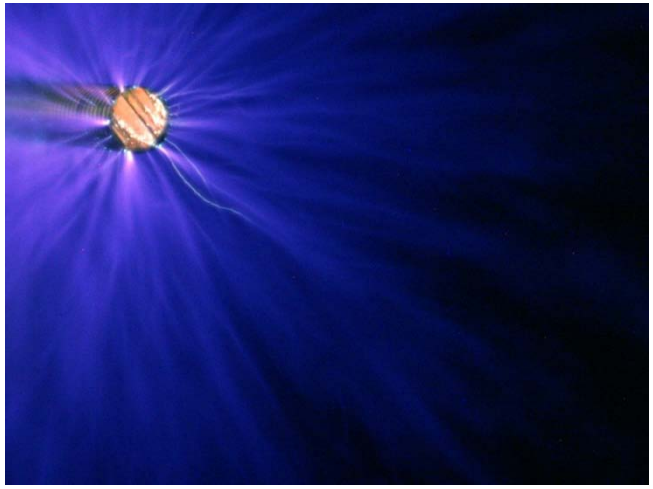
Transient Plasma Ignition
for
Improved Fuel Efficiency in Natural Gas Engines

Martin Gundersen



USC: Dan Singleton, Scott Pendleton, Alex Simone, Andras Kuthi, Jason Sanders, M. Gundersen

This project is at the stage of engineering and testing in engine platforms, and has been tested in several engine platforms

Collaborators for engine testing and industrial collaboration have been identified

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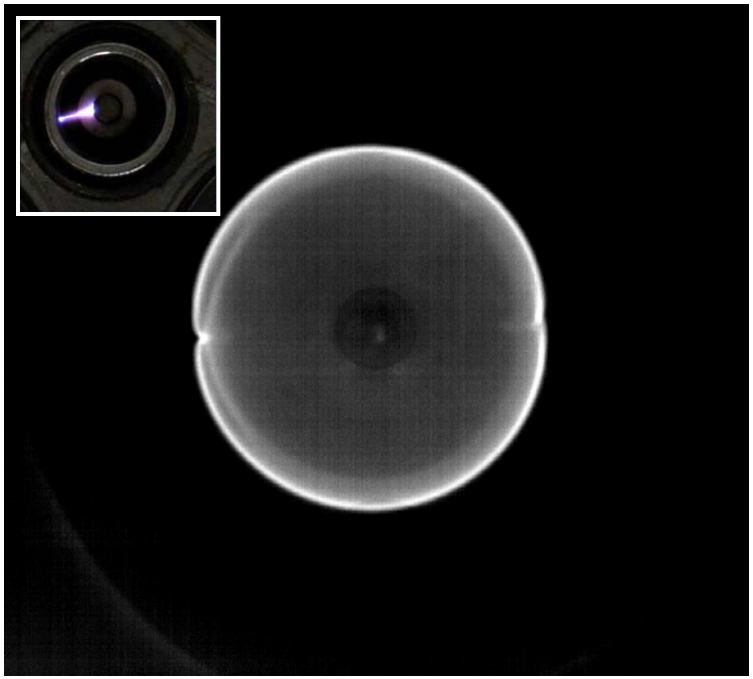
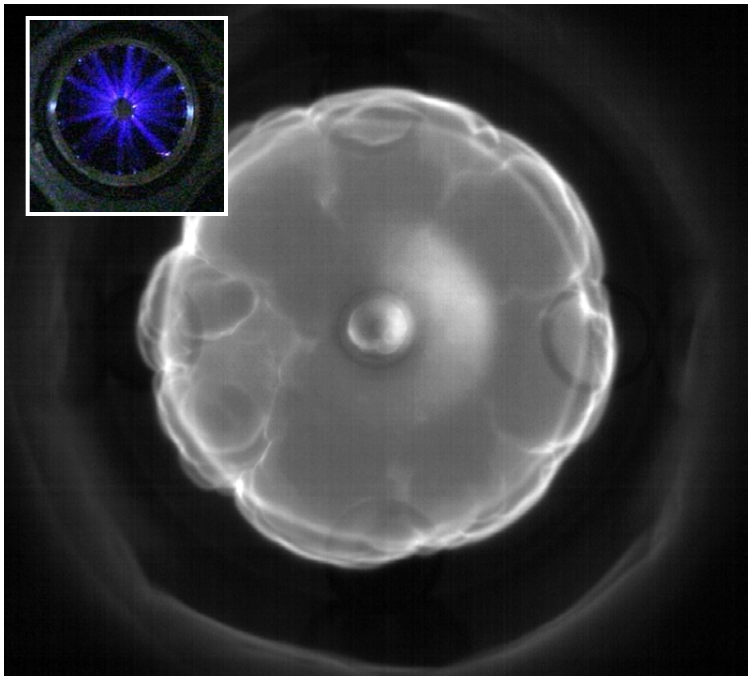
Pulsed Power and Transient Plasma Ignition

- Ignition method that increases fuel efficiency
  - Uses ultra-short pulses



Methane-air combustion started with a traditional spark



Methane-air combustion started with transient plasma

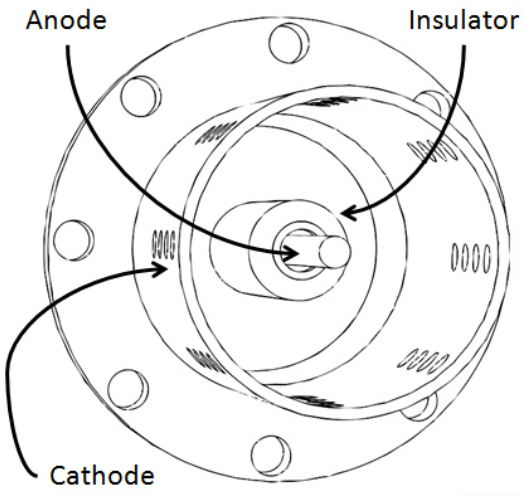
Pulsed Power and Transient Plasma Ignition

- Ignition method that increases fuel efficiency
  - Uses ultra-short pulses
- Demonstrated improvements in engine platforms
  - Single-cylinder gasoline ICE
    (Nissan, 20% improvement in combustion efficiency)
  - Four-cylinder gasoline ICE
    (USC, 20% improvement in combustion efficiency)
  - Single-tube PDE's with gaseous and liquid fuels
    (Navy and Air Force, up to 3 times improvement in thrust)
  - Single-cylinder diesel ICE tests underway

Transient Plasma: Streamers, Arcs, and Breakdown

Transient plasma

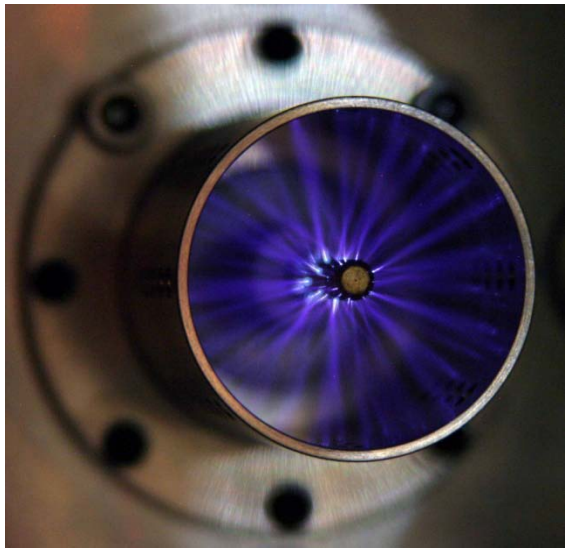
- Non-equilibrium (cold) plasma
- Initiates the breakdown process prior to arc formation in a gas
- Fast rise time, short (typically <100 ns), high-voltage pulses are needed
  - Holds-off spark breakdown and produces an array of streamers



Typical electrode geometry

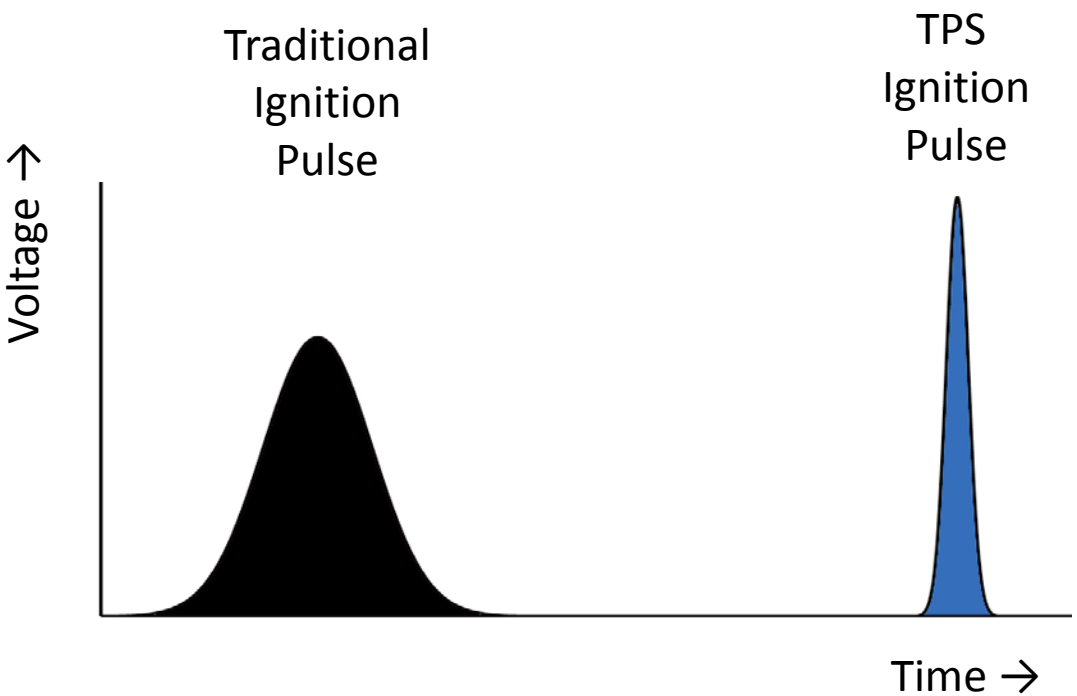
Streamers

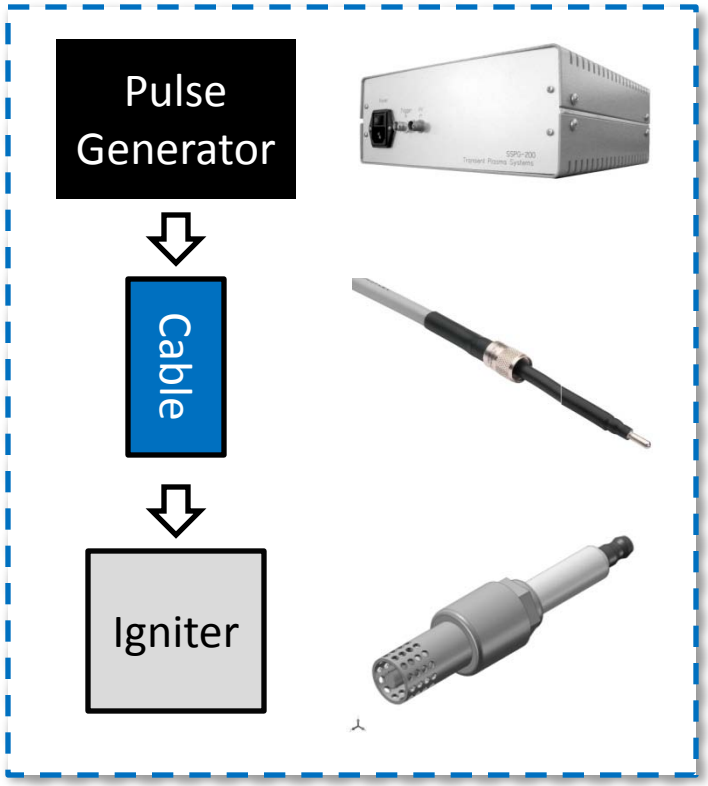
- Streamers branch throughout the volume
  - Have high energy electrons in their heads (>10 eV)
  - Produce radicals throughout the discharge volume through impact ionization and dissociation



Pulsed Power and Transient Plasma Ignition

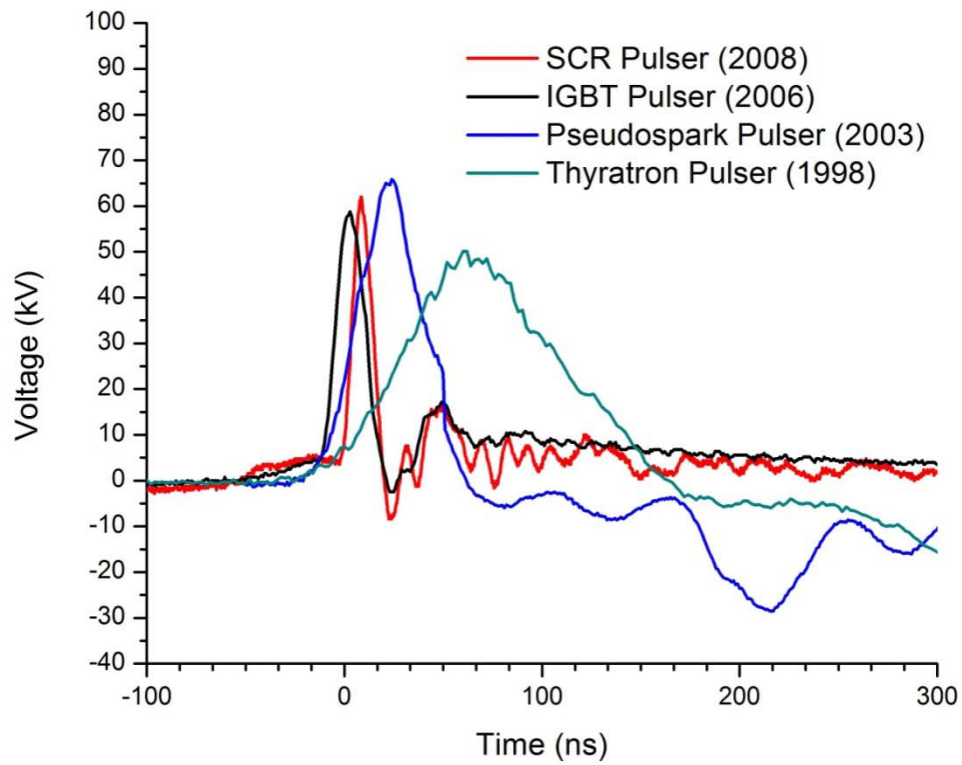
- Ignition with nanosecond pulsed power enables transient plasma ignition, and resultant efficiency
- USC has advanced generation and transmission of nsec pulsed power for ignition and other applications

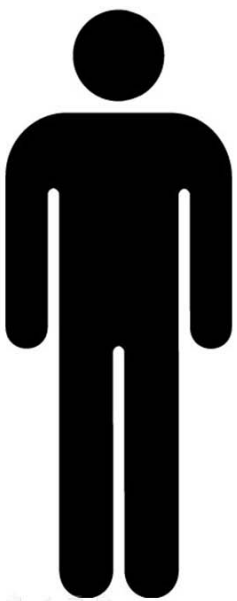


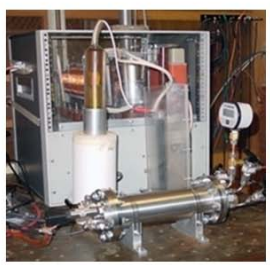


Compact Nanosecond Pulsed Power Systems at USC

Pulse Generator Switch Type	Peak Voltage (kV)	Pulse Width (ns)	Energy Pulse (mJ)
Thyratron (1998)	50	150	1000
Pseudospark (2003)	90	85	1500
IGBT (2006)	60	20	300
SCR (2008)	65	12	200







1998

Thyratron

2003

Pseudospark

2006

IGBT

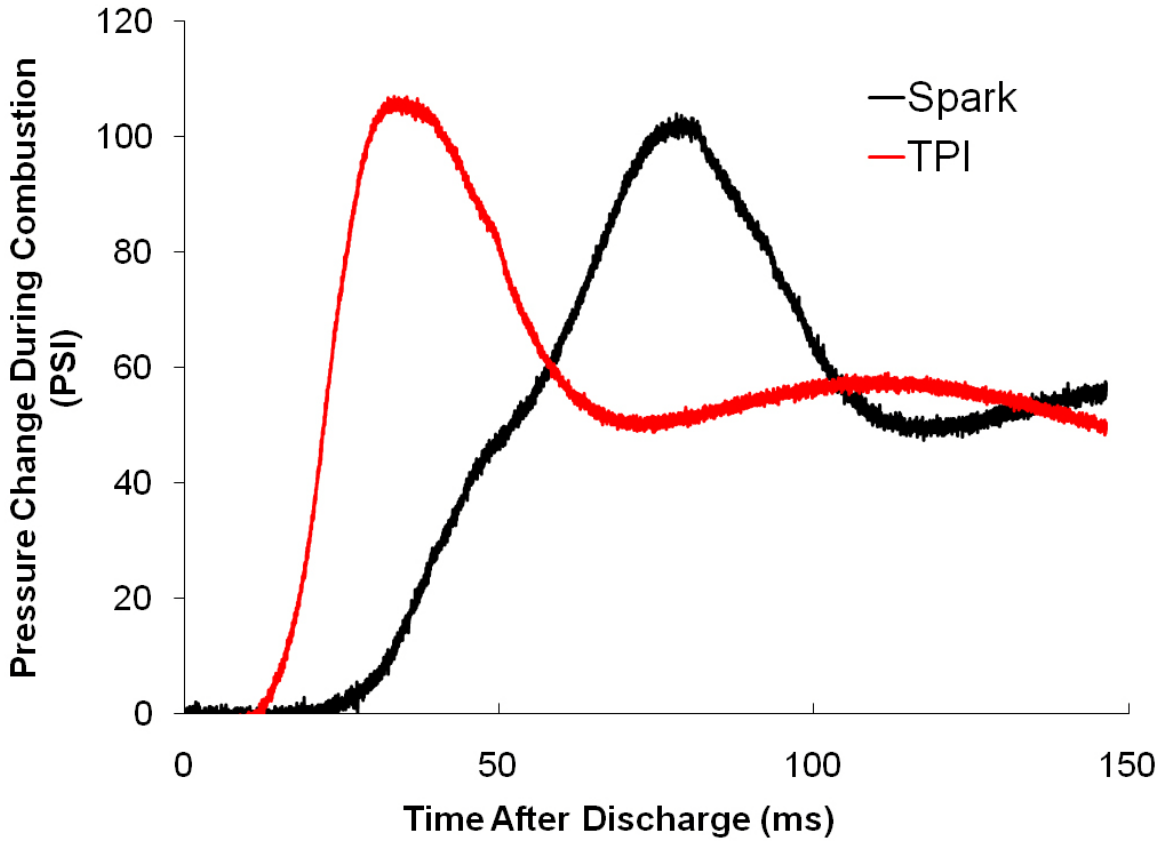
2008

SCR

USC has

- **Pulse generation**
- **Pulse transmission**
- **Igniters**

TPI in Methane-Air in a Static Combustion Chamber



- Ignites quicker (up to 9 times)
- Gets more power from the fuel (approx. 20%)
- More easily ignites complex fuels
- Ignites lean mixtures easily (below $\phi = 0.5$)
- Burns faster (more than 50%)

Result: Using natural gas, TPI can improve fuel efficiency by 20%, and reduce emissions

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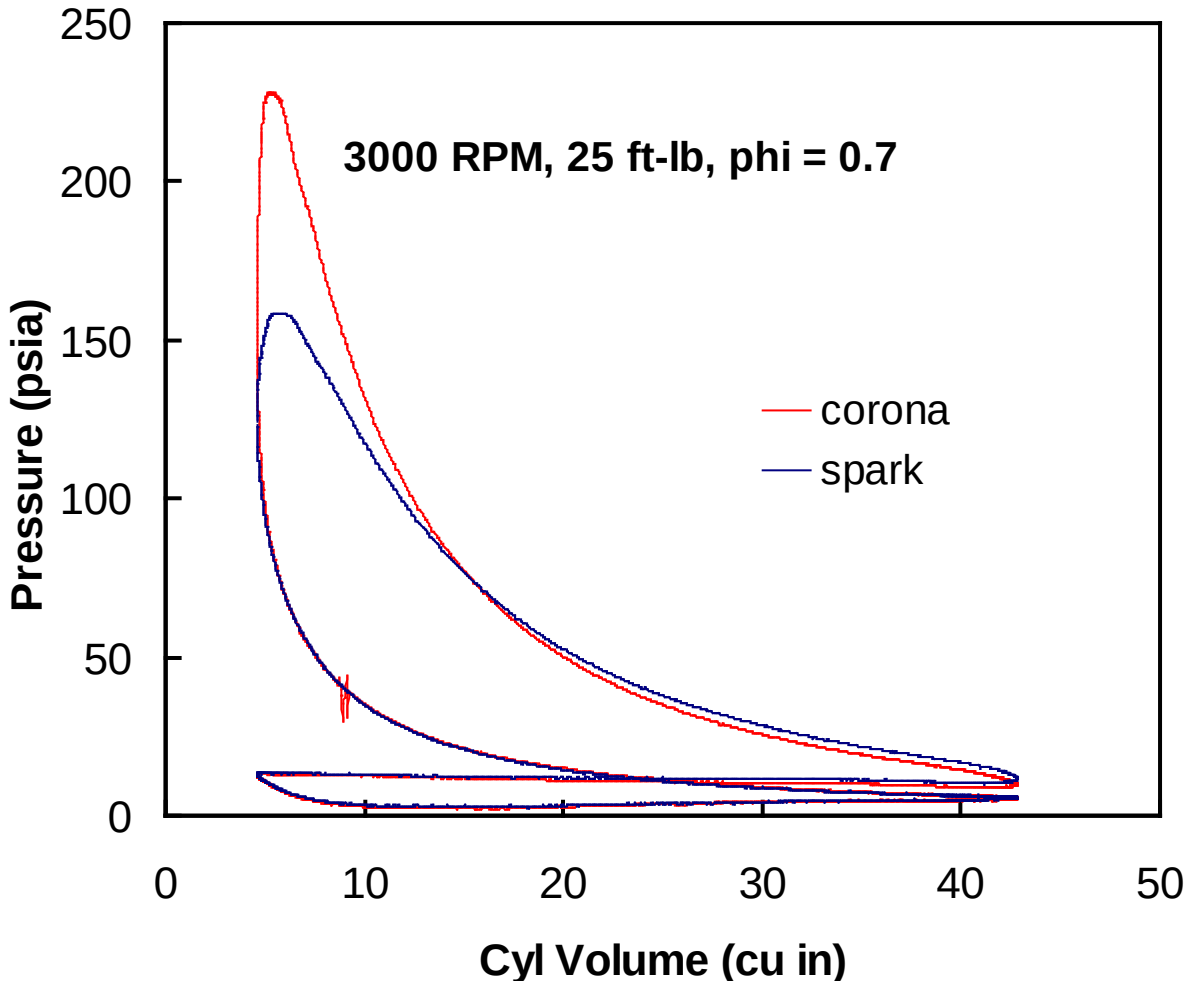
Improving Performance in a Natural Gas ICE at USC



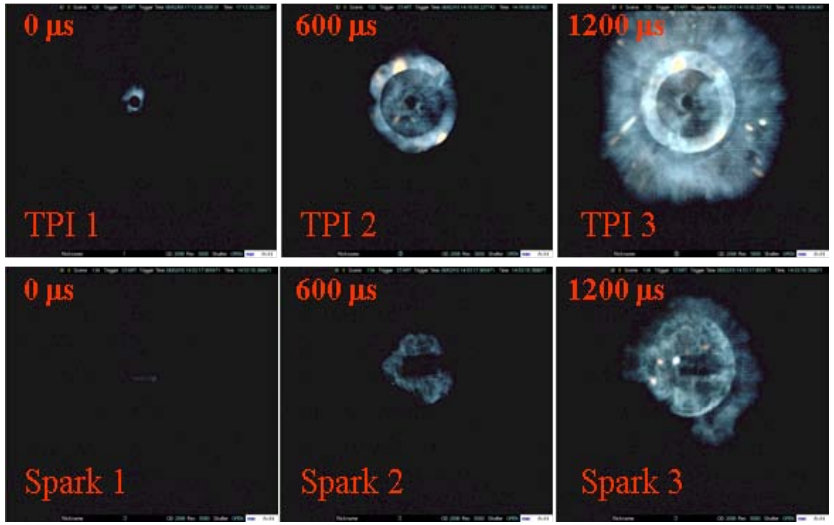
Demonstrated in Dr. Ronney's engine at USC:

- Higher IMEP (15% - 20%) for same conditions with same or better $BSNO_x$
- Shorter burn times and faster heat release
- Higher peak pressures

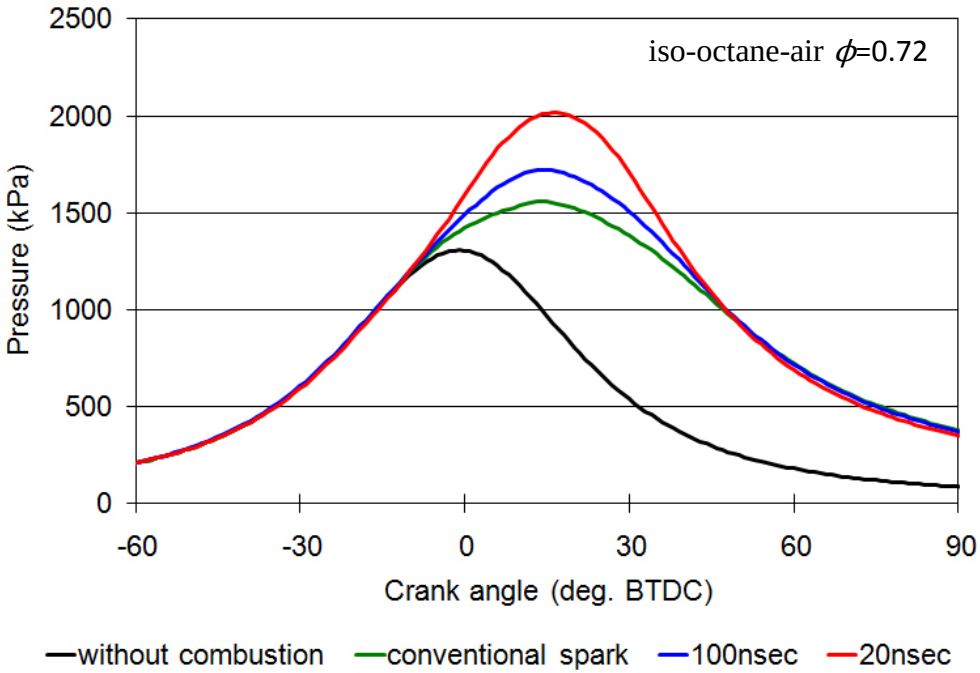
Improvements due to:

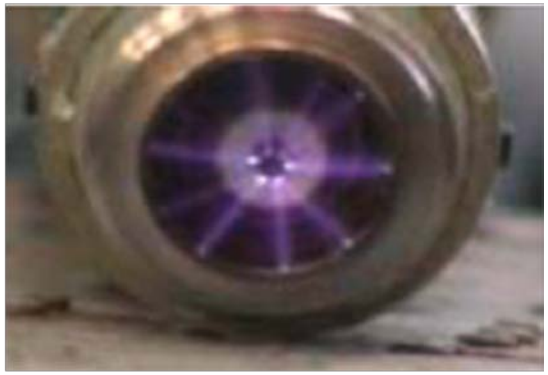
- Chemical effects (delay time) - radicals vs. thermal energy
- Geometrical effects - (delay & rise time) - more distributed ignition sites

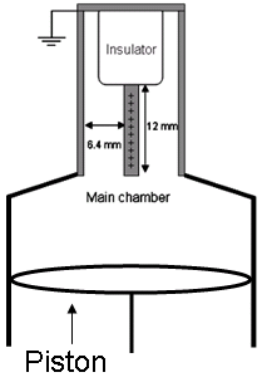
Improving Performance in a Gasoline ICE at Nissan Research Center



1200 rpm iso-octane-air combustion (200 µs exposure)







Streamers generated via a 60 kV, 20 ns pulse, using a modified spark plug

- Using TPI in an internal combustion engine resulted in
  - More than a 20% increase in peak pressure using less energy (57 mJ TPI vs 80 mJ spark plug)
  - Faster flame propagation (200-400 µs)
  - Result is ability to run lean and improve fuel efficiency

C. Cathey, T. Tang, T. Shiraishi, T. Urushihara, A. Kuthi, and M. A. Gundersen, "Nanosecond Plasma Ignition for Improved Performance of an Internal Combustion Engine," IEEE Trans on Plasma Sci, Dec. 2007.

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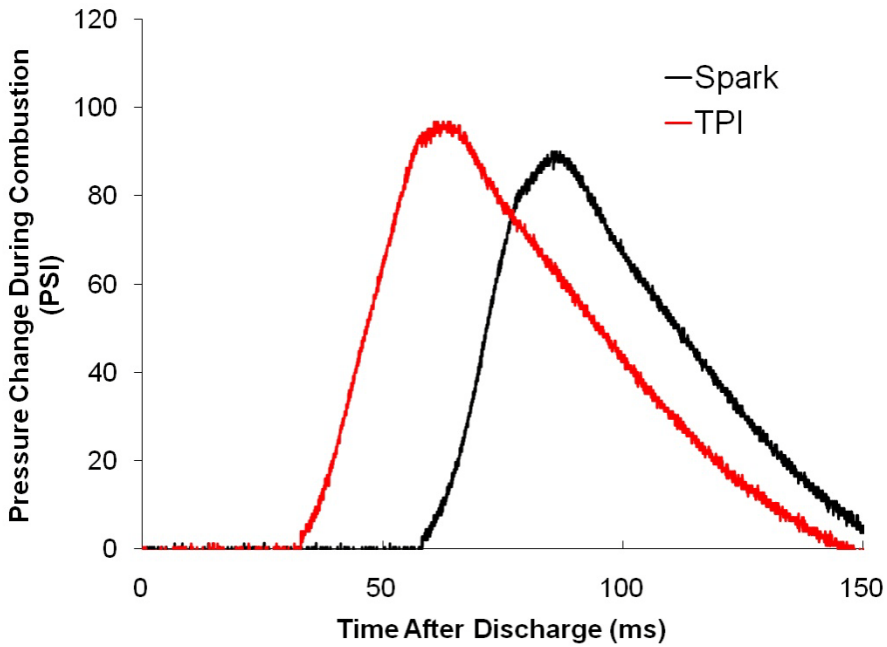
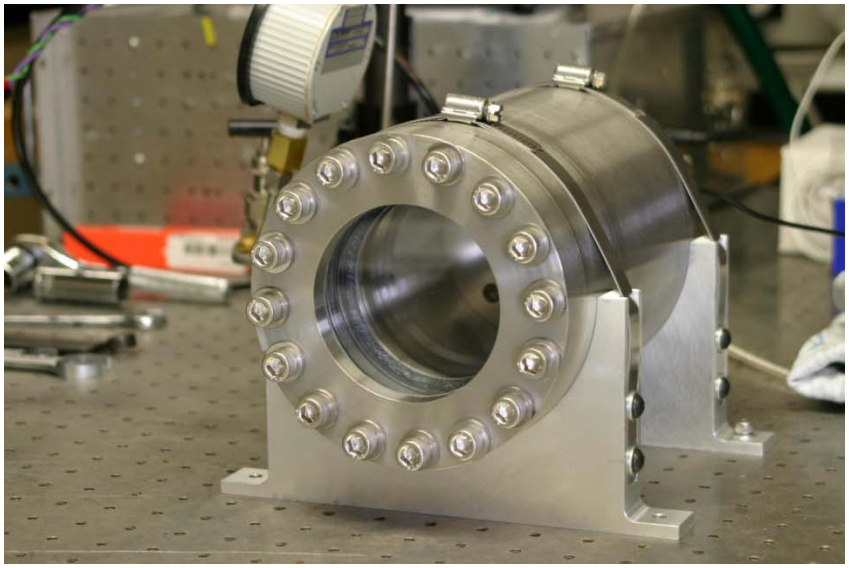
Methane-Air in a High-Pressure Static Cell





With an initial pressure of 15 atm :

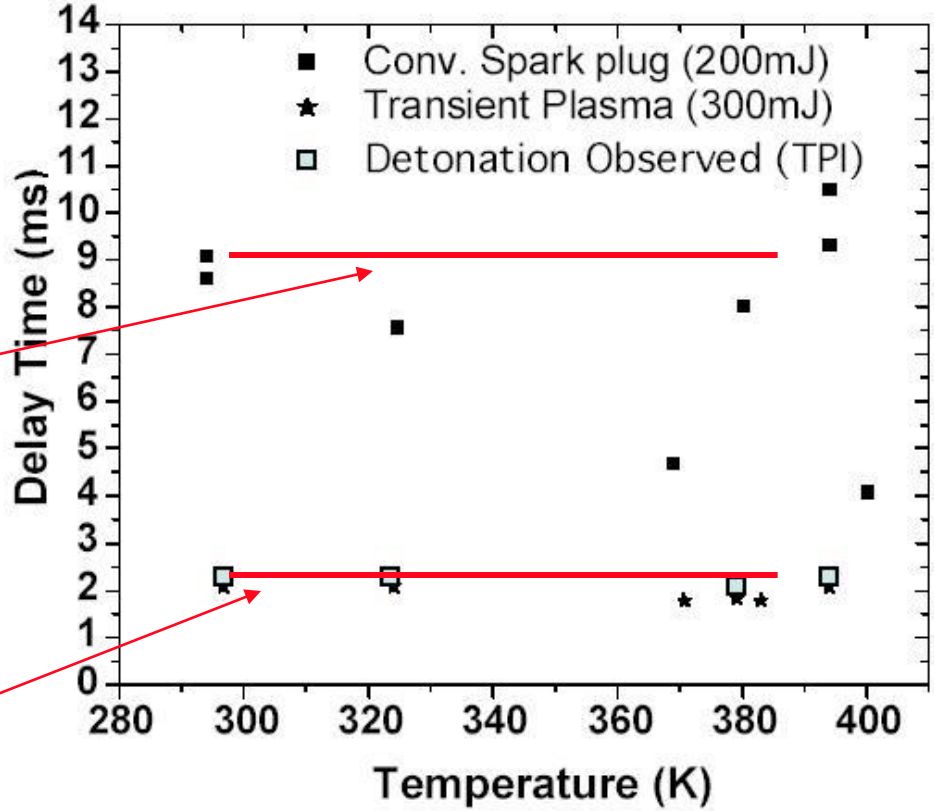
- Higher peak pressure (15% - 20%) using a single point igniter (no geometrical effects)
- Shorter ignition delay

Results show potential for benefits in CNG engine even with a non-ideal igniter

Improving Performance in a PDE at NPS

Traditional spark ignition 9 ms delay

USC Transient plasma ignition 2 ms delay



C_2H_4/Air
Fixed 0.35 kg/s
Constant ϕ=1.44
P_{INIT} = 602 kPa

Unc: +/- 0.25 ms
+/- 10 kPa
+/- 12 K

Using transient plasma in a pulse detonation engine, we:

- Considerably shortened the peaking time
- Created a detonation without added oxygen (propane-air)
- Improved the DDT time and increased the peak pressure
- ***Enabled higher repetition rate operation of the PDE***
- High flow rates (1/3 kg/sec)
- Shortened DDT by factors >4 (9 to 2 msec)

Summary

- **TPI has shown potential in NG engines and lab bench experiments :**
  - **20-30% increase in engine efficiency in NG, diesel, and gasoline**
  - **Reduction in emissions (NOx)**
  - **Reductions in ignition delay 3X in methane**
  - **Lean burn capability**
- TPI uses the same amount of electrical energy as traditional ignition
- Cost driven by economy of scale
- **Next steps include industry partners, testing in CNG engines and further developing technology for use in commercial applications (longevity, varying conditions)**