Fundamental Mechanisms, Predictive Modeling, and Novel Aerospace Applications of Plasma Assisted Combustion

AFOSR MURI Review Meeting

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Main Tasks

Thrust 1. Experimental studies of nonequilibrium air-fuel plasma kinetics using advanced non-intrusive diagnostics

- Task 1: Low-to-Moderate (T=300-800 K) temperature, spatial and time-dependent radical species concentration and temperature measurements in nanosecond pulse plasmas in a variety of fuel-air mixtures pressures (P=0.5-5 atm), and equivalence ratios
- Task 4: Moderate-to-high (T=800 – 1800 K) temperature PAC oxidation kinetics in Discharge Shock Tube Facility at pressures up to 10 bar
- Task 5: PAC oxidation and combustion initiation at high pressure, high temperature conditions

Thrust 2. Kinetic model development and validation

- Task 8: Development and validation of a predictive kinetic model of non-equilibrium plasma fuel oxidation and ignition
- Task 9: Mechanism Reduction and Dynamic Multi-time Scale Modeling of Detailed Plasma-Flame Chemistry

Thrust 3. Experimental and modeling studies of fundamental nonequilibrium discharge processes

- Task 10: Characterization and Modeling of Nanosecond Pulsed Plasma Discharges

Thrust 4. Studies of diffusion and transport of active species in representative two-dimensional reacting flow geometries

- Task 13: Ignition and flameholding in high-speed non-premixed flows
- Task 14: High Fidelity Modeling of Plasma Assisted Combustion in Complex Flow Environments
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Major International Collaborations and International Projects

Nickolay Aleksandrov (MIPT, Russia)
Sergey Pancheshnyi (NEQLab, Netherlands)
Svetlana Starikovskaya (LPP, France)

PROJECTS:
PARTNER UNIVERSITY FUND “Physics and Chemistry of Plasma-Assisted Combustion” (Princeton-LPP)

PUBLICATIONS

BOOKS

Aeronautics and Astronautics. Edited by: Max Mulder; TUDelft, The Netherlands.

  http://www.intechopen.com/books/show/title/aeronautics-and-astronautics

  http://www.intechopen.com/books/show/title/aeronautics-and-astronautics

PATENTS

IS Engines Ignition System

• A.Nikipelov, A.Rakitin, S.Panchesnyi, A.Starikovskiy An ignition method, an ignition plug and an engine using an ignition plug.
PUBLICATIONS

JOURNAL PAPERS

Review


Kinetics


Plasma-Assisted Detonation


Physics of Pulsed Discharges


PAC: New Dimensions in Combustion

- $P$, atm:
  - 0.02
  - 1
  - 40

- $T$, K:
  - 250 K
  - 2500 K

- $S/I$:
  - 0.1
  - 3.0

- $B/S$:
  - 0.1
  - 1
  - 3
  - 0.3

- $E/n$:
  - 10

- $\phi$$^+$
  - 3.0

- $P$, atm:
  - 40

- $E/n$:
  - 10
Electron Energy Distribution in Discharge Plasmas

\[ \text{N}_2 : \text{O}_2 : \text{H}_2 = 4:1:2 \]
Plasma Assisted Ignition at Low \( E/n \)

Energy Cost of Radicals Production at Different Nitrogen Concentrations

**Low E/n**
- \( \text{O}_2(1\text{D}) + \text{H} = \text{OH} + \text{O} \)
- \( \text{O}_2(1\text{D}) + \text{H} = \text{O}_2 + \text{H} \)
- \( \text{O}_2(1\text{D}) + \text{H}_2 = \text{O}_2 + \text{H}_2 \)

**High E/n**
- \( \text{O}_2 + \text{e} = \text{O} + \text{O} + \text{e} \)
- \( \text{O}_2 + \text{N}_2(\text{A,B,C...}) = \text{O} + \text{O} + \text{N}_2 \)

---

E/n ~ 6 Td
- 0.98 eV
- 1.63 eV

E/n ~ 300 Td
- 8.4 eV

Radical's Production Cost
- e-impact and N\textsubscript{2} \* quenching
- O\textsubscript{2}(1\Delta), no quenching
- O\textsubscript{2}(1\Delta), quenching by H\textsubscript{2}
- O\textsubscript{2}(1\Delta), quenching by CH\textsubscript{4}
Electron Energy Distribution in Discharge Plasmas

\[ \text{N}_2 : \text{O}_2 : \text{H}_2 = 4:1:2 \]
Chemical Reactions with Excited Reagents

\( AB(v) + C = A + BC(w) \)

Rate constant from modified \( \alpha \)-model
(Starikovskii, Lashin 1996)

\[ \frac{K(T_{vib}, T_h)}{k(T_h)} \]

\( T_{vib}/T_{tr} \)

**Graphs:**

1. \( H_2(v) + O = H + OH \)
2. \( H_2(v) + OH = H_2O + H \)

\( H_2(v=1) + O = OH(w=1) + H \) \hspace{1cm} (R1)

\( H_2(v=0) + O = OH(w=0) + H \) \hspace{1cm} (R2)

\( \frac{k_{R1}}{k_{R2}}_{\text{exp}} = 2600 \) (O’Neal, Benson 1973);

\( \frac{k_{R1}}{k_{R2}}_{\text{theor}} = 2750 \)
Kinetics. Influence of Vibrational Excitation

Distribution Of Vibrational-Excited Components

$\text{H}_2$  
$\text{O}_2$

$\text{H}_2\text{O}$ (defomational mode)  
$\text{OH}$

![Graph showing the distribution of vibrational-excited components with vibrational excitation on and off.](image-url)
Electron Energy Distribution in Discharge Plasmas

\[ \text{N}_2 : \text{O}_2 : \text{H}_2 = 4:1:2 \]

Energy loss fraction

E/N, Td
Radicals Production in Discharge
$\text{CH}_4$-containing mixture
Ignition Delay Time: Methane-Containing Mixture

![Graph showing ignition delay time for CH₄ mixtures](chart.png)
Electron Energy Distribution in Discharge Plasmas

\[ \frac{N_2}{O_2} : \frac{H_2}{} = 4:1:2 \]

Energy loss fraction

\[ \frac{E}{N} , T_d \]
Mechanism of Fast Heating in Discharge Plasmas (High E/n)

High (> 200 Td) E/N:

*electron-ion and ion-ion recombinati*

\[ e + O_2^+(M) \rightarrow O + O^*(M) + \Delta E \]

\[ O_2^- + O_2^+ + M \rightarrow 2O_2 + M + \Delta E \]
Mechanism of ultra-fast heating in a nonequilibrium weakly-ionized air discharge plasma in high electric fields
Mechanism of fast heating in discharge plasmas (low \(E/N\))

Air

Low (< 20 Td) \(E/N\):
- elastic scattering
- rotational excitation
Mechanism of fast heating in discharges (moderate E/N)

Moderate (20 - 200 Td) E/N:

Popov (2001)  

heating $\rightarrow$ 28 % of power spent on $N_2^* + O_2^*$

$e + O_2 \rightarrow e + 2O + \Delta E$

$e + N_2 \rightarrow e + N_2^*(A, B, C, a', ...)$

$N_2^*(A, B, C, a', ...) + O_2 \rightarrow N_2 + 2O + \Delta E$

$O(^1D) + N_2 \rightarrow O + N_2 + \Delta E$ \quad k $\sim$ $10^{-10}$ cm$^3$/s
Fractional electron power transferred into heat via various channels in dry air at $E/N = 10^3$ Td

<table>
<thead>
<tr>
<th>Channel</th>
<th>$n_{ef} = 10^{14}$ cm$^{-3}$</th>
<th>$n_{ef} = 10^{15}$ cm$^{-3}$</th>
<th>$n_{ef} = 10^{14}$ cm$^{-3}$</th>
<th>$n_{ef} = 10^{15}$ cm$^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$p = 20$ Torr</td>
<td>$p = 20$ Torr</td>
<td>$p = 1$ atm</td>
<td>$p = 1$ atm</td>
</tr>
<tr>
<td>Lower excited N$_2$ states and dissociation by e-impact</td>
<td>10.9</td>
<td>10.1</td>
<td>8.3</td>
<td>9.1</td>
</tr>
<tr>
<td>Higher excited N$_2$ states</td>
<td>11.1</td>
<td>10.7</td>
<td>11.2</td>
<td>12.8</td>
</tr>
<tr>
<td>Ion-molecule reactions</td>
<td>3.9</td>
<td>1.6</td>
<td>8.0</td>
<td>6.1</td>
</tr>
<tr>
<td>Electron-ion recombination</td>
<td>10.8</td>
<td>9.1</td>
<td>7.6</td>
<td>10.7</td>
</tr>
<tr>
<td>Ion-ion recombination</td>
<td>0.5</td>
<td>0.1</td>
<td>20.6</td>
<td>12.6</td>
</tr>
<tr>
<td>Total</td>
<td>37.2</td>
<td>31.5</td>
<td>55.7</td>
<td>51.3</td>
</tr>
</tbody>
</table>
Mechanism of fast heating in discharge plasmas (high E/N)

- Electron-ion and ion-ion recombination kinetics

High (> 200 Td) E/N:

$$e + O_2^+ \rightarrow O + O^* + \Delta E$$
$$O_2^- + O_2^+ + M \rightarrow 2O_2 + M + \Delta E$$
$$e + O_4^+ \rightarrow O_2 + O_2 + \Delta E$$
Difference between the Models

Popov (2011)

\[ \begin{align*}
N^+ + e & \rightarrow N_2(C^3Π_u) + N_2 \\
O_2^+ + e & \rightarrow O(3P) + O(3P, 1D) \\
O^+_2 + e & \rightarrow O(3P) + O(3P, 1D) + O_2 \\
O^-_2 + O^+_2 + O_2 & \rightarrow 2 \cdot O + 2 \cdot O_2 \\
O^-_2 + O^+_4 + O_2 & \rightarrow 2 \cdot O + 3 \cdot O_2 \\
O^-_4 + O^+_2 + O_2 & \rightarrow 2 \cdot O + 3 \cdot O_2 \\
O^-_4 + O^+_4 + O_2 & \rightarrow 2 \cdot O + 4 \cdot O_2
\end{align*} \]

Aleksandrov & Starikovskiy (2010)

\[ \begin{align*}
e + N_2^+ & \rightarrow N + N \\
O_2^+N_2 + e & \rightarrow O_2 + N_2 \\
A^+_2 + e + e & \rightarrow A_2 + e \\
N^+ + e & \rightarrow N_2 + N_2 \\
O^+_2 + e & \rightarrow O(3P) + O(3P, 1D) \\
O^+_4 + e & \rightarrow O_2 + O_2 \\
O^-_2 + O^+_2 + O_2 & \rightarrow O_2 + 2 \cdot O_2 \\
O^-_2 + O^+_4 + O_2 & \rightarrow O_2 + 3 \cdot O_2 \\
O^-_4 + O^+_2 + O_2 & \rightarrow O_2 + 3 \cdot O_2 \\
O^-_4 + O^+_4 + O_2 & \rightarrow O_2 + 4 \cdot O_2
\end{align*} \]
Evolution in Time of Total Fractional Electron Power Transferred into Heat in Dry Air

$E/N=1000 \text{ Td, } p=20 \text{ Tor}$

$E/N=1000 \text{ Td, } p=1 \text{ atm}$

$N_2^+ + e \rightarrow N + N$

$O^+_2 + e \rightarrow O^{(3P)} + O^{(3P, 1D)}$

$O_2^+ N_2 + e \rightarrow O_2 + N_2$

$N^+_4 + e \rightarrow N_2 + N_2$

$O^+_4 + e \rightarrow O_2 + O_2$
Measurements of Ozone Production in SDBD

Ozone Concentration, cm$^{-3}$

Time, sec

P = 736 Torr
U = 14.2 kV

HV pulse

Discharge chamber
Back-current shunt
Tektronix TDS3054
Pulsed Generator
PC

Camera PicoStar HR 12

Sliding discharge: thickness measurements. a) 760 torr; 18 kV; top view. b) 220 torr; 18 kV; front view. c) 925 torr; 18 kV; front view. Picture dimensions are 10×7 mm.
Calculations of Ozone Production in SDBD

\[
\begin{align*}
N_2^+ + e & \rightarrow N + N \\
O_2^+ + e & \rightarrow O(3P) + O(3P, 1D) \\
O_2 + N_2 + e & \rightarrow O_2 + N_2 \\
N_4^+ + e & \rightarrow N_2 + N_2 \\
O_4^+ + e & \rightarrow O_2 + O_2
\end{align*}
\]
Plasma volume measurements. $U = 28$ kV, pulse duration 25 ns, rise time 7 ns. Air, $P = 1$ atm

**Side View**

- Direct Plasma Emission
- Reflection from the Surface

**Top View**

- Cathode-directed discharge
- Anode-directed discharge
Rotational Temperature Measurements

\[ dt = 1 \, \mu s \]

\[ f(j, 0-0) \]

\[ \lambda, \text{ nm} \]

\[ N_2 \text{ second positive system emission, 337.1 nm} \]
Fractional Electron Power Transferred into Heat in Different Mixtures

\[ \text{N}_2:\text{O}_2 = 1:1 \]

\[ \text{O}_2 + \text{N}_2 + e \rightarrow \text{O}_2 + \text{N}_2 \]

\[ \text{N}^+ + e \rightarrow \text{N}_2 + \text{N}_2 \]

\[ \text{O}^+ + e \rightarrow \text{O}_2 + \text{O}_2 \]
Air and Oxygen Plasma Recombination at Low Temperatures
Dynamics of electrons concentration at $P=1$ - $10$ Torr, $T=295$ K

**Nitrogen**

$N_2$, $U=+11$ kV, $p=1$-$10$ torr

**Carbon Dioxide**

$CO_2$, $U=+11$ kV, $p=1$-$10$ torr

**Air**

$O_2$, $U=+11$ kV, $p=1$-$10$ torr

$N_2:O_2=4:1$, $U=+11$ kV, $p=1$-$10$ torr
Decay of Initial Electron Density

T = 295 K
Decay of Initial Electron Density
O2 and Air

The evolution in time of the electron density in the air afterglow for (a) 3.5 and (b) 5 Torr.

\[
\begin{align*}
O_2^+ + e + e &= O_2 + e \\
O_2^+ + e + e &= O + O + e
\end{align*}
\]

Curve 2: three-body coefficient, \( k_3 = aT_e^{-n}, \) \( n = 9/2, \)
Curve 3: \( k_3 \) value increased by an order of magnitude, \( n \) being the same,
Curve 4: \( k_3 \) value increased by an order of magnitude and \( n = 2. \)

Higher density of states near the threshold for molecular ions
Decay of Initial Electron Density - Air

The effective electron-ion recombination coefficient in air, O₂ and N₂ as a function of pressure.

The coefficient was determined:
(a) the beginning of the afterglow
(b) the instant at which \( n_e \) decreased to \( 2 \times 10^{11} \) cm\(^{-3} \)
Kinetics of Plasma Recombination

(R1) \( e + N_2^+ \rightarrow N + N \)
(R2) \( e + O_2^+ \rightarrow O + O \)
(R3) \( e + N_4^+ \rightarrow N_2 + N_2(C) \)
(R4) \( e + O_4^+ \rightarrow O_2 + O_2 \)
(R5) \( e + O_2^+ N_2 \rightarrow O_2 + N_2 \)
(R6) \( e + A_2^+ + e \rightarrow A + A + e \)
(R7) \( N_2^+ + O_2 \rightarrow N_2 + O_2^+ \)
(R8) \( N_2^+ + 2N_2 \rightarrow N_4^+ + N_2 \)
(R9) \( O_2^+ + 2O_2 \rightarrow O_4^+ + O_2 \)
(R10) \( O_2^+ + 2N_2 \rightarrow O_2^+ N_2 + N_2 \)
(R11) \( N_4^+ + O_2 \rightarrow 2N_2 + O_2^+ \)
(R12) \( O_2^+ N_2 + N_2 \rightarrow O_2^+ + 2N_2 \)
(R13) \( O_2^+ N_2 + O_2 \rightarrow O_4^+ + N_2 \)
(R14) \( e + 2O_2 \rightarrow O_2^- + O_2 \)

\[
\frac{dT_e}{dt} = -\nu_e (T_e - T) - \frac{2}{3} T_e^2 \left( \frac{dk_3}{dT_e} n_e n_i + \sum_j \frac{dk_{2j}}{dT_e} n_{ij} \right)
\]
Kinetics of Plasma Recombination

(R1) $e + N_2^+ \rightarrow N + N$
(R2) $e + O_2^+ \rightarrow O + O$
(R3) $e + N_4^+ \rightarrow N_2 + N_2(C)$
(R4) $e + O_4^+ \rightarrow O_2 + O_2$
(R5) $e + O_2^+ N_2 \rightarrow O_2 + N_2$
(R6) $e + A_2^+ + e \rightarrow A + A^+ + e$
(R7) $N_2^+ + O_2 \rightarrow N_2 + O_2^+$
(R8) $N_2^+ + 2N_2 \rightarrow N_4^+ + N_2$
(R9) $O_2^+ + 2O_2 \rightarrow O_4^+ + O_2$
(R10) $O_2^+ + 2N_2 \rightarrow O_2^+ N_2 + N_2$
(R11) $N_4^+ + O_2 \rightarrow 2N_2 + O_2^+$
(R12) $O_2^+ N_2 + N_2 \rightarrow O_2^+ + 2N_2$
(R13) $O_2^+ N_2 + O_2 \rightarrow O_4^+ + N_2$
(R14) $e + 2O_2 \rightarrow O_2^- + O_2$

The evolution in time of the frequencies for the main processes of electron loss for 5 Torr in air (a) and for 8 Torr in $O_2$ (b).
Plasma-Assisted Ignition at High Pressures
Rapid Compression Machine: High-Pressure, Low-Temperature

a) ICCD images of the discharge at 1 atm dry air. Negative polarity of the high-voltage electrode, 22 kV, 25 ns duration, $f = 40$ Hz [Kosarev et al, 2009].

b) Camera gate is 0.5 ns. Single pulse sliding DBD ignition of $\text{C}_2\text{H}_6$:$\text{O}_2$=2:7 mixture at 1 bar and ambient temperature [Sagulenko et al, 2009].
Propane
Surface DBD
E < 50mJ
PAC at High Pressure: ER = 0.4

T2 = 794 K
P2 = 32.0 bar

Propane
Surface DBD
E < 50mJ
High-Pressure PAC: Delay Times

HCCI 1 + EGR, $f = 1.0$, EGR = 30%. Discharge after compression.
Plasma-Assisted Ignition at High Pressures

\[
\begin{align*}
\text{CH}_4 + \text{O} & \Rightarrow \text{CH}_3 + \text{OH} \\
\text{CH}_3 + \text{OH} & \Rightarrow \text{CH}_2\text{O} + \text{H}_2 \\
\text{CH}_3 + \text{O}_2 & \Rightarrow \text{CH}_2\text{O} + \text{OH} \\
\text{CH}_3 + \text{O}_2 + \text{M} & \Rightarrow \text{CH}_3\text{O}_2 + \text{M}
\end{align*}
\]

\(T_2 = 672 \text{ K}, P_2 = 20 \text{ bar}\)

\(T_2 = 794 \text{ K}, P_2 = 32 \text{ bar}\)

Ignition delay time for modified mixtures, \(f=1.0,\ EGR=30\%\). Discharge 20ms before compression stroke.
Plasma Assisted Ignition below Self-Ignition Threshold
Problems in Low-T Combustion

**Experiment:** [Choi et al, 2011], H₂–air, \(\phi = 1.0\); \(P = 94\) Torr, \(T_0 = 473\) K. Pulse energy 0.5-0.8 mJ, frequency 40 kHz, \(V \sim 8.5\) cm³, \(\Delta T \sim 320\)K (\(T_i = 793\) K, \(P_i = 94\) Torr)

**Kinetic model:** [Choi et al, 2011] Radicals production + GRI-3.0

**Experiment:** [Wu et al, 2010], H₂-air; C1-C4 – air; \(\phi = 0.1\); \(P = 760\) Torr, \(T_0 = 300-800\) K. Pulse energy 10-15 mJ, \(\Delta T \sim 100\)K (\(T_i = 400-900\) K, \(P_i = 760\) Torr)

**Kinetic model:** [Levko et al, 2010] Radicals production + Low-Temperature Extension of Konnov

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**Graph:**
- **H₂/air, \(P=94\) torr, \(\varphi=1.0, T=200\) C**
  - **OH LIF**
  - **Model**
  - Time, msec: 0.01, 0.1, 1, 10, 100
  - [OH], cm⁻³: 1E+11, 1E+12, 1E+13, 1E+14, 1E+15

- **Methane Eq=0.1**
  - **OH LIF, Grisch et al, Eq=0.05, a.u.**
  - Temperature: 300K, 400K, 500K, 600K, 700K, 800K
  - OH calculated, a.u.
  - Time, \(\mu\)s: 1, 10, 100, 1000
Plasma Assisted Oxidation

$P = 1\text{atm}; T = 300-800\text{ K}$
OH dynamics in lean methane-air (1) and butane-air (2) mixtures for different temperatures below self-ignition threshold. P = 1 atm. ER = 0.1
OH Dynamics: Decay Time

Models:


Influence of Vibrational Excitation on Low-Temperature Kinetics

\[ \text{N}_2 + e = \text{N}_2(\text{C}^3) + e \]
\[ \text{N}_2(\text{C}^3) + \text{O}_2 = \text{N}_2 + \text{O} + \text{O} \]
\[ \text{O}_2 + e = \text{O} + \text{O} + e \]

\[ \text{N}_2 + e = \text{N}_2(\text{v}) + e \]
\[ \text{N}_2(\text{v}) + \text{HO}_2 = \text{N}_2 + \text{HO}_2(\text{v}) \]
\[ \text{HO}_2(\text{v}) = \text{O}_2 + \text{H} \]

Synergetic Effect of High and Low Electric Fields
Non-Thermal Decomposition of HO$_2$

Vibrational relaxation time of N$_2$ in the mixture 3%H$_2$-air

Monomolecular decomposition rate of HO$_2$ for different vibrational temperatures
Influence of Vibrational Excitation on Low-Temperature Kinetics

Dynamics of OH concentration in the case of non-equilibrium dissociation (a) and nonequilibrium dissociation and nonequilibrium vibrational excitation (b); $T_{\text{vib}}(t=0) = 3000$ K
Influence of Vibrational Excitation on Low-Temperature Kinetics

Measured and calculated OH decay time. P = 1 atm.

a) 3%H₂ + air; b) 0.3%C₄H₁₀ + air.
Plasma Generation and Modeling.
Distributed Nanosecond Spark
Distributed nanosecond spark

- Streamer corona
- Localized spark
- Distributed spark

- 12 kV @ 100 Ohm
- 12 ns duration
- Still air
- Room temperature

- < 1 kHz
- 1 ... 10 kHz
- > 10 kHz

Exposure time 1/500 sec
(= 20 sparks at 10 kHz)
Ultra-Lean Mixtures Ignition by Plasmatron

**T_{flow} 580 C**

**T_{flow} 400 C**

**T_{flow} 200 C**
Transition from Streamer Corona to Distributed Spark in Air flow

100 slpm

70 slpm

distributed spark

0 slpm

localized spark

streamer corona
Plasma Channel Displacement

Two key processes, strong detachment in the channel on O atoms mainly and fast electron-ion recombination, lead to o-axis residual charge maximum formation in millisecond time range.
Plasma-Assisted Ignition at High Pressures
Lean-burn gas power generation efficiency up to 50% (Wärtsilä Engines, 2010) requires air excess ratio $\lambda > 2$

Conventional spark-plug systems ignite at $\lambda < 1.6$
Flammability Limit
Existing Plug-based Ignition Systems

• Regular spark plugs
  \[ \lambda < 1.4 \]

• Regular spark plugs with thin (Iridium/Platinum) electrodes
  \[ \lambda < 1.6 \]

• RF, “plasma”, etc. plugs
  \[ \lambda < 1.8 \]
Distributed Nanosecond Sparks

NGK BUHZV plug
air, N2, Ar
room temperature

high-pressure discharge behavior with gas flow

4 bar
16 bar
20 bar
Distributed Spark Ignition System – Engine Tests. Honda GX160, 3.8 kW
Fuel Economy with Distributed Plasma Ignition System: $\lambda = 1$

- Fuel consumption, g/kWh for original magneto ignition
- Fuel economy percentage, distributed spark ignition compared to magneto ignition

- up 25% of fuel saving at low load
- mainly due to elimination of misfiring
Fuel Economy with Distributed Plasma Ignition System

- from 15% (high load) up 45% (low load) of fuel saving
- lean-burn operation => lower max power

Fuel economy percentage for $\lambda = 1$, distributed spark ignition compared to magneto ignition.

Fuel economy percentage for $\lambda = 2$, distributed spark ignition compared to magneto ignition.
Distributed Spark Ignition System – Engine Tests

**Honda GX160**

- **Engine Type**: Air-cooled 4-stroke OHV
- **Bore x Stroke**: 68 X 45 mm
- **Displacement**: 163 cm³
- **Net Power Output**: 4.8 HP (3.6 kW) @ 3,600 rpm
- **Net Torque**: 7.6 lb-ft (10.3 Nm) @ 2,500 rpm
- **Fuel System**: Carburetor
- **Compression Ratio**: 9.0 : 1

**BMW/PSA Peugeot Citroën EP6DT**

- **Engine Type**: straight-4 turbocharged
- **Bore x Stroke**: 77 X 85.8 mm
- **Displacement**: 1600 cm³
- **Net Power Output**: 148 HP (110 kW) @ 5,500 rpm
- **Net Torque**: 177 lb-ft (240 Nm) @ 1,400 rpm
- **Fuel System**: gasoline direct/port injection and variable valve timing
- **Compression Ratio**: 9.5:1-14 :1
Distributed Spark Ignition System
BMW/PSA Peugeot Citroën *EP6DT Engine*

### Graph 1

**Equation:** \( \text{Std Deviation} [%] = f(\text{E.R.}), \text{IMEP}=2.8 \text{ bar}, 2000 \text{ rpm}, \text{C.R.}=10.5 \)

**Graph Details:**
- Y-axis: Std Deviation [%]
- X-axis: Equivalence Ratio
- Lines:
  - Blue: Std Deviation Plasma
  - Green: Std Deviation STD

### Graph 4

**Equation:** \( \text{Std Deviation} [%] = f(\text{E.R.}), \text{IMEP}=2.8 \text{ bar}, 2000 \text{ rpm}, \text{C.R.}=14 \)

**Graph Details:**
- Y-axis: Std Deviation [%]
- X-axis: Equivalence Ratio
- Lines:
  - Blue: Std deviation Plasma
  - Green: Std Deviation STD
Distributed Spark Ignition System
BMW/PSA Peugeot Citroën EP6DT Engine

Std Deviation [%] = f(EGR), IMEP=2.8 bar, 2000rpm, C.R.=10.5

Std Deviation [%] = f(EGR), IMEP=10bar, 2000rpm, C.R.=10.5
Distributed Spark Ignition System
BMW/PSA Peugeot Citroën \textit{EP6DT Engine}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{\% of misfiring = f(E.R.), IMEP=2.8 bar, 2000 rpm, C.R.=10.5}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{\% misfiring = f(E.R.), IMEP=2.8 bar, 2000 rpm, C.R.=14}
\end{figure}
Discharge Formation and Flame Stabilization in High Speed Flow - SCRAMJets

PAC Kinetics at High T, Low P
Physics of Pulsed Discharges
Kinetics in Nonequilibrium Plasma

Peak Voltage 224 kV
Rise Time: 0.15 ns
Duration: 0.4 ns

Pulser:
- Output voltage – 120 kV
- Load – 300 Ohm
- Peak current – 400 A
- Rise time – 1 ns
- Pulse width – 12 ns
- Maximum PRF – 1 MHz

Pac Kinetics at High T, High P

PicoStar HR ICCD camera system (LaVision GmbX) and 8-channel Berkeley Nucleonic Corp Model 575 Pulse Delay Generator.

Minimal ICCD gate ~ 80 ps
Inter-channel jitter < 50 ps
Nano (Pico) second High-Voltage Generators

The most promising scheme is based on DSRD or DRD switches

- 80% achieved efficiency “from plug”
- up to 1 GW of peak power in 1 liter
SUMMARY

Major Results
1. Model of plasma recombination in oxygen and air;
2. Model of fast energy transfer in nonequilibrium plasma;
3. Model of distributed spark formation by pulsed periodic discharge;
4. Model of nonequilibrium oxidation at low temperatures;
5. Plasma assisted ignition demonstration up to $P = 40$ atm;

Future Plans
1. High-temperature kinetics of PAC;
2. High-pressure kinetics of PAC;
3. Physics of pulsed discharges – nano- and picosecond scale;
4. Kinetics of nonequilibrium plasma – role of plasma density;
5. Plasma-assisted flame stabilization for GTEs and SCRAMJets.