Nanosecond Pulsed Power and Transient Plasma Ignition

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Collaborators:
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NumerEx: J. Watrous, J. Luginsland
Stanford: E. Barbour, R. Hanson
Ecole Poly: S. Starikovskaia
WPAFB: C. Carter, F. Schauer
tOSU: S. Bowman, A. Montello, W. Lempert
...the list goes on
Transient Plasma Ignition Overview

• Introduction and Background
  - Pulsed Power Group
  - Transient Plasma

• Early Work at USC
  - Emission Treatment
  - Initial Ignition Work

• Combustion Studies
  - Pulsed Detonation Engines
  - Internal Combustion Engines
  - Static Volume Combustor Studies
  - Diesel/CNG

• Pulse Generation Development

• Streamer Physics Experiments

• Summary and Future Work
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USC Pulsed Power Research Group

• Pulsed Power Development
• Transient Plasma Ignition
• Biomedical Pulsed Power Applications
• Catalyst
Transient Plasma

Generated by nsec pulsed power
- Initiates the breakdown process prior to arc formation in a gas
- Fast rise time, short (<100 ns), high-voltage pulses
- Turn off pulse before spark breakdown occurs
- Produce an array of streamers
- Higher energy electrons in streamer head produce radicals, ions

Photos by J. Liu

 transient plasma (left), ≤100 ns, after which transition to an arc (right)
Streamer Image (Canon EOS 10D, 80 mm Lens, 15 sec exposure)

Single Pulse

Pseudospark Pulse Generator
61 kV, 54 ns Pulse (1000 mJ)
15 mm Gap
110 kV/cm (440 Td)

Stainless Steel Porous Cathode
Stainless Steel Threaded Anode (8-32)

Photo credit: Dan Singleton
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Emission Abatement Experiments

Co-Axial VW Rabbit Set-up at USC

Need for initial test set-up
Explored surface, corona, and dielectric barrier discharge cells
Allowed modification of pulsed power
Promise with corona, short pulse first seen
NO Removal Results

Shown are results obtained from various sources, and compared.

Major sources of variation between engines are power conditioning, local fields (reactor configuration), and role of particulates and hydrocarbons (HC).

Hydrocarbons play role in NO2 removal.

Energy cost function of V, short pulse, polarity, repetition rate, electrode configuration, dielectric, and current density
Achieved <10 ev/mol! Corresponds to <5% engine energy requirement.

NO PLIF Study

• Needle/plane corona discharge (20 kV, 30 nsec pulse)
• 1b: Before pulse
• 1c: 10 ms after pulse
• 1a: Difference, showing single-pulse destruction of NO

Use LIF to probe the time and spatial profiles of NOx in the plasma.

Initial Ignition Experiments

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Both ignition delay time (0 - 10% of peak P) & rise time (10% - 90% of peak P) ≈ 3x smaller with “corona ignition” (constant-volume combustion chamber, “optimal” energy)

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Pulsed Detonation Engine Work

Robust, miniaturized hi-rep multitube pulse generation

PDE Cycle

Fuel/Air Feed Lines
High Data Rate Pressure Transducers (7)
Test Cell Silencer
CD Spark Plug MSD Unit
Combustor Tube (7 Segments)
Using transient plasma ignition in a pulse detonation engine:
• 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)

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

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

Further PDE Work

Ignition Delay in a Pulse Detonation Engine

Reducing electrode gap and pulse duration:
• Reduced energy input (1J \(\rightarrow\) 100mJ)
• Maintained combustion improvements
• Allowed use of more compact, more robust pulse generator
• Demonstrated that improvement was chemical, not volumetric

Internal Combustion Engines

Using TPI in an ICE resulted in a 20% increase in peak pressure using less energy (57 mJ vs 80 mJ).

Faster flame propagation

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

Data taken in collaboration at Nissan, Yokohama Japan.

Pressure vs. crank angle, for a spark, 100 ns pulse, and 20 ns pulse, ϕ=.72.

1200 rpm, 100 mm-Hg, ADV: 20 deg BTDC, iso-octane-air combustion, each frame is 200 µs long.

Static Constant Volume Combustion

- Compared to spark ignition, TPI produces:
  - Shorter ignition delay
  - Faster pressure rise time
  - Higher peak pressure
- TPI can also ignite leaner mixtures ($\phi < 0.7$)

Stoichiometric ($\phi=1$) $\text{C}_2\text{H}_4$-air at 1 atm

Spark: 10 $\mu$s, 15 kV, 105 mJ pulse
TPI: 12 ns, 50 kV, 70 mJ pulse
Flame Propagation

Flame propagation 6.0 ms after ignition, $\text{C}_2\text{H}_4$-air at 1 atm, $\phi=1.1$, 300 µs exposure

Discharge: 10 µs, 15 kV pulse (105 mJ)
Electrode: Spark plug, 1 mm gap

Flame Diameter = 74 mm

Discharge: 12 ns, 42 kV pulse (70 mJ)
Electrode: 3.2 cm anode, 6 mm gap

Flame Diameter = 93 mm

Average increase in flame speed of 15% TPI compared to spark ignition
Multiple Ignition Sites

$t_{\text{start}} = 0$ s after discharge. 1000 µs exposure

- Multiple spatially separated ignition sites can be generated efficiently
- Low energy, short pulses ($\leq 1$ mJ/streamer)

High Pressure Static Combustion

Ignition of Methane-Air in a High-Pressure Static Chamber

A comparison of combustion in a static chamber via 12 ns pulse and 85 ns pulses producing transient plasma across a 4 mm gap using a coaxial, 32 mm long electrode vs thermal ignition using a glow plug. The CH₄/air mixture is stoichiometric, and the initial pressure is 30 atm (441 psi). The combustion volume is 572 cc.
Diesel Combustion

Ignition of Diesel-Air in a High-Pressure Static Chamber

A comparison of thermal vs. plasma enhanced combustion of diesel fuel in a static chamber. Ignition is achieved by injecting the diesel fuel into air heated by a glow plug. The plasma enhanced case includes an 85 ns pulse delivered at 15 ms, producing transient plasma across a 4 mm gap. The initial pressure is 30 atm (441 psi).
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While the components change, the core architecture of pulse generation remains unchanged.

Development of smaller, more robust pulse generators enables new ignition applications

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OH· PLIF demonstrated formation of radicals in streamer channel, but also highlighted the absence of OH· by relevant ignition times (1-5 ms)

OH· vs. O₃, Water Vapor?

Behavior of PDE at NPS with and without vitiator led the suspicion of role of water vapor. Kinema calculations by J. Luginsland at NumerEx highlighted greater role of water vapor in O pathways.
OH· vs. O₃ Experiment

Experiment confirms greater impact of water vapor on O₃ than on OH·. In addition, O₃ lifetimes in discharge afterglow could be long enough to impact combustion directly. 100 kV on 3 cm gap with 80 ns pulse (20 ns rise)
Discharge Characteristics

26 kV peak voltage at 13 ns FWHM with 3 ns rise time, 30 mJ energy input per pulse, 8 mm gap

Streamers are highly filamentary, with excitation of N₂(C) propagating from center HV anode to grounded outer cathode
Comparison to ICEPIC

ICEPIC calculations by J. Watrous at NumerEx propose low energy and density e- propagation from cathode to anode before propagation of relatively high energy e- in opposite direction; working on experiments to confirm this model.
Temperature Measurements by OES: Coaxial Streamer Discharge in Air

Using a custom-built double-pulser, N2 SPS emission measurements from two points in time can be compared to extract rotational temperature
Optical Diagnostics on the Discharge

For practical applications and OES a coaxial electrode geometry is used; for laser-based measurements, however, it is necessary to reduce the dimensionality of the discharge, thus a point-to-plane geometry was adopted.
Optical Diagnostics on the Discharge

For practical applications and OES a coaxial electrode geometry is used; for laser-based measurements, however, it is necessary to reduce the dimensionality of the discharge, thus a point-to-plane geometry was adopted.
28 kV on an 8mm gap with 12 ns FWHM (4 ns rise). Uncertainty is high, with ~40% error even with averaging 3000 shots.
Statistics on individual points bear out reasonable distributions
O· TALIF in Fuel/Air Mixtures

Emission intensity is also spread out, “uncertainty” is a physical phenomenon.
O· TALIF in Fuel/Air Mixtures

The addition of fuel radically alters the discharge afterglow chemistry, even outside the limits of combustion. Propane/Air was also measured, yielding O atom behavior similar to methane/air.

Thanks to the Lempert group at tOSU for the collaboration!
N2 CARS can be compared to OES for temperature measurement consistency, as well as determining energy pathways through N2*. Also thanks to the Lempert group at tOSU for the collaboration.
The vibrational populations of ground state N2 behaves in an interesting manner, increasing well after the end of the discharge before layer decaying.
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Summary

• Ignition method increases fuel efficiency
  • Uses nanosecond-scale 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
Future Work

• Develop even smaller, more robust pulse generators
• Continue transient plasma ignition implementation into engines, including the use of transient plasma in a “plasma-assisted combustion” role where no ignition necessary (turbines, diesel)
• Measure species and plasma properties in order to better understand mechanisms of transient plasma ignition
Acknowledgements
Questions?
Bio-Medical Research with Nanosecond Plasma and Electric Fields

Experiments and Projects

- Nanosecond Pulsed Power–Based
- Cold Plasma Sterilization: Endodontic studies (C. Jiang)
  - Nooks and Crannies – Root Canal studies
- Cancer: in vitro studies–Phosphatidylserine inversion
  - localized, experiment, simulation
- Cancer: in vivo studies
  - mice – human pancreatic cancer tumors
  - Human basil cell carcinoma
- Cardiomyocyte response to ns pulses
- Carbon Nanotube (CNT) probes

Multidisciplinary collaboration disciplines:
Electrical Engineering, Chemical Engineering and Materials Science, Medicine, Biology, Cancer and Oncology, Biomedical Engineering.

UNITS: Viterbi School of Engineering, Cedars-Sinai Research Center, ISI-MOSIS, Keck School of Medicine, College of Letters Arts and Science

Thomas Chen  KSoM Neurology
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Tao Tang  Grad student EE
Miguel Valderrabano DeBakey cardiology
Tom Vernier  Res. Assoc Prof. USC
Pulsed Power for Dental Sterilization, Root Canal study

Before Treatment

After Treatment


Pulsed Electric Field Skin Cancer Study

Directions:

Apply field directly to tumor

Experimental setup.
NanoElectroPulse Therapy for Skin Cancer

With Koeffler Group, Cedars-Sinai
Pulsed Power for Treatment of Tumors

0 weeks

1 week

2 weeks
Mouse Conclusions

1. Nanopulses cause the death of tumor cells in vitro. \( ED_{50} \) is between 100–200 pulses, 3000 V and 1 mm electrode spacing.

2. 200 or 400 pulses, 7000 V, 20 ns, 50 Hz eliminates skin cancer from mice with 1–2 treatments.
   - 1 Treatment: 18 tumors (80%)
   - 2 Treatments: 3 tumors (15%)
   - 3 Treatments: 2 tumors (5%)

3. If part of a tumor is not treated, it will continue to progress, and another treatment is required to remove the tumor entirely.
Cardiomyocyte Response to Pulsed Field

Rabbit cardiomyocyte, dormant, 3 ns, 6MV/m
(Miguel Valderrabamo, UCLA)

Cardiomyocyte Response to 3 ns pulse

Voltage delivered to cardiomyocytes

![Graph showing voltage delivered to cardiomyocytes over time](image)

- Voltage (kV)
  - 0.7
  - 0.6
  - 0.5
  - 0.4
  - 0.3
  - 0.2
  - 0.1
  - 0

- Time (ns)
  - 0
  - 10
  - 20
  - 30
  - 40
  - 50

Diagram of experimental setup:
- Anode
- Cathode
- Pulse Generator
- Microscope Lens
- Emission Filter
- Excitation Filter
- LED
- CCD

100 µm
20 x

Miguel Valderrabamo, UCLA
- Average juice yield increase after PEF treatment ≈30%
- Beneficial compounds (antioxidants) increased
Created a Workshop to teach scriptwriting to scientists
Joe Petricca, Alex Singer

2005 Catalyst Workshop participants

Directors Alex Singer and Martha Coolidge at the 2004 AFI Catalyst Screenwriting Workshop for scientists and engineers. Photographs reproduced from Nature, 430, 720, 12 Aug. 2004
Noise Reduction
Proposed Work (with Gutmark)

Fan/Core Shear Layer
Mach Wave Radiation as a result of Instability Wave
Core Stream Potential Core

lower speed secondary flow
unheated bypass stream
flow

Plasma
Fan/Core Shear Layer

Cold Plasma Layer Disrupts Instability Wave Formation

High Voltage Wire

Ground Wire

High Voltage Strip

Ground Strip

Core Cowl Nozzle (insulator)

Electroporation of Wine and Food Grapes
(UC Davis Collaboration, reported at ASEV)

PEF produced here an increase of juice volume (30%)
Platform for Bio-Electro-Optical Imaging of Living Cells

Zeiss, Axiovert 200

Multiple-channel, time-lapse, Z-stacks
5 ports
LaVision 80 ps camera

Electrode  Channel  Micro slide

4 Channel Microchamber, 30µm square sidewall (right)

Pulse: 32 ns, with a leading edge transition time of 2.2 ns
Electric field: 450 MV/m (mV/nm) from top (anode) to bottom (cathode).

Red-White – water  Green – choline  Blue – serine  Yellow – glycerophosphate  Gray – HC tails

Nanoporation and PS translocation in a bilayer in a 450 mV/nm electric field

Water atoms are red (O) and white (H); phospholipid tails are gray; glycerophosphate atoms are yellow, choline atoms green, serine atoms blue.

Serine atoms are enlarged to enhance visibility.

To appear JACS