Nanosecond Pulsed Power-Generated Transient Plasma for Energy and Environmental Applications

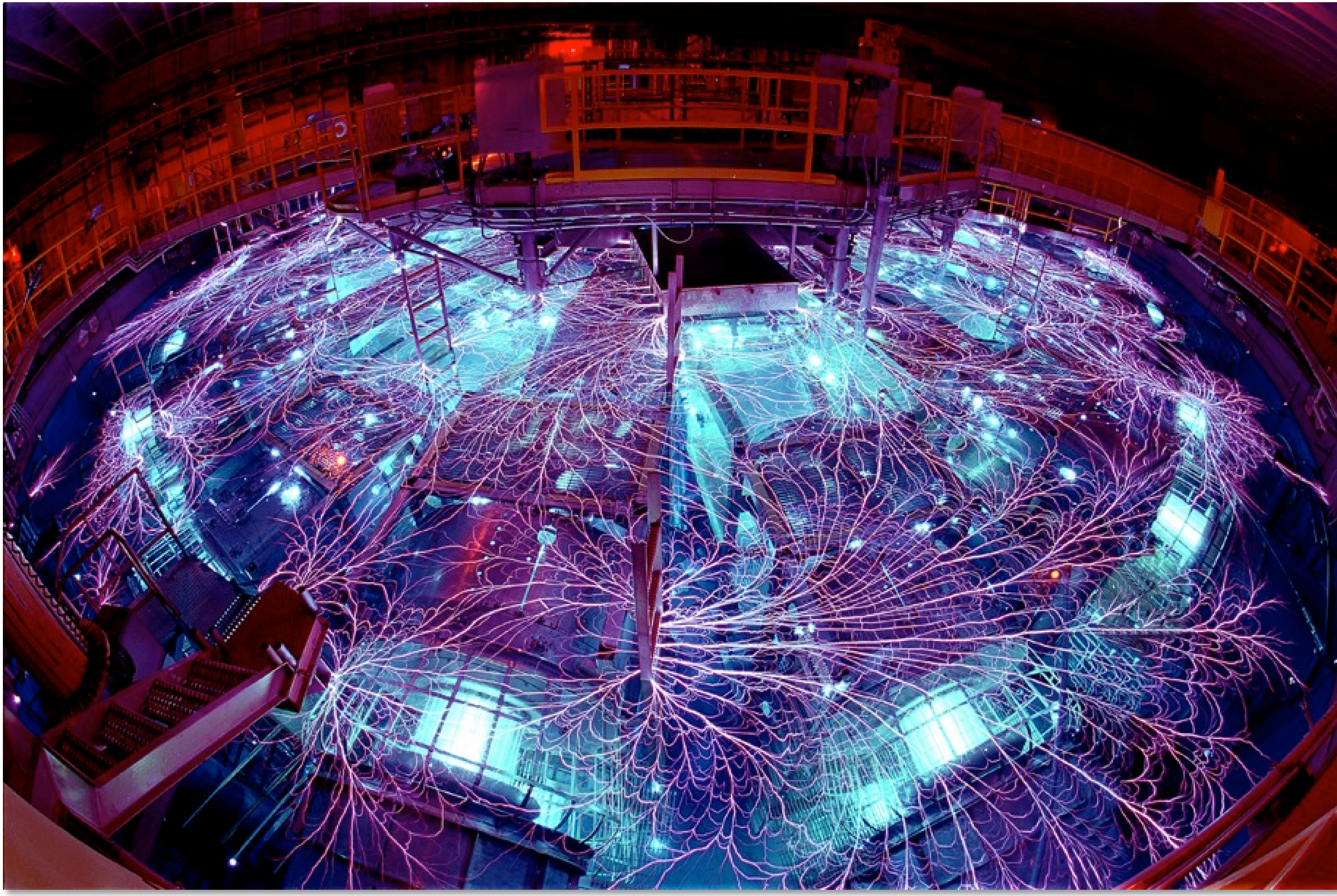
Research includes:

- Transient Plasma Ignition and Combustion.
- Plasma Remediation of Emissions
- Why transient plasma (corona, streamers) vs DBD, other
  - Works — and is efficient. But the physics is hard. And requires short (nsec) pulses
- Pulsed Power Research Role?
  - Required to enable short pulses
- Bioelectrics, apoptosis, therapeutic applications
- Wine Production, Educational Outreach

USC Pulsed Power Group including Martin Gundersen

Research has been supported the AFOSR, DOE, ONR, NIH, Nissan Corp., the Alfred Mann Institute, TCC Group, NumerEx, ISSI, LLNL, LANL, and others.

Presentation for U. Michigan MIPSE, Sept 20, 2017 Martin Gundersen



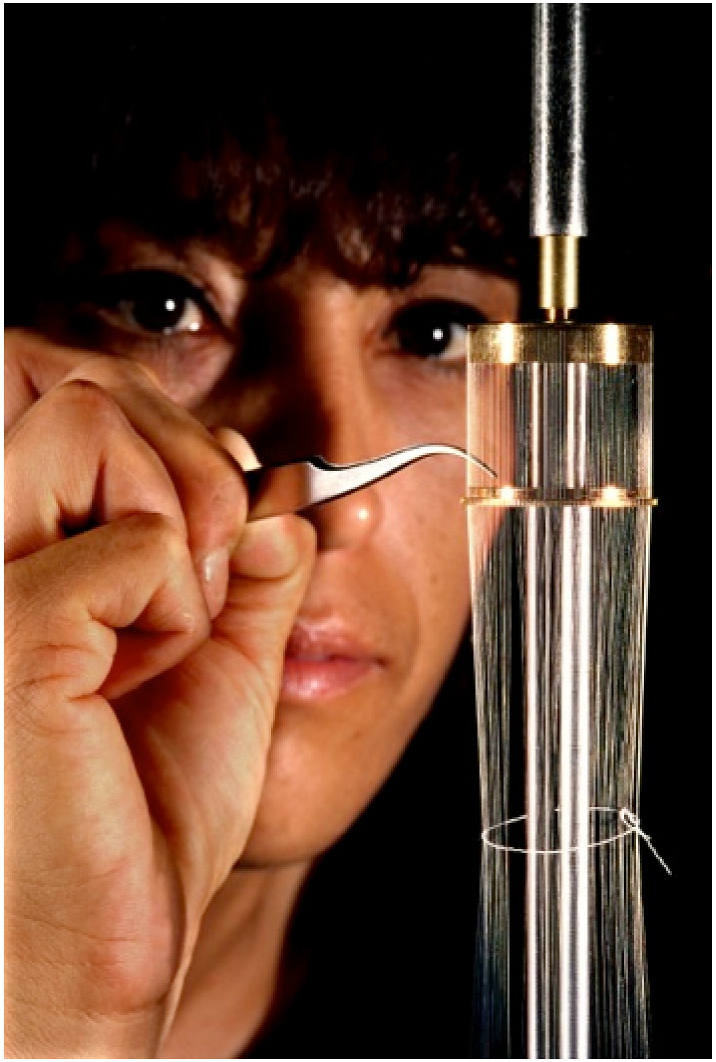
What is Pulsed Power? Example: The Sandia National Labs “Z” Machine
Swimming pool-sized pulse generator. (Could have used UM “Z”)

What is Pulsed Power?

Often Misunderstood Potential

- There are many roles and applications for pulsed power –potential of uses still not fully understood.
- Liner for the "Z" Machine (right); with current passing through, phenomenon called **Z Pinch.**

- *Fusion Research Application:*
  - All energy is conducted through the Liner creating a 'pulse'.
    - Sandia National Laboratory Fusion Program: Goal is to drive sufficient current through the Liner to compress & induce fusion.



Source: SNL

Our Pulsed Power: Exploring Miniaturized Applications

- Applications such as transportation require low-power, lightweight and compact systems
- Size decreasing as high-voltage switch technology advances
- Pulse width decreasing
  - **Reduces energy consumption**
  - And--Increases effectiveness

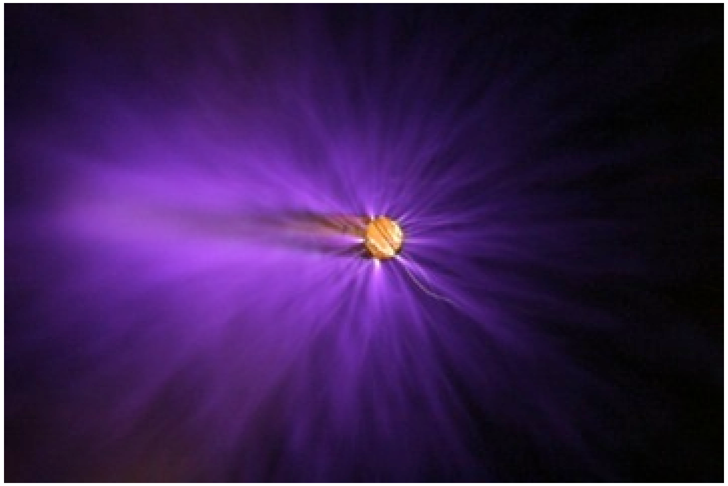
Year	Front End Switch	Voltage (kV)	Pulse Width (ns)	Pulse Energy (mJ)	PRF (Hz)	System Weight (kg)
1998	Thyratron	50	150	1000	10	35
2003	Pseudospark	90	85	1500	50	15
2006	IGBT	60	20	300	100	7
2008	SCR	60	12	200	200	5
2012	MOSFET	60	12	200	10000	3

Our Pulsed Power

Ignition, Combustion, and Remediation

- **Nanosecond Pulsed Power Enables High Power with Low-Energy**

- Transient plasma flame ignition
  - Applications: fuel flame ignition, combined cycle, pulse detonation engine, internal combustion engine, flame holding, high altitude relight
  - *Source: Short (ns), high power, low energy* pulses were observed to be effective for plasma chemistry – through true non-thermal processes.
  - Nomenclature: Streamer, transient plasma, corona
  - Distinctive element: True non-thermal electron energy distribution
- Short pulse generation to produce streamers.



- **Contributors:**
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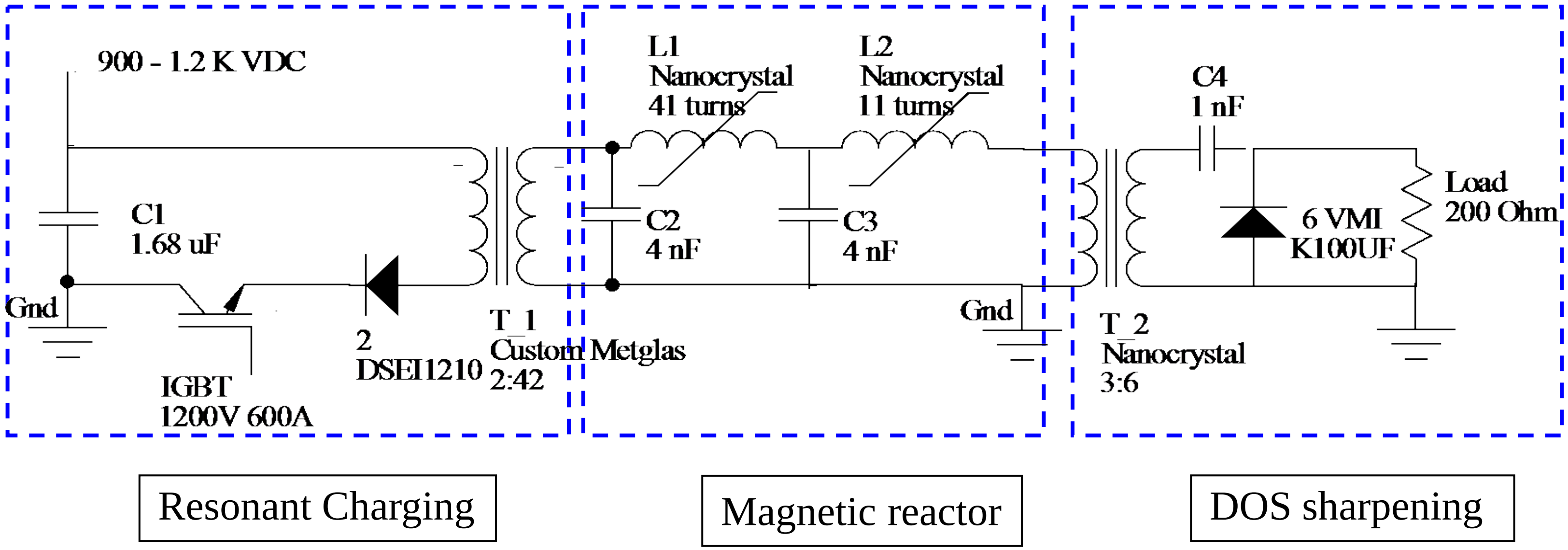
  - o *Chris Brophy and Jose Sinibaldi (NPS)*
  - o *Ron Hanson, Jay Jeffries, Ethan Barbour (Stanford)*
  - o *M. Kushner (UI, UM, BLT Melt)*
  - o *Fred Schauer (WPAFRL)*
  - o *Effie Gutmark (U. Cincinnati)*
  - o *Joe Shepherd (Caltech)*

Diode sharpened Magnetic Compression Pulser



- Magnetic Compression, takes a low voltage long pulse, and compresses it through a series of LC resonant stages.
- Novel diode sharpening of the pulse
- 57 kV, 20 ns (FWHM) pulse
- Used to explore advantages of a shorter pulse length for ignition applications

Tao Tang, *A. Kuthi, F. Wang, C. Cathey, and M. A. Gundersen, "***Design of 60kV 20ns solid state pulse generator based on magnetic reactor driven diode opening switch***," 27th International Power Modulator Conference 2006, Washington D. C., District of Columbia, May 14-18th, 2006.*

Also design, build and use pseudsopark-based pulsers

These are analogous to thyratron (or SCR) based, 'line-type' but faster rise, higher current than thyratron.

Typical Pulsed Power Design (cont.)

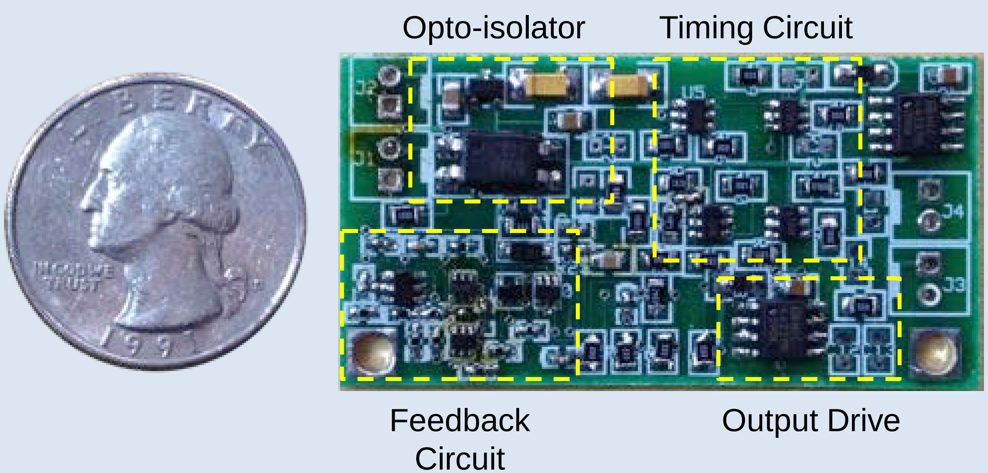
Managing Electromagnetic Compatibility

Goal: Keep High Current Transient Signals *Confined* to Pulse Generator and Cable

All internal modules are shielded

- Differential Output Cable / Electrodes
  - Keep high currents from flowing through system ground.
- Embedded Power and Trigger Signals
  - Minimize exposed wires that can pick up noise.
- Isolated Power Supplies
  - Provide isolation from noise sensitive equipment.

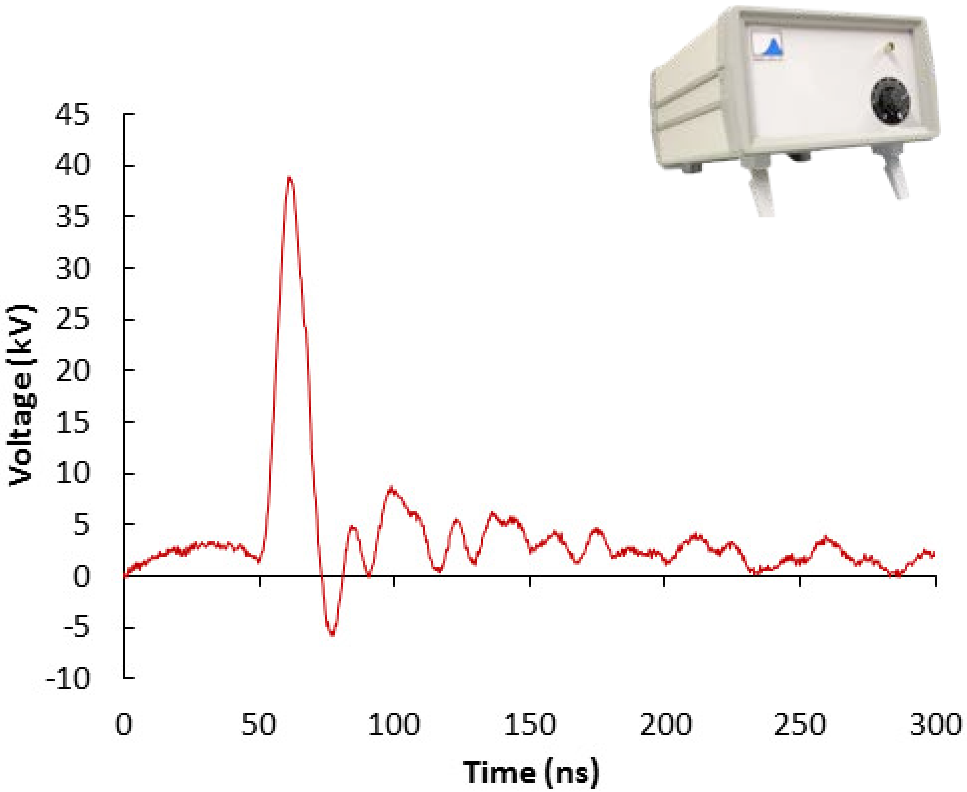
Optically Isolated Controller with Feedback Control

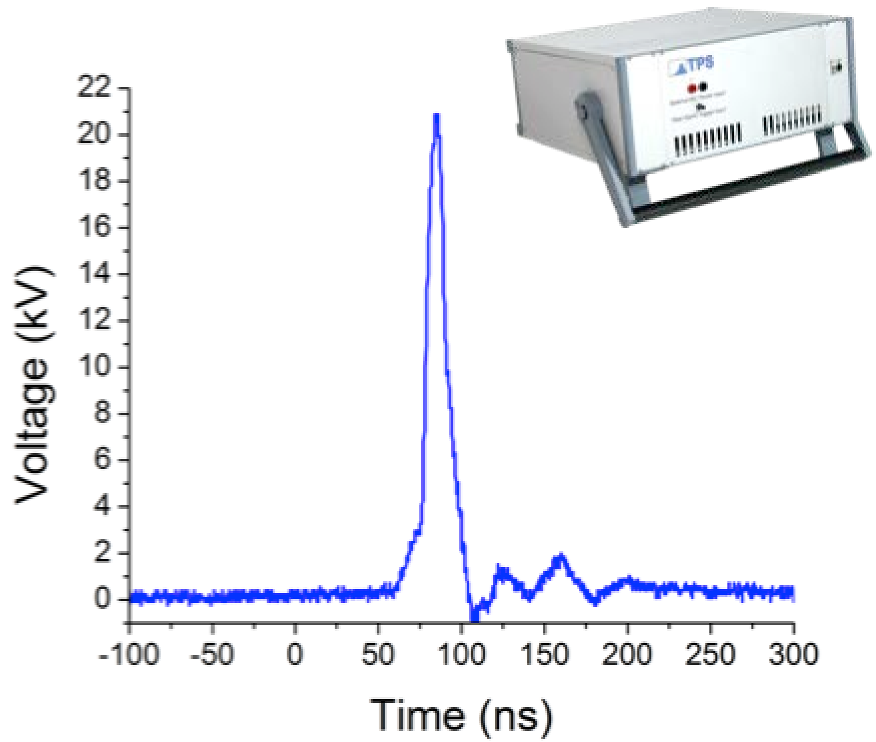


Features:

- ***Optical Isolation***
- ***Variable width and amplitude***
- ***External Trigger Capability***
- ***Feedback regulates rep rate to keep it below a maximum***

New Pulse Generators for Combustion and Medicine





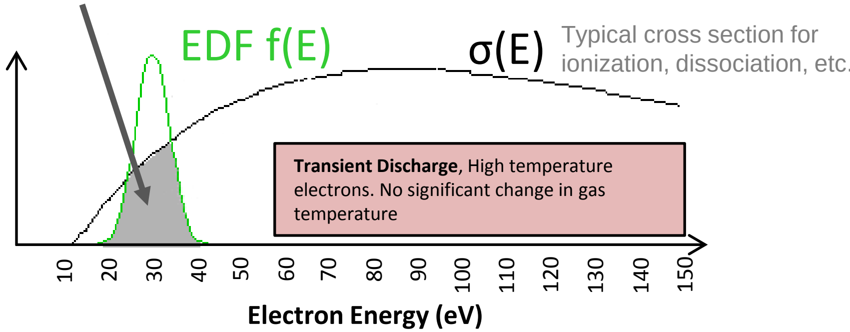
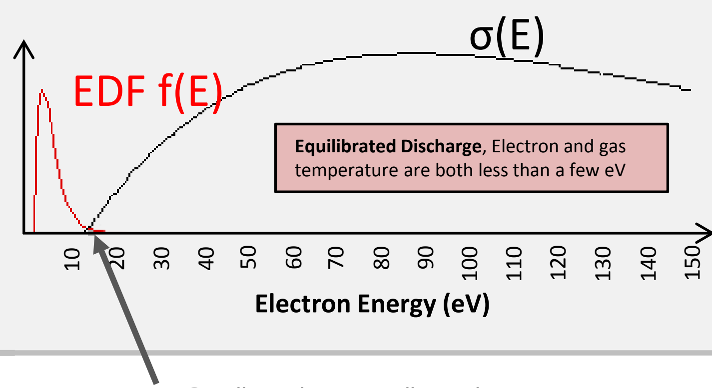
Specifications:
- 40 kV into 200 Ω
- 12 ns Full-Width-Half-Max Pulse Duration
- 5 ns Pulse Risetime
- 10 kHz Pulse Repetition Rate (Burst)

Specifications:
- 20 kV into 50 Ω
- 15 ns Full-Width-Half-Max Pulse Duration
- 4 ns Pulse Risetime, $dV/dt = 5 \times 10^{12}$ V/s
- 20 kHz Pulse Repetition Rate (Burst)

Why? Transient Plasma → Energetic Electrons

During a transient phase, prior to arc formation, there are relatively more energetic electrons -- **while there is still a high voltage across the gap**

Reaction rate proportional to overlap. Large overlap during this time.

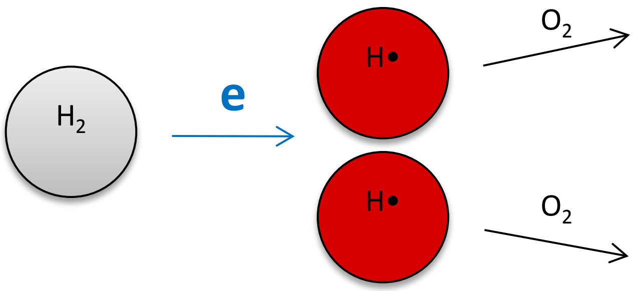
For first **T<10 ns** There is a Transient Plasma and **Hot, energetic** electrons	Typical electron distribution function, f(E), and cross section, σ(E), **during** first 10 ns of the discharge	
After transient, or hot phase, **T>100 ns,** Arc Discharge – with Cold electrons	Typical electron distribution function, f(E), and cross section, σ(E), **after** first 100 ns of the discharge	

Small overlap = small reaction rate

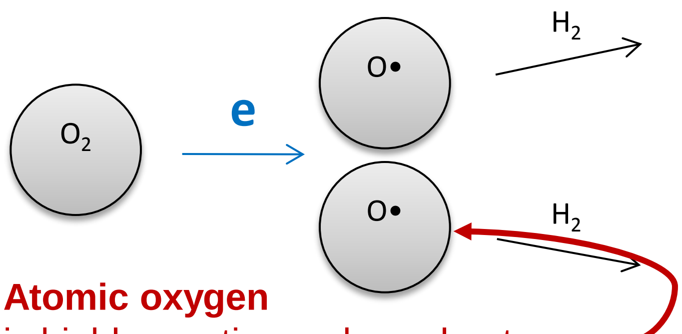
$$\text{Reaction Rate} \propto \int f(E)\sigma(E)dE$$

The Associated Reactive Chemistry

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

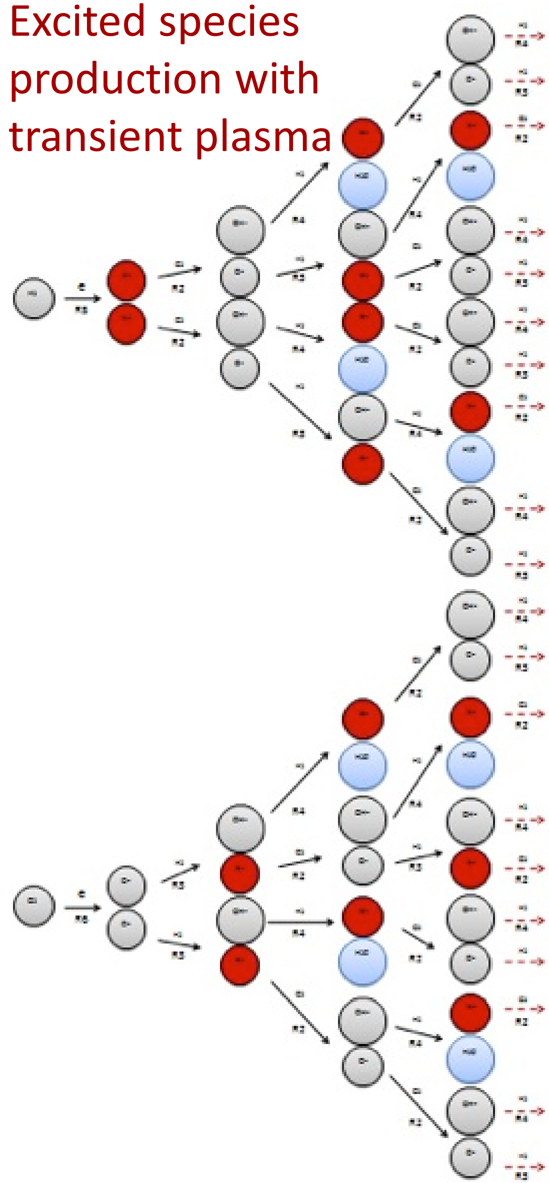


- Transient plasma dissociates molecules via electron impact
- Produces very reactive excited species, Increases chain branching and propagation reactions

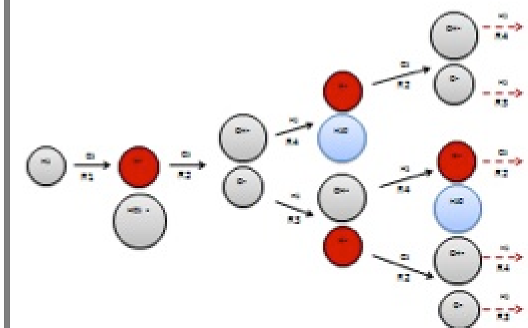


Atomic oxygen
is highly reactive and accelerates combustion and improves stability

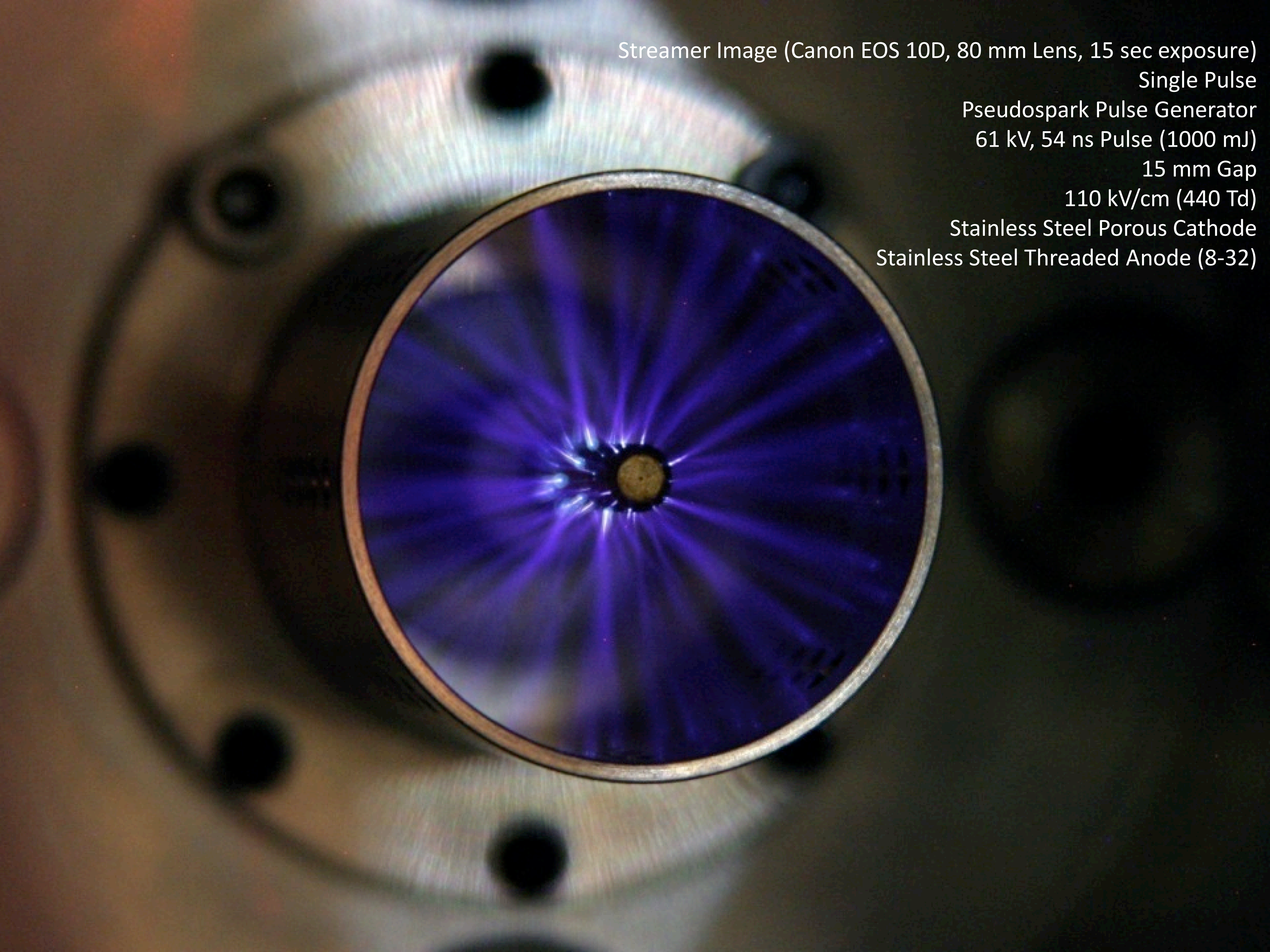
Excited species production with transient plasma



With spark discharge



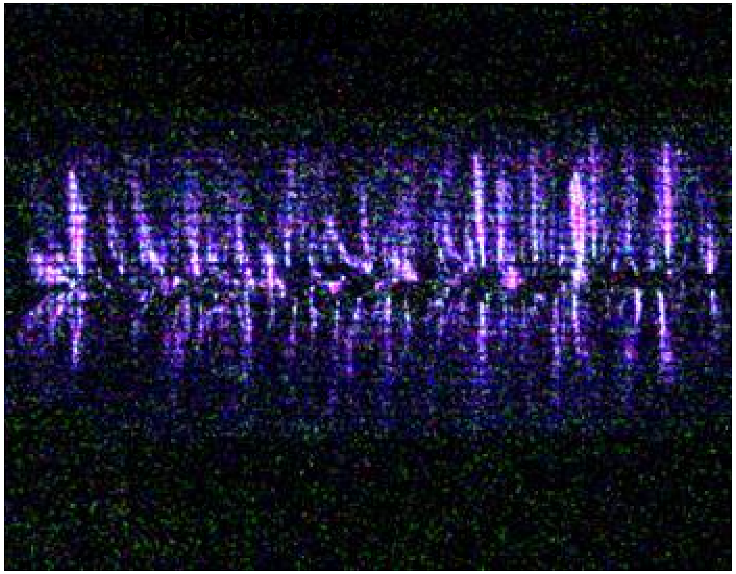
S. M. Starikovskaia, "Plasma Assisted Ignition and Combustion," J. Phys. D: Appl. Phys. 39 (2006) R265–R299.


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)

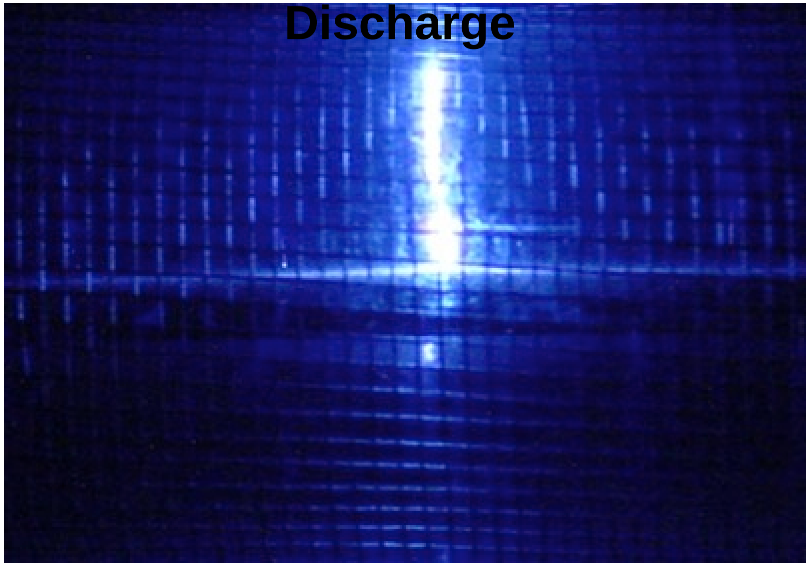
Transient Plasma Introduction

TP Corona

Arc Discharge



Streamers formed over ½ m distance, 5 cm width tube, center electrode, using pulse ≈ 50 ns at ≈ 40 kV.



Same setup, but with >100 ms pulse.

The streamers, which have higher energy electrons, and which fill the volume tube (left image), have degenerated into a single constricted arc, with low electron energy (right image).

Streamer and arc images taken at Seaver Science Center, Los Angeles, CA

Support provided by US Air Force Office of Scientific Research (US-AFOSR)

Two Important Areas for Use of Transient Plasma

Exhaust remediation

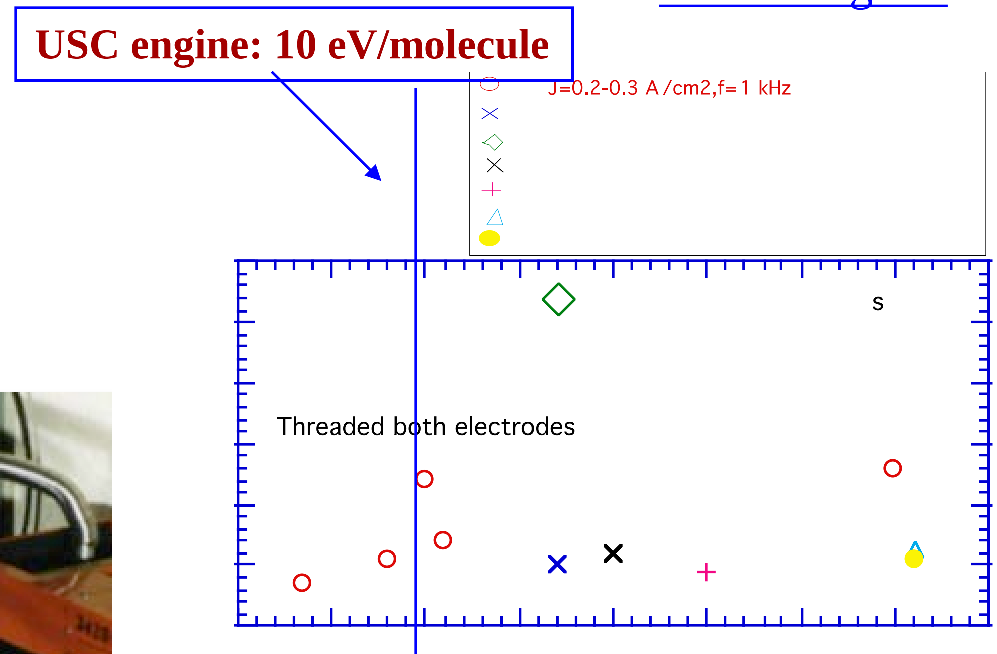
Ignition and combustion enhancement

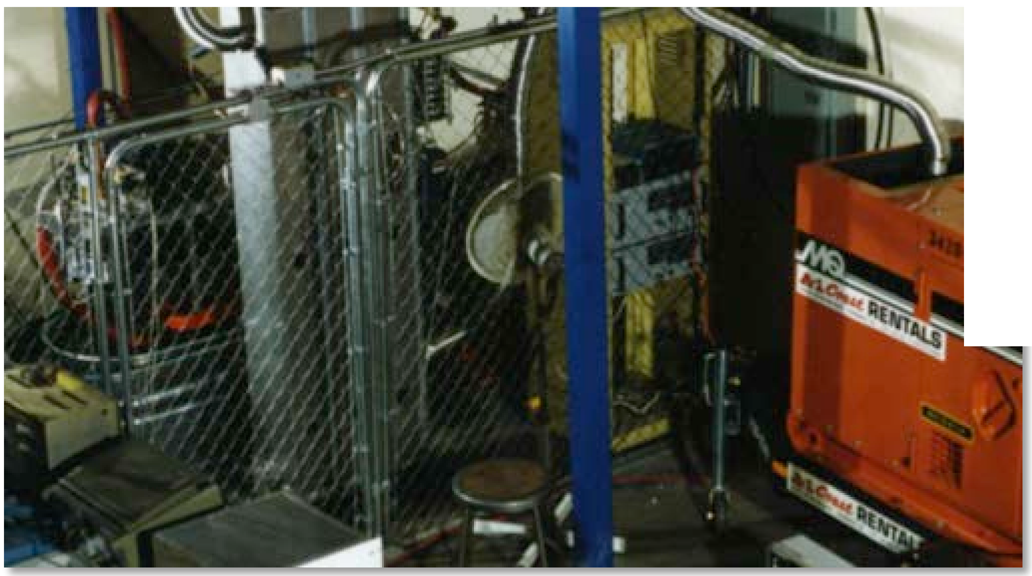
Remediation with Transient Plasma: NOx, SOx, Soot

Mid 90s (ONR, DOE, ARO)
Diesel, reactor, nsec pulses

Key result: Efficient remediation enabled by using **short pulses (<50nsec)**

97-98 Program





Energy cost

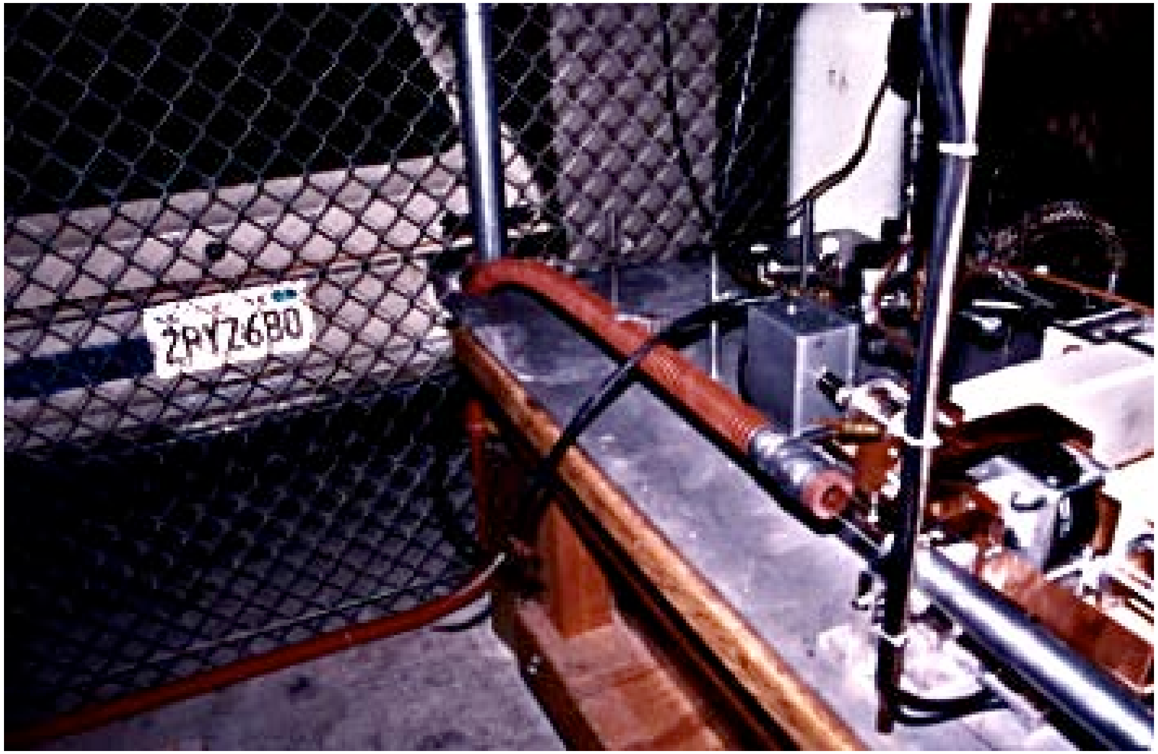
Achieved <10ev/molecule!

<5% engine energy requirement.

V. Puchkarev and M. Gundersen, "Energy efficient plasma processing of gaseous emission using short pulses," Appl. Phys. Lett. **71** (23), 3364 (1997) + patent 1997

Transient Plasma Remediation History of NOx (cont.)

Volkswagen Rabbit Experiment



Co-Axial Diesel Rabbit Set-up at USC

Reported CNN Future Watch

Ticketed by Campus police

Simple early test set-up

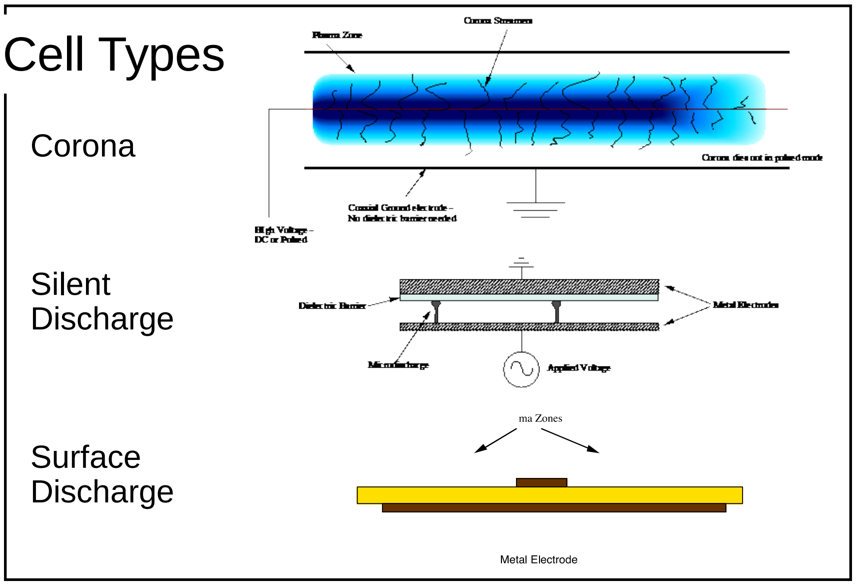
Explored surface, corona, and silent barrier discharge cells

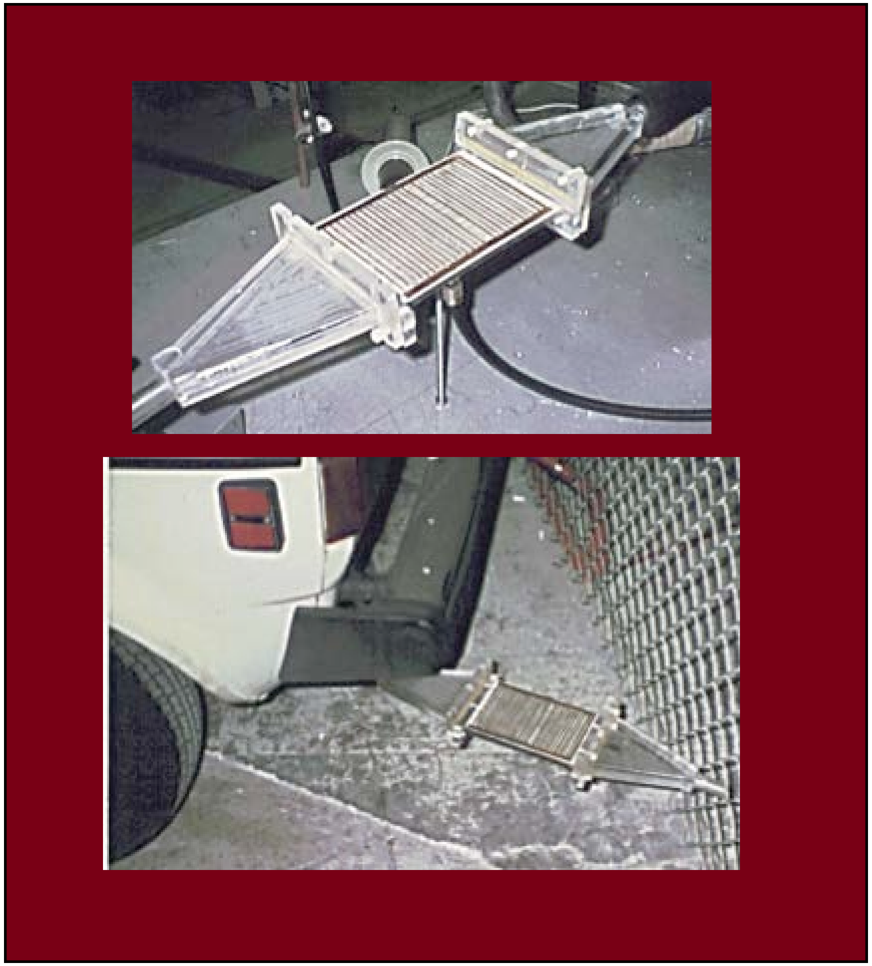
Allowed modification of pulsed power

Promise with corona, short pulse seen

Transient Plasma Remediation History of NOx (cont.)

Volkswagen Rabbit Experiment (cont.)

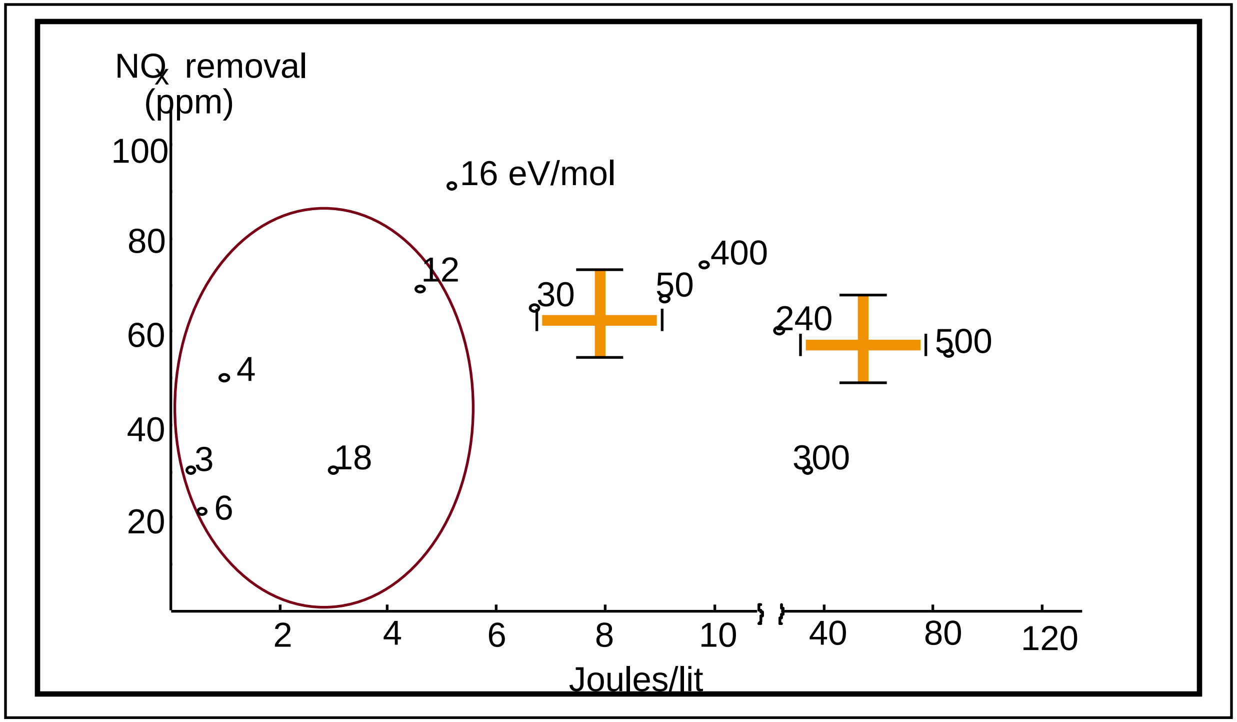




Plasma mufflers:
Above: Various cell types investigated.
Best results were achieved with corona (transient plasma)
Right: Surface discharge plasma cell attached to diesel Volkswagen Rabbit.

Transient Plasma Remediation History of NOx (cont.)

Efficiency & eV/Molecule of Various Cells

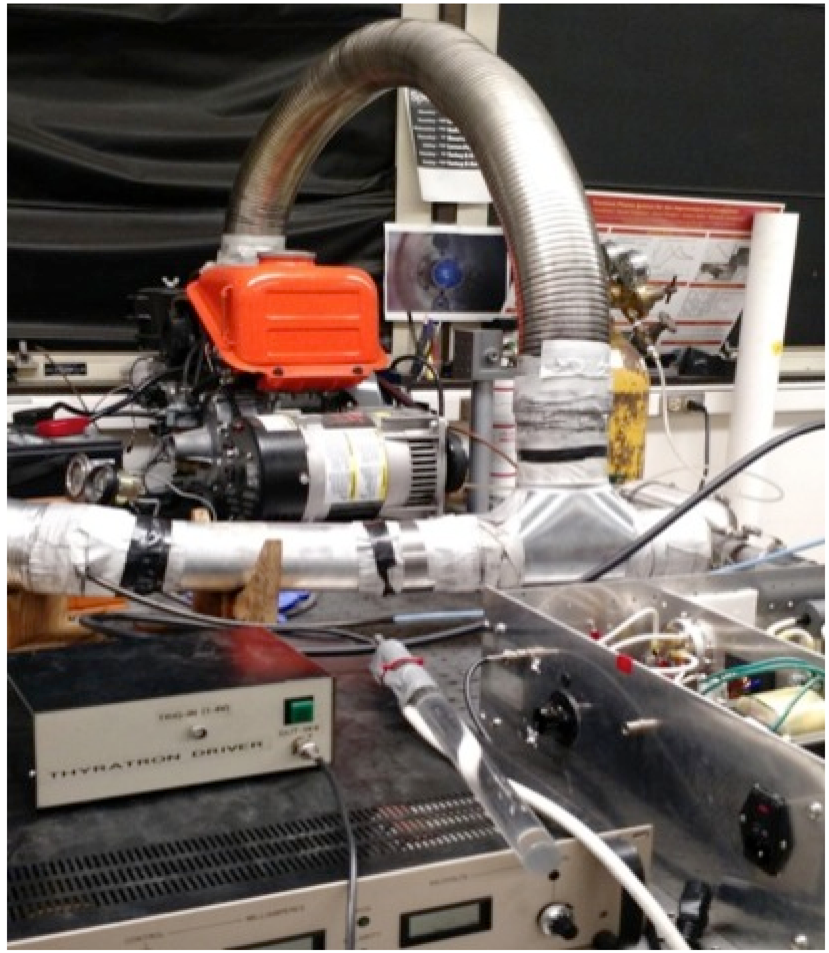


- Data (approximate) showing energy/molecule under various conditions, differing cell configurations. Data are for 100 ppm initial conditions NO_x.
- Efficiency for data within ellipse corresponds to requirement of approximately 2% engine power.
- Low current density, transient processes, lead to efficiency

V. Puchkarev and M. Gundersen, "Energy efficient plasma processing of gaseous emission using short pulses," Appl. Phys. Lett. **71** (23), 3364 (1997) + patent 1997

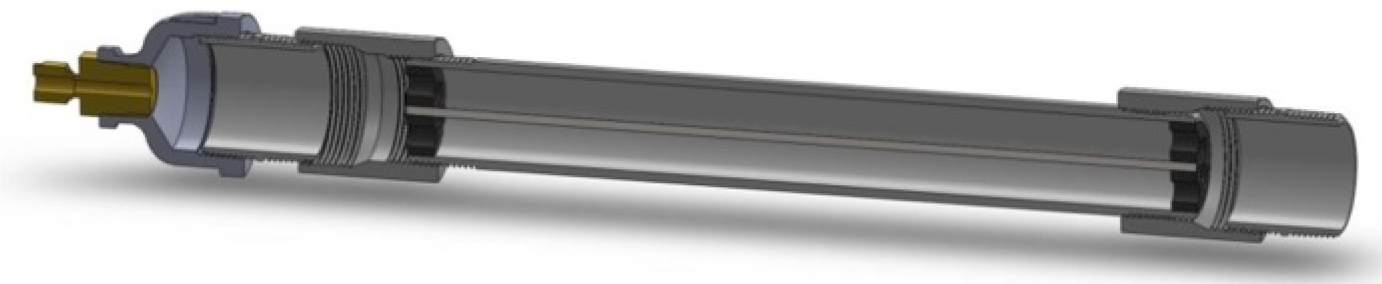
USC 5 kW Engine Setup

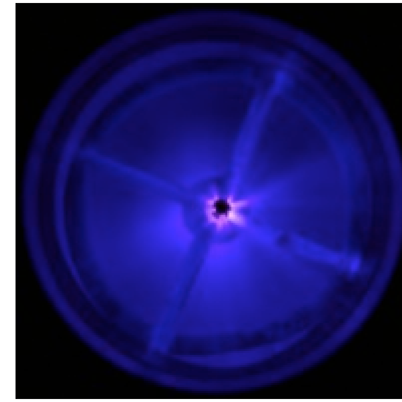
Experimental setup showing Kubota diesel engine, thyratron pulser and plasma reactor.



Transient Plasma Emission Remediation

Slip-Stream Experimental Setup





Engine → Exhaust → Reactor → Exhaust → Horiba® PG350 Exhaust Analyzer

TPS® Pulser → Reactor

TSI DustTrak® Particle Analyzer

Teledyne® UF Particle Analyzer

Slip-Stream USC Test Experimental Setup

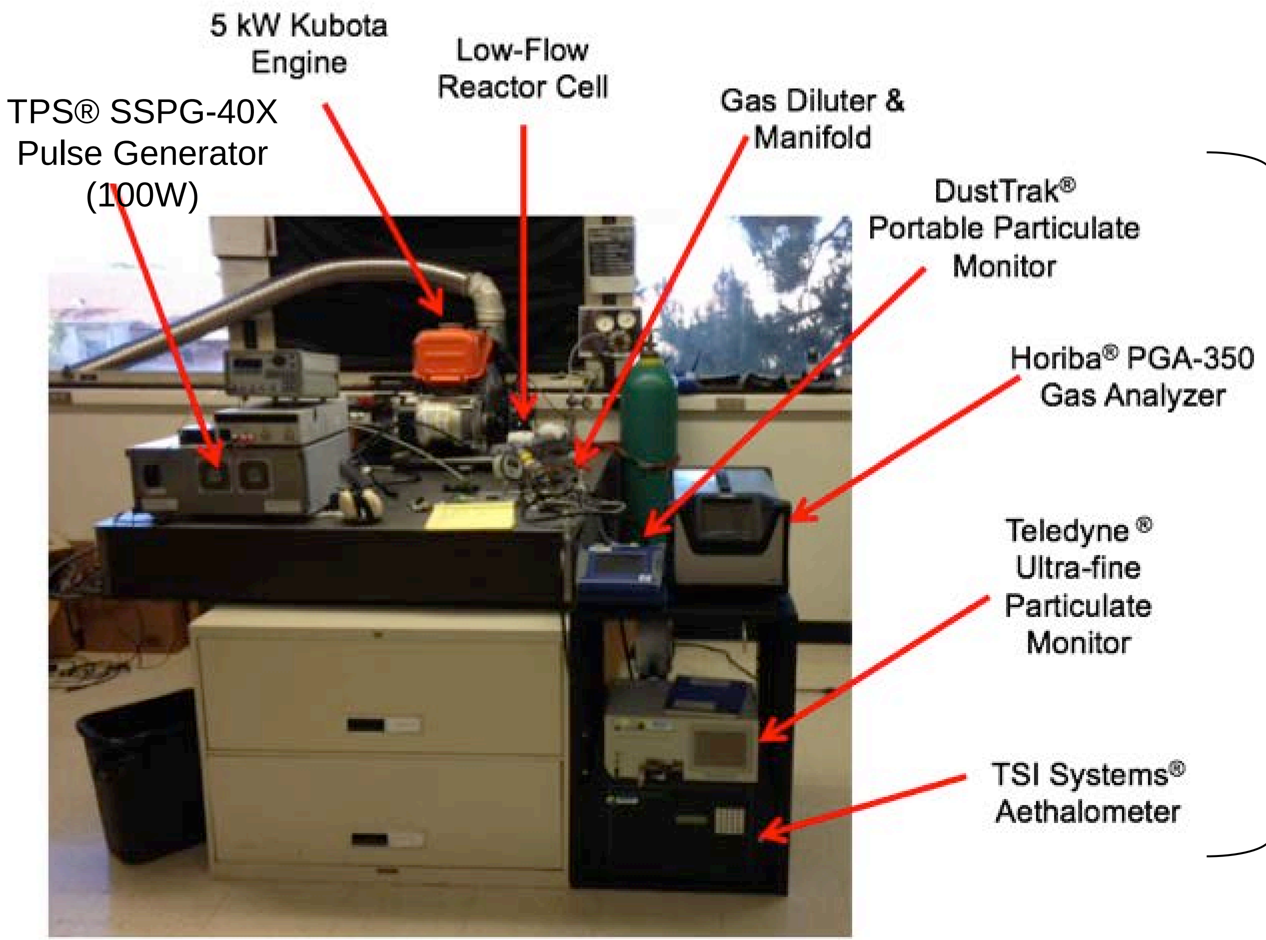


Photo taken at Seaver Science Center
University of Southern California, Los Angeles, CA

South Coast AQMD

Particle monitoring instrumentation generously provided by the South Coast Air Quality Management District (SC-AQMD) through active collaboration on research for emissions reduction.

All instrumentation and methodology comply with US EPA and California Air Resources Board (CARB) protocols

California Environmental Protection Agency AIR RESOURCES BOARD

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Slip-Stream Field Test Experimental Setup

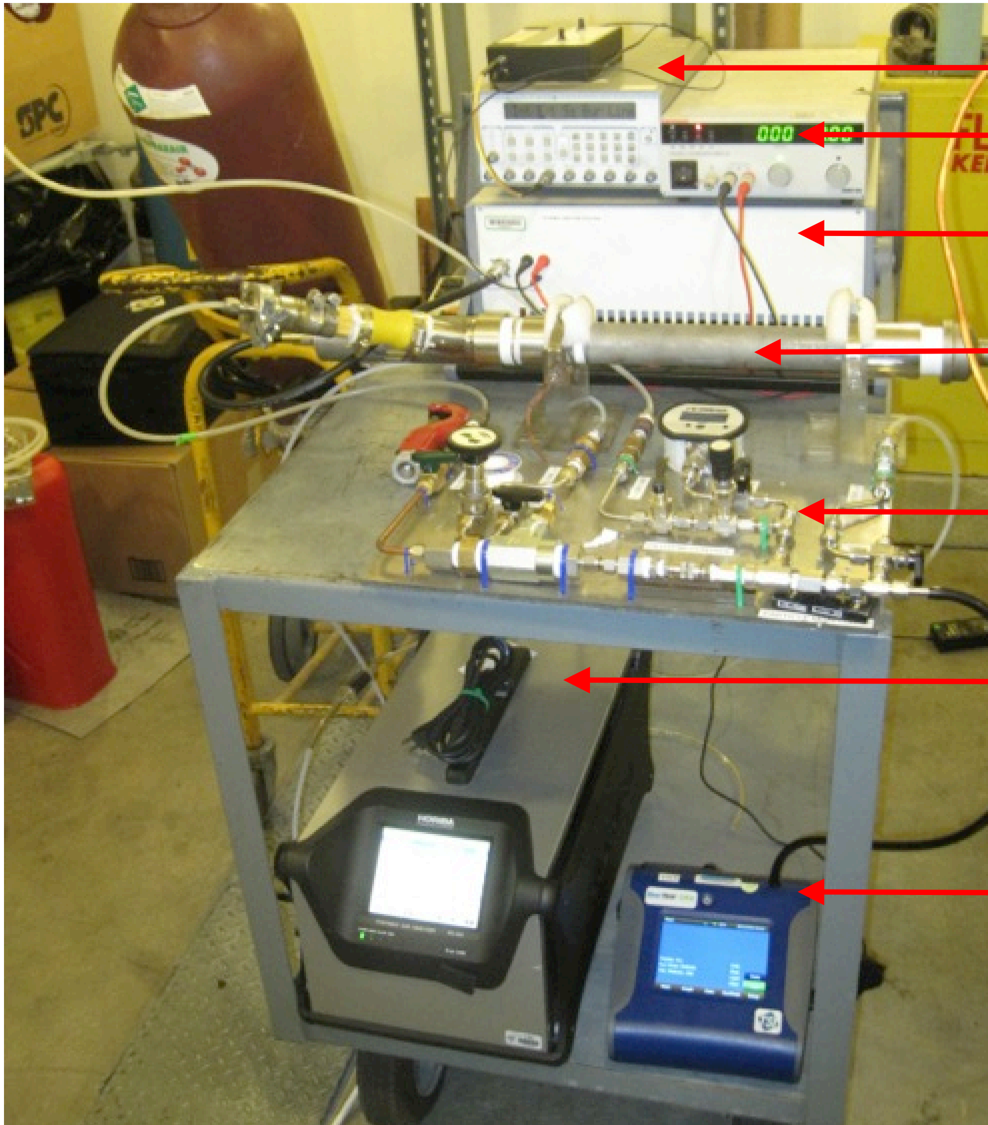
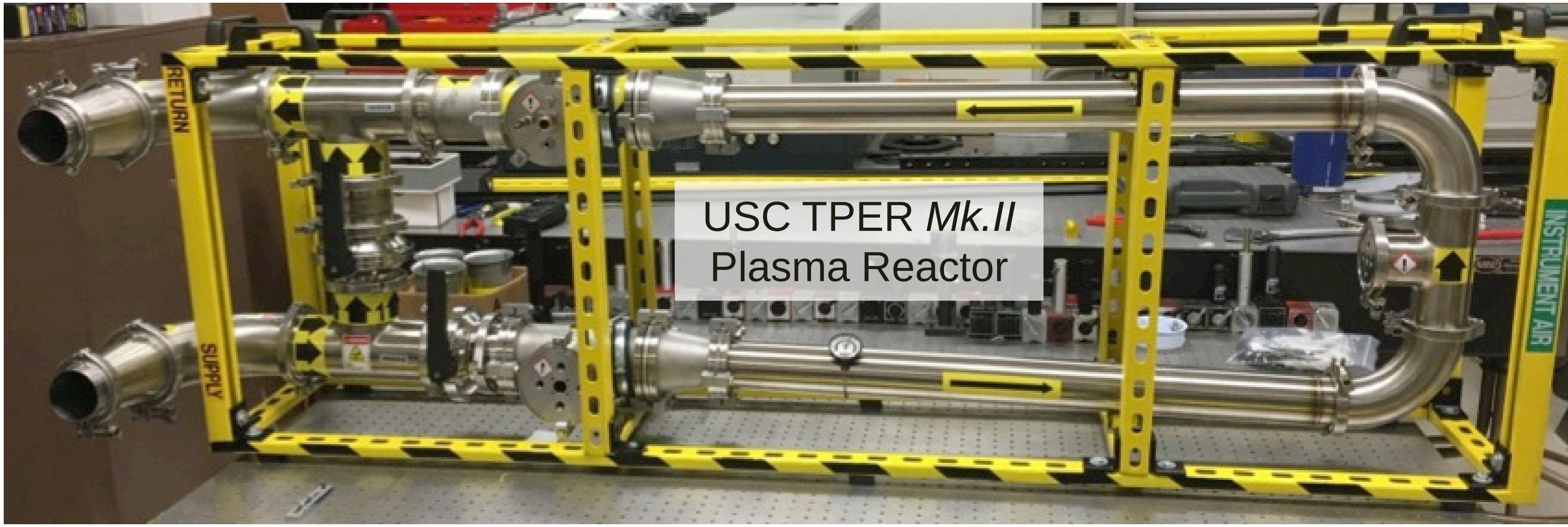


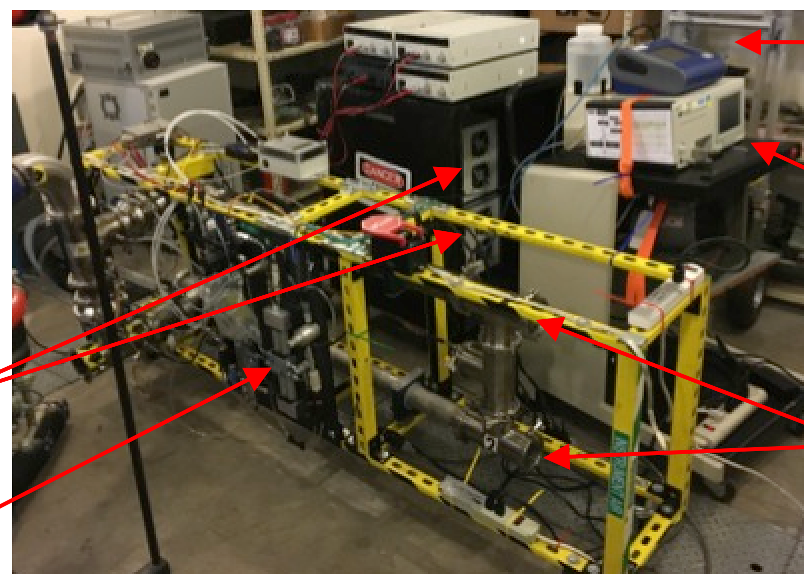
Photo taken during field tests at the Naval Postgraduate School - Monterey, CA

NPS
PRAESTANTIA PER SCIENTIAM
NAVAL
POSTGRADUATE
SCHOOL

USC Laboratory Full-Flow Setup



USC *Mk.II* Reactor
Provides 5000X
Increase in Scale-Up!



TSI DustTrak® Particle Monitor

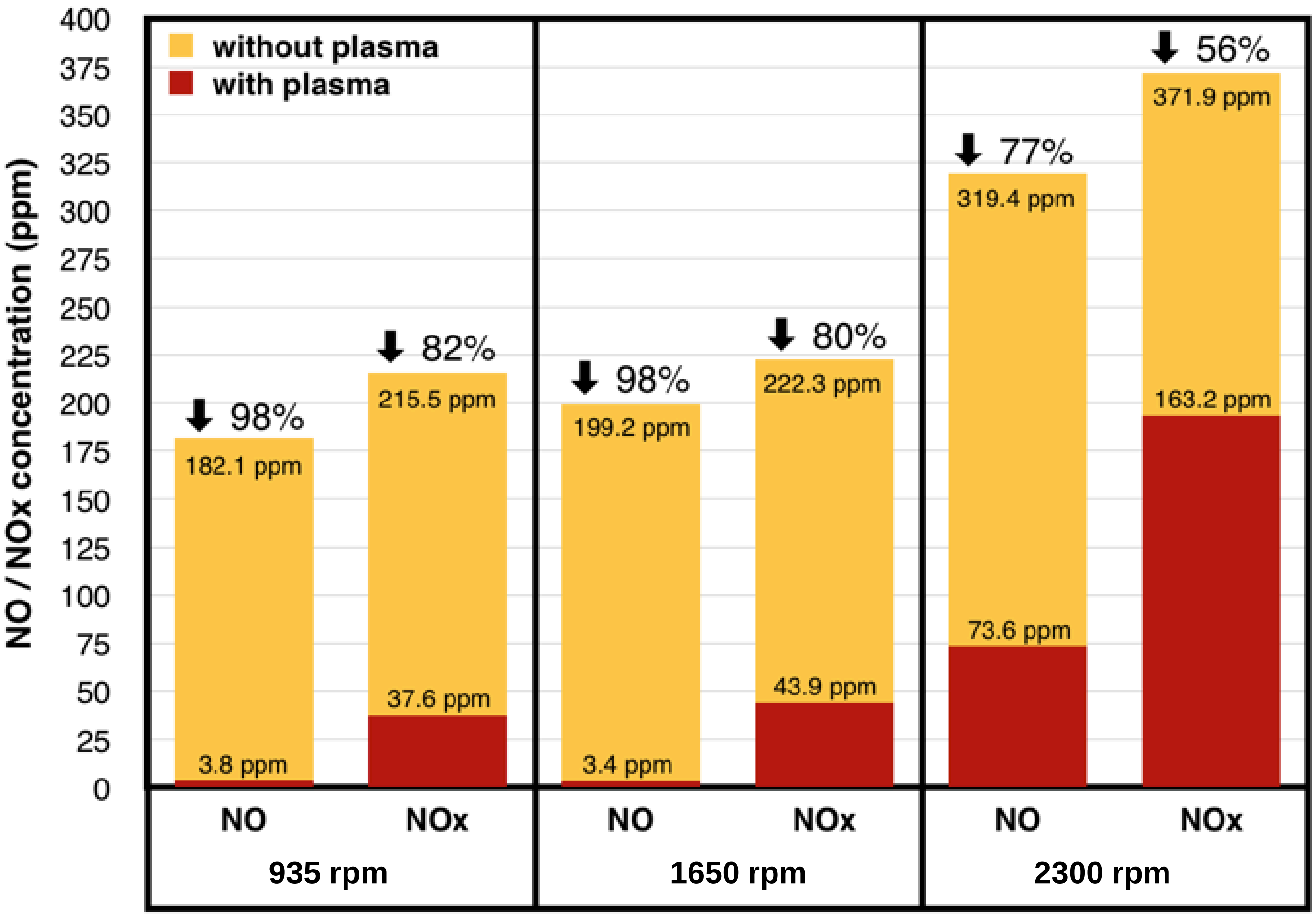
Teledyne® Ultrafine Particulate Monitor

TPS® SSPG-20X Pulse Generator 1 kW (x2)

Gas and Particulate Analysis Sampling Manifold

Transient Plasma Reactor (x2)

5 kW Engine Load Testing
(Slip-stream Data)

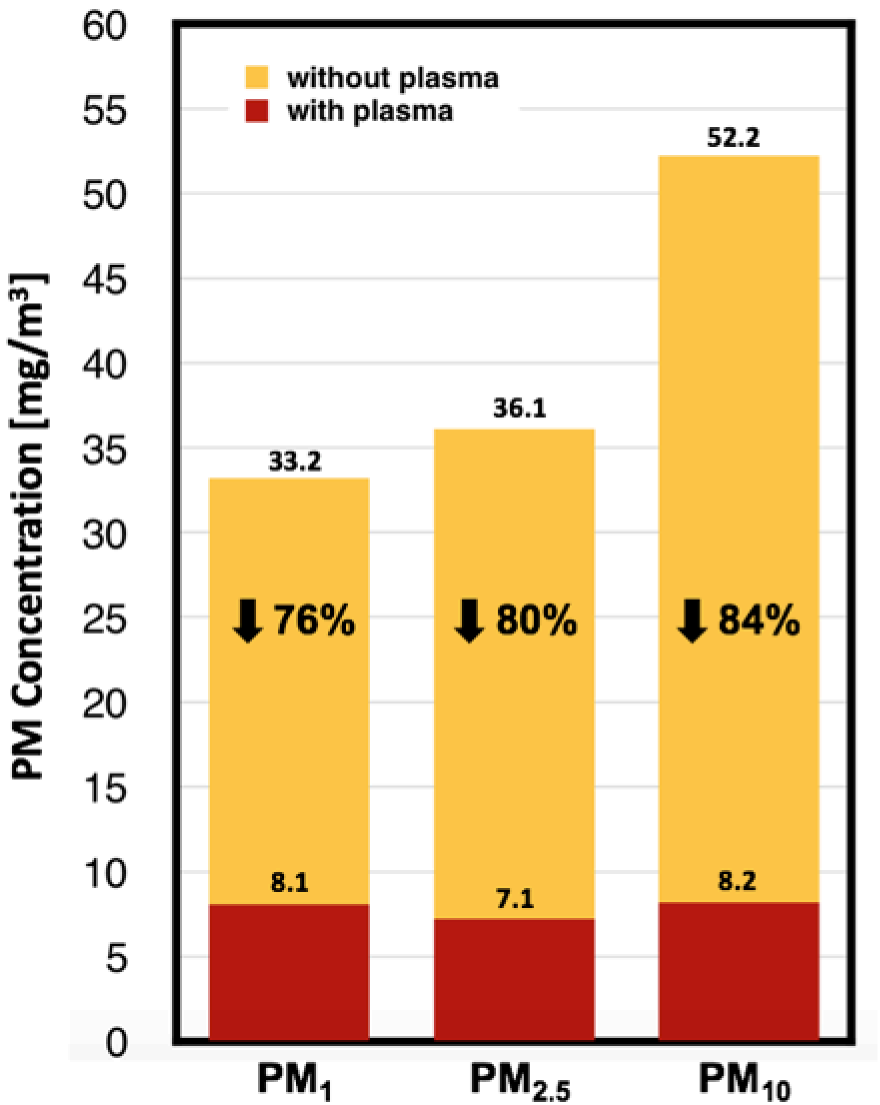


Pulser Parameters	
Rise Time	10 ns
Peak Voltage	40 kV
Repetition Rate	40 Hz
Burst Mode	1 shots/burst
Sample Flow Rate	0.6 L/min

Engine Specifications	
Engine Model	Kubota EA-330
Engine Type	4-cycle Diesel
Engine Fuel	MGO
Engine Power	5.15 kW @ 2300 rpm
Exhaust Temp	225 °C @ 2300 rpm
Exhaust Flow Rate	18.6 L/s @ 2300 rpm

Testing carried out in 2.54 cm diameter cell (1.27 cm discharge gap).
Relative uncertainty in measurement = $\pm$3%

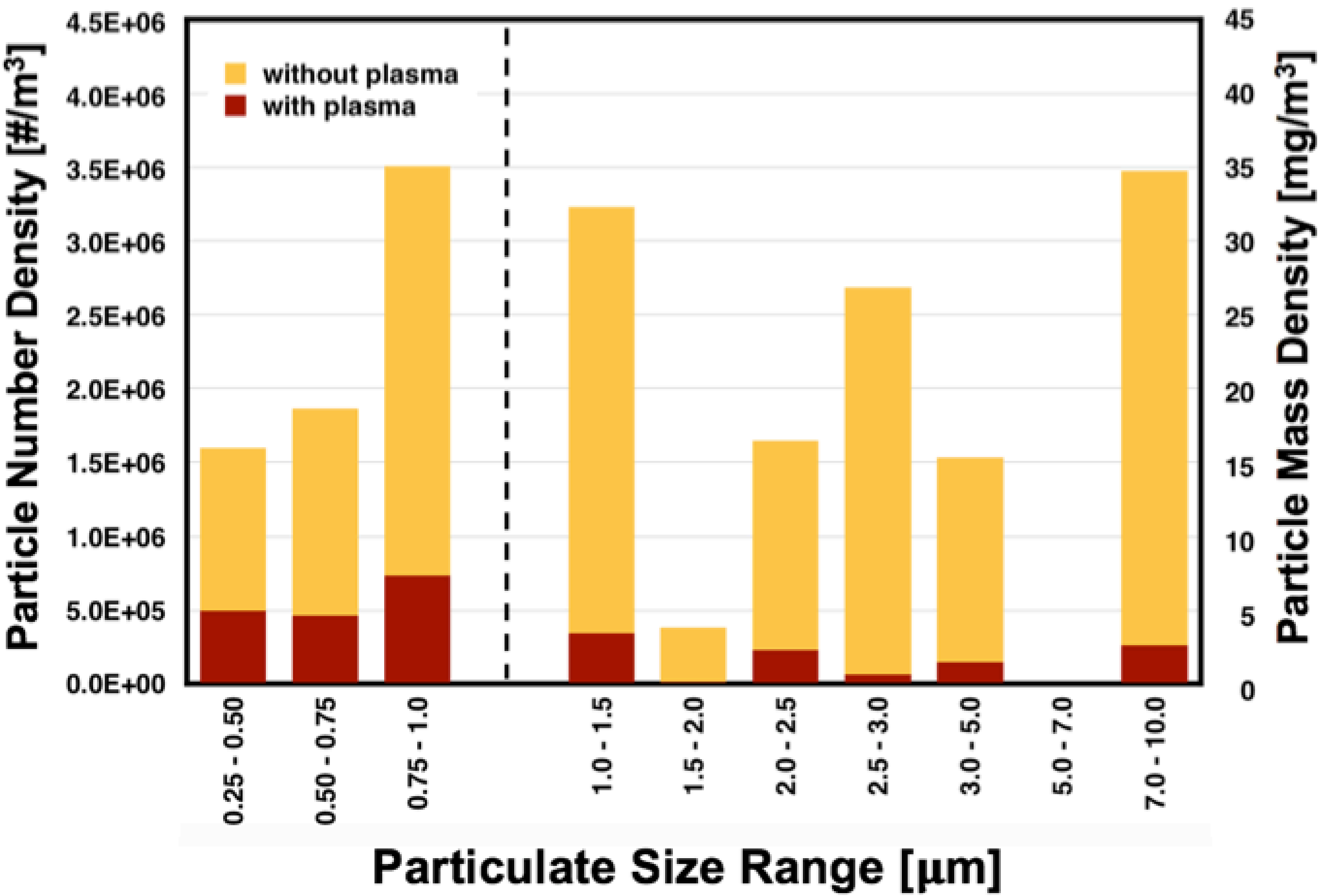
PM Remediation Results



Engine Specifications	
Engine Model	Sulzer 6RND 68M
Engine Power	8,053 kW @ 137 rpm
Exhaust Temp	305 °C
Exhaust Flow Rate	67,500 kg/hr

Engine Parameters	
Engine Speed	131 rpm
Engine Load	76%
Exhaust Temp	238°C
Engine Fuel	IFO 180

Preliminary PM Remediation Results



Pulser Parameters	
Rise Time	10 ns
Peak Voltage	40 kV
Repetition Rate	200 Hz
Burst Mode	1 shots/burst

Engine Parameters	
Engine Speed	995 rpm
Engine Load	idle
Exhaust Temp	214 °C
Exhaust Flow Rate	9.8 L/s
Engine Fuel	MGO

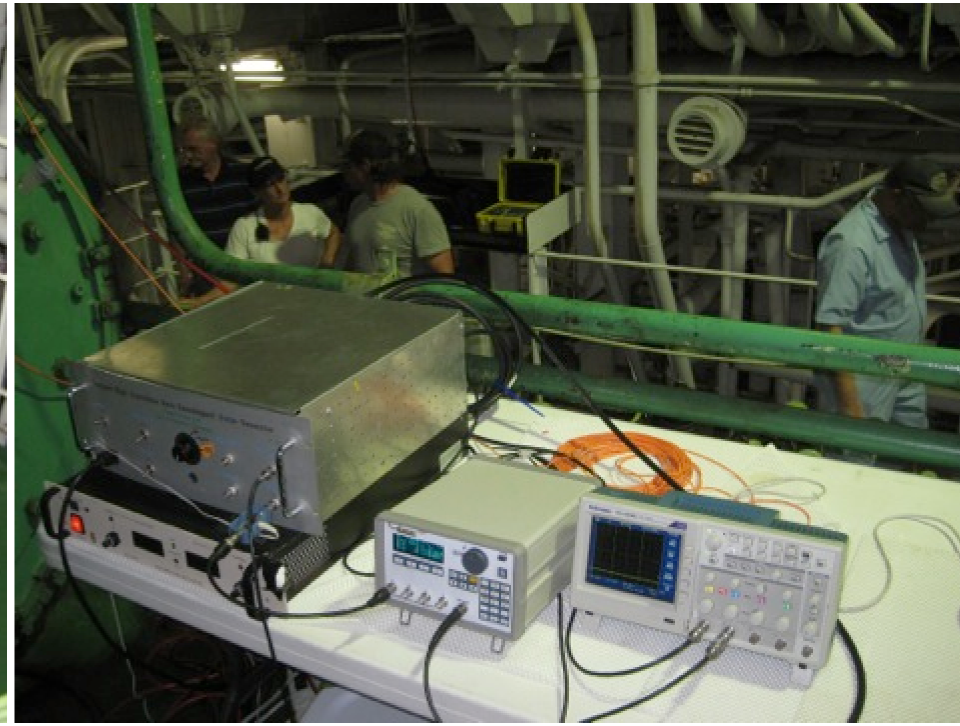
Engine Specifications	
Engine Model	Kubota EA-330
Engine Type	4-cycle Diesel
Engine Fuel	MGO
Engine Power	5.15 kW @ 2300 rpm
Exhaust Temp	225 °C @ 2300 rpm
Exhaust Flow Rate	18.6 L/s @ 2300 rpm

Relative uncertainty in measurement = ±6%

Plasma Assisted Combustion Efficiency

Transient Plasma Relief Valve Electrode for Sulzer 6RN

Photograph of TP relief valve being inserted into cylinder of Sulzer 6RND engine aboard MARAD vessel.



Photograph of nanosecond high voltage pulser and associated equipment used to generate plasma inside cylinder of Sulzer 6RND engine aboard MARAD vessel.

Left – Engineer …....

Right – (From left to right) Dr. Andras Kuthi, Galia Kaplan, Engineer, Captain Vinay Patwardhan.

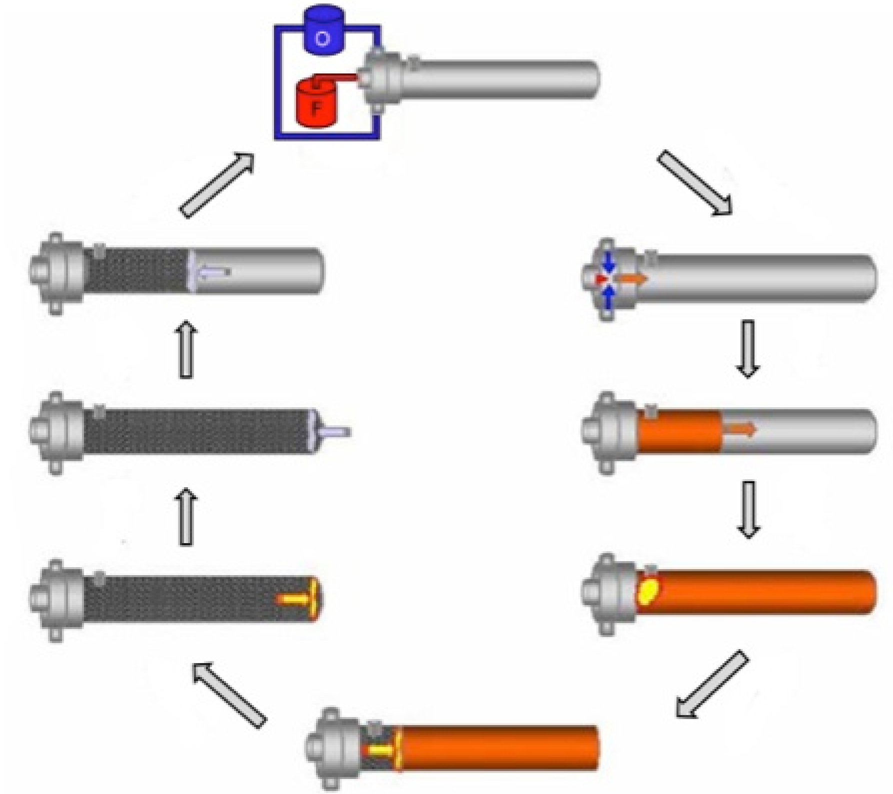
USC Viterbi School of Engineering

Ignition Snapshots

Gasoline, natural gas, other fuels

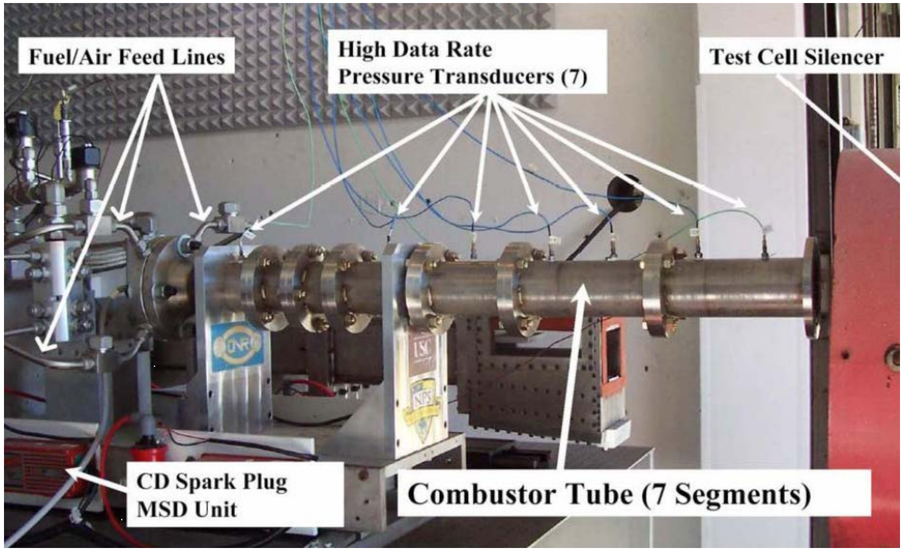
Various engine types: ICE, PDE, etc.

The Rocket Part: Pulse Detonation Engines (PDE)



PDE Cycle

Collaborations with the Naval Postgraduate School (NPS, Brophy), WPAFRL (Schauer et al), Stanford (Hanson et al)



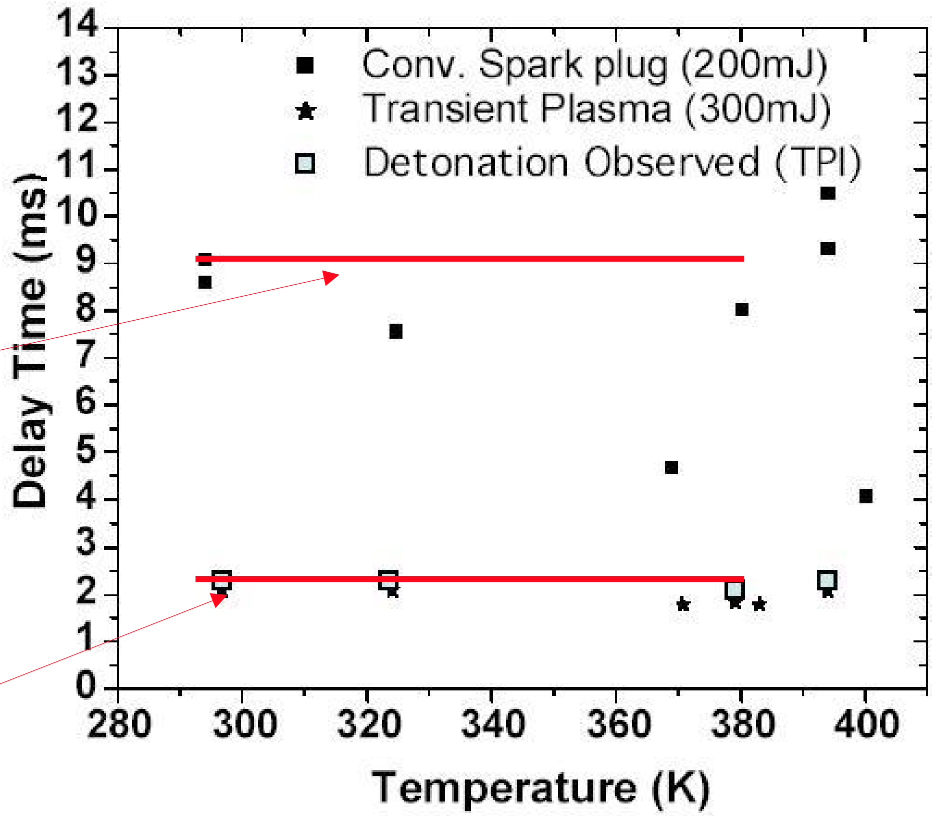
PDE at the NPS Rocket Lab

C. Cathey, et.al., "Transient Plasma Ignition for Delay Reduction in Pulse Detonation Engines," 45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 8-11 Jan 2007

Greatly Improving Thrust in a PDE at the 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

C. Cathey, et.al., “Transient Plasma Ignition for Delay Reduction in Pulse Detonation Engines,” 45th AIAA Aerospace Sciences Meeting, Reno, Nevada, 2007

Transient plasma in the NPS PDE

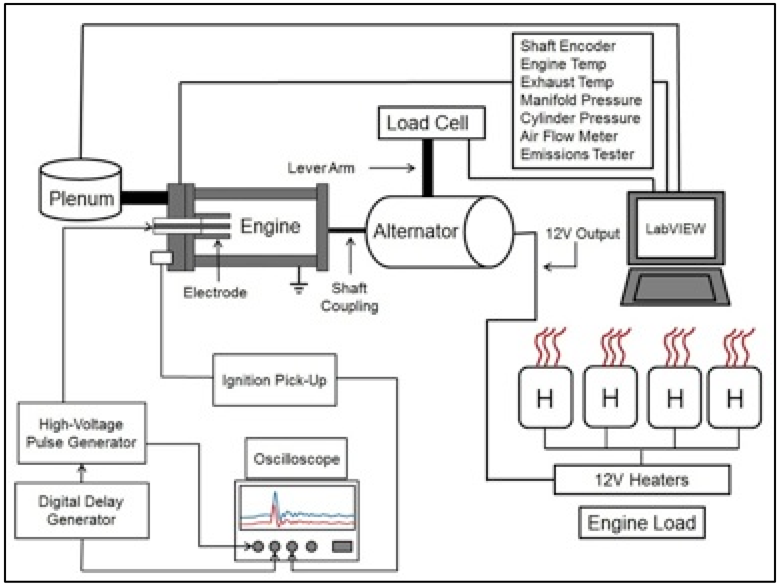
- Reduced delay (shortened DDT) by ≈ factor >4
- Created a detonation without added oxygen (propane-air)
- Increased peak pressure
- ***4X Higher repetition rate of the PDE means > 4X thrust***
- Operated at high flow rates (1/3 kg/sec)

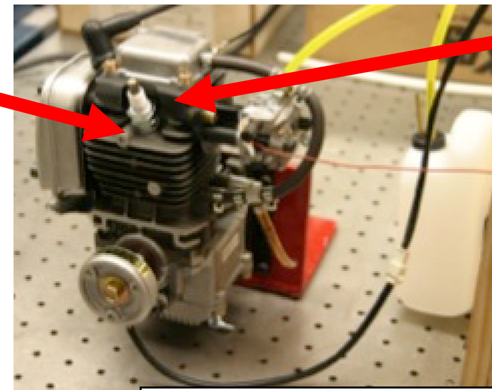
Ignition: Small Engine Experiment

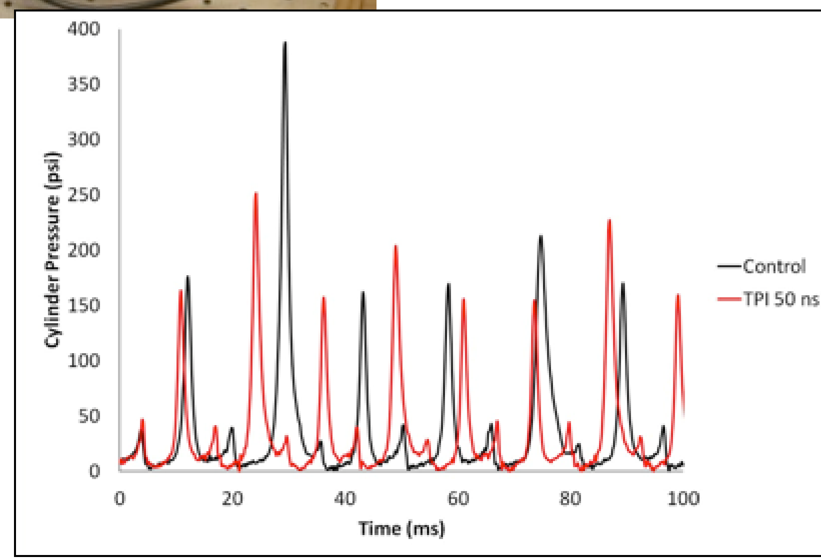
AFOSR Undergraduate Capstone Project

Pressure transducer installed above spark plug

Non-resistive spark plug with uniform gap size used for both TPI and spark



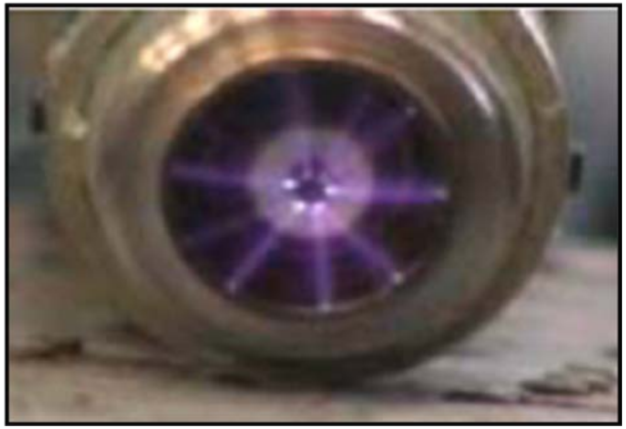


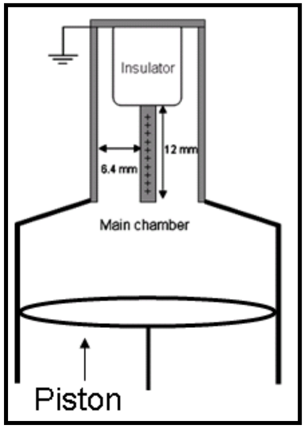


TPI produced *25% increase in RPM,* same throttle setting indicating higher efficiency

AFOSR Capstone Project, C. Li, Program Manager,
Dan Singleton, Max Reynolds, Jared Fleitman, David Kingman, P Ronney, M Gundersen WPAFRL
F. Schauer and J. Hoke

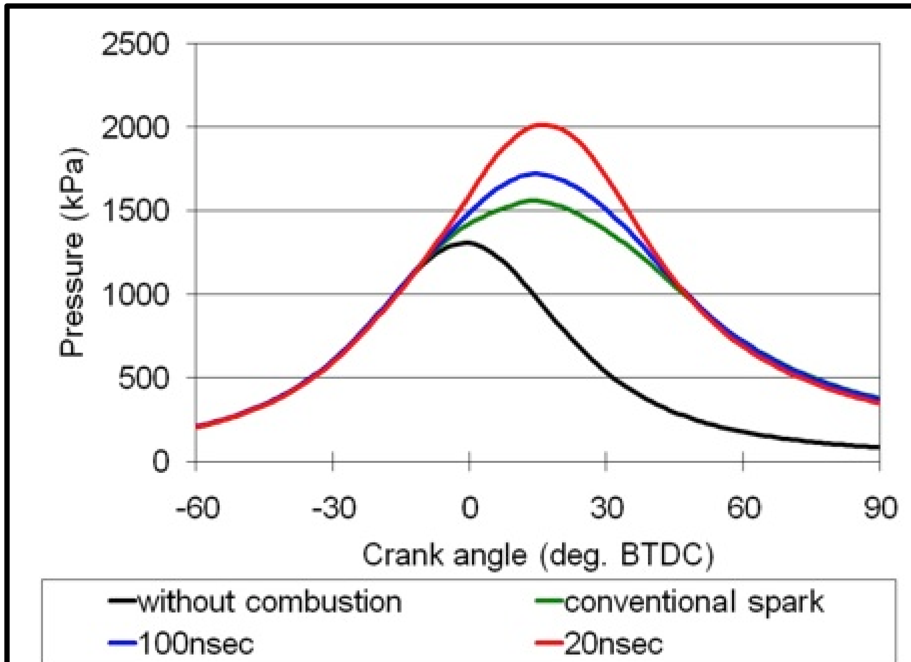
Nissan Gasoline Ignition: Increased Pressure



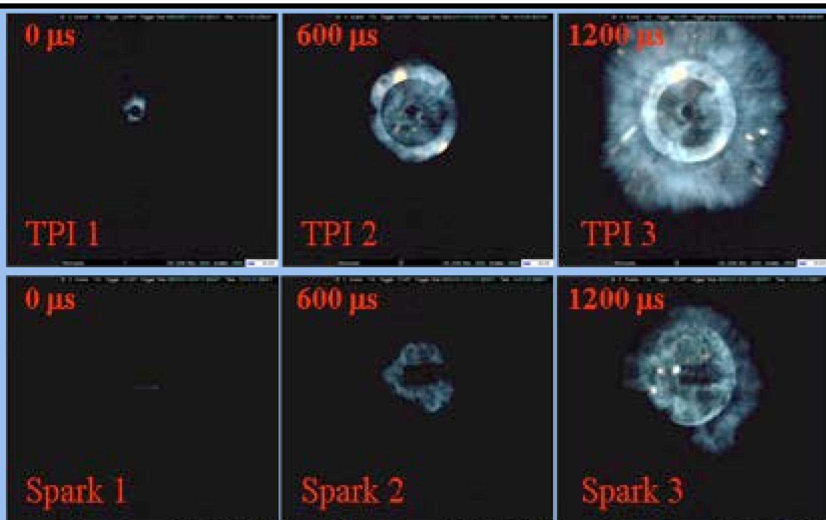


Streamers generated via a 60 kV, 20 ns pulse, using a modified spark plug

Data taken in collaboration at Nissan, Yokohama Japan



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



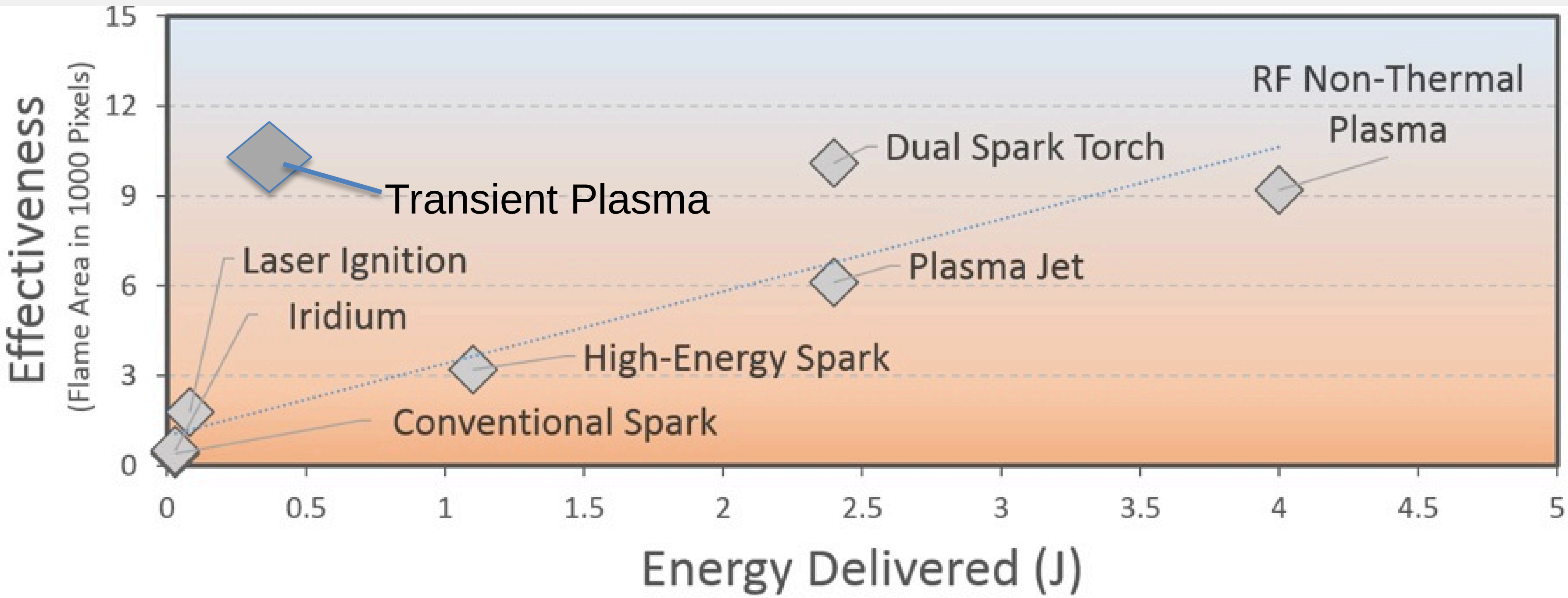
1200 rpm, 100 mm-Hg, ADV: 20 deg BTDC, iso-octane-air combustion, each frame is 200 µs long.

- Using TPI in an ICE resulted in
  - 20% increase in peak pressure using less energy (57 mJ vs 80 mJ)
  - Faster flame propagation

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.

High-Energy Ignition

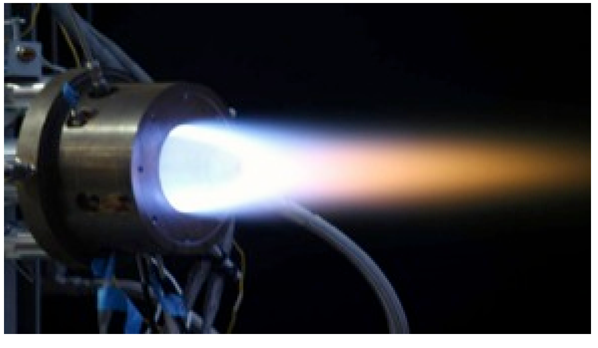
- 10x conventional spark energy
  - Frequent replacement of spark plugs

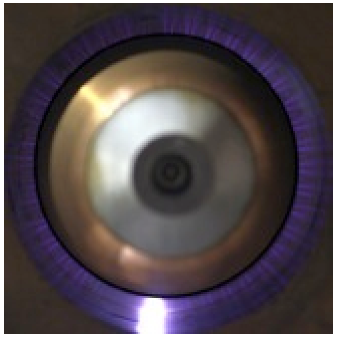


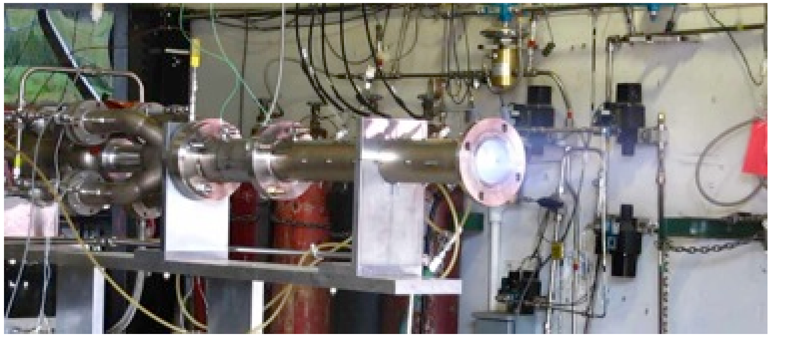
Briggs, T., Alger, T., and Mangold, B., "Advanced Ignition Systems Evaluations for High-Dilution SI Engines," SAE Int. J. Engines 7(4):1802-1807, 2014, doi:10.4271/2014-01-2625.

Engine Ignition Experiments: Typical Results

Engine Type	Location of Testing	Typical Result
Single-cylinder gasoline ICE	Sandia National Labs Combustion Research Facility	20% improvement in fuel efficiency and increased stability
Single-cylinder gasoline ICE	Nissan Research Center	30% increase in combustion efficiency
Natural gas ICE	Argonne National Lab, several industrial locations	Important improvement in ignition at high pressures
Pulse Detonation Engine	Air Force Research Lab and Office of Naval Research Lab	More than 3 times improvement in thrust
Continuous Detonation Engine	Pratt & Whitney Rocketdyne	30% improvement in combustion efficiency



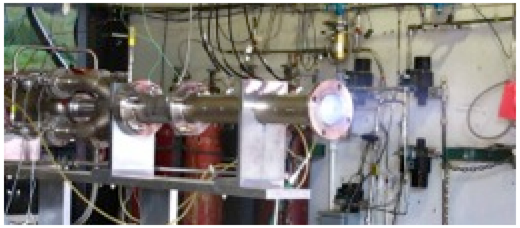




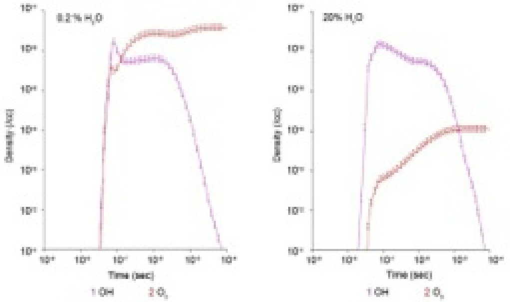
The Role of O, H_2O During Transient Plasma Ignition

Completed Work

- Measured ignition delay in a PDE with transient plasma and spark discharges



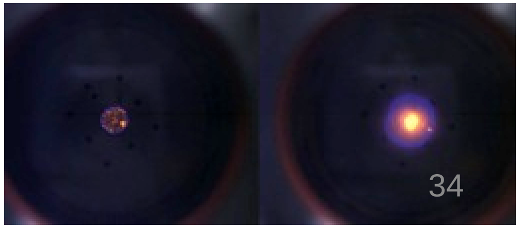
- Simulated OH and O_3 produced in a transient plasma discharge (John Luginsland)



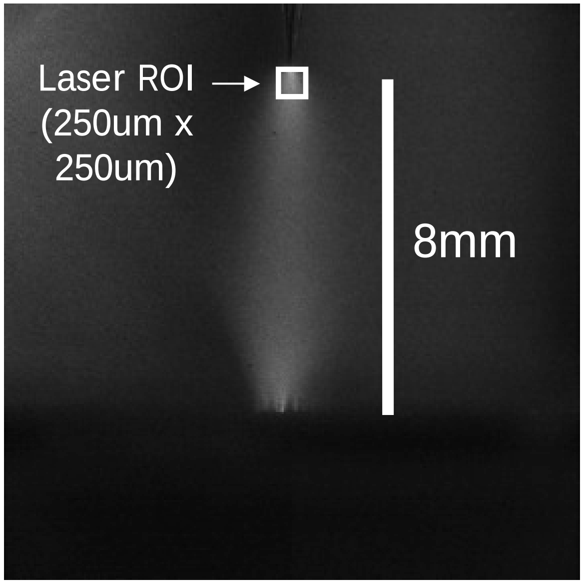
- Measured density of OH and O_3 produced in a transient plasma discharge (Cam Carter)

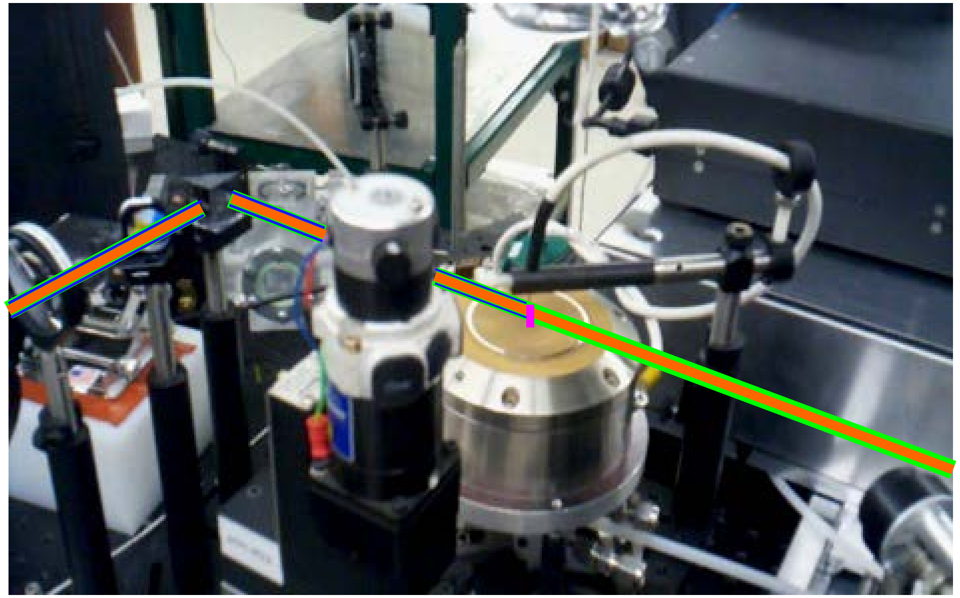
Upcoming Work

- Measure ignition delay in a combustion chamber with transient plasma and spark discharges



Thermal vs. Non-Thermal? Energy Distribution Studies with CARS



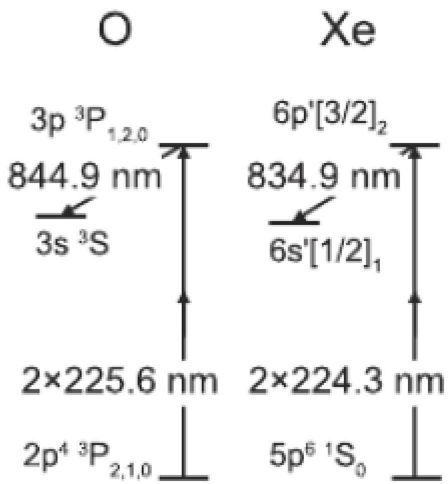


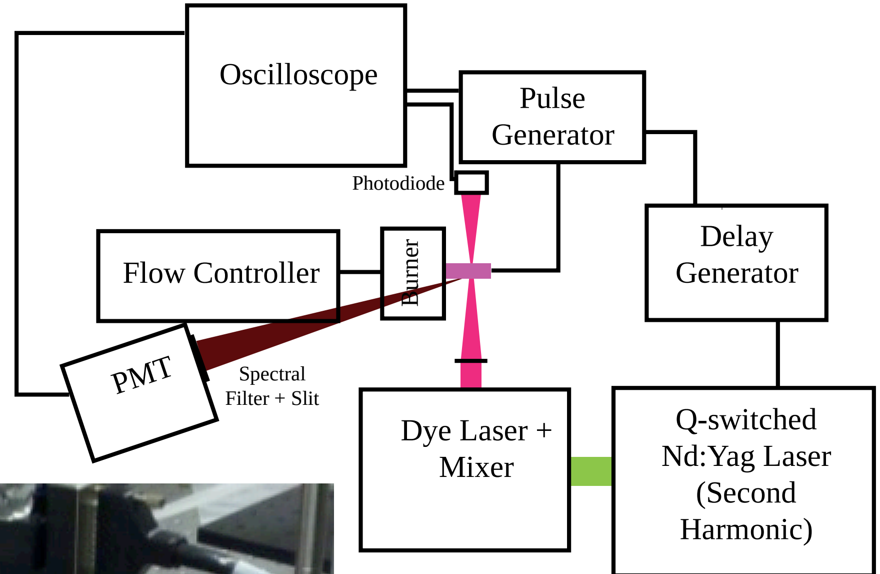
Recent work by USC has demonstrated that ignition occurs primarily in regions of highest E/N and active species production.

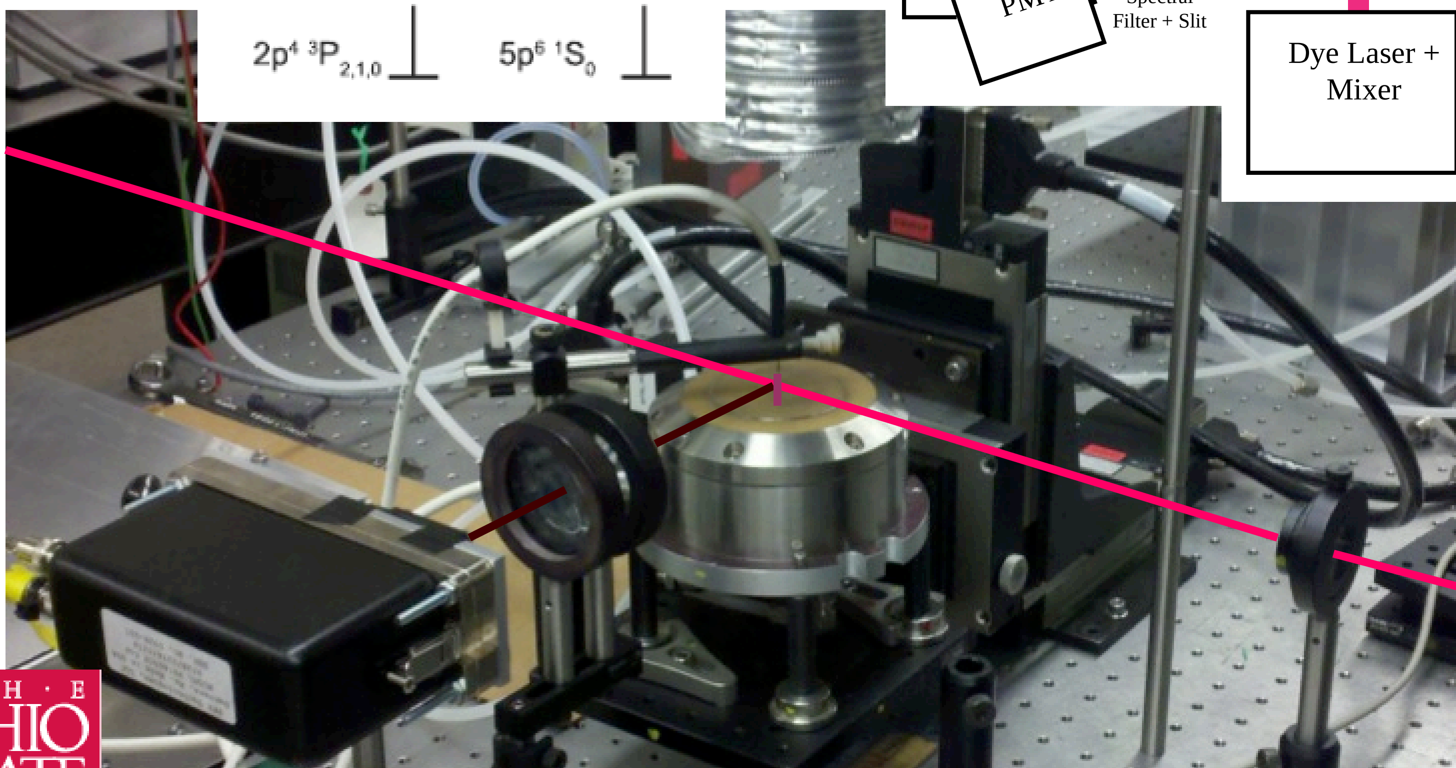
We investigated the region nearest a sharp anode in a point-plane configuration with CARS and TALIF experiments.

Collaboration with Aaron Montello and Prof. Walter Lempert, in labs at tOSU

Experimental Setup: Two-photon Absorption Laser Induced Fluorescence







Dobele, H.F., T. Mosbach, K. Niemi, and V. Shulz-von der Gathen, 2005. Laser-Induced Fluoresence Atomic Densities: Concepts and Limitations. *Plasma Sources Science and Technology*. **14** S31-S41.

O/Xe Conversion

THE OHIO STATE UNIVERSITY

Collaboration with Sherrie Bowman and Prof. Walter Lempert, tOSU

Challenges

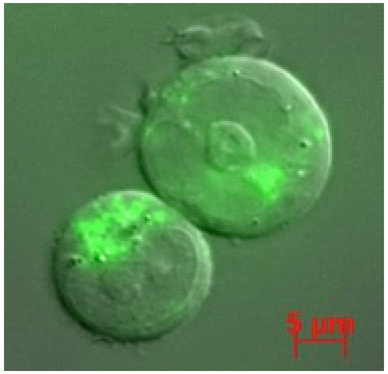
- Transient plasma, DBD
- Physics – streamer-head role in production of excited species and pathways to efficient remediation and ignition
- Technology of ns pulsed power

Nano-Bio-Med Summary

- Nanosecond pulses penetrate the intracellular environment
- Phosphatidylserine inversion–induced apoptosis
- Cancer cell Studies
- In vivo experiments with tumors show promise

New venture: Pulse Biosciences

- Cardiomyocyte Studies
- Cold plasma



Images: Top: Quantum dots in lymphocyte
Below: Internal response of jurkat cell to nsec pulsed electric field

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Cheryl Craft	*KSoM*
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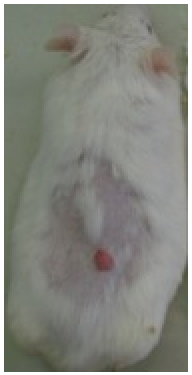
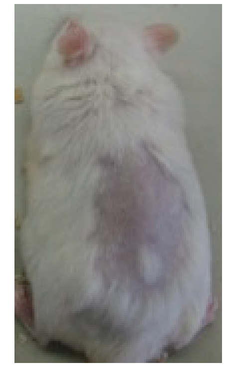
Laura Marcu	*UC Davis*
David Sawcer	*KSoM Dermatology*
Miguel Valderrabano	*UCLA*
Tom Vernier	*Res. Assoc Prof. USC*

NanoElectroPulse Therapy for Cancer: in vivo study

Treatment of human pancreatic cancer tumor grown on nude mice at Cedars Sinai, Koeffler group collaborating
Typical results compliments of Mouse 1 (cage 154937) below:





06/30/09 | 7/7/09 | 7/14/09

Garon, E. B., et. al., "In vitro and in vivo evaluation and a case report of intense nanosecond pulsed electric field as a local therapy for human malignancies", *Int. J. Cancer* 121:675-682, 2007

Translational Outcomes

- Pulse Biosciences
- Transient Plasma Systems
- Integrated Applied Physics

Pulsed Electric Field treatment of wine grapes

Increase

- Juice yield (~30%)
- Yeast digestible nitrogen

  (prevents "atypical aging note of the wine"*)
- Tanning substances
- Taste (wine)

Decrease

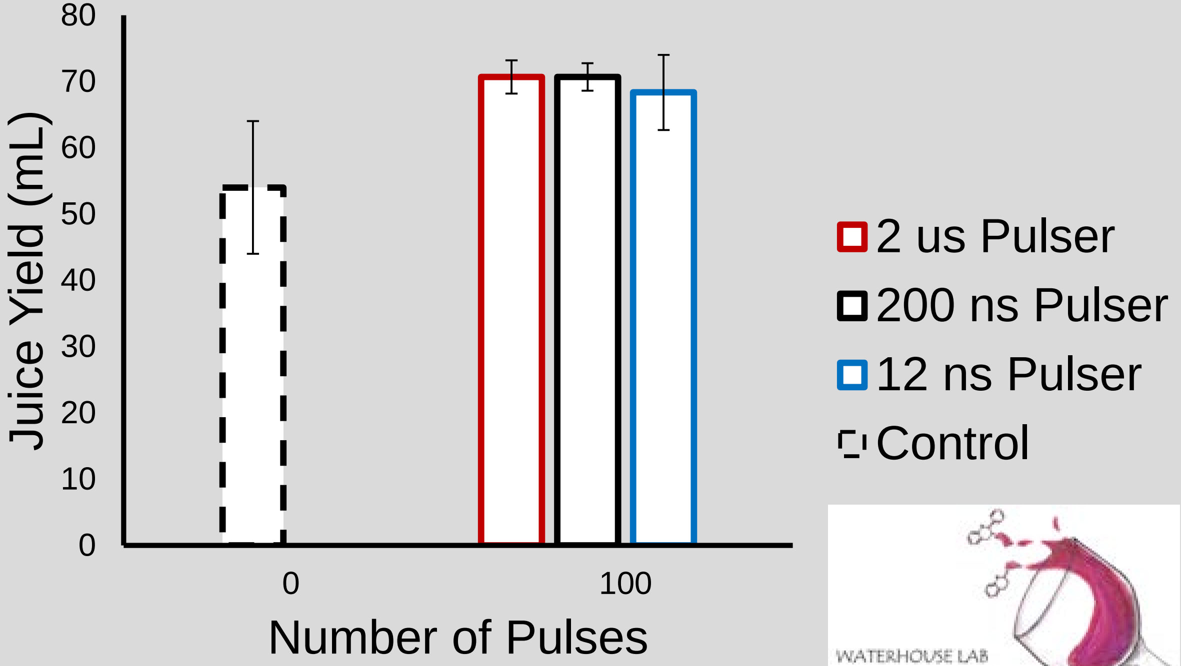
- Total processing time
- Total acid

Wine Treatment with Repetitive Pulsed Power

Control

PEF Treated

PEF Treatment of Sauvignon Blanc Wine Grapes (UC Davis)



- Study of semillion and sauvignon blanc grape crush
- Average juice yield increase after PEF treatment ≈30%
- Beneficial compounds (antioxidants) increased

M. Anderson, M. A. Gundersen, J. M. Sanders, D. R. Singleton, and A. Waterhouse, "Effects of Pulsed Energy Field Treatments on White Wine Grapes," *Annual Meeting of the American Society for Enology and Viticulture*, Napa, 2009

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- Naval Postgraduat... (NPS)

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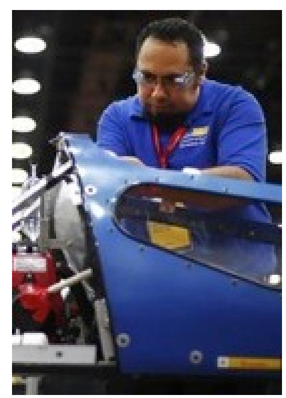

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