Experimental Analysis of Breakdown With Nanosecond Pulses for Spark-Ignition Engines

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ABSTRACT The influence of pulse rise rate and pulse duration for ignition purposes in engines is investigated. A constant volume cell is used to characterize the breakdown voltage under nanosecond pulsed voltages with automotive sparkplugs having electrode gaps ranging from 0.2 mm to 1 mm. Two pulse generators are used to compare pulses with durations of 10 ns and 50 ns. Different pulse amplitudes are used, and air gaps with breakdown voltages ranging from 4 kV to 15 kV are investigated. The cell is filled with synthetic air with densities gap distances products that are relevant for internal combustion engines. This study shows that the pulse shape and rise rate influence the breakdown voltage. Under pulsed discharge, the breakdown voltage is always above the static breakdown voltage. The probability of pulsed discharge breakdown increases as both the pulse amplitude and duration increases. Furthermore, the breakdown voltage value increases with increasing pulse rise rate. The delay time between reaching the static breakdown voltage and the actual breakdown voltage decreases with increasing overvoltage. The delay time is constituted by statistical and formative times. Both the statistical and formative times decrease with increasing overvoltage. For ignition purposes, the pulse rise rate should be as high as possible to deliver a larger energy input in the breakdown phase. Furthermore, for reduced electrode erosion, the pulse duration should be short (10-20 ns) to reduce the probability for a transition to an arc.

INDEX TERMS Breakdown, nanosecond pulsed discharge, ignition, nanosecond repetitive pulsed discharge, NRPD, nonthermal plasma, pulsed discharge, spark-ignition engines, sparkplug, streamer.

I. INTRODUCTION

In spark-ignition engines, increased efficiency is often limited by the ignition process. It is known that ignition limits the range of useable air excess or exhaust gas recirculation, affects later stages of combustion, and generates unwanted cycle-to-cycle variation [1].

Classical ignition systems for internal combustion engines are characterized by their typical current and voltage waveforms during discharge. Three distinct phases constitute the discharge: breakdown, arc, and glow. The breakdown is defined as the first very short (nanoseconds) phase. In this phase, the current rises to reach its maximal value, which is given by the ratio of the ignition voltage and near-gap impedance. At the same time, the gap voltage drops to low values [2]. The voltage drop rate depends solely on the inductive (ca. 5 nH) and capacitive (5-15 pF) components of the sparkplug. The arc is the second phase, which lasts for approximately 1 μs. The cable capacitance and coil capacitance are discharged through the spark resistance in series with the high-voltage cable impedance. The final phase is the glow discharge, which lasts several milliseconds, during which time the main energy storage device (inductor or capacitor) dumps energy into the plasma [3].

During the breakdown phase, the energy stored in the parasitic cap capacitance (sparkplug) is transferred, with low
heat losses, from the electric field gap to the electrons and subsequently to the heavy particles (molecules and ions). The associated rapid rise in gas temperature results in a rapid increase in pressure, resulting in a shockwave. The breakdown phase ends when the electron supply mechanism changes from photo or field emission (glow) to thermionic emission, i.e., when cathode hot spots are formed, which turns the discharge into an arc [4]. The electrode erosion that diminishes the sparkplug lifetime is most significant once a cathode spot, and therefore, an arc is formed [3].

The objective of ignition is to start a self-sustained chemical reaction. During discharge, the energy-transfer process is dominated by plasma expansion. Regardless of the plasma interior condition, there will always be a reaction zone on the plasma surface where temperatures below 8000 K offer ideal conditions for very intense chemical reactions leading to self-sustained flame propagation. This layer’s thickness is of the same order of magnitude as the flame-front thickness, while the spark discharge determines its energy density. The laminar flame propagation speed is inversely proportional to the flame-front thickness, which is proportional to the temperature difference between the burned and unburned mixtures. High energy densities and temperature gradients in the transition between plasma expansion and flame formation are achieved if spark discharge is accomplished in the shortest possible time interval [3]. Ultrafast highly powerful discharges should lead to a fast and repeatable transition from ignition to the early flame kernel to turbulent flame propagation [5].

With nanosecond pulsed discharge, the energy input is applied mainly during the breakdown phase, where high-temperature gradients should lead to high flame speeds [6]. Very high pulse amplitudes are needed to supply the energy necessary for ignition with a single nanosecond pulse. High amplitudes result in significant electromagnetic interference and require careful shielding and measurement techniques. Similar advantages of efficient activation of atoms/molecules can be obtained using multiple pulses but with moderate voltage amplitudes at a high repetition rate; such an ignition system is called nanosecond repetitively pulsed discharge (NRPD) [7].

The promising potential of NRPD ignition in internal combustion engines at high-pressure conditions has been investigated by several researchers [8], [9], showing its effectiveness in improving ignitability, flame stabilization, and engine performance, as well as in extending engine operation to leaner mixtures [7], [10]–[12]. NRPD appears to be a promising solution for advanced ignition systems. Although research into ignition using NRPD has gained considerable momentum in recent years [13], [14], the mechanism leading to breakdown under pulsed discharge in strongly inhomogeneous fields at high pressures remains largely unclear. Breakdown at a high overvoltage is advantageous for achieving reliable ignition in challenging conditions (e.g., lean mixture, stable fuels, high or low turbulence levels). The dynamics of the applied voltage influence the breakdown voltage, but it is not yet fully understood how this occurs. Pulse generators available on the market have various rise times, amplitudes, and pulse durations, but their influence on breakdown level and discharge probability is still unclear, especially for the conditions necessary for engine application.

In this article, the breakdown onset at density conditions relevant for internal combustion engine applications (pressures from 1 bar to 12 bar and temperatures of 300 K and 350 K) is experimentally investigated. These conditions correspond to gas densities ranging from 1.2 kg/m$^3$ to 13.9 kg/m$^3$.

The connection between the pulse generator and automotive sparkplugs is described, and the electrical circuit active during discharge under nanosecond pulses is analyzed. A methodology to measure the voltage and current waveform applicable to running engine operation is proposed and experimentally validated.

Based on electrical measurements, the breakdown mechanisms are experimentally investigated and interpreted on the basis of gas discharge theory. In particular, the relevant parameters affecting the breakdown voltage level and the time lags are identified. Based on these findings, optimized values for the pulse rise rates and the pulse durations are proposed for ignition purposes.

II. METHODS
A. BREAKDOWN MECHANISM
When the electric field strength exceeds the gas’s critical field strength, an electron can develop into an electron avalanche by impact ionization. The first electron (seed electron) can appear in the gas gap via several mechanisms: ionization of the background gas by energetic radiation (cosmic, radioactive, UV), detachment from negative ions in electronegative gases, or emission from the cathode surface. If the electron number in the avalanche becomes so large that its associated space-charge electric field distorts the background electric field, the avalanche-to-streamer transition can occur. The corresponding critical number $n_c$ of electrons at which this transition occurs depends on some degree on the discharge gap geometry and the gas type and pressure, with typical values lying in the range of $n_c \sim 10^6 \ldots 10^8$ [15]. After its inception, the streamer can propagate the ionization into regions where the undistorted electric field is below the critical field strength. Secondary avalanches growing from seed electrons provided by UV radiation emitted by excited species feed into the streamer head and extend the streamer channel toward the electrodes. Due to UV photon participation, streamer growth is a fast process, occurring at velocities exceeding the electron drift velocity. Once the streamer channel bridges the discharge gap, it can develop into a strongly ionized, highly conducting spark channel (transient discharge) or even into an arc (thermally ionized plasma channel driven by a low impedance voltage source) [16], [17].

Under quasi-static voltage stress, streamers are usually not considered to occur in submillimeter gaps at ambient
pressure [15]. The reason for this is that for typical electron feedback emission coefficients for the cathode ($\gamma \gtrsim 10^{-3}$), i.e., the number of secondary electrons per electron in the avalanche [15], Townsend breakdown occurs at voltages where streamers cannot yet be incepted. The Townsend breakdown develops over many generations of electron avalanches, wherein secondary electron emission at the cathode generates new seed electrons. These secondary electrons are generated via photon or ion impact on the electrode surface [17].

The average formative time for the Townsend discharge can be estimated using the Legler equation [18] expressed as Equation (1):

$$t_{f,T} = \frac{\ln[e^n a(\mu - 1)]}{\ln \mu} \tau_s$$

where $C = 0.577$ is the Euler constant; $n_a \sim 10^8$ is the number of avalanches required for the onset of fast current growth; $\mu$ is the avalanche amplification number, which is the average number of emitted secondary electrons per avalanche; and $\tau_s$ is the time interval between successive avalanches. $\tau_s$ depends on the average deexcitation time and the electron drift time if the Townsend discharge is sustained by photoemission or is on the order of the ion drift time if it is sustained by ion impact.

Due to the high pressures (1 bar to 12 bar) relevant for this project and the inhomogeneous electrode geometry (Figure 1 shows the sparkplug electrodes), the streamer mechanism can lead to breakdown at a lower voltage than the Townsend mechanism. The value of the feedback coefficient $\gamma$ can explain the presence of streamer breakdown instead of Townsend breakdown: the lower the feedback coefficient, the more likely it is that streamer breakdown will occur. Two factors in the current electrode configuration considerably reduce the feedback coefficient: first, the relatively high densities make it more difficult for photons to reach the cathode. Second, the electrode inhomogeneity: the edge provides favorable conditions for generating large avalanches. Nevertheless, it also means that secondary electron feedback must occur in a very narrow area of the cathode. Hence, the probability that a photon hits this area is relatively small. The feedback coefficient values for SF6 (electrical insulator gas) are shown as a function of pressure and field in [19]. An increase in pressure from 13 mbar to 133 mbar leads to a decrease in $\gamma$ by a factor of $\sim 100$. Two factors are reported to reduce secondary electrons with higher pressure: first, a higher photon absorption coefficient, and, second, a higher probability for nonradiative deexcitation of excited molecules via collisions with other molecules.

Due to relatively slow current growth over many-electron avalanche generations, the Townsend breakdown features a higher formative time than the streamer breakdown. High formative times are the reason why the streamer mechanism becomes the dominant breakdown mechanism above a certain overvoltage: even though Townsend discharge can occur already, it is too slow. Instead, the streamer mechanism kicks in at a certain overvoltage and leads to breakdown before the multiple electron generations have time to build up.

For streamer breakdown, an initial seed electron needs to be present at a favorable location in the discharge gap (near the cathode) to start an avalanche. This provision of seed electrons is ruled by processes subject to statistical fluctuations and leads to a discharge delay known as the statistical time lag. The statistical time lag can vary over many orders of magnitude depending on the active seed electron generation mechanisms. Once a seed electron is present, for breakdown to occur, it needs to grow into a streamer and induce a charge displacement within the gap that is large enough to ensure gap voltage collapse [15]. The associated time interval is called the formative time lag.

The formative time for streamer breakdown is mostly influenced by the time an electron avalanche needs to reach the critical size. It can be approximated by Equation (2) [20], where $\alpha$ is the ionization coefficient, $E$ is the electric field strength, $N$ is the gas number density, and $v_e$ is the electron drift velocity.

$$t_{f,s} = \frac{\ln(n_e)}{\alpha \left( \frac{E}{N} \right) v_e \left( \frac{N}{\pi} \right)}$$

If the formative time for a given condition shows minor scatter, an upper limit for the formative time is given by the minimum value for all observed delay times. The higher the number of observations, the closer one gets to the actual values.

**B. EXPERIMENTAL SETUP**

In the present work, the constant volume cell introduced in [2] is used in conjunction with two commercial nanosecond pulse generators (FID 15-10NK, FID 30-100NM) coupled to an automotive sparkplug to characterize the single pulse discharge in air at different gas densities and sparkplug gap distances. Table 1 lists the main specifications for the pulse generator used.

Kobayashi et al. [21] detected only a minor influence of different air-to-fuel ratios in reacting mixtures on the
discharge dynamics and structure up to plasma channel formation. For this reason, the discharge analysis is performed only in dry synthetic air throughout this paper. Furthermore, even at stoichiometric air to methane mixtures, the fuel percentage volume is only ca. 9%.

The pulse generator is connected to a commercial sparkplug via a coaxial cable with an impedance of 75 Ohms. Commercial sparkplugs (NGK-7471-C8E) are used, modified to have different gap sizes ranging from 0.2 mm to 1 mm with an accuracy of ±0.05 mm. Figure 1 depicts the electrode shape.

The center electrode is connected to the center core of the coaxial cable, while the ground electrode is connected with the shield of the coaxial cable through the ignition cell (see Figure 2).

When a positive polarity pulse is applied to a commercial sparkplug (as done here), the center electrode is positive (anode), while the ground electrode is negative (cathode). Therefore, the electrons are attracted to the center electrode, and the ions travel toward the ground electrode.

C. CURRENT AND VOLTAGE MEASUREMENT

When a pulse produced from the pulse generator arrives at the anode, it is reflected and transmitted depending on the ratio between the cable impedance and air-plasma resistance. The pulse travels one meter in approx. 5 ns, and for cables longer than 10 m, the pulse is completely contained inside the cable; there is no connection between the pulse generator and sparkplug. Therefore, it can be assumed that the applied voltage is independent of the pulse generator [22]. In this configuration, the transmission line wave Equations describe the voltage and current.

For a purely resistive load between the electrodes, the gap voltage $U_{gap}$ and total current $I_{tot}$ can be reconstructed by measuring the incident $I_{pulse}$ and reflected $I_r$ pulse current and knowing the coaxial cable impedance $Z$ according to Equations (3), (4), and (5):

$$U_{gap} = U_{pulse} - U_r$$
$$I_{tot} = I_{pulse} + I_r$$
$$U_{pulse} = ZI_{pulse}; U_r = ZI_r$$

To measure the incident and reflected waveforms without superposition, a 30 m long cable is used. The shielding is removed from a small section in the middle of the 30 m long coaxial cable. A shielded current monitor (Pearson current monitor model 6585 with a rise time of 1.5 ns) is placed around the exposed cable section to measure the current. In this way, at the measurement location, the incident and reflected pulses are divided by 30 m of cable (ca. 150ns). Any further reflection at the pulse generator will also have a similar delay w.r.t. the reflection. The cable shielding is reconstructed around the current monitor. Negligible reflections at the current probe location are detected. Pulses sent at the open circuit result in signal attenuation between the incident and reflected pulses of approximately 2%. To validate the measurement technique, a pulse is sent to a 470 Ohm noninductive resistance. Two measurements are performed: the current measurement in the middle of the cable and a voltage measurement using a high-voltage probe (Tektronix p6015a) placed directly across the resistance. Subplot (a) in Figure 3 depicts the current and the equivalent voltage measurement in the middle of the coaxial cable. Subplot (b) shows the measured voltage in blue and the reconstructed voltage from the current measurement in red (subplot (a)) according to Equations (3) and (5).
The voltage can be accurately reconstructed with the current measurement. The theoretical propagation delay for the chosen cable length matches the measured delay time ($\Delta t$).

Due to the impossibility of placing the voltage probe in the immediate vicinity of the sparkplug during pressurized operation of the cell, the current and voltage at the gap are reconstructed using the measured current waveforms in the middle of the cable. Therefore, the voltage probe is not used in actual experiments.

D. SPARKPLUG CAPACITANCE

As shown in Equation (6), the measured current $I_{tot}$ is the sum of the displacement current $I_C$, which corresponds to the current that charges the capacitance of the high-voltage electrode, and the conduction current flowing through the plasma $I_{plasma}$ [23]:

$$I_{tot} = I_{plasma} + I_C$$  \hspace{1cm} (6)

The displacement current is related to the derivation of the gap voltage by the sparkplug capacitance according to Equation (7):

$$I_C = C_{sp} \frac{dU_{gap}}{dt}$$ \hspace{1cm} (7)

The value of the capacitance is affected by the electrode geometry. The sparkplug capacitance is measured using low amplitude pulses where the entire measured current is the capacitive current (no breakdown). The sparkplug capacitance $C_{sp}$ for the used sparkplugs ranges from 5.1 pF to 5.7 pF depending on the bending of the ground electrode. One would expect a higher capacitance for a smaller gap distance, but since the ground electrode bend shape affects the capacitance, this is not always the case. The displacement current is directly proportional to the capacitance, and a maximal displacement current of up to 30 A is measured. These values are small in comparison with the plasma current (~200 A). The average value (5.5 pF) for the measured capacitance between different sparkplugs is used, which results in maximal variation of capacitive current below 5%.

This uncertainty is even less relevant when compared to the plasma current, which lies below 0.5% on average. The average value is also used because the sparkplug gap is frequently adjusted, and the capacitance slightly vary (different bend radii).

III. RESULTS

A. STATIC BREAKDOWN VOLTAGE

When fast-rising voltages are applied to the gap, as with the nanosecond pulsed discharge under investigation, the time needed to reach breakdown influences the value of the measured breakdown voltage $U_{bd}$ [15].

To quantify this effect, the breakdown voltage under slowly rising voltage (DC) is experimentally determined for the same electrode configuration and gas densities to relate the breakdown voltages under fast-pulsed voltages to quasi-static conditions. A high-voltage generator module capable of generating up to 20 kV is used. An empirical formula for estimating the static breakdown voltage $U_0$ as a function of the gap distance, density, and electrode gap is derived according to Equation (8):

$$U_0 = A + B \left( \frac{d_{gap}}{T} \right) \eta_{rel}$$ \hspace{1cm} (8)

Figure 4 outlines the agreement between the experiments and the fitted empirical formulas.

The parameters A and B for the linear regression are 1.9 kV and 838.0 $\frac{kV}{mmbar}$, respectively. The factor ($\eta_{rel}$) depends on the electrode geometry, and it decreases with increasing electrode distance. It is set to 1 for the smallest gap size of 0.2 mm and 0.64 for a gap size of 1 mm; $\eta_{rel}$ varies with the degree of homogeneity.

Photon absorption is expected to increase with higher pressures. The effective absorption coefficient scaled by pressure depends on the product between pressure and distance from the radiation sources [24]. Data from [25] are used to estimate typical photon absorption lengths for air. Figure 5 shows the ratio between the photon absorption length and gap distance.
The distance ratio decreases with increasing product of pressure and distance. For low pressure distance products, the absorption length and the gap distance are similar in value, while for higher values, the gap length is approximately twice the absorption length.

B. ELECTRICAL CHARACTERIZATION

At the sparkplug, the pulse is partially transmitted and reflected depending on the ratio between the cable impedance and gas electrical impedance. In the analyzed setup, the plasma and electrode configuration form a loop. Therefore, the actual electrode and plasma impedance consist of a resistance in series with an inductance. As shown in [22], for a small loop radius (tens of mm), the inductance of the electrode configuration is much smaller (5-10 nH) than the inductance of meters of coaxial cable: the assumption of a purely resistive plasma impedance is a valid approximation. Throughout this analysis, the plasma impedance is treated as a resistance ($R$). The plasma current is the difference between the total gap current and the capacitive current necessary to charge and discharge the "natural" sparkplug capacitance.

The schematic representation shown in Figure 6 qualitatively depicts the coaxial cable ($Z$) and electrode configuration ($R$), where a high-voltage nanosecond pulse (blue shape) creates a discharge between the electrodes.

When the gas resistance is high (insulating air between the electrodes), only the displacement current is measured. This applies to the situation before the electric field in the gap leads to significant ionization of the gas, thus increasing its electrical conductivity. The pulse is reflected at the high-voltage electrode (negative slope in the red reflection). At a certain moment, the streamer bridges the gap, the gap resistance decreases, and the current increases accordingly. When the gap resistance is equal to the cable impedance, the pulse power is entirely absorbed by the plasma, and nothing is reflected (red reflection equal to zero). The current after the transition between the electrodes returns to the coaxial cable through the shielding (positive part in the red reflection in Figure 6). At breakdown (minimum point in red reflection), the streamer develops into a strongly ionized, highly conducting spark (transient discharge) channel, and if the discharge is long enough, a spark-to-arc transition occurs.

A defining feature of arc discharge is the high temperature of the neutral gas particles. The gas particles receive energy via collision with energetic electrons, and these collisions occur with an average frequency $f_{en}$. The associated timescale for the equilibration of temperature is calculated according to Equation (9) [26]:

$$\tau \sim \frac{m_n}{2f_{en}m_e}$$  (9)

The mass ratio between air molecules and electrons is ca. 5-10$^4$. The effective frequency for momentum transfer is extracted from the Boltzmann equation solver BOLSIG+ [27] using the cross-sectional data sets reported in [28]–[30]. The total collision frequency ranges between 5.10$^{12}$ and 4.10$^{13}$ (s$^{-1}$).

The calculated characteristic time for energy equilibration ranges between 0.5 ns and 5 ns. However, this estimation can only represent a lower bound estimate for the arc formation time. The breakdown to arc transition is a complex multistage process that also involves a transient glow discharge phase and cathode spot formation [31]. Nonetheless, the derived range of values agrees well with typical spark arc transition times for discharges using sparkplugs under the investigated conditions [32].

When the spark channel is established, the spark gap acts as a low-impedance termination for the cable, reflecting most of the source’s pulse power.

Two discharge regimes are recognizable during this type of discharge. First, the low (displacement) current regime, where a low-conductivity medium (nonionized gas) is present between the electrodes, and the voltage across the gap is twice as high as the pulse voltage due to the pulse reflection. The second regime is the high current regime, in which only the cable impedance limits the maximal current.

Equations (10) and (11) describe the voltage across and the current through the spark gap: the voltage and the current magnitude are affected by the pulse (voltage $U_{pulse}$, current...
I_{pulse}), sparkplug gap capacitance C_{sp} and varying air-plasma electrical resistance (R).

\[ U_{\text{gap}} = U_{\text{pulse}} \frac{2R}{Z + R} \]  \hfill (10)

\[ I_{\text{tot}} = \frac{U_{\text{pulse}}}{Z} \frac{2Z}{Z + R} + C_{sp} \frac{dU_{\text{gap}}}{dt} \]  \hfill (11)

The two different regimes can be recognized as well from Equations (10) and (11). Before breakdown, the air between the electrodes provides a very high resistance (> 1 MΩ), preventing electrical charge flow in the gas. Therefore, the cable impedance Z of 75 Ω is negligible with respect to R, resulting in a negligible current flowing through the gap and a doubling of the gap voltage with respect to the pulse voltage. Experimentally, the measured current before breakdown is tens of amperes. The measured current is not a conduction current but a pure displacement current that charges the sparkplug capacitance. After breakdown, when the plasma is formed, the resistance is much lower (< 1 Ω) than the cable impedance. In this case, U_{gap} drops to low values. This setup offers the advantage of doubling the pulse generator voltage to initiate breakdown at high electric fields and limited current injection after breakdown, which should prevent or slow down the transition to a thermal plasma [33].

**Figure 7.** Discharge analysis.

**Figure 8.** Current and voltage relation during nanosecond pulsed discharge.

The blue line in subplot (b) of **Figure 7** in relation to the blue line in subplot (a) outlines the voltage doubling before breakdown. The high current (~ 100 A) and discharge time (tens of nanoseconds) after the breakdown outline the probable transition to an arc. As expected, the resistance of the plasma transitions from high values to low values. The breakdown is the point where the maximal voltage is reached, in this case at seven ns and 6.4 kV.

**Figure 8** shows the voltage across the gap (full blue line) and the plasma current multiplied by the coaxial cable impedance (dotted blue line). The dashed blue line is twice the incident pulse voltage (i.e., the voltage that would develop in the absence of breakdown and without any displacement current (called U_{max}) calculated according to Equation (12)).

\[ U_{\text{max}}(t) = 2ZI_{\text{pulse}}(t) \]  \hfill (12)

The red line depicts the cumulative energy injected into the plasma, which is calculated according to Equation (13):

\[ E_{\text{cum}}(t) = \int_{0}^{t} I_{\text{plasma}}(t)U_{\text{gap}}(t)dt \]  \hfill (13)

With the current setup, the sum of the total current multiplied by the cable impedance and the gap voltage is always double the supplied pulse voltage. This relation is due to the electrical circuit being active during discharge. When no current flows through the gap, the voltage is doubled due to full reflection. When the gap resistance is equal to the cable impedance, the gap voltage is equal to the total current multiplied by the cable impedance. At this point, no reflection is present, and the power transferred to the plasma is the highest (matched load). The high power input during the matched regime is also visible in the cumulative energy deposition (highest energy deposition rate); afterwards, the voltage decreases, and the current increases, reaching double the pulse current. **Figure 8** also reports the static breakdown voltage (U_0) interpolated.
from the results presented in section III.I, the breakdown voltage \( (U_{bd}) \), and the prospective voltage \( (U_{\text{max}}) \).

**C. BREAKDOWN VOLTAGE**

By changing the output amplitude of the pulse generator, different breakdown voltages are recorded for air densities ranging from 1.2 kg/m\(^3\) to 11.6 kg/m\(^3\) and for four different gap distances (0.2 mm, 0.3 mm, 0.5 mm, and 0.8 mm). Since the pulse rise time is constant for each pulse generator, different pulse amplitudes result in different pulse rise rates. The cell conditions defined as the multiplication of gas density and gap distance are relevant conditions for internal combustion engine operations (where a typical density gap distance of approximately 1 kg/m\(^3\) mm to 6 kg/m\(^3\) mm can be expected). The total experimental count was 1754, with breakdown found to occur in 1302 experiments. Figure 9 depicts the experimentally measured breakdown voltage under pulsed voltage for all the experiments as a function of the discharge condition (defined as the product of density and gap distance).

To understand the difference in breakdown voltage, the time needed to achieve breakdown (the time lag) needs to be considered.

The ion mobility swarm data \( (\mu_i) \) were extracted from LXCat [34]. For oxygen and nitrogen, the maximal values are ca. 2 cm\(^2\) V\(^{-1}\) s\(^{-1}\) for a density gap distance of 5.5 kg/m\(^3\) mm and applied voltage of 12 kV. The drift time was then calculated according to Equation (14):

\[
\tau = \frac{d_{\text{gap}}}{\mu_i E_{bd}}
\]  

(14)

The corresponding ion drift times range from 20 ns to 400 ns. The electron drift time is ca. two orders of magnitude lower ranging from 0.5 ns to 7 ns.

Equation (1) is used to estimate the Townsend formative time: for \( \mu \) equal to 2 and a fast electron drift time of 1 ns, the deexcitation time dominates the \( \tau_s \) values \( (\tau_s \sim 10\text{ns}) \) [18]. The minimum expected formative time for these experiments is ca. 300 ns.

The streamer formative time is estimated using Equation (2) without accounting for electric field inhomogeneity with a reduced electric field equal to that at breakdown and neglecting attachment, the average formative time among all experiments is ca. 3 ns with a maximum value of 60 ns. The formative time estimated from Equation (2) is reported in yellow in Figure 11.

Figure 10 subplot (a) shows different gap voltages for the same cell condition (4 bar, ambient temperature, and gap distance of 0.8 mm). Subplot (b) shows the corresponding incident pulse current.

The two different pulse generators are recognizable by the different pulse durations of 10 ns and 50 ns (subplot (b)). In addition to the pulse duration, the pulse rise rate also plays a role in the breakdown voltage; the higher the rise rate, the higher the average breakdown voltage. Furthermore, very similar pulse shapes can lead to different breakdown voltage levels, and, thus, to successful or failed breakdown: the blue and red traces lead to discharge in one case and no discharge in the other (identical red and blue traces in subplot (b); the blue trace in subplot (a) shows a breakdown, the red trace does not).

In all experiments, no breakdown is measured for voltages below the static breakdown voltage \( (U_0) \). The impulse factor is a measure of the overvoltage, and it is defined as the relative difference between the measured pulse breakdown voltage and the static breakdown voltage, according to Equation (15):

\[
K = \frac{U_{bd}}{U_0} - 1
\]  

(15)

The maximal impulse factor \( \delta \) is calculated in the same way, but with the breakdown voltage replaced by the maximal voltage that would appear across the gap if no discharge was present, i.e., the prospective voltage, according to Equation (16):

\[
\delta = \frac{U_{\text{max}}}{U_0} - 1
\]  

(16)

\[
U_{\text{max}} = 2 \max (U_{\text{pulse}}(t))
\]  

(17)
The two parameters $K$ and $\delta$ quantify the actually achieved and maximal possible overvoltages, respectively. The selected pulse generator amplitude and the cell condition alone limit the maximal impulse factor value. Breakdown static and prospective voltages are reported in Figure 8.

Figure 11 shows the delay time analysis for all 1754 experiments as a function of the maximal impulse factors.

The total time lag is the sum of the statistical and formative time lags (Equation (17)).

$$t_{\text{delay}} = t_s + t_{f,S}$$

Subplot (a) outlines the minimal observed delay time, which is an upper bound for the formative time, and the yellow line represents the estimated formative time according to Equation (2). Subplot (b) in Figure 11 shows the mean statistical time for each maximal impulse factor, which is calculated as the mean of the difference between the measured delay and its minimum. The blue and red colors represent the measurements for the 50 ns and 10 ns pulses, respectively.

Both the formative and the statistical time decrease for higher maximum impulse factors. With the only exception being the peak in statistical time for the 10 ns pulse duration for $\delta$ between 0.5 and 1.5. For high impulse factors, the delay time levels off at approximately 3 ns for both pulse generators with a low statistical variation.

Figure 12 depicts the discharge probability (number of breakdowns divided by number of applied pulses) and the measured impulse factor as a function of the maximal impulse factor in subplots (a) and (b), respectively. For subplot (b), the error bars depict the minimal and maximal measured values.

For maximal impulse factors above $\sim 1.25$, discharge is always present. When the discharge probability is below 100%, the measured impulse factor is limited by, and closely follows, the maximal possible impulse factor.

The trends reported in Figure 11 and Figure 12 remain invariable by taking into account only experiments having a similar density and gap distance product.

D. MULTIPLE PULSES

Multiple pulses at high repetition frequency will be used, per ignition event in engines, to provide the energy necessary for robust ignition. Similar trends are visible in multiple pulse modes. Ten pulses with a duration of 50 ns at a repetition frequency of 10 kHz in synthetic air at 8 bar and ambient temperature are applied to a sparkplug having a gap distance of 0.35 mm. Figure 13 shows the amplitude of the supplied pulse (subplot (a)), the voltage at the gap (subplot (b)), and the total current, namely, the sum of the displacement and plasma currents (subplot (c)). The breakdown is present when the current rises to hundreds of amperes.
from the data shown in Figure 11b). In this case, for the first three pulses, no discharge is present. The first breakdown voltage at 11 kV is in line with that for the single-pulse experiments. For the following pulses, breakdown occurs at a lower voltage.

Figure 14 depicts the discharge characteristics at 12 bar, a gap size of 0.5 mm, and a higher pulse voltage. The static breakdown voltage is 14 kV, and the maximal impulse factor is 0.1 and 0.5 for the first and second pulses, respectively. For the first pulse, the overvoltage is low, and breakdown is, therefore, difficult (probability of discharge approx. 30%). For the second pulse, which has a higher maximal impulse factor (often, the first pulse in multiple pulse mode has a lower amplitude), the discharge probability is higher (60%), and breakdown is achieved at 18 kV. Afterward, the breakdown occurs at lower voltage levels as in the previous experiment (Figure 13). The discharge probabilities are interpolated from the data presented in Figure 11 using the maximal impulse factor as the interpolation point.

IV. SUMMARY AND DISCUSSION
The static breakdown voltage is linearly correlated to the product of the density gap distance and $\eta_{rel}$. The decrease in $\eta_{rel}$ for larger gaps correlates with the expected increase in electric field inhomogeneity. The field inhomogeneity increases with increasing gap size.

The secondary avalanche plays a minor role in the breakdown onset for the analyzed electrode configuration. Two factors contribute to the increase in breakdown voltage sustained by the Townsend mechanism. First, the relatively high densities make it more difficult for photons to reach the cathode. The length ratio between the gap distance and absorption length decreases with increasing pressure gap distance product from ca. 1 to 0.5. At higher pressure, it is increasingly difficult for photons to reach the cathode. Second, it is difficult for secondary electron emission to occur in a strongly inhomogeneous electrode configuration. The sharp edges of the electrodes and the corresponding electric field enhancement provide favorable conditions for strong electron multiplication, but secondary electron feedback can then only occur in a relatively small area. Nevertheless, for slowly varying voltages, secondary avalanches may play a role in the discharge process in a narrow range of small overvoltages.

A Townsend breakdown in a pulsed discharge is very unlikely, as there is not sufficient time for its formation even when the breakdown is sustained by photoelectrons from the cathode (minimum formativetime of ca. 300ns). For the pulse durations employed in this work, the Townsend breakdown mechanism is not compatible with the observed delay times.

In pulsed discharge mode, the breakdown voltage is always above the static voltage. Under pulsed discharge, the delay time between reaching the static breakdown voltage and the actual breakdown voltage is affected by the pulse shape. With the current setup for a given condition, the higher the maximal impulse factor, the higher the pulse rise rate. Statistical time variations are present due to the time needed for the appearance of seed electrons. The formative time is the time necessary for an avalanche to grow to the critical size, bridge the gap, and form a conductive channel. Differences between practically identical experiments suggest that statistical influences of seed electron generation are present. Thus, statistical time lag variation gives rise to different discharges for similar pulses.

The decreasing trend for the formative time lag for higher impulse factors agrees with Equation (2). The formative time lag is inversely proportional to the ionization coefficient and the electron drift velocity, both of which increase with increasing electric field. The streamer formative time, Equation (2), is estimated without accounting for field inhomogeneity and temporal electric field variation. These assumptions give the proper order of magnitudes for the time involved. Nevertheless, assuming a homogenous field will probably lead to higher estimates of the formative times when in reality the avalanche to streamer transition occurs near the electrodes where the electric field, and, therefore, the ionization coefficient are enhanced. For avalanche to streamer transition positions far from the electrodes, the difference should be lower [35]. The non-varying electric field assumption will lead to underestimation of the formative time when breakdown occurs on the fast rising pulse flank. In this case, the streamer will develop at a lower reduced electric field than the breakdown electric field. Due to formative time, the breakdown voltage is higher than the average voltage during avalanche formation [36]. The first assumption will probably have more influence at lower overvoltages, where the avalanche will propagate in the more favorable part.

The second assumption will likely have a more significant impact at high overvoltage because the static breakdown voltage is crossed during the fast-rising phase of the pulse. The real formative time is perhaps lower for low overvoltage and higher for high overvoltage. This hypothesis agrees well with the discrepancies observed between the estimated...
and measured values. The formative time is experimentally defined as the minimal measured delay time for a given condition. The statistical time reduction can be explained by the increase in the critical volume, i.e., the volume where a seed electron can lead to breakdown with a high probability (>50%). The possible discharge volume increases, and with that, the probability that one seed electron is present and develops into a streamer also increases.

When a sufficiently high external electric field is applied to a metal surface, the electrons can escape by tunneling from the metal [37]. This mechanism can also reduce the statistical time, increasing the seed electron generation rate at higher overvoltages.

When the discharge probability is below one, the delay times are limited by the pulse duration. The peak of the statistical time lag for the 10 ns pulses can be explained by the limited pulse time; even though the seed electron generation rate is lower for lower overvoltages, the average statistical time is lower, but a seed electron was not present (no breakdown) for all the experiments.

For high overvoltages, the formative time is below ten nanoseconds. Low formative times result in discharge times above the characteristic timescale for temperature equilibration (1-5 ns), suggesting that the plasma has enough time to thermalize. Therefore, a spark-arc transition is likely to occur. If an arc transition occurs, the discharge is sustained by electron emission from the cathode hot spot, diminishing the sparkplug life. For the temperature equilibration characteristic time, the field is assumed to be homogenous at the breakdown voltage level, but the electric field during plasma thermalization decreases, and, therefore, the actual characteristic time increases. Field inhomogeneity should lead to different characteristic times, namely, faster plasma heat up in the electric field enhanced regions and slower plasma heat up where the electric field is locally lower.

The higher the maximal impulse factor for a given pulse generator, the higher the measured impulse factor. This means that breakdown at a higher voltage can be reached by using higher amplitude pulses with a higher rise rate.

The discharge probability is influenced by the pulse duration and overvoltage. The higher the maximal impulse factor and the higher the pulse duration, the more likely the breakdown. When the pulse overvoltage is below 1.25, the probability of discharge is below one. For shorter pulses, the breakdown probability is lower.

The breakdown voltage under pulsed discharge can be successfully estimated for each pulse generator as a function of the maximal impulse factor and the static breakdown voltage. The discharge probability and the breakdown voltage depend on the pulse duration, overvoltage, and pulse rise rate.

Multiple pulses at a high repetition frequency will be used in future engine applications to give the minimum energy necessary for ignition at moderate amplitudes. Short-duration pulses are advantageous to reduce arc discharge as much as possible, which is believed to be an effective way to reduce electrode wear.

Experiments with ten pulses at a repetition frequency of 10 kHz show that the discharge probability, breakdown voltage, and formative time in multiple pulse modes can be interpolated from single-pulse experiments up to the first breakdown. Afterward, the breakdown occurs at a lower level. A possible explanation for this is the reduced local density due to the energy deposition in the previous pulse or the presence of ionized molecules, excited species and free electrons (no lack of seed electrons).

V. CONCLUSION

Experiments have outlined that in addition to pulse duration, the pulse rise rate is the factor that mostly influences discharge characteristics. The maximal overvoltage dictates the discharge probability, total delay time, and breakdown value. Moreover, these findings can be used in repetitively pulsed discharge up to the first breakdown.

Theoretical estimates of the formative times for the Townsend and streamer mechanisms suggest that only the streamer mechanism is compatible with the observed delay times under pulsed voltage conditions.

For the investigated configuration, both the statistical and formative time lags can be of the same order of magnitude, and it is, thus, not generally possible to neglect the influence of the formative time on the breakdown voltage. These findings can be successfully used to describe the breakdown voltage as well as the discharge probability.

The experimental results indicate that high breakdown voltages of up to 290% of the breakdown voltage with a slowly varying voltage are achievable with high pulse amplitudes with steep voltage rise rate. High breakdown voltages are expected to create a more favorable ignition area (high temperatures with high radical concentrations), leading to a fast and reproducible transition to a self-sustained chemical reaction.

The ideal pulse shape for ignition purposes is probably one that gives the maximal amount of energy in the breakdown phase. Therefore, the voltage rise rate should be as high as acceptable (considering electromagnetic interference, cost) because this will lead to a high breakdown voltage. The ideal pulse duration should be short (ca. ten to twenty nanoseconds) to avoid or reduce the transition to an arc. The reduced time, or, ideally, absence of an arc should extend the lifetime of the sparkplug.

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