



Air Force Research Laboratory



Plasma Excited Oxygen Effects on Combustion and Perspectives on Applications to High-Speed Propulsion



Date: 10 November 2011

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Innovative Scientific Solutions

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Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE 10 NOV 2011		2. REPORT TYPE		3. DATES COVERED 00-00-2011 to 00-00-2011	
4. TITLE AND SUBTITLE Plasma Excited Oxygen Effects on Combustion and Perspectives on Applications to High-Speed Propulsion				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Research Laboratory, Wright Patterson AFB, OH, 45433				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES presented at the AFOSR MURI 2nd Annual Review Meeting, 9-10 Nov 2011, Columbus, OH.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 37	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			



Aerospace Propulsion Division



Focus on Scramjet Scaling, Performance, and Operability

Extramural research, including:

Scramjet Engine Demonstrator, X-51

HiFiRE: U.S.-Australian flight-test program

Inhouse research, including

Ignition and Flameholding in high-speed flow

Flowfield characterization

Sub-atmospheric pressure flame studies

Flame speed, stabilization, and detailed structure

Kinetic mechanism validation

Plasma-assisted combustion

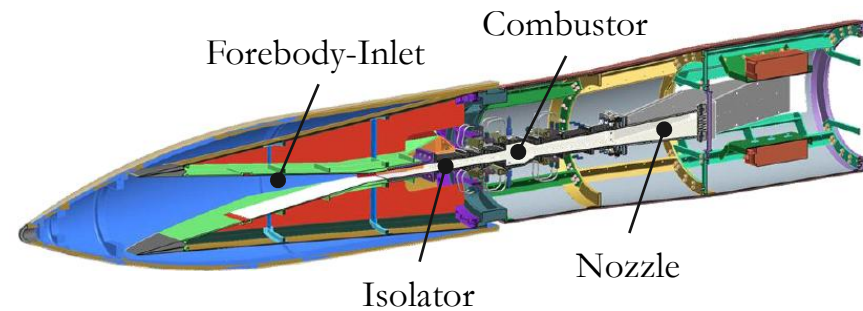
Plasma system design and optimization

Plasma species measurement

Mechanism development



X-51 Vehicle



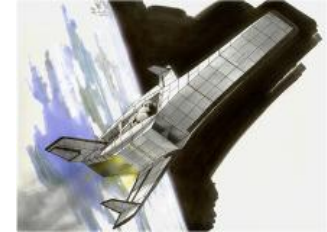
Mach 6-8 HiFiRE-2 Vehicle



Hypersonics: Stair-Step Approach Building Upon Prior Success



Development of New
Technology for the Next
Generation of High-Speed Flight



Operationally Responsive Spacelift
(Robust and Responsive)



Large Hypersonic Missiles/
Small Launch Systems

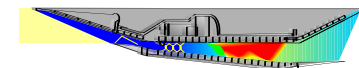
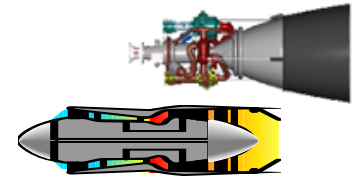


Hypersonic Missiles/
Small Launch Systems

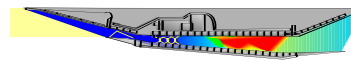


Hypersonic Missiles
(Time-Critical Targets)

*Large
Scramjets
and CCE's*



*Medium
Scramjets*

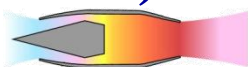


*Small
Scramjets*



X-51 Program

Ramjets





Crucial Areas for Success



Cold Start/Ignition

cold combustor surfaces, sub-atmospheric pressure, and limited residence time

Flame Stabilization

anchoring/stabilizing a flame in Mach 2-4

Complete Combustion/Heat Release

limited time for complete chemical heat release and therefore conversion to thrust

Developing techniques to enhance fuel reactivity and heat release are extremely important for the success of high-speed propulsion systems such as scramjets



Scaling Up to Larger Systems:

What about 100 lbm/s
or even 1000 lbm/s?

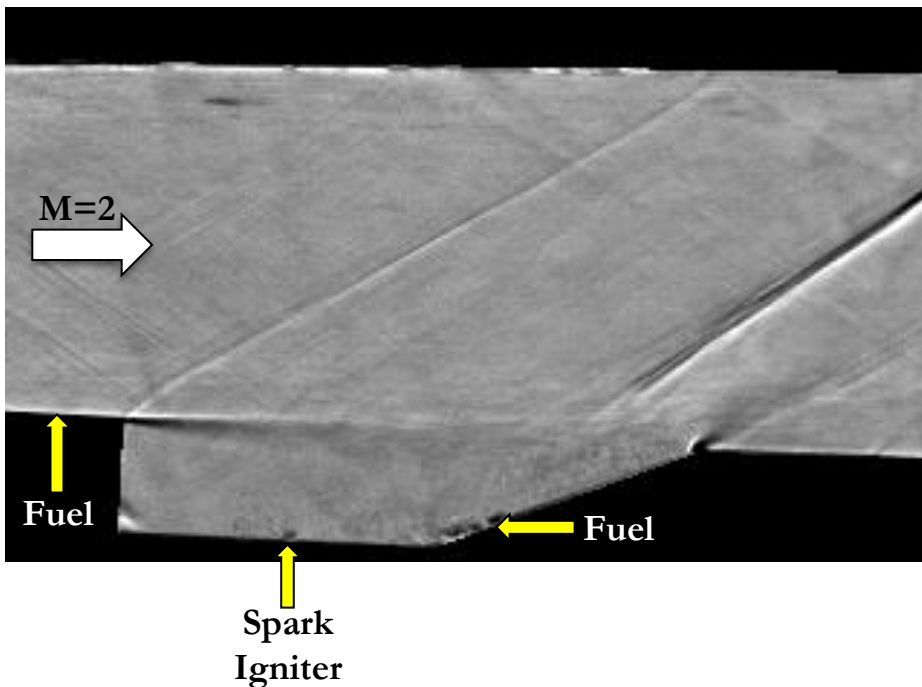


Dynamics of an Ignition Process in High-Speed Flow

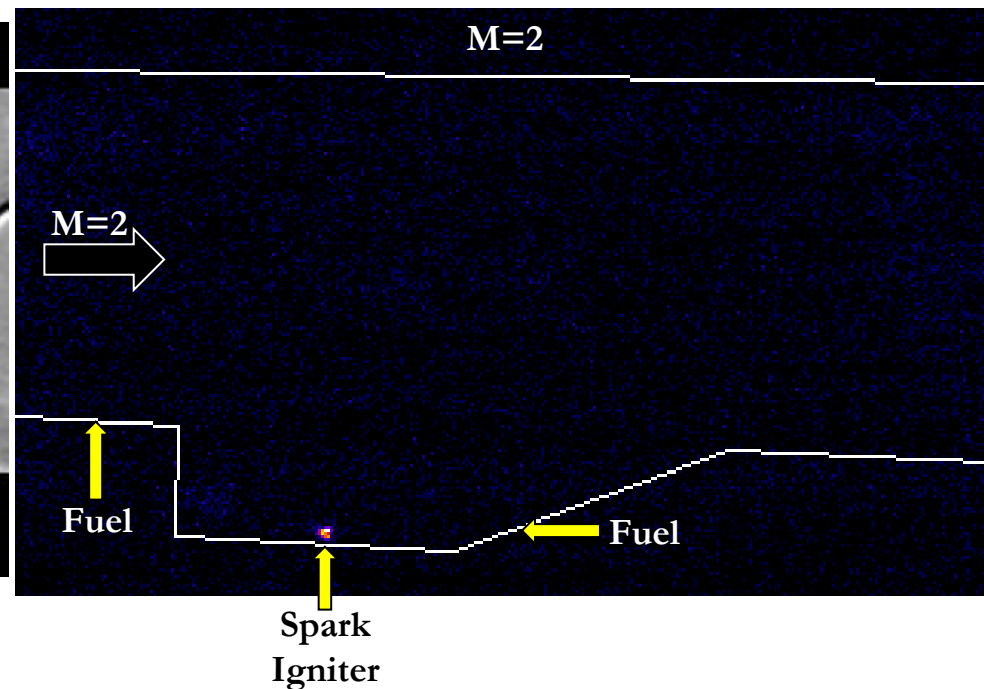


High Speed Imaging Captured at 100,000 fps (10 μ s per frame)
Slowed 10,000 times

Shadowgraph



Chemiluminescence





Motivation

Restrictive Combustion Environments

e.g. High-Speed Air-Breathing Propulsion Systems



Short Residence Time for Chemical Reactive Processes

Specifically Ignition, Flame Stabilization, Flame Propagation, Extinction, and Flammability Limits



Necessitates Development of Techniques for Enhancing the Rate of Chemical Heat Release



The Application of Plasma

Providing Radicals, Intermediate Species, Excited Species, Ions, Electrons, and Elevated Temperatures



Understand the Key Species and Mechanisms of Enhancement

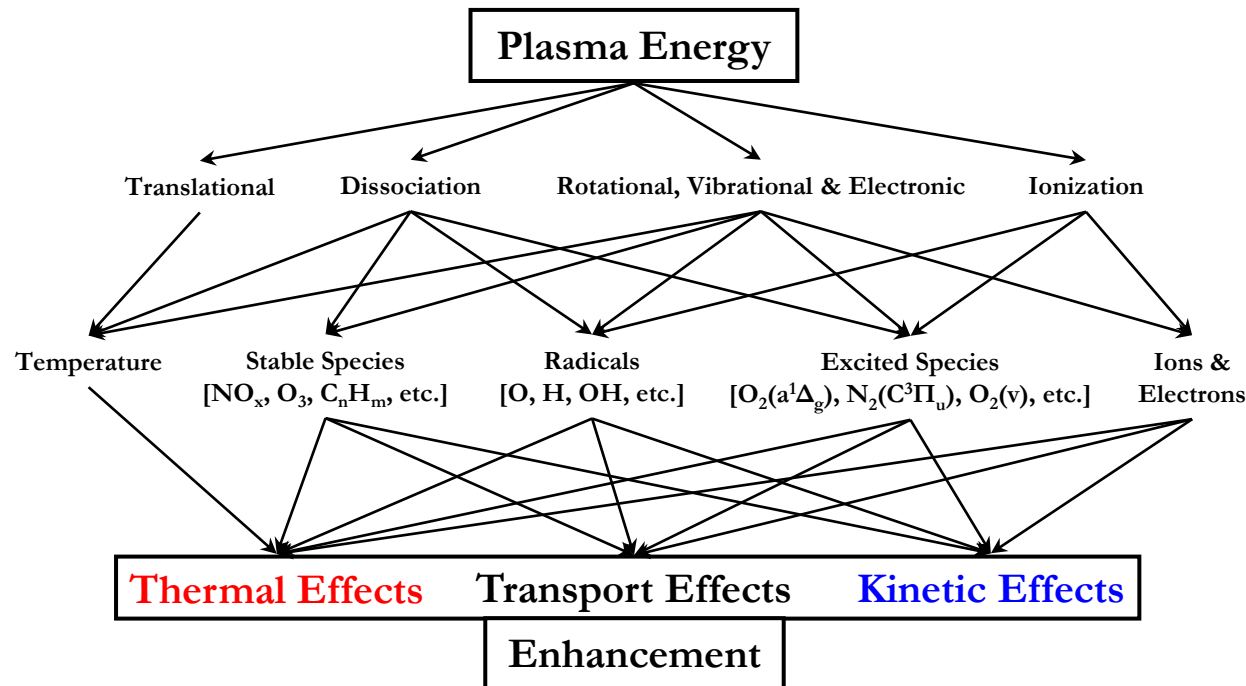
Allowing for Optimization and Practical Application



Develop Simplified and Decoupled Plasma-Assisted Combustion Platforms for Detailed Studies



Taking a Selective Approach



Multiple Combustion Processes

Ignition

Flame Propagation

Flame Stabilization

Extinction

Flammability Limits

Building Block Approach

1. Isolate the effect of specific plasma-produced species
2. Validate kinetic mechanism
3. Optimize the production of specific plasma species
4. Apply knowledge to practical systems



Investigating O_3 and $O_2(a^1\Delta_g)$



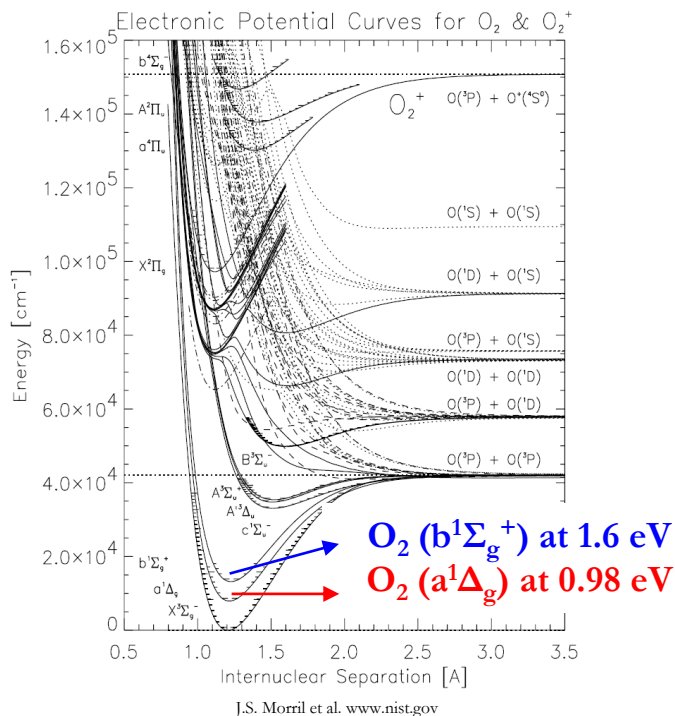
O_3

Stable But Weakly Bound O to O_2 

Long Lifetime

Deposition of O
Into Flame Front

$O_2(a^1\Delta_g)$



$O_2(a^1\Delta_g) \rightarrow O_2(^3\Sigma_g^-)$
Magnetic Dipole Transition
(singlet-triplet inter-combination) 

Long Lifetime

Efficient production at
1 eV $\approx$ 10 Td 

Pulsed or Low Power
Discharge

Unpaired Valence Electrons 

High Chemical Reactivity

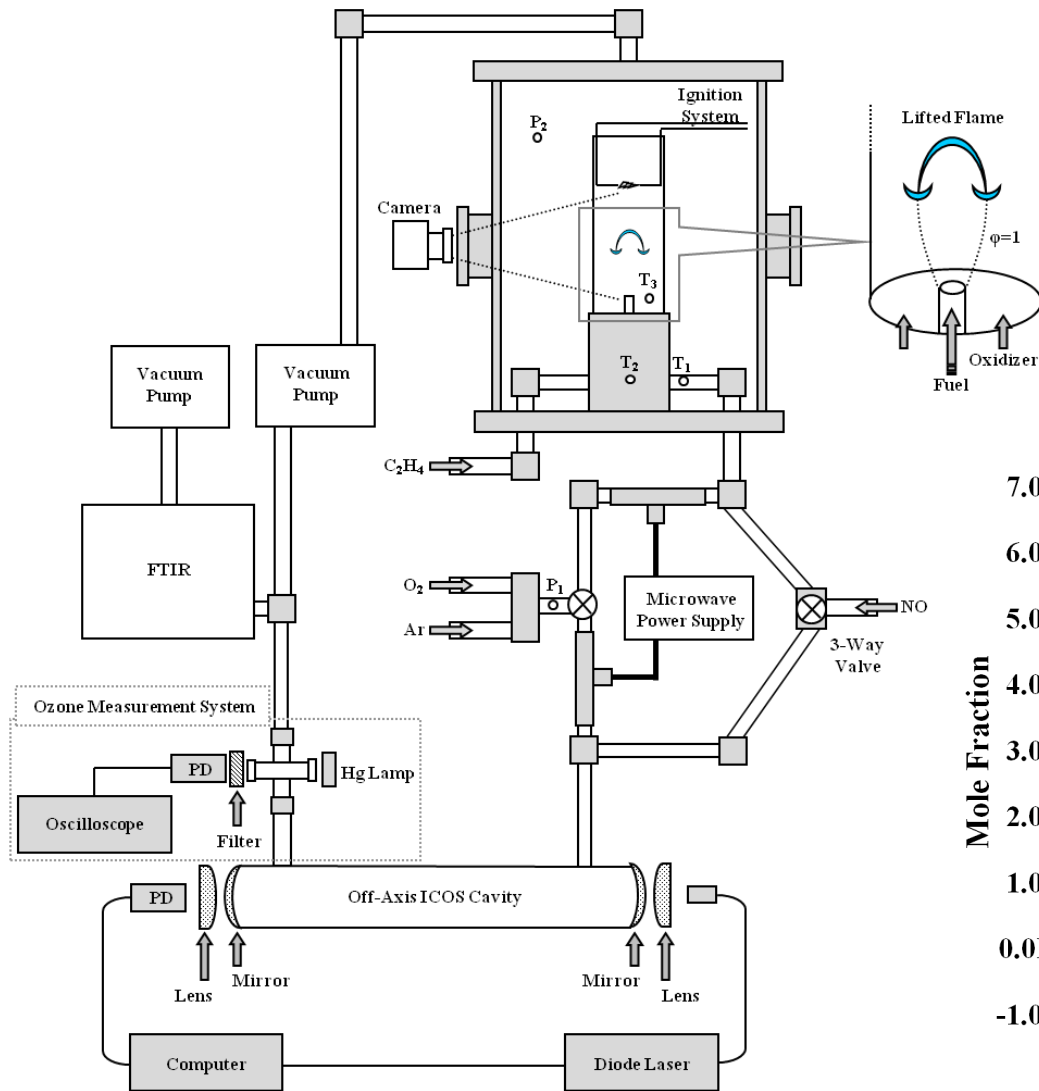
Detailed Kinetic Mechanisms for
 $O_2(a^1\Delta_g)$ Effect on H_2 , CO, and CH_4
Flames But Little Experimental Data

(Multiple Publications by Starik and
co-workers from 2001 to the present)

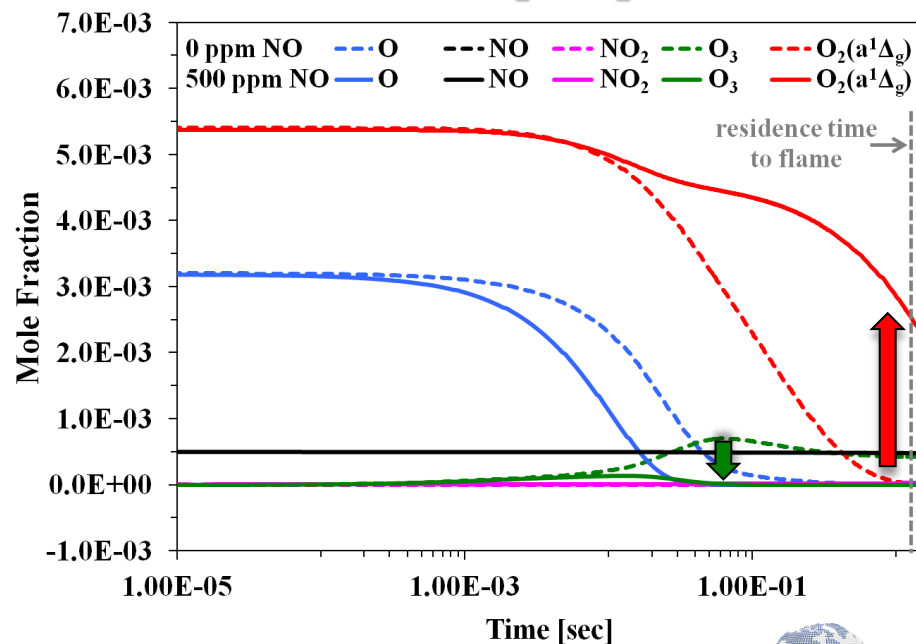
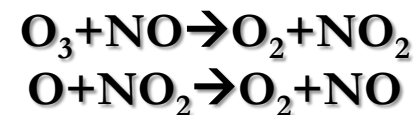


Lifted Flame Platform

Effect of O_3 and $O_2(a^1\Delta_g)$

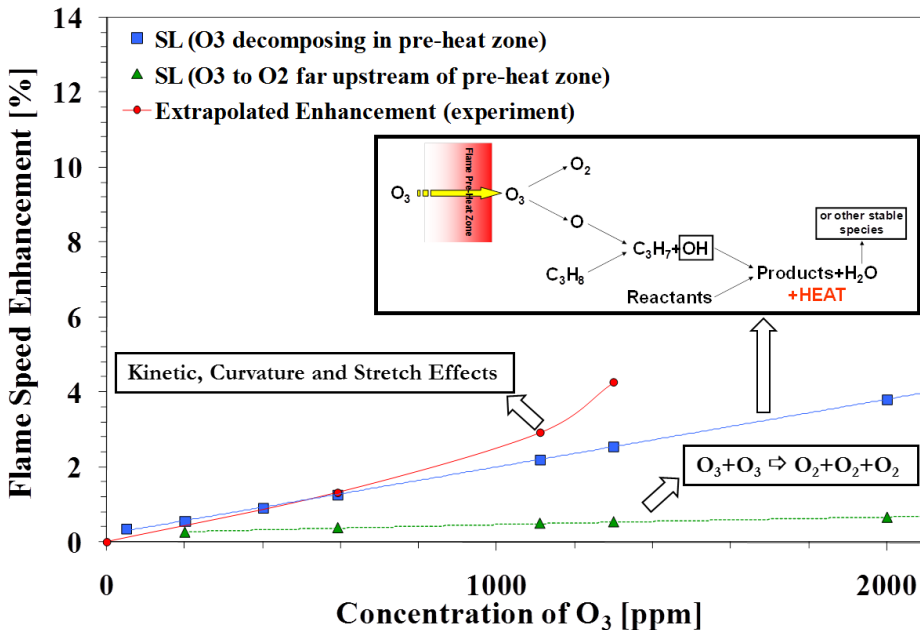
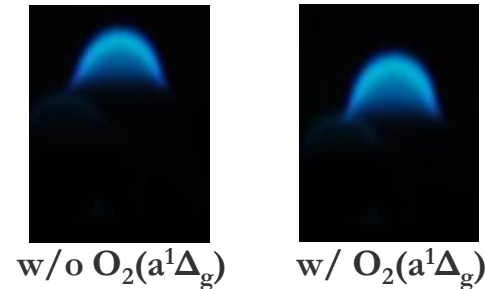
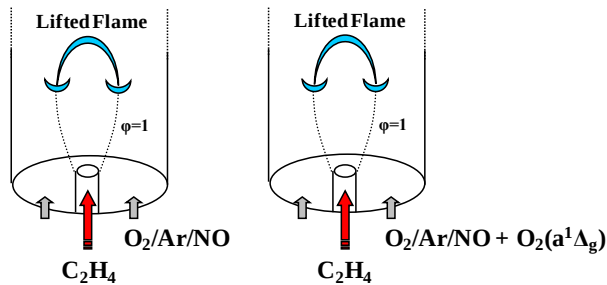


- Quantitative O_3 Measurement
- Quantitative $O_2(a^1\Delta_g)$ Measurement
- Extended $O_2(a^1\Delta_g)$ Lifetime with Catalytic Removal of O and O_3 with NO Injection

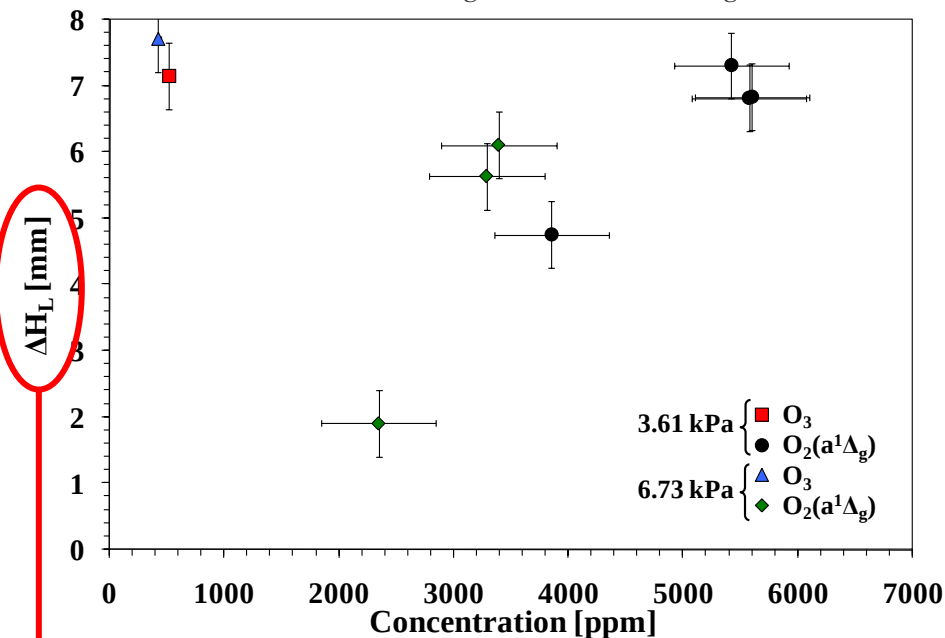




C_2H_4 Lifted Flame Speed Enhancement by O_3 and $O_2(a^1\Delta_g)$



Coupled Equivalence Ratio, Stretch, and Curvature Effects



Lack of Quantitative Experimental Data of Effects of $O_2(a^1\Delta_g)$ on Flame Propagation



New Plasma-Assisted Combustion Platform



Combustion Platform Allowing for:

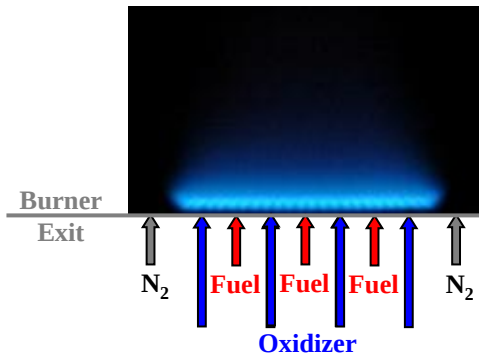
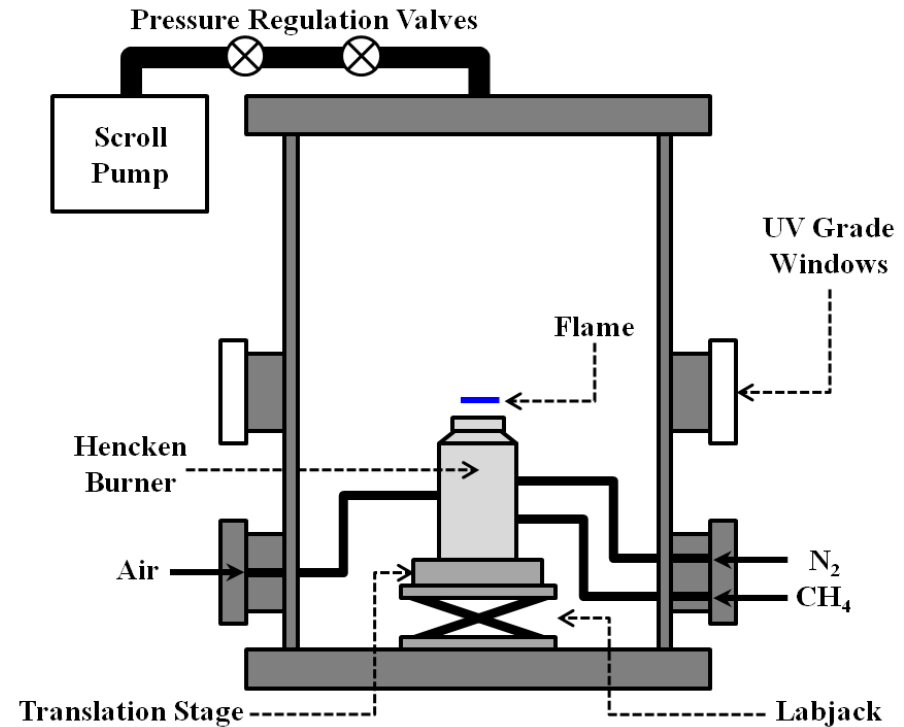
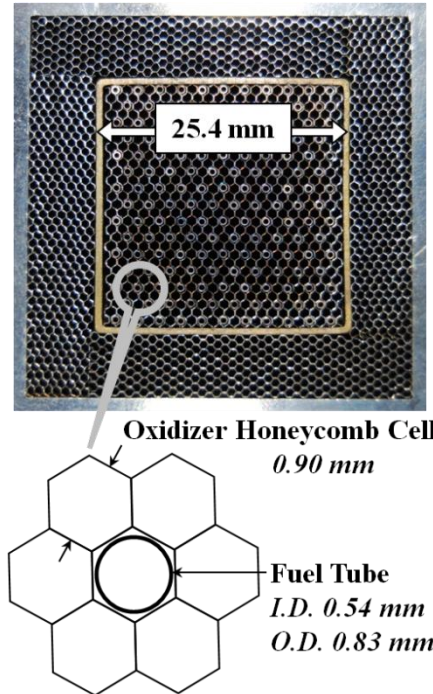
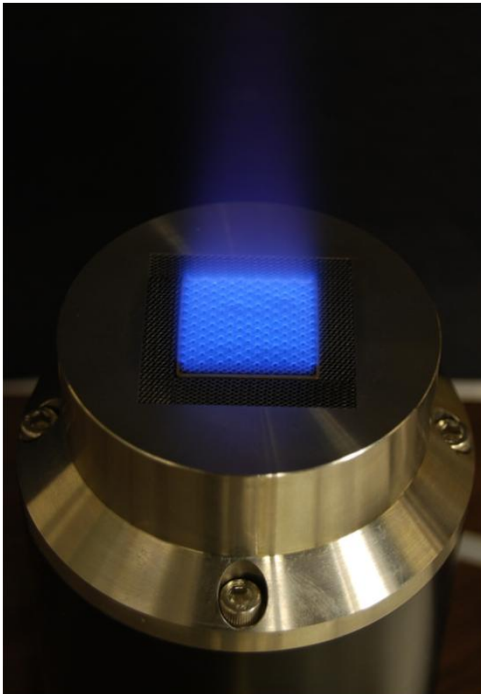
1. Full Optical Access to Detailed Structure of Flame
2. Quantification of Combustion Parameters
 - Flame Speed and Radical Concentrations

Plasma Platform Allowing for:

1. More Production of $\text{O}_2(a^1\Delta_g)$ at Higher O_2 Loadings and Higher Pressures
2. Quantification of Plasma Species Concentrations



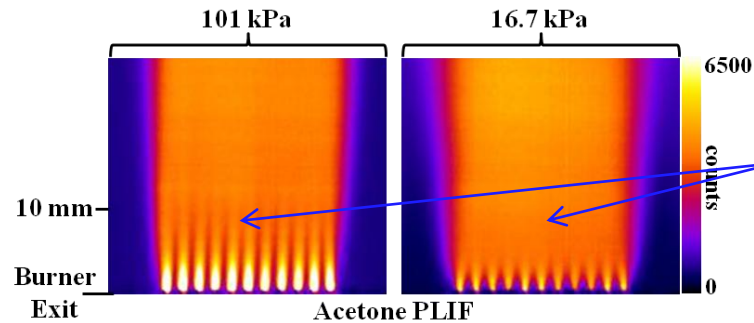
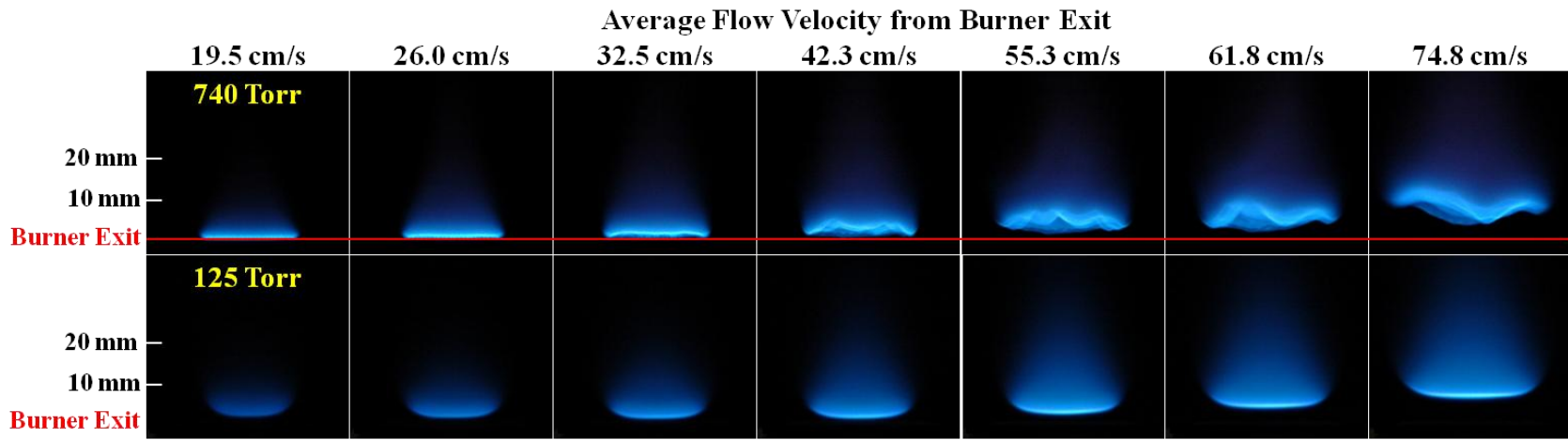
The Hencken Burner



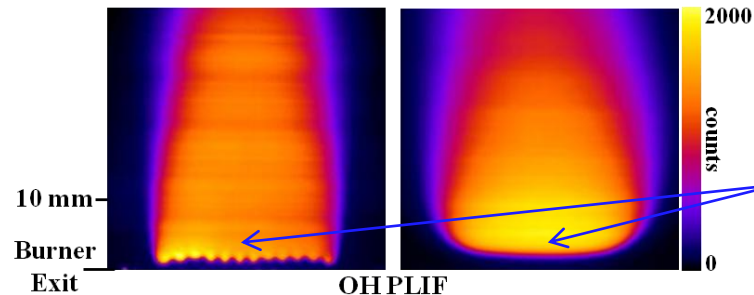
Typically Used as a Calibration Source for Laser Diagnostic Measurements
Not for Flame Speed Measurements



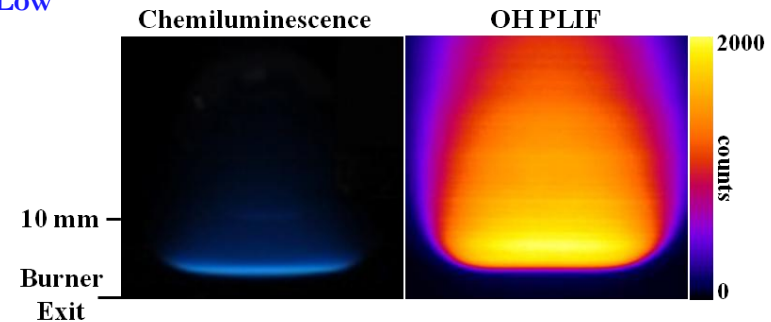
Burner Platform at Sub-Atmospheric Pressure



Enhanced Mixing at Low Pressure



Unwrinkled Flame Front at Low Pressure

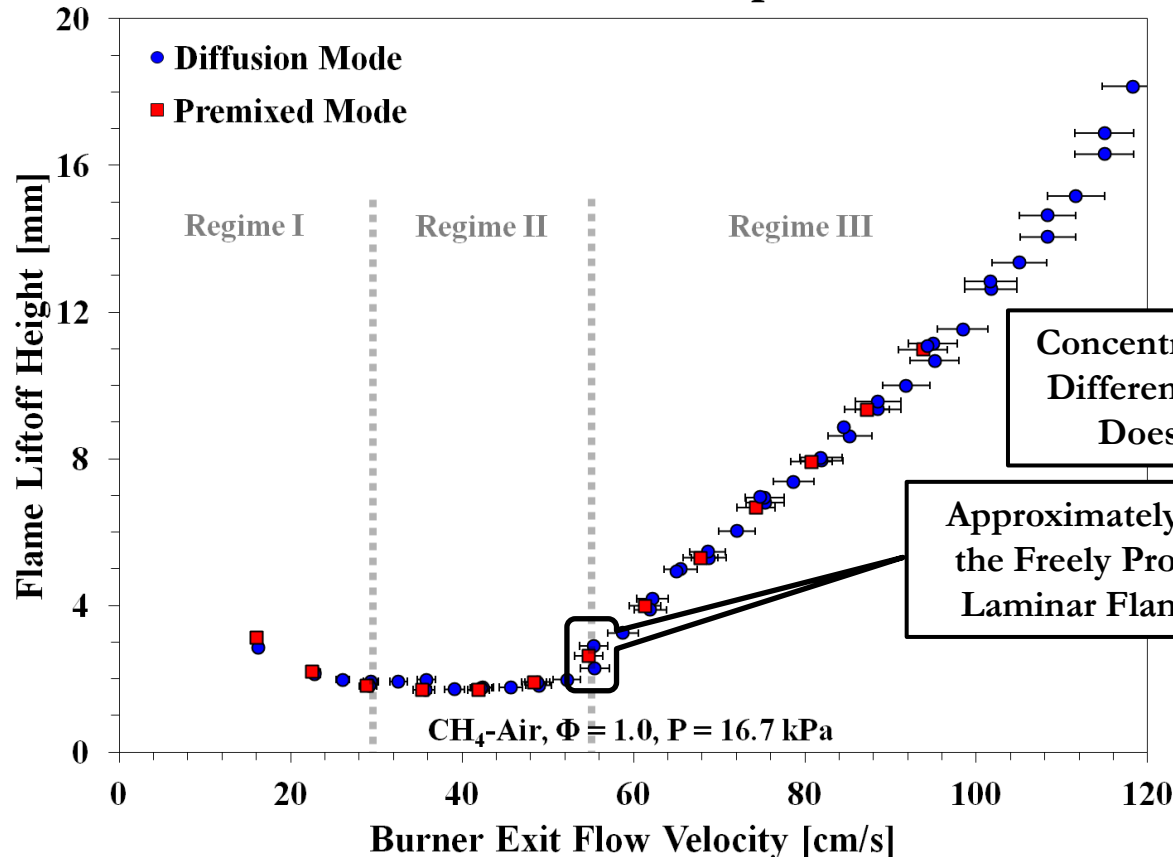
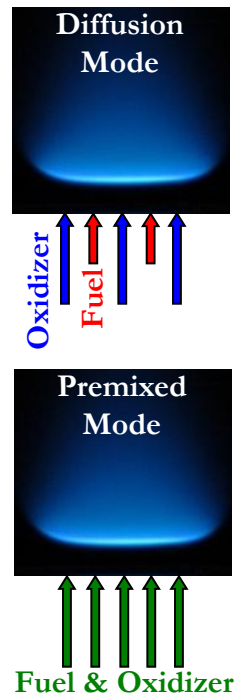




Flame Liftoff Height vs. Flow Velocity



Different Modes of Operation



Regime I: weakly burning with considerable losses from the flame

Regime II: little change in liftoff height with flow velocity

flame propagates to region of mixing and has small amount of heat loss to the burner surface

Regime III: flame is in a dynamic balance with the local flow velocity, i.e. freely propagating



Plasma-Integrated Hencken Burner System



Optical Access
Through Entire
Flame Structure

Flame
Fuel Fuel
Oxidizer

10 mm
Burner
Exit

125 Torr

25 Torr

Rapid Mixing at 300 K Prior to Flame Front

O₂/Inert

Plasma
Discharge

Emission/Absorption
Measurements

Hencken
Burner

Fuel

Plasma
Discharge

Emission/Absorption
Measurements

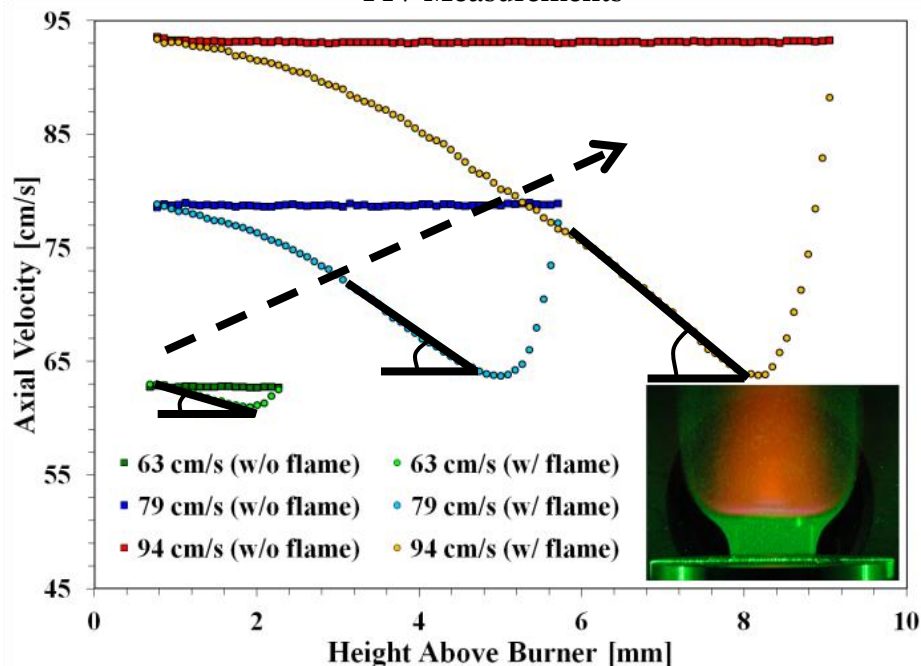
**Burner Platform Can be Used for Plasma Activation of Fuel or Oxidizer
and Quantification of Enhancement via Flame Speed
and Detailed Flame Structure Measurements**



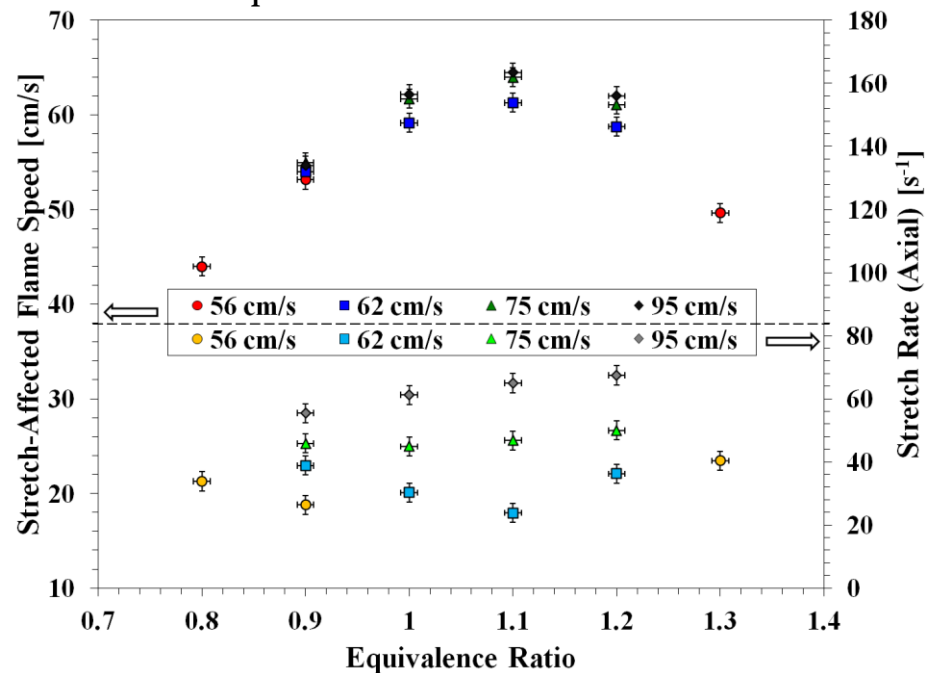
Flame Speed and Stretch Rates



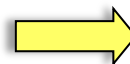
PIV Measurements



Flame Speeds & Associated Axial Stretch Rates



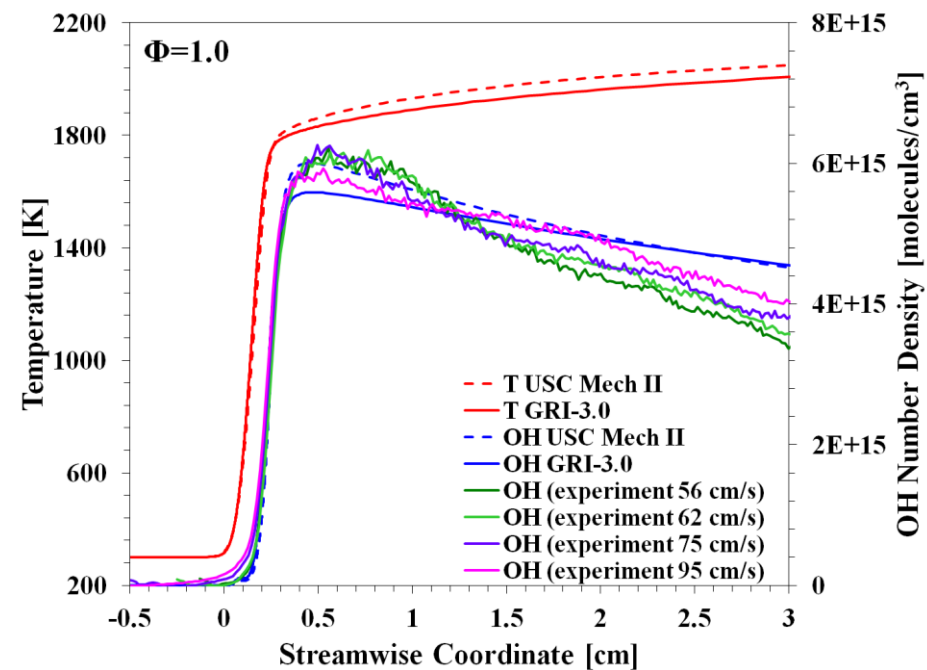
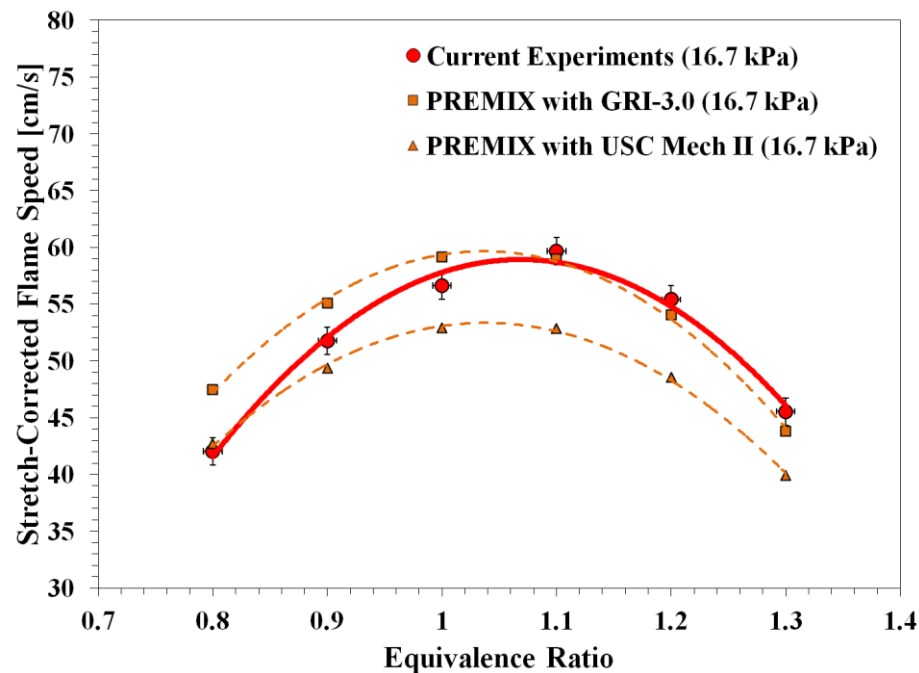
**Increased Stretch Rates with Velocity
and Height Above Burner**



**But Low Stretch Rates
(10-100 s⁻¹)**



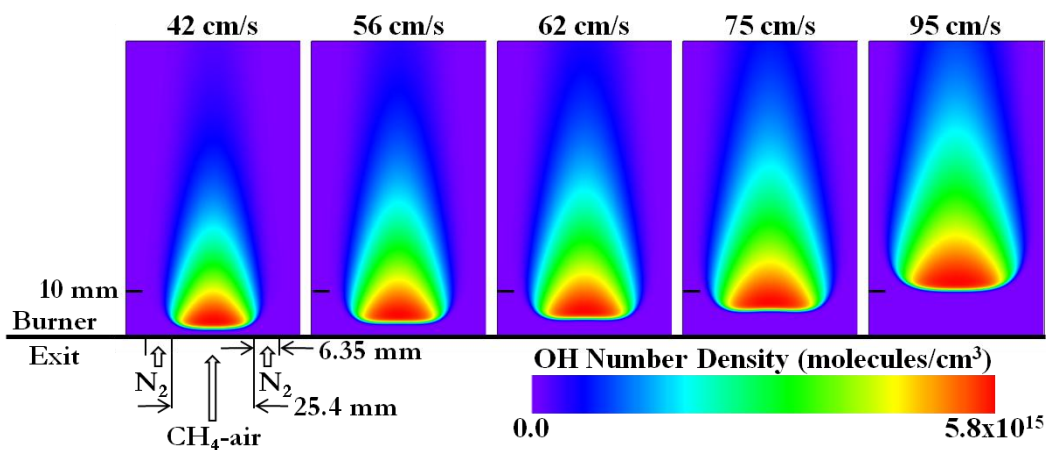
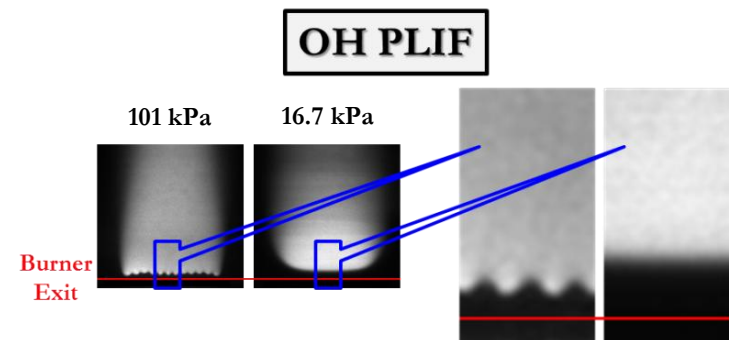
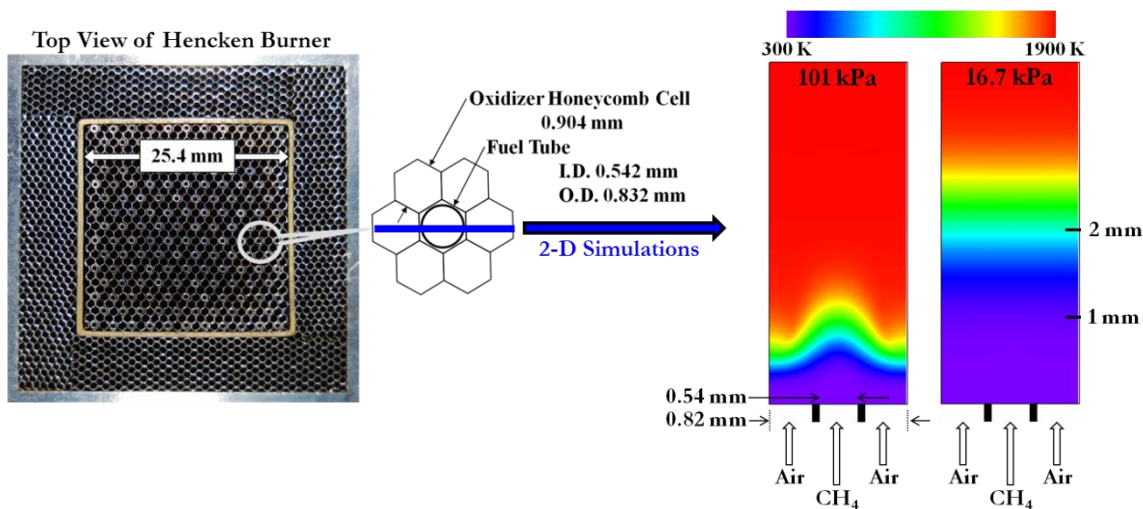
Flame Speed and OH Profiles: Comparison to 1-D Simulations



**Good Agreement Between Experiments and 1-D Simulations
with Minimal Corrections and Extrapolations**



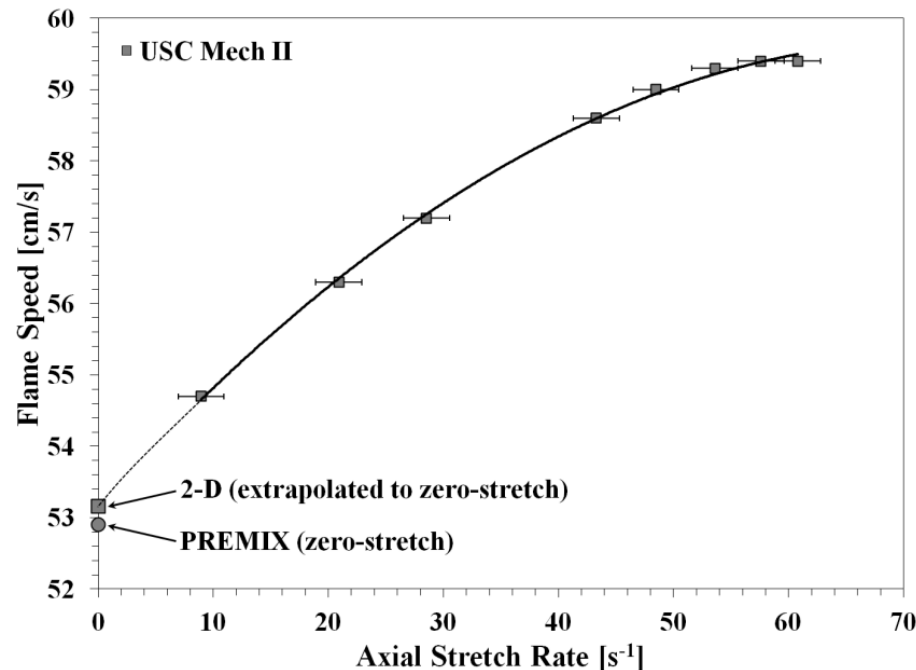
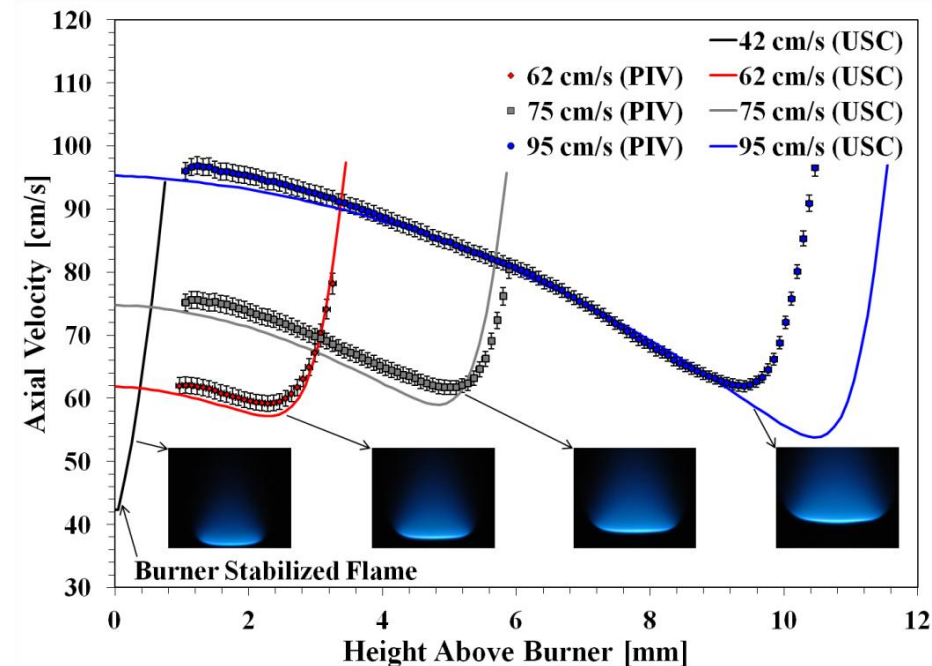
2-D Effects: Simulations



2-D Simulations Allow for
Exploration of Stretch
Rate Effects



PIV Velocity Profile Comparisons



Velocity Profiles from 2-D Simulations in Good Agreement With Experiments

2-D Simulations of Flame Speed In Limit of Zero Stretch in Good Agreement With 1-D Simulations



The Hencken Burner Platform for Plasma-Assisted Combustion Studies



Nearly 1-D, Adiabatic, and Freely Propagating Flame

Weakly Stretched, But Can Investigate a Range of Stretch Rates (~ 10 - 100 s^{-1})

Diffusion Mode – Fuel and Oxidizer Separated Until Burner Exit

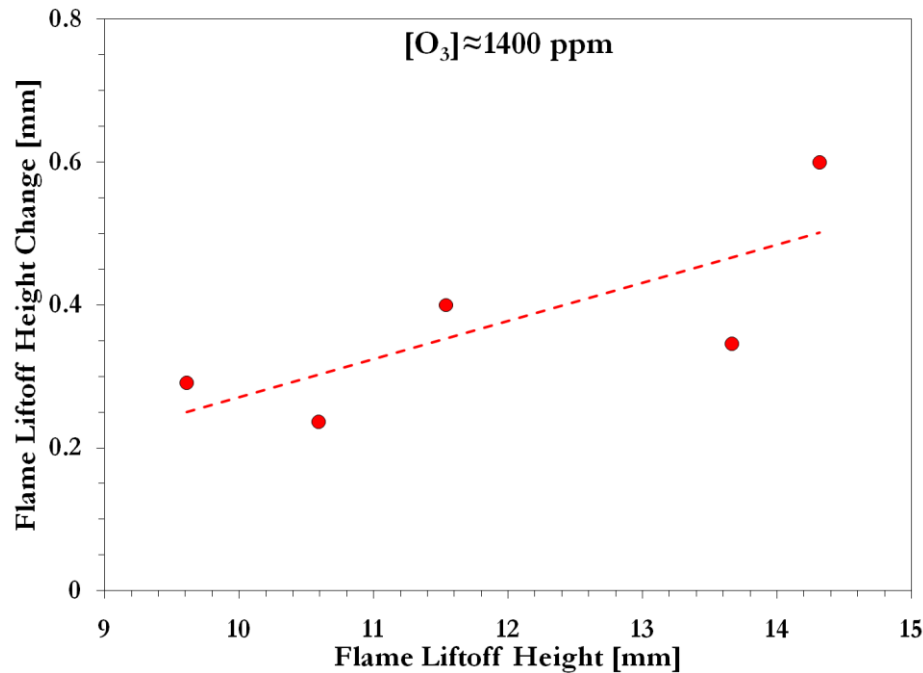
Full Optical Access to Flame Structure



Towards Quantification of the Effect of Specific Plasma Species on Flame Propagation



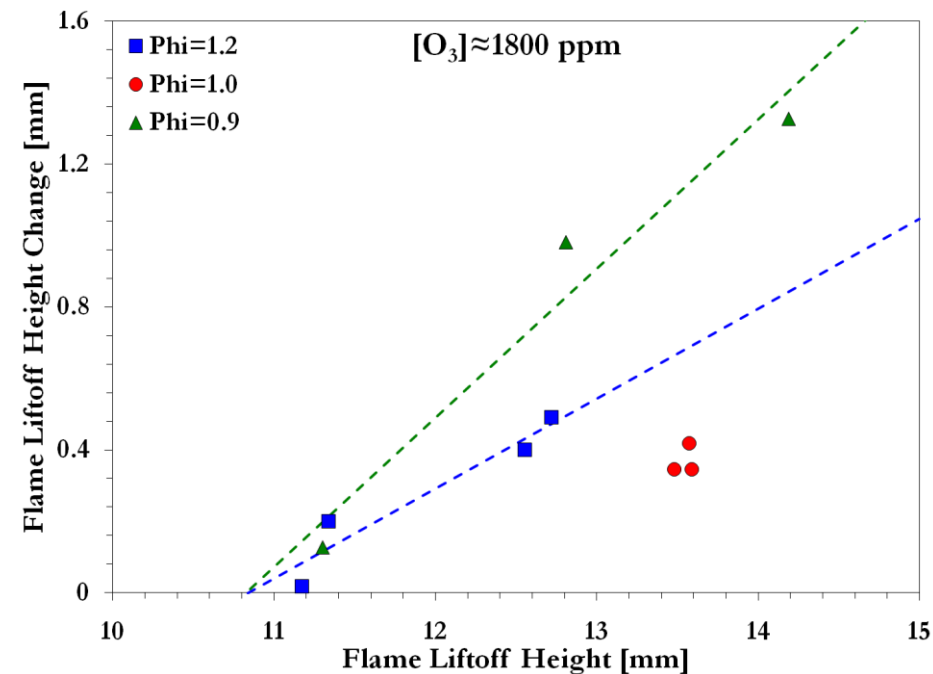
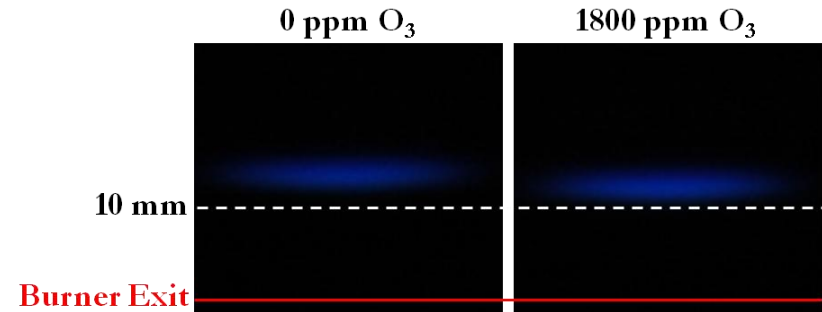
Change in C_2H_4 Flame Liftoff Height with O_3 Addition



More Liftoff Height Change
with Higher Liftoff Heights

Flames Enhanced More for Lean
and Rich versus Stoichiometric

Photographs of $C_2H_4/O_2/Ar$ Flames w/ and w/o O_3

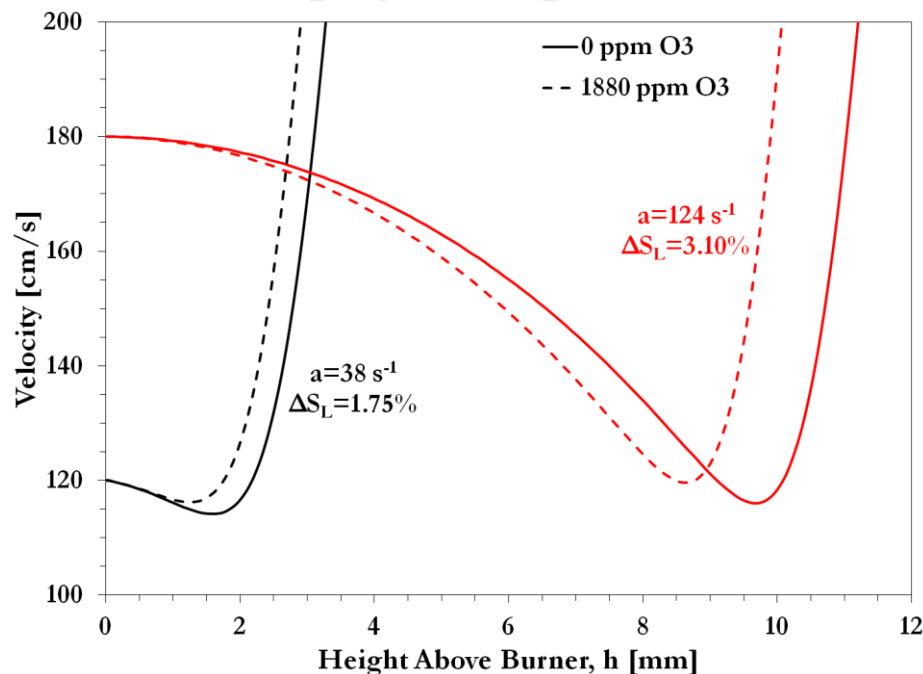




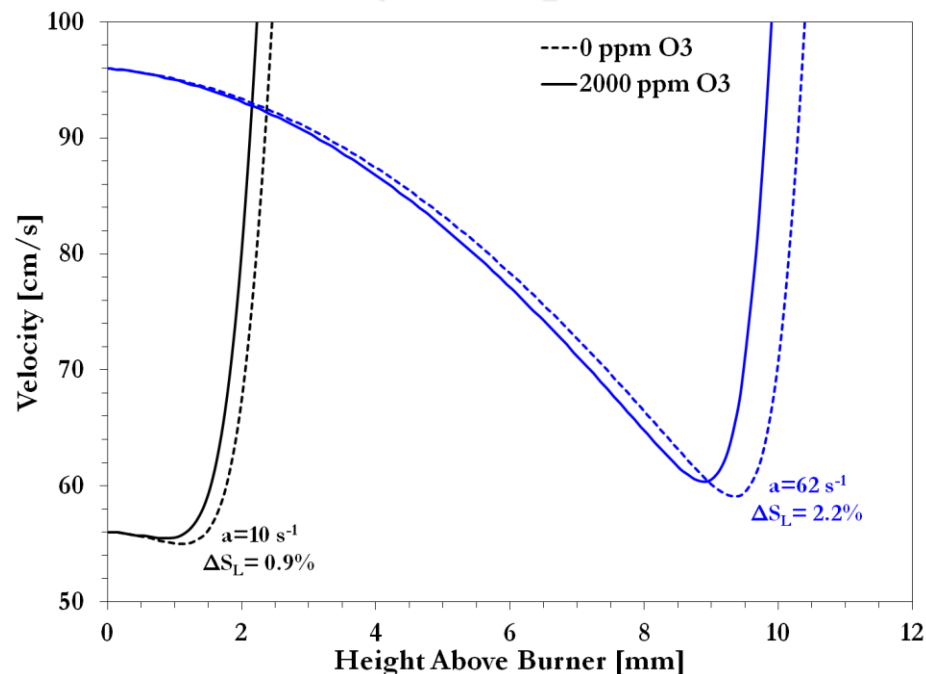
Computations of Flame Speed and Stretch Rate with O_3 Addition



$C_2H_4/Ar/O_2$, $\Phi=1.0$



$CH_4/Ar/O_2$, $\Phi=1.0$



Increased Flame Speed
Enhancement with Increased Stretch
Because of Relative Deposition of O
Within Reaction Zone

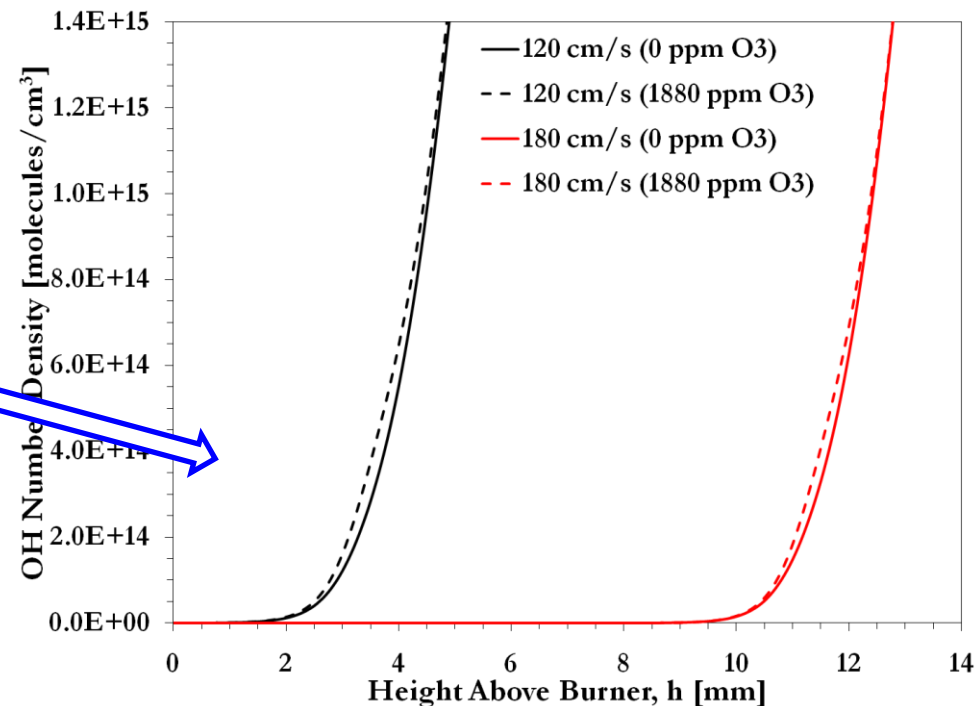
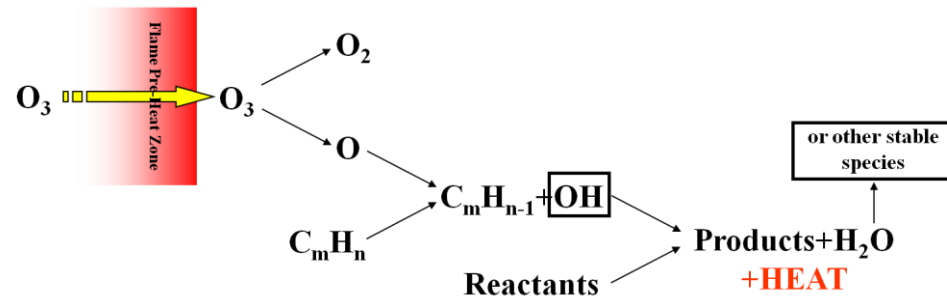
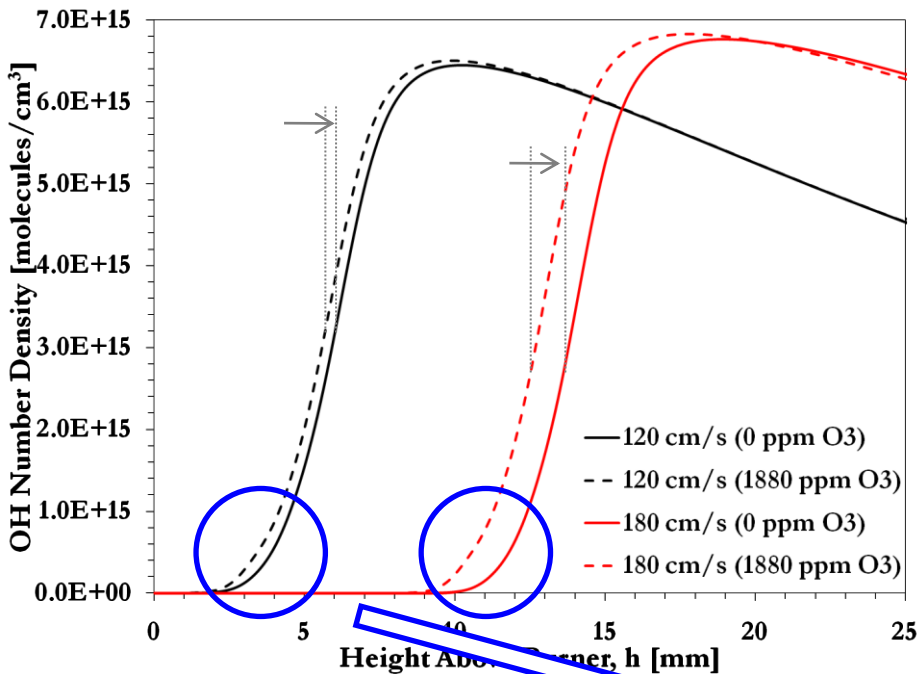
Possible Implications
~2000 ppm O_3



15+ % S_L Enhancement at $a=1000 s^{-1}$



OH Profile Differences with O₃ Addition



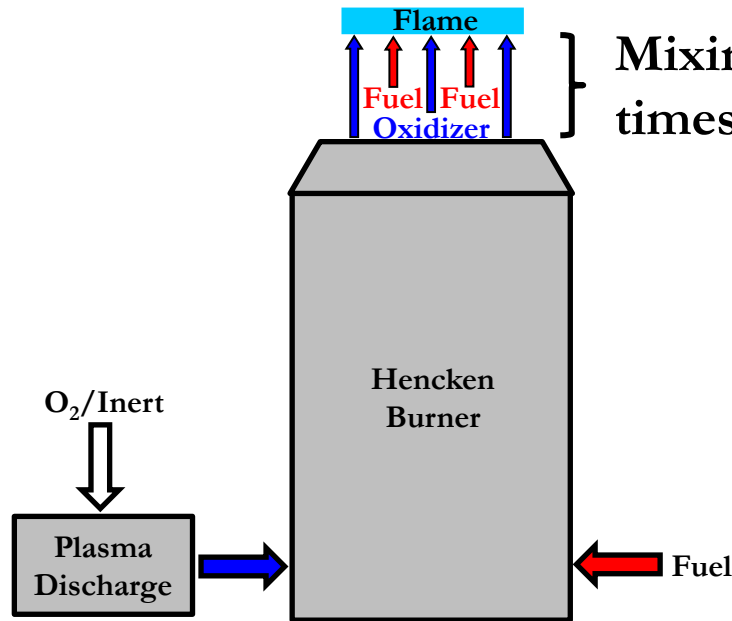
Can Deposition of O From O₃
Relative to Flame Structure
Significantly Affect Enhancement?



On To $O_2(a^1\Delta_g)$



Compatibility With Hencken Burner



Mixing with Fuel at 300 K for times on the order of milliseconds

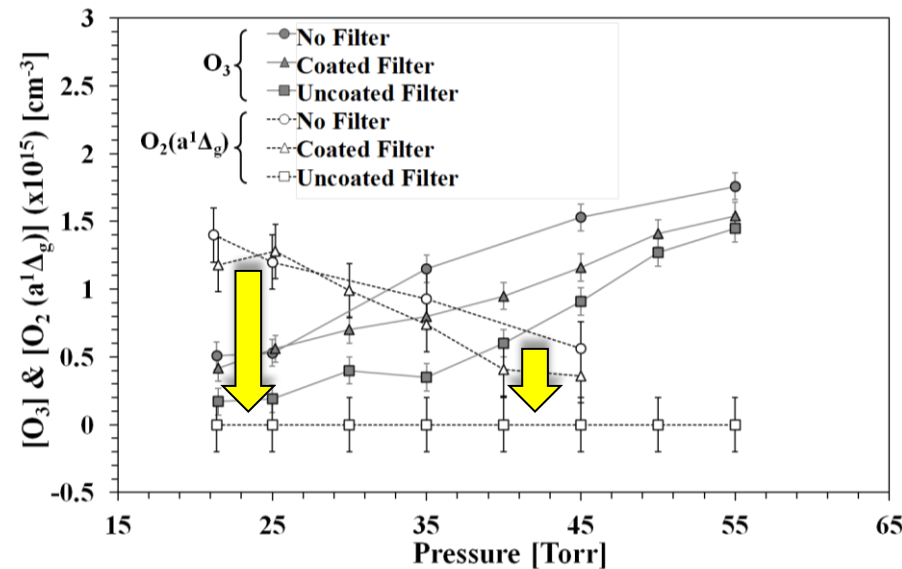
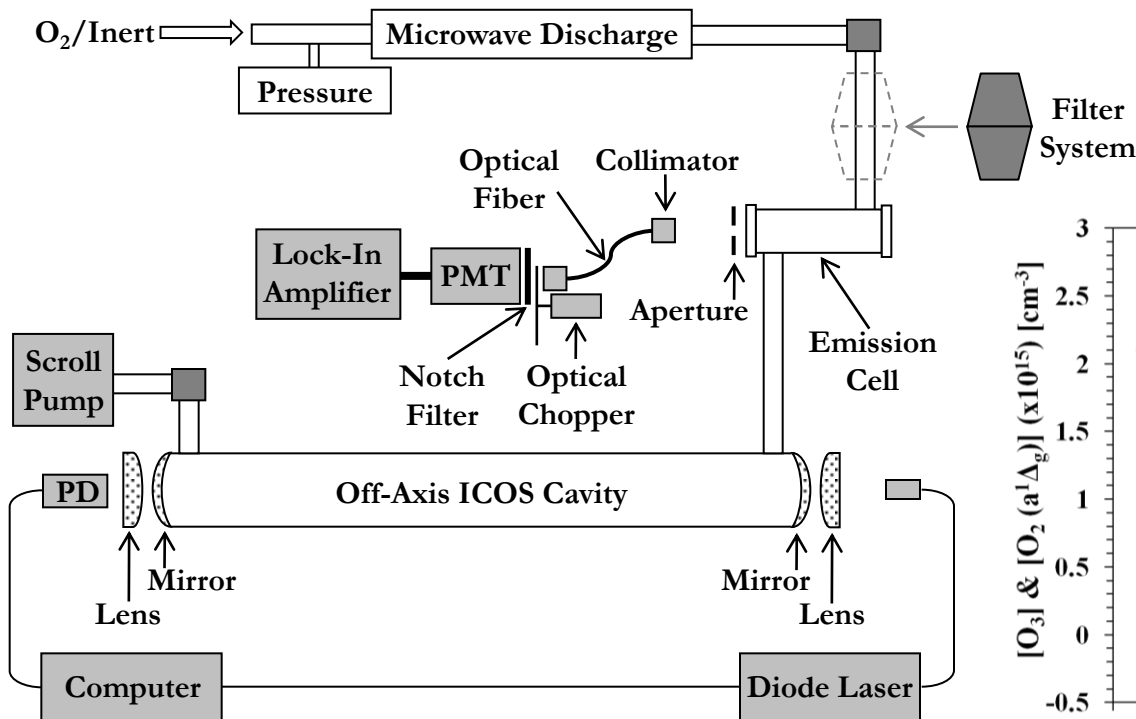
-Large Surface Area to Volume Ratio

-Multiple Types of Flow Surfaces That Will Quench $O_2(a^1\Delta_g)$

Exploration of $O_2(a^1\Delta_g)$ Quenching vs. Surface Composition



Filter Based System For Surface Quenching Study



Plain 304 SS Quenches $O_2(a^1\Delta_g)$

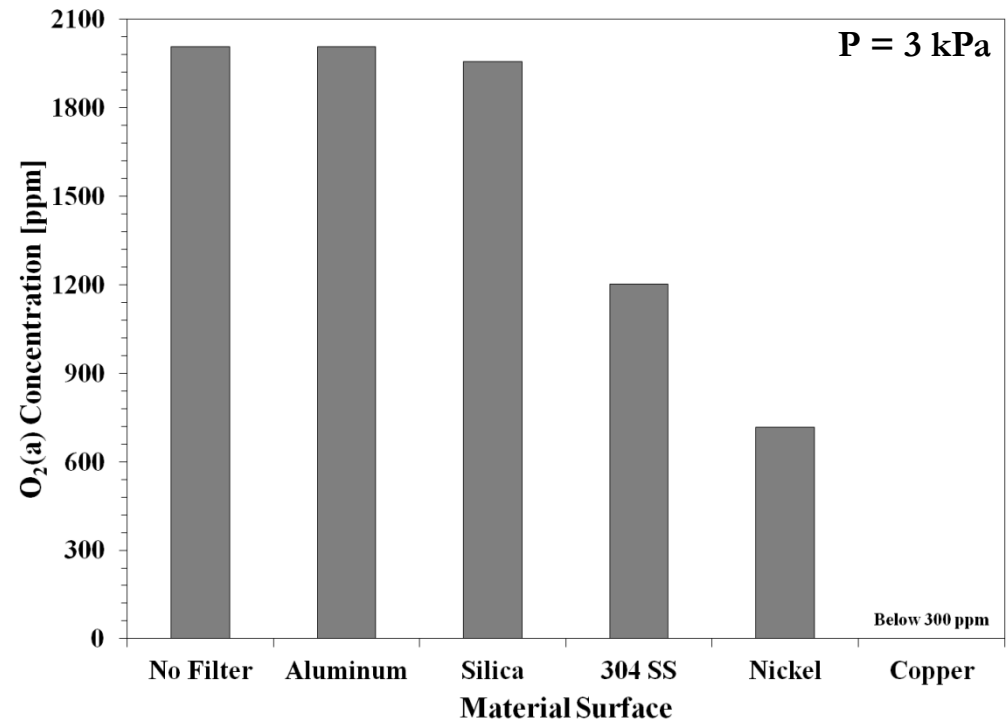
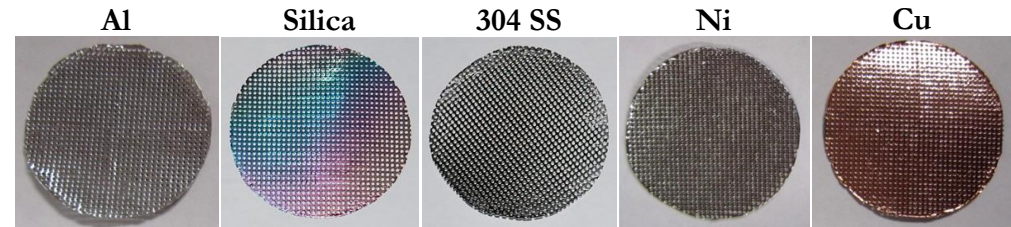
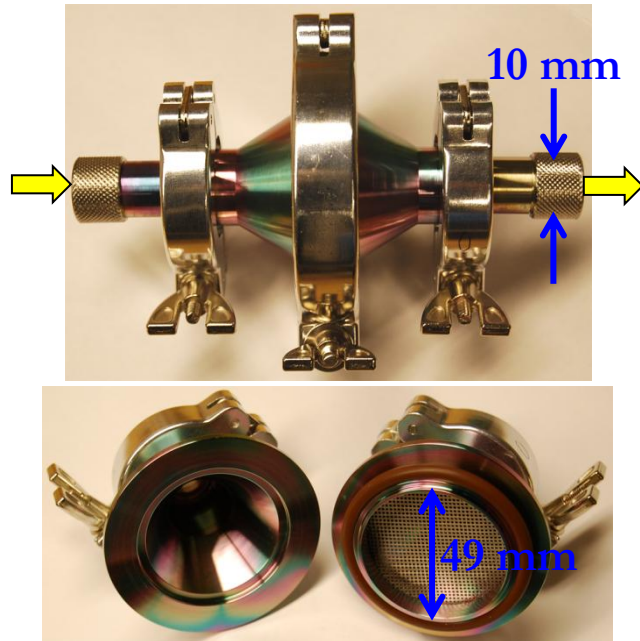
Silica Coating Makes Surface Fairly Inert



Using Surface Reactions For Selective Species Removal



Filter Housing



Other Materials

Metal Oxides (e.g. HgO)

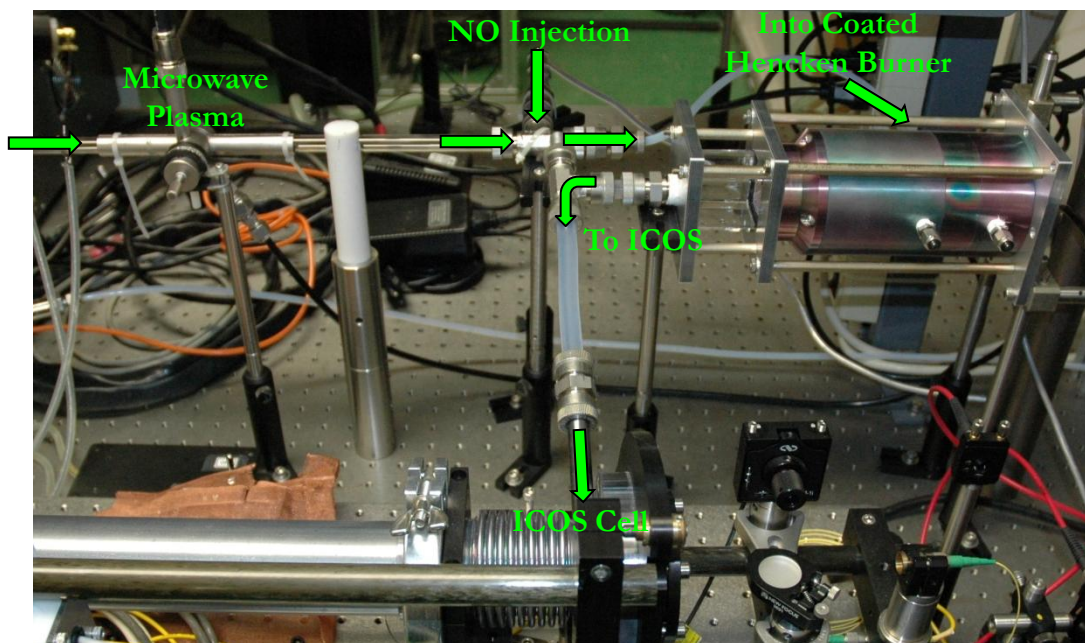
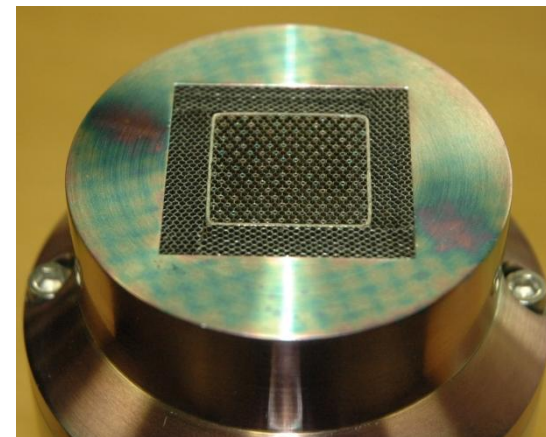
Catalytic Surfaces



Coated Hencken Burner For $O_2(a^1\Delta_g)$ Flame Studies



Solution:
Silica Coating on All Flow Surfaces



Conditions at 3-4 kPa:

20% O_2 in Ar
with 600 ppm NO Injection

3000-4000 ppm of $O_2(a^1\Delta_g)$

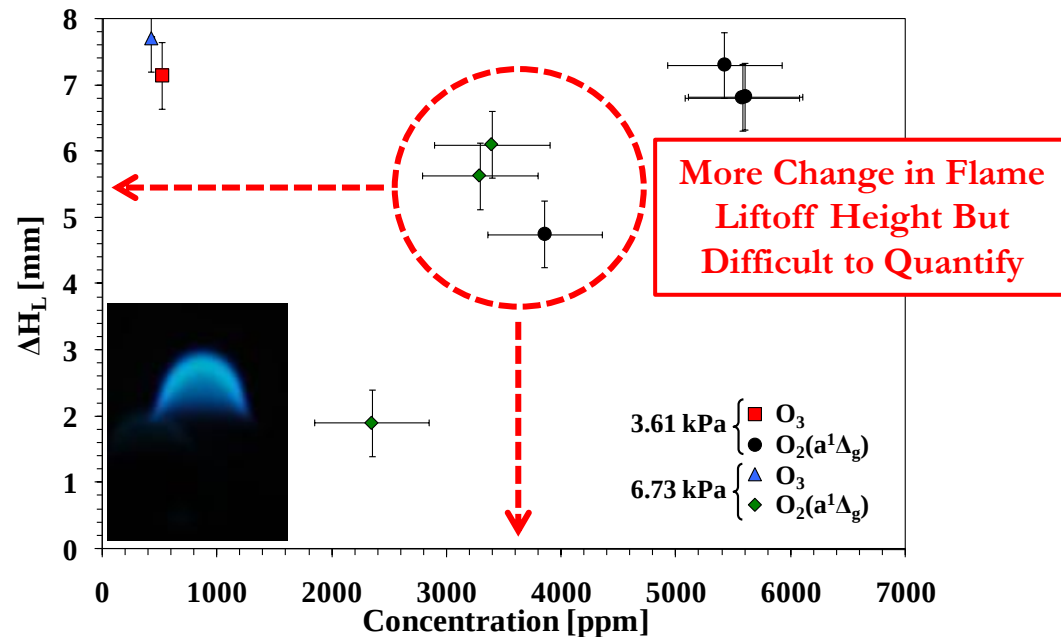
~1-2% Conversion of O_2
to $O_2(a^1\Delta_g)$



Quantitative Measurements of Enhancement by $O_2(a^1\Delta_g)$



Looking Back at the Lifted Flame Experiments



Hencken Burner Experiments

PIV for Flame Speed
Detailed Flame Structure Measurements
(e.g. PLIF)
Comparison to 1-D Simulations



Preliminary Results

3000-4000 ppm of $O_2(a^1\Delta_g)$



Change in Flame Liftoff Height
→ Can Be Quantified



New Plasma-Assisted Combustion Platform



Combustion Platform Allowing for:

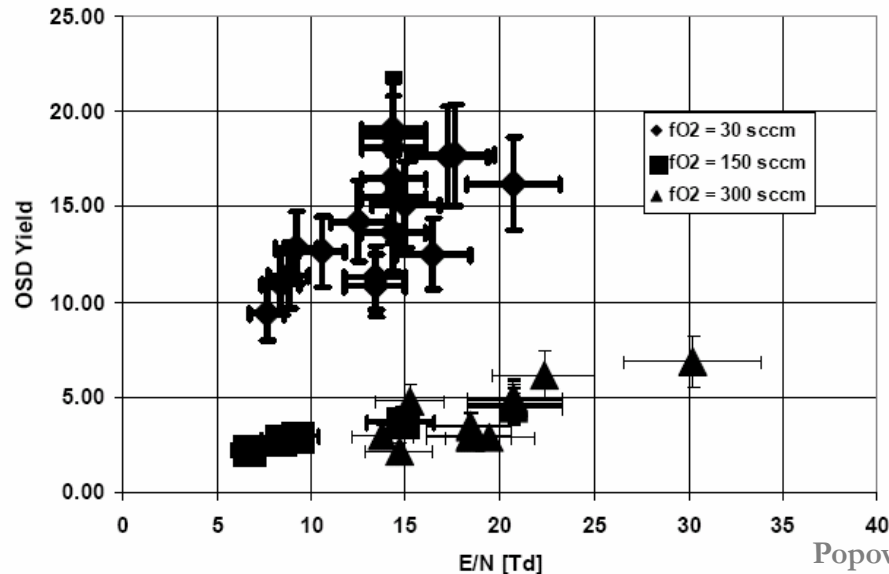
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Plasma Platform Allowing for:

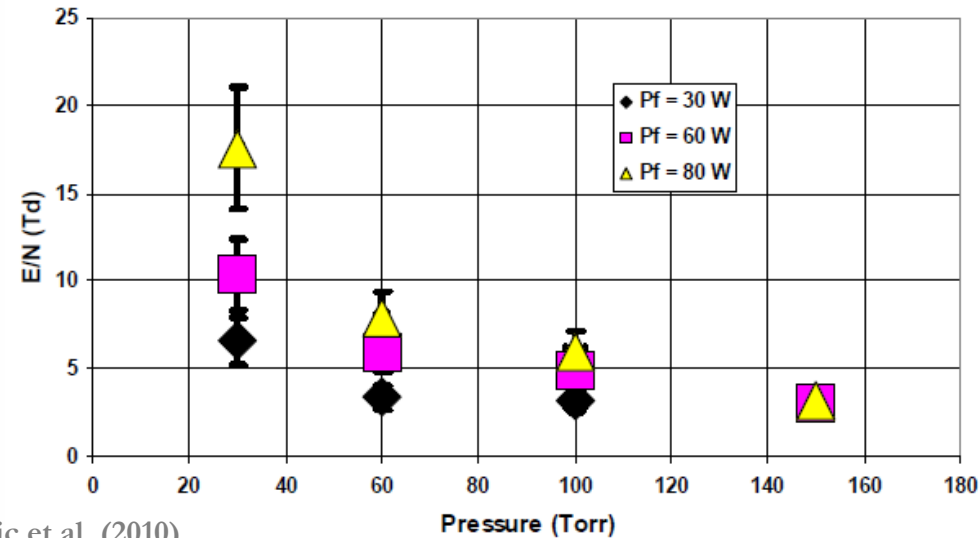
1. Higher Production of $O_2(a^1\Delta_g)$ at Higher O_2 Loadings and Higher Pressures
2. Quantification of Plasma Species Concentrations



Source of $O_2(a^1\Delta_g)$ at Higher Pressure and O_2 Loading



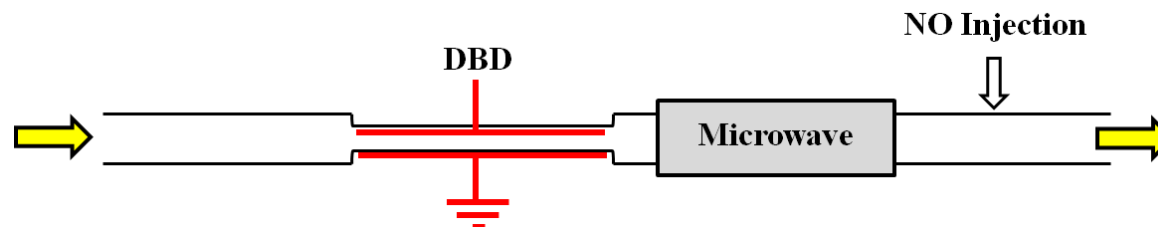
Popovic et al. (2010)



Higher O_2 Concentrations and Higher Pressures Create Significant Challenge for $O_2(a^1\Delta_g)$ Production

Tandem Discharge

Prof. Svetozar Popovic (Old Dominion Univ.)





Measurement Techniques of $O_2(a^1\Delta_g)$



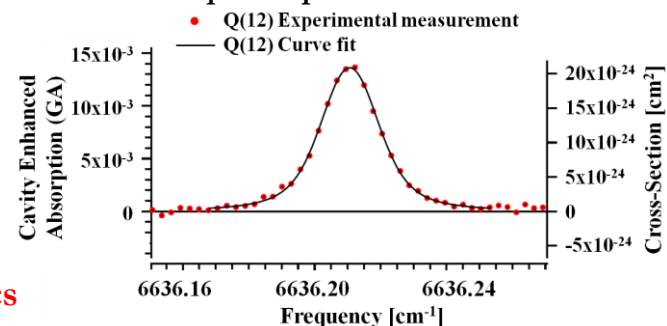
ICOS

Highly Sensitive and Quantitative
Temporally and Spatially Averaged

Emission (634 nm and 1268 nm)

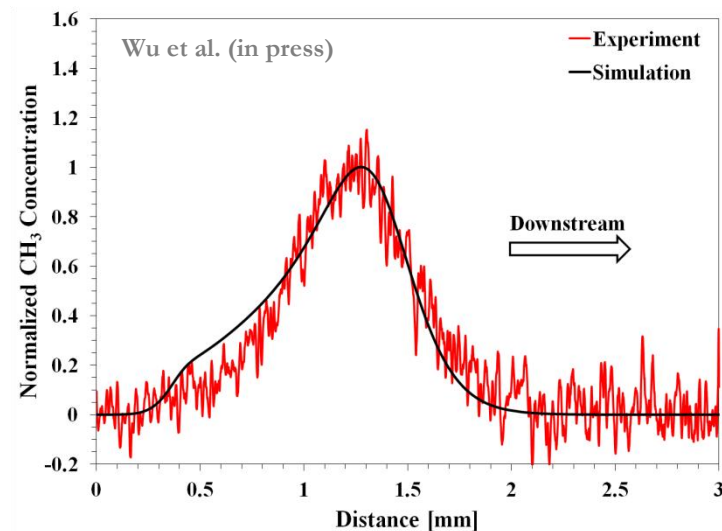
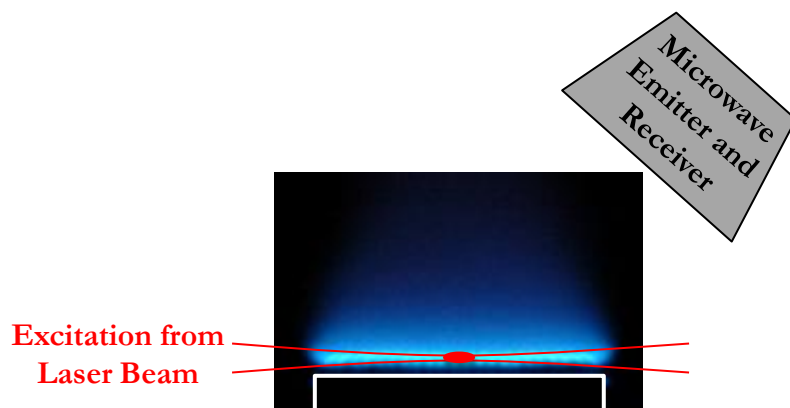
Minimal Averaging
Requires Knowledge of Quenching Species and Their Kinetics

Absorption Spectrum from ICOS



Radar REMPI (Prof. Zhili Zhang, Univ. Tenn.)

Demonstrated on Multiple Platforms
Successful for CH_3 Detection in Flame Front





Summary



1. New Plasma-Assisted Combustion Platform Developed
2. Preliminary Results of Enhancement by O_3 and $O_2(a^1\Delta_g)$ Demonstrated
3. Optimization of $O_2(a^1\Delta_g)$ Production at Higher Pressures and O_2 Loadings
4. New Diagnostic Technique for $O_2(a^1\Delta_g)$



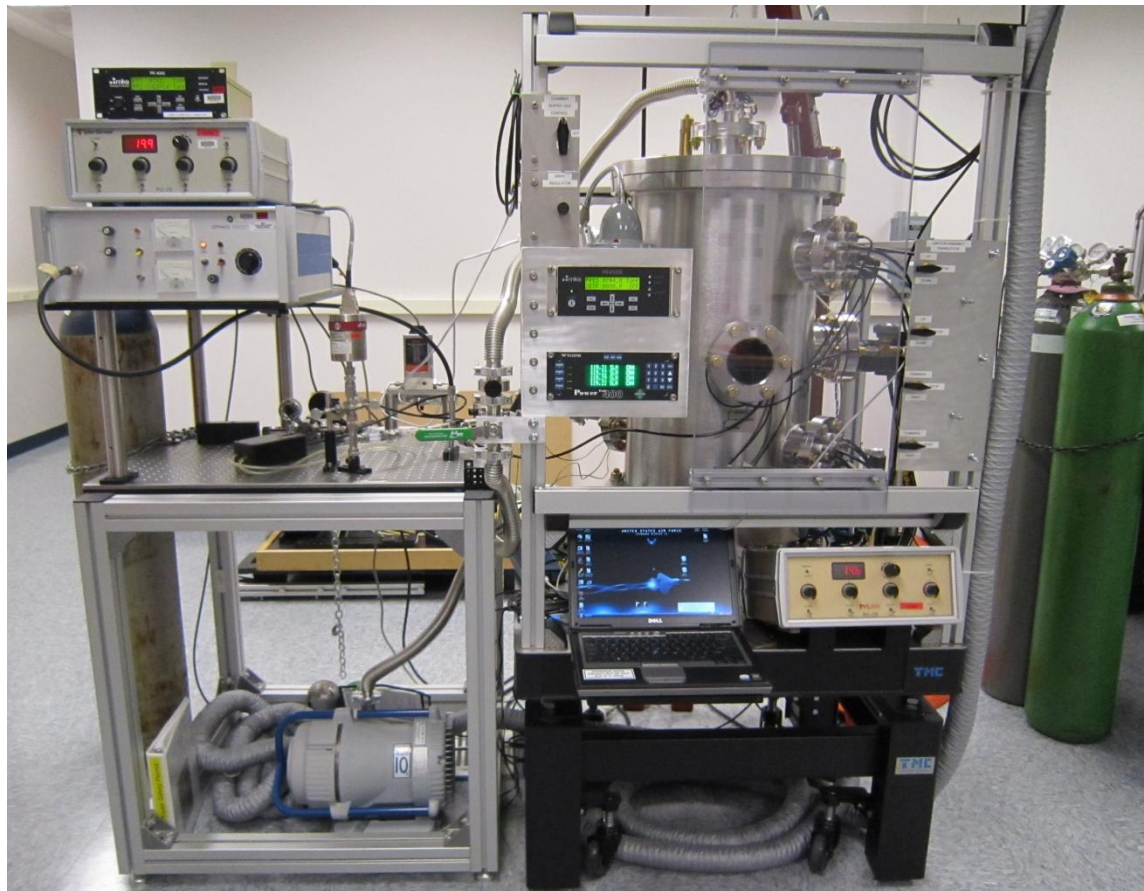
Working With AFRL Collaborations Encouraged



“Bench Top” Scale

New Optical Diagnostics Laboratory With Array of Diagnostic Capabilities, Including:
PIV, LIF, Raman Spectroscopy, Rayleigh Scattering, TDLAS, etc.

Low-Pressure Chamber for Combustion and Plasma Studies





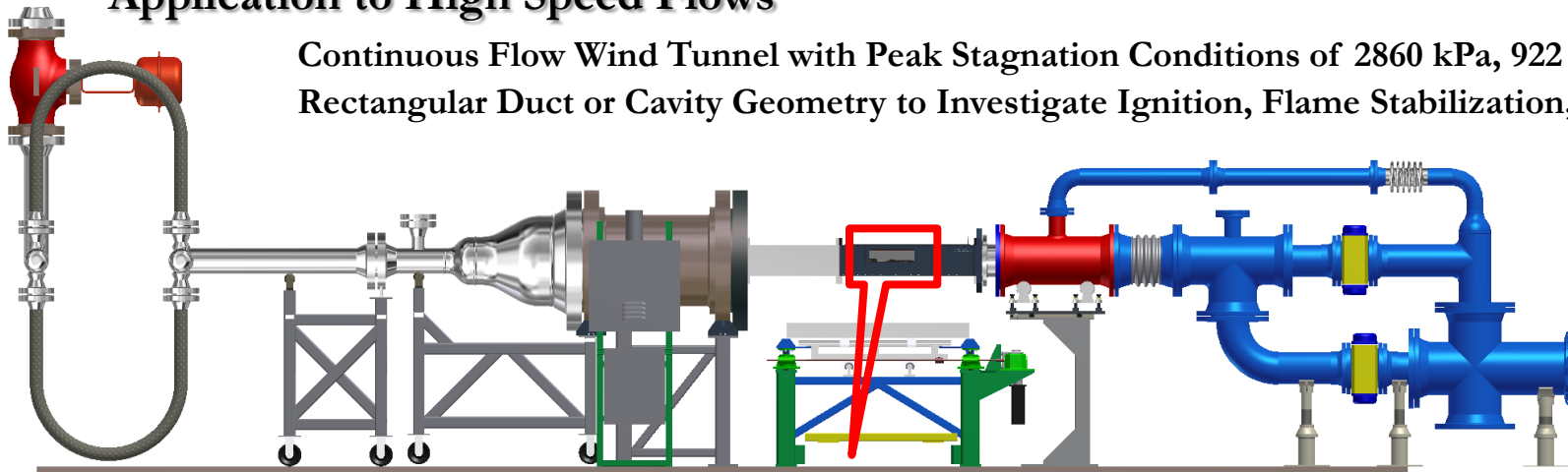
Working With AFRL

Collaborations Encouraged



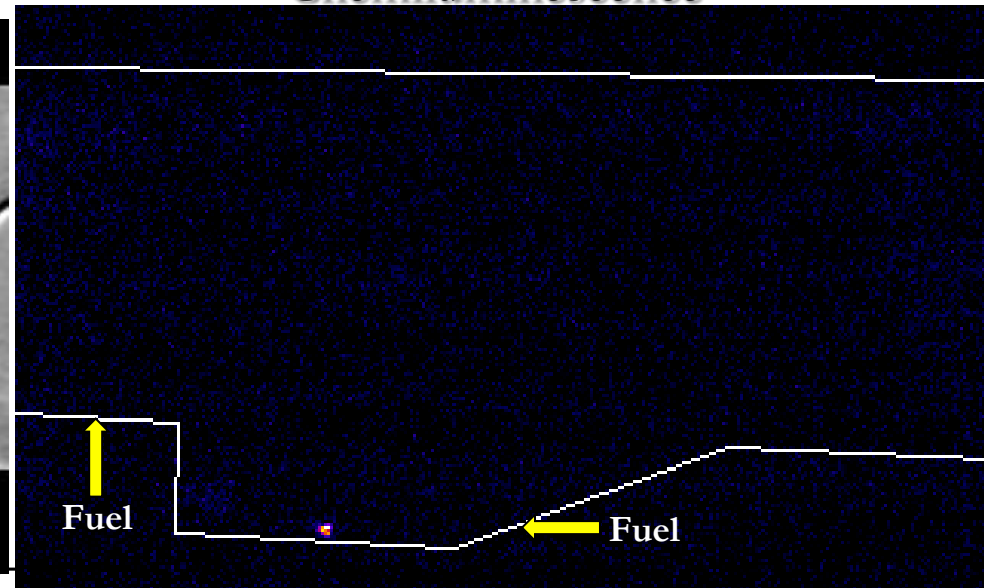
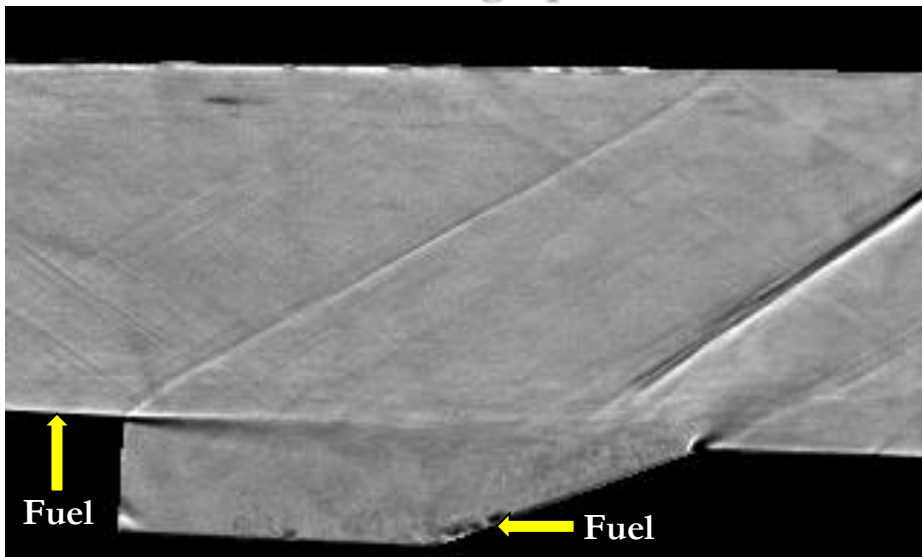
Application to High Speed Flows

Continuous Flow Wind Tunnel with Peak Stagnation Conditions of 2860 kPa, 922 K, 15.4 kg/s
Rectangular Duct or Cavity Geometry to Investigate Ignition, Flame Stabilization, etc.



Shadowgraph

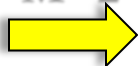
Chemiluminescence

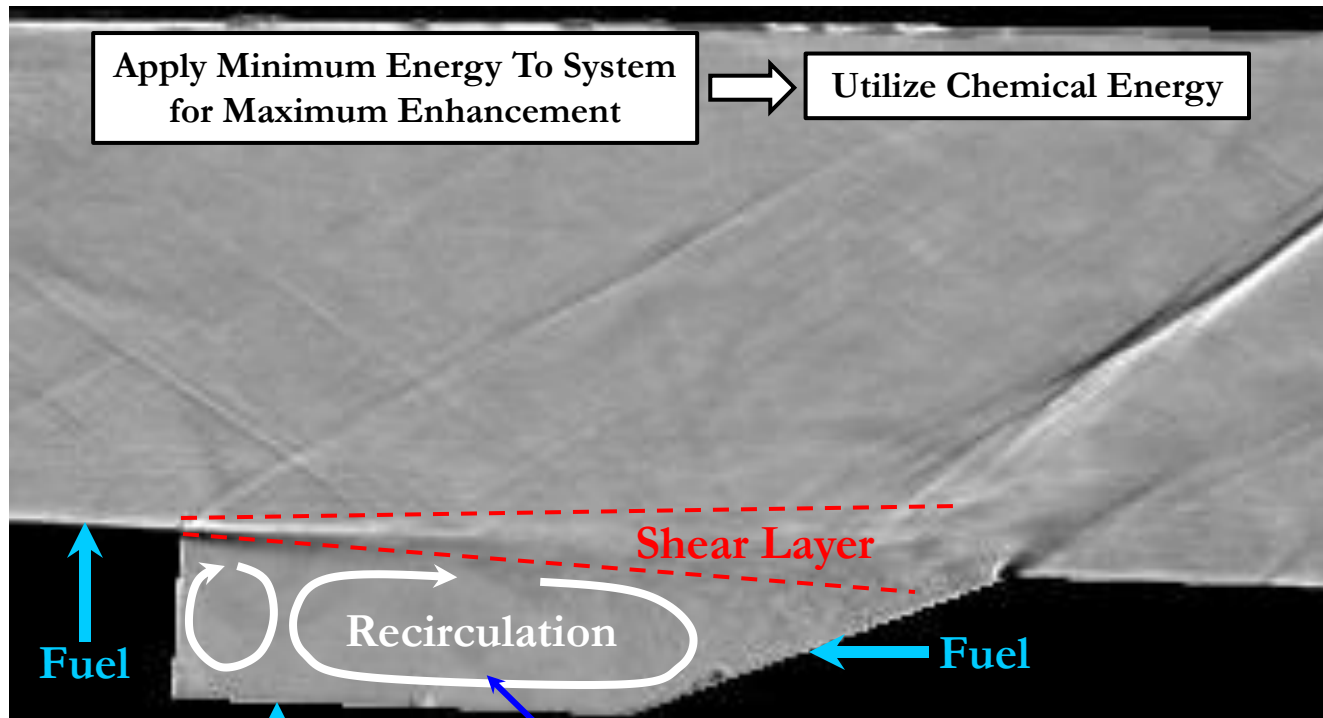




Plasma Application to High-Speed Flow



Cold
 $M=2$




Plasma Activation of Fuel to
Change Chemical Reactivity

Activation of Local Portion of
Flow With Plasma and Rely Upon
System Dynamics For Propagation

Use Plasma to Change
Local Flow Structure



Acknowledgements



Prof. Svetozar Popovic (Old Dominion University)

Prof. Zhili Zhang (University of Tennessee)

NRC

The National Research Council

Research Associateship Program

**Air Force Office of
Scientific Research**

The Basic Research Manager of the Air Force Research Laboratory



Questions?

