

FUNDAMENTAL MECHANISMS, PREDICTIVE MODELING, AND NOVEL AEROSPACE APPLICATIONS OF PLASMA ASSISTED COMBUSTION

**AFOSR
MURI KICK OFF MEETING**

**THE OHIO STATE UNIVERSITY
Nov 4, 2009
MILES — SHNEIDER GROUP**



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MILES – SHNEIDER GROUP

PRIMARY FOCI

- THRUST 1. EXPERIMENTAL STUDIES OF NONEQUILIBRIUM AIR-FUEL PLASMA KINETICS USING ADVANCED NON-INTRUSIVE DIAGNOSTICS
 - Task 2: *Laminar Flow Reactor and Nanoparticle Studies at Low to Intermediate Temperatures (Radar REMPI and Filtered Rayleigh Scattering in flames)*
 - Task 7: *Fundamental studies on microwave enhanced combustion at atmospheric and higher pressures (Laser designated microwave driven ignition and microwave enhanced flame propagation)*
- THRUST 3. EXPERIMENTAL AND MODELING STUDIES OF FUNDAMENTAL NONEQUILIBRIUM DISCHARGE PROCESSES
 - Task 10: *Characterization and Modeling of Nsec Pulsed Plasma Discharges (Modeling and Radar REMPI of nonequilibrium states)*
 - Task 11: *Experimental and Modeling Study of Plasma properties using Radar REMPI (Radar REMPI measurement of electron loss mechanism and rates and local electron number density)*



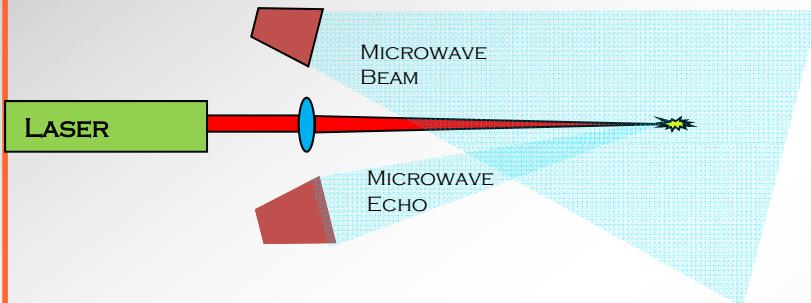
PRELIMINARY WORK

- RADAR REMPI
 - Atomic oxygen in a flame
 - NO mole fractions in laboratory air to <10 ppb
 - Limited by natural NO concentration in NJ air (~10 ppb)
 - Electron attachment and recombination rate measurements in nitrogen, air and humid air
- LASER DESIGNATED MICROWAVE DRIVEN IGNITION
 - Point ignition with 180 μ J, 200 fsec laser designator plus 50 mJ, 2 μ sec microwave pulse
 - Line ignition with 600 μ J, 200 fsec laser designator plus 50 mJ, 2 μ sec microwave pulse
 - > 50% ignition kernel growth rate enhancement with triple pulsed microwave
 - Multiple point ignition

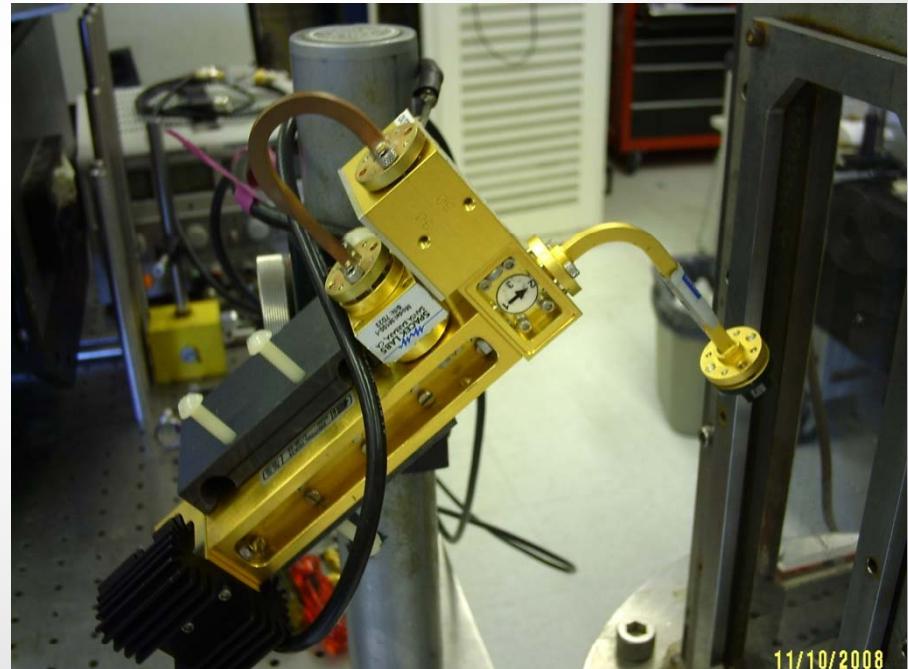


RADAR REMPI

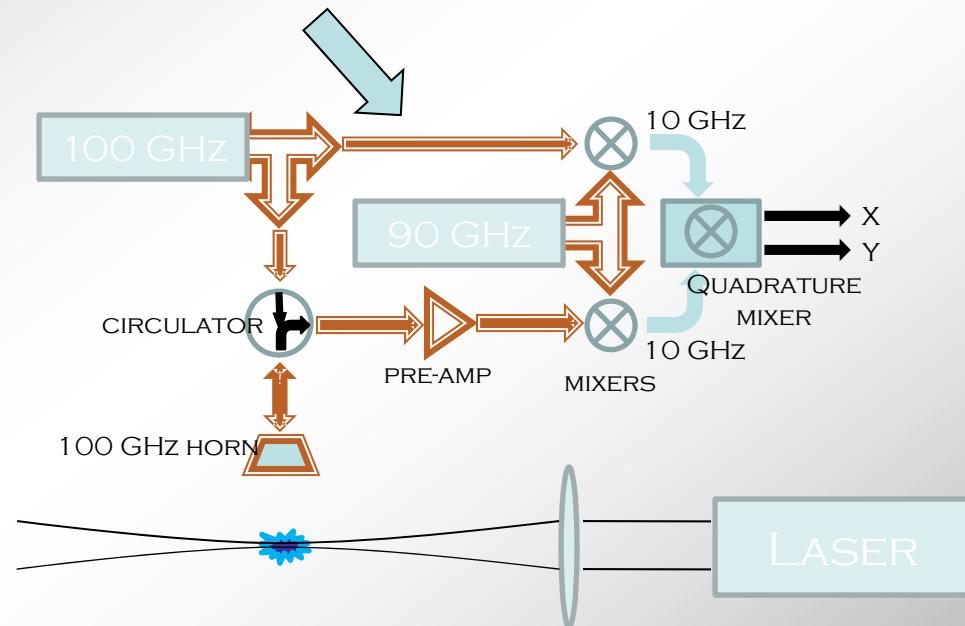
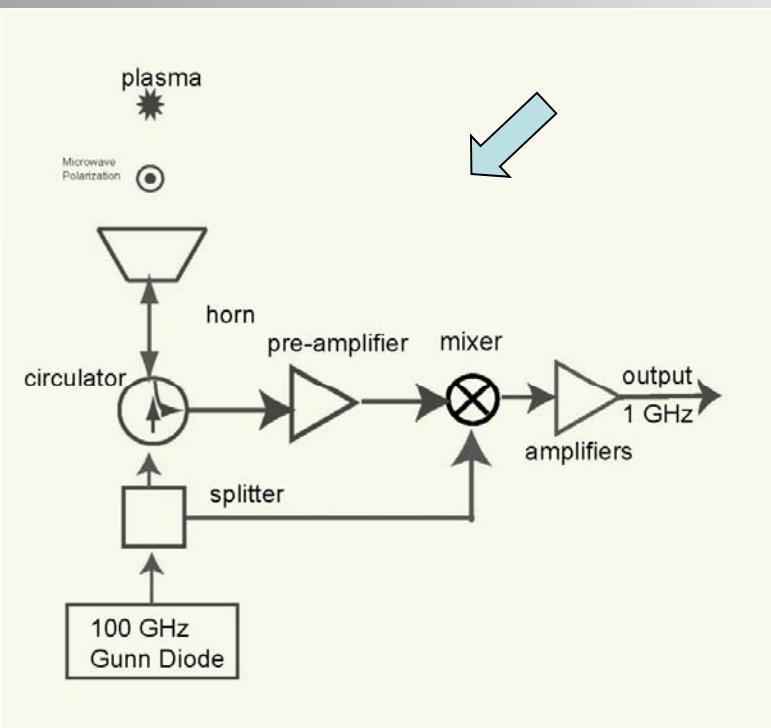
- MICROWAVE SCATTERING FROM LASER-INDUCED CARRIERS
- MICROWAVE ILLUMINATES THE IONIZATION SPOT.
- MICROWAVE SCATTERING IS COLLECTED.



MICROWAVE/LASER MEASUREMENT CONFIGURATION. THE FOCUSED LASER CREATES A SMALL REGION OF IONIZATION AND THE MICROWAVES ARE SCATTERED FROM THAT REGION INTO THE MICROWAVE DETECTOR.



MICROWAVE EXPERIMENTAL SETUP: HOMODYNE AND HETERODYNE

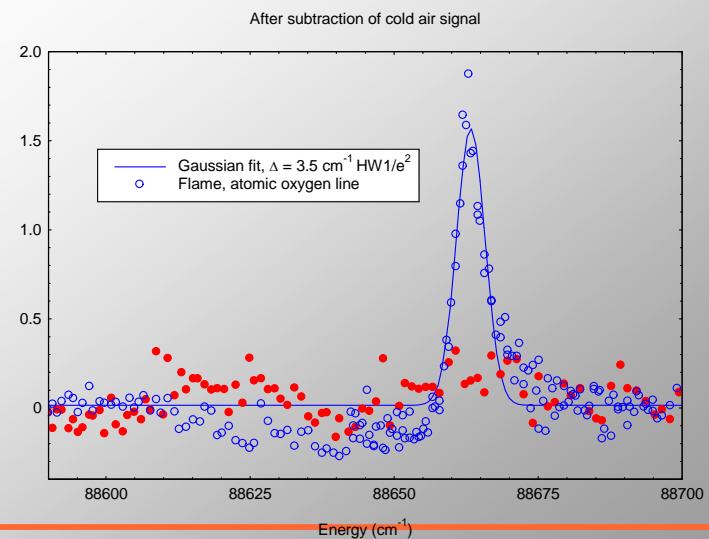
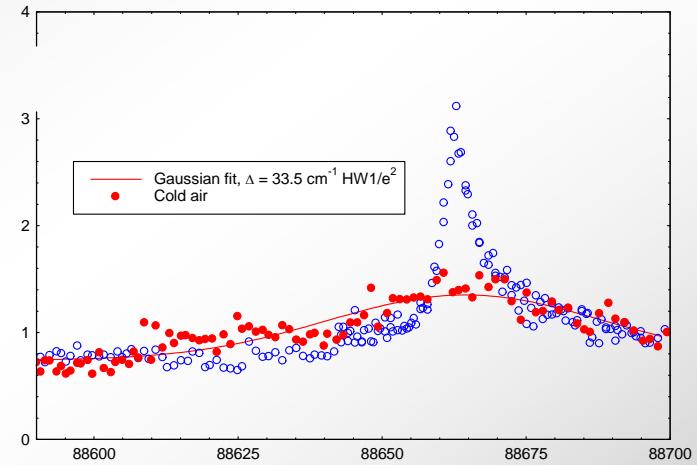


- Homodyne 100 GHz system.
- 100 GHz probes the plasma.
- The mixer output is proportional with the scattering amplitude, hence electron density
- Heterodyne 100 and 90 GHz system.
- 100 GHz probes the plasma, the phase shift is measured on the 10 GHz beating signal.
- The quadrature mixer provides the X and Y components, hence we also measure the phase.

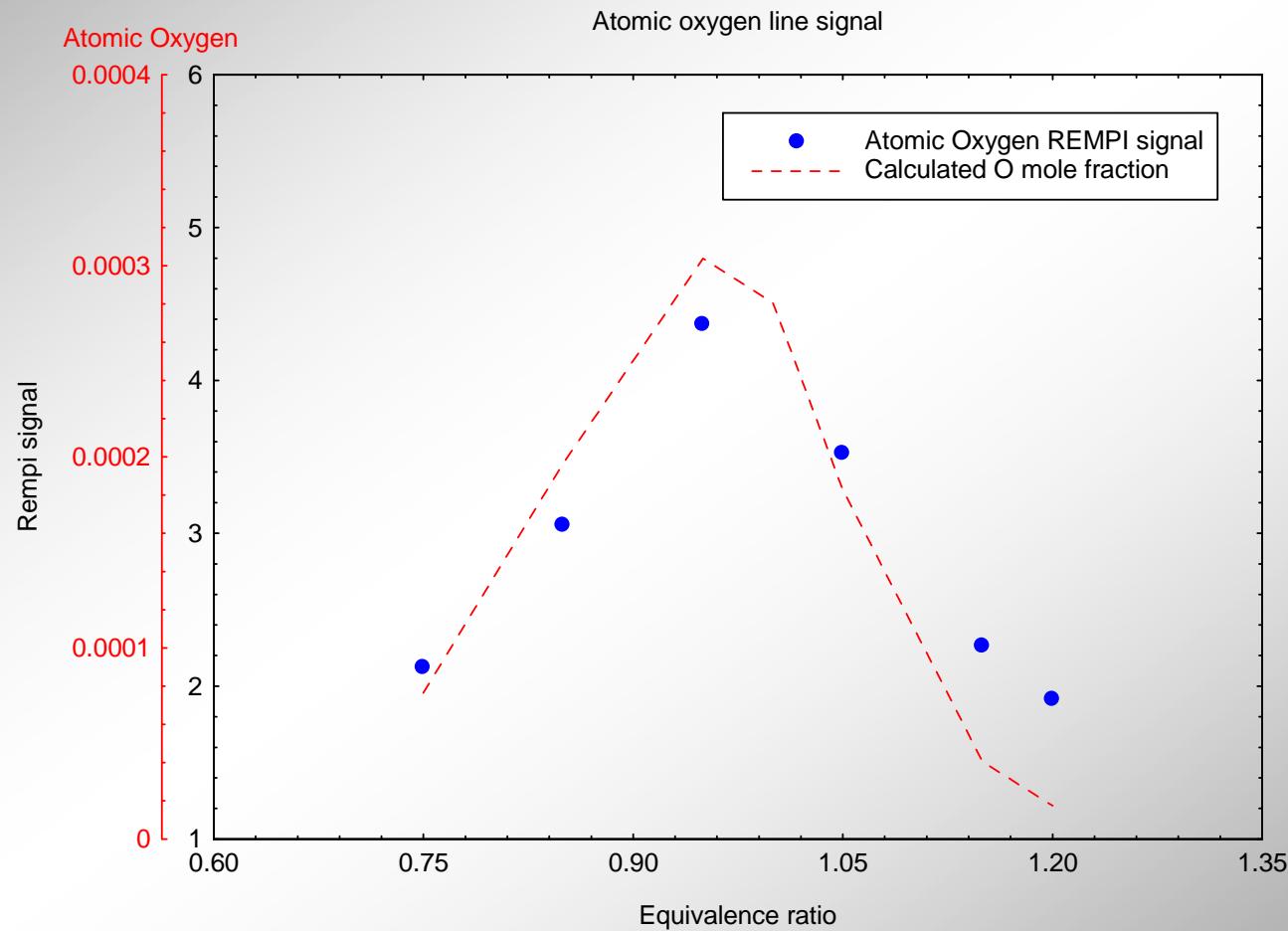
SUB-NANOSECOND TEMPORAL RESOLUTION!

ATOMIC OXYGEN IN A FLAME

- 2000K METHANE – AIR FLAME
- ATOMIC LINE OF OXYGEN IN FLAME IS NARROW (34 cm^{-1} LIMITED BY LASER BANDWIDTH)
- SPECTRAL LINE IN COLD AIR – ATOMIC OXYGEN VIA PHOTOLYSIS IS 10 TIMES BROADER: HIGH TEMPERATURE (50,000K) IMPOSED BY INTENSE LASER PULSE.
- RADAR REMPI CAN DISTINGUISH BETWEEN FLAME AND PHOTOLYSIS ATOMIC OXYGEN.



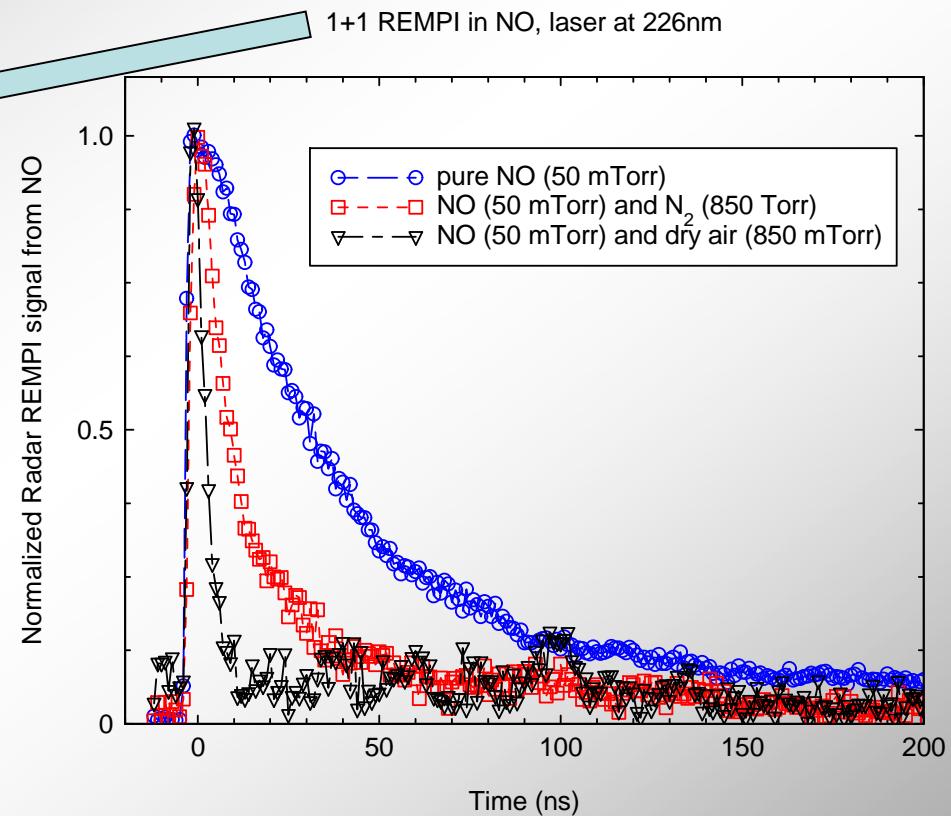
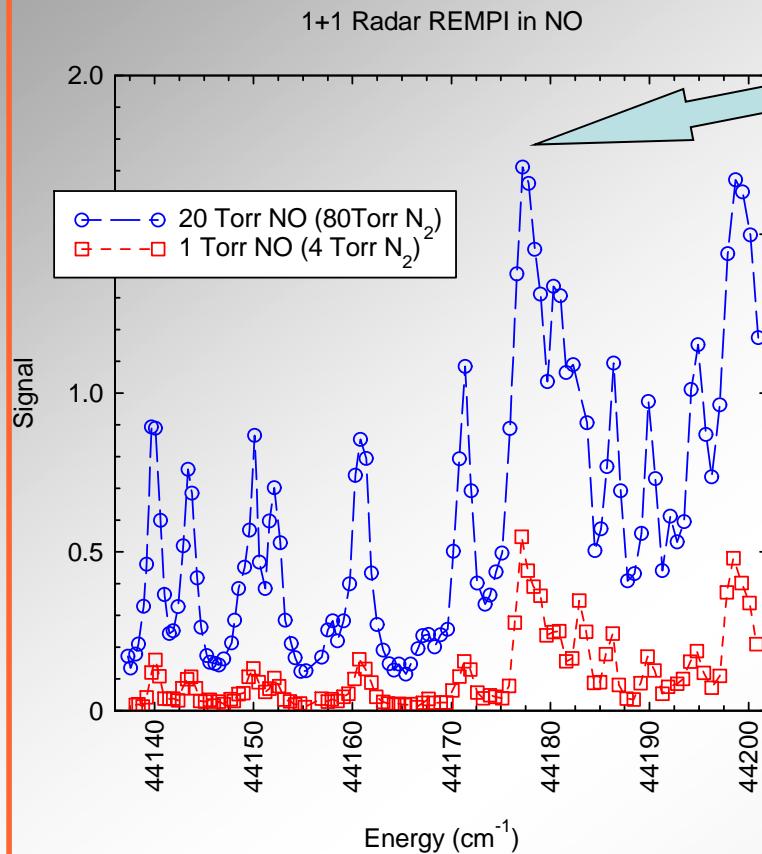
RESONANT SIGNAL FROM ATOMIC OXYGEN VS. EQUIVALENCE RATIO



EQUILIBRIUM MODEL — 1D CHEMKIN



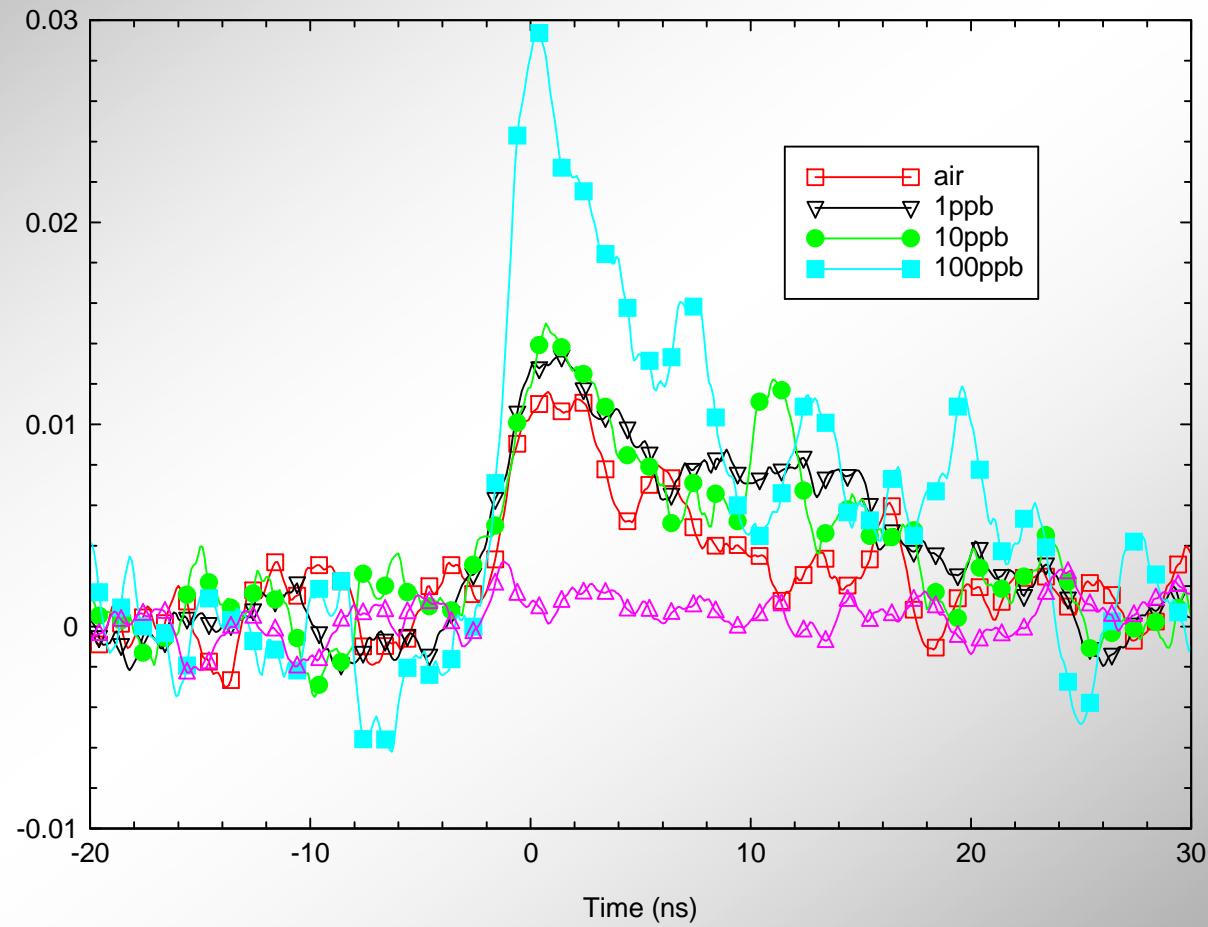
1 + 1 RADAR REMPI IN NO



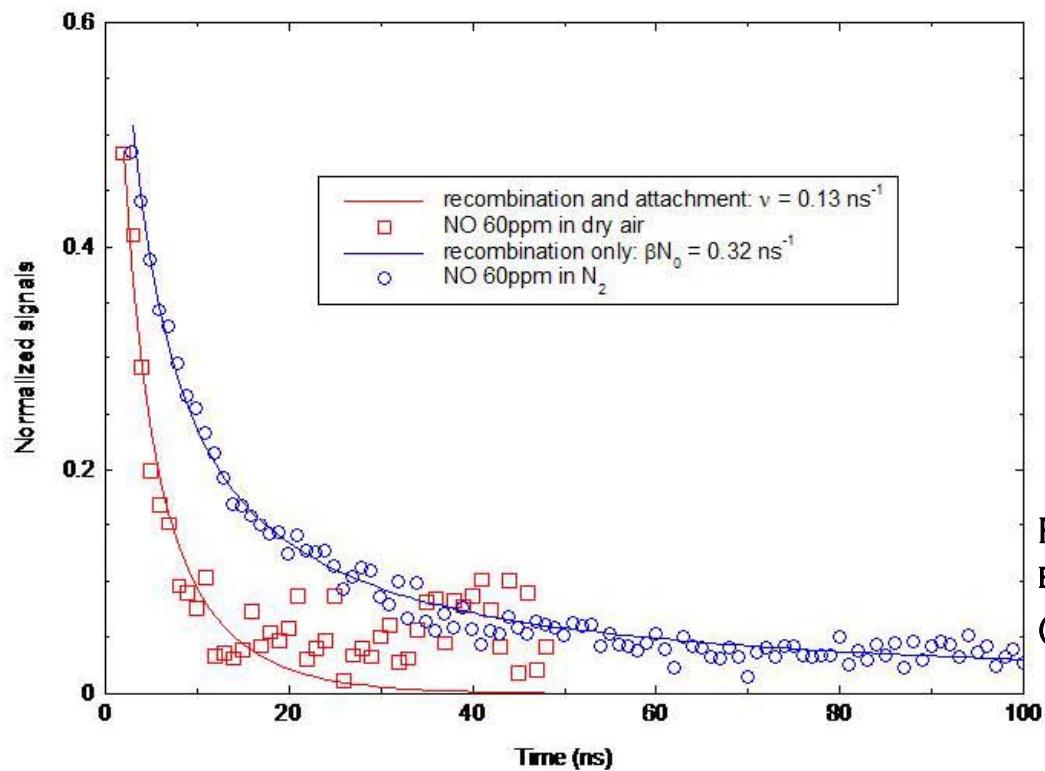
- PURE NO SHOWS LONGER LIFETIME DUE TO ELECTRON DIFFUSION.
- IN ORDER TO MEASURE THE RECOMBINATION RATE WE SUPPRESS DIFFUSION BY ADDING N_2 .
- IN AIR WE CAN MEASURE ATTACHMENT RATE.

NO TRACE DETECTION

(LIMITED BY BACKGROUND ~ 10 PPB NO IN AIR)



DIRECT MEASUREMENT OF ELECTRON ATTACHMENT IN ATMOSPHERIC AIR



recombination

attachment

$$\frac{\partial N}{\partial t} = -\nu_a N - \beta N^2$$

$$\beta = 2 \cdot 10^{-13} \sqrt{\frac{300}{T_e(K)}} \frac{m^3}{s}$$

PREVIOUS EXTRAPOLATED
ESTIMATE FOR 850 TORR DRY AIR
(78%N₂, 21%O₂, 1% AR):

$$\nu_a \approx 1.05 \cdot 10^8 s^{-1}$$

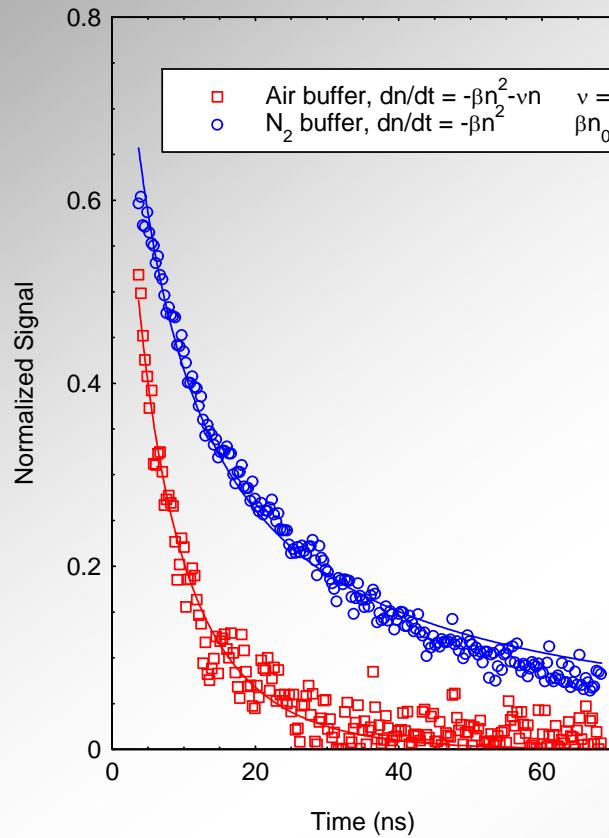
NO in N₂ - recombination only: $N(t) = \frac{N_0}{1 + \beta N_0 t}$ gives $\beta N_0 = 3.2 \times 10^8 s^{-1}$

NO in air - recombination and attachment: $N(t) = \frac{N_0 e^{-\nu_a t}}{1 + \frac{\beta N_0}{\nu_a} (1 - e^{-\nu_a t})}$ gives $\nu_a = 1.3 \times 10^8 s^{-1}$

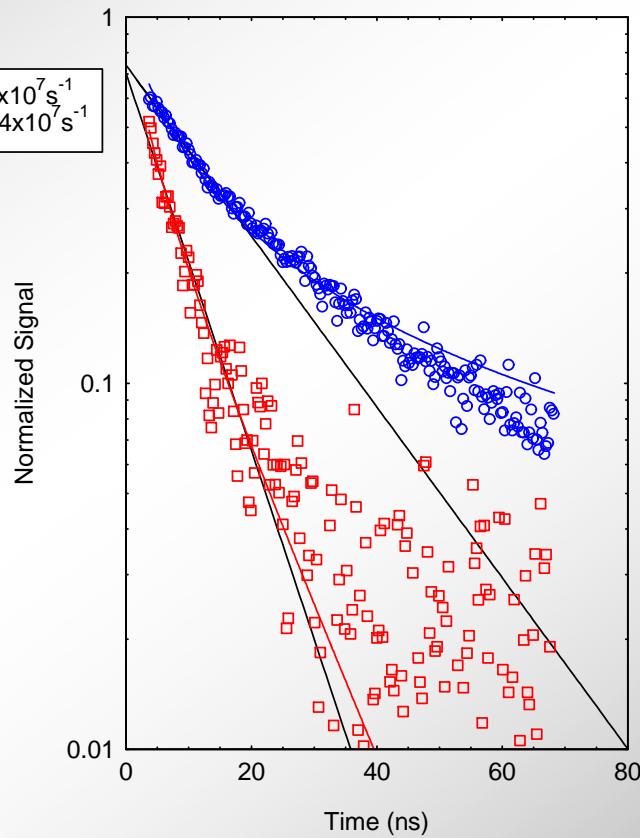


IDENTIFYING ELECTRON LOSS MECHANISM AND RATE

NO at 0.13 Torr in 1atm. buffer (170ppm)



NO at 0.13 Torr in 1atm. buffer (170ppm)



$$\ln N_2 \cdot N(t) = \frac{N_0}{1 + \beta N_0 t}$$

RECOMBINATION
ONLY, NOT AN
EXPONENTIAL
DECAY

ATTACHMENT IN AIR:

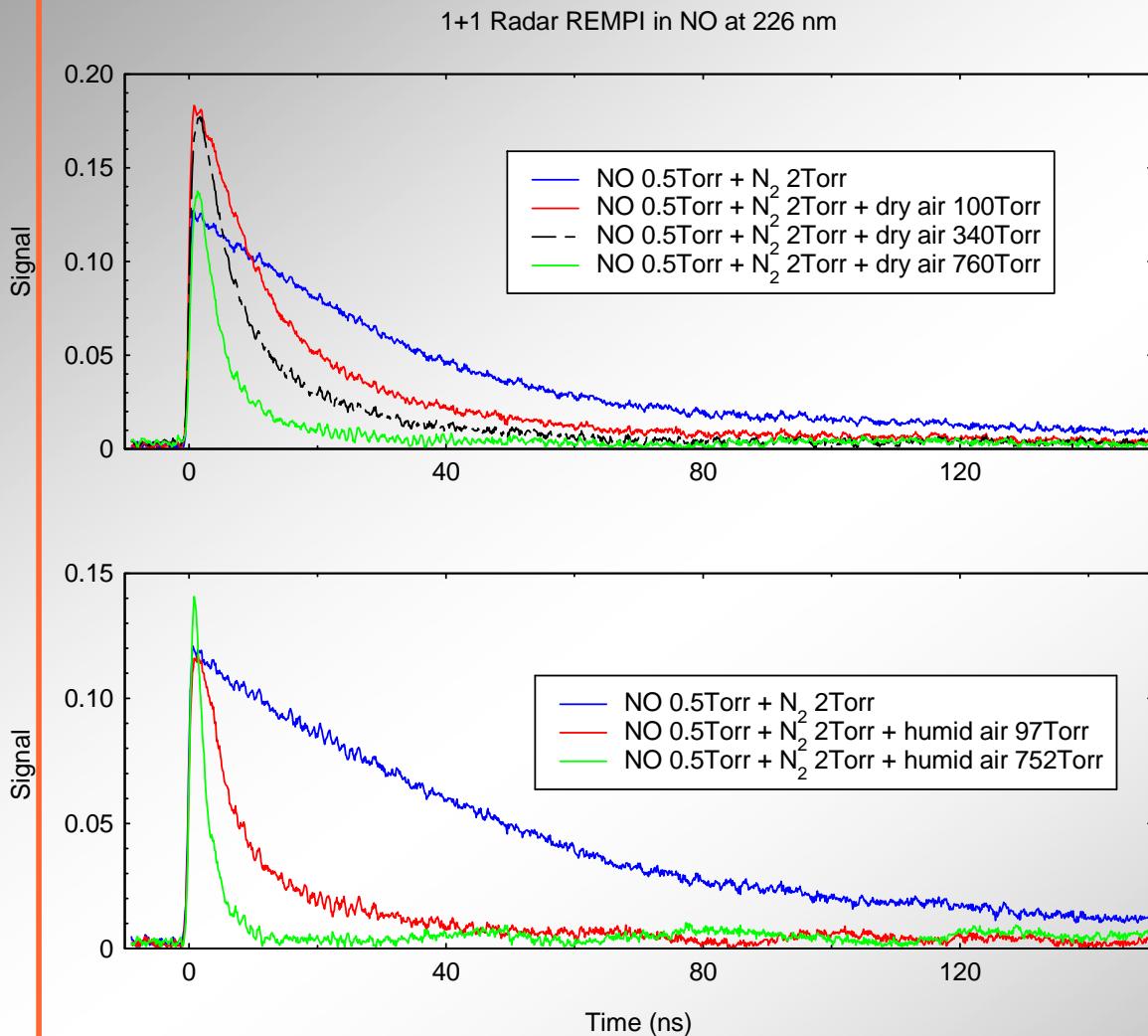
$$N(t) = \frac{N_0 e^{-\nu_a t}}{1 + \frac{\beta N_0}{\nu_a} (1 - e^{-\nu_a t})},$$

$$N(t) \approx \frac{N_0}{1 + \frac{\beta N_0}{\nu_a}} e^{-\nu_a t}$$

CLOSE TO
EXPONENTIAL



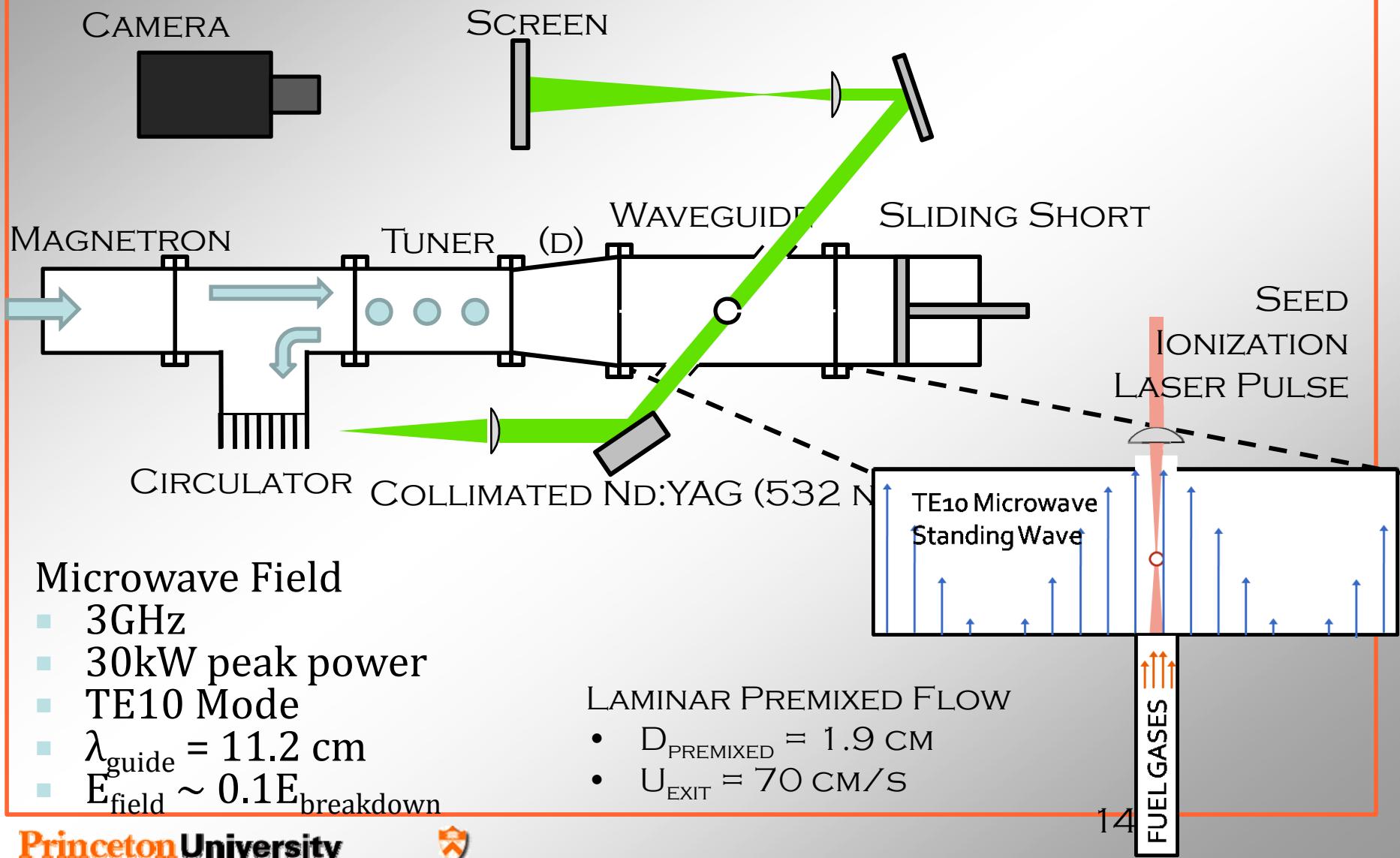
TESTING NO IN BUFFER GASES



- N₂ INCREASES ELECTRON LOSS VIA RECOMBINATION BY SUPPRESSING DIFFUSION
- DRY AIR – FASTER DECAY DUE TO ELECTRON ATTACHMENT TO O₂
- HUMID AIR – FURTHER INCREASE OF LOSSES DUE TO HIGHER ATTACHMENT RATES IN WATER

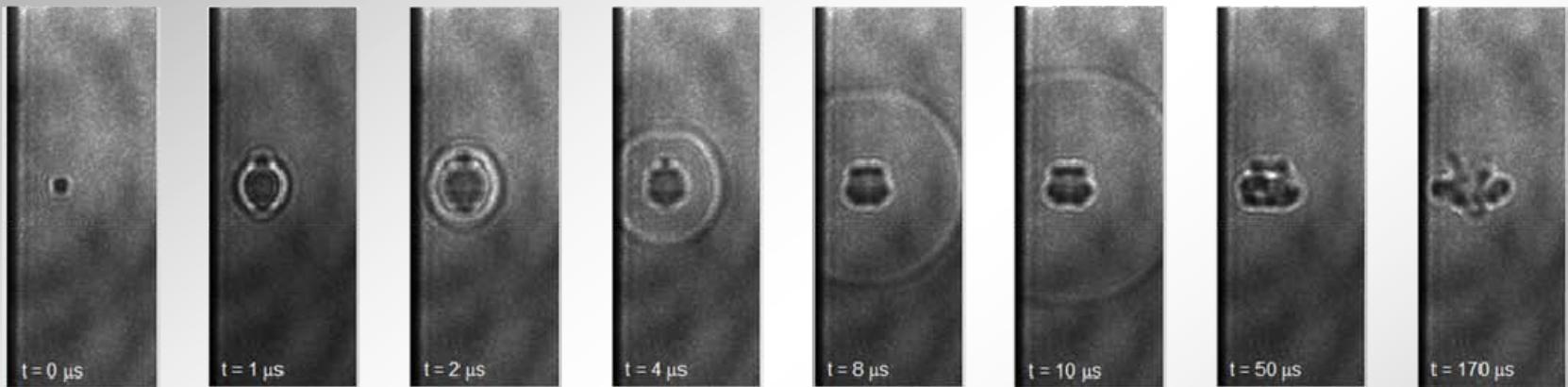
LASER DESIGNATED MICROWAVE IGNITION

EXPERIMENTAL APPARATUS

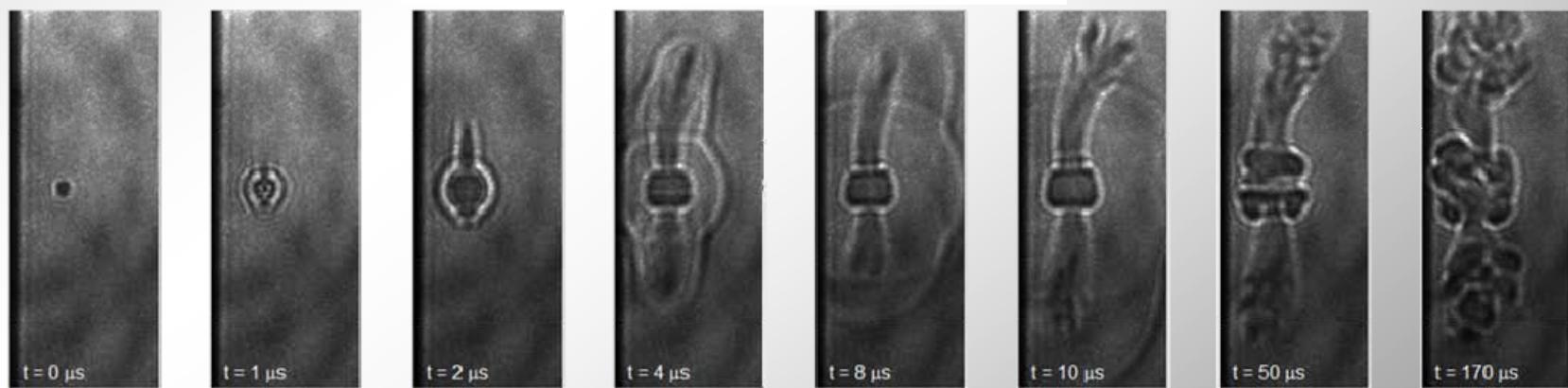


Ps LASER-MW EVOLUTION IN AIR

Laser spot evolution

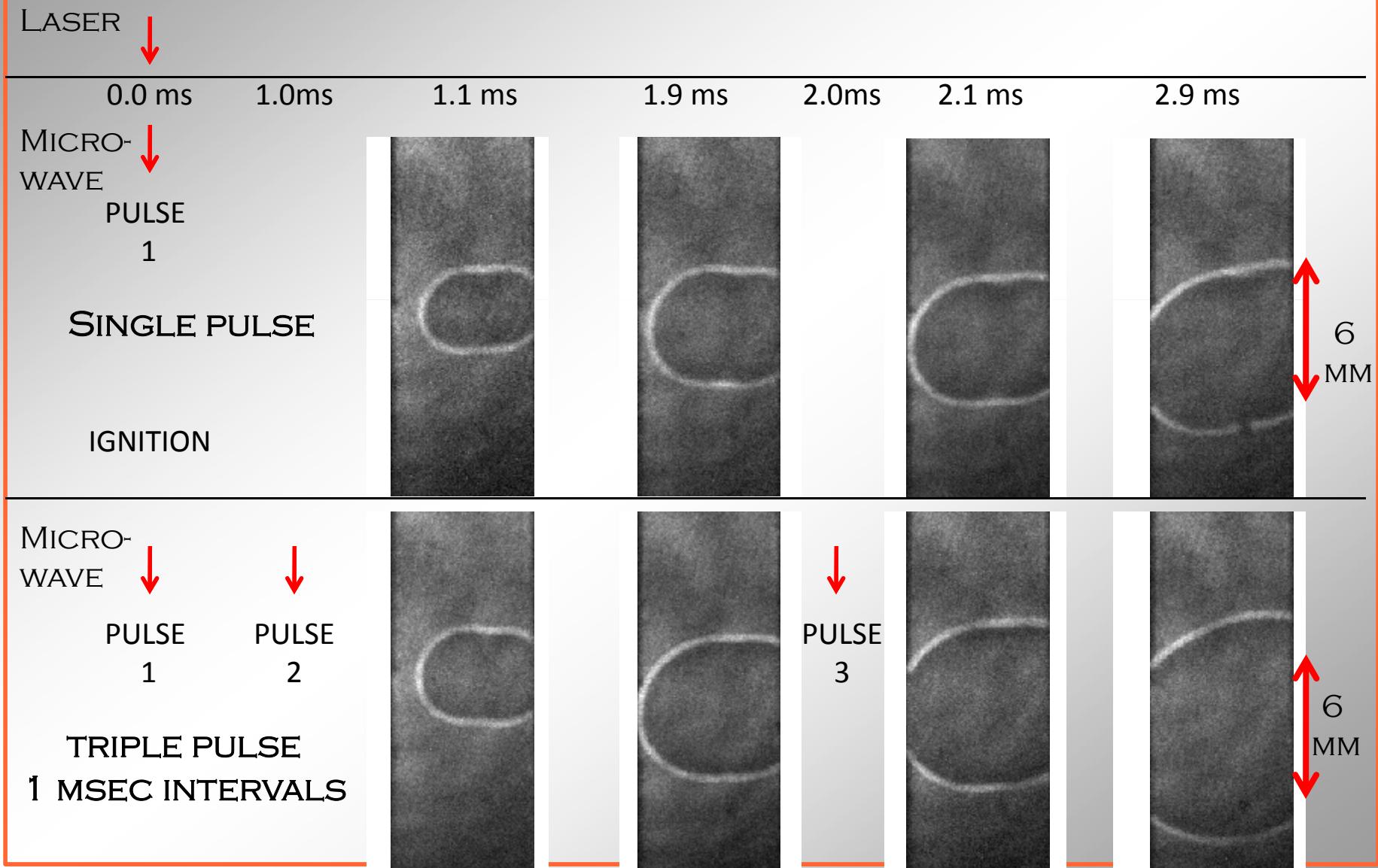


Laser + MW evolution

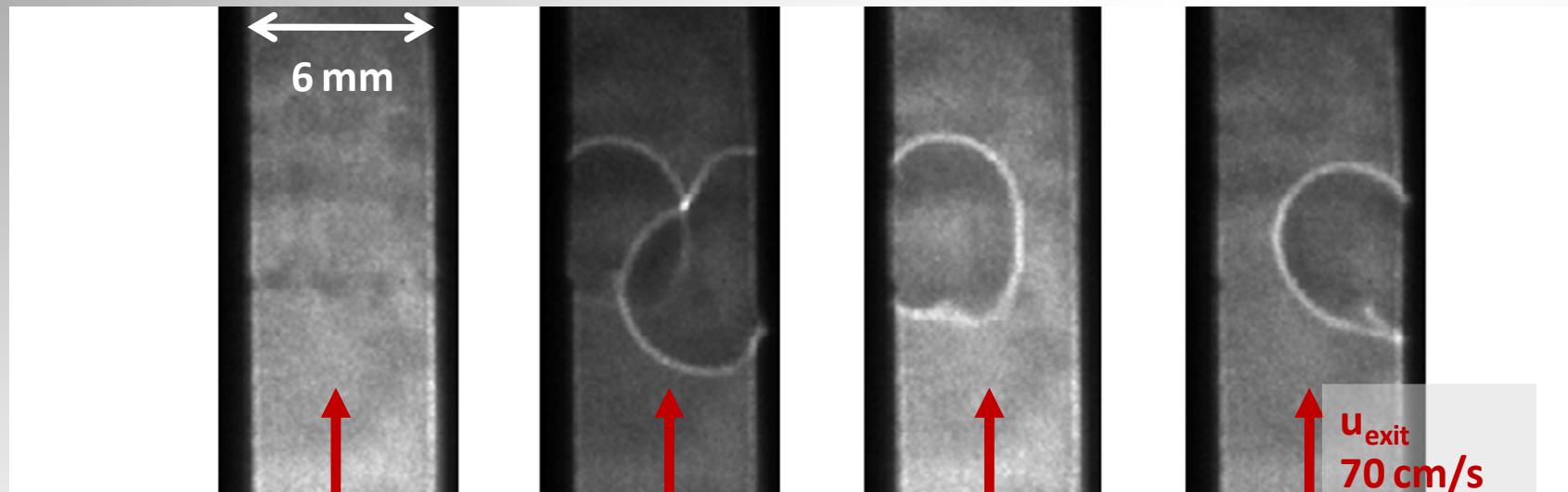


IGNITION: KERNEL GROWTH COMPARISON

SINGLE AND MULTIPLE PULSE MICROWAVE



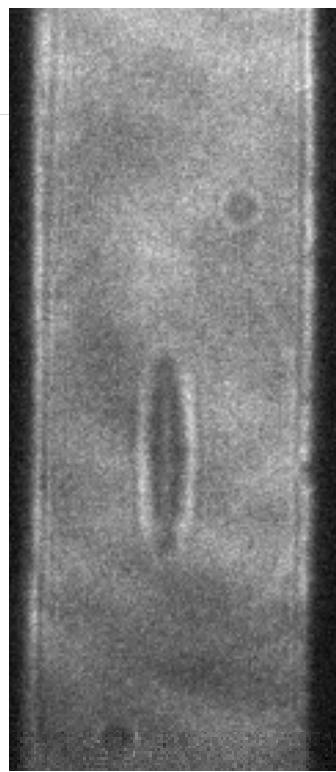
MULTI-POINT IGNITION



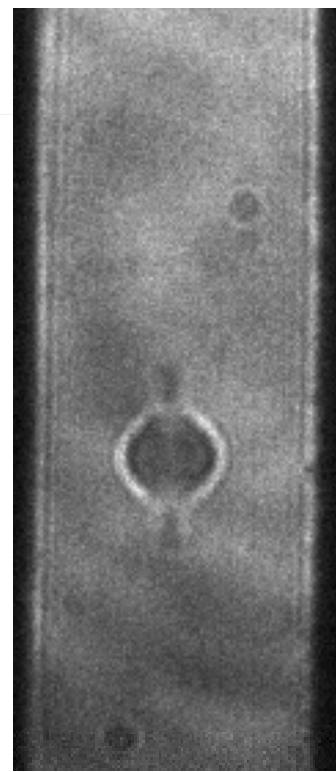
- TWO 7MJ SEED LASER SPOTS
- 75 MJ MW PULSE
- $\varphi = 0.7$; $U_{EXIT} = 70 \text{ CM/S}$
- 3 MS AFTER INITIAL SEED LASER PULSE
- FLAME KERNEL INDICATES IGNITION

200 FEMTOSECOND SEED – 180 μ J

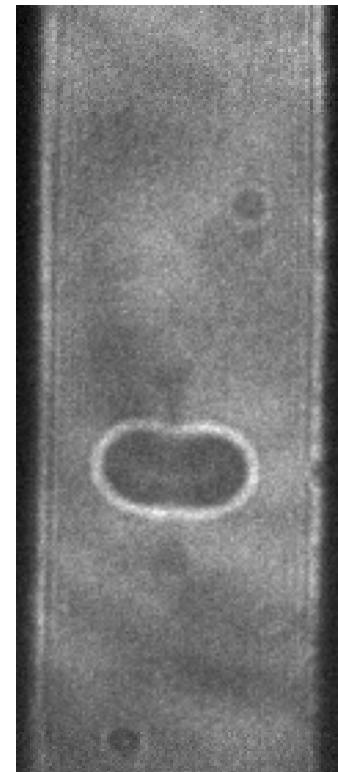
10 us



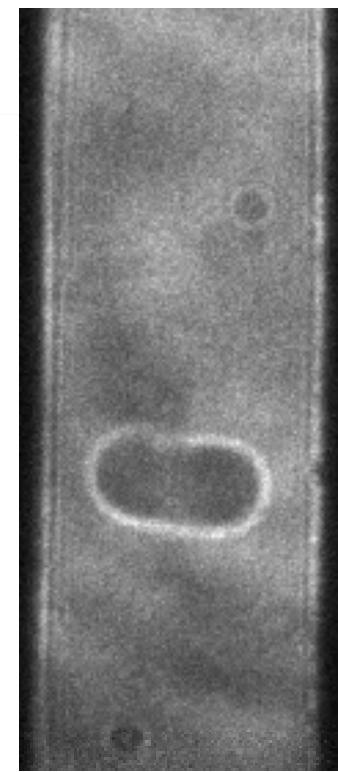
100 us



500 us



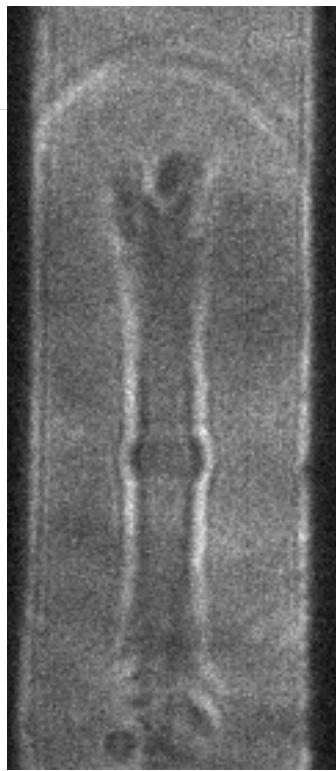
1000 us



6 mm

200 FEMTOSECOND SEED –600 μ J

10 us



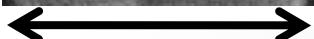
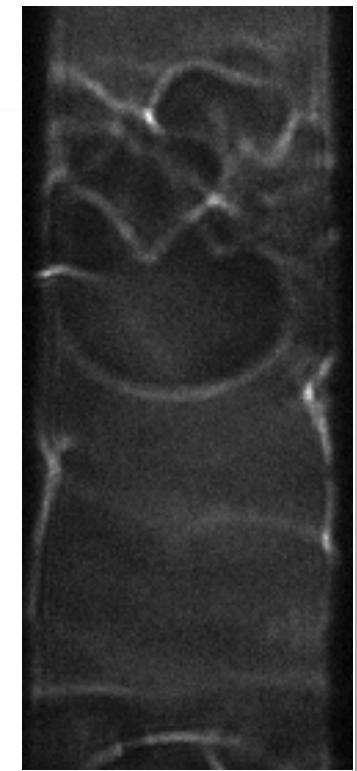
100 us



500 us



1000 us

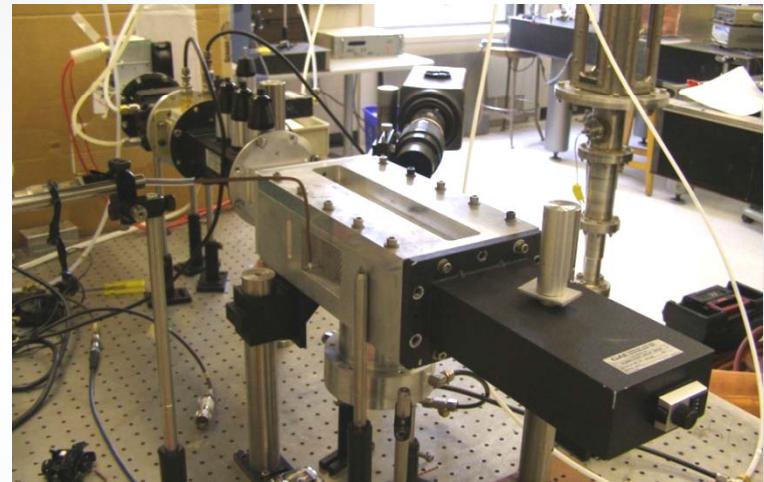


6 mm



IGNITION OF METHANE/AIR MIXTURES

- SEED IONIZATION PULSE
7MJ; 200 ps, 780 nm
- MW HEATING PULSE
50MJ; 2 μ s, 3GHz



Observed Minimum Seed Laser Energies

λ_{seed} [nm]	φ	f [m]	E_{laser} [mJ]	* E_{MW} [mJ]*
800 (200 fs)	0.8	0.06	0.2	50
780	0.8	0.06	3	50
780	0.8	0.10	7	50
780	0.7	0.10	7, 7	75
390	0.8	0.10	1.5	50

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

Yiguang Ju

AFOSR MURI Kick off meeting

The Ohio State University
Nov 4, 2009

Team members:

Wenting Sun, Sanghee Won, Mruthunjaya Uddi

Collaborators:

Interactional: Fei Qi, University of Science and Tech. China

AFLR collaborators: Campbell Carter, Timothy Ombrello, Skip Williams

Ju's Group Primary Research Focus

Thrust 1. The effects of kinetic and transport of plasma assisted ignition

- Task 1: Experimental measurements of minimum ignition energies using a spherical bomb with different electrode geometries
- Task 2: Experimental measurements of ignition/extinction limits by using counterflow flames

Thrust 2. Intermediate Species Measurements at Elevated Pressures by Using a Plasma Assisted Jet Stirred Reactor with Molecular Beam Sampling

- Task 1: Development of plasma assisted a jet stirred reactor
- Task 2: Measurements of intermediate species of fuel oxidation

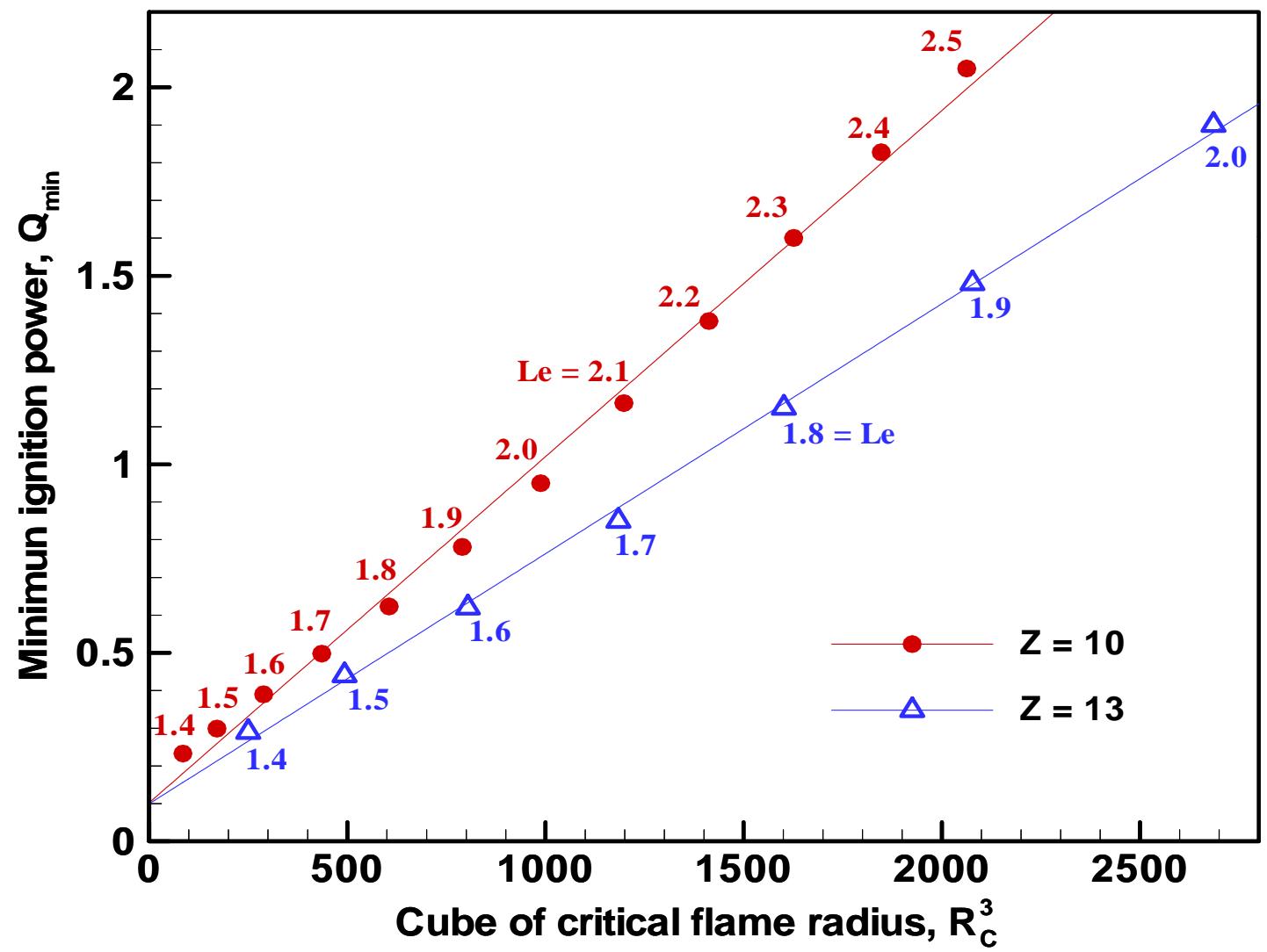
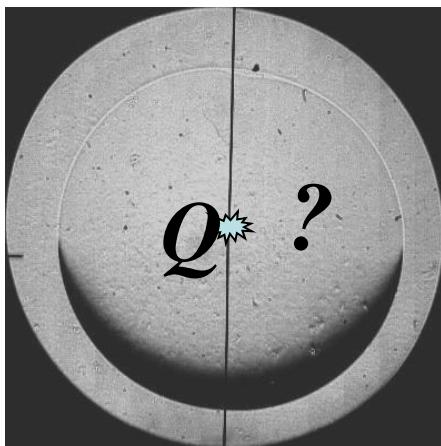
Thrust 3. Mechanism Reduction and Dynamic Multi-time Scale Modeling of Detailed Plasma-Flame Chemistry

- Task 1: Development of dynamic multi-timescale modeling
- Task 2: Simulations of unsteady ignition and extinction of plasma discharge with detailed kinetic mechanisms

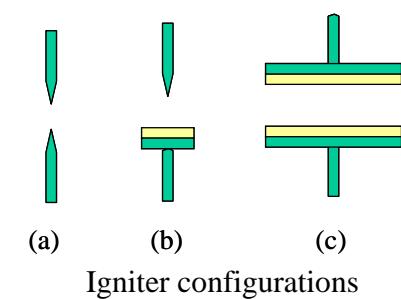
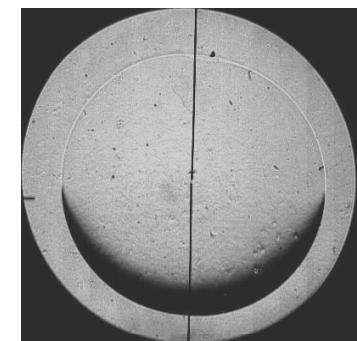
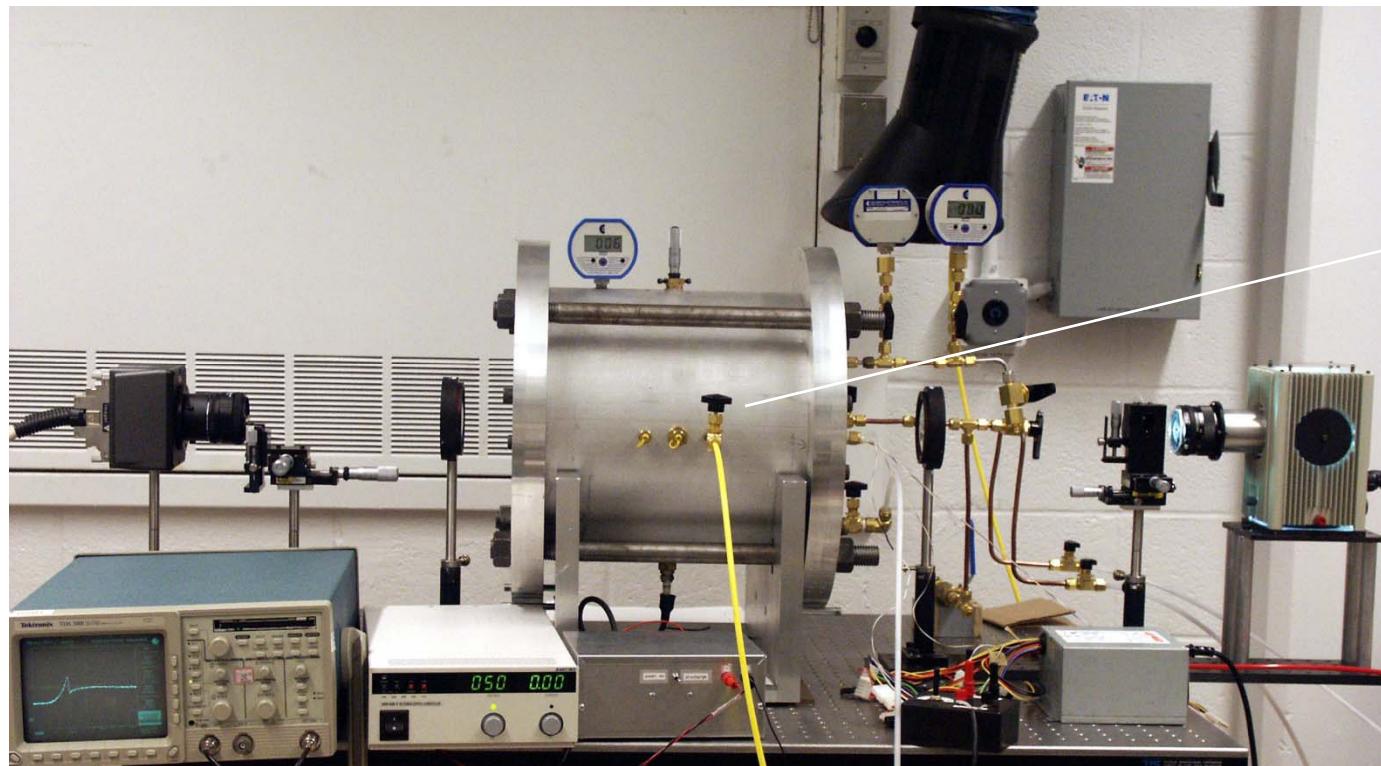
Research Task Description, Methods, and Preliminary Results

Thrust 1. The effects of kinetic and transport of plasma assisted ignition

- Task 1: Experimental measurements of minimum ignition energies using a spherical bomb with different electrode geometries



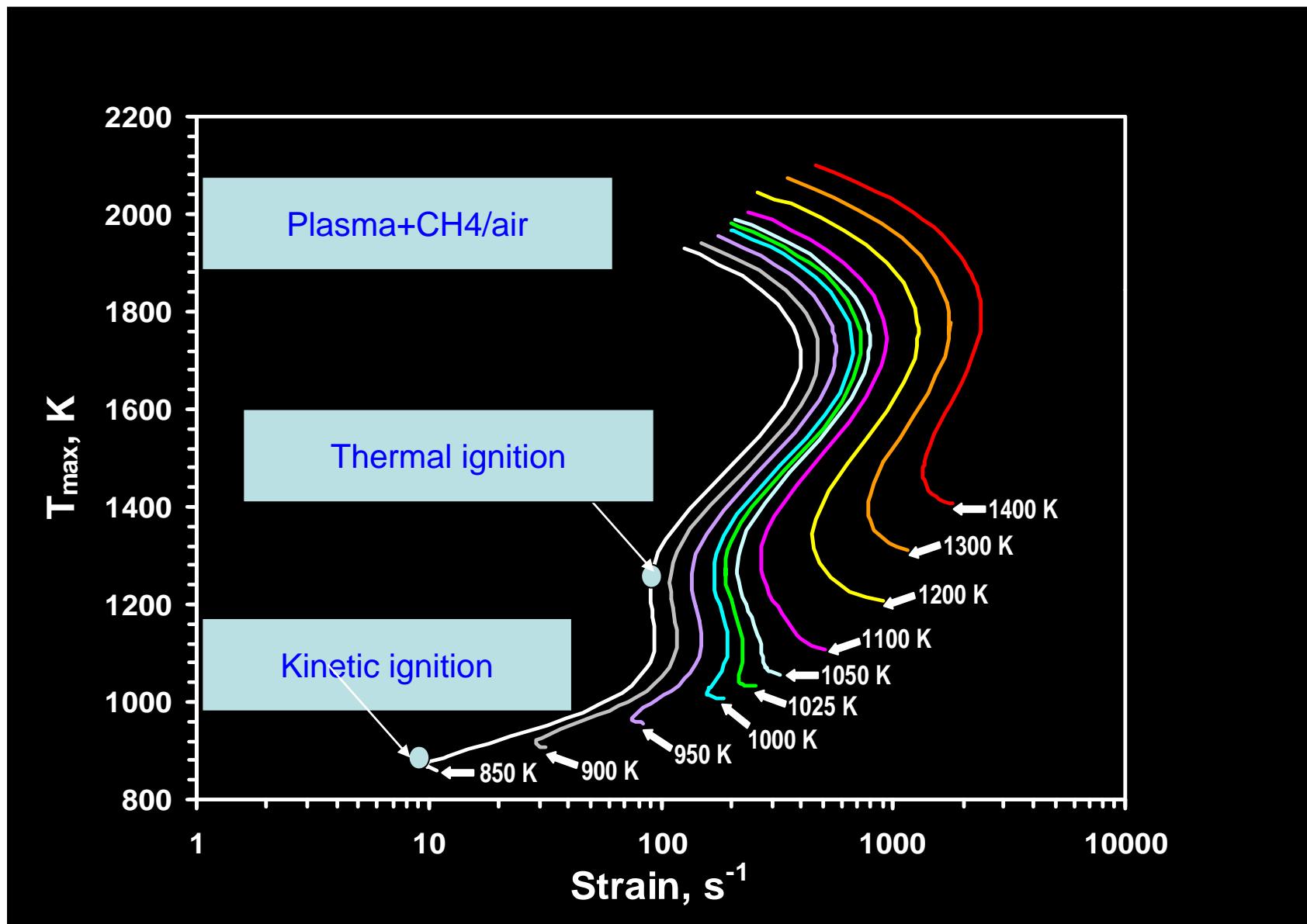
Experimental methods



(a) (b) (c)
Igniter configurations

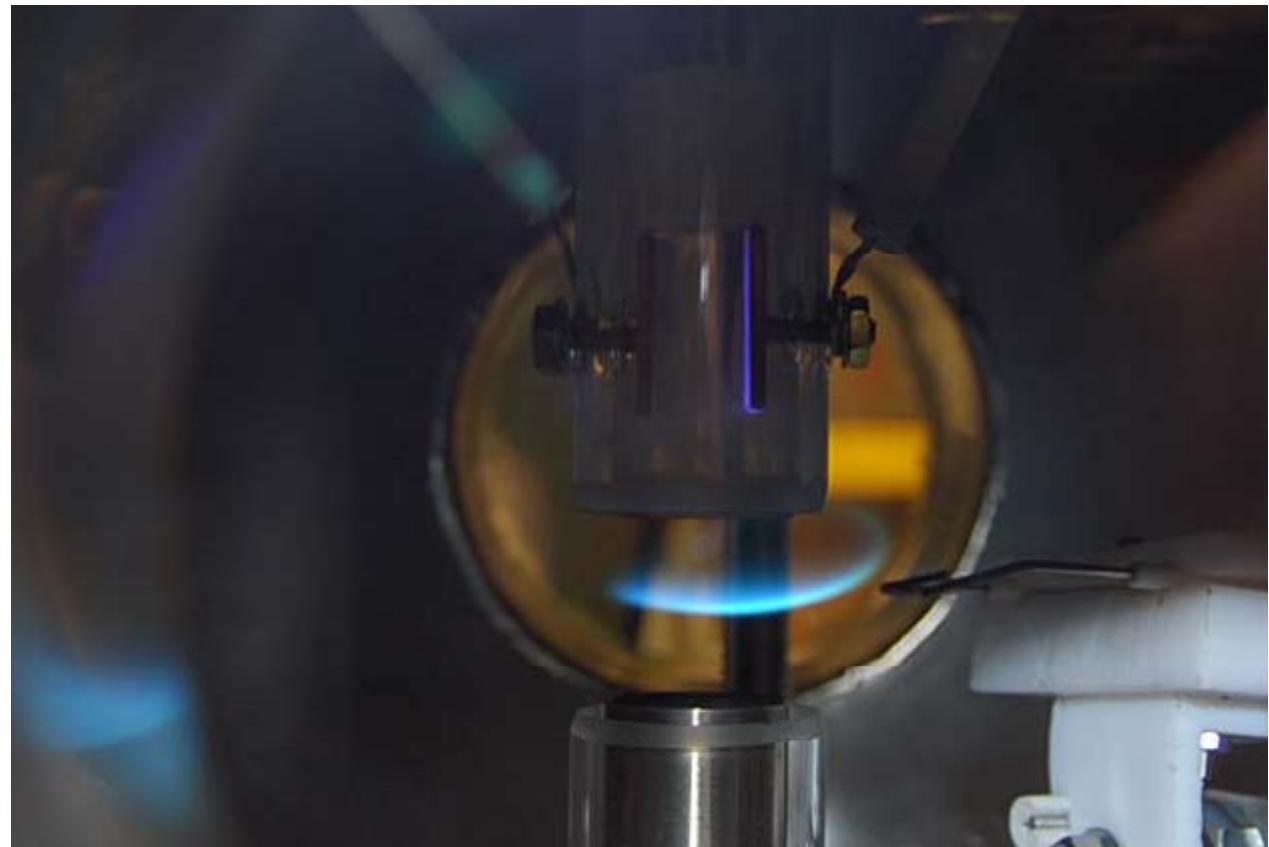
Thrust 1. The effects of kinetic and transport of plasma assisted ignition

- Task 2: Experimental measurements of ignition/extinction limits by using counterflow flame w/wo non-equilibrium plasma discharge



Thrust 1. The effects of kinetic and transport of plasma assisted ignition

- Task 2: Experimental measurements of ignition/extinction limits by using counterflow flame w/wo non-equilibrium plasma discharge

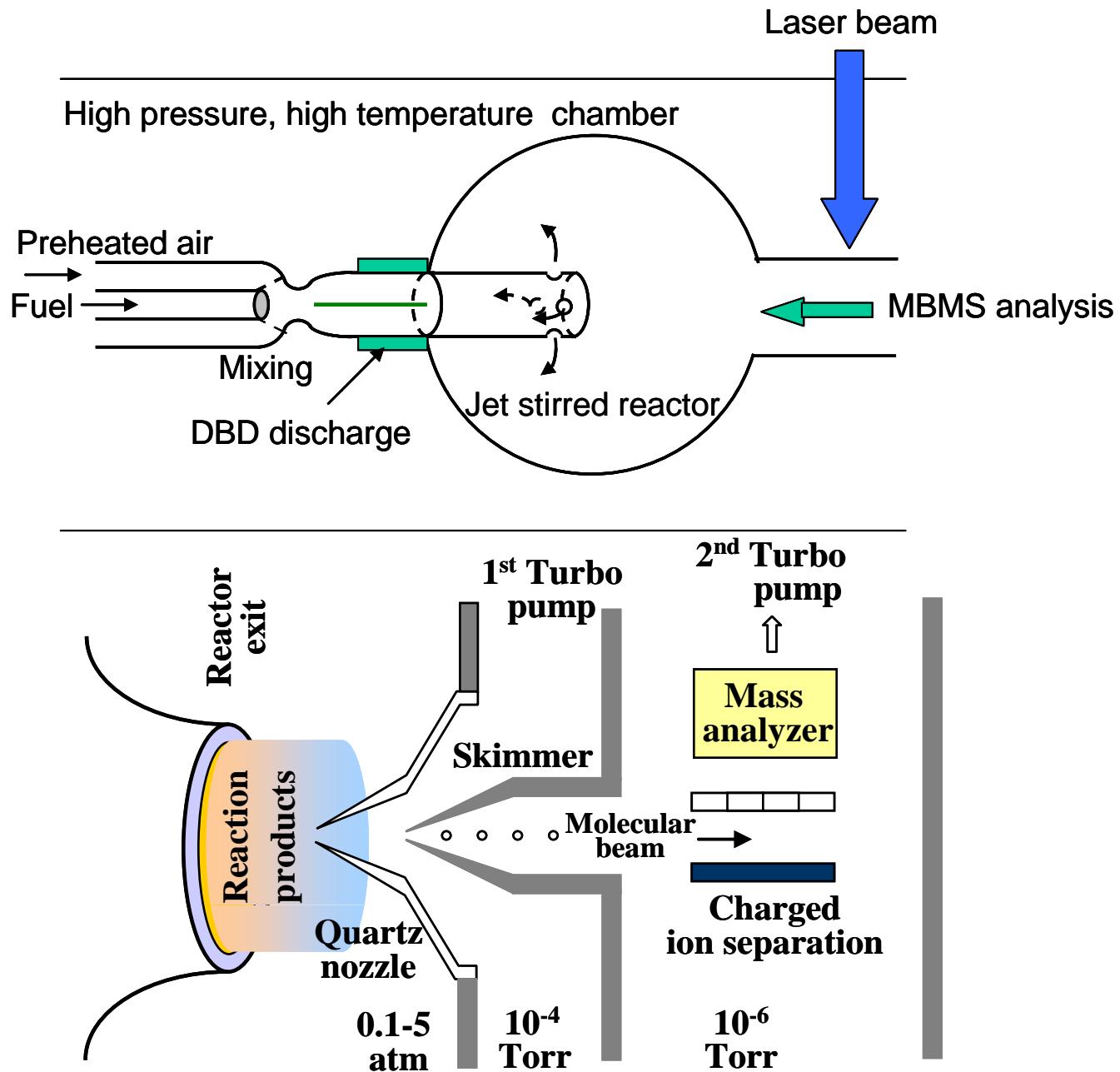


LIF: OH, NO, CH₂O

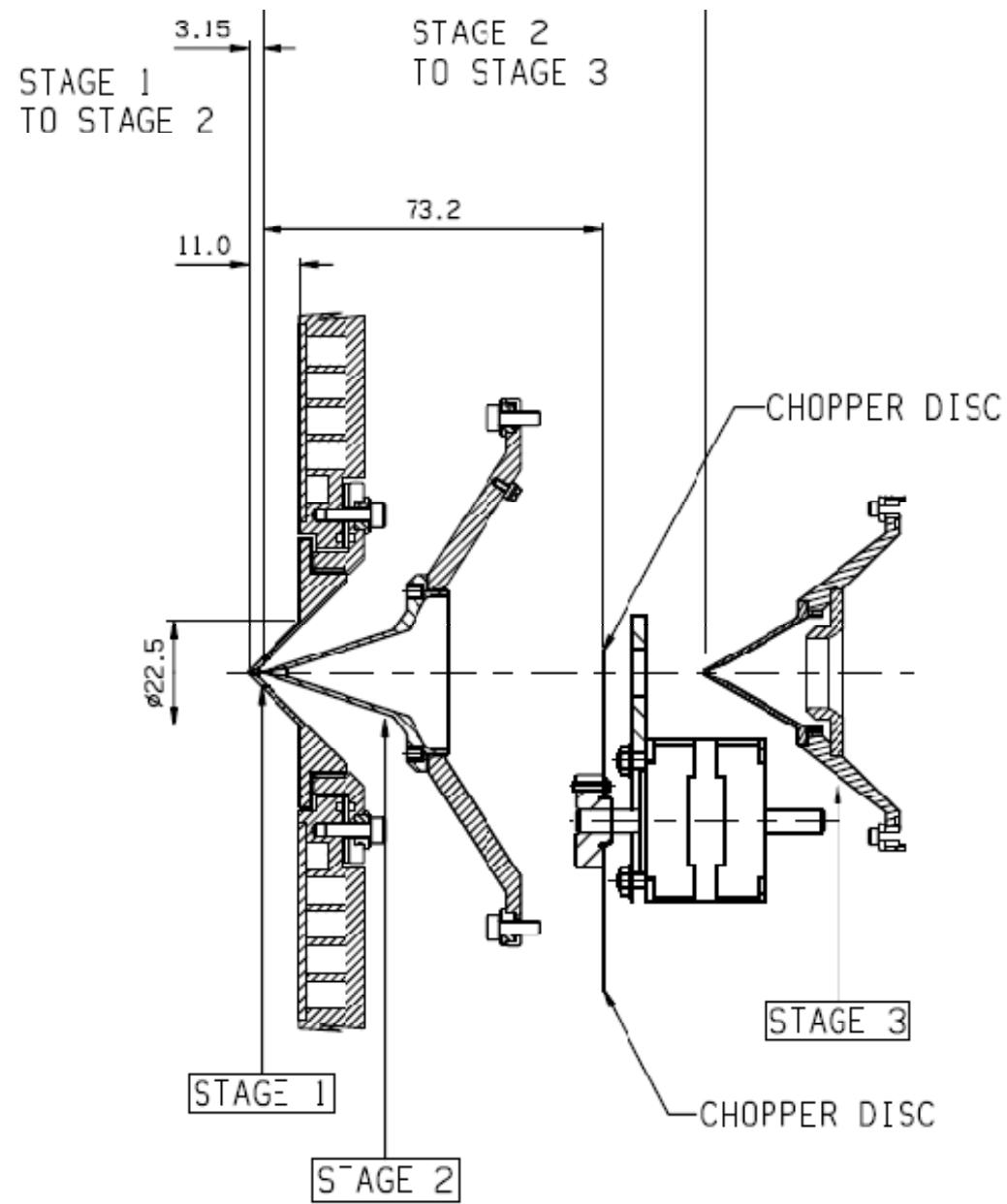
TALIF: O, H

Nanosecond pulser: Carter

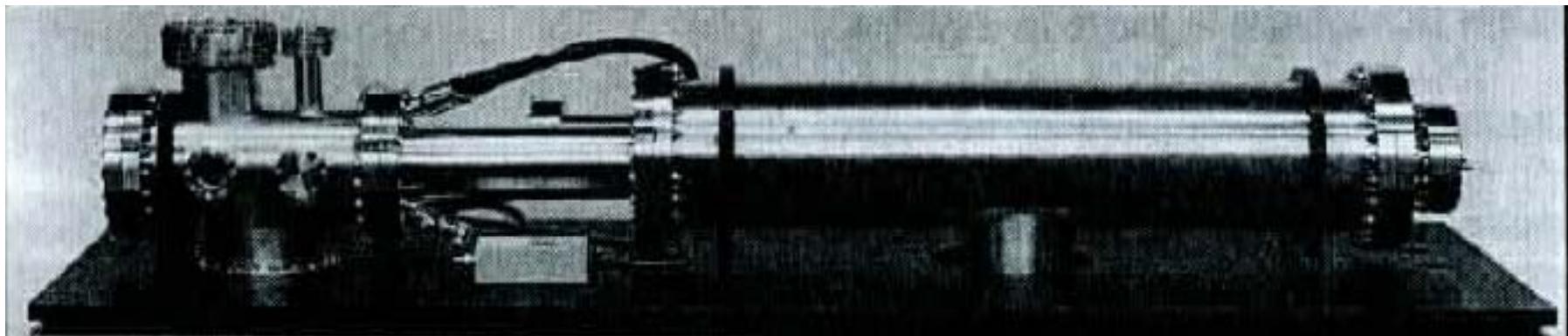
Thrust 2: High pressure JSR and MBMS experimental methods of intermediate species measurements



Three stage molecular beaming sample for high pressure

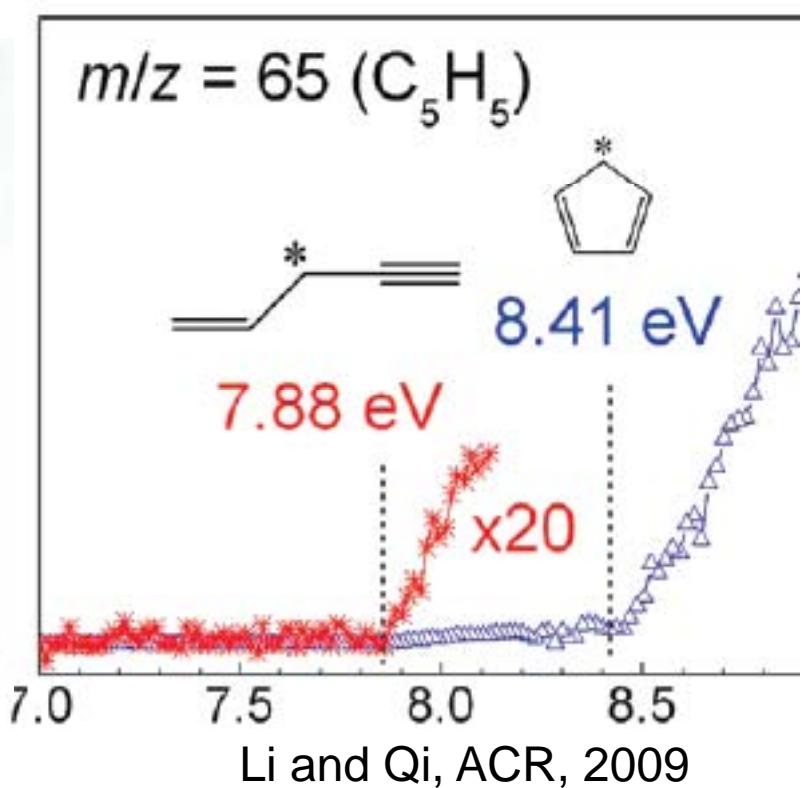
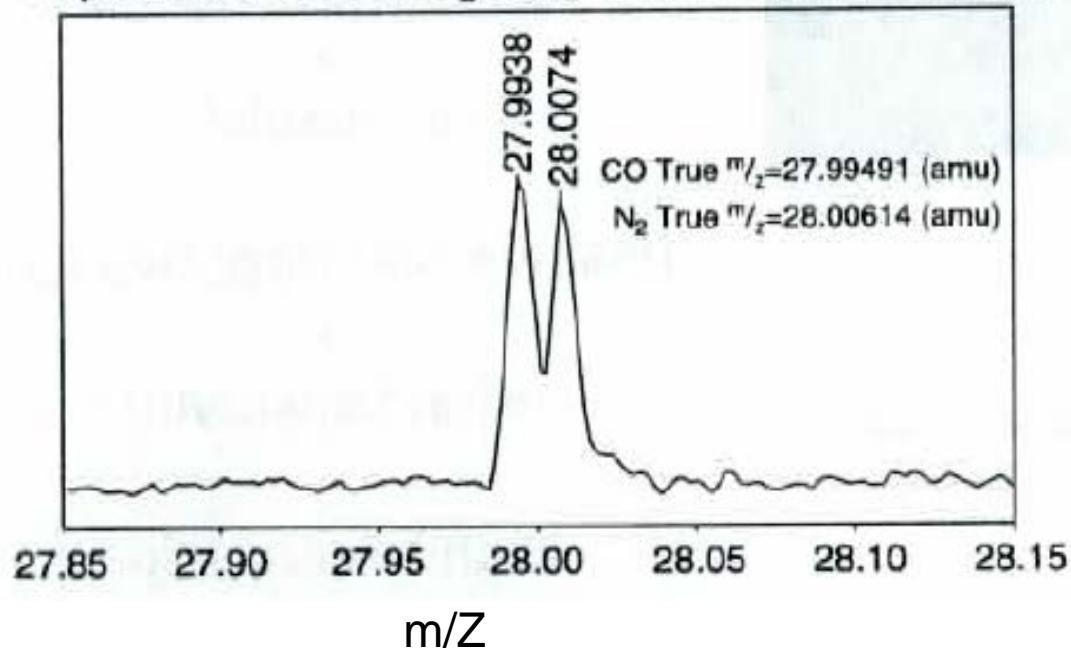


Equipment installation (EFRC program)



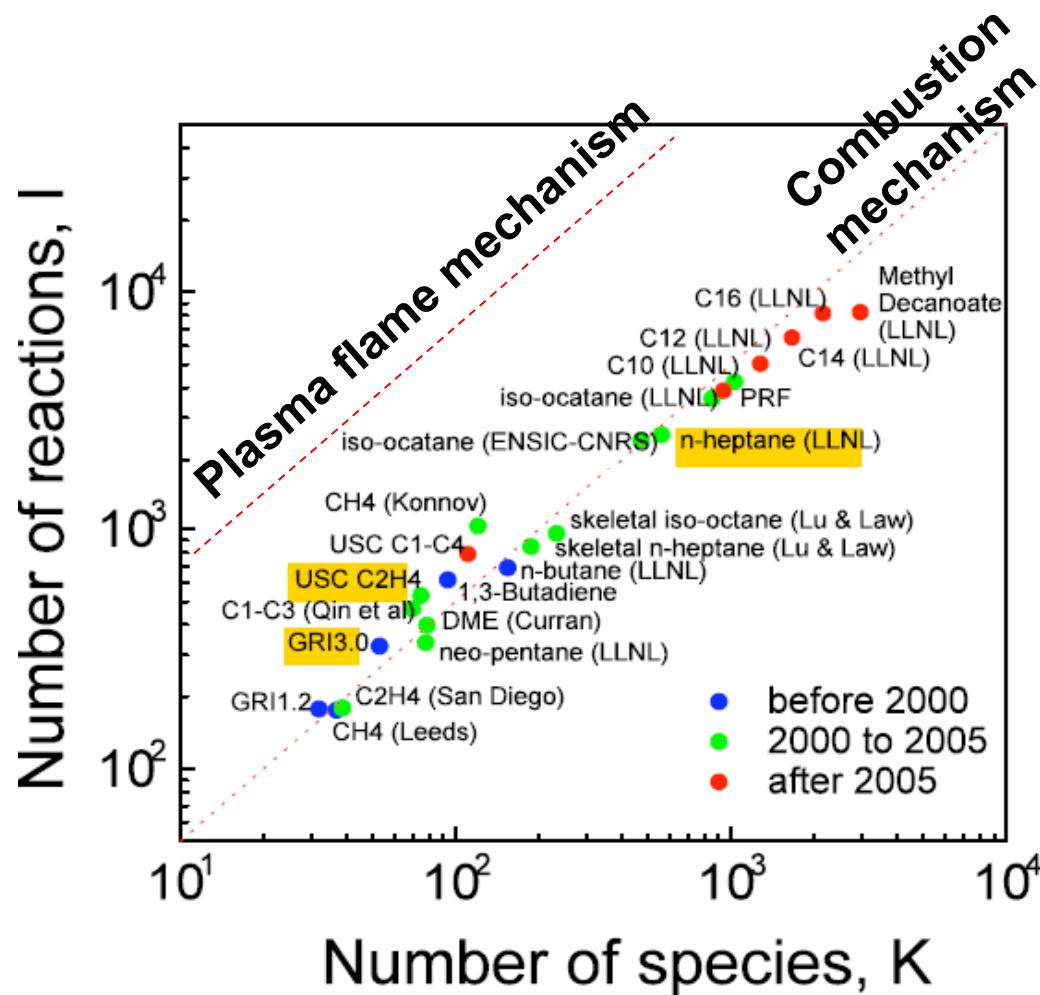
Comstock Time of flight (TOF) MB system: RTOF210: Mass resolution up to 5000

Separation of CO from N₂ using Comstock's EI-TOF-210



Thrust 3. Mechanism Reduction and Dynamic Multi-time Scale Modeling of Detailed Plasma-Flame Chemistry

- Task 1: Development of dynamic multi-timescale modeling approach
- Task 2: Simulations of unsteady ignition and extinction of plasma discharge with detailed kinetic mechanisms



Total computation time $\propto K^3$

$t_{Chem} \approx 80\% t_{total}$



Multi Time Scale Method (MTS)

The Basic Idea of Multi-Time Scale Method: timescale changes!

$$Y_k = K_k e^{-\frac{t}{\tau_k}}$$

Fastest Group

Medial Groups

Slowest Group

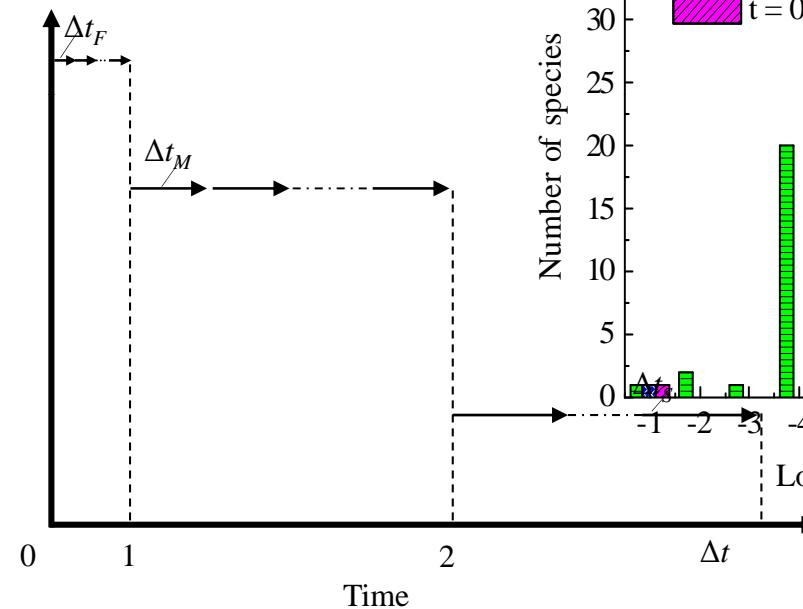


Diagram of multi time scale scheme

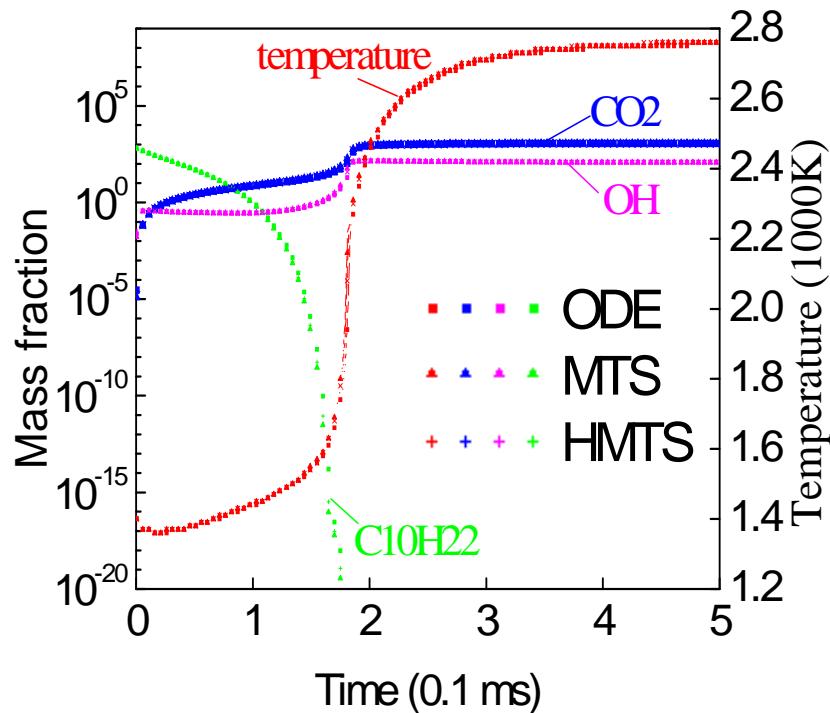
Δt_F is the time step of the fastest group, Δt_M is the time step of the medial group, and Δt_S is the time step of the slowest group



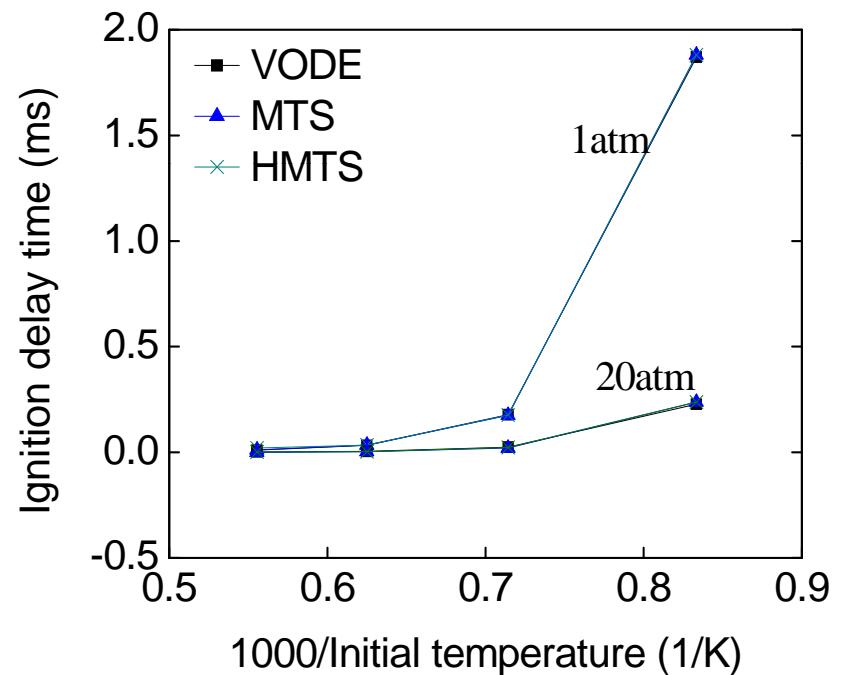
Validation by homogeneous ignition

n-decane/Air 121 species (M. Chaos, IJCK,2007)

Ignition in
homogeneous
mixture



Temperature and species profiles



Ignition delay time for n-decane-air



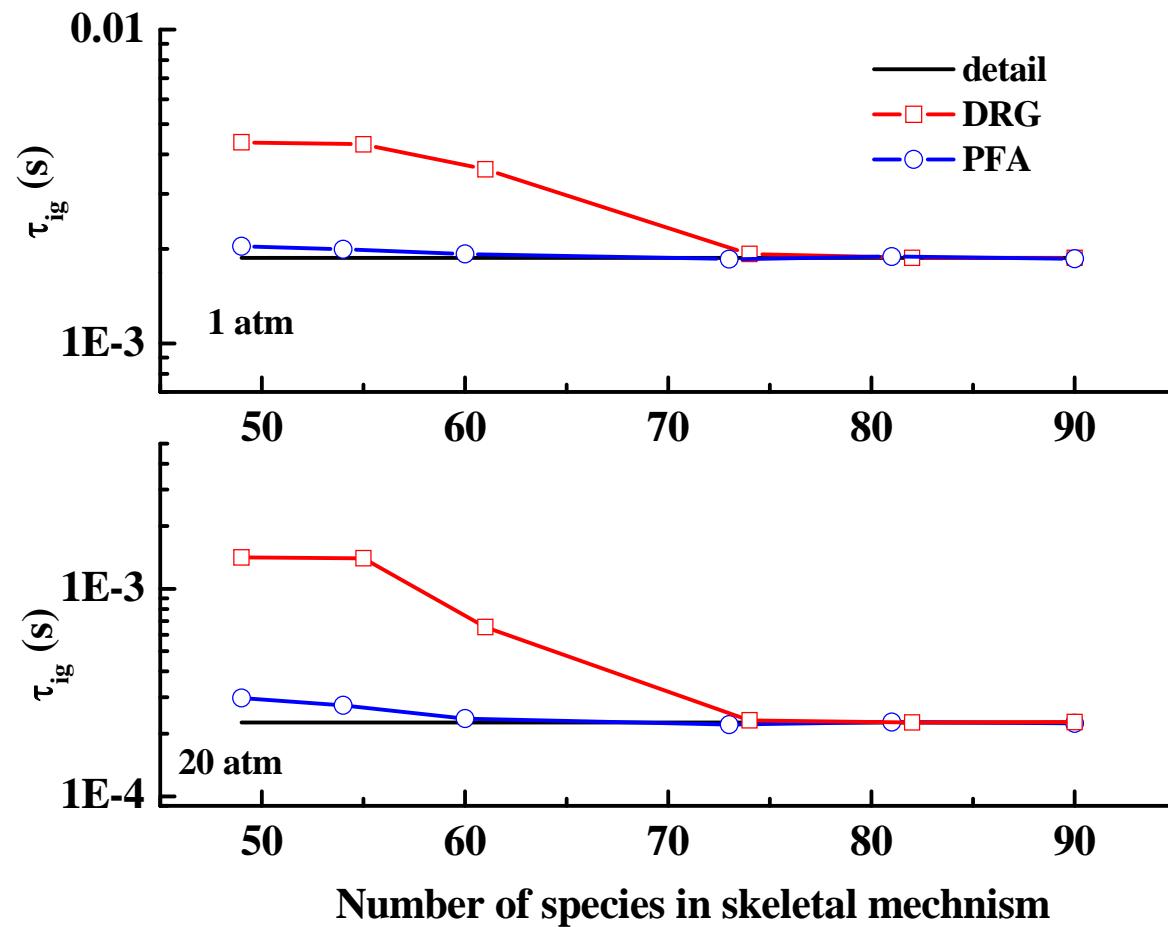
Computation efficiency vs. Mechanism size

No.	Mechanism	Base	Initial	Initial	RTOL	ATOL	CPU Time(s)		CPU	Time
		Time	Pressure	Temperature			VODE	MTS		
Step(s)	(atm)	(K)								
a1	H ₂	1.0E-6	1	1200	1.0E-4	1.0E-13	0.28	0.13	53.6%	
a2	H ₂	1.0E-7	1	1200	1.0E-4	1.0E-13	2.58	1.31	49.2%	
a3	H ₂	1.0E-8	1	1200	1.0E-4	1.0E-13	24.9	7.56	69.6%	
a4	H ₂	1.0E-9	1	1200	1.0E-4	1.0E-13	260	18.4	92.9%	
b1	CH ₄	1.0E-6	1	1400	1.0E-4	1.0E-13	123	25	79.7%	
b2	CH ₄	1.0E-7	1	1400	1.0E-4	1.0E-13	1269	181	85.7%	
b3	CH ₄	1.0E-8	1	1400	1.0E-4	1.0E-13	14639	1029	93.0%	
c1	C ₁₀ H ₂₂	1.0E-6	1	1400	1.0E-4	1.0E-13	86	14	83.7%	
c2	C ₁₀ H ₂₂	1.0E-7	1	1400	1.0E-4	1.0E-13	773	125	83.8%	
c3	C ₁₀ H ₂₂	1.0E-8	1	1400	1.0E-4	1.0E-13	7609	1049	86.2%	



A path flux analysis method for model reduction

$T_0=1200 \text{ K}$





Modeling of flame front trajectories of spherical propagating flames using MTS

