Demonstration of improved dilution tolerance using a production-intent compact nanosecond pulse ignition system

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Abstract. Transient plasma ignition using nanosecond pulses has demonstrated the potential to enable improved fuel economy and reduced emissions by enabling lean and EGR limit extension in dilute burn engines. Existing spark ignition technology is not adequate because the energy transfer mechanisms between the spark and the fuel-air mixture are not efficient enough to guarantee stable ignition for dilute mixtures at high-load conditions. Additionally, long duration sparks and other advanced ignition solutions that require increased energy delivered accelerate spark plug electrode wear. To date, non-thermal plasma ignition with nanosecond pulses have demonstrated a lean ignition limit beyond an air/fuel ratio of 24 [1], demonstrated high-pressure ignition at densities equivalent to over 100 bar at the time of ignition [2], and demonstrated stable (COV <3%) ignition at EGR dilution levels >20% [3]. While low-energy nanosecond pulses have demonstrated strong performance compared to existing solutions, they currently only exist on the market in laboratory systems, rather than a production ready system in a single rugged, weather-proof, under-the-hood enclosure. Transient Plasma Systems (TPS) has recently demonstrated the potential for a retroffitable solution similar to coil-on-plug architecture that allows a direct replacement of existing ignition technology without any engine modification. The system was run on a gasoline direct injection engine at Argonne National Laboratory and demonstrated the same trends as previously observed with research grade systems, including lean and EGR limit extension and more stable ignition across a range of loads. The system was capable of delivering 30 kV pulses in bursts of up to 20 pulses at 30 kHz, and demonstrated stable combustion at an air/fuel ratio of 23.5, exhaust gas recirculation of 23%, and ignition at 19.2 bar with COV<3% using only 20 kV pulses.

Keywords: Non-equilibrium plasma; nanosecond pulsed power; transient plasma ignition

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1 Introduction

With over 16 million new vehicles with internal combustion engines sold each year in the U.S., even small advances in fuel economy will have a significant impact on the health, economy, and environment. Dilute-burn gasoline engines are considered one of the most attractive solutions to developing more energy efficient and environmentally friendly highway vehicles; however, ignition instability associated with dilute mixtures prevents wide-spread application [4]. For this work, the concept for a novel low-energy and cost effective nanosecond pulsed ignition system based on technology that has been shown to reliably ignite dilute mixtures [3] [1] was developed and demonstrated in a plug & play form factor similar to coil-on-plug ignition modules.

Dilute burn gasoline engines, whether lean or EGR, allow for improved fuel efficiency and reduced emissions by limiting thermal losses, but they also reduce the engine's peak power. This lost power can be recovered through turbocharging, but the combination of dilution and intake pressure boost makes ignition increasingly difficult. Traditional ignition methods can ignite this mixture if the ignition energy is significantly increased, but this causes unacceptable spark plug wear. Data collected from numerous engine experiments conducted by Transient Plasma Systems, Inc. with collaborators including Argonne National Laboratory [3], Sandia Combustion Research Facility [1], and the University of California at Berkeley [5] have shown that low-energy, high peak power nanosecond pulses show great potential as an ignition source to enable stable, dilute-burn ignition without accelerated ignition system fatigue.

Low-energy nanosecond pulses have demonstrated performance benefits compared to existing solutions, but they currently only exist in laboratory systems, rather than a production ready system in a single rugged, weather-proof, under-the-hood enclosure. The work reported here as part of a U.S. Department of Energy funded project resulted in a prototype system demonstrating the feasibility of developing such a production ready system.

1.1 Technical Approach

The widely used capacitive and/or inductive coil spark ignition system has remained essentially unchanged for over 100 years. For dilute-burn engines, existing spark ignition technology is not adequate because the energy transfer mechanisms between the spark and the fuel-air mixture are not efficient enough to guarantee stable ignition for dilute mixtures at high-load conditions. Dilute-burn engines require a high-energy conventional spark to transfer enough heat into the combustible mixture for ignition, with the energy required generally increasing with higher pressure and dilution. The current state-of-the-art for ignition systems requires long duration sparks at high-voltage and current, which accelerates spark plug wear and minimizes spark plug wire life. TPS's approach is based on the generation of a non-thermal, low-energy transient plasma with nanosecond pulses that enables extended dilute-burn combustion (Figure 1).

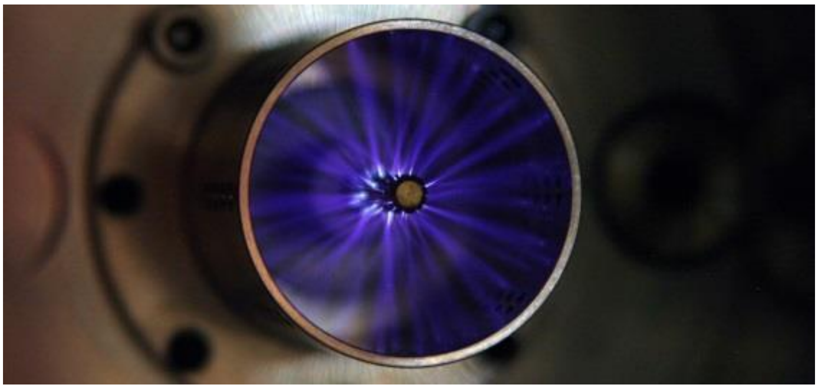

Figure 1 - Photo of transient plasma (low-temperature plasma) formed by TPS nanosecond pulsed power technology.

Low-energy nanosecond pulses can be used to produce a non-thermal plasma (also referred to here as transient plasma) which uses less power and is more effective compared with the thermal or quasi-thermal plasmas that are commonly generated by alternative advanced ignition techniques [6]. Traditional thermal ignition systems heat a zone of combustible mixture to a temperature where radicals are thermally generated and produce rapid chemical reactions that generate heat faster than heat transfer can cool the zone, resulting in ignition. This technique has limitations in dilute mixtures because thermally generating radicals is inefficient and slow, and excess air in lean mixtures cools the ignition zone more quickly. In non-thermal plasma, radicals are produced directly, which is more than 50 times more efficient [7], and therefore less energy is needed to generate heat more quickly and the mixture can be leaner (Figure 2).

To date, non-thermal plasma ignition with nanosecond pulses has:

1. Demonstrated a lean ignition limit lower than a fuel/air equivalence ratio (ϕ) of 0.50 [1];
2. Demonstrated high-pressure ignition in static cells > 60 bar in cold air [2];
3. Enabled operation under high EGR [3];
4. Demonstrated stable (COV <3%) ignition at EGR dilution levels up to 35% [8].

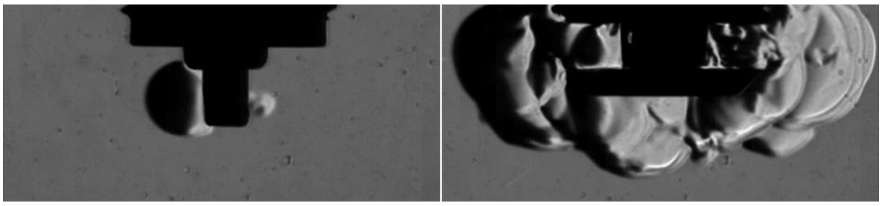

Figure 2 – Ignition of natural as part of EISG grant 13-03T NG demonstrating the feasibility of the TPS technology for enabling stable lean burn combustion in NG SI engines. The work was performed with Prof. Robert Dibble at UC Berkeley. The images show ignition of a lean mixture (λ =1.67, φ = 0.599) of natural gas and air 5 ms after ignition. Left: High-energy spark ignition (300 mJ). Right: Low-energy non-thermal plasma ignition (approximately 20 mJ/pulse). This clearly demonstrates a better investment of energy.

There are two distinct advantages to transient plasma ignition via low-energy nanosecond pulses:

- Fundamentally different ignition chemistry using low-energy nanosecond pulses that enables dilute ignition and combustion stability, potentially improving electrode life.
- Multi-point ignition due to the plasma's volumetric properties that improves dilute-burn efficiency and stability by increasing flame wrinkling and propagation speed (Figure 3).

Non-thermal plasmas are characterized by a high electron temperature T_e and a low gas temperature T_g ($T_e >> T_g$). In the extreme case, the gas temperature can be close to room temperature and the electron temperature can be well above 20,000 K [9]. In non-thermal plasma, the ionization process is dominated by field-driven, energetic electrons impacting with non-excited atoms and molecules. The energy transfer efficiency is high and significant energy goes into creating highly energetic electrons instead of heating of the gas. The energetic electrons collide with the fuel and air molecules, producing highly reactive species such as atomic oxygen [10], reducing ignition delays and improving dilute burn capability [7].

Non-thermal plasmas can be produced using various methodologies, including glow and RF discharges at low pressures, barrier and hollow cathode discharges, and nanosecond pulses. TPS's nanosecond pulse approach produces streamers with energetic electrons filling 60-80% of the volume with highly reactive species, accelerating combustion reactions and enabling multi-point ignition [11].

The goal of using nanosecond pulses is to apply an electric field as quickly as possible and avoid spark breakdown. Operating in this mode requires the voltage, gap, and electrode configuration to be considered with respect to the temperature and pressure between the electrodes. When primary streamers bridge the gap between the anode and the cathode, secondary streamers form and the plasma channel becomes highly conductive, leading to a spark [12]. When a spark forms, energy delivered increases, but combustion is not enhanced, since the combustion chemistry has already been initiated by the active species formed during the rise of the voltage pulse. Therefore, it is desirable to avoid spark breakdown to extend spark plug life by adjusting the peak amplitude of the voltage pulses. In this work, voltage and current was monitored during the engine operation and the voltage was adjusted to avoid full spark breakdown wherever possible, but could not be avoided entirely. Future work will focus on optical diagnostics along with voltage and current measurement to clarify the role of primary streamers, secondary streamers, and spark breakdown.

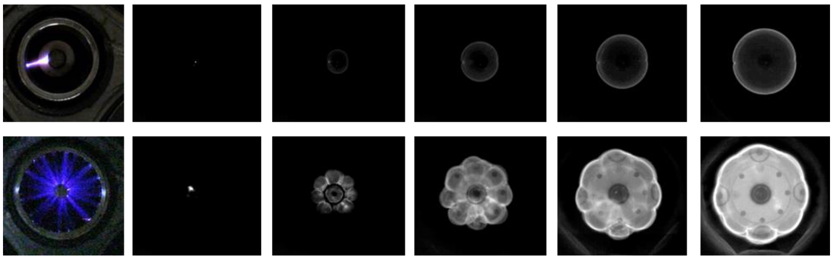

Figure 3 – 105 mJ conventional spark ignition (above) compared to 40 mJ transient plasma ignition (below) in a stoichiometric methane-air mixture. Images taken 1.5 ms apart.

The ability to achieve multi-point ignition can be enhanced by operating the ignition system in burst mode, whereby a pulse train of nanosecond pulses is generated, typically at kHz rates. When a spark plug with multiple ground cathodes is used, this can generate a volumetric distribution of primary streamers, secondary streamers, and sparks, as demonstrated in Figure 4. This example is for a 10-pulse burst with a repetition rate of 9.7 kHz. It was captured by a Phantom v611 color camera, operated at 180 kHz. The spark timing was 30°CA before TDC, at a gas pressure of 12 bar. In this engine cycle, the first nanosecond pulse did not transition into spark, so it could not be detected with this optical setup. At the voltage setting being used for this experiment, pulses 2 through 10 all transitioned into visible streamers and sparks. Pulses 2 – 5 all engaged with the ground cathode in the 2 o'clock direction, showing only one spark per pulse. However, each of pulses 6 – 9 showed two sparks or streamers, while a gradual transition to the ground cathode in the 4 o'clock direction occurred. For pulse 10, only one ground cathode was engaged with the two closely situated sparks. This procession of the sparks means that a large volume of fuel-air mixture can be ignited during a burst, shortening the time required for a fully turbulent flame to develop. Determining the role of the energy delivered in each stage, e.g. primary streamers, secondary streamers, and sparks, will be the focus of future work.

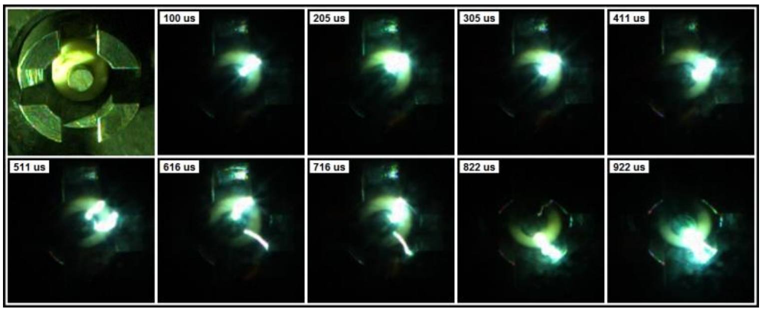

Figure 4 - High-speed imaging of multi-pulse transient plasma in an optically accessible engine, showing an example of breakdown-site procession. Time is given in μs from the first pulse, which did not transition into an arc. Exposure duration = 4.8μs. All dark or nearly dark images in between pulses have been omitted.

The goal of this work was to develop and test a prototype ignition module with a form factor consistent with modern day, commercially available ignition systems, e.g. Figure 5. The ignition module was built around the technology that was used to produce the results reported in [3], advancing the state of that technology. The system was tested on a single-cylinder gasoline direct injection (GDI) engine at Argonne National Laboratory in Lemont, IL, with the intention of demonstrating the potential to achieve the results reported above with a system closer in form factor to existing ignition technology.

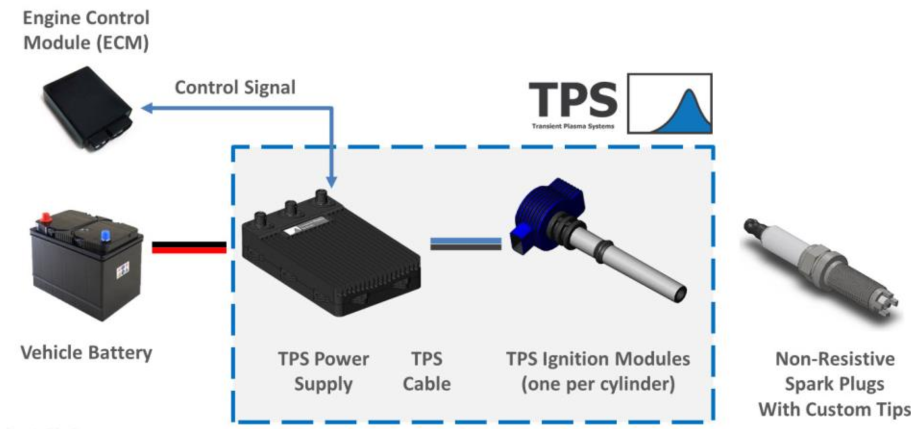

Figure 5 – Schematic of a concept for a low-energy non-thermal plasma ignition system. The system is targeted for OEM use in existing or future gasoline engines.

2 Ignition System

A prototype ignition module based on TPS's solid state, low-energy, high-peak power, nanosecond pulse technology was developed in a form factor similar to existing ignition technologies. The system produces pulses with 25 ns duration. It was bench tested up to 30 kV, 30 kHz burst pulse repetition rate (PRR), 20 pulses per burst with a duty cycle equivalent to 2400 RPM.

Figure 6 – TPS prototype ignition module TPS to demonstrate that the technology can be made as a retrofit solution in the form factor of existing ignition technology.

2.1 Ignition Module

The module, shown in Figure 6, was designed to house the switching components that produce the fast rising, high-voltage pulse, which produces the transient plasma inside the engine. It is referred to as a "coil-on-plug" form factor module because it was designed to replicate current state-of-the-art commercial ignition coils in order to demonstrate the feasibility of this technology as a drop-in substitute that is compatible with existing technology. The resulting prototype has not yet been optimized to maximize operating power density at temperatures present in the vicinity of the engine block and consequently, is larger than the state of the art commercial coil-on-plug ignition modules. An external controller was used to determine the number of pulses (1-20), the pulse repetition rate (1 kHz – 30 kHz), and the pulse amplitude and energy. The maximum energy per pulse the system was capable of delivering was less than 50 mJ. Maximum voltage was not used in the engine tests reported here. The energy per pulse delivered was less than 10 mJ at the 20 kV setting, resulting in approximately 200 mJ delivered in a 20 pulse burst. The system parameters are shown in Table 1.

Table 1 - Ignition Module Specifications

System Parameter	Specification
Max Peak Amplitude	30 kV
Pulse Duration	25 ns
Pulse Rise Time	10 ns
Max Pulse Repetition Rate	30 kHz
Max Pulses Per Burst	20
Max Burst Repetition Rate	20 Hz
Max Average Power Rating	50 W

2.2 Measurement

The short pulse duration (approximately 25 ns) makes real-time measurement of delivered pulse energy during engine operation somewhat challenging. A compact, high-bandwidth, high-impedance capacitive voltage probe was implemented in the ignition module, which provided real-time voltage measurement and was used to monitor peak voltage amplitude and wave shape during engine testing. The high frequency 3-dB point of the probe was above 150 MHz, providing adequate response time for the ~ 10 ns risetime of the pulse. The low frequency -3-dB point was 2 MHz, which resulted in a measured under-shoot on the fall-time of the waveform.

3 Experimental Setup

Experiments were carried out on a single-cylinder research engine, set up for steady-state operation. The engine is representative of GDI engines currently available on the market, with specifications listed in Table 2. More details about the engine can be found in [3]. The spark plug used is shown in Figure **7**.

Figure 7 - Modified spark plug. The base plug is a Brisk spark plug, the four-pronged tip was laser welded onto the shell to create four 1.5mm gaps.

Table 2 - Single-cylinder research engine specifications

Displacement	0.6 L
Bore	89.04 mm
Stroke	100.6 mm
Compression Ratio	12.1:1
Intake Valve Maximum Opening Position (MOP)	100°CA ATDC
Exhaust Valve Open/Close [°aTDC fired]	150/-350
Intake Valve Open/Close [°aTDC fired]	350/-140
Exhaust Valve MOP	255°CA ATDC
GDI Injector	6 hole, solenoid
Injection Pressure	150 bar
Spark Plug	Custom
Fuel	EPA Tier II EEE Gasoline

4 Results

Figure 8 shows a sweep of EGR dilution at 1500 RPM 5.6 bar IMEP. EGR extension was demonstrated compared to conventional ignition, which in this case was a production Ford EcoBoost coil that nominally delivers 75 mJ to a 0.8 mm gap NGK-R spark plug. The TPS system was set to deliver 20 kV, 20 pulses, delivered at 20 kHz. The

EGR limit was extended from around 20% for spark to 23% at the 3% COV_{IMEP} stability limit for the TPS system.

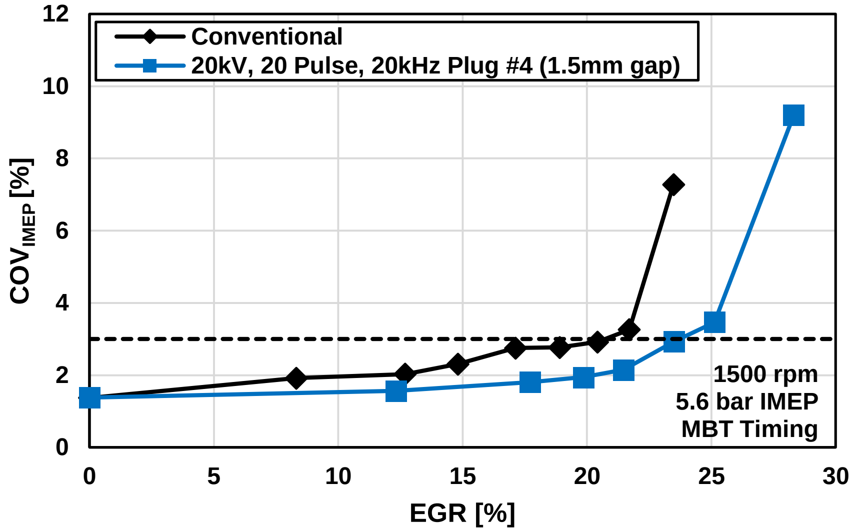

Figure 8 - EGR sweep comparing conventional ignition with compact TPS prototype ignition system at 1500 RPM, 5.6 bar IMEP.

The indicated thermal efficiency was measured to be very similar to conventional spark ignition, as seen in Figure 9. This is similar to previous results obtained in [3]. There, with respect to the conventional ignition system, the TPS system the low-energy transient plasma system allowed for an increase in EGR dilution, while maintaining ITE levels and marginally increasing losses associated with combustion.

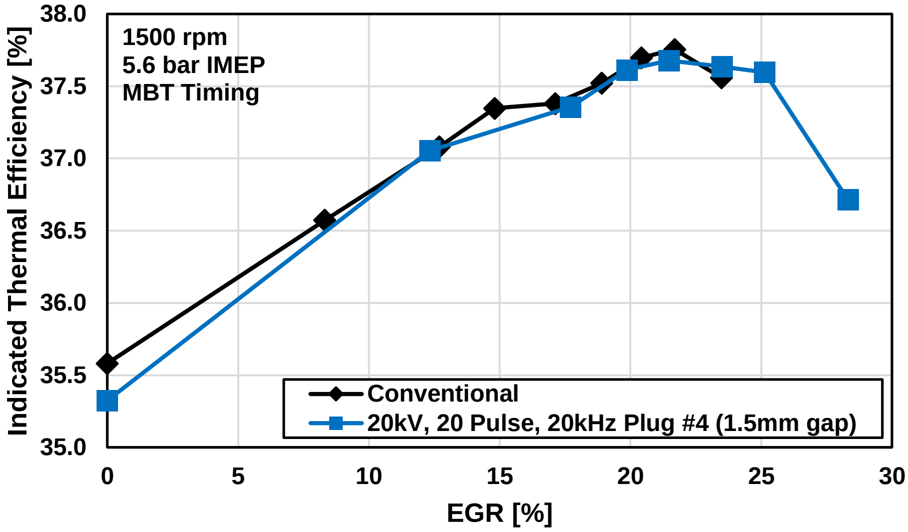

Figure 9 - EGR sweep comparing indicated thermal efficiency with conventional ignition and compact TPS prototype ignition system.

The flame development angle, or ignition delay, was shown to be faster with the TPS system compared to conventional ignition, as shown in Figure 10. This is expected due to the non-thermal plasma ignition chemistry, which decreases the time duration from early flame kernel to turbulent combustion, as shown by the decrease in flame development angle.

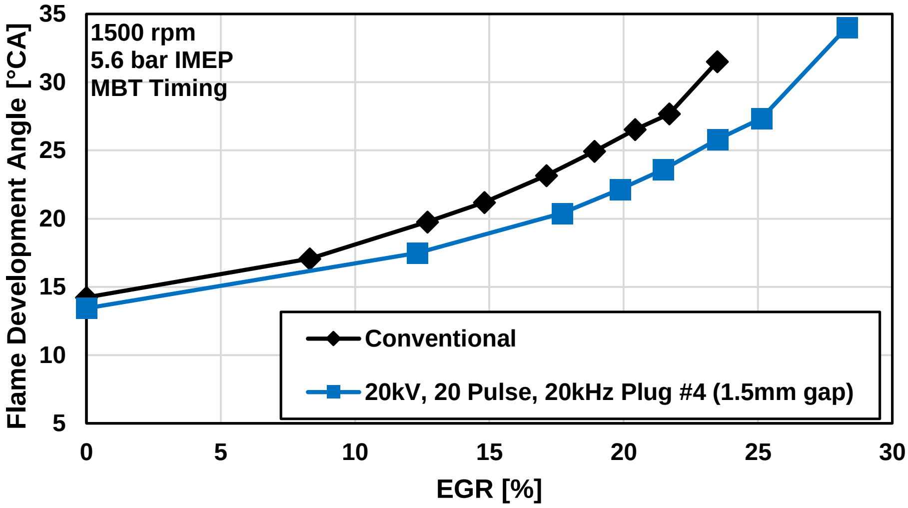

Figure 10 - EGR sweep comparing flame development angle with conventional ignition and compact TPS prototype ignition system.

Finally, the combustion duration was shown to be only slightly faster with the TPS system for a given EGR rate, as shown in Figure 11. This is expected since the heat-release rate during the main combustion phase is controlled by turbulent deflagration throughout the charge, with general turbulence levels not affected significantly by the ignition system. It can be noted that for both ignition systems, the combustion duration increases rapidly with increasing EGR rates, contributing to a reduction of thermal efficiency for EGR rates higher than 22% (Fig. 8). Some of the current design efforts in industry are aiming at maintaining short burn duration even at high EGR rates by the use of increased turbulence levels near top-dead-center (TDC) [13]. For such high-turbulence engines, the current TPS system is expected to provide higher thermal efficiency gains for operation with EGR, as compared to a conventional ignition system.

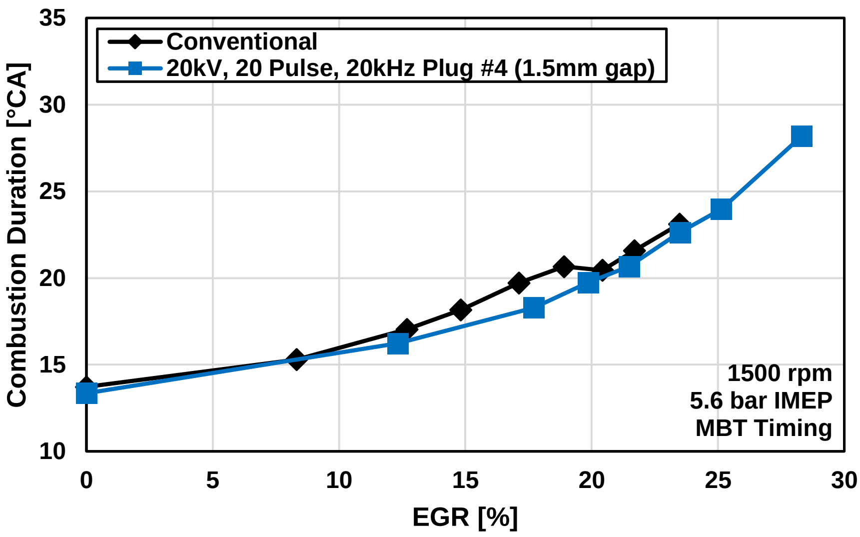

Figure 11 - EGR sweep comparing 10 – 90% combustion duration with conventional ignition and compact TPS prototype ignition system.

5 Discussion

An approach to a nanosecond pulsed power ignition system similar in form factor to existing ignition technology and therefore retrofittable to existing engines was developed and demonstrated on a single-cylinder engine. One way to benchmark this system is to compare the results to previously published engine test results in the same engine with a TPS lab bench research system [3], shown in Figure 12.

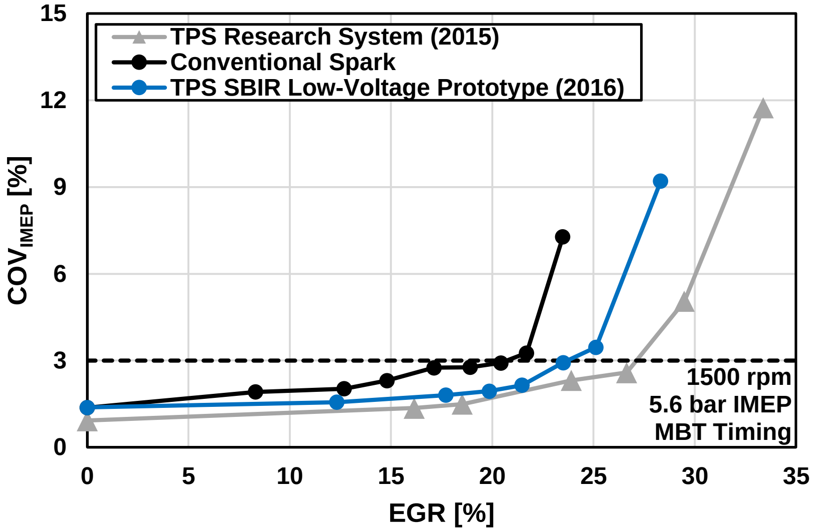

Figure 12 - Comparison of EGR extension using a 20 kV ignition module compared with a with 40 kV research system from **[3]**.

The performance of the new 20 kV prototype system is in between conventional spark, and the 40 kV TPS research system. There were several differences between the two systems, including pulse width, pulse amplitude, electrode gap, and electrode geometry, so it is not possible to point to one feature to explain the difference in performance. However, voltage likely played a significant role. It is well known that there is a relationship between the reduced electric field (E/n) and the density of radicals produced in the discharge available to enhance energy release. An increase in E/n beyond 300 Td does not significantly improve combustion, however, prior to that an increase of E/n significantly accelerates ignition development [14]. It is estimated that the peak voltage of the TPS SBIR system was delivering max E/n lower than 100 Td. Follow up work will include increased maximum voltage capability.

Another benefit of increased voltage is improved volumetric ignition. Increasing the gap size increased the system performance, until the voltage could no longer be increased to maintain the minimum reduced electric field necessary for ignition (Figure 13), which in this case, was 1.5 mm. The improvement in using a larger gap is likely due to the separation of multiple ignition sites.

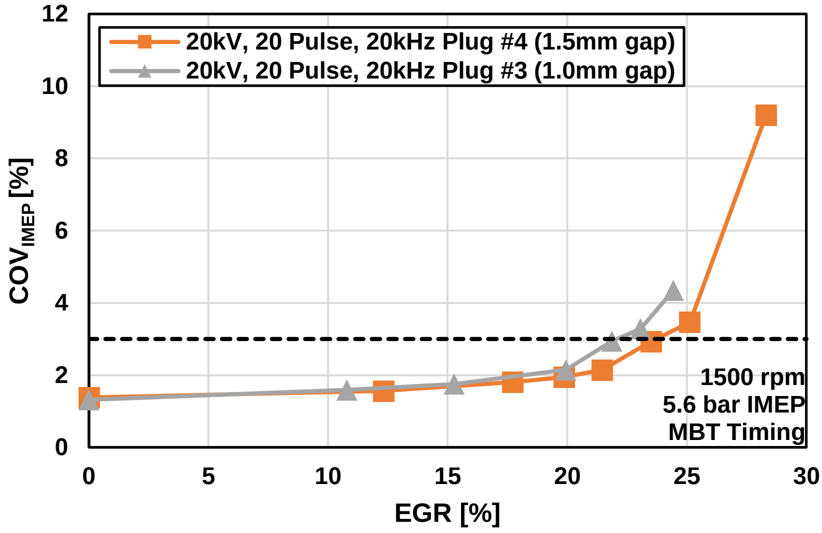

Figure 13 - EGR sweep with increasing spark plug gap.

6 Conclusion

A prototype low-energy nanosecond pulse based ignition system was developed and tested on a single-cylinder gasoline direct injected engine, demonstrating EGR extension compared to conventional spark ignition technology. This milestone marks the first time this nanosecond pulsed power system architecture similar to existing "coil-on-plug" form factor was developed and tested, critically moving the technology toward a "plug & play" solution. The system demonstrated stable combustion at an air/fuel ratio of 23.5, exhaust gas recirculation of 23%, and ignition at 19.2 bar with COV of IMEP < 3%. Future work will focus on the relationship between primary streamers, secondary streamers, and sparks with ignition, combustion, and spark plug lifetime.

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