
| $i_{c1}(0)$ | 0.013 | $U_{c1}(0)$ | -12.687 |
| $K_1$ | 0.013 | $\alpha$ | 521 |
| $K_2$ | 30.2 | $\omega_d$ | 14,160 |
| $K_3$ | -174.11 | $C_t$ | 100 |
| $K_4$ | 421.44 | $C_T$ | 166 |

Figure A10. Equivalent circuit of T6 discharge.

Figure A11. Comparison between measurement and calculation of elastic breakdown events.