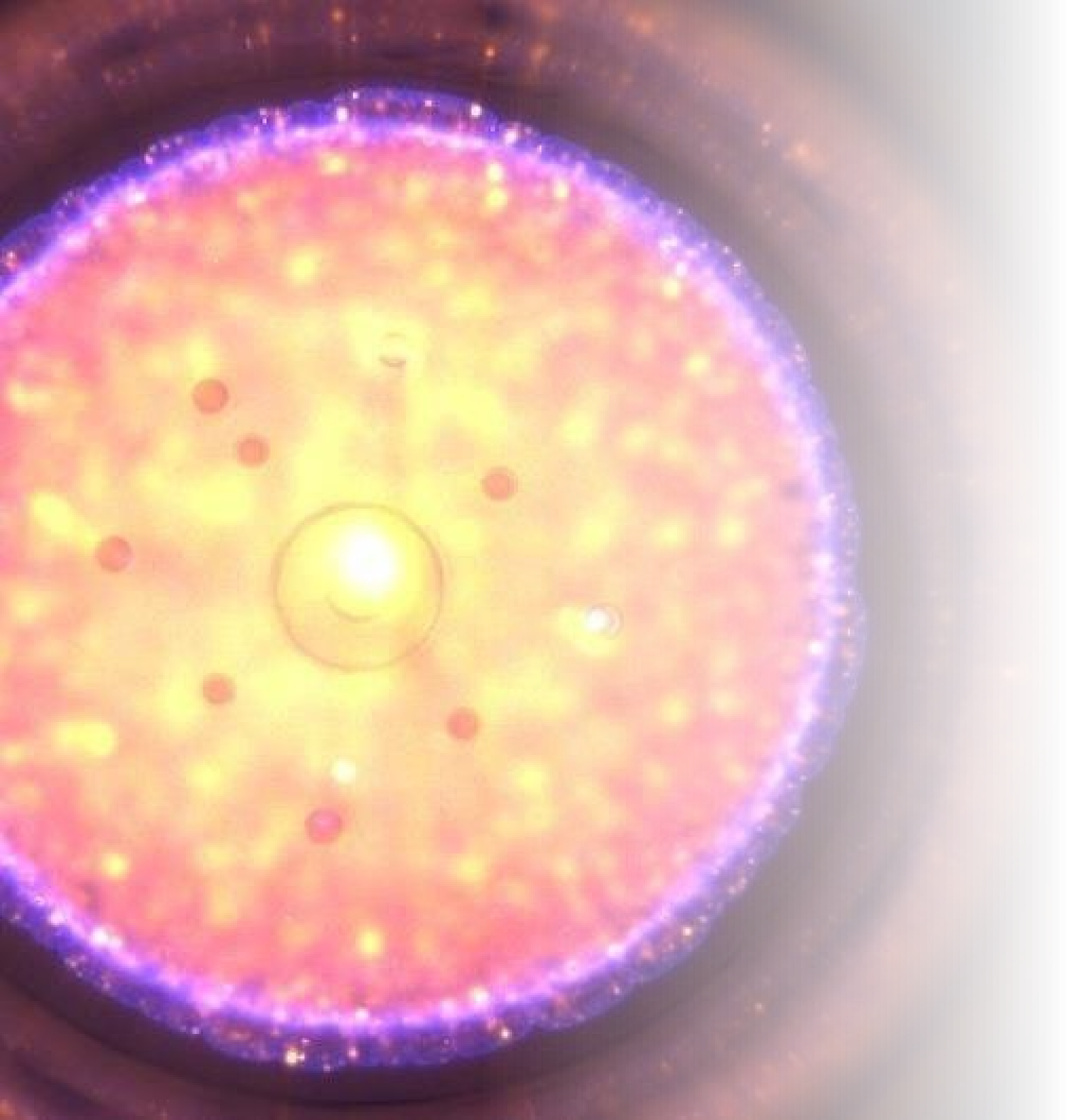


TRANSIENT PLASMA SYSTEMS

Final Project Presentation

NREL Subcontract No. AHQ-9-82305-08

A Multi-cylinder Transient Plasma Ignition System for Increased Efficiency and Reduced Emissions in Natural Gas Engines

Feb 1, 2023

Final Project Presentation ***Agenda***

Introduction

Project Approach

Project Results

Project Tasks

Conclusions

TPS ***Overview***

- Founded in 2009 as a new venture spin-out from USC
- Technology development firm based on **nanosecond pulsed power technology platform for emissions reduction and efficiency improvement**

FUNDING

Commercial (non-grant) Revenue

Government Grants:

NREL, US Departments of Energy and Defense, State of California

VC Investment: Series A

VISIBILITY

Peer reviewed publications in refereed journals

Panel presentations at conferences

Positive coverage from national and industry trade media (**links below**)

WIRED | Forbes | ars TECHNICA | Automotive News PACEpilot 2020 HONOREE | MOTORTREND | AUTOLINE | THE WALL STREET JOURNAL WSJ

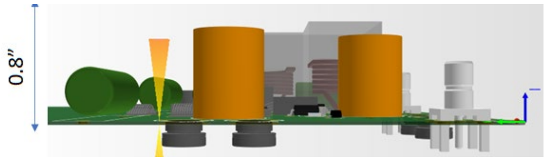
TPS’ Unique **Pulsed Power Technology**

Turning megawatts of power on and off in 1 billionth of a second is *hard*, the TPS team has decades of experience

- TPS is the only proprietary technology that solves the most challenging problems for commercial applications

Fast Switching | EMI | Size & Cost | Durability with a variable load

- The key to TPS technology is the ability to make very short pulses, which allows us to drive high-power loads



Project **Purpose**

- The primary goal of this project was to advance previously demonstrated transient plasma low-energy ignition technology toward a production system
- A production system that allows an increase in natural gas engine efficiency with minimal additional capital or operational costs improves competitiveness with diesel
- Increases to natural gas engine efficiency to be realized by extending dilute burn limits of the engine by using an advanced transient plasma ignition source developed by TPS
- Potential benefits of changing large portions of California's medium and heavy-duty truck fleet from diesel to natural gas using transient plasma ignition include:
    - Immediate reduction in greenhouse gas emissions
    - Significant reductions in imported oil
    - Significant reduction (90 percent) in PM in the exhaust
    - Higher engine efficiency

The Challenge **Market-Ready Advanced Ignition**

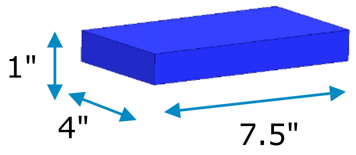
Advanced Ignition Systems

can unlock significant reduction in CO_2 yet none have been adopted

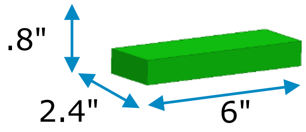
What's needed for mass adoption?

- *Extend current dilution limits*
- *Compact size with cost that matches benefit*
- *Transient performance*
- *Nominal load on battery power*
- *Seamless fit with engine architecture*
- *Spark plug lifetime*

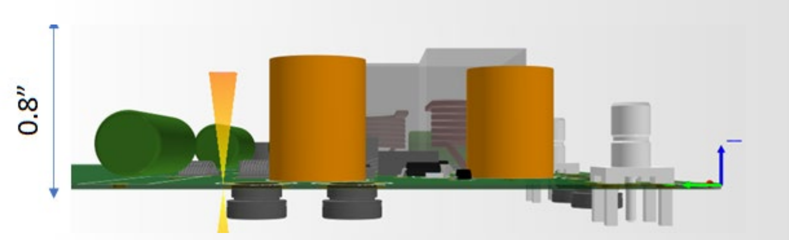
The Solution **Design of an Advanced Ignition System**



DC-DC Converter
for up to 6 Modules



Pulse Module
1 per igniter



- ***Extends current dilution limits***
- ***Compact size with cost that matches benefit***
- ***Transient performance***
- ***Nominal load on battery power***
- ***Seamless fit with engine architecture***
- ***Spark plug lifetime -*** Positive data but still need long term studies

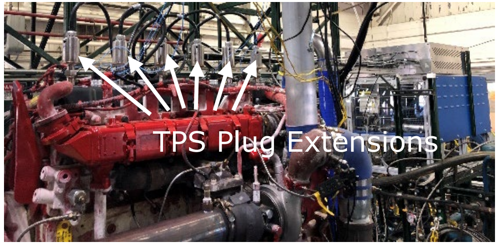
Project Overview **TPS Development**

NATIONAL RENEWABLE ENERGY LABORATORY

CEC Agreement

PIR-16-024

- Goal was to demonstrate multi-cylinder operation of the TPS ignition approach
- This was the first demonstration of multi-cylinder transient plasma ignition using solid-state hardware



Cummins ISX12N

NREL Agreement

AHQ-9-82305-08

- With lessons learned through development and testing during the CEC agreement and from **DOE Grant DE-SC0017880**, TPS formed a new approach to multi-cylinder ignition that would have the potential to meet cost and size targets necessary for a commercial system
- The result was not intended to be a commercial package, but the confirmation of an approach that has the potential to meet size and cost

Next Steps

Future Production System with Partner

- TPS, as a technology development firm, has taken the technology to the point where it could work with an engine technology manufacturer with deep experienced resources and infrastructure available to advance the technology through design validation and product testing.

Final Project Presentation ***Agenda***

Introduction

Project Approach

Project Results

Project Tasks

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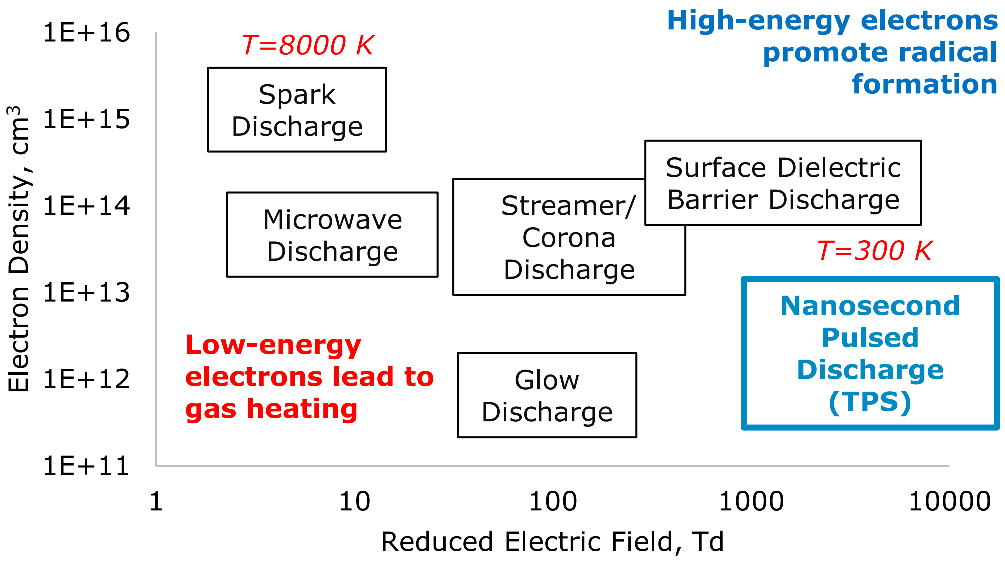
Project ***Approach***

- Determine nanosecond pulse parameters based on six-cylinder testing conducted at Argonne as part of a previous CEC funded effort (PIR-16-024)
- Design a pulse tracking sense and control method to enable "smart pulse train" operation that can adjust pulse parameters in real time based on discharge mode
- Miniaturize the six cylinder system that had been developed during previous CEC effort (PIR-16-024)
    - Redesign key component packaging and thermal management to increase power density and to enable hermetically sealed design
    - Design custom DC-DC converter for efficient operation from 12 VDC
- Test with Argonne National Lab to validate system performance

TPS Approach **vs Other Plasma**

Different types of plasma leads to changes in ignition mechanisms, with different tradeoffs (e.g. energy required, voltage required, electrode wear, etc)



Starikovskiy & Aleksandrov, Prog Energy & Combust Sci, 39, 2013.

Transient Plasma Ignition **Advantage**

Enhanced Chemistry

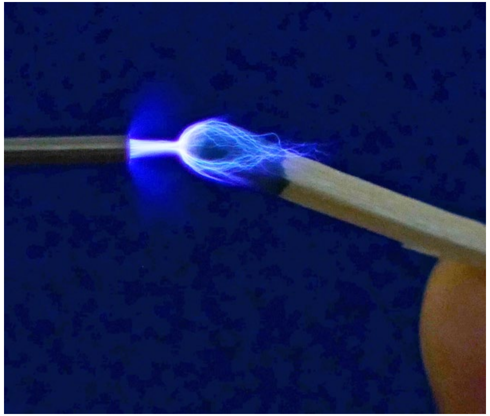
Electrons collide with the gas producing chemically reactive species which catalyze the combustion process, enhancing ignition and stabilizing lean burn combustion

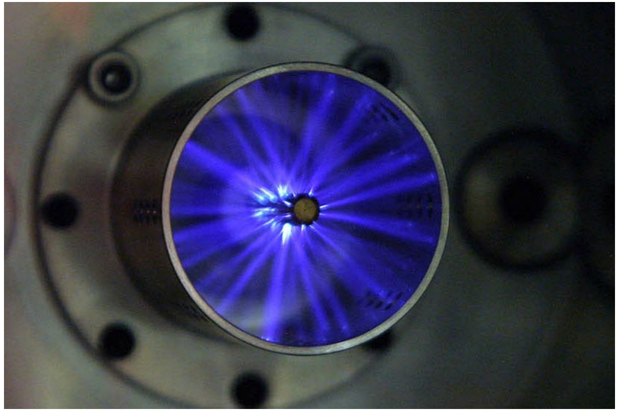
Volumetric Opportunity

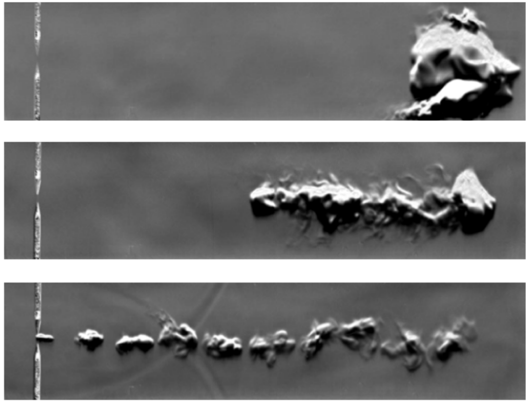
Spatial distribution of plasma enables a single streamer discharge to impact a large volume

Controlled Energy Delivery

Depositing energy at small precise amounts and rates to initiate strong flame propagation in challenging environments



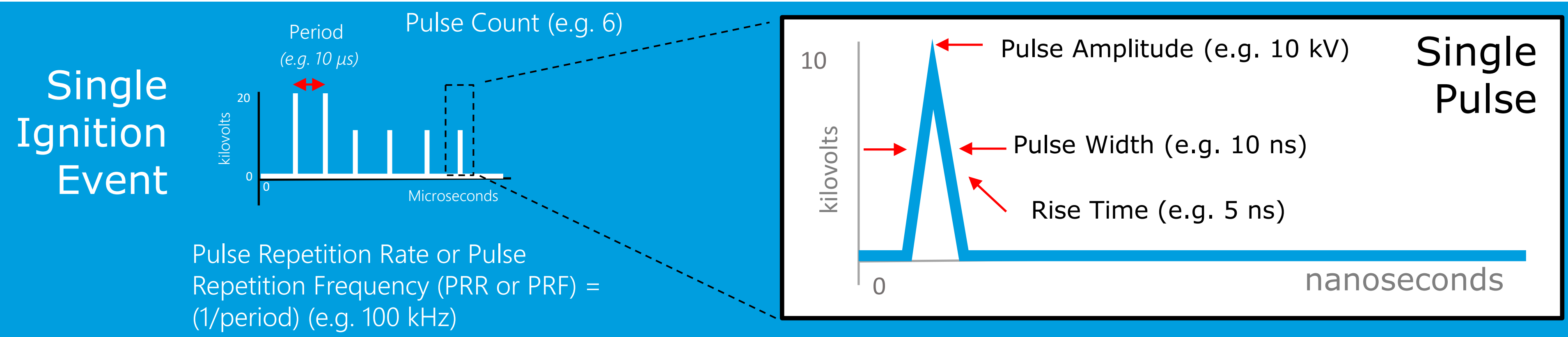




Demonstrated stable operation at: **λ>2, EGR>40%, ignition pressure >100 bar**

Ignition Event ***Examples & Terminology***

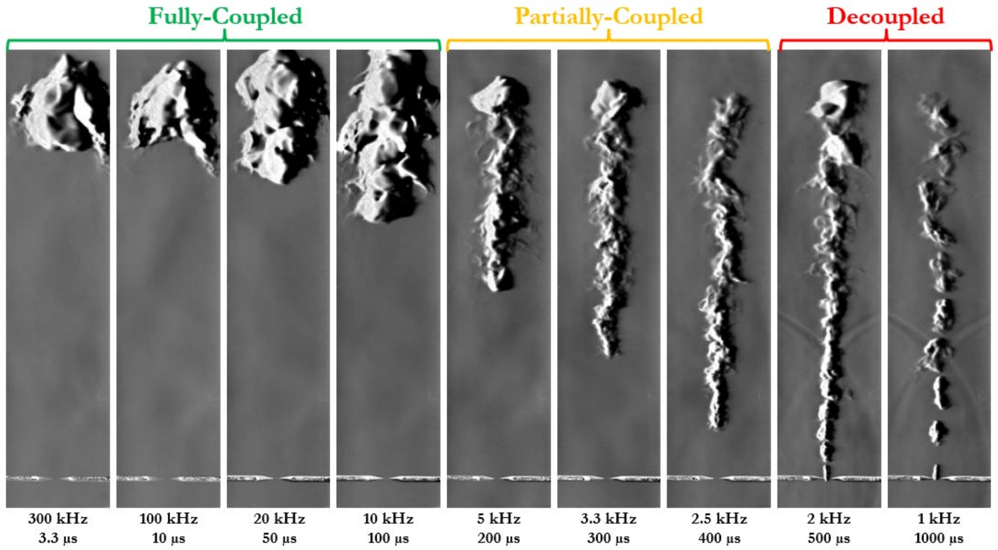
- In a single ignition event, the TPS ignition system delivers multiple (e.g. 1 to 200) nanoseconds (e.g. 10-15 ns) high-voltage (e.g. 5-40 kV) discharges at a high-repetition rate (e.g. hundreds of kHz)
  - **Pulses can also be run continuously in applications like gas turbines or other air breathing engines for continuous plasma assisted combustion**
- The TPS ignition system can modulate **pulse count**, **pulse amplitude**, and **pulse repetition rate** to minimize energy consumption and maximize combustion stability



Ignition Event ***Impact of PRR***

Effect of Time Scale of Energy Deposition
Fixed Total Energy and Varying Pulse Repetition Rate (PRR)

CH_4-Air, φ = 0.6, U = 10 m/s, D = 2 mm, and N = 20



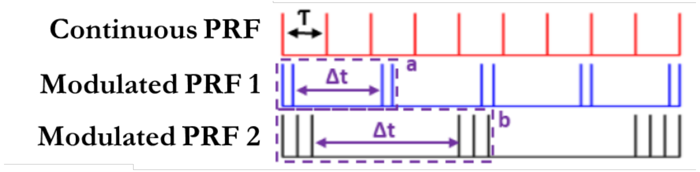
Timothy Ombrello, "Shifting the Paradigm of How Forced Ignition is Approached: Using Repetitive Pulsed Discharges to Interact with Critical Ignition Time Scales", AEROSPACE SYSTEMS DIRECTORATE, HIGH SPEED SYSTEMS DIVISION, 18 March 2020

DESCRIPTION

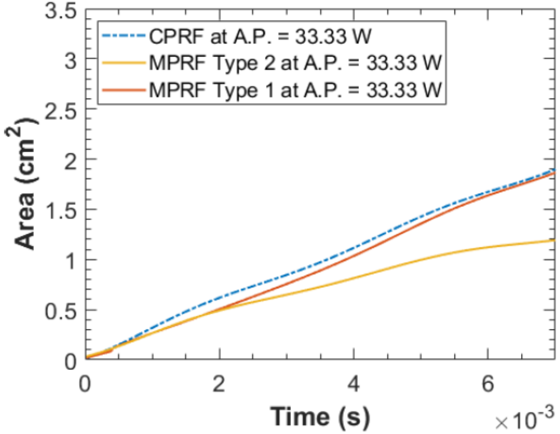
- **Ignition probability is dependent on PRR (inter-pulse time), not total energy deposition!**
  - That means the system size, cost and weight can be reduced as power requirements lessen
- Increasing power deposition rate (high PRR) is a superior method to ensure ignition vs adding energy
- Flame growth rate enhanced at low PRR (Opposite trend from ignition probability)
- Number of pulses (total energy) increases growth rate only at low PRR
- The above indicates optimization of PRR is critical to minimizing energy consumption

Ignition Event ***Impact of Power Modulation***

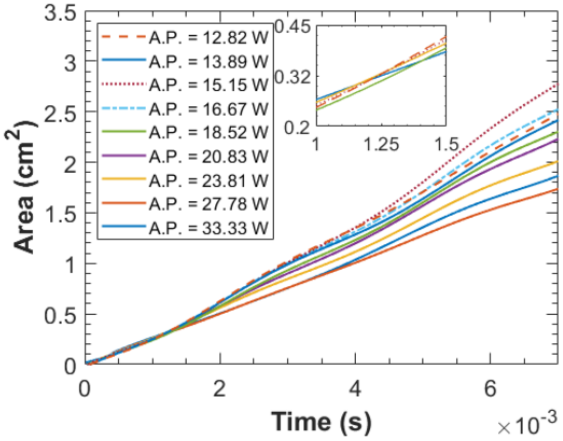
KERNEL GROWTH COMPARISON



Comparison of Flame Growth at Same Power



Comparison of Flame Growth at Different Power



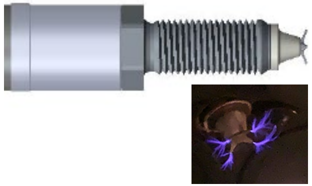
DESCRIPTION

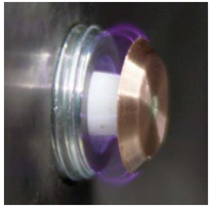
- **Better combustion stability can be achieved by *removing* energy at the right times**
- Continuous PRF kernel growth can be significantly enhanced with Modulated PRF 1
- 65% increase in kernel size with 40% lower power
- Again, this translates to reduced system size, cost and weight depending on the application

Timothy Ombrello, "Shifting the Paradigm of How Forced Ignition is Approached: Using Repetitive Pulsed Discharges to Interact with Critical Ignition Time Scales", AEROSPACE SYSTEMS DIRECTORATE, HIGH SPEED SYSTEMS DIVISION, 18 March 2020

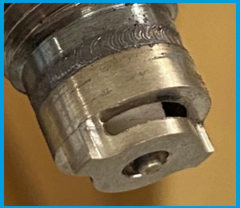
Ignition Event ***Impact of Electrode Design***

ELECTRODE DESIGNS





Design A



DESCRIPTION

- Spark gap geometry has significant impact on performance and power requirements
- The “best” design will depend on the application and requirements
  - E.g. Tradeoffs between maximum performance, energy requirements / system cost / lifetime, etc.
- The electrode best for natural gas vehicles (**Design A**) due to its lower power requirements

Final Project Presentation ***Agenda***

NATIONAL RENEWABLE ENERGY LABORATORY

Introduction

Project Approach

Project Results

Project Tasks

Conclusions

Project **Results**

- All of the bullet points listed in the previous Project Approach slide were addressed during this effort
- Highlights include successful development of a closed-loop, automated control system and plasma plug optimization that together have the potential to:
  - Extend spark plug lifetime
  - Reduce prime power consumption
  - Improve performance in dilute conditions
- Multiple versions of TPS nanosecond ignition systems were designed, built, and vetted
  - Miniaturized system was ultimately guided by work to optimize pulse train by means of control and plug optimization
- The system with closed loop control and new plug design was tested at Argonne

Final Project Presentation **Agenda**

Introduction

Project Approach

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Project Tasks

Conclusions

Project **Tasks**

Task 1 - Refine Pulse Parameters

Task 2 – Design and incorporate a pulse tracking feedback system

Task 3 – Miniaturize existing multi-cylinder prototype

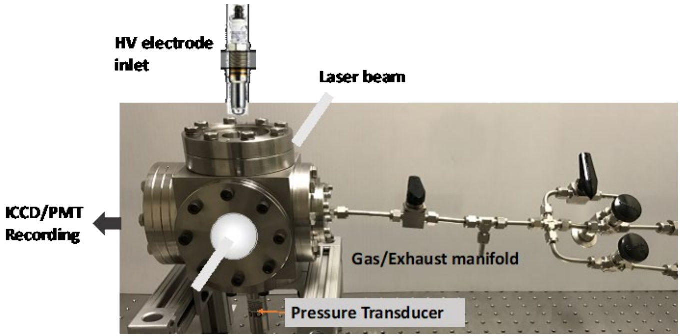
Task 4 – Redesign thermal management

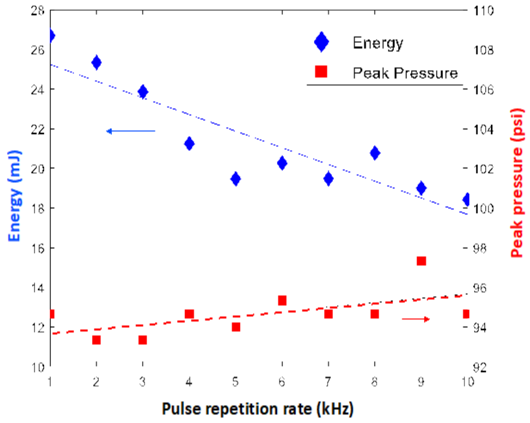
Task 5 – 12 VDC Compatibility

Task 6 – Validate performance

Task 1 **Determine target pulse parameters**

NREL
NATIONAL RENEWABLE ENERGY LABORATORY





- Initial pilot studies conducted in a static cell indicated that pulse repetition rate is an important parameter for reducing total energy required for ignition
- The goal then became to achieve the highest practical repetition rate, which was determined to be 100 kHz
- Additional work conducted throughout this effort on plug design further helped to reduce pulse energy required for ignition.

Pulse Parameter	Target Specification
Peak Voltage into 50 Ohm	20 kV
Pulse Duration (FWHM)	10 ns
Pulse Risetime (10-90%)	5-7 ns
Maximum Pulse Energy	75 mJ
Max Pulses per Burst	20
Pulse Repetition Rate	100 kHz

Project **Tasks**

~~Task 1 – Refine Pulse Parameters~~

Task 2 – Design and incorporate a pulse tracking feedback system

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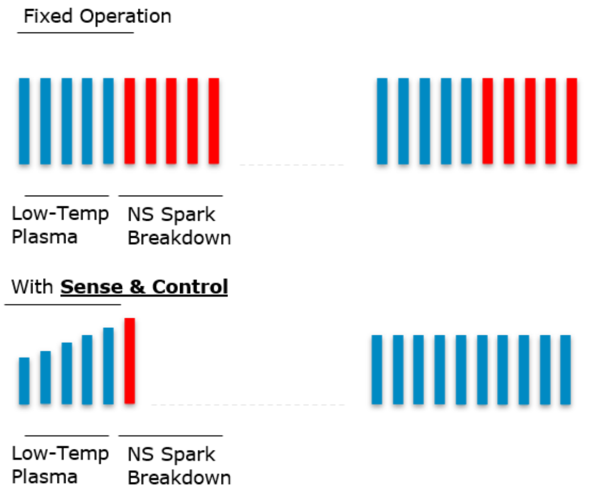
Task 6 – Validate performance

Task 2 ***Closed-Loop Control***

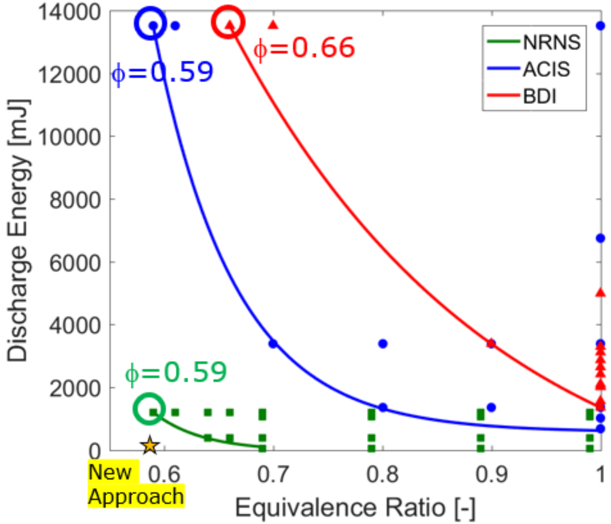
- Why used closed-loop control for ignition? Potential for:
    - Extending spark plug lifetime
    - Reducing prime power consumption
    - Improving performance in dilute conditions

- Our approach to a more automated, adaptive pulse train for ignition requires the integration of three main components:
    - Hardware and algorithm for sensing the discharge mode (i.e., no discharge, corona/glow plasma, or spark)
    - Hardware and algorithm for rapidly adjusting the output voltage of our pulser
    - Microcontroller for storing / executing the process

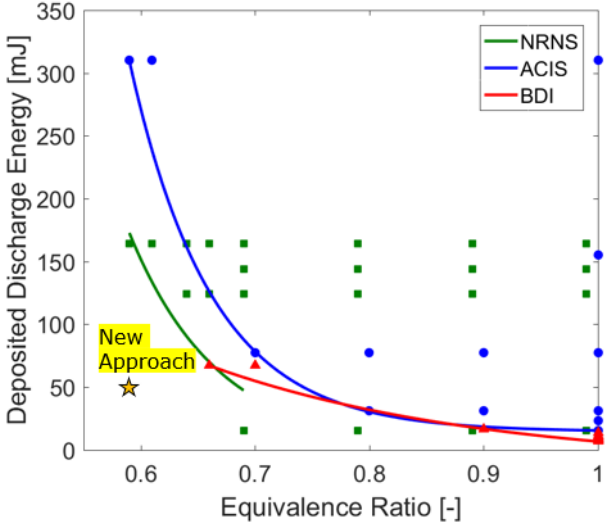


Task 2 Energy Efficiency with New Controls

Energy Required



Energy Deposited



Results showing reducing in energy required for new ignition approach. For comparison, the other data shown include measurements made using repetitive nanosecond pulses driving either (a) a j-gap spark plug geometry (NRNS), (b) a star-point geometry designed by Tenneco (ACIS), or (c) a custom plug with the center electrode encased in dielectric (BDI). Data taken with Isaac Ekoto at Sandia National Laboratories CRF.

Project ***Tasks***

~~Task 1 - Refine Pulse Parameters~~

~~Task 2 – Design and incorporate a pulse tracking feedback system~~

Task 3 – Miniaturize existing multi-cylinder prototype

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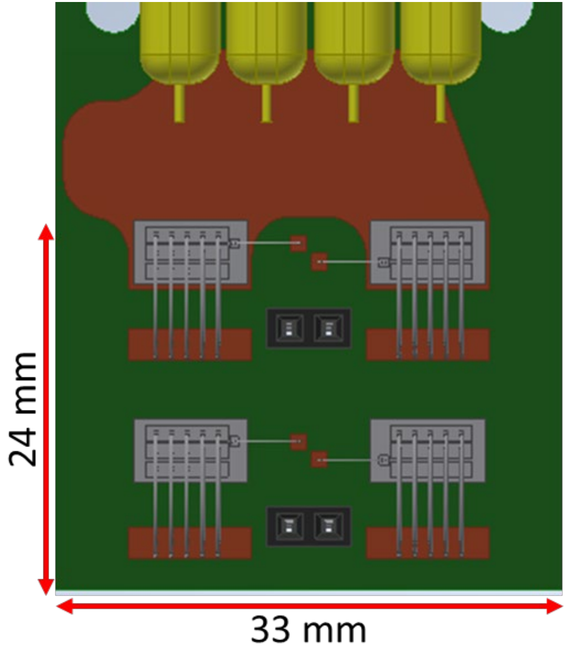
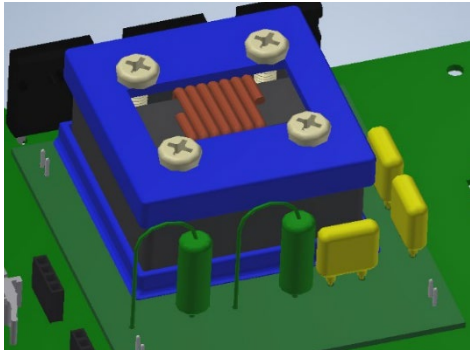
Task 6 – Validate performance

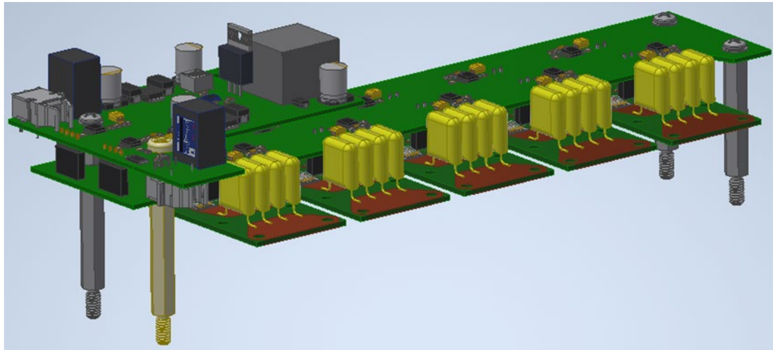
Task 3 **Reduce Overall Size**



Board with bare die and wire bonds; dimensions give the footprint for this chip-on-board approach



Inductor with mounting bracketry



Board to Board design method

- One approach to reducing system size is to increase the overall power density of the pulser through a variety of avenues:
  - Forego conventional device packaging and instead use bare die wirebonded to board (left)
  - Use dielectric oil not just for heat transfer but also for electrical insulation / high voltage hold-off
  - Direct to board inductor cores (top middle)
  - Board-to-board connections to help eliminate cable harnesses (top right)

Project **Tasks**

~~Task 1 - Refine Pulse Parameters~~

~~Task 2 – Design and incorporate a pulse tracking feedback system~~

~~Task 3 – Miniaturize existing multi-cylinder prototype~~

Task 4 – Redesign thermal management

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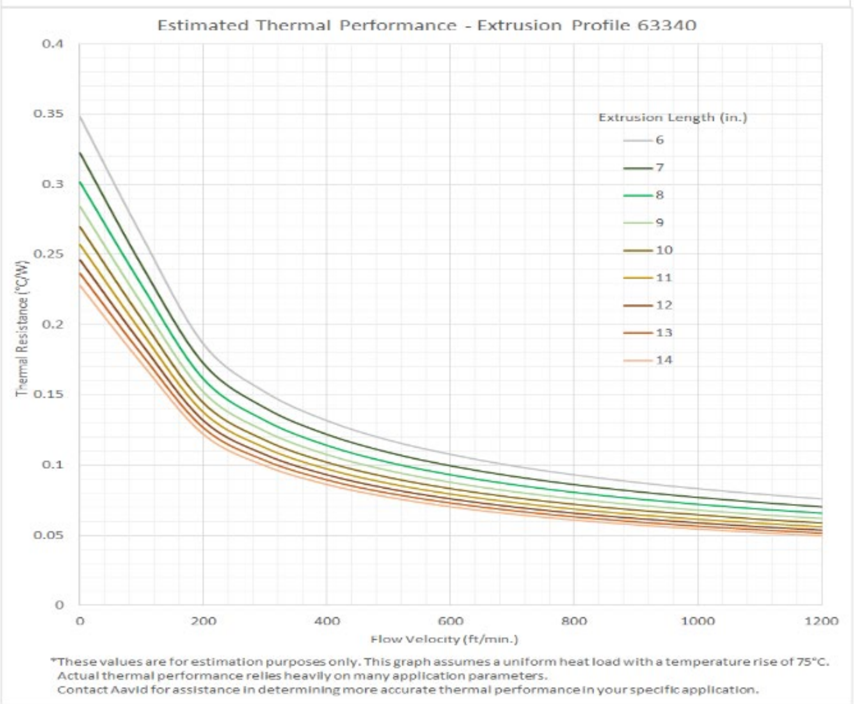
Task 6 – Validate performance

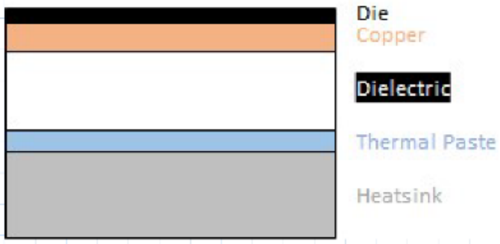
Task 4 **Thermal Design**



Thermal resistance curves as a function of flow rate provided by Aavid Thermalloy for extruded heatsink

- First-order model developed using MathCAD
- Purpose of model is to
  - Calculate device junction temperatures
  - Calculate ambient temperature of dielectric fluid for a given heat load
  - Evaluate potential thermal expansion mismatch issues that could occur
- Two approaches considered
  - Bulk heat transfer from devices to dielectric fluid to heat sinking surfaces
  - Bulk heat transfer from devices through ceramic mounting material to heat sink surface

Example cross-section for heatsinking strategy of mounting devices directly to heatsink via a ceramic insulator



Materials stackup from die to ambient

Project **Tasks**

~~Task 1 - Refine Pulse Parameters~~

~~Task 2 – Design and incorporate a pulse tracking feedback system~~

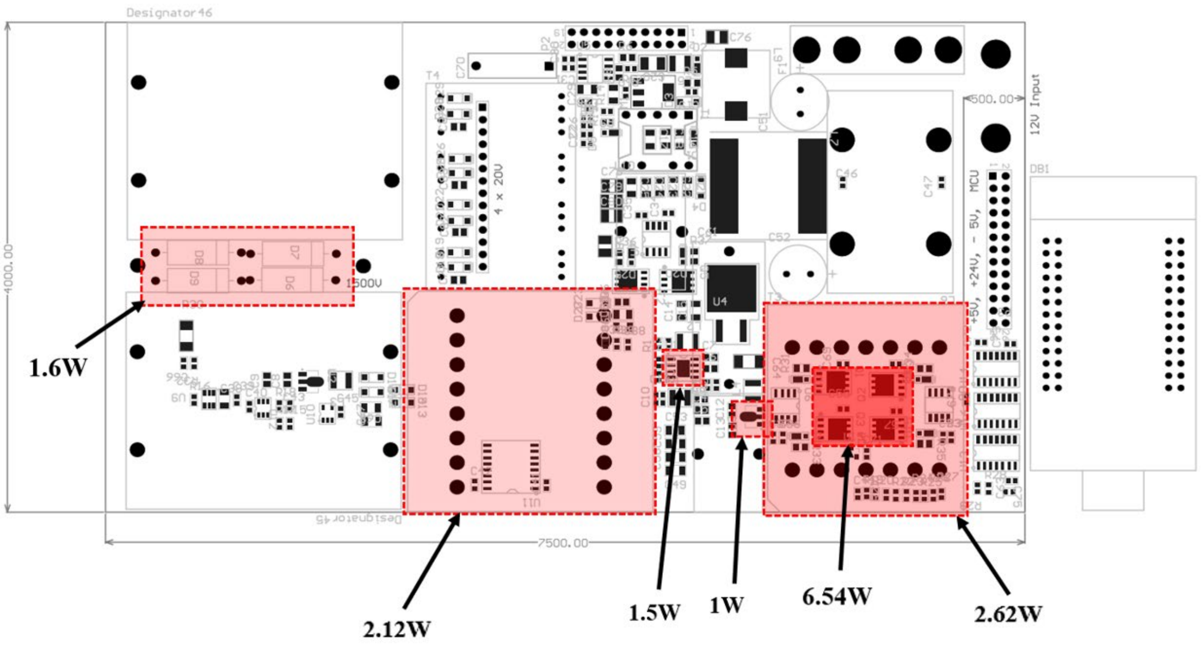
~~Task 3 – Miniaturize existing multi-cylinder prototype~~

~~Task 4 – Redesign thermal management~~

Task 5 – 12 VDC Compatibility

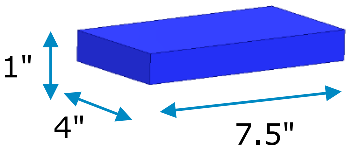
Task 6 – Validate performance

Task 5 **Final DC-DC Converter Footprint**

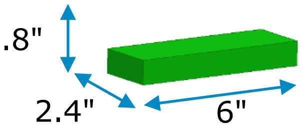


- A detailed design has been completed in Altium Designer and a complete bill of materials (BOM) has been generated
- Emphasis of this design is to hit a target BOM cost based on a cost analysis that TPS conducted with an outside consultant
- The BOM cost target has been met
- Preliminary parts placement (left) shows that the initial size target (4" x 7.5" is realizable
  - Heatsinking design from top layer to bottom layer of the PCB still must be considered and designed.

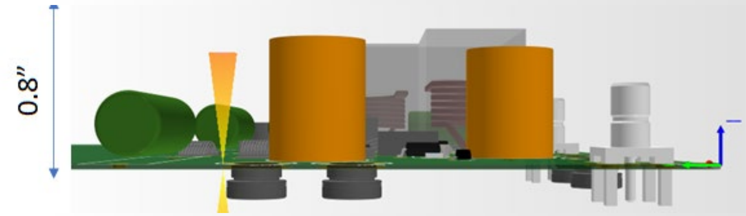
Final Design **Advanced Ignition System**



DC-DC Converter
for up to 6 Modules



Pulse Module
1 per igniter



- TPS designed and patented custom compact DC-DC converter
  - 95% efficient at max load
  - 400W, 12VDC input
  - Max output is 1500V
- TPS latest pulse module under development
  - Power electronics on 50 ohm card
  - Layout can be reconfigured
  - 100 kHz PRF, 10 kV output
  - 30 pulses max
  - 250W max average power
  - Automated precision control of break down voltage and energy delivery

Project **Tasks**

~~Task 1 – Refine Pulse Parameters~~

~~Task 2 – Design and incorporate a pulse tracking feedback system~~

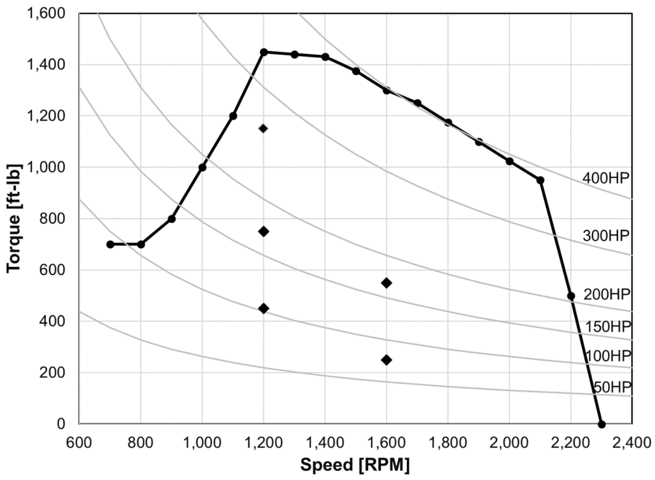
~~Task 3 – Miniaturize existing multi-cylinder prototype~~

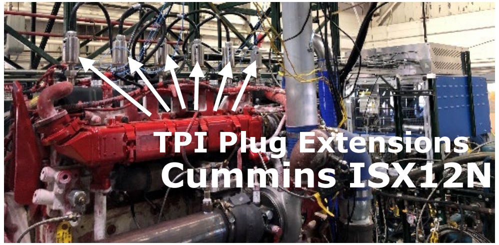
~~Task 4 – Redesign thermal management~~

~~Task 5 – 12 VDC Compatibility~~

Task 6 – Validate performance

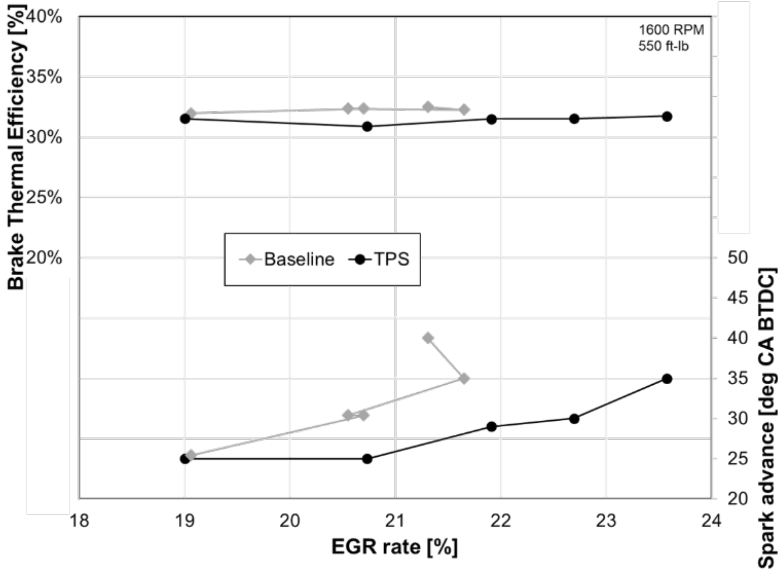
Task 6 **Validate Performance**

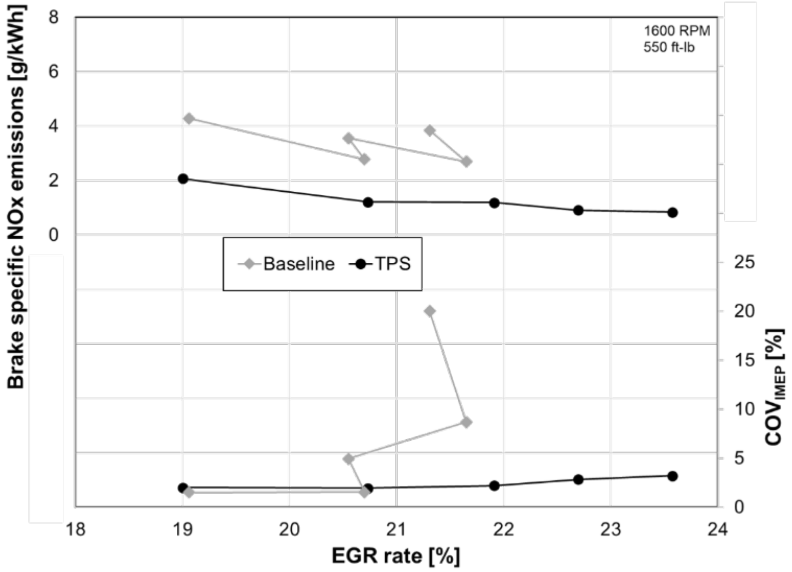




- The primary goal of the engine test is to confirm that we still see EGR extension with the new system architecture
- During the prior test run under the CEC Agreement (PIR-16-024), we were unable to run the high-load point shown left due to a voltage limit
- A secondary goal was to be able to run all points
- **Both goals were achieved**

Task 6 **Engine Test Results**





- Able to run all load and speed points
- Saw EGR extension with this hardware configuration
  - Did not have sufficient time to adjust pulse parameters and ignition timing to improve BTE (1 day of testing) but expect that would have been possible as with the previous test

Final Project Presentation ***Agenda***

Key Considerations

- The Transient Ignition Module architecture that was developed during the initial CEC effort was shown to perform well and to extend stable dilute burn operation, but there are challenges with achieving size and cost targets required for commercial adoption
- A new architecture was implemented as part of this effort to achieve size and cost targets and pulse sense and control and spark plug design enabled efficient operation at all load and speed points
- Engine testing was extremely limited since most of the testing budget went into upgrading the air system at Argonne National Laboratories
  - TPS paid extra cost share to ensure minimum engine testing
- **The result of this grant is a design – further funding is needed to build and test**

Conclusions

- The design of a transient plasma ignition system that has the potential to meet size, cost and performance targets required of a natural gas engine manufacturer looking for and advanced ignition solution.

- TPS, as a technology development firm, has taken the technology to the point where it could work with an engine technology manufacturer with deep experienced resources and infrastructure available to advance the technology through design validation and product testing.

Recent accomplishments

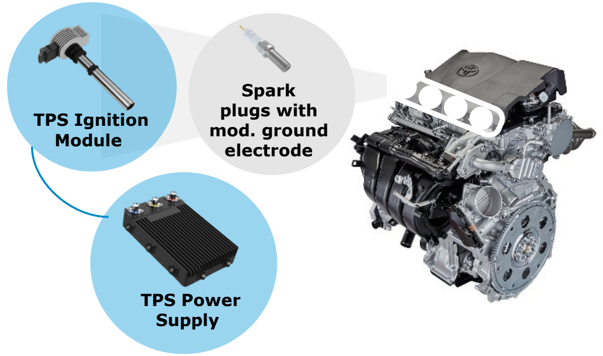
NATIONAL RENEWABLE ENERGY LABORATORY

Testing on the most efficient production car engine

- Conducted tests of the TPS ignition system with FEV on the 2021 Toyota 2.5L I-4 LE engine in a test cell at FEV North America in April 2022

- Majority of the engines produced will still be gasoline and hybrids through 2035.
- TPS's solution is critical to avoiding global CO_2 levels beyond the Paris Climate Agreement target by bridging the gap to a possible EV future with immediate application to late model spark ignited engines with EGR to reduce CO_2 emissions.

Ignition technology setup diagram



6.1% Maximum improvement in fuel economy

10 Watts Approximate average power needed

0 Hardware changes to engine

Ignition performance claims

1. **>20% improvement in fuel efficiency at highway conditions**
2. **>10% improvement in fuel efficiency across the drive cycle**
3. **>6% improvement in fuel efficiency on a stock engine with no hardware changes**
4. **~25% improvement in fuel efficiency across the drive cycle possible with new engine design**

TRANSIENT
PLASMA
SYSTEMS

1751 Torrance Blvd, Torrance, CA 90501 USA

transientplasmasystems.com