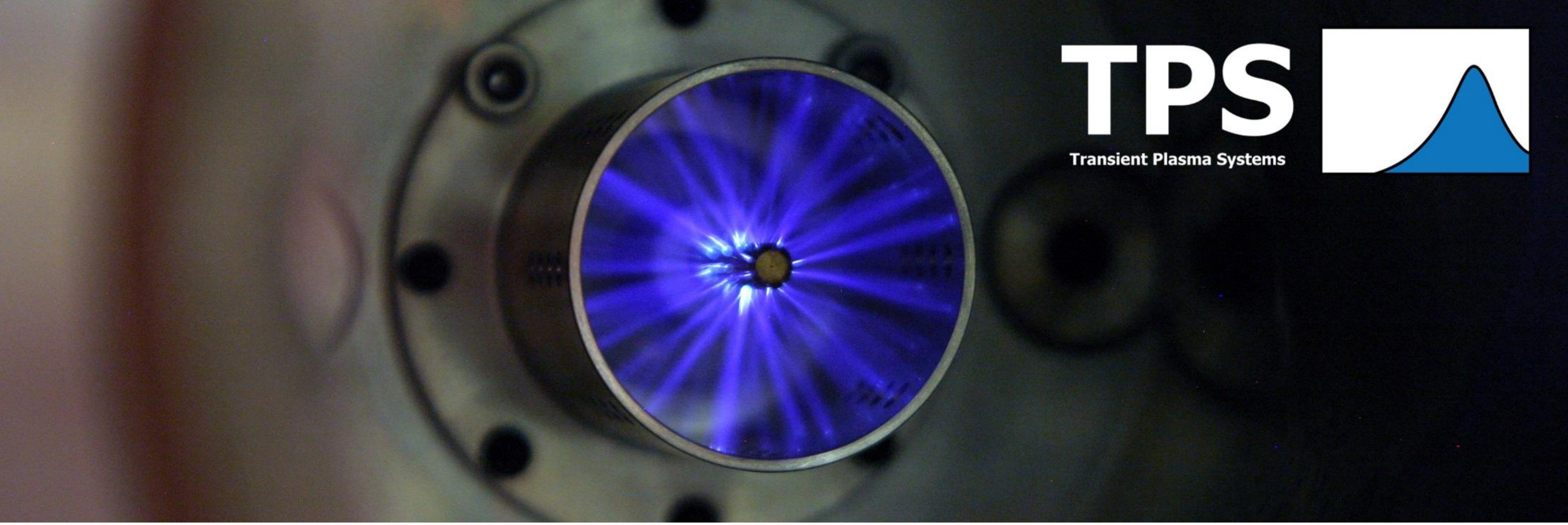


Transient Plasma Ignition System for Natural Gas Engines

CEC PIR-16-024

Cummins Westport

Natural Gas Vehicle Technology Forum
February 22, 11:00 am

www.transientplasmasystems.com

Argonne National Laboratory

1751 Torrance Blvd, Torrance, CA 90501

State of California Energy Commission

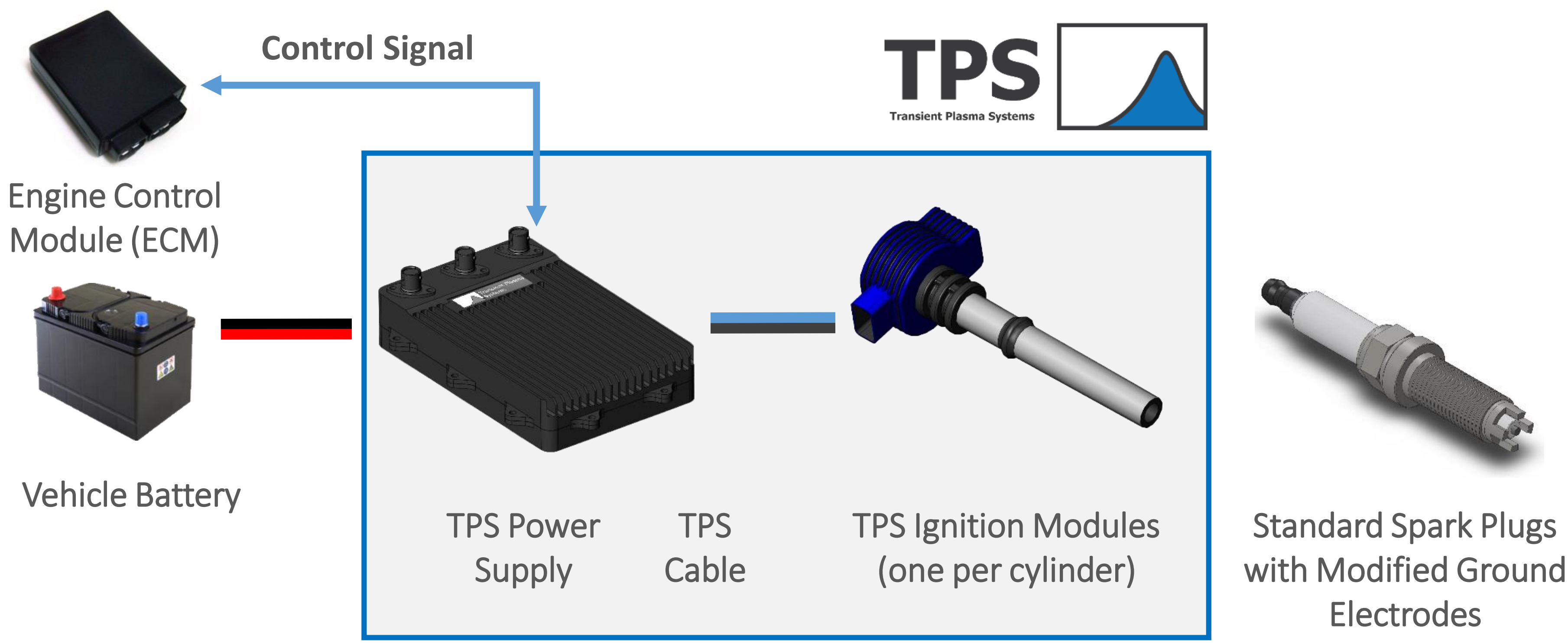
U.S. Department of Energy

TPS Technology Development

TPS ignition approach is based on nanosecond pulses

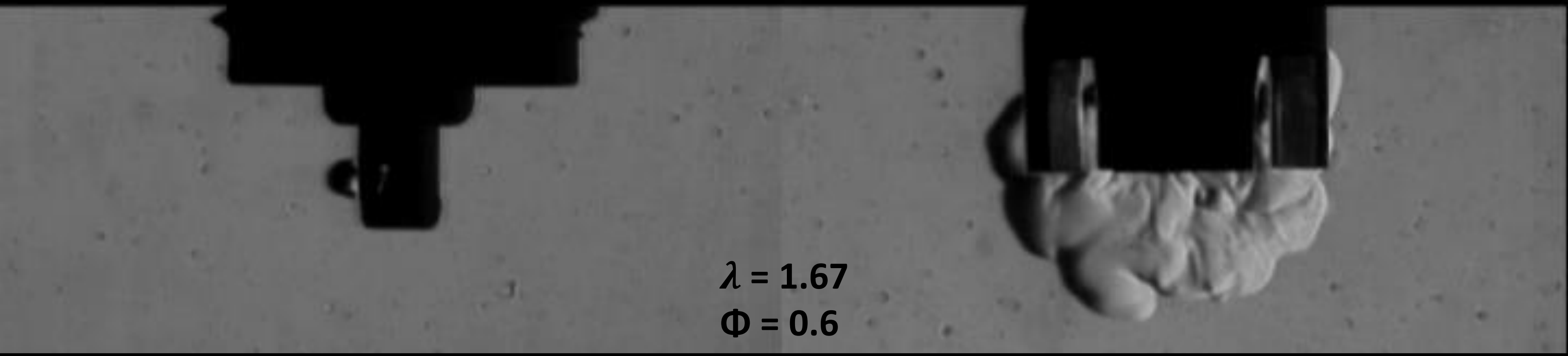
- Fundamentally different physics from other plasma ignition systems
- Less energy than high-energy spark or dual-spark for longer spark plug lifetime
- TPS is developing a direct plug & play replacement for coil-on-plug

TPS Ignition System Concept:



TPS Ignition

Demonstration of Lean Combustion



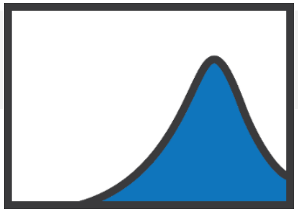
Currently Used Technology
Spark Ignition

New TPS Technology
Transient Plasma Ignition

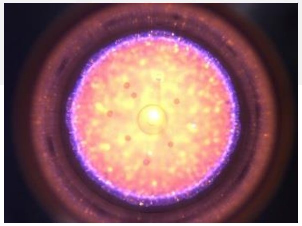
D. I. Pineda, B. Wolk, T. Sennott, J. Chen, R. W. Dibble, and D. Singleton, "Nanosecond Pulsed Discharge in a Lean Methane-Air Mixture," in Laser Ignition Conference, OSA Technical Digest (online) (Optical Society of America, 2015), paper T5A.2.

Agenda

- Transient Plasma Systems
  - History
  - Team and traction

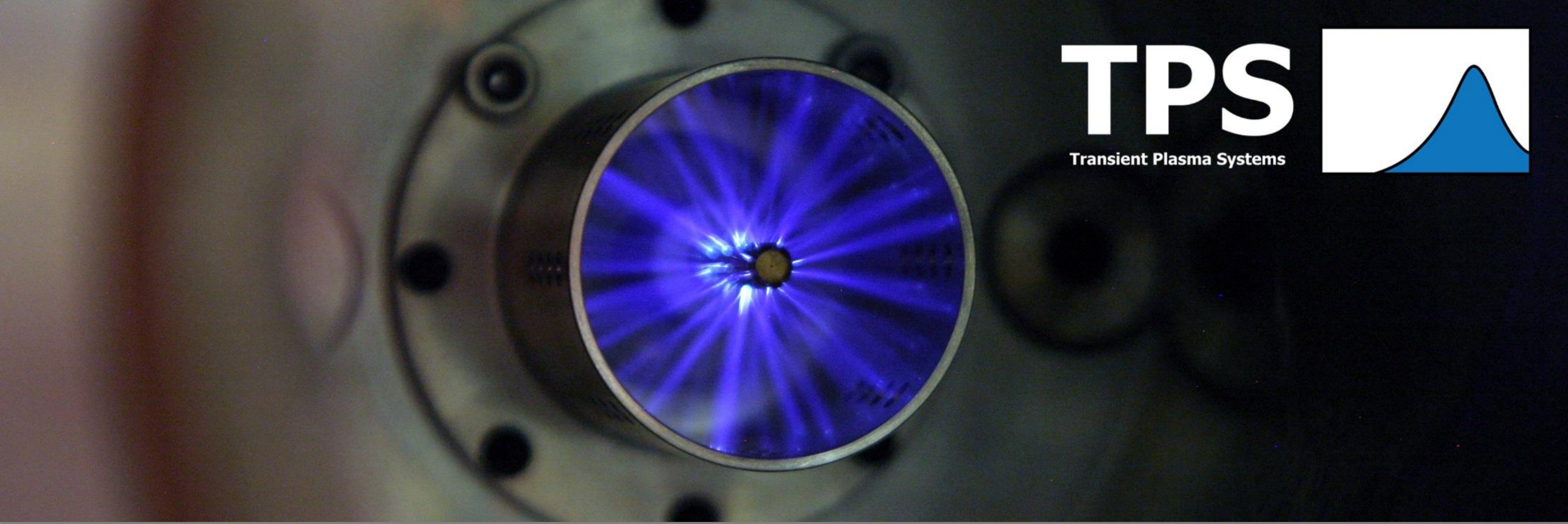


- Transient Plasma Ignition
  - Nanosecond pulses
  - Transient plasma ignition chemistry
  - Comparison to other approaches



- Engine testing
  - Natural gas and gasoline single cylinder engines
  - Key questions remaining
  - CEC Project – Multi-cylinder engine testing

- Overview
  - Additional application – Emissions Treatment
  - Summary

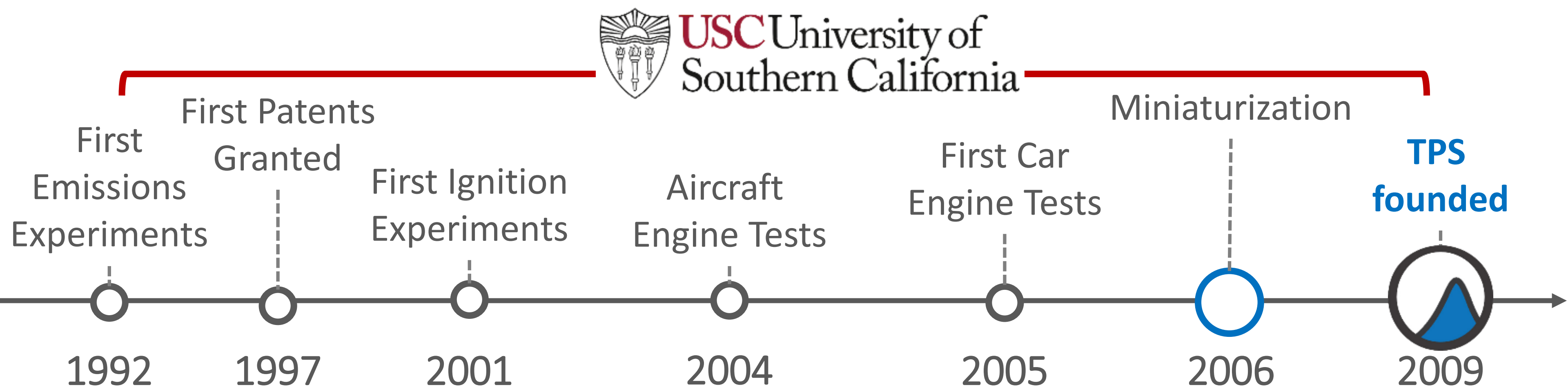


Transient Plasma Systems

- History
- Team and Traction

TPS Background

- TPS core technology is proprietary nanosecond high-voltage pulsed power
- TPS was founded in 2009 by researchers from Prof. Martin Gundersen's group at USC based on technological breakthroughs reducing the size and cost of nanosecond pulsed power systems



Management Team & Traction

TPS founded — 2009

2013 — Development project with Aerospace Companies

3rd Party Validation At Sandia National Labs

2014 — Development project for ignition systems. TPS leaves the garage for an office and hires first employees.

Key Papers Published from Validations

2015 — Strategic Partnerships Formed with Engine Manufacturers

2016 — $1M DOE Grant Awarded

2017 — $1M CEC Grant Awarded Venture Capital Investment

Founding Team

Dan Singleton Ph.D.
CEO

- Startup CEO experience
- Subject-matter

Jason Sanders Ph.D.
Chief Research Scientist

- Subject-matter expert
- Award winning leader in the field

Andy Kuthi Ph.D.
Advisor

- 20+ years experience in the field
- 30+ patents, published 30+ papers

Martin Gundersen Ph.D.
Advisor

- World leader in field
- 30+ years experience
- 350+ published papers

University of Southern California

Board

Michael Mann Ph.D.

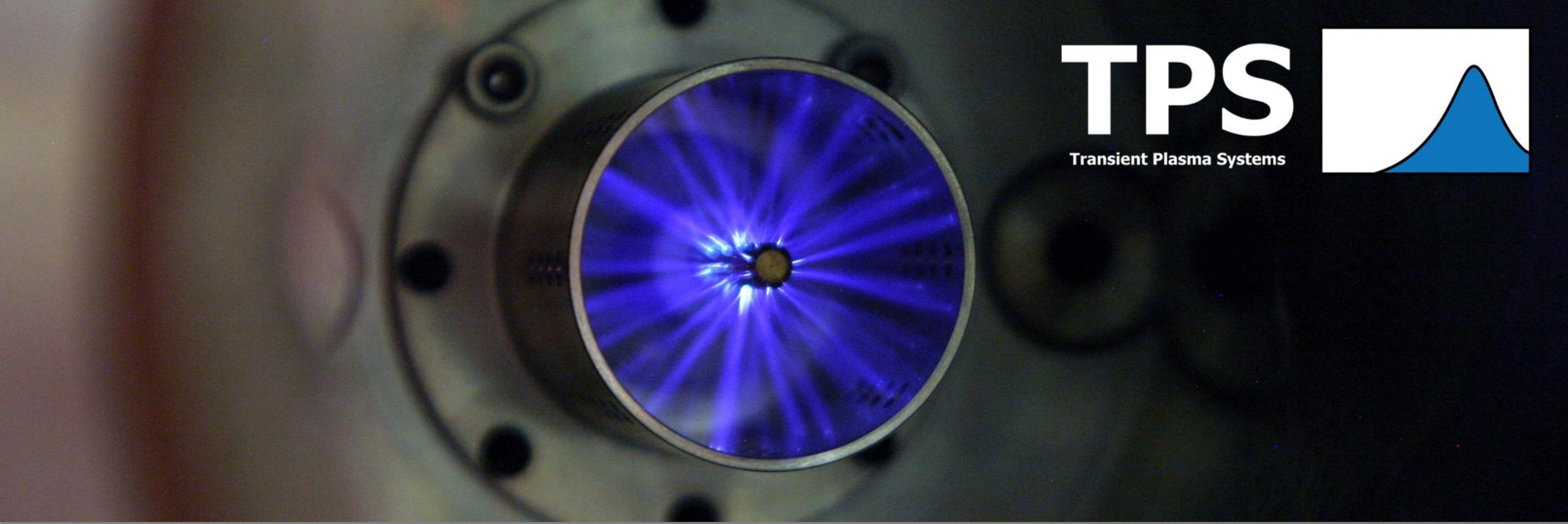
- Strategic management of technology expert
- Former Senior Executive at Northrop Grumman
- Formerly CEO of both public and private companies

Mario Leone

- Automotive industry expert
- Business development expert
- Senior Executive at both an OEM and Tier 1 supplier

Hoshi Printer

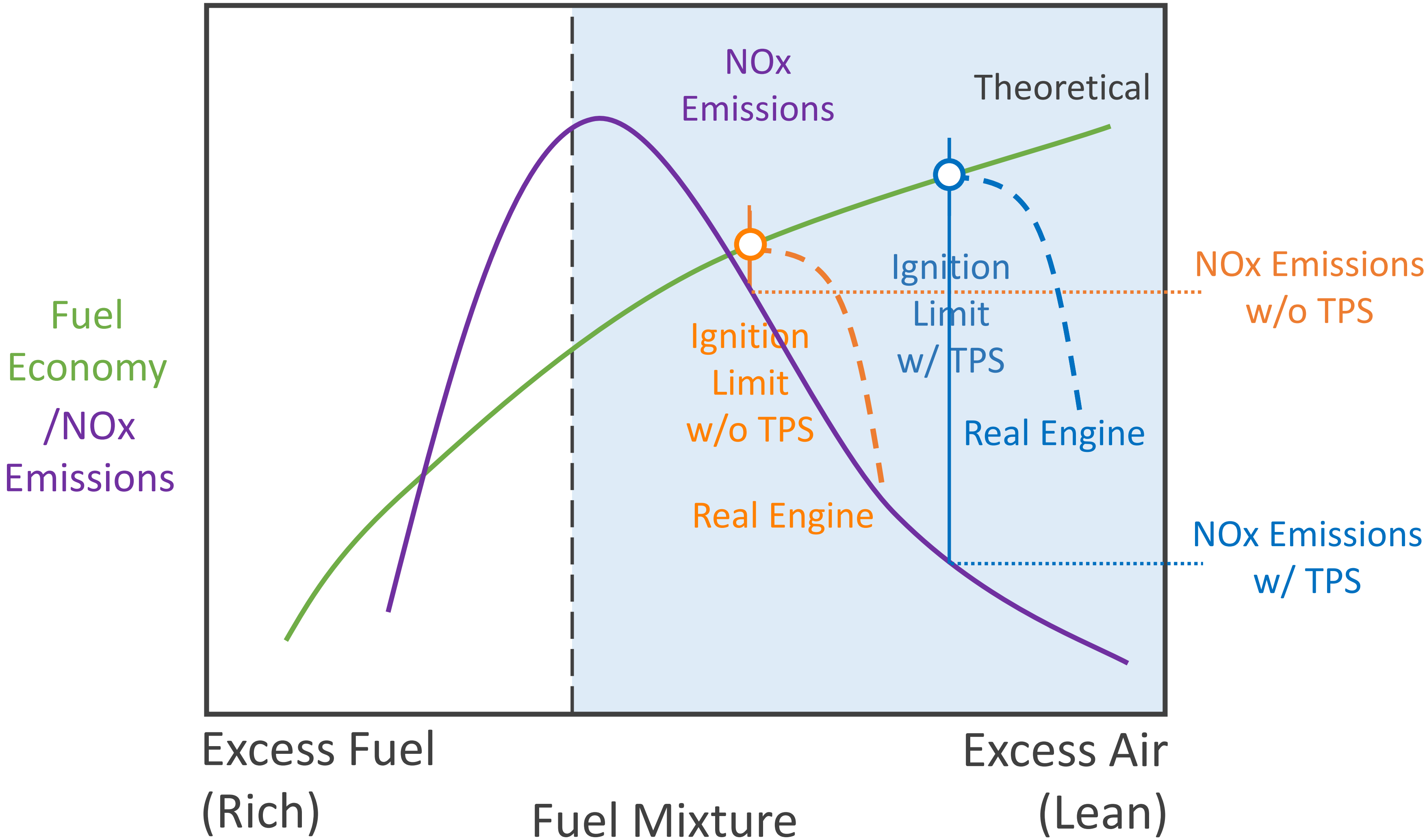
- Financial expert
- Corporate governance
- Former VP of Finance from Xerox
- Decades of experience as a CFO for over 10 technology companies



Transient Plasma Ignition

- Dilute combustion benefits
- Transient plasma ignition chemistry
- Comparison to other approaches

TPS Tech Enables More Efficient Combustion



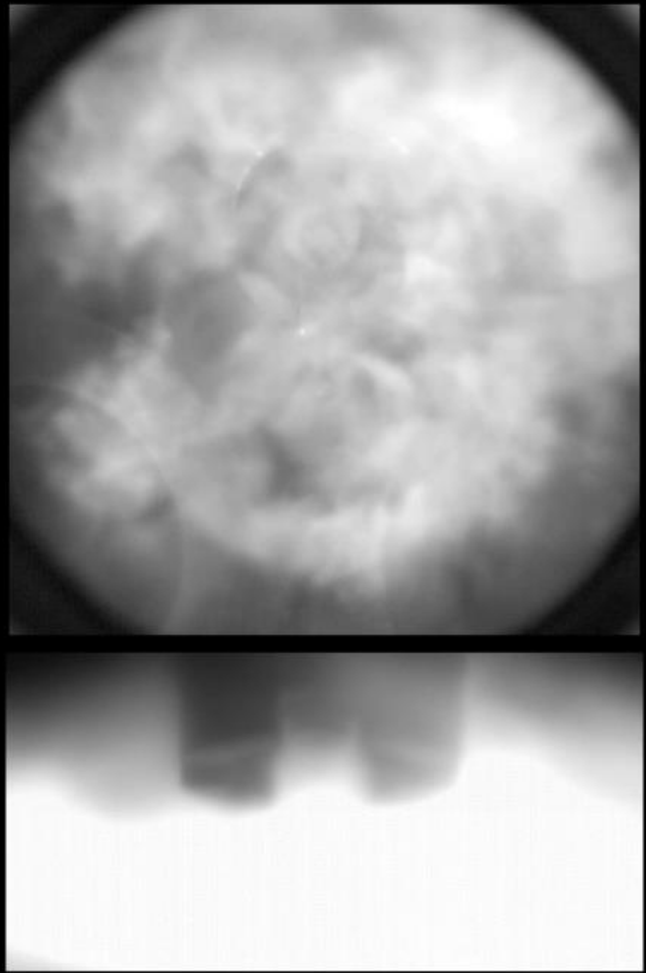
K. Packham, "Lean-burn engine technology increases efficiency, reduces NOx emissions," Power topic #7009, Technical information from Cummins Power Generation

In Engine Validation at Sandia National Labs CRF

20,000 frames/sec

Time Elapsed: 15 ms

λ = 1.33
Φ = 0.75



Spark Ignition

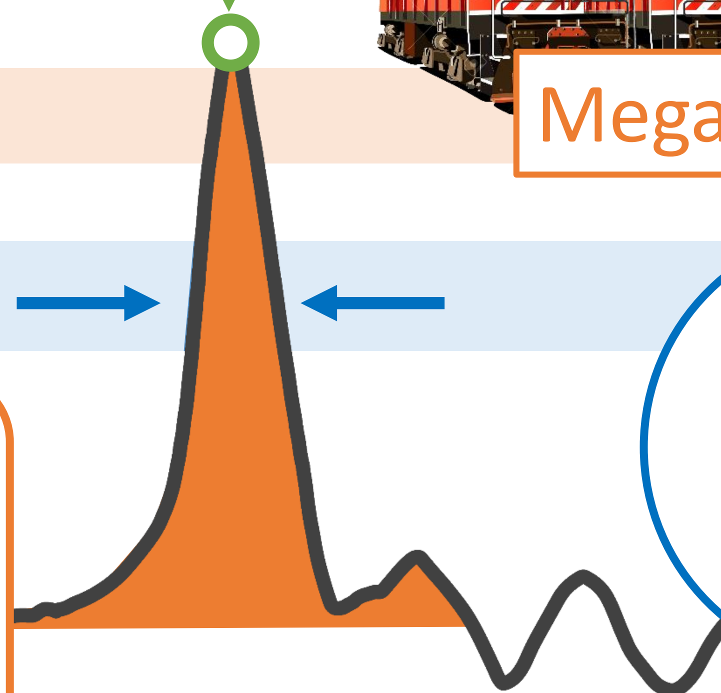
TPS Ignition

TPS Uses Short Pulses

Up to 40,000 Volts

Megawatts power

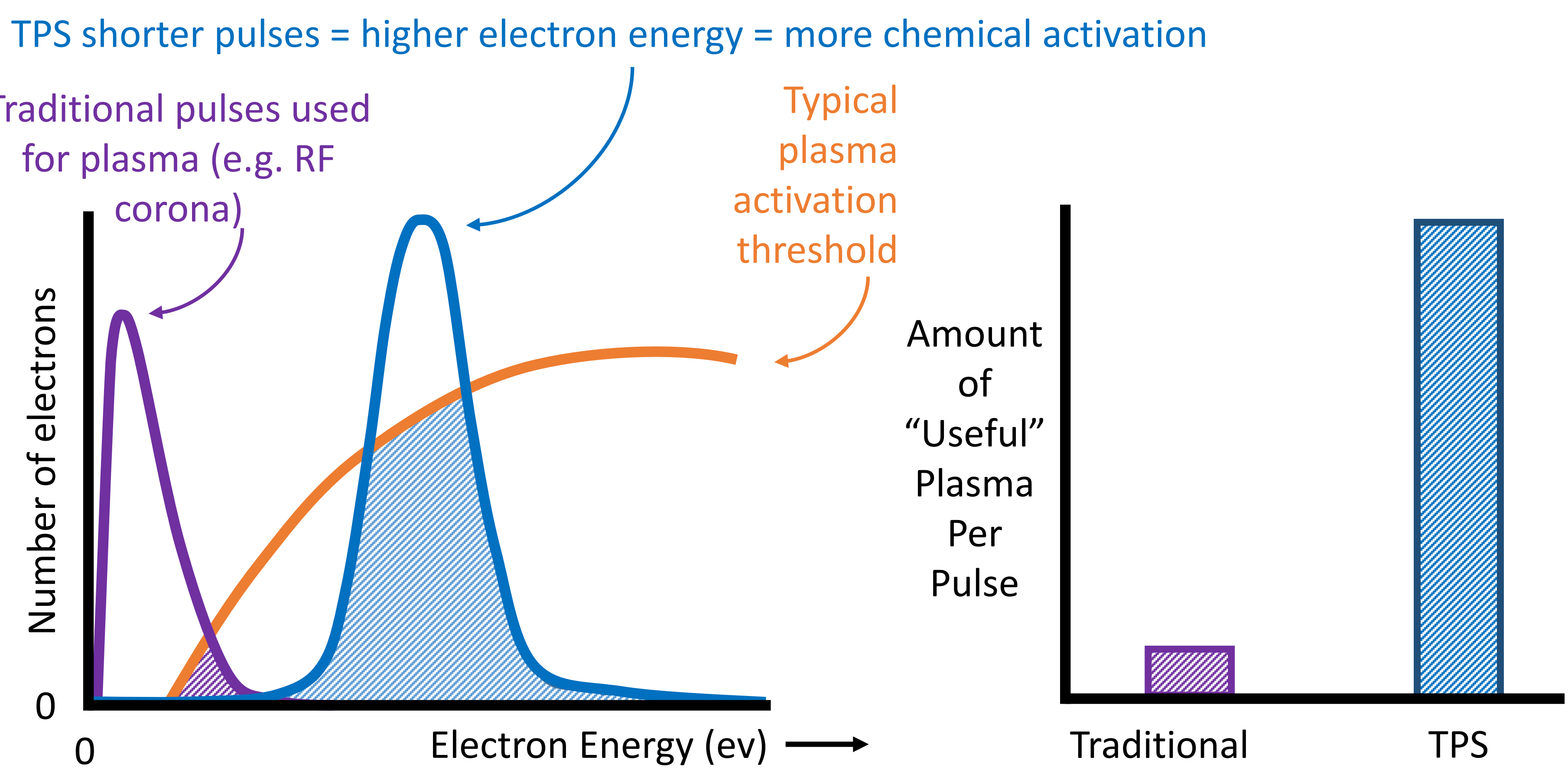
10 nanoseconds



4 Million times faster than the blink of an eye

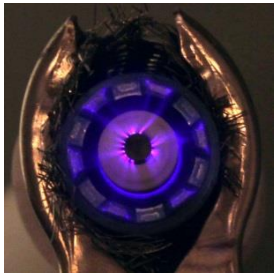
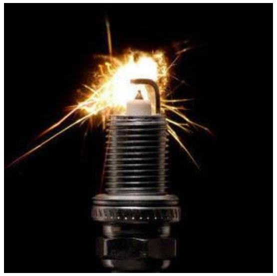
High Power
&
LOW ENERGY

Short Pulses Enable Better Plasma



Low-Temperature Plasma vs Other Plasmas

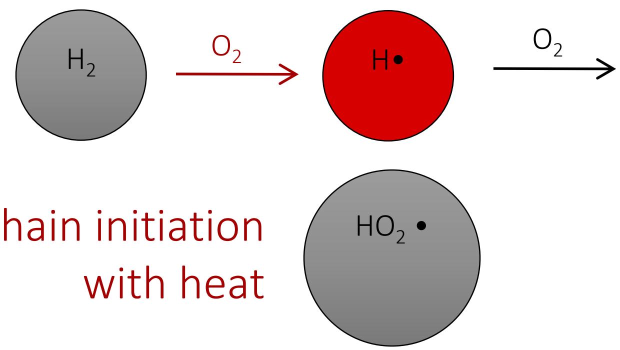
Gas Temp. During Ignition Discharge

Nanosecond Pulses (TPS)	RF Corona Discharges	High-Energy Spark, Microwave Plasmas, Plasma Jet
		

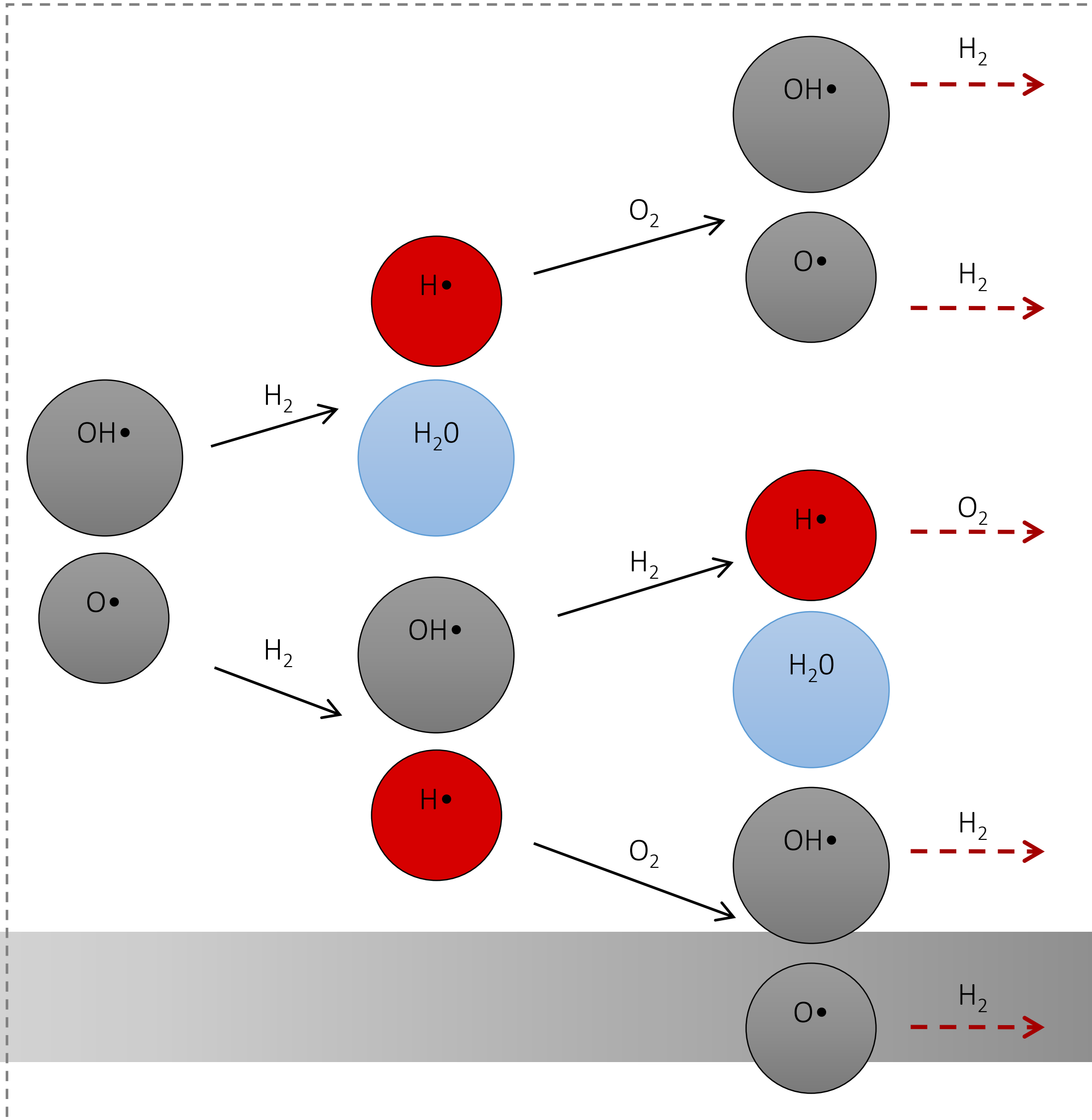
Thermal Ignition Process

Example: H_2-O_2 Combustion started with thermal ignition (spark)

- A small number of chain branching and propagation reactions have a large impact on combustion time



chain initiation with heat

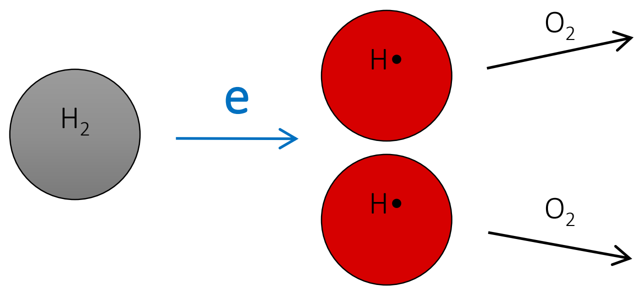


chain branching and chain propagation reactions

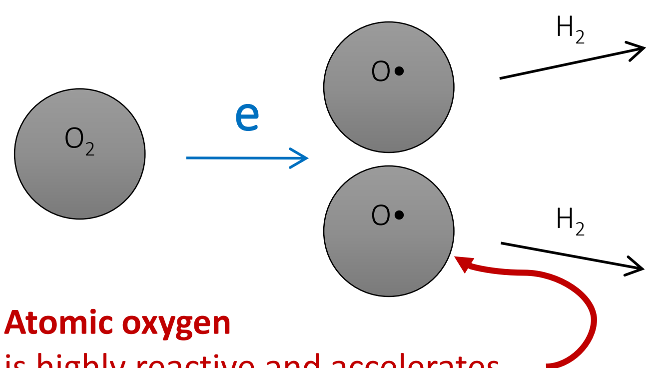
- One H• produces three H• in this sequence of reactions

Transient Plasma Ignition Process

Example: H_2-O_2 combustion started with non-thermal ignition (transient plasma)

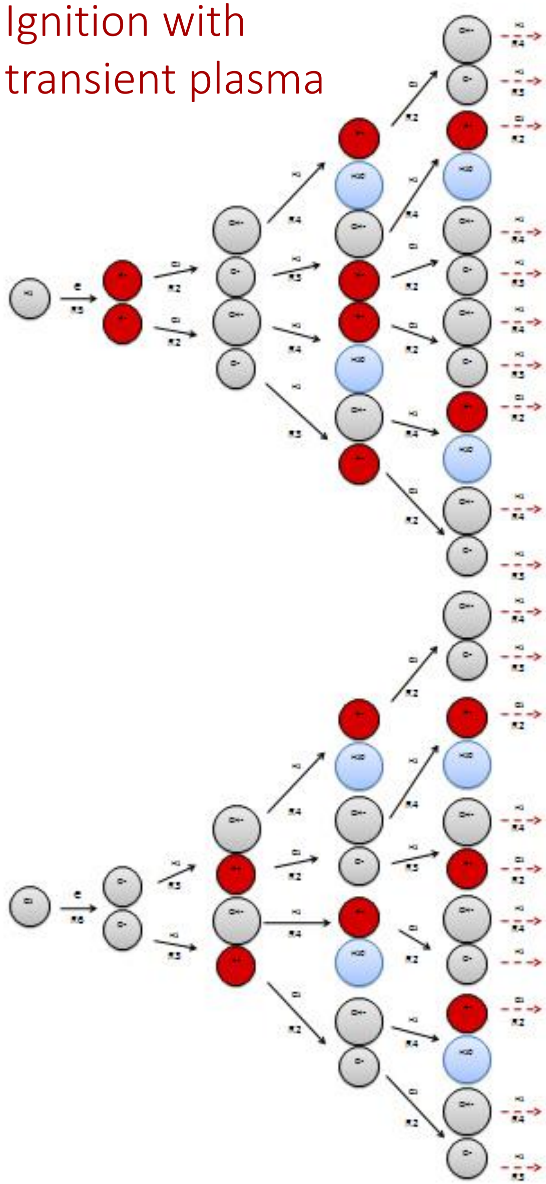


- Transient plasma dissociates molecules via electron impact
- Increases chain branching and propagation reactions
    - Accelerates combustion

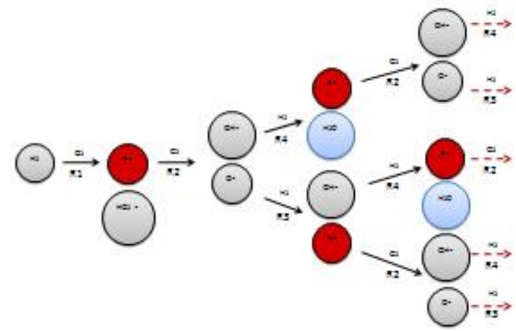


Atomic oxygen
is highly reactive and accelerates combustion and improves stability

Ignition with transient plasma

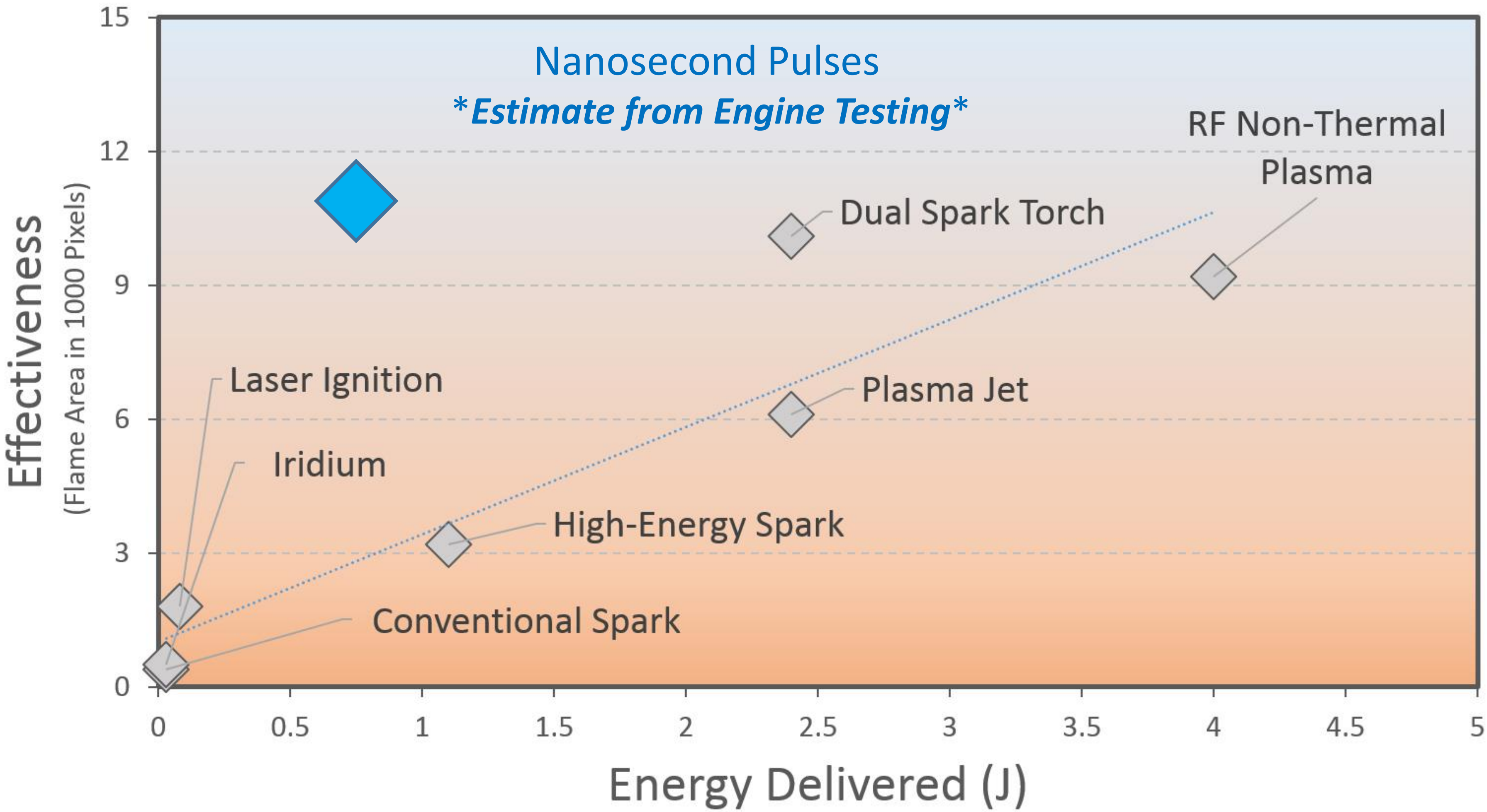


Ignition with spark



S. M. Starikovskaia, "Plasma Assisted Ignition and Combustion," J. Phys. D: Appl. Phys. 39 (2006) R265–R299.

Nanosecond Pulses Are More Energy Efficient



Briggs, T., Alger, T., and Mangold, B., "Advanced Ignition Systems Evaluations for High-Dilution SI Engines," SAE Int. J. Engines 7(4):1802-1807, 2014, doi:10.4271/2014-01-2625.

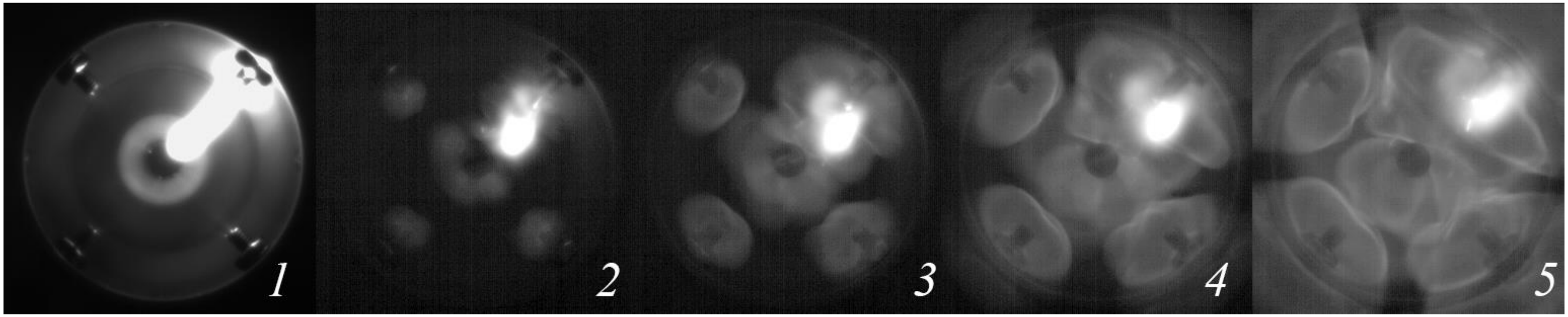
Benefits Come From Two Factors

Enhanced Chemistry

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

Volumetric Impact

- Spatial distribution of plasma (see picture) enables a single streamer discharge to impact a large volume and develop multiple flame kernels

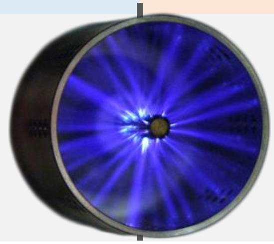


- Regardless of discharge mode (a spark can be seen in figure 1 that occurs AFTER the transient plasma discharge), the benefits of transient plasma ignition are achieved through the fast-rising pulse

Two Energy Applications

Ignition and combustion

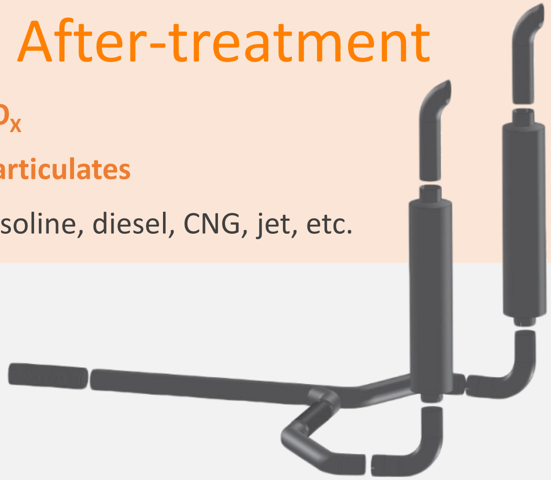
- Potential for **>20% better fuel economy** through dilute-combustion
- **>50% less NO_x emissions** in spark ignited engines (any fuel)



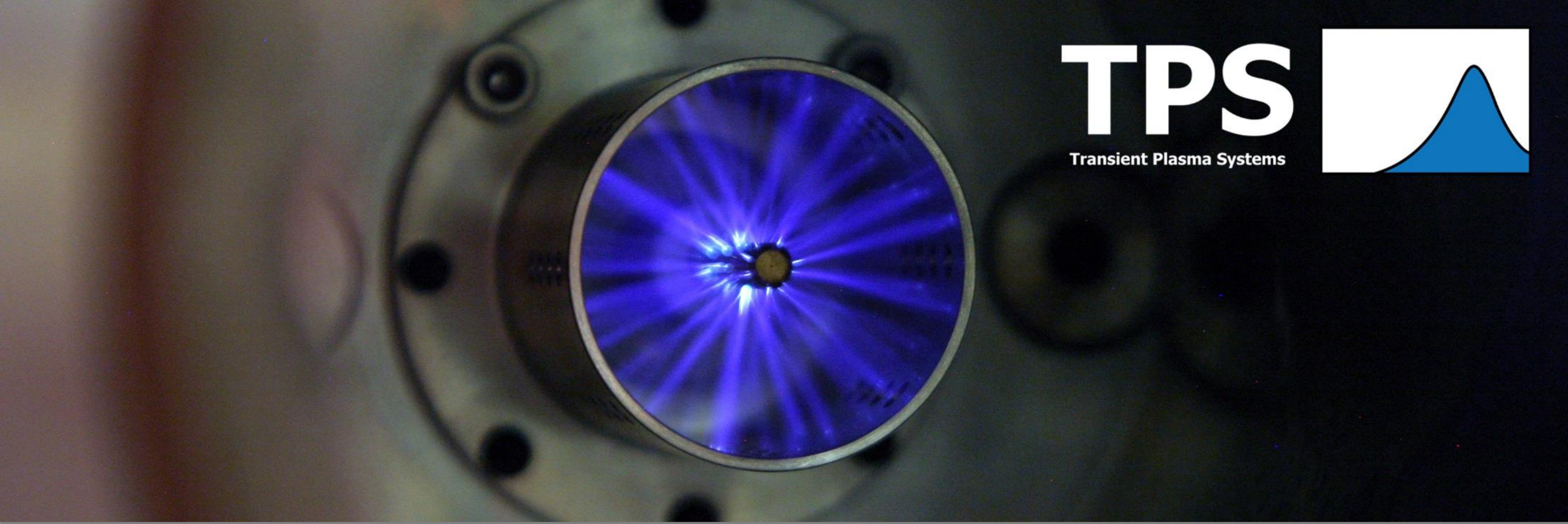
- TPS technology validated by world leading research facilities;
    - Sandia National Labs Combustion Research Facility in collaboration with GM
        - Resulted in peer-reviewed publications including;
- *M. Sjöberg, et. al, "Combined Effects of Multi-Pulse Transient Plasma Ignition and Intake Heating on Lean Limits of Well-Mixed E85 DISI Engine Operation," SAE Int. J. Engines, pp. 7(4):1781-1801, 2014.*
- *M. Sjoberg and W. Zeng, "Combined Effects of Fuel and Dilution Type on Efficiency Gains of Lean Well-Mixed DISI Engine Operation with Enhanced Ignition and Intake Heating for Enabling Mixed-Mode Combustion," SAE Int. J. Engines, pp. 9(2):750-767, 2016.*
    - Argonne National Labs in collaboration with Ford
        - Resulted in peer-reviewed publications including;
- *J. Sevik, T. Wallner, M. Pamminger, R. Scarcelli, D. Singleton and J. Sanders, "Extending lean and EGR-dilute operating limits of a modern GDI engine using a low-energy transient plasma ignition system," ASME. J. Eng. Gas Turbines Power, pp. 138(11):112807-112807-8, 2016.*

Exhaust After-treatment

- **>90% reduction in NO_X**
- **>60% Reduction in particulates**
- **Any fuel,** including gasoline, diesel, CNG, jet, etc.



- Unlike the existing after-treatment approach that TPS technology would replace, SCR (e.g. the technology discussed in the VW diesel story), it does not require fluid replacement
    - In some applications the TPS treated exhaust still may require some post-processing
- TPS co-founder, Prof. Martin Gundersen, began work on this application in the early 1990's
- The application has been reported on in peer-review literature since then, for example:
- *H. Kim, "Nonthermal Plasma Processing for Air-Pollution Control: A Historical Review, Current Issues, and Future Prospects", Plasma Processes Polym., 1: 91–110, 2004.*
- The reason it has not yet been commercialized is because plasma generation approaches in the past have required too much energy to be practical (roughly 25% of the engine power)
    - TPS has recently demonstrated that its nanosecond pulse approach requires less than 5% engine power on numerous engine types for potential strategic partners



Engine Testing

- Natural gas and gasoline single cylinder engines
- Key questions remaining
- CEC Project – Multi-cylinder engine testing

Immediate Market: Natural Gas

- The ignition temperature of natural gas is much higher than diesel (580°C versus 210°C), making it difficult to achieve stable combustion

- There are currently two main alternatives

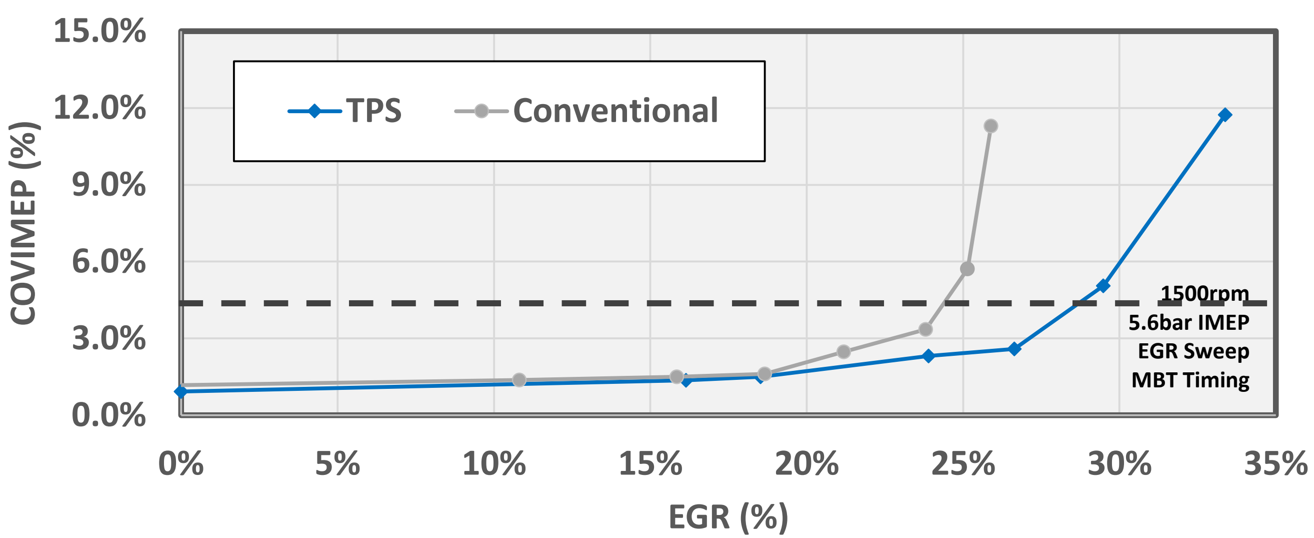
1) Dual-fuel

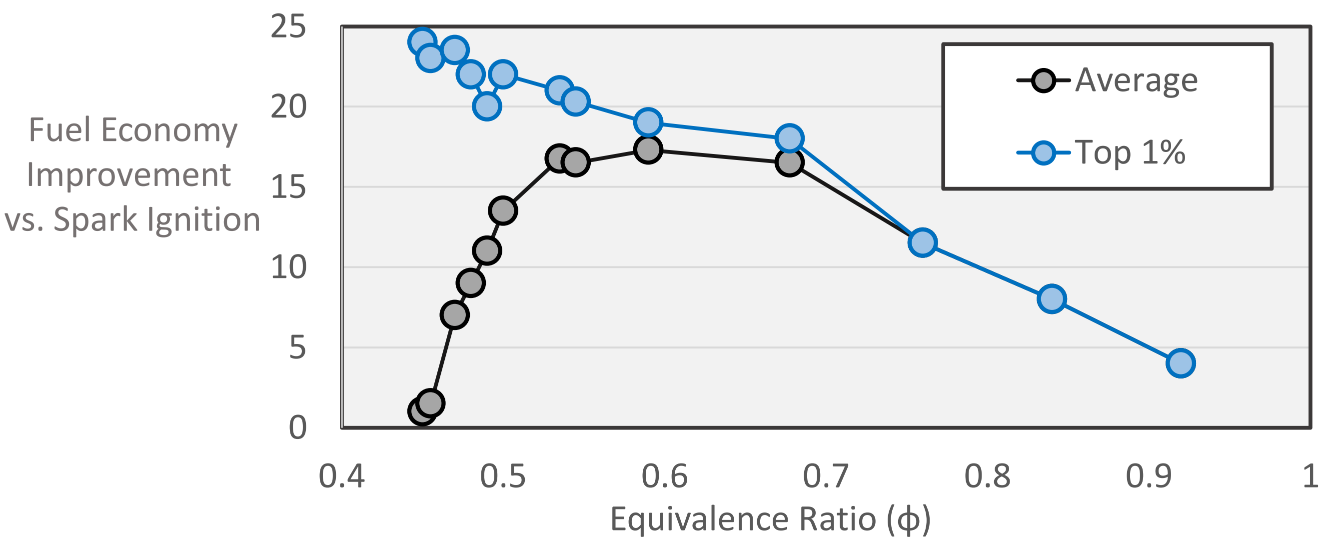
- Burst of diesel fuel increases the temperature so that natural gas will ignite
- Requires expensive exhaust gas after-treatment and frequent fluid replacement

2) High-energy ignition source

- Requires 10x the spark energy to ignite the natural gas, causing the spark plugs to erode quickly thereby increasing expensive maintenance cycles
- Requires reduced engine pressure for ignition, decreasing fuel efficiency, power, and range

Increased Dilute Burn Capability





J. Sevik, T. Wallner, M. Pamminger, R. Scarcelli., D. Singleton, J. Sanders. "Extending lean and EGR-dilute operating limits of a modern GDI engine using a low-energy transient plasma igni-tion system." ASME. J. Eng. Gas Turbines Power, (2016) 138(11):112807-112807-8.
Sjöberg, M., Zeng, W., Singleton, D., Sanders, J. et al., "Combined Effects of Multi-Pulse Transient Plasma Ignition and Intake Heating on Lean Limits of Well-Mixed E85 DISI Engine Operation," SAE Int. J. Engines 7(4):1781-1801, 2014.

Single-cylinder Ford engine at Argonne National Labs using gasoline

Bore = 89.04 mm
Stroke = 100.6 mm,
Displacement = 0.6264 L

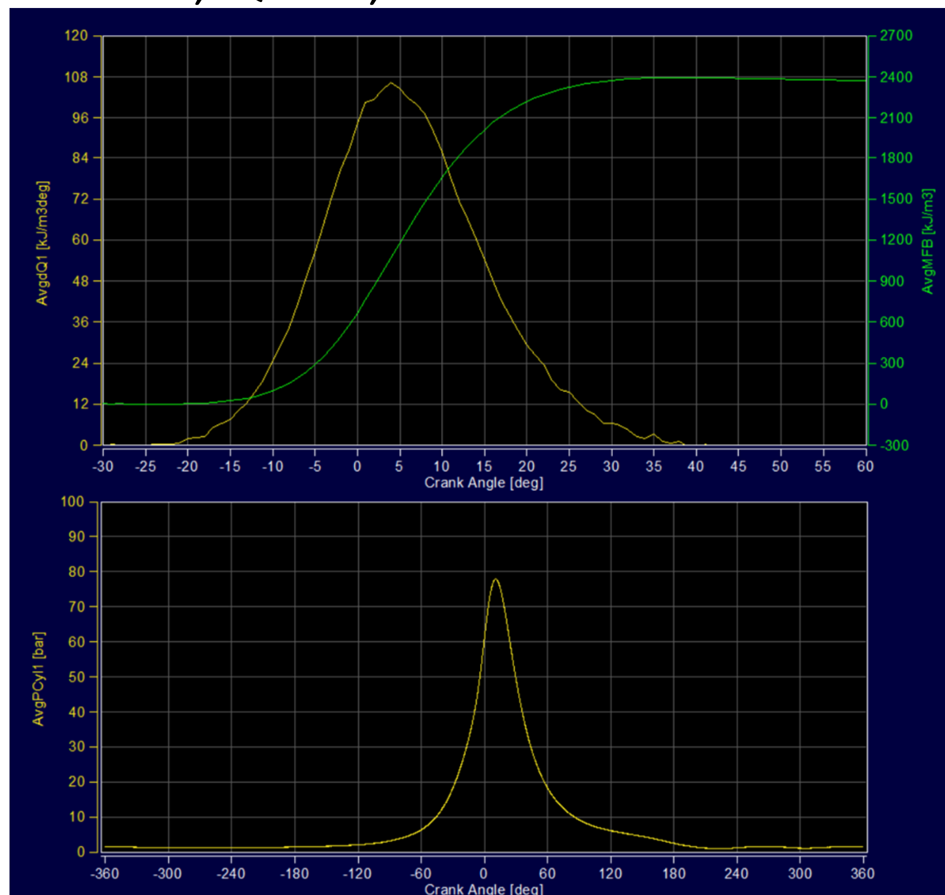
Program goal to demonstration 25% fuel economy improvement in GTDI engine from mid-sized sedan

Work supported by DOE Grant DE-SC0013824, Program Manager: Dr. Leo Breton

Natural Gas Engine Testing

Speed	BMEP	EQR	FCE/BTE	CO_2	O_2	THC	NOx	CO	CoV IMEP	TPS Settings			
RPM	bar	ϕ	%	%	%	g/kW-hr	g/kW-hr	g/kW-hr	%	Volts	% Energy	#Pulses	Gap (mm)
1200	9.79	0.56	37.03	6.22	10.27	10.05	4.43	2.43	2.96	15KV	51	20	0.5 mm

1200RPM;EQR0.56; IT:31BTDC



- Data taken by Muni Biruduganti, Principal Research engineer, ANL

Engine Test Example – Video – Argonne National Labs

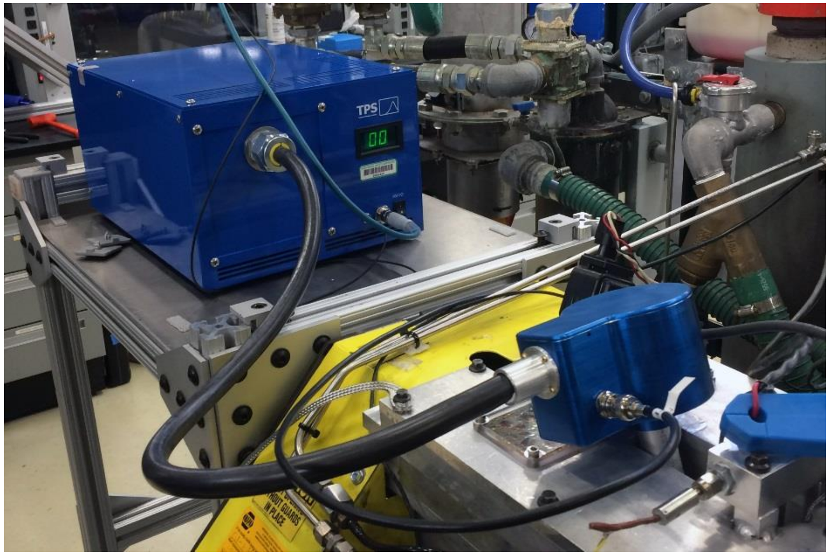


Photo of TPS Power Supply (AC/DC converter and 24 V DC supply) and TIM

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

Photo of TPS external controller located in engine control room

Modified spark plug

Key Questions Remain

GOAL:

Demonstrate better fuel economy and reduced emissions with new low-energy ignition technology

IP = In Progress

- ✓ Enable stable dilute combustion (AFR>20) at high-pressure (100 bar)
- IP Deliver less thermal energy than alternative solutions to increase spark plug lifetime
- IP Design as a direct replacement with existing ignition systems

U.S. DEPARTMENT OF ENERGY

STATE OF CALIFORNIA ENERGY COMMISSION

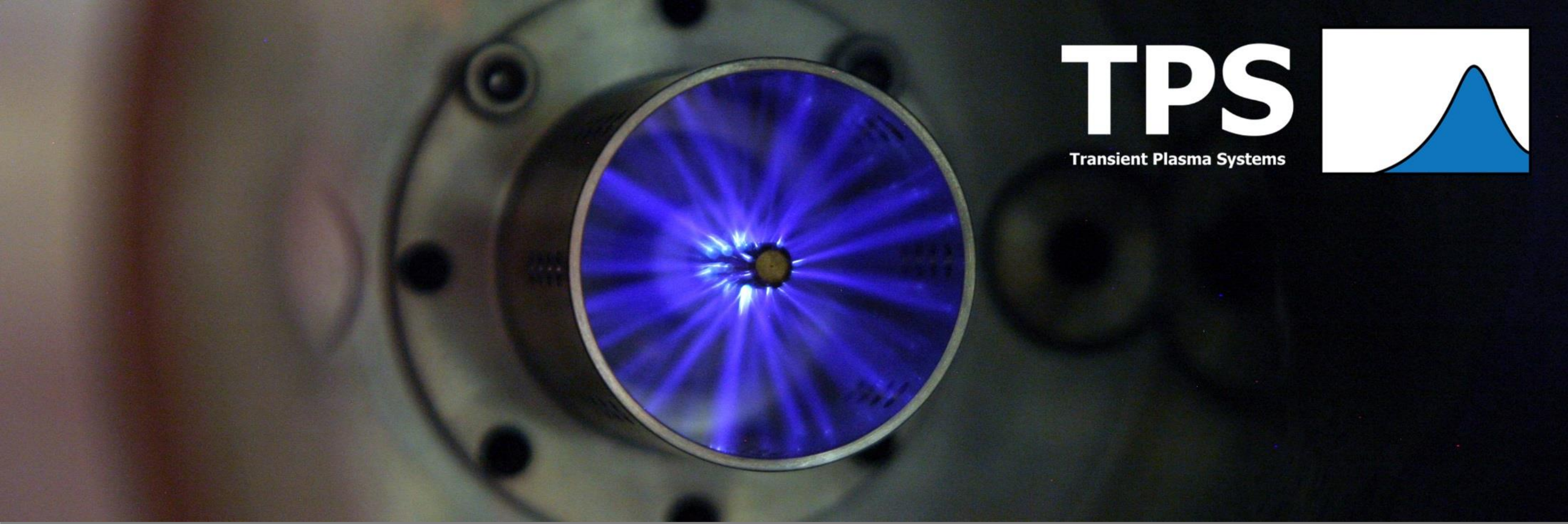
Engine Test for CEC PIR-16-024

- Cummins Westport ISX12 G natural gas engine is a larger-displacement natural gas engine suitable for a variety of heavy-duty vehicles, including regional-haul truck/tractor, vocational, and refuse applications

- TPS will perform a a multi-cylinder engine test on this engine at Argonne National Labs in 2019/2020

Argonne NATIONAL LABORATORY

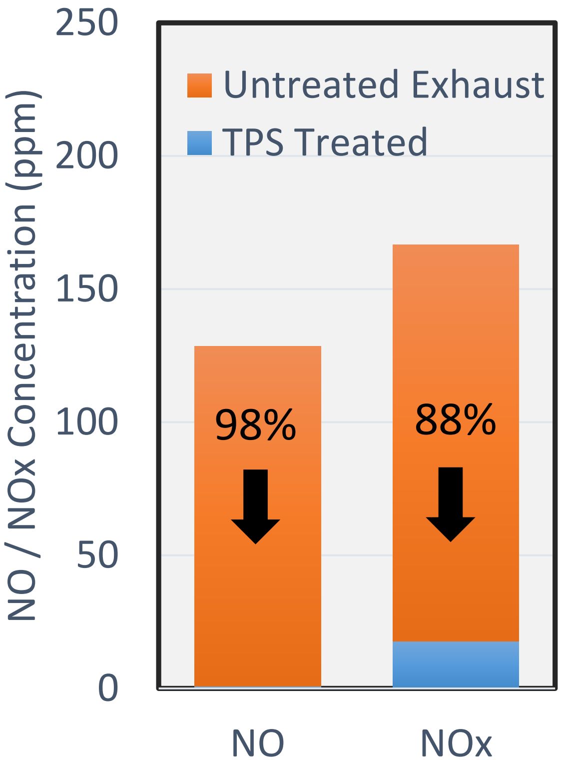
Cummins Westport

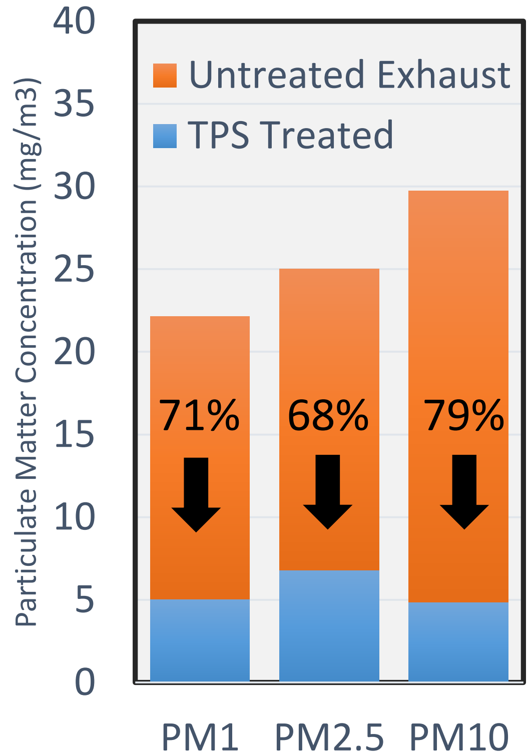


Overview

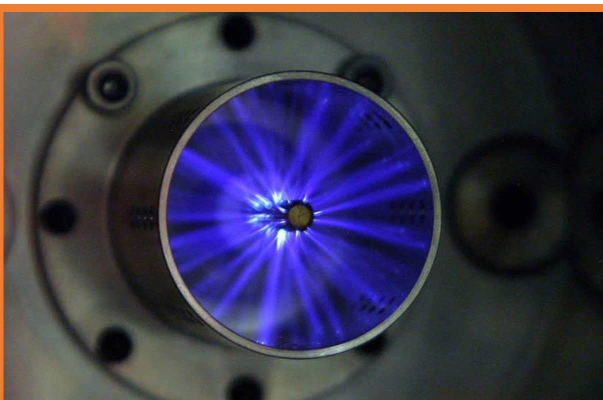
- Additional application – Emissions Treatment
- Active non-confidential projects
- Summary

Different Application - Emissions Treatment





- Enhanced process
- Extends life of catalyst
- Operational cost savings
- Any fuel
- Allows existing engines to Tier 4 emissions standards
- Application to stationary generators, off-highway and on-highway vehicles



>80%

Reduction in regulated emissions possible with <5% engine power

Non-Confidential TPS Active Ignition Projects

Funding	Primary Goal	Partners
KV	Venture capital: commercialization and miniaturization	
State of California Energy Commission	Multi-cylinder system	Cummins, Westport, Argonne National Laboratory
U.S. Department of Energy	Spark breakdown avoidance	Argonne National Laboratory
U.S. Department of Energy	Advanced ignition systems modeling and evaluation	Ford, Argonne National Laboratory, GM, Combustion Research Facility
U.S. Department of Energy	Optimization of pulse shape	Old Dominion University

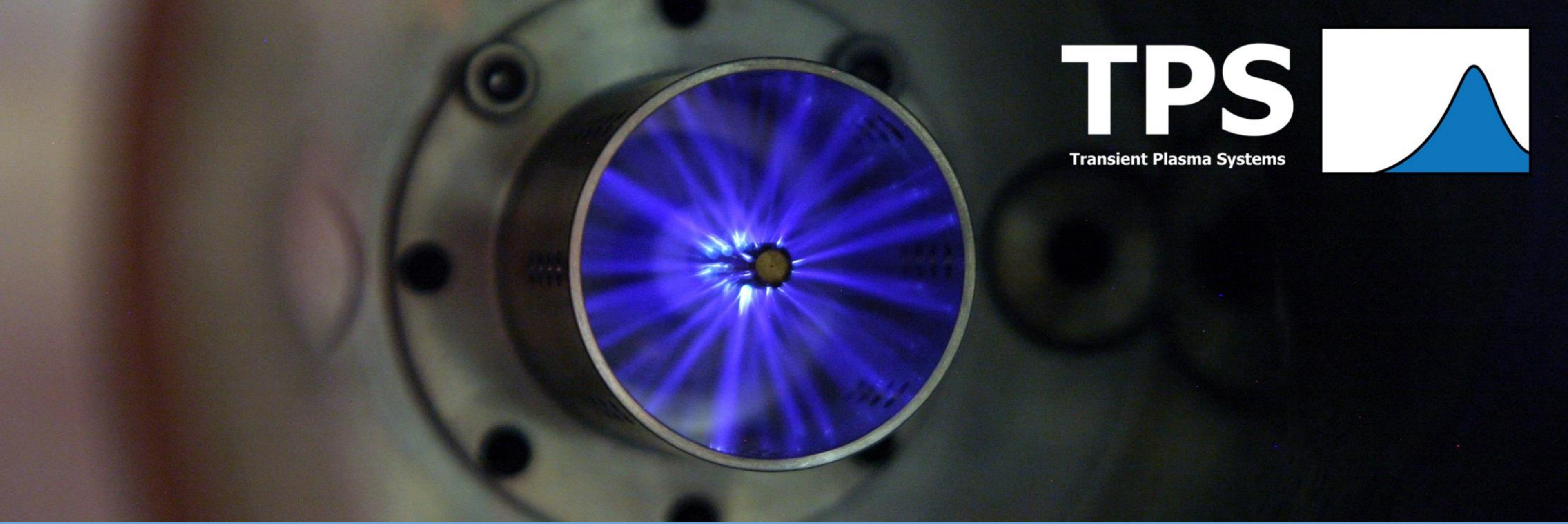
Summary

To date transient plasma ignition has:

- Demonstrated a lean ignition limit lower than a fuel/air equivalence ratio (ϕ) of 0.50 [1];
- Demonstrated high-pressure ignition in engines and static cells >20 bar BMEP equivalent [2];
- Demonstrated stable (COV EGR dilution levels up to 35% <3%) ignition at [3]

- A prototype multi-cylinder system is being developed and tested on a Cummins Westport engine in 2019
- Additional application to emissions treatment is being explored

[1] M. Sjöberg, W. Zeng, D. Singleton, J. Sanders and M. Gundersen, "Combined Effects of Multi-Pulse Transient Plasma Ignition and Intake Heating on Lean Limits of Well-Mixed E85 DISI Engine Operation," *SAE Int. J. Engines,* pp. 7(4):1781-1801, 2014.
[2] Y. Lin, D. Singleton, J. Sanders, A. Kuthi and M. Gundersen, "Experimental study of pulsed corona discharge in air at high pressures," in *Bulletin of the American Physical Society*, Austin, 2012.
[3] M. Sjoberg and W. Zeng, "Combined Effects of Fuel and Dilution Type on Efficiency Gains of Lean Well-Mixed DISI Engine Operation with Enhanced Ignition and Intake HEating for Enabling Mixed-Mode Combustion," *SAE Int. J. Engines,* pp. 9(2):750-767, 2016.



TPS
Transient Plasma Systems

- Better fuel economy
- Less emissions
- Plug & Play
- Longer spark plug life
- Platform technology

Dan Singleton, CEO

dan@transientplasmasystems.com
www.transientplasmasystems.com

1751 Torrance Blvd, Torrance, CA 90501