Plasma-Assisted Combustion Studies at AFRL

MURI Kickoff Meeting
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Prescribed by ANSI Std Z39-18

Overview

Areas where plasmas and E-fields can have an influence

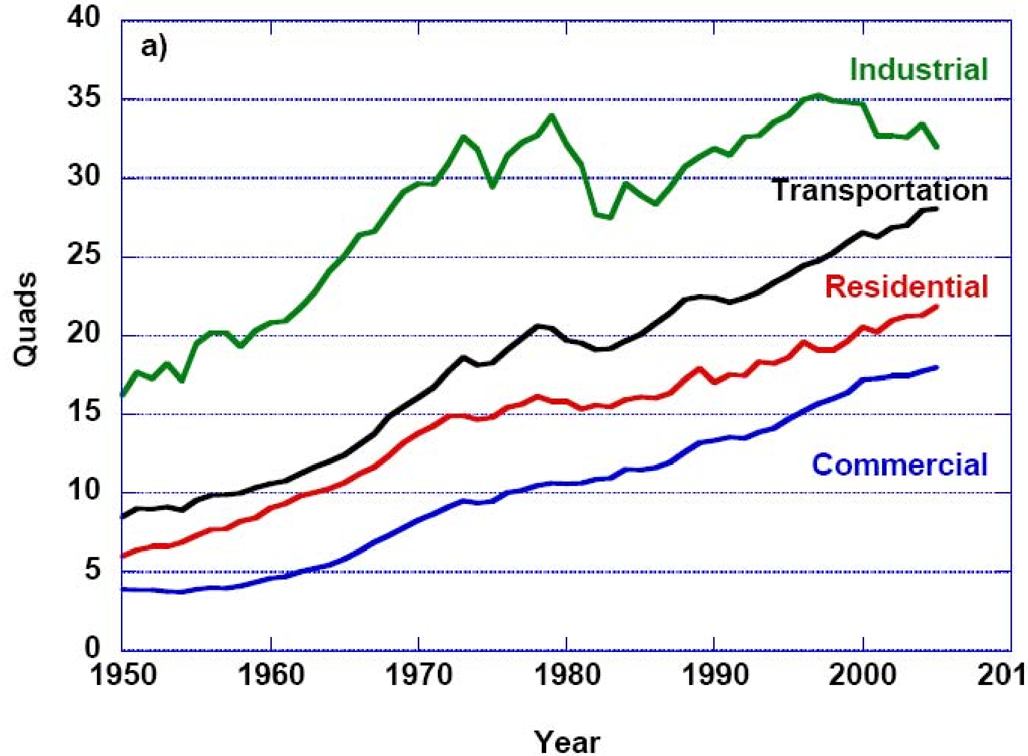
- Enhance reaction rate & flamespeed
  - Important for high-speed combustors (& other combustors too):
    - Ignition, from *cold* state especially & with liquid fuel
    - Steady operation, through flamespeed enhancement and flameholding
  - Potentially important for lean, gas-turbine (powerplant) operation
    - Might one also mitigate/influence acoustic fluctuations?
    - Potential for *uniform* performance with *nonuniform* fuel source
- Enhance fuel-air mixing & penetration
  - Potential alternative to intrusive mechanisms (struts/pylons)
  - Potential for dynamic control of penetration/mixing
  - Potential for creating recirculation region for flameholding
- Boundary-layer & surface interactions
  - Trip boundary layer; hold shock

Overview

Fun Facts on US Energy Consumption

- HC sources provide ~85% of nation's energy
  - 97% for transportation
- Transportation's consumption about 28% of total
  - ≈ 1 million gallons/minute
- Quads = quadrillion (10^{15}) BTU ≈ 10^{18} J

US Energy Consumption, 1950-2005



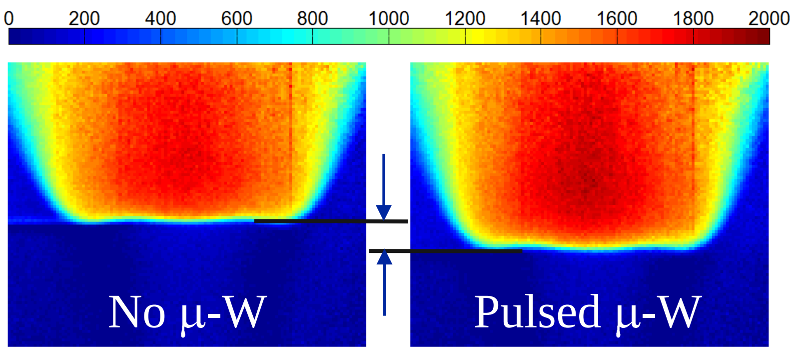
Source: Energy Information Administration, Annual Energy Review 2005, Report DOE/EIA-0384 (2005).
See also *Report of the Basic Energy Sciences Workshop on Basic Research Needs for Clean and Efficient Combustion of 21st Century Transportation Fuels*

Overview

Plasma/E-field Effects on Ignition & Flame Behavior

μ-W E-field Effects on Flame Propagation

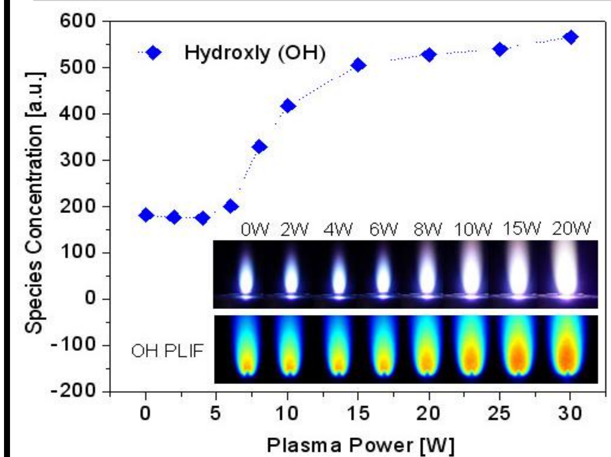
Stockman, Miles, Zaidi (Princeton), Ryan



Planar FRS Thermometry with pulsed μ-W Source

Diagnostics of Plasma Enhanced Flames

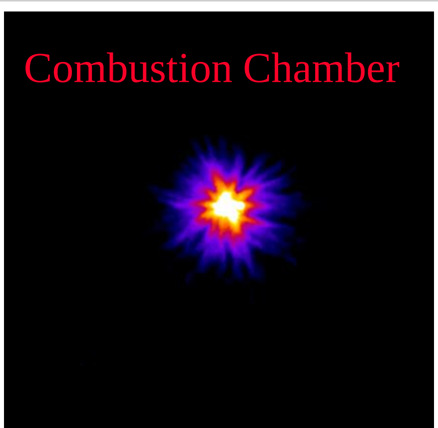
Lee (MSU)

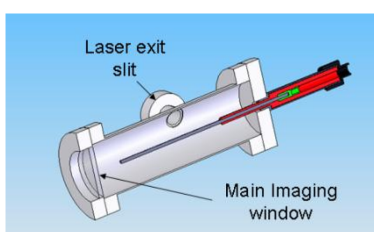


Direct coupled plasma torch: flame OH vs. μ-wave power:

Plasma-assisted Ignition

Cathey, Gundersen, Wang, Cain (USC), Ryan

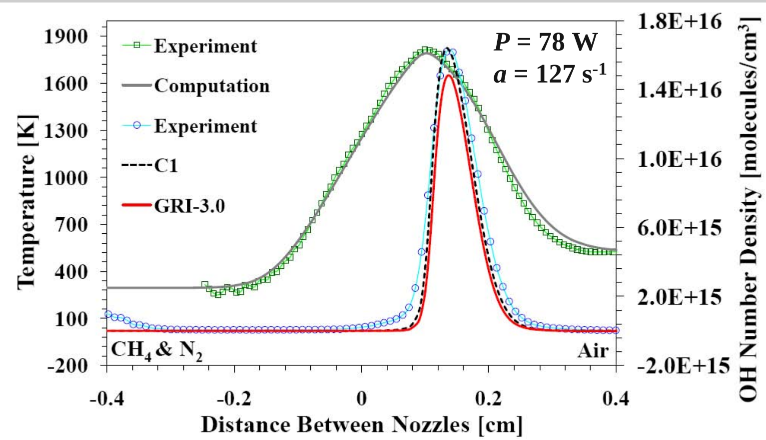




Ignition event

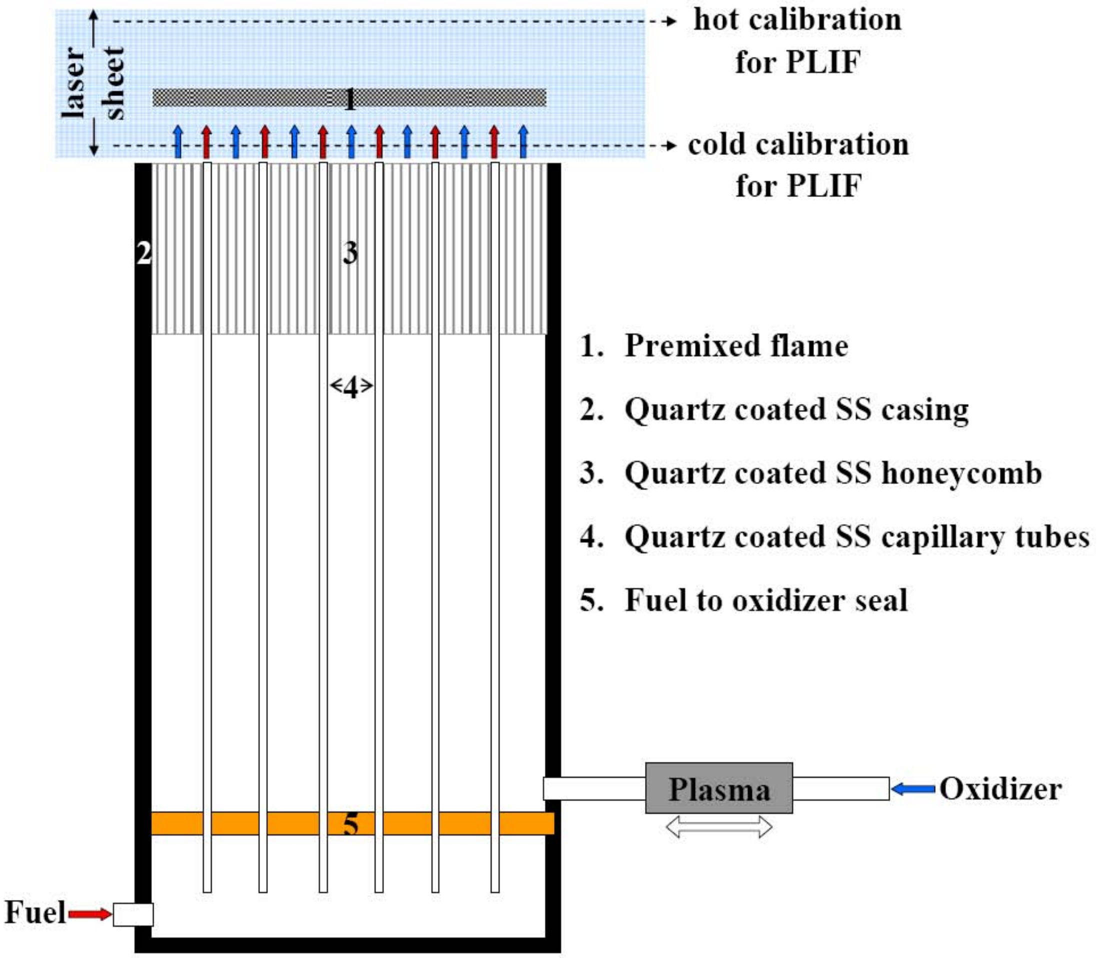
Effects of Gliding Arc on Flame Chemistry

Ombrello, Ju (Princeton), Gutsol, Fridman, (Drexel)



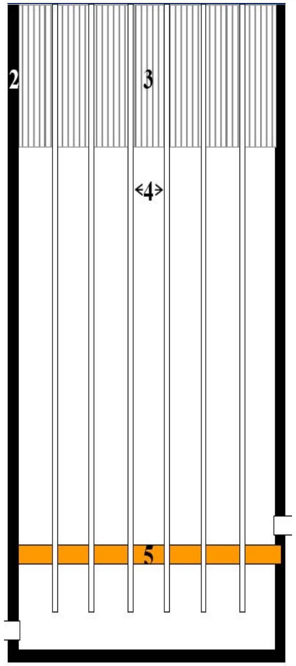
*Enhancement of Flamespeed through Plasma Activation**

- ***Goal:*** Study flame propagation increase with plasma-excited oxidizer
- Integrate plasma source with custom *Hencken* burner
  - Gases mix at burner exit
  - Quartz coating of metal surfaces
- Operate at low *P*
  - Reduced reaction rates
  - Allow mixing of fuel & oxidizer upstream of flame



*Ombrello, Ju, Sun, Carter, Brown, Katta

*Enhancement of Flamespeed through Plasma Activation**



- Decrease chamber *P* to lift flame from surface
  - Flame has fully premixed character at low *P*
- Apply diagnostics to characterize plasma species, *T* & *V*
  - Species of interest: O_3, $O_2(a^1\Delta_g)$, $O_2(b^1\Sigma_g)$, O, $O(^1D)$

*Ombrello, Ju, Sun, Carter, Brown, Katta

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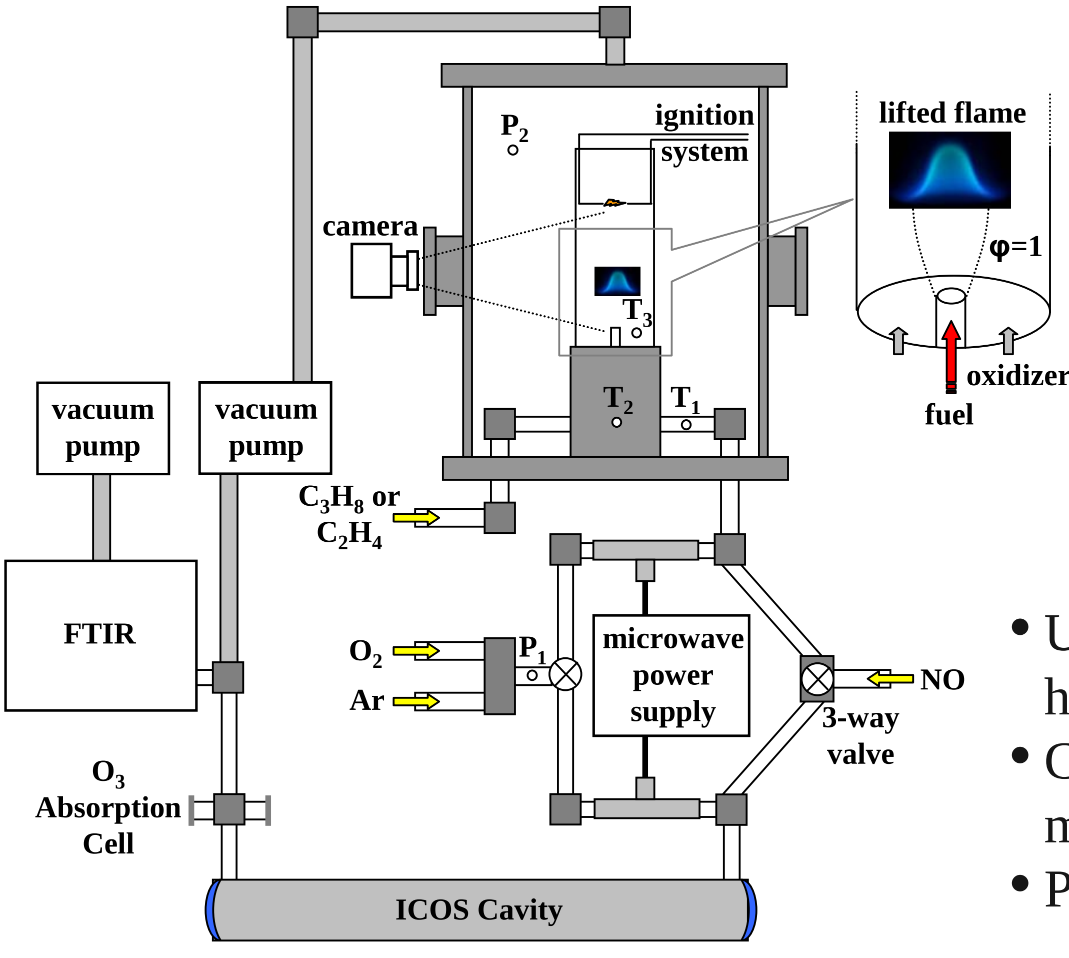
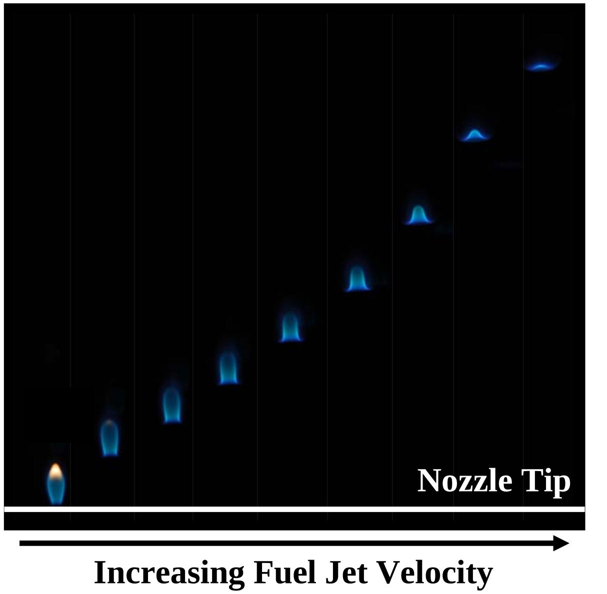


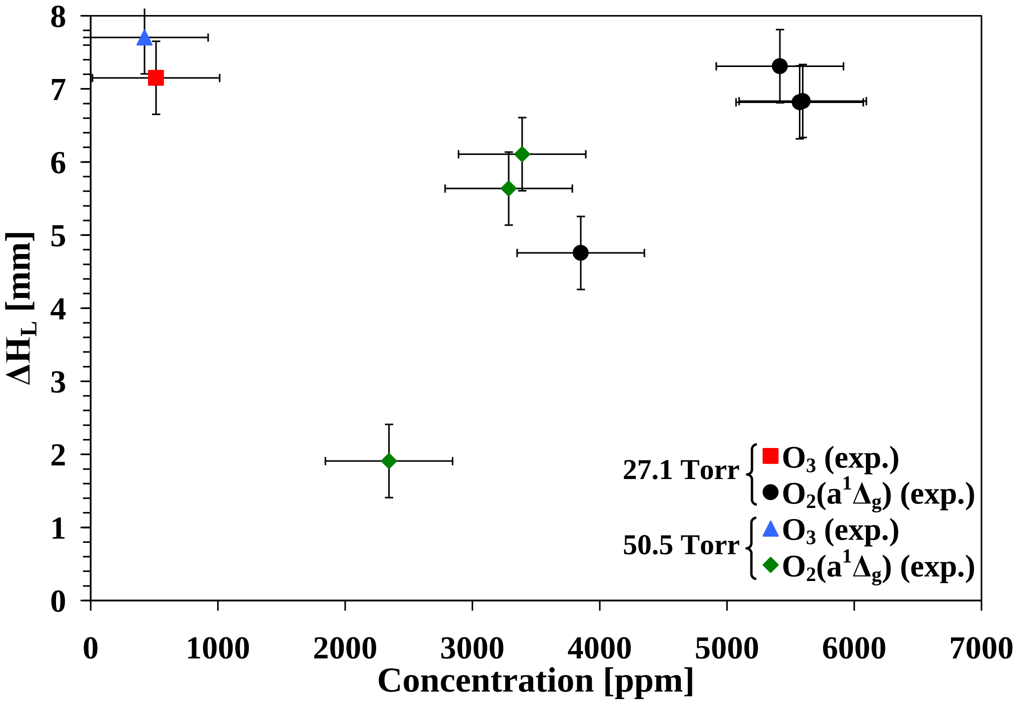


- Use low-*P* lifted jet flame: lift-off height ΔH_L sensitive to flamespeed, S_L
- Characterize S_L increase with ΔH_L measurement
- Produce & quantify O_3 and $O_2(a^1\Delta_g)$
  - measure ΔH_L

*Ombrello, Ju, Won, Williams

Enhancement of Flamespeed through Plasma Activation*

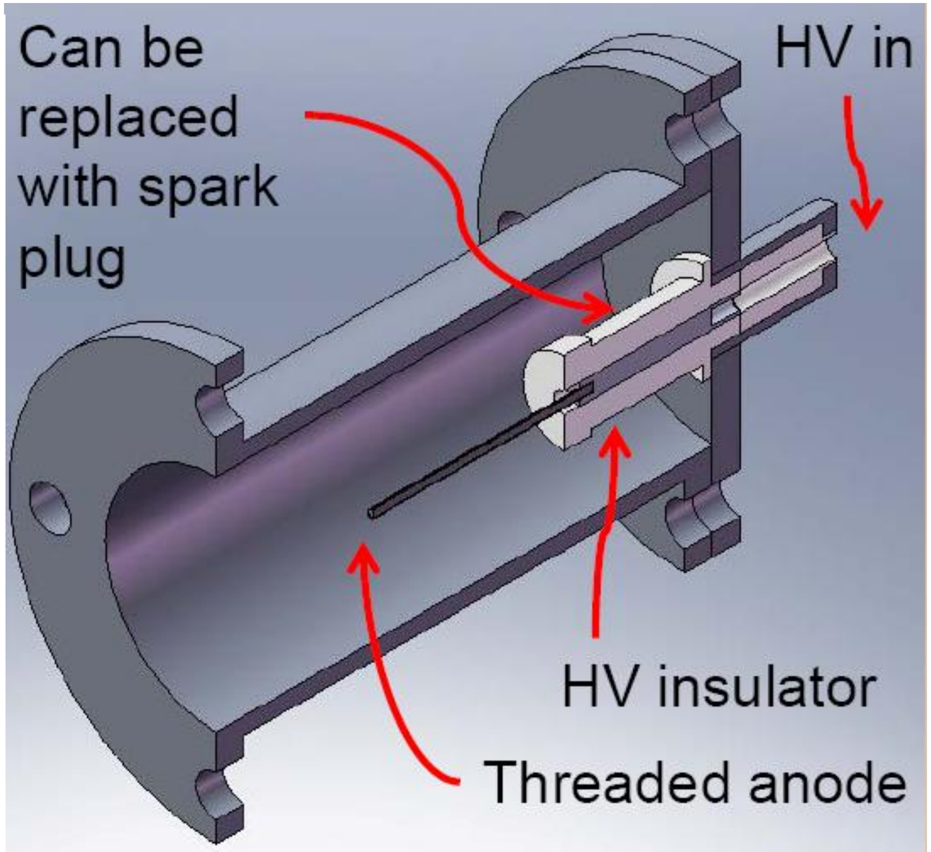
- Graph shows isolated effect of O_3 and $O_2(a^1\Delta_g)$
  - P = 27 or 51 Torr
- Concentrations of $O_2(a^1\Delta_g)$ as large as ~X = 0.6%
- Conversion of ΔH_L to S_L requires additional measurements and/or modeling
- Work with Hencken flame will be follow-on effort



*Ombrello, Ju, Won, Williams

*Ignition Enhancement with Transient Plasma (TP)**

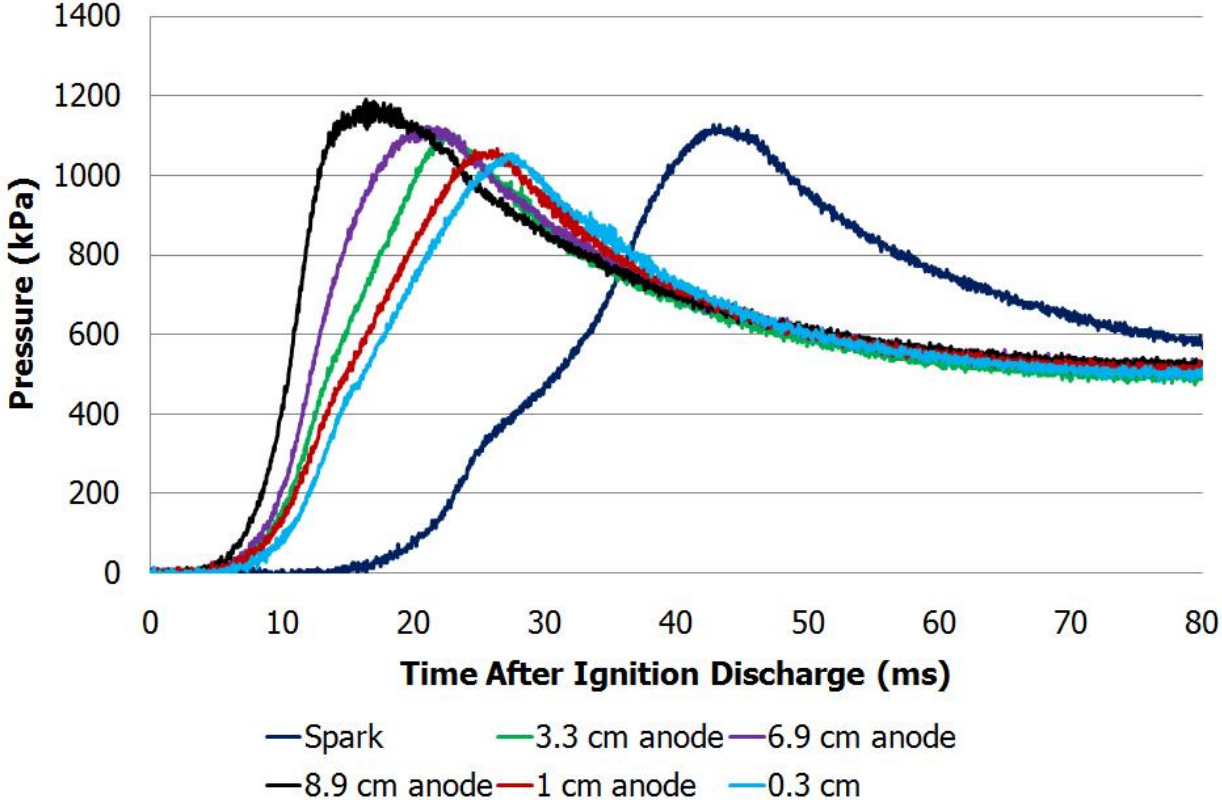
- ***Goal:*** Determine physical mechanism, primarily for *transient plasma* ignition
  - *What is role of humidity:* X_{H2O} affects detonation wave speed in PDE but not t_{ign}
- Measure X_{OH} and X_{O3} vs. X_{H2O} in air
  - OH from PLIF & O_3 from absorption
  - Need to sample along anode, especially since flame originates from anode surface
- Highly desirable: O-atom distribution
  - Also CH_3 and CH_2O



Combustion chamber
- Variable anode lengths & materials
- Optical access: windowed-slits (not shown) & end-flange window

*Singleton, Pendleton, Gundersen (USC), Stockman, Carter, Brown

Ignition Enhancement with TP*

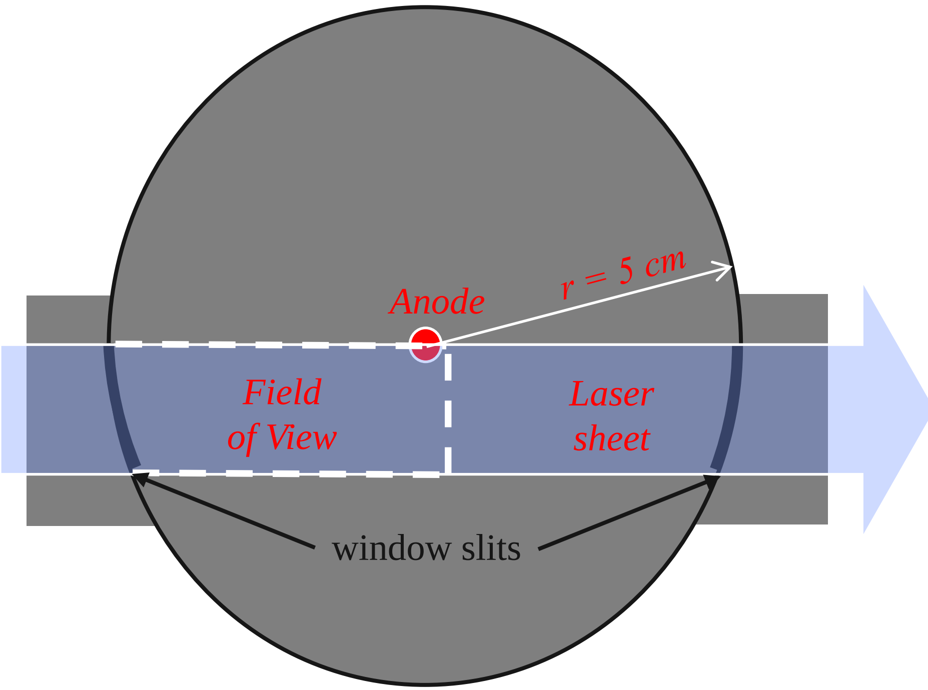


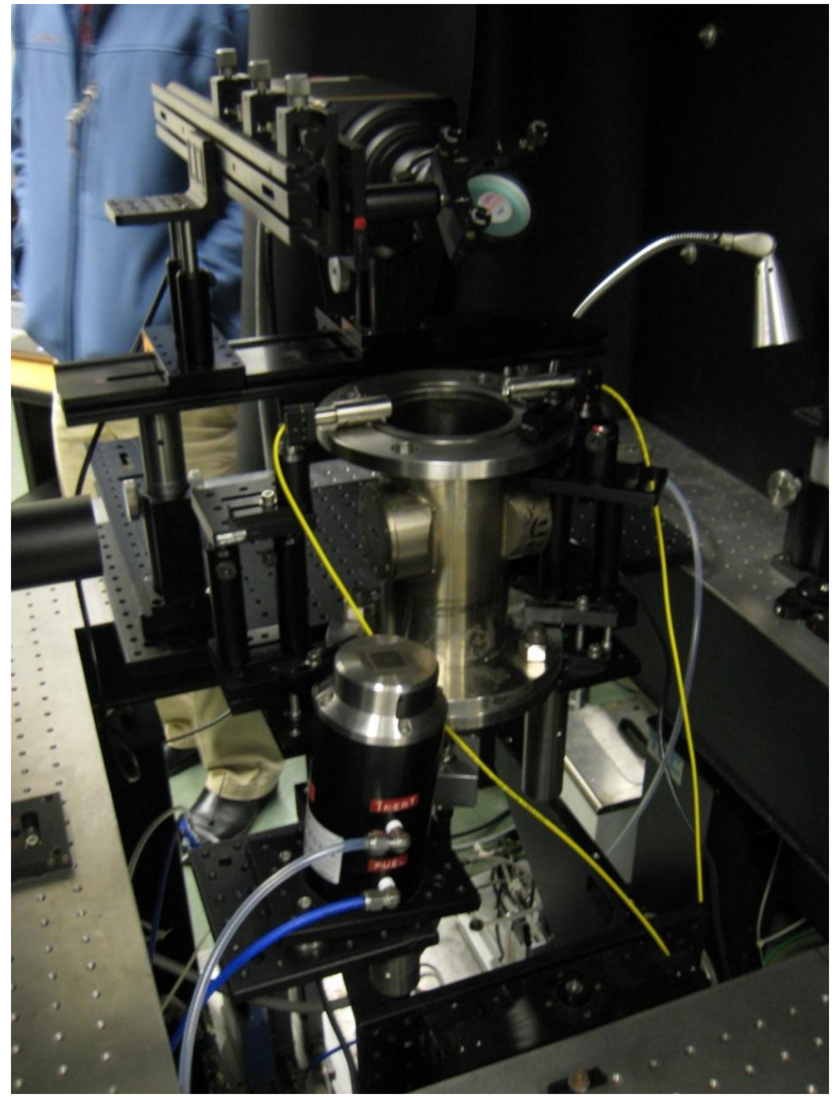
stoichiometric C_2H_4-air
$P = 1$ atm
$E_{pulse} = 550$ mJ (75 kV)
$t_{\text{pulse}} \approx 100$ ns

- Effect of anode length & comparison to spark plug (2 cm from back wall)
  - Significant reduction in t_{ign} even with 3-mm length protrusion
- Flame propagates from anode to wall
  - Flame initiation and propagation approx. uniform along perimeter & length

*Singleton, Pendleton, Gundersen (USC), Stockman, Carter, Brown

Ignition Enhancement with TP*





- Camera looking down into chamber
- Continuous flow of moist air
  - 1-Hz pulse frequency
  - X_{H2O} measured with TDLAS
- PLIF of OH: Peak signals ~10^{15} cm^{-3}

*Singleton, Pendleton, Gundersen (USC), Stockman, Carter, Brown

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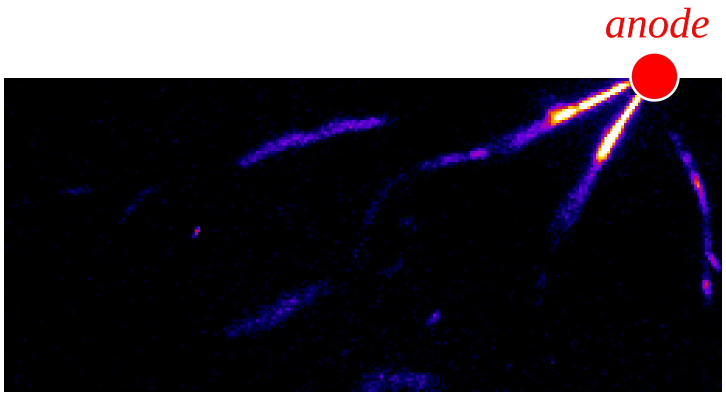

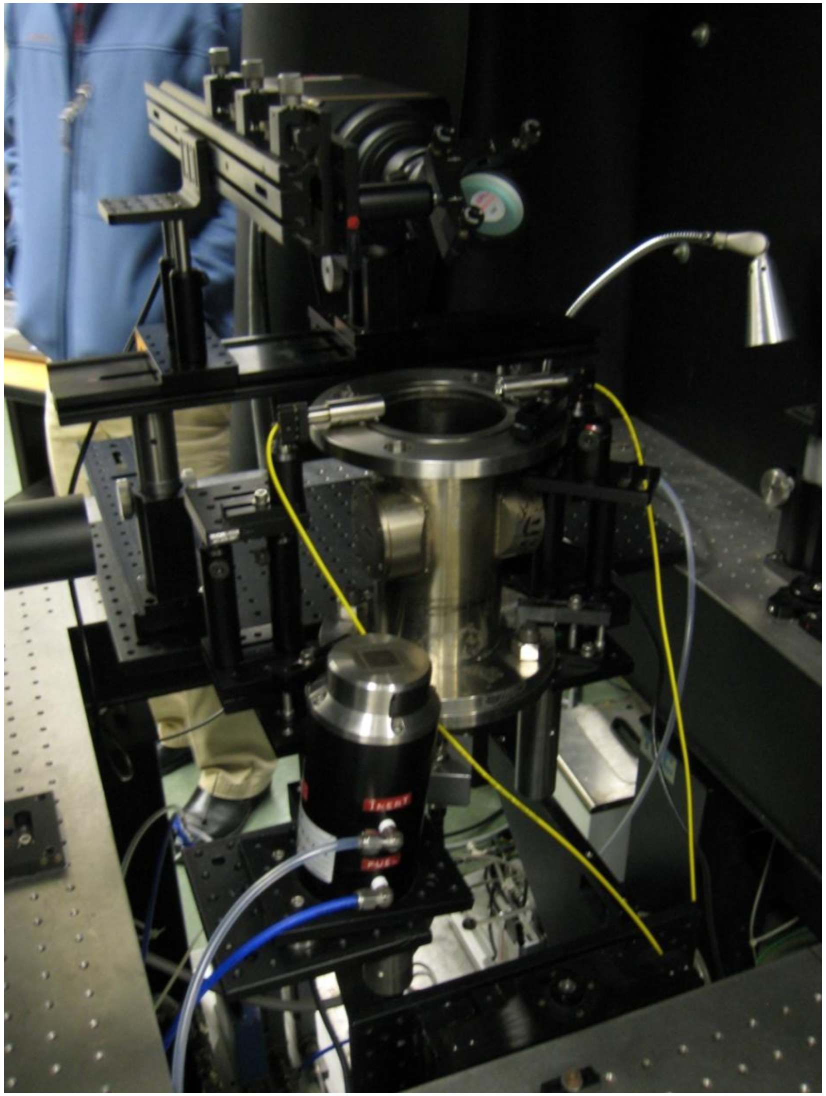

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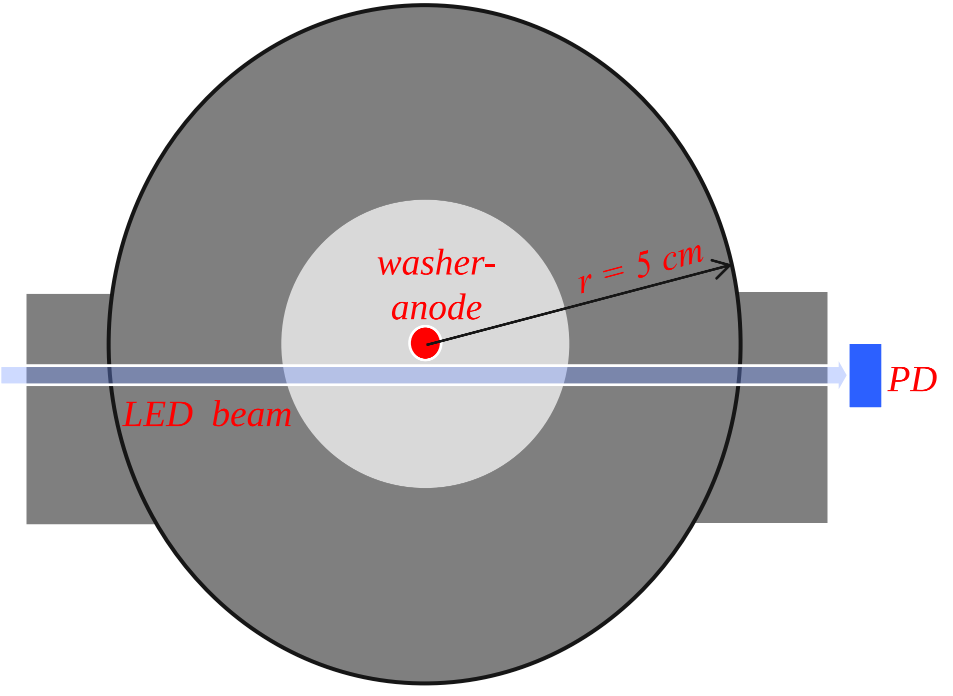
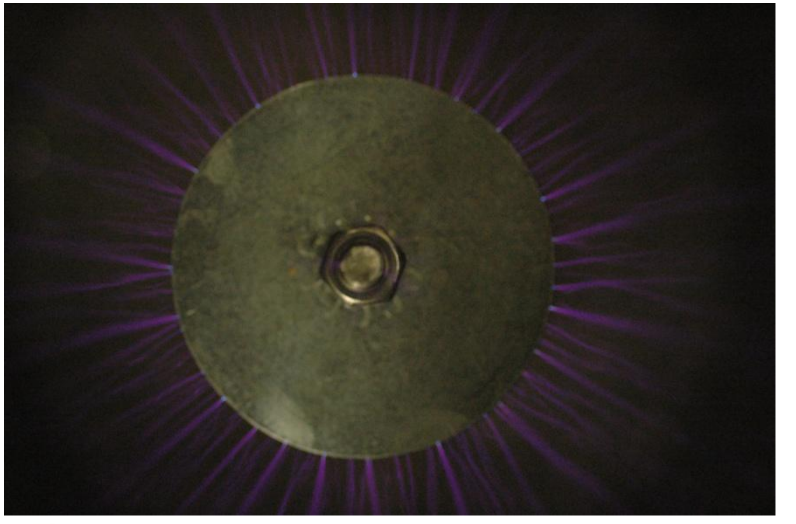
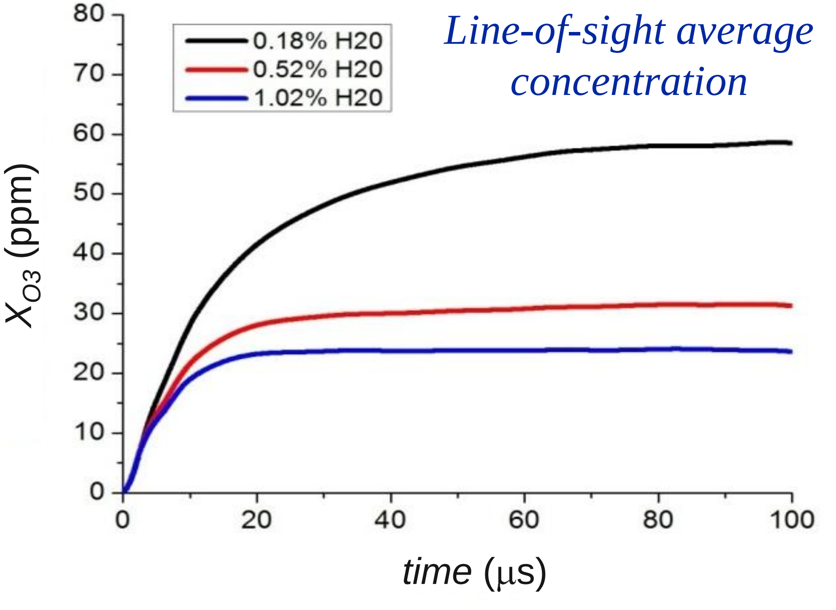




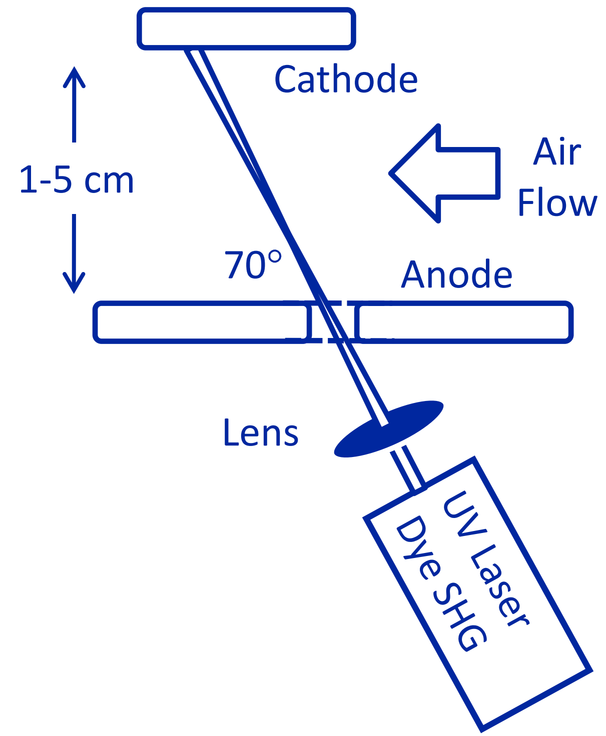
- UV LED beam positioned over washer
  - Undetectable X_{O3} with normal config.
- 1-ms LED pulse synched to TPI pulse
  - 200 o-scope waveforms recorded
  - Presumably, X_{O3} distribution nonuniform



*Singleton, Pendleton, Gundersen (USC), Stockman, Carter, Brown

*Resonant Laser Induced Breakdown for Fuel-Air Ignition**

- ***Goal:*** Investigate effectiveness of low-energy REMPI laser pulse to control spatial & temporal behavior of ignition spark in air crossflow
- ***Approach:***
  - Apply potential (below breakdown value)
  - Focus UV laser pulse at REMPI transition & ionize channel between gap

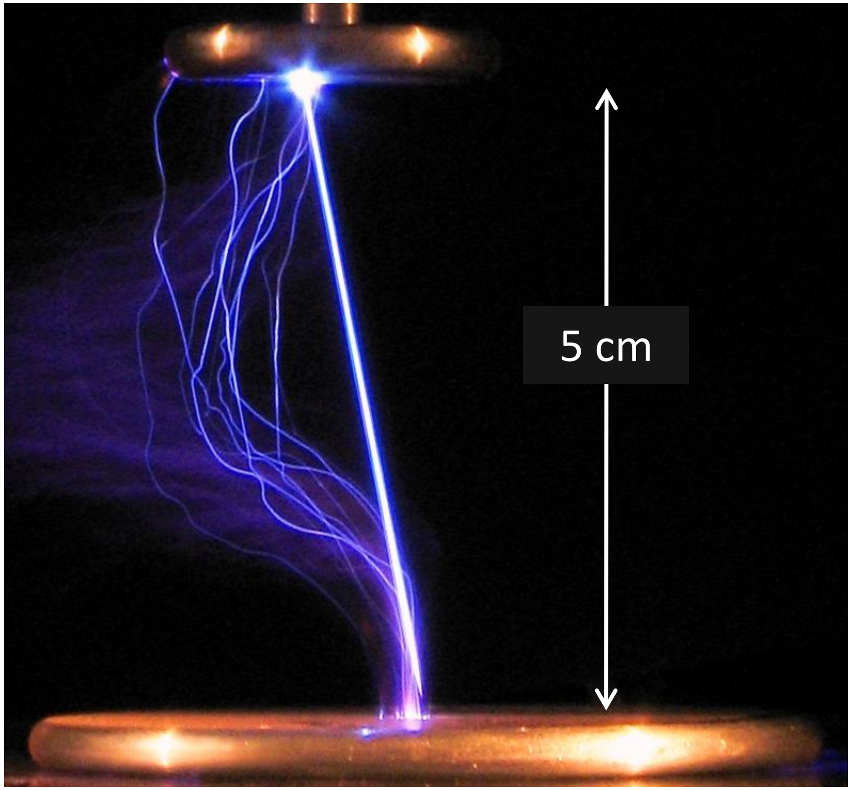


To be presented at ASM-2010

*S. Adams, J. Miles, and A. Laber (AFRL/RZPE)

Resonant Laser Induced Breakdown for Fuel-Air Ignition*

- Sample photo of a laser induced arc
  - Main arc follows laser path
  - Secondary arcs & plasma glow occur after main arc; result of leakage current as capacitor recharges

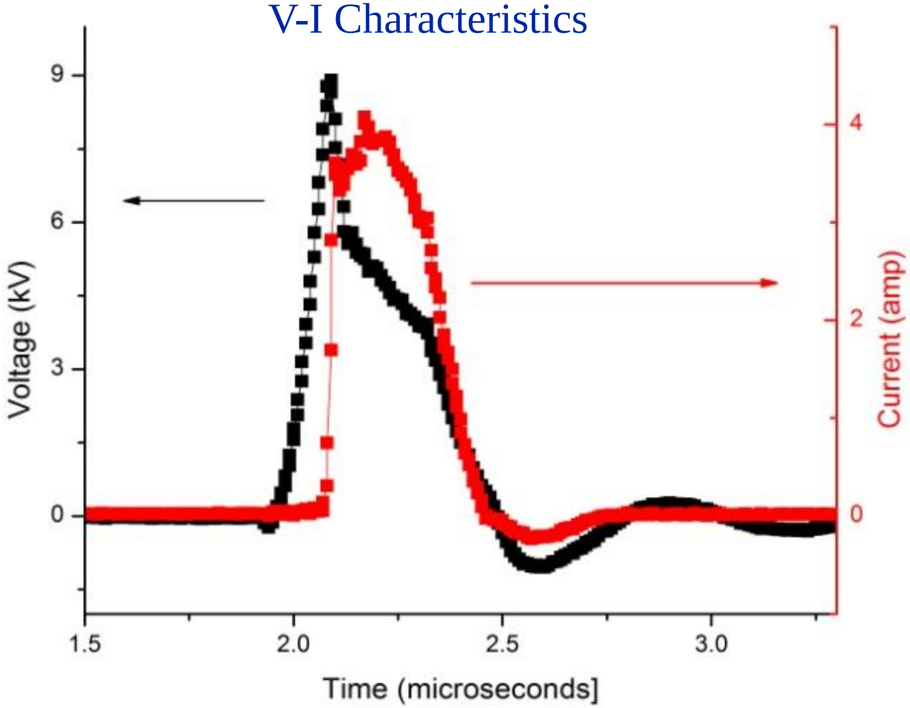


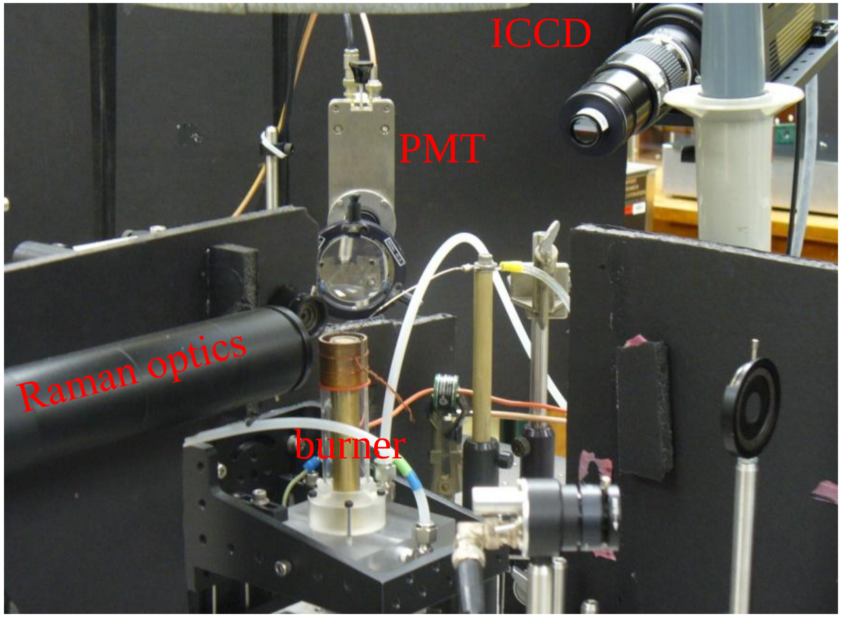
*S. Adams, J. Miles, and A. Laber (AFRL/RZPE)

Non-thermal Plasmas to Modify Combustion Kinetics*

- ***Goal:*** Study effect of pulsed plasma on a C_3H_8/air Bunsen flame
- Quantify with phase-averaged Raman scattering and CH chemiluminescence & time-resolved OH chemiluminescence

V-I Characteristics





*B. Ganguly, J. Schmidt (AFRL/RZPE)

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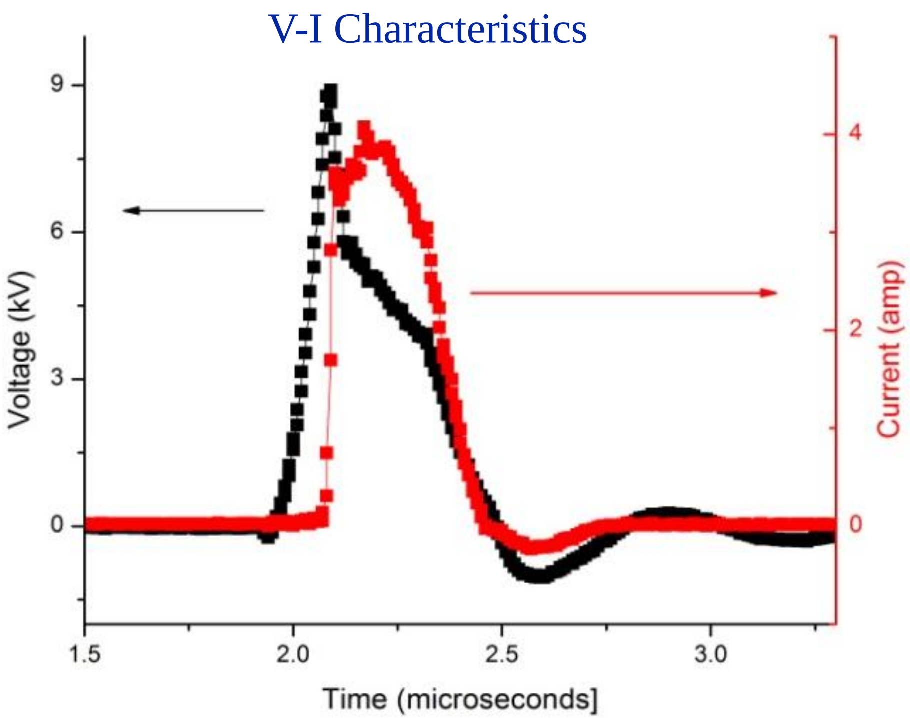

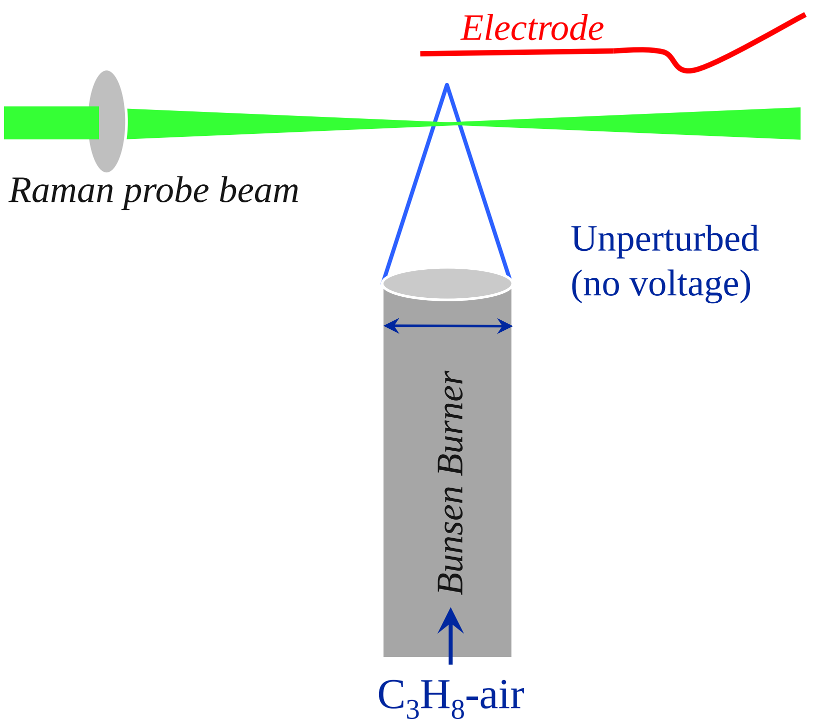

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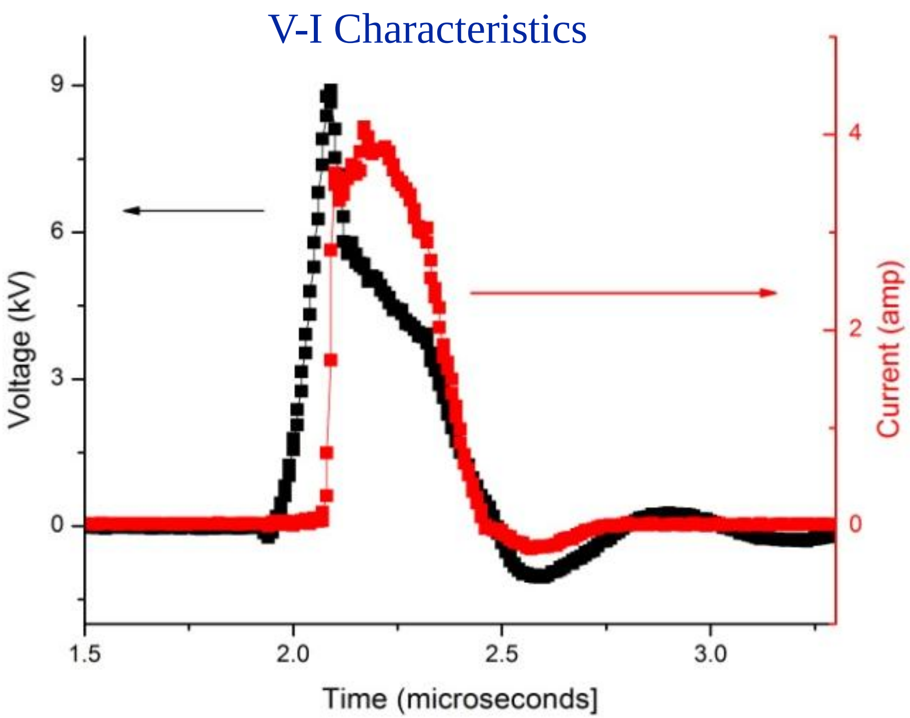
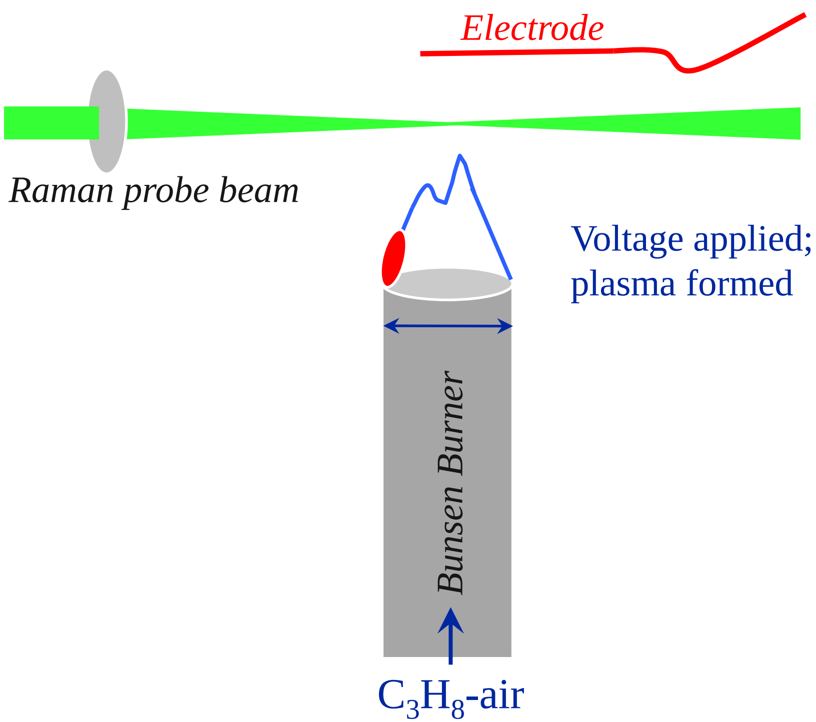
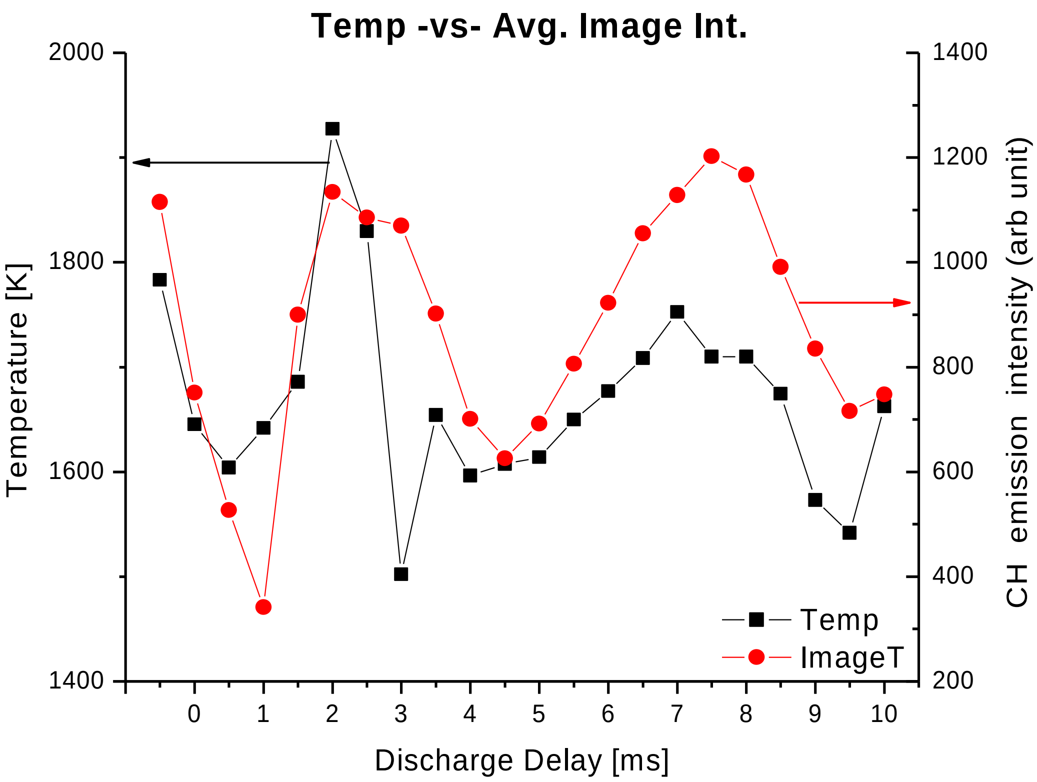


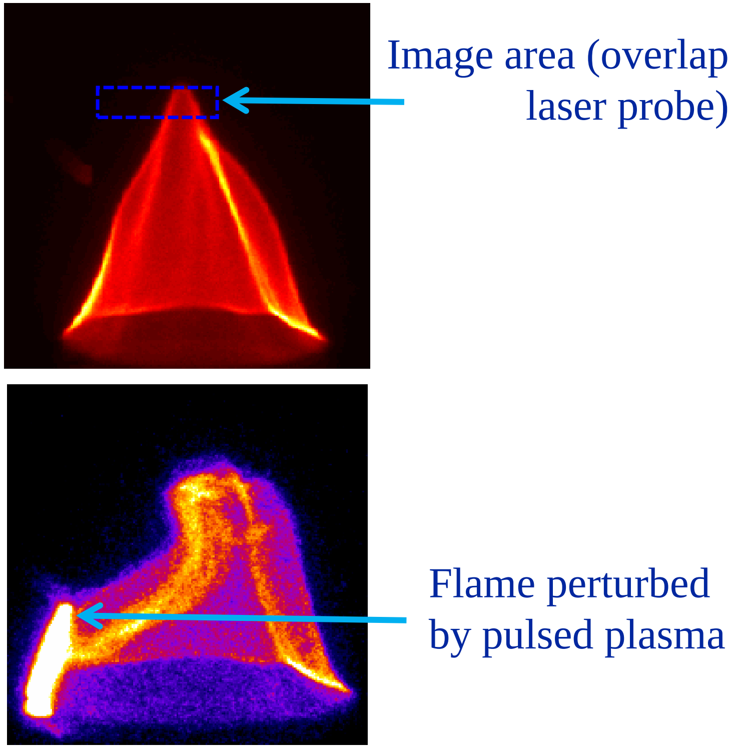


*B. Ganguly, J. Schmidt (AFRL/RZPE)

*Non-thermal Plasmas to Modify Combustion Kinetics**

- 200 Hz rep rate pulsed discharge
  - Few mJ of energy input; significant perturbation
- Phase-locked measurement of *T* and CH chemiluminescence
  - Finite response of flame; some recovery before next pulse





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Summary

Three final thoughts:

- Understanding the role of electric fields, plasma & *plasma-derived species* in initiating and sustaining combustion of critical importance to more effective use
  - Potential for impacting many areas related to use of hydrocarbons
- We (AFRL) welcome collaborations!
  - Many already with MURI team members
  - We'll even do some crazy stuff
- Good luck on efforts!